Retesting of Liquefaction and Non-Liquefaction Case Histories in the Imperial Valley using CPT

by

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Abstract

This report documents the retesting of liquefaction and non-liquefaction field case histories in the Imperial Valley with the cone penetration test (CPT). The River Park and Heber Road sites were originally tested using a mechanical cone following the 1979 Imperial Valley Earthquake (Bennett et al., 1981; Youd & Bennett, 1983). These two sites are rich in information because they have experienced several earthquakes in recent history, have been subjected to moderate levels of strong ground shaking, the liquefiable soils have appreciable fines content, and the sites contain a number of non-liquefied data points.

Recent liquefaction case histories databases (Moss et al., 2003) are based on data acquired using the electric cone, following ASTM spec. 5778. Case histories previously explored with the mechanical cone are now obsolete and the data non-standard. This report describes the acquisition and analysis of electric cone data at the Heber Road and River Park sites. These important sites can now be incorporated into liquefaction case history databases and used in back-analysis of liquefaction triggering.

1.0 INTRODUCTION

This report describes the retesting of liquefaction case histories sites in the Imperial Valley with the cone penetration test (CPT). The River Park and Heber Road sites were originally tested using a mechanical cone following the 1979 Imperial Valley Earthquake (Bennett et al., 1981; Youd & Bennett, 1983; Youd, 1985). These two sites are rich in information because they have experienced several earthquakes in recent history (1979 Imperial Valley, 1981 Westmoreland, and 1987 Superstitious Hills Earthquakes), have experienced high levels of strong ground shaking, the liquefiable soils have appreciable fines content, and the sites contain important non-liquefied data points in liquefiable material.

Recent liquefaction case histories databases (Moss et al., 2003) are based on data acquired using the electric cone, following ASTM spec. 5778. Field case histories previously explored with the mechanical cone are now obsolete and the data non-standard. This report describes field testing at the Heber Road and River Park sites using an electric cone. The purpose is so that these important case histories can be incorporated into liquefaction case history databases and used in back-analyses of liquefaction triggering.

2.0 REGIONAL TECTONICS, GEOMORPHOLOGY, AND SEISMICITY

The River Park and Heber Road sites both lie within the Imperial Valley, near the U.S.-Mexican border, in southern California (Figure 1). The Imperial Valley is located in the central part of the Salton Basin, a basin that has been formed due to tectonic rifting, the same crustal rifting that is associated with the Sea of Cortez, Baja California. The Imperial Valley is a deep sediment valley filled with over 6000m of sediment deposited over the last 4 million years (Sharp, 1982).

Parts of the Salton Basin are where an ancient lake, Lake Cahuilla, periodically resided. This ancient lake was found to have filled the basin four times between 700 A.D. and 1580 A.D, fed by the changing course of the Colorado River. The Salton Sea now fills in the lower part of the basin and was formed when the Colorado River jumped its course, with the aid of an irrigation mishap, and ran unchecked from 1905 to 1907.

The Imperial Valley is located at the southern reach of the San Andreas fault complex. Mapped seismogenic faults in the region include the San Andreas complex to the northwest, the Imperial and Brawley faults in the valley (Figure 1), the Mexicali fault to the south across the border, the Elsinor fault along the southwest edge of the Salton Basin, and the Superstition Hills and Superstition Mountain faults to the west.

This area has experienced a high rate of seismicity in recent years. Of particular interest are the 1940 M=7.0 El Centro, 1979 M=6.5 Imperial Valley, 1981 M=5.9 Westmoreland, and 1987 M=6.7 Superstition Hills events. The epicentral locations of primary rupture for these earthquakes are shown in Figure 1.

3.0 PREVIOUS STUDIES

A significant amount of liquefaction was observed following the 1979 Imperial Valley earthquake. This event produced a 35-km long trace of surface fault rupture along the Imperial fault, the same fault that ruptured in the 1940 El Centro event. Two sites of pronounced liquefaction were investigated by Mike Bennett and Les Youd of the USGS (Bennett et al., 1981; Youd and Bennett, 1983). These were the River Park and Heber Road Sites.

Subsurface investigations were conducted between December of 1979 and May of 1982 to quantify the *in situ* soil conditions. Testing included standard penetration tests (SPT) with continuous sampling, thin walled tube sampling, and mechanical cone penetration tests (CPT). The extent of liquefaction and lateral spreading was carefully documented. Grain size analysis and plasticity tests were performed on disturbed samples from the SPT, relatively undisturbed thin walled tubes samples, and surface samples of boil ejecta. The subsurface conditions were characterized in detail resulting in highly detailed cross sectional profiles of both sites.

Additional site investigations and analyses were carried out over the years relating to these sites and subsequent earthquakes (e.g., Bennet et al., 1984; Youd, 1984; and Youd and Wieczorek, 1984).

4.0 SITE DESCRIPTION

The geographic locations of the River Park and Heber Road sites are shown in Figure 1. Description of the sites, the near surface soil stratigraphy, and the observations of liquefaction follow.

4.1 RIVER PARK

River Park is a rodeo grounds located in the city of Brawley (Figure 1). River Park, also known as Cattle Call, is situated in the flood plain of the New River (Figure 2). The sediments that are of interest for liquefaction studies are the near surface fluvial deposits that are present across the site.

Subsurface investigations by Bennett el al. (1981) revealed that River Park stratigraphy was composed of three main soil layers (Figure 3). Unit A, the upper soil layer, consists of loose, brown, sandy silts grading to clayey silts. The sandy silts are interpreted as flood plain deposits and the clayey silts from a flood basin environment. Meandering of the river can produce these type of deposits in succession.

Unit B, the middle soil layer, is predominantly fine-grained silty clay and clay. The clay varies across the site in color and composition, with generally a high organic content. A back swamp depositional environment can result in these type of deposits.

Unit C, the lower unit, is a generally dense, well sorted fine sand. The sand appears to be massive with a slight change in color with depth. The upper part of this unit is noticeably less dense than the lower part.

Hundreds of sand boils, slumping, and surface cracking occurred at the River Park site as a result of the 1979 Imperial Valley Earthquake (Youd & Bennett, 1983). Sand boil ejecta was collected and traced to both Units A and C. Liquefaction is estimated to have occurred throughout Unit A, and in the loose upper portion of Unit C.

This site was investigated following the 1981 Westmoreland and 1987 Superstition Hills Earthquakes as well. No surface manifestation of liquefaction was recorded after either of these two events. In this report, we confine our assessment of liquefaction to Unit A.

4.2 HEBER ROAD

Heber Road is located near the Mexican border south of Holtville and northwest of Bonds Corner (Figure 1). The testing at the site occurred along Heber Road, adjacent to an irrigation canal and the Heber Dunes (Figure 4). The sediments of interest at this site are fluvial deposits from a relic river channel of the Alamo River.

Subsurface investigation by Bennett et al. (1981) found three units of sand and silty sand distributed across the site to a depth of 5 m (Figure 5). Unit A1 is found along the west side of the abandoned river channel, and is composed of dense to very dense, well sorted, very fine grained sand. This unit is upward fining, has horizontal laminations in the lower portion, and ripple beds in the upper portion. This deposit is considered to have formed as a river point bar.

Unit A2 is composed of very loose, moderately sorted silty sand and sand. Bennett et al. (1981) used aerial photos, the presence of fresh water gastropods, and geomorphic interpretation to determine that this deposit is channel sediments from the abandoned river channel.

Unit A3, along the east side of the channel, consists of medium dense, moderately sorted sand and silty sand. This deposit was interpreted to be a natural levee and overbank deposit based on the grain size distribution and its location in relation to the Units A1 and A2 (Bennett el al.,1981).

The 1979 Imperial Valley Earthquake caused liquefaction and a large lateral spread to occur at the Heber Road site. The lateral spread was approximately 160 m wide and 100 m long, and disrupted the pavement as it spread across the road, the adjacent canal, and into the dunes. Sand boils were found on the lateral spread and along the spread margins. Further studies of this site were carried out by Bierschwale and Stokoe (1984) and Norton (1983).

The Heber Road site was inspected following the 1987 Superstition Hills Earthquakes as well. No surface manifestation of liquefaction was recorded after this event. In this report, we perform assessments of liquefaction for all three soil units (A1, A2, A3) for the 1979 and 1987 earthquakes.

5.0 NEW FIELD WORK

5.1 RECONNASAINCE

Previous CPT soundings were located as accurately as possible. The information available on previous CPT locations included maps, figures, and photos from the literature (Bennett et al., 1981; Youd & Bennett, 1983; Youd, 1985), UTM coordinates supplied by Mike Bennett, and field notes provided by Les Youd.

Les Youd assisted in locating the previous CPT soundings in the field. Several field markers such as power poles, canals and trees remained unchanged since the previous investigations and thus aided in the field location process. Unfortunately, the UTM coordinates that had been previously collected were generated using an unknown baseline and therefore their reference datum could not be resolved. Using all information that was available, the previous CPT soundings were located as accurately as possible. The estimated confidence in relocating the old CPT test locations is on the order of 1 m. Figures 2 and 4 show the locations of the old and new CPT soundings, where the new soundings have the suffix RM to differentiate them from the old tests.

5.2 DGPS

Old and new CPT soundings were located using a differential global positioning system (DGPS) with sub-meter absolute accuracy. For DGPS locating we used a Trimble Ag132 differential ready GPS unit that is capable of receiving two separate sources of differential correction. As opposed to typical hand-held GPS unit surveys which rely solely on the constellation of satellites already available by the U.S. Dept. of Defense, differential GPS relies on the collection of an additional base station correction. The purpose of the base station correction is to account for and minimize the various errors associated with non-differential GPS surveys including atmospheric induced errors, satellite clock error, and satellite geometry or ephemeris error.

Differential GPS is typically employed using one of two methods. The first is capable of sub-centimeter resolution and requires the collection of data from both base station and rover units in the field, while the second is capable of sub-meter resolution and requires only a rover unit with a transmitted satellite or radio beacon base station signal. While the first method is much more precise in positional data, it also requires two units in the field in addition to the establishment of suitably accurate base station control points. On the other hand, if sub-meter precision is adequate for the project, the second method is much more easily implemented. Since this project required locating in the field several historic positions known to meter accuracy and since the availability of highly accurate control points was not known, the sub meter differential accuracy provided by our equipment was utilized for this project.

We used the differential signal provided by Omnistar's North American West satellite in real-time mode in order to provide instantaneous positions at the sub-meter level. This signal works through the transmission of a correction value that is sent via satellite and includes a specific correction for the particular area that the GPS unit is located. For example, the North American West satellite correction provides an accurate differential signal to the sub-meter level for most of the western United States. GPS positional data collected for this project was obtained using typically 7 constellation satellites at a dilution of position (DOP) value of 2 and a signal to noise ratio (S/N) of at least 11. This data was collected at a high level of accuracy; typical values of less than 4 DOP and a S/N ratio greater than 6 are normally recommended for differential GPS.

Data was collected in latitude/longitude and UTM coordinate systems, both referenced to the NAD83 three dimensional datum. For our study sites, the UTM zone is 11S. Elevation is referenced to the NAVD88 vertical datum and was obtained through a conversion from the NAD83 ellipsoid using the GEOID99 geoid. Data for both sites are included in Table 1 and correlate to the site maps for the River Park and Heber Road sites in Figures 2 and 4.

Table 1. GPS Data of CPT Locations

Location	Easting (m)	Northing (m)	NAVD88 Elevation (m)	Latitude	Longitude	Ellipsoid Height (m)

River Park Site (UTM 11S, NAD83)						
RVP002-RM	635294.0	3648838.5	-45.0	N32°58'10.28"	W115°33'08.15"	-79.4
RVP003-RM	635243.3	3648839.3	-45.7	N32°58'10.33"	W115°33'10.10"	-80.1
RVP005-RM	635071.5	3648839.2	-47.8	N32°58'10.40"	W115°33'16.71"	-82.2
Heber Road Site (UTM 11S, NAD83)						
HEB001-RM	651143.6	3622560.6	13.5	N32°43'49.78"	W115°23'13.23"	-21.1
HEB005-RM	651235.9	3622562.3	12.0	N32°43'49.79"	W115°23'09.69"	-22.6
HEB008a-RM	651325.8	3622563.6	12.6	N32°43'49.79"	W115°23'06.24"	-22.0
HEB008b-RM	651304.4	3622563.8	10.1	N32°43'49.80"	W115°23'07.06"	-24.5

Note: Maximum precision of data is 1 meter or approximately 0.03 seconds of latitude/longitude at these locations.

5.3 CONE PENETRATION TESTING

The University of California, Los Angeles Network for Earthquake Engineering Simulation (nees@UCLA) cone penetration testing truck was used in the field investigations. The nees@UCLA CPT truck is a Hogentogler rig equipped with a seismic-piezocone to characterize soil consistency, pore water pressure and shear wave velocities. The rig has a 20-ton hydraulic push capacity and side augers to provide the necessary reaction force. A fully automatic 5-channel ESFCS data acquisition system records measurements of cone tip resistance, sleeve friction, probe inclination, pore water pressure and shear wave velocities.

6.0 RESULTS & ANALYSIS

6.1 PRESENTATION OF RESULTS

The collection of electric CPT data from these two sites adds nine (9) liquefaction/non-liquefaction case histories to the worldwide database. The pertinent data for each case history is summarized in Table 2 for each of the three earthquakes and their effect on the individual soil layers investigated (Unit A at River Park and Units A, B, and C at Heber Road). The processing techniques used are described in detail in Chapter 4 of Moss (2003).

The estimates of strong ground shaking shown in Table 2 were taken from Cetin et al. (2000), in which site response analyses for these two Imperial Valley sites were performed. The site response analyses were based on detailed stratigraphy of the sites and strong ground motion recordings from nearby instruments. The mean and variance of the peak ground acceleration (PGA) were calculated in each analysis, thereby giving a best estimate of the accelerations experienced at the critical depths in question.

Complete details of each case history are included within Figures 6 through 9. The response of each earthquake at a particular site location is outlined. Each case history has a summary sheet and accompanying sheets with soil profiles and CPT logs. The critical layer in each profile is clearly marked by a box encompassing the layer extents. CPT logs are included in Appendix A and Appendix B as graphical and tabulated data, respectively.

The case histories of liquefaction/non-liquefaction are shown in relation to probabilistic liquefaction triggering curves from Moss & Seed (2004) in Figures 10 through 12. Figures 10 and 11 show the new case histories in direct relation to the curves for the uncorrected and corrected fines content respectively while Figure 12 shows the new case histories relative to the existing worldwide database and the triggering curves. Figure 10 shows the normalized tip resistance ($q_{c,1}$) versus the duration adjusted cyclic stress ratio (CSR*), whereas Figures 11 and 12 show the case histories by the normalized tip resistance which has been corrected for "apparent" fines content as measured by the friction ratio ($q_{c,1,mod}$). The tip resistance corrected for "apparent" fines content can be considered analogous to a clean sand corrected blow count ($N_{1,60,CS}$). Note that because of the large tip resistance measured in Heber Road Unit A1, this case history does not appear on the triggering plots.

TABLE 2. SUMMARY OF LIQUEFACTION AND NON-LIQUEFACTION CASE HISTORIES

EVENT	M_w	±														
1979 Imperial Valley	6.50	0.13														
SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	$q_{c,1}$ (MPa)	±	R_f (%)	±	c	σ_v' (kPa)	±	$q_{c,1,…}$ (MP…
Rver Park A	Y	C	0.5 to 2.5	1.50	0.33	0.30	0.17	0.07	7.99	6.95	1.28	1.66	0.47	15.83	4.03	8.6
Heber Road A1	N	B	1.9 to 4.2	3.05	0.38	1.80	0.33	0.07	25.84	11.32	1.21	0.80	0.37	41.81	4.40	26.5
Heber Road A2	Y	B	1.75 to 5.25	3.50	0.58	1.80	0.35	0.10	4.51	1.03	0.71	0.29	0.56	42.72	5.46	4.7
Heber Road A3	N	B	1.8 to 4.9	3.40	0.45	1.80	0.33	0.09	8.91	5.71	0.92	1.00	0.51	43.50	4.56	9.3
EVENT	M_w	±														
1981 Westmoreland	5.90	0.15														
SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	$q_{c,1}$ (MPa)	±	R_f (%)	±	c	σ_v' (kPa)	±	$q_{c,1,…}$ (MP…
Rver Park A	N	B	0.5 to 2.5	1.50	0.33	0.30	0.19	0.04	7.99	6.95	1.28	1.66	0.47	15.83	4.03	8.6
EVENT	M_w	±														
1987 Superstition Hills	6.70	0.13														
SITE DESCRIPTION	LIQ?	DATA CLASS	CRIT LAYER (m)	MEDIAN (m)	±	w.t. (m)	CSR	±	$q_{c,1}$ (MPa)	±	R_f (%)	±	c	σ_v' (kPa)	±	$q_{c,1,…}$ (MP…
Rver Park A	N	C	0.5 to 2.5	1.50	0.33	0.30	0.19	0.09	7.99	6.95	1.28	1.66	0.47	15.83	4.03	8.6
Heber Road A1	N	B	1.9 to 4.2	3.05	0.38	1.80	0.12	0.03	25.84	11.32	1.21	0.80	0.37	41.81	4.40	26.3
Heber Road A2	N	B	1.75 to 5.25	3.50	0.58	1.80	0.12	0.03	4.51	1.03	0.71	0.29	0.56	42.72	5.46	4.6
Heber Road A3	N	B	1.8 to 4.9	3.40	0.45	1.80	0.11	0.03	8.91	5.71	0.92	1.00	0.51	43.50	4.56	9.1

6.2 ANALYSIS

These sites have been explored and analyzed by numerous researchers (Youd, Bennet, Stokoe, Cetin, Moss) and in relation to the worldwide database of liquefaction/non-liquefaction case histories, can be considered to have minimal epistemic uncertainty.

It is interesting to note that River Park Unit A was observed to have liquefied during the 1979 Imperial Valley Earthquake which produced an uncorrected CSR=0.17, yet did not liquefy during the 1981 Westmoreland and 1987 Superstition Hills Earthquake that resulted in an uncorrected CSR=0.19 for both events. Correcting the CSR for duration using a magnitude correlated duration weighting factor (DWF_M ; Seed et al., 2003) the CSR* values become 0.14, 0.14, and 0.16 for the 1979, 1981, and 1987 events respectively. Any further discrepancy between CSR and liquefaction may due to a number of factors:

- First, the tip resistance of a liquefied layer is usually measured after liquefaction, and therefore after densification that can occur following liquefaction. The CPT measurements of Unit A were performed after liquefaction occurred. Therefore the measurements better represent the post-liquefaction resistance of the soil. However for soils that are near critical state when liquefaction occurs, it has been hypothesized that little overall densification results (Moss, 2003).
- Second, the characteristics of the ground shaking may be different between the earthquakes. Peak ground acceleration is only a single measure of complexity that is better characterized by considering frequency content, duration, and other characteristics of the strong ground shaking.

  Figure 13 shows plots of the 1979 Imperial Valley, 1981 Westmoreland, and 1987 Superstition Earthquakes, all recorded at the Brawley Station located approximately 5 km from the River Park site, with the 225 degree orientation shown. The acceleration, velocity, and displacement time histories are shown. The bracketed durations (±0.05g) for the three events are 11s for the 1979 event, 6s for the 1981 event, and 14.5 sec for the 1987 event. The 1979 event shows higher peak velocities (and thus higher strains) with several velocity pulses present, and higher peak displacements. Figure 14 shows a comparison of response spectra of the three events with the 1979 event having a higher response over a large portion of frequencies, particularly in the longer periods that coincide with site periods for deep soil profiles such as found at the River Park site. It has also been noted by Cetin et al. (2000) that the 1979 event had directivity effects that most likely resulted in the duration and velocity trends observed above. Therefore, even though the 1981 and 1987 events resulted in higher average peak ground accelerations at the site, the 1979 event tended to shake the site in the manner that was more conducive to liquefaction.
- Third, site response of a deep soft site like the River Park site will exhibit strong non-linearities once a threshold strain is reached. It is apparent from site response analyses (Cetin et al., 2000) that more strain softening resulted from the 1979 event than the 1981 and 1987 events. This strain softening decreased the PGA values for the 1979 event.

Based on these factors, we find that the higher CSR of the 1987 event is an artifact of the simplified procedure used in assessing liquefaction that only accounts for strong ground shaking through PGA. These results reinforce the benefits of a probabilistic triggering analysis that can quantify uncertainties within the simplified model (parameter uncertainty) and uncertainties that the simplified model fails to capture (model error).

As a final note, comparison plots of the mechanical and electric cone tip resistance and friction ratio values have been included in Appendix C. There is generally good agreement between the two, yet there is not enough data in this study to statistically quantify the variance. The electric cone appears to be generally more sensitive to changes in soil resistance and therefore more capable of picking up thin layers and seams.

7.0 CONCLUSIONS

This report presents nine (9) liquefaction/non-liquefaction case histories from the Imperial Valley that have been retested using the electric CPT. These sites were originally tested using the currently non-standard and obsolete mechanical cone, and could therefore not be included in the worldwide liquefaction/non-liquefaction database until now.

Included in this report is a full description of these sites, the new CPT data, and assessment of the validity of this data. These sites are important to include in the liquefaction database because they have experienced several earthquakes in recent history, have been subjected to moderate levels of strong ground shaking, the liquefiable soils have appreciable fines content, and the sites contain important non-liquefied data points.

8.0 ACKNOWLEDGEMENTS

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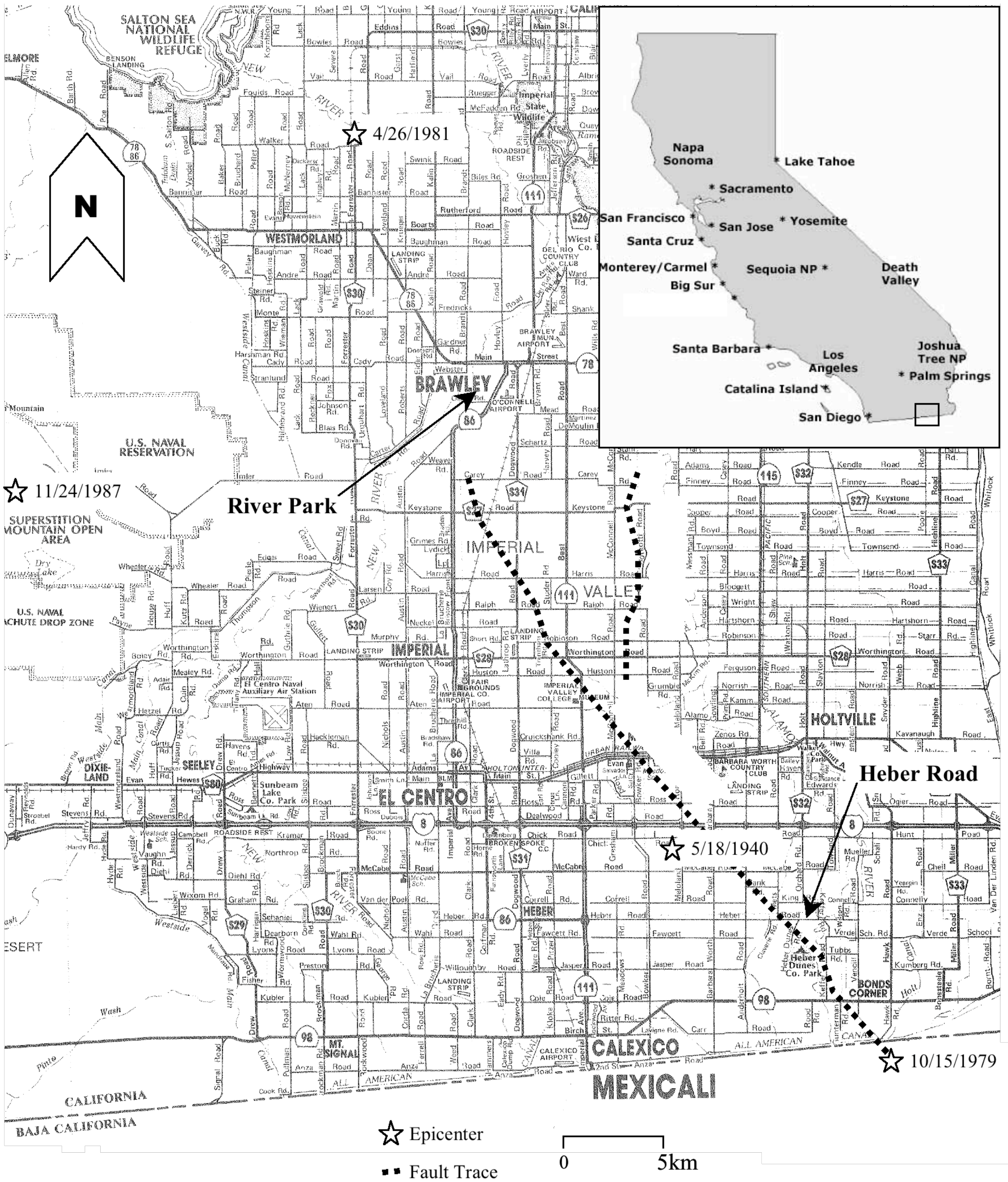

Figure 1. **Regional map showing locations of investigated sites, epicentral locations of recent earthquakes, and approximate locations of fault traces.**

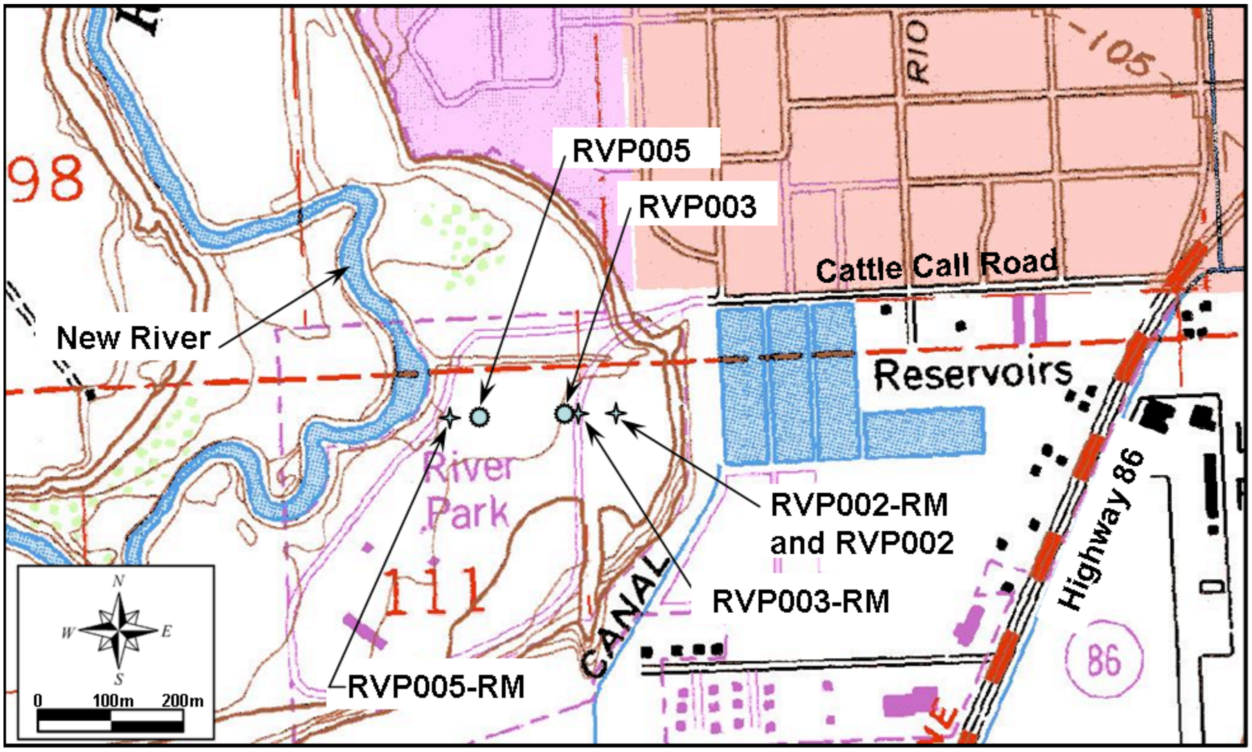

Figure 2. Map of the River Park Site, Brawley, California. Shown are the locations of the old (RVP00X) and new (RVP00X-RM) CPT tests.

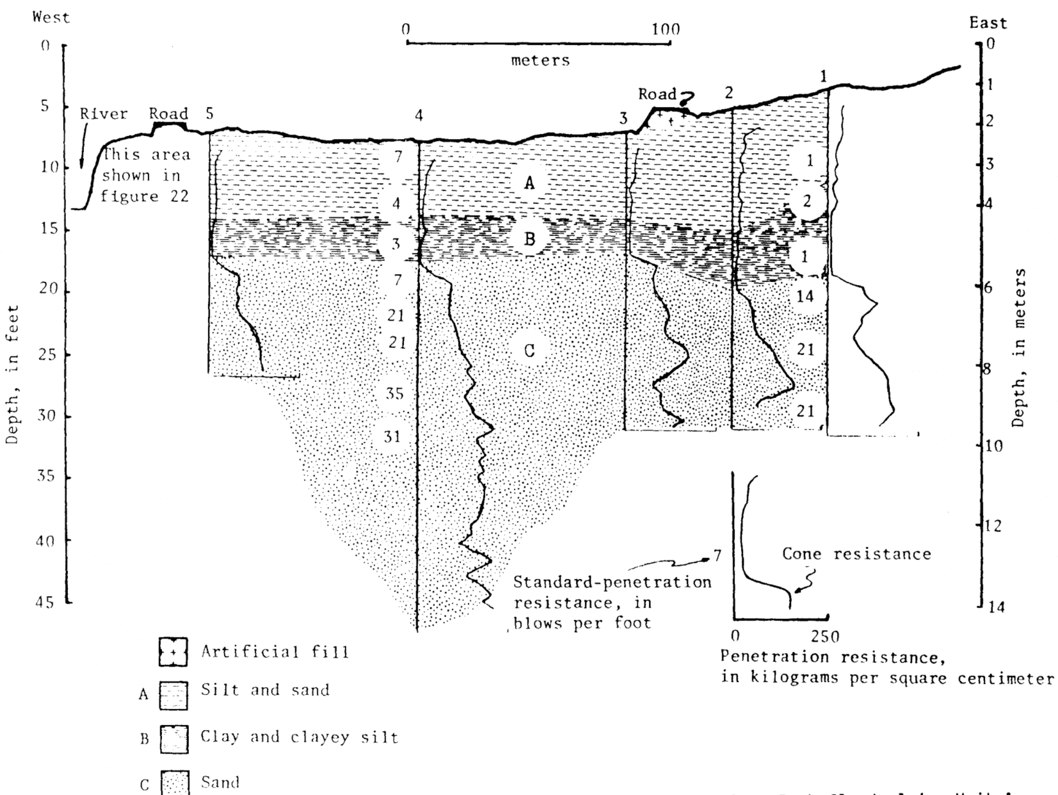

Figure 21. Profile of sediment units on River Park flood plain. Unit A represents overbank flood plain deposition. Unit B represents flood basin deposition. Unit C represents channel deposition, probably a point bar.

Figure 3. River Park cross section from Bennett et al. (1981). Locations of RVP002, 003, and 005 shown on Figure 2.

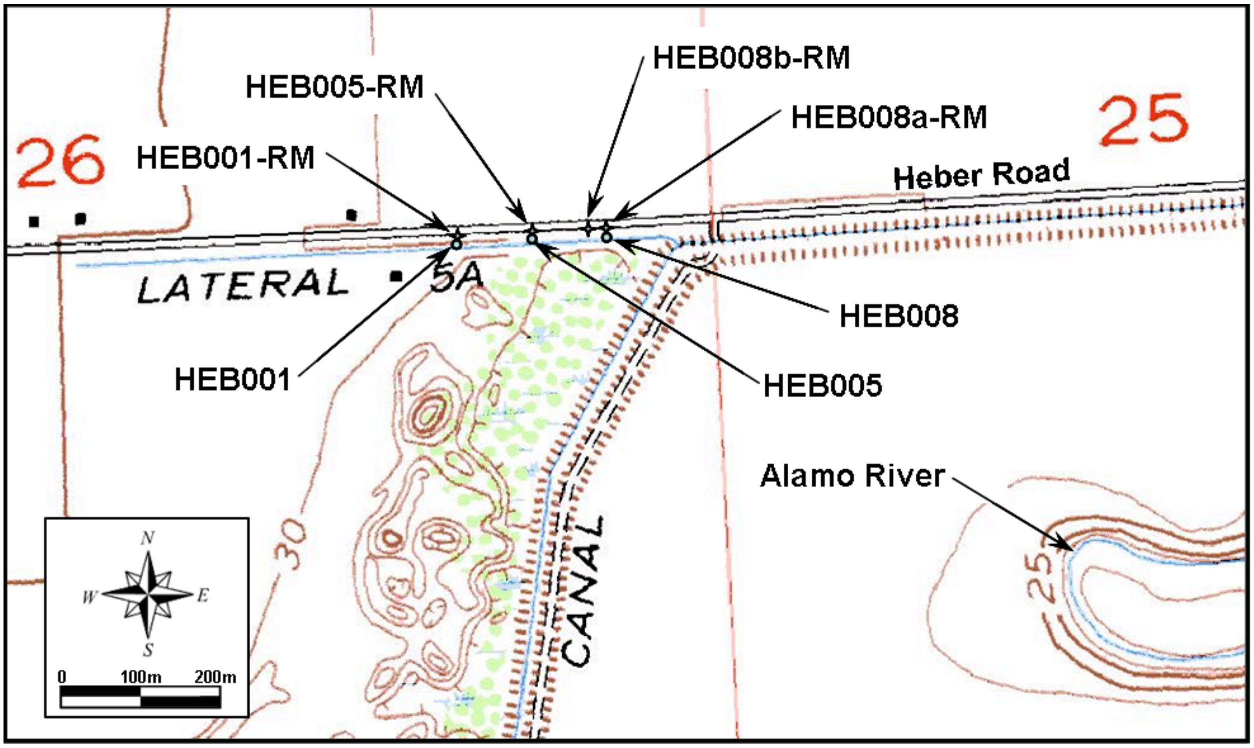

Figure 4. **Map of the Heber Road Site, Imperial County, California. Shown are the locations of the old (HEB00X) and new (HEB00X-RM) CPT tests.**

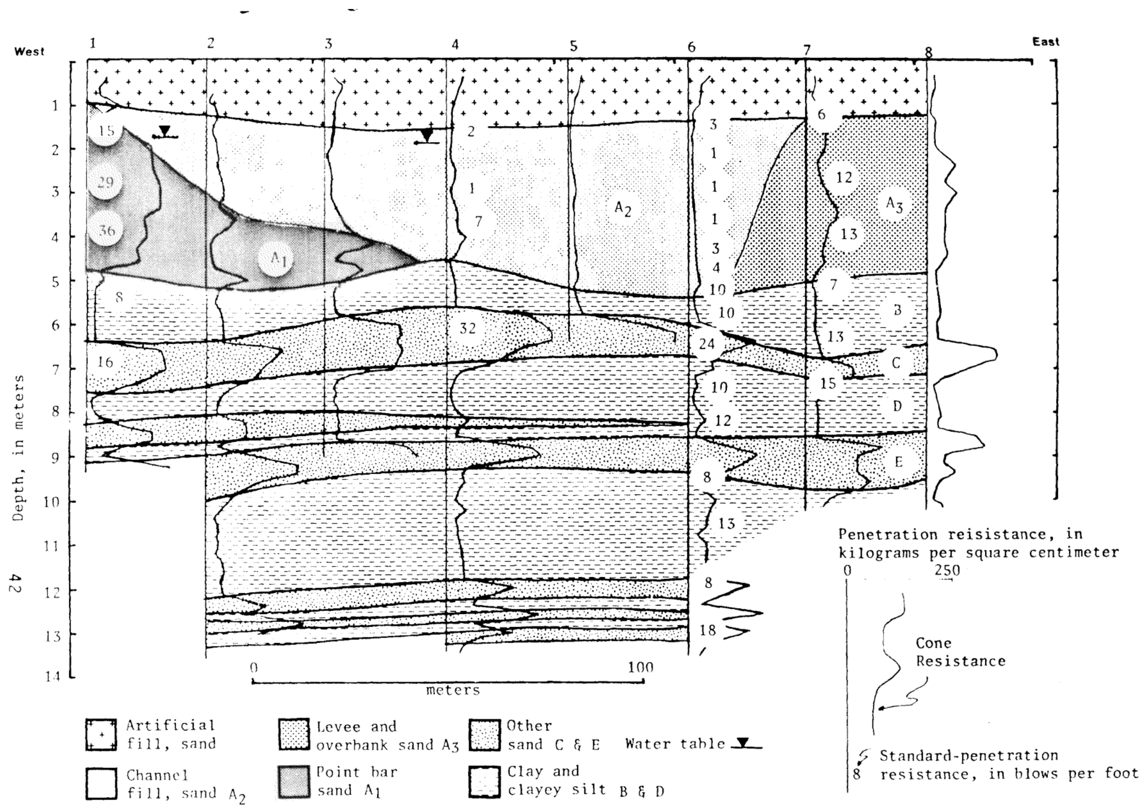

Figure 15. Profile of sediments at Heber Road site. Unit A_2 represents loose channel fill. Units A_1 and A_3 represent point bar deposits and overbank deposits, respectivly. Units B-F represent alternating stream channel and lacustrine deposits.

Figure 5. Heber Road cross section from Bennett et al. (1981). Locations of HEB001, 005, and 008 shown in Figure 4.

Earthquake:	1979 Imperial Valley, California
Magnitude:	M_L=6.6
Location:	River Park A
References:	Bennett et al. (1981), Youd & Bennett (1983)
Nature of Failure:	Numerous sand boils and surface cracking

Comments:

The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

This site is a flood plain of the New River. Surficial deposits are predominantly fluvial in nature.

The site lies 3.4 km from the norther terminus of fault rupture. Nearby strong motion instruments recorded the event.

Site response analysis was performed by Cetin et al. (2000) indicating ~0.16g for the River Park site.

Summary of Data:

Stress		**Strength**	
Liquefied	Y		
Data Class	C	Soil Class	ML
Critical Layer (m)	0.5 to 2.5	D_{50} (mm)	0.04
Median Depth (m)	1.50	%Fines	80
st.dev.	0.33	%PI	na
Depth to GWT (m)	0.30		
st.dev.	0.30		
σ_v (kPa)	27.60	q_c (MPa)	3.99
st.dev.	6.54	st.dev.	3.48
σ_v' (kPa)	15.83	f_s (kPa)	51.12
st.dev.	4.03	st.dev.	49.18
a_{max} (g)	0.16	norm. exp.	0.47
st.dev.	0.05	C_q, C_f	2.00
r_d	0.99	C_{thin}	1.00
st.dev.	0.02	f_{s1} (kPa)	102.23
Corrected Magnitude	6.50	st.dev.	98.36
st.dev.	0.13	q_{c1} (MPa)	7.99
CSR_{eq}	0.17	st.dev.	6.95
st.dev.	0.07	R_{f1}(%)	1.28
$C.O.V._{CSR}$	0.39	stdev	1.66

Figure 6a. Data Sheet, Imperial Valley Earthquake, River Park A.

Earthquake:	1981 Westmorland, California
Magnitude:	M_s=6.0
Location:	River Park A
References:	Bennett et al. (1981), Youd (1985)
Nature of Failure:	No Liquefaction

Comments:

The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

This site is a flood plain of the New River. Surficial deposits are predominantly fluvial in nature.

River Park is ~14km from the epicenter.
Nearby strong motion instruments recorded the event.

Site response analysis was performed by Cetin et al. (2000) indicating ~0.17g for the River Park site.

Summary of Data:

Stress		**Strength**	
Liquefied	N		
Data Class	B	Soil Class	ML
Critical Layer (m)	0.5 to 2.5	D_{50} (mm)	0.04
Median Depth (m)	1.50	%Fines	80
st.dev.	0.29	%PI	na
Depth to GWT (m)	0.30		
st.dev.	0.30		
σ_v (kPa)	27.60	q_c (MPa)	3.99
st.dev.	5.77	st.dev.	3.48
σ_v' (kPa)	15.83	f_s (kPa)	51.12
st.dev.	3.90	st.dev.	49.18
a_{max} (g)	0.17	norm. exp.	0.47
st.dev.	0.02	C_q, C_f	2.00
r_d	0.99	C_{thin}	1.00
st.dev.	0.00	f_{s1} (kPa)	102.23
Corrected Magnitude	5.90	st.dev.	98.36
st.dev.	0.15	q_{c1} (MPa)	7.99
CSR_{eq}	0.19	st.dev.	6.95
st.dev.	0.04	R_{f1}(%)	1.28
C.O.V.$_{CSR}$	0.23	stdev	1.66

Figure 6b. Data Sheet, Westmoreland Earthquake, River Park A.

Earthquake:	1987 Superstition Hills, California
Magnitude:	M_w=6.7
Location:	River Park A
References:	Bennett et al. (1981), Youd & Bennett (1983)
Nature of Failure:	No Liquefaction

Comments:

The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

This site is a flood plain of the New River. Surficial deposits are predominantly fluvial in nature.

River Park site is ~30km from epicenter.
Nearby strong motion instruments recorded the event.

Site response analysis was performed by Cetin et al. (2000) indicating ~0.19g for the River Park site.

Summary of Data:

Stress		**Strength**	
Liquefied	N		
Data Class	C	Soil Class	ML
Critical Layer (m)	0.5 to 2.5	D_{50} (mm)	0.04
Median Depth (m)	1.50	%Fines	80
st.dev.	0.33	%PI	na
Depth to GWT (m)	0.30		
st.dev.	0.30		
σ_v (kPa)	27.60	q_c (MPa)	3.99
st.dev.	6.54	st.dev.	3.48
σ_v' (kPa)	15.83	f_s (kPa)	51.12
st.dev.	4.03	st.dev.	49.18
a_{max} (g)	0.19	norm. exp.	0.47
st.dev.	0.02	C_q, C_f	2.00
r_d	0.99	C_{thin}	1.00
st.dev.	0.01	f_{s1} (kPa)	102.23
Corrected Magnitude	6.70	st.dev.	98.36
st.dev.	0.13	q_{c1} (MPa)	7.99
CSR_{eq}	0.19	st.dev.	6.95
st.dev.	0.09	R_{f1}(%)	1.28
$C.O.V._{CSR}$	0.46	stdev	1.66

Figure 6c. Data Sheet, Superstition Hills Earthquake, River Park A.

River Park A

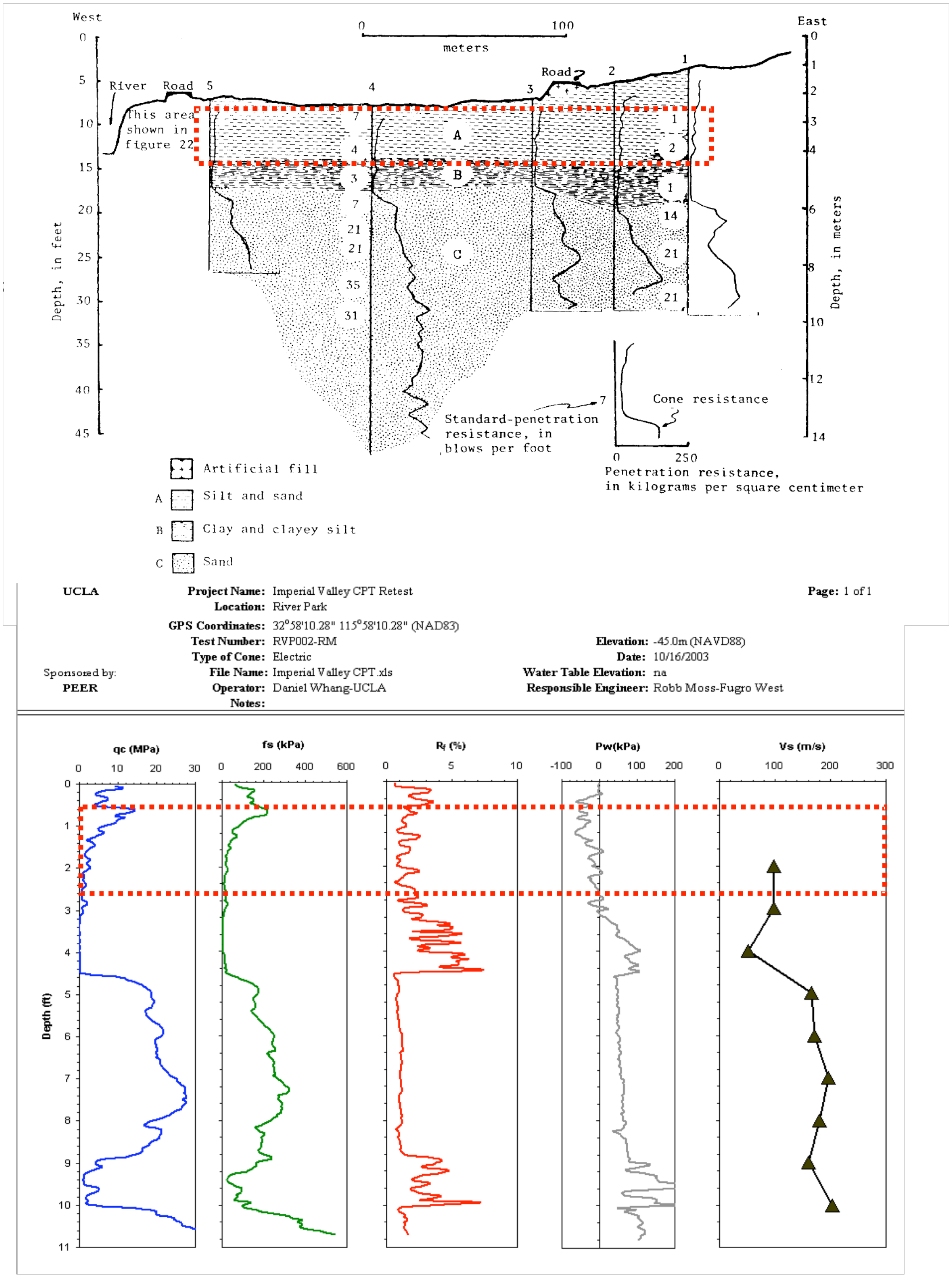

Figure 6d. Logs, River Park A.

River Park A

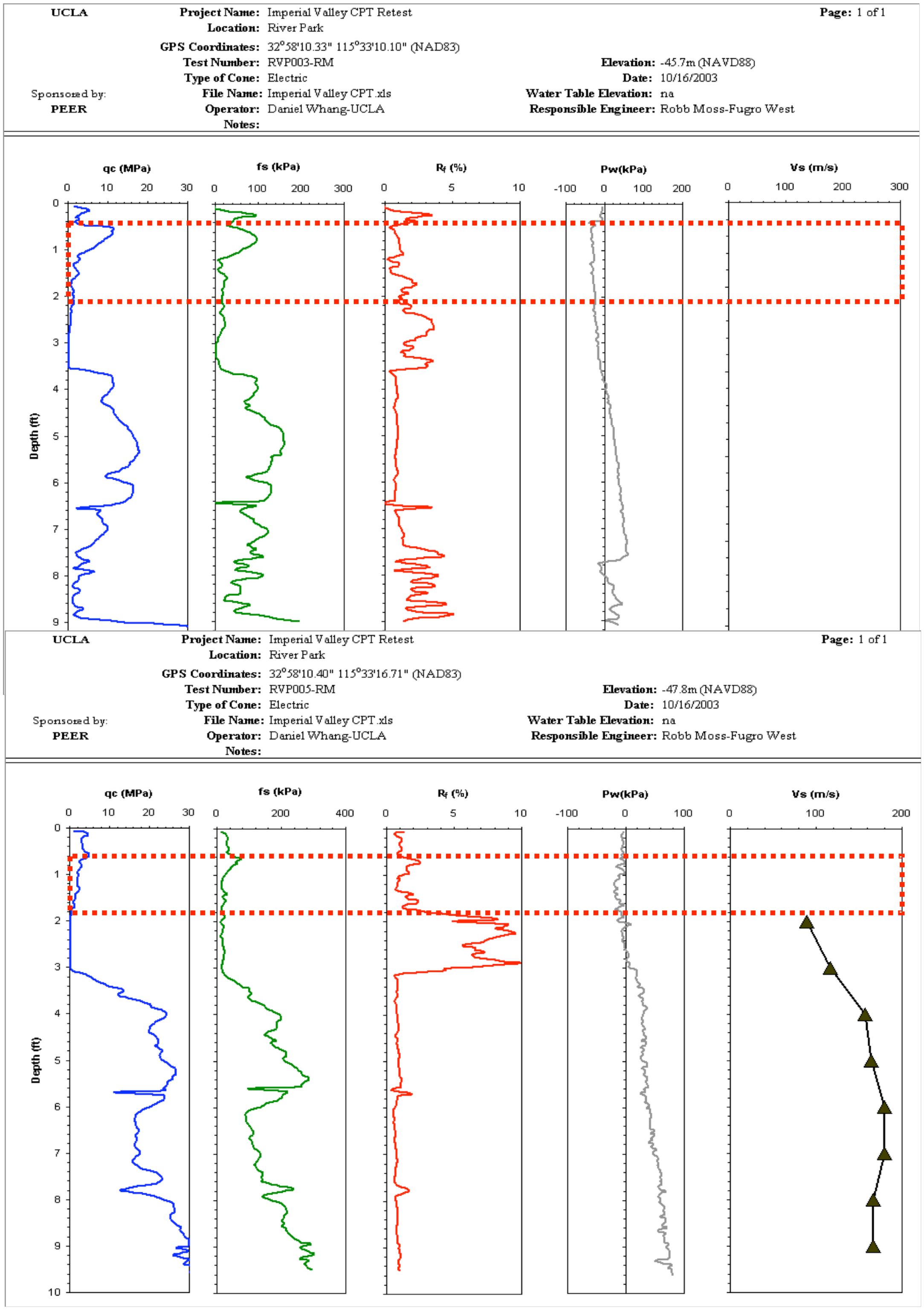

Figure 6e. Logs, River Park A.

Earthquake:	1979 Imperial Valley, California
Magnitude:	M_L=6.6
Location:	Heber Road A1
References:	Bennett et al. (1981), Youd & Bennett (1983)
Nature of Failure:	No Liquefaction

Comments:

The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

A lateral spread formed at this site and spread from the road south into the dunes. The lateral spread was approximately 160m wide by 100m long.

The liquefaction occurred in river channel deposits from an relic braid of the Alamo River, unit A2. Units A1 and A3 are point bar and overbank deposits, respectively.

The site is < 2km from the southern end of fault rupture. Nearby strong motion instruments recorded the event. Cetin et al. (2000) performed site response analysis which yielded ~0.45 to 0.50 g.

Summary of Data:

Stress		**Strength**	
Liquefied	N		
Data Class	B	Soil Class	SM/ML
Critical Layer (m)	1.9 to 4.2	D_{50} (mm)	0.12
Median Depth (m)	3.05	%Fines	25
st.dev.	0.38	%PI	na
Depth to GWT (m)	1.80		
st.dev.	0.90		
σ_v (kPa)	54.08	q_c (MPa)	18.71
st.dev.	7.70	st.dev.	8.20
σ_v' (kPa)	41.81	f_s (kPa)	225.84
st.dev.	4.40	st.dev.	113.27
a_{max} (g)	0.47	norm. exp.	0.37
st.dev.	0.05	C_q, C_f	1.38
r_d	0.82	C_{thin}	1.00
st.dev.	0.01	f_{s1} (kPa)	311.83
M_w	6.50	st.dev.	156.40
st.dev.	0.13	q_{c1} (MPa)	25.84
CSR_{eq}	0.33	st.dev.	11.32
st.dev.	0.07	R_{f1}(%)	1.21
$C.O.V._{CSR}$	0.23	stdev	0.80

Figure 7a. Data Sheet, Imperial Valley Earthquake, Heber Road A1.

Earthquake:	1987 Superstition Hills, California
Magnitude:	M_w=6.7
Location:	Heber Road A1
References:	Bennett et al. (1981), Youd & Bennett (1983)
Nature of Failure:	No Liquefaction

Comments:

The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

A lateral spread formed at this site and spread from the road south into the dunes. The lateral spread was approximately 160m wide by 100m long.

The liquefaction occurred in river channel deposits from an relic braid of the Alamo River, unit A2. Units A1 and A3 are point bar and overbank deposits, respectively.

The site is ~60 km from the epicenter.
Nearby strong motion instruments recorded the event.
Cetin et al. (2000) performed site response analysis which yielded ~0.16 g.

Summary of Data:

Stress		**Strength**	
Liquefied	N		
Data Class	B	Soil Class	SM/ML
Critical Layer (m)	1.9 to 4.2	D_{50} (mm)	0.12
Median Depth (m)	3.05	%Fines	25
st.dev.	0.38	%PI	na
Depth to GWT (m)	1.80		
st.dev.	0.90		
σ_v (kPa)	54.08	q_c (MPa)	18.71
st.dev.	7.70	st.dev.	8.20
σ_v' (kPa)	41.81	f_s (kPa)	225.84
st.dev.	4.40	st.dev.	113.27
a_{max} (g)	0.16	norm. exp.	0.37
st.dev.	0.02	C_q, C_f	1.38
r_d	0.82	C_{thin}	1.00
st.dev.	0.02	f_{s1} (kPa)	311.83
M_w	6.70	st.dev.	156.40
st.dev.	0.13	q_{c1} (MPa)	25.84
CSR_{eq}	0.12	st.dev.	11.32
st.dev.	0.03	R_{f1}(%)	1.21
$C.O.V._{CSR}$	0.21	stdev	0.80

Figure 7b. Data Sheet, Westmoreland Earthquake, Heber Road A1.

Heber Road A1

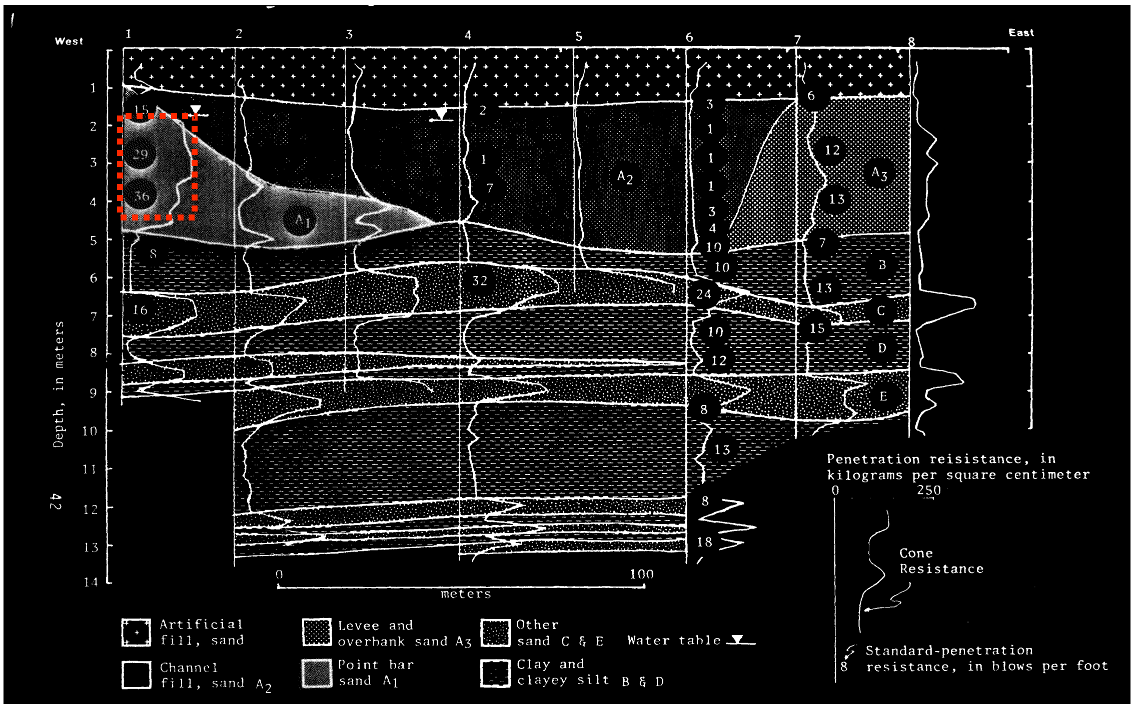

Figure 15. Profile of sediments at Heber Road site. Unit A_2 represents loose channel fill. Units A_1 and A_3 represent point bar deposits and overbank deposits, respectivly. Units B-F represent alternating stream channel and lacustrine deposits.

Figure 7c. **Logs, Heber Road A1.**

Heber Road A1

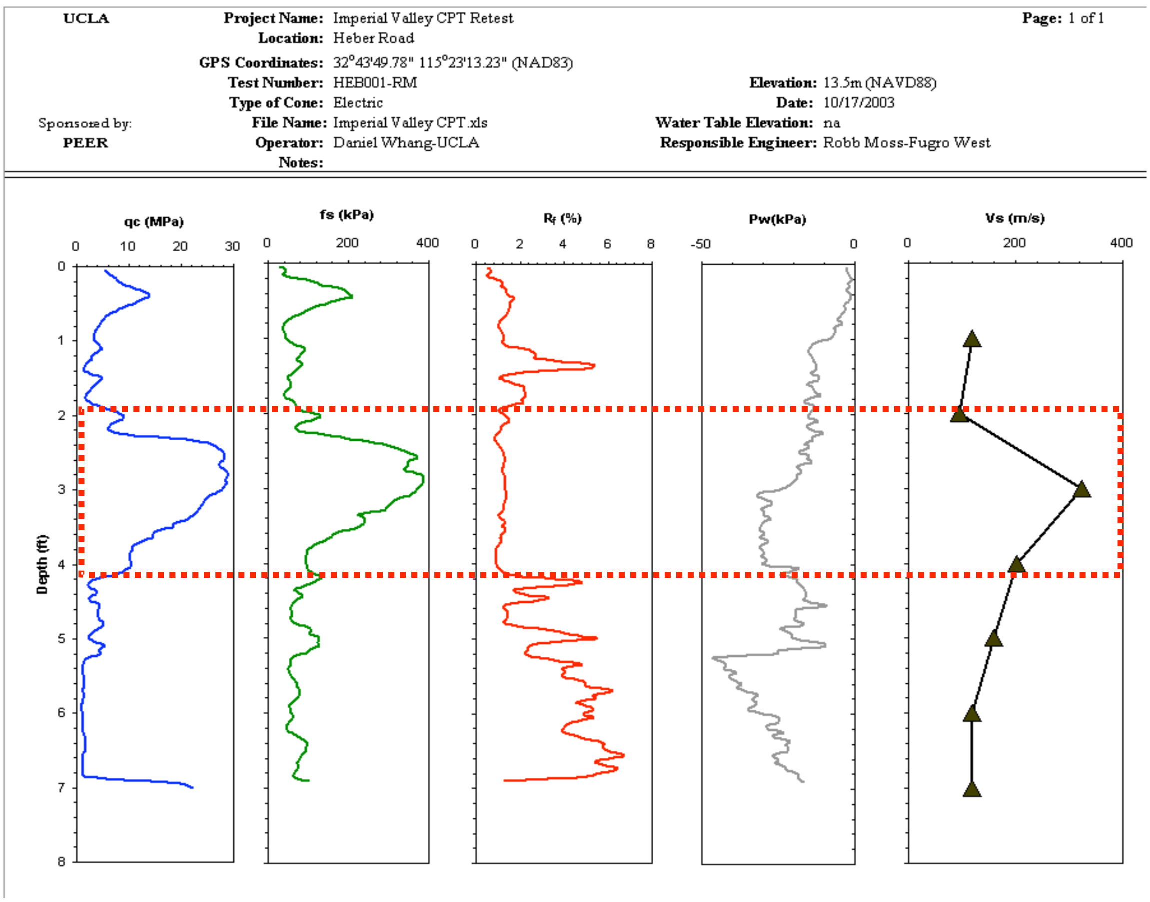

Figure 7d. Logs, Heber Road A1.

Earthquake:	1979 Imperial Valley, California
Magnitude:	M_L=6.6
Location:	Heber Road A2
References:	Bennett et al. (1981), Youd & Bennett (1983)
Nature of Failure:	Lateral spreading and sand boils

Comments:

The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

A lateral spread formed at this site and spread from the road south into the dunes. The lateral spread was approximately 160m wide by 100m long.

The liquefaction occurred in river channel deposits from an relic braid of the Alamo River, unit A2. Units A1 and A3 are point bar and overbank deposits, respectively.

The site is < 2km from the southern end of fault rupture. Nearby strong motion instruments recorded the event. Cetin et al. (2000) performed site response analysis which yielded ~0.45 to 0.50 g.

Summary of Data:

Stress		**Strength**	
Liquefied	Y		
Data Class	B	Soil Class	SM
Critical Layer (m)	1.75 to 5.25	D_{50} (mm)	0.11
Median Depth (m)	3.50	%Fines	29
st.dev.	0.58	%PI	na
Depth to GWT (m)	1.80		
st.dev.	0.90		
σ_v (kPa)	59.40	q_c (MPa)	2.80
st.dev.	10.62	st.dev.	0.64
σ_v' (kPa)	42.72	f_s (kPa)	19.75
st.dev.	5.46	st.dev.	6.58
a_{max} (g)	0.47	norm. exp.	0.56
st.dev.	0.05	C_q, C_f	1.61
r_d	0.78	C_{thin}	1.00
st.dev.	0.02	f_{s1} (kPa)	31.80
Corrected Magnitude	6.50	st.dev.	10.59
st.dev.	0.13	q_{c1} (MPa)	4.51
CSR_{eq}	0.35	st.dev.	1.03
st.dev.	0.10	R_{f1}(%)	0.71
C.O.V.$_{CSR}$	0.29	stdev	0.29

Figure 8a. Data Sheet, Imperial Valley Earthquake, Heber Road A2.

Earthquake:	1987 Superstition Hills, California
Magnitude:	M_w=6.7
Location:	Heber Road A2
References:	Bennett et al. (1981), Youd & Bennett (1983)
Nature of Failure:	No Liquefaction

Comments:

The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

A lateral spread formed at this site and spread from the road south into the dunes. The lateral spread was approximately 160m wide by 100m long.

The liquefaction occurred in river channel deposits from an relic braid of the Alamo River, unit A2. Units A1 and A3 are point bar and overbank deposits, respectively.

The site is ~60 km from the epicenter.
Nearby strong motion instruments recorded the event.
Cetin et al. (2000) performed site response analysis which yielded ~0.15 g.

Summary of Data:

Stress		**Strength**	
Liquefied	N		
Data Class	B	Soil Class	SM
Critical Layer (m)	1.75 to 5.25	D_{50} (mm)	0.11
Median Depth (m)	3.50	%Fines	29
st.dev.	0.58	%PI	na
Depth to GWT (m)	1.80		
st.dev.	0.90		
σ_v (kPa)	59.40	q_c (MPa)	2.80
st.dev.	10.62	st.dev.	0.64
σ_v' (kPa)	42.72	f_s (kPa)	19.75
st.dev.	5.46	st.dev.	6.58
a_{max} (g)	0.15	norm. exp.	0.56
st.dev.	0.02	C_q, C_f	1.61
r_d	0.78	C_{thin}	1.00
st.dev.	0.02	f_{s1} (kPa)	31.80
Corrected Magnitude	6.70	st.dev.	10.59
st.dev.	0.13	q_{c1} (MPa)	4.51
CSR_{eq}	0.12	st.dev.	1.03
st.dev.	0.03	R_{f1}(%)	0.71
$C.O.V._{CSR}$	0.28	stdev	0.29

Figure 8b. Data Sheet, Superstition Hills Earthquake, Heber Road A2.

Heber Road A2

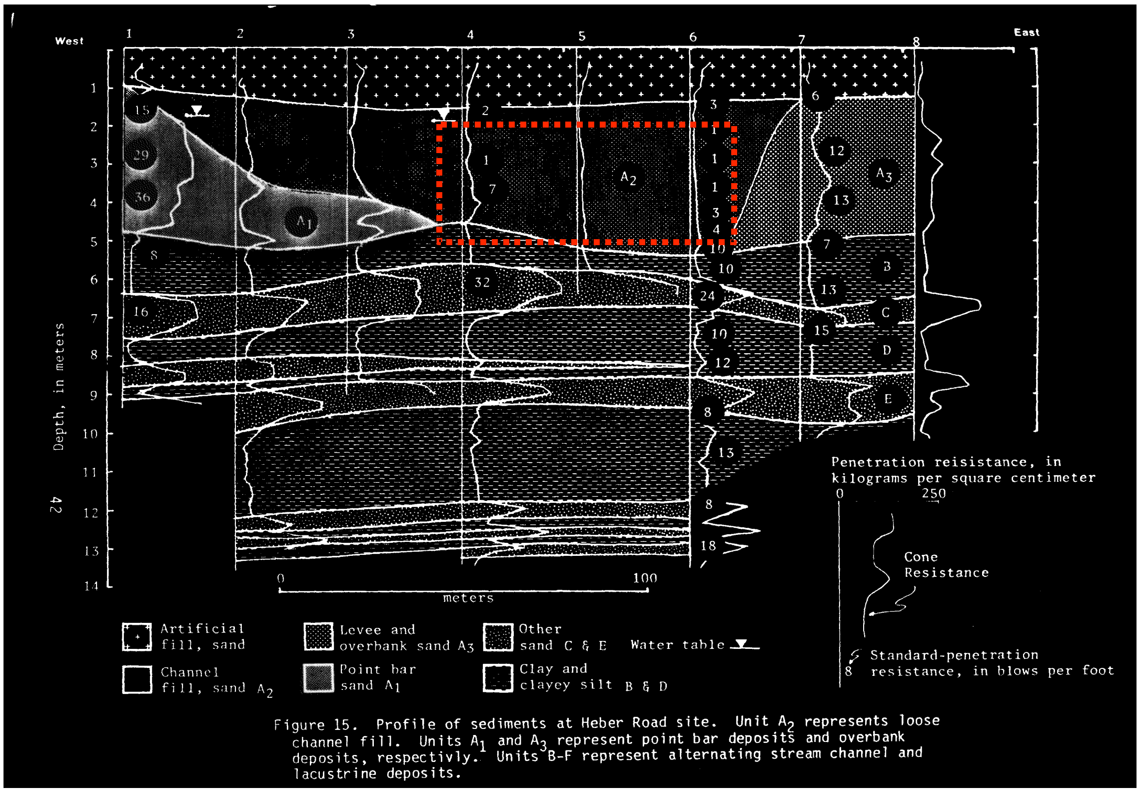

Figure 8c. Logs, Heber Road A2.

Heber Road A2

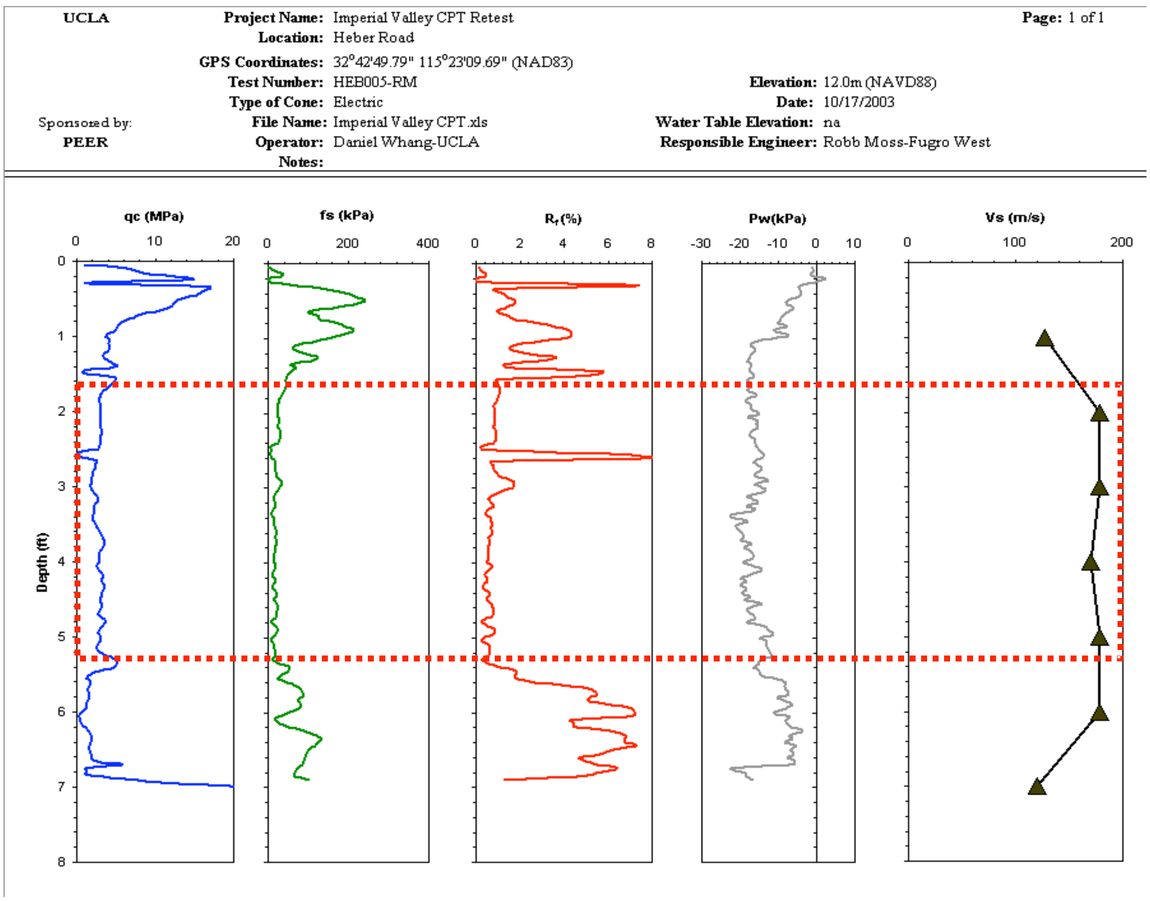

Figure 8d. Logs, Heber Road A2.

Earthquake:	1979 Imperial Valley, California
Magnitude:	M_L=6.6
Location:	Heber Road A3
References:	Bennett et al. (1981), Youd & Bennett (1983)
Nature of Failure:	No Liquefaction

Comments:

The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

A lateral spread formed at this site and spread from the road south into the dunes. The lateral spread was approximately 160m wide by 100m long.

The liquefaction occurred in river channel deposits from an relic braid of the Alamo River, unit A2. Units A1 and A3 are point bar and overbank deposits, respectively.

The site is < 2km from the southern end of fault rupture. Nearby strong motion instruments recorded the event. Cetin et al. (2000) performed site response analysis which yielded ~0.45 to 0.50 g.

Summary of Data:

Stress		**Strength**	
Liquefied	N		
Data Class	B	Soil Class	SM/ML
Critical Layer (m)	1.8 to 4.9	D_{50} (mm)	0.10
Median Depth (m)	3.40	%Fines	37
st.dev.	0.45	%PI	na
Depth to GWT (m)	1.80		
st.dev.	0.90		
σ_v (kPa)	59.20	q_c (MPa)	5.83
st.dev.	8.76	st.dev.	3.74
σ_v' (kPa)	43.50	f_s (kPa)	53.71
st.dev.	4.56	st.dev.	46.90
a_{max} (g)	0.47	norm. exp.	0.51
st.dev.	0.05	C_q, C_f	1.53
r_d	0.75	C_{thin}	1.00
st.dev.	0.03	f_{s1} (kPa)	82.11
M_w	6.50	st.dev.	71.69
st.dev.	0.13	q_{c1} (MPa)	8.91
CSR_{eq}	0.33	st.dev.	5.71
st.dev.	0.09	R_{f1}(%)	0.92
$C.O.V._{CSR}$	0.26	stdev	1.00

Figure 9a. Data Sheet, Imperial Valley Earthquake, Heber Road A3.

Earthquake: 1987 Superstition Hills, California
Magnitude: M_w=6.7
Location: Heber Road A3
References: Bennett et al. (1981), Youd & Bennett (1983)
Nature of Failure: No Liquefaction

Comments: The Imperial Valley lies in the Salton Basin. This basin is a regional depression formed by large scale tectonic rifting. The basin is tectonically active, the primary seismogenic sources being the Imperial, Brawley, and Mexicali faults.

A lateral spread formed at this site and spread from the road south into the dunes. The lateral spread was approximately 160m wide by 100m long.

The liquefaction occurred in river channel deposits from an relic braid of the Alamo River, unit A2. Units A1 and A3 are point bar and overbank deposits, respectively.

The site is ~60 km from the epicenter.
Nearby strong motion instruments recorded the event.
Cetin et al. (2000) performed site response analysis which yielded ~0.13 g.

Summary of Data:

Stress		**Strength**	
Liquefied	N		
Data Class	B	Soil Class	SM/ML
Critical Layer (m)	1.8 to 4.9	D_{50} (mm)	0.10
Median Depth (m)	3.40	%Fines	37
st.dev.	0.45	%PI	na
Depth to GWT (m)	1.80		
st.dev.	0.90		
σ_v (kPa)	59.20	q_c (MPa)	5.83
st.dev.	8.76	st.dev.	3.74
σ_v' (kPa)	43.50	f_s (kPa)	53.71
st.dev.	4.56	st.dev.	46.90
a_{max} (g)	0.13	norm. exp.	0.51
st.dev.	0.02	C_q, C_f	1.53
r_d	0.75	C_{thin}	1.00
st.dev.	0.03	f_{s1} (kPa)	82.11
M_w	6.70	st.dev.	71.69
st.dev.	0.13	q_{c1} (MPa)	8.91
CSR_{eq}	0.11	st.dev.	5.71
st.dev.	0.03	R_{f1}(%)	0.92
$C.O.V._{CSR}$	0.24	stdev	1.00

Figure 9b. Data Sheet, Superstition Hills Earthquake, Heber Road A3.

Heber Road A3

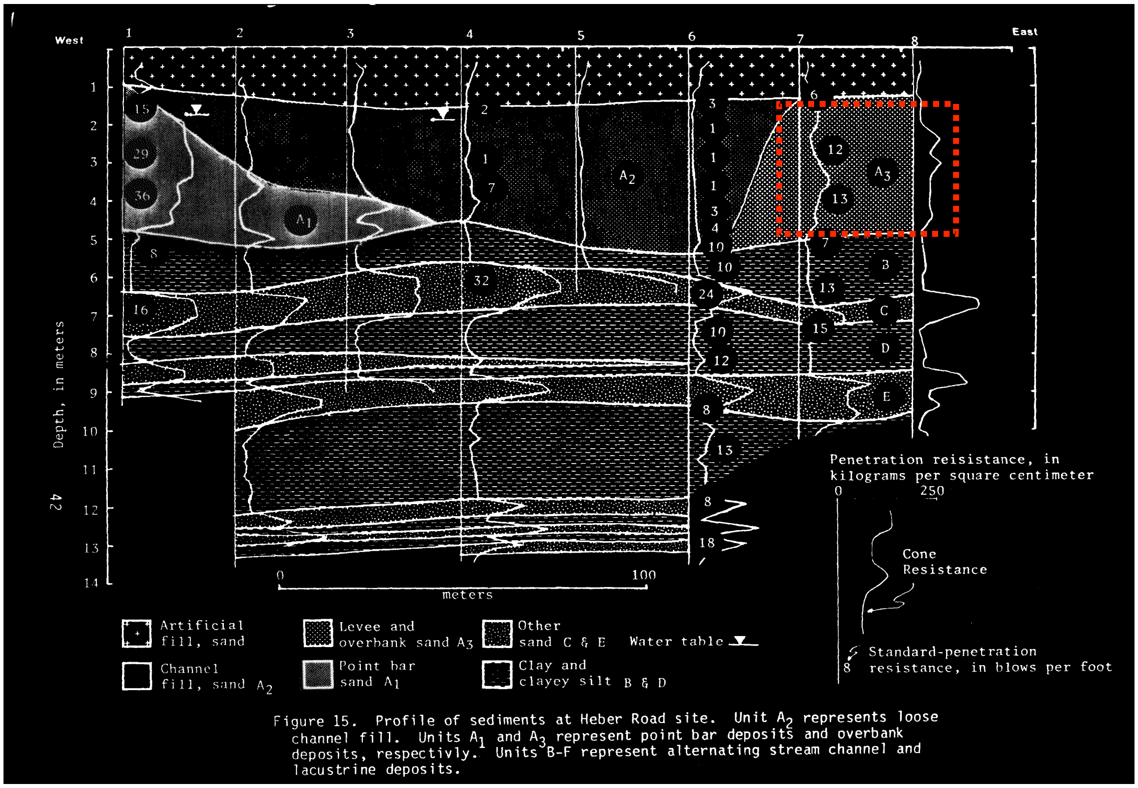

Figure 9c. Logs, Heber Road A3.

Heber Road A3

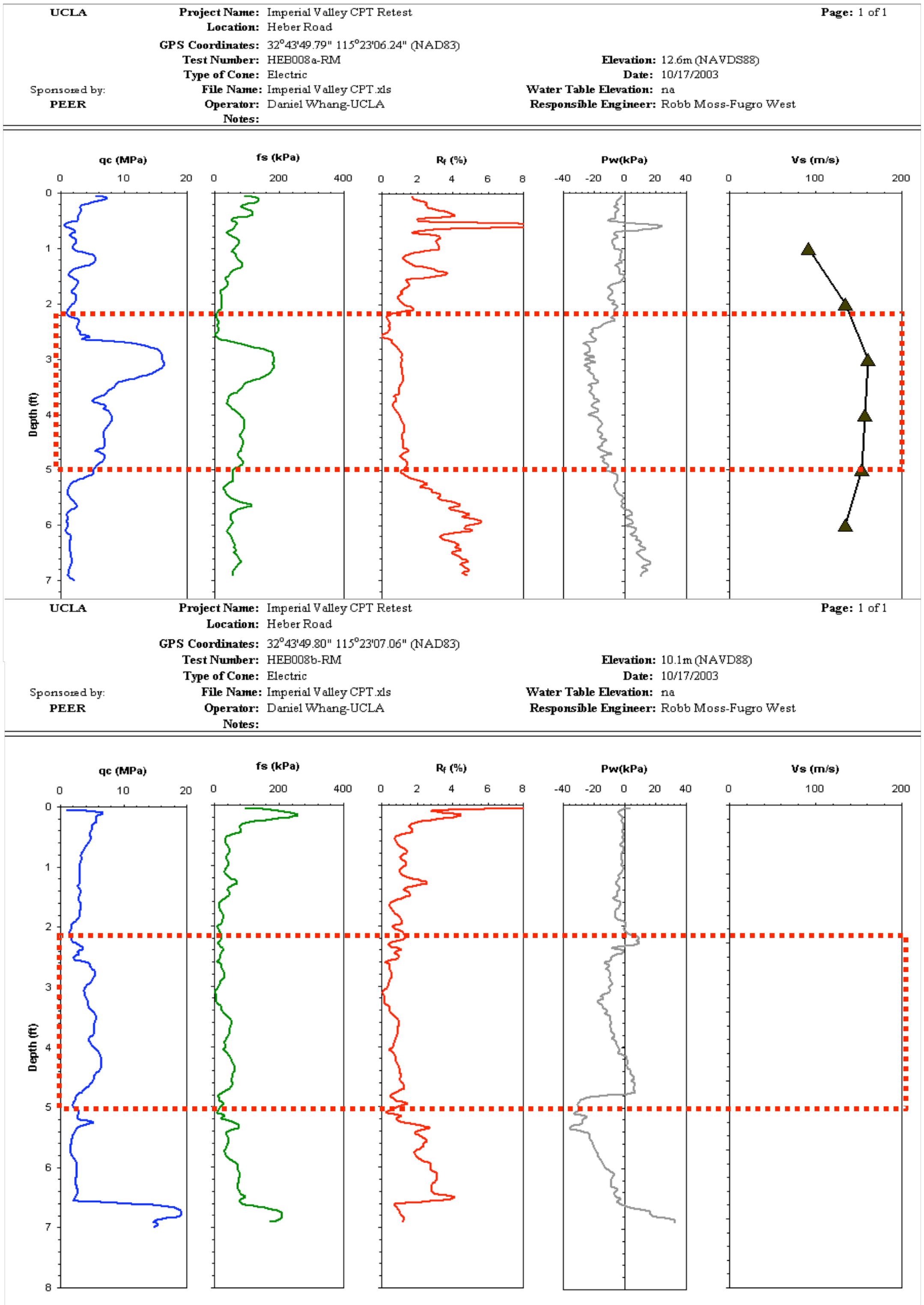

Figure 9c. Logs, Heber Road A3.

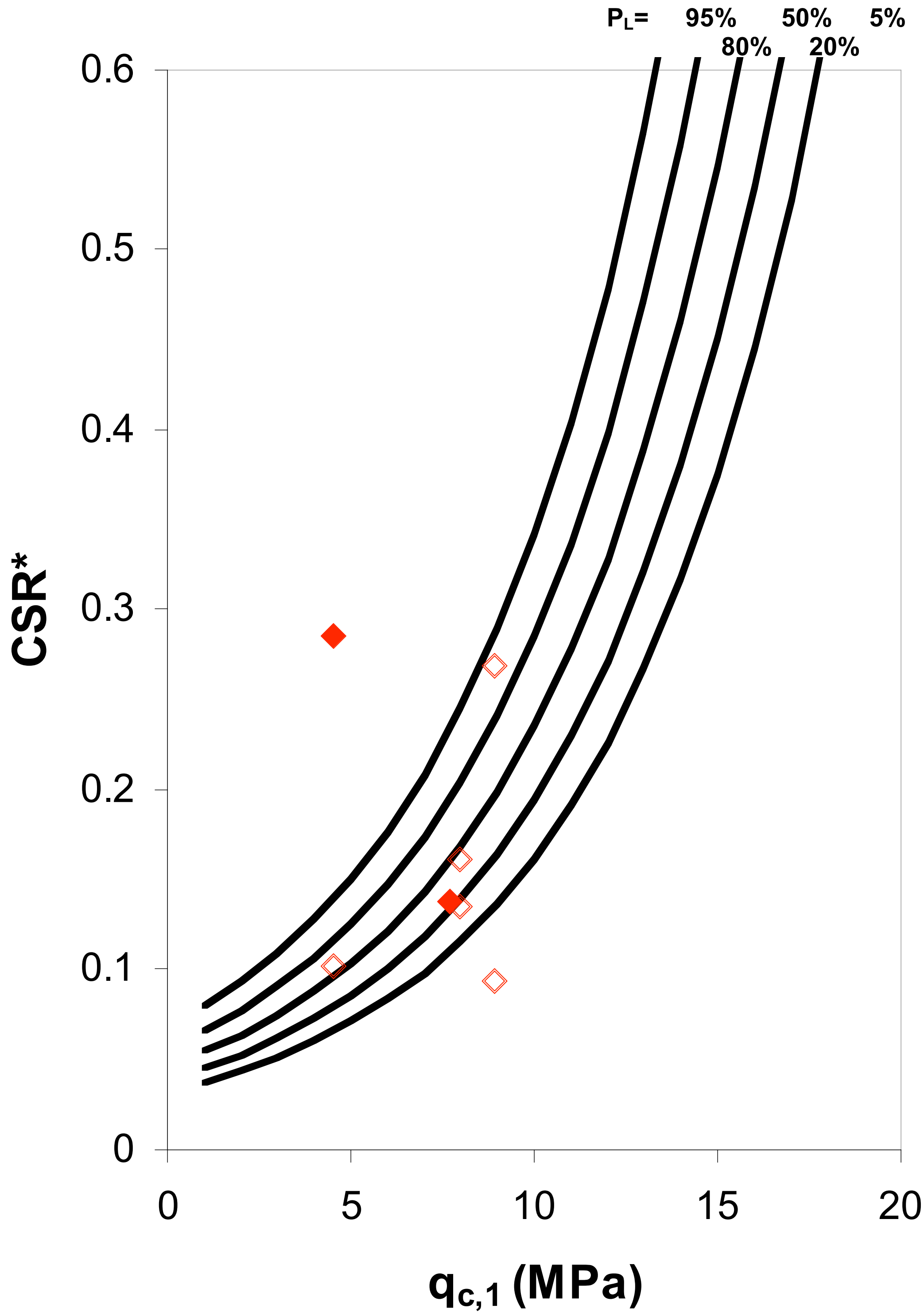

Figure 10. New liquefaction/non-liquefaction case histories shown with probabilistic liquefaction triggering curves of Moss & Seed (2004). Filled symbols are liquefaction data points and hollow symbols are non-liquefaction data points.

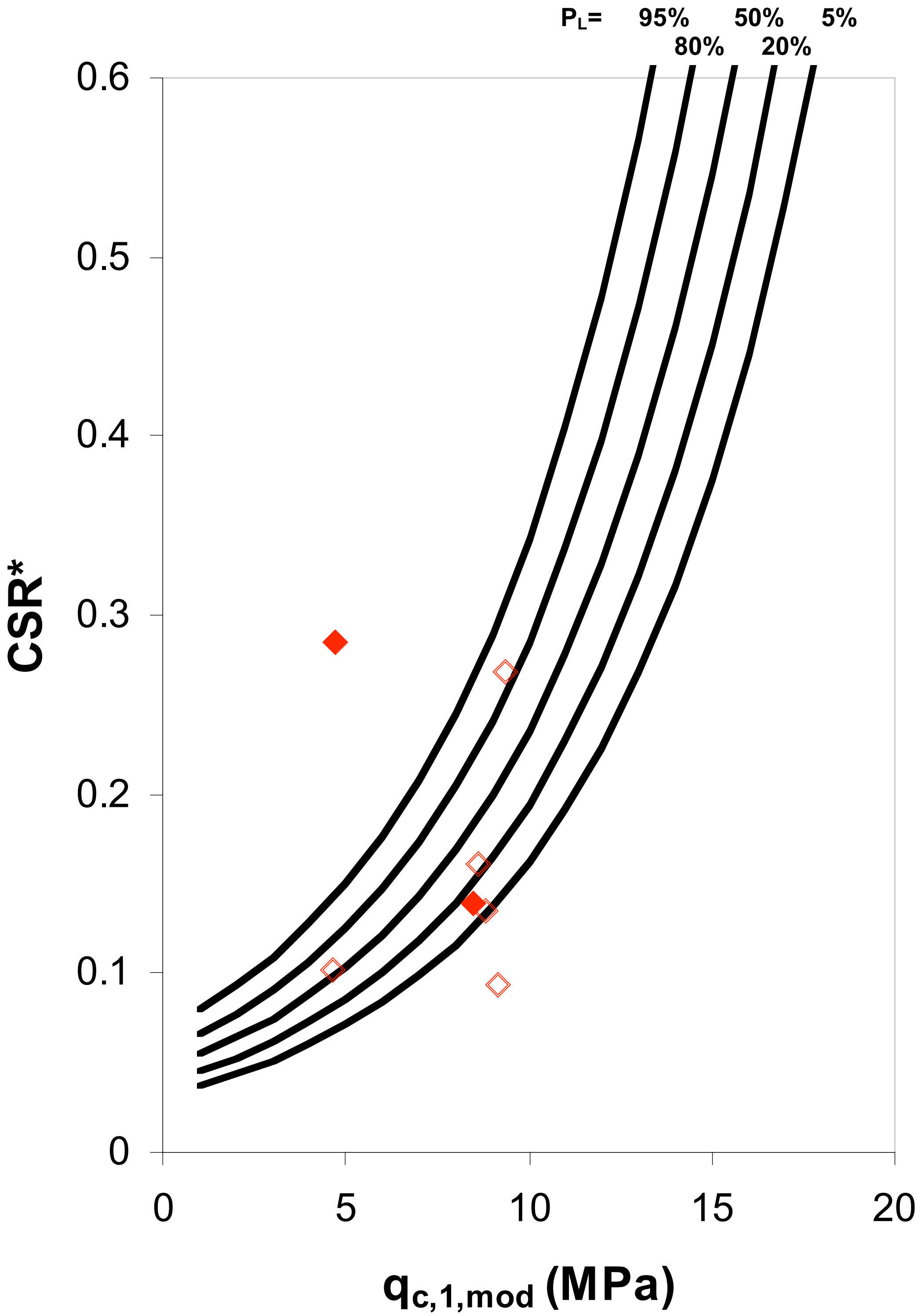

Figure 11. **New liquefaction/non-liquefaction case histories, corrected for friction ratio, shown with probabilistic liquefaction triggering curves of Moss & Seed (2004). Filled symbols are liquefaction data points and hollow symbols are non-liquefaction data points.**

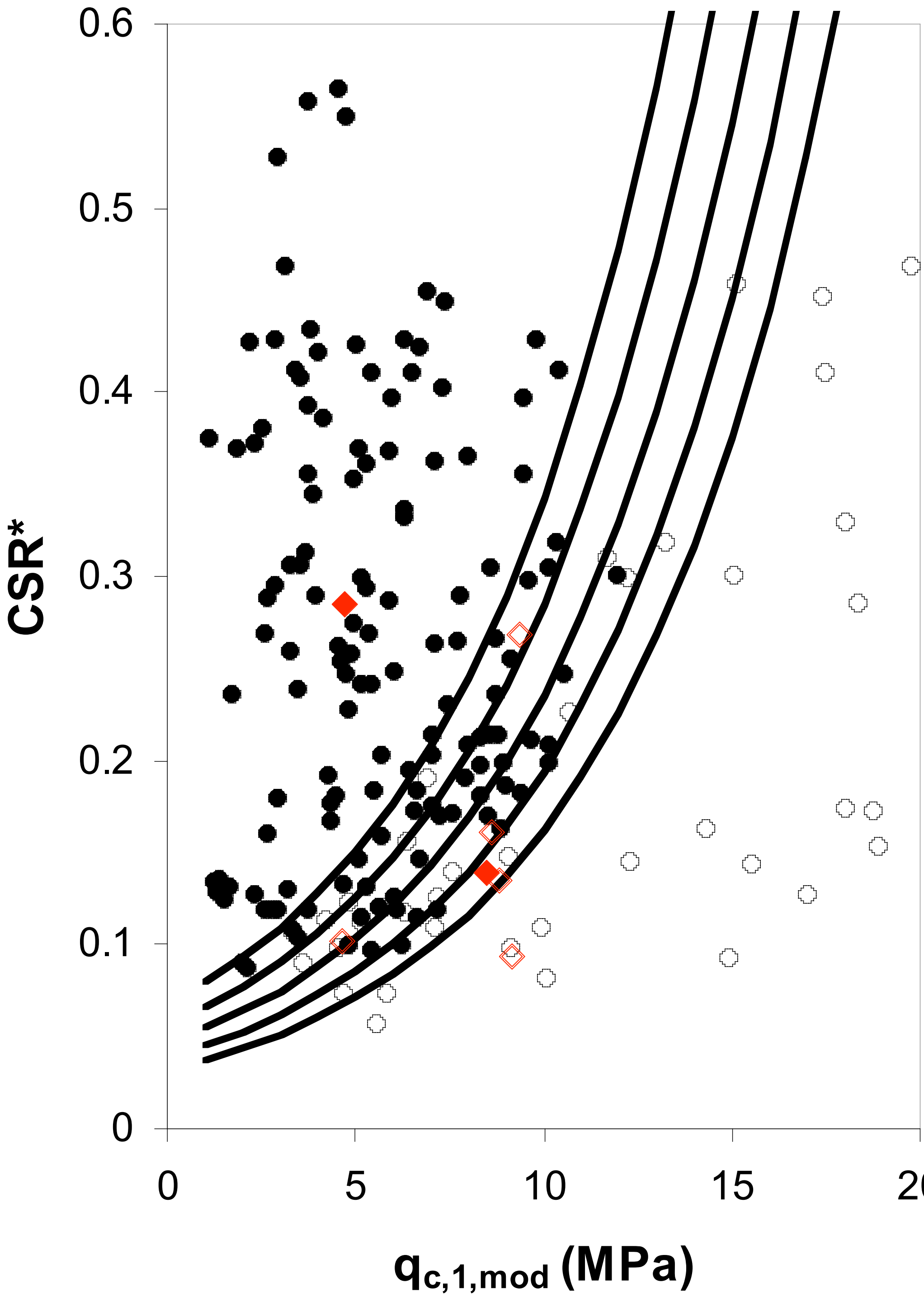

Figure 12. New liquefaction/non-liquefaction case histories, corrected for friction ratio, shown with probabilistic liquefaction triggering curves and worldwide database of Moss & Seed (2004). Filled symbols are liquefaction data points and hollow symbols are non-liquefaction data points.

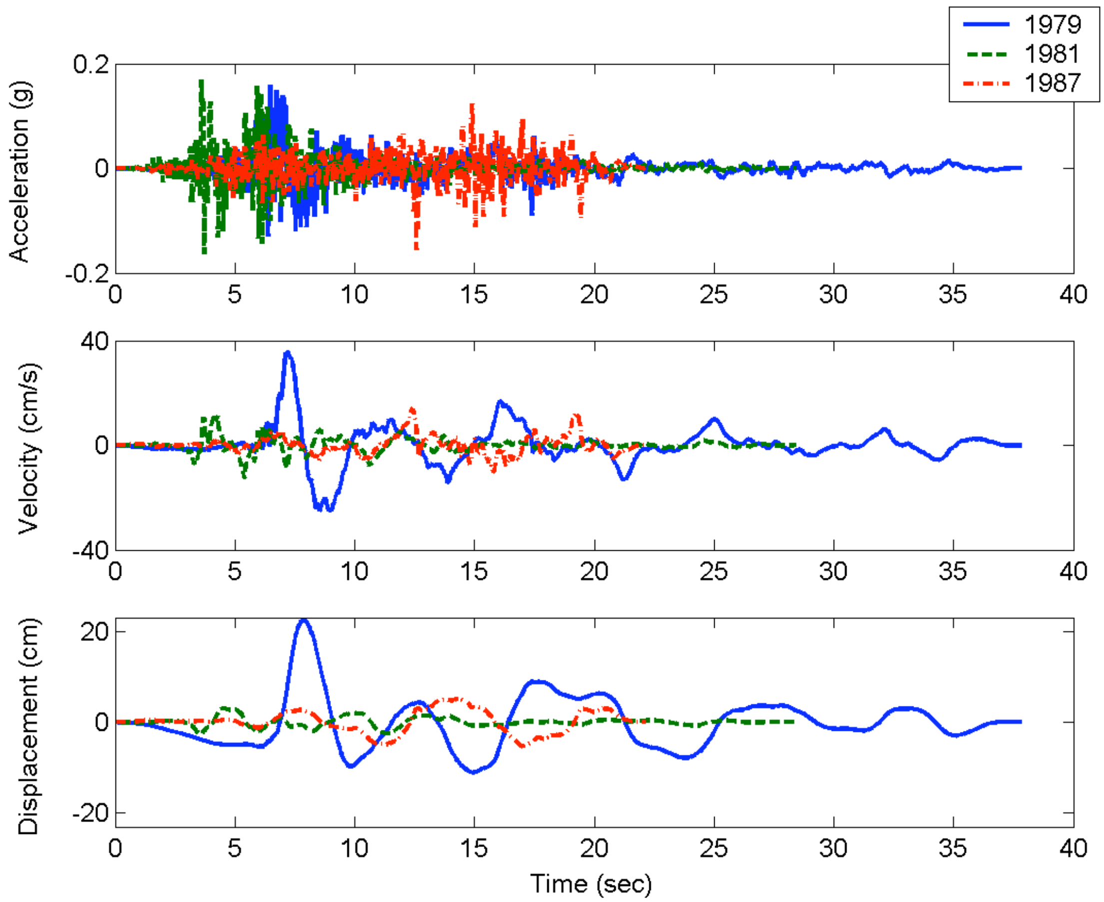

Figure 13. **Acceleration, velocity, and displacement time histories for the 1979 Imperial Valley, 1981 Westmoreland, and 1987 Superstition Hills Earthquakes, Brawley Station, orientation 225 degrees.**

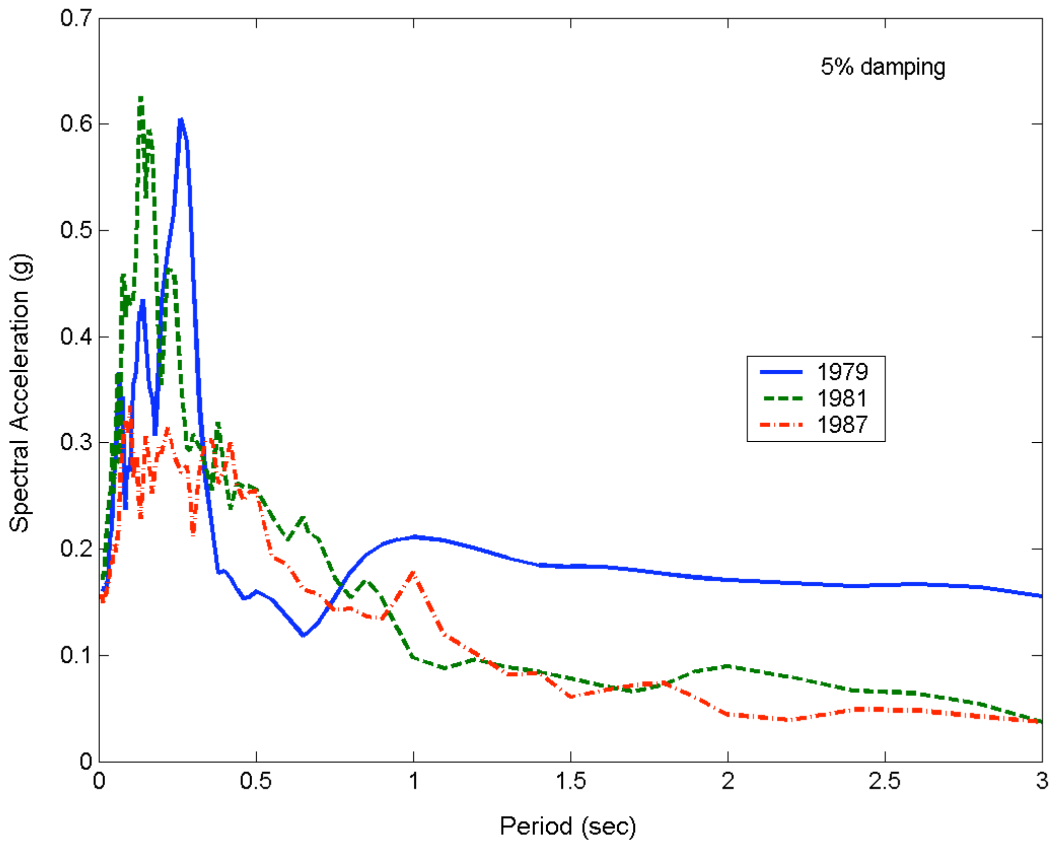

Figure 14. Comparison or response spectra showing the 1979 Imperial Valley , 1981 Westmoreland, and 1987 Superstitious Hills Earthquakes, Brawley Station, orientation 225 degrees.