Ground Motion Characteristics and their Relation to Soil Liquefaction at the Wildlife Liquefaction Array, Imperial Valley, California.

Kayen R.E.[1], Mitchell, J.K.[2], and Holzer, T.L.[3]

Abstract

We use the earthquake shaking severity parameter Arias intensity, I_h, to assess the site specific characteristics of ground motion, and investigate the relation of those characteristics to soil liquefaction occurrence at the Wildlife liquefaction array, in response to the Elmore Ranch and Superstition Hills earthquakes of November 23 and 24, 1987. We found that for both earthquake events, the Arias intensities calculated from motions recorded by the downhole seismometer were significantly less than those calculated from recordings of the surface seismometer. By normalizing the downhole cumulative Arias intensity-time history with that of the surface record, it can be shown that the ratio of the recorded intensity response of the downhole seismometer to that of the surface seismometer was essentially a constant during the Elmore Ranch event, when no excess pore-water pressures were observed. In the Superstition Hills event record, this ratio of Arias intensities climbs erratically throughout the period of strong shaking during which there is a rise in pore-water pressure and softening of portions of the soil column. We attribute the erratic rise in the intensity ratio to a de-coupling of the surface and downhole seismometers, caused by liquefaction of a layer between them.

We interprete the data to show that the surface measured intensity of shaking at the site, in response to the Elmore Ranch earthquake (I_h = 0.44 m/sec) , was insufficient to elevate pore-water pressures in soil with a fines corrected $(N_1)_{60}$ penetration resistance of 12-14. During the Superstition Hills event, which occurred the following day, pore-water pressure begins to develop at 13.6 seconds when the surface intensity had reached 0.54 m/sec. Between 27 seconds (I_h = 1.37 m/sec.) and 40 seconds ($I_{h\ surface}$ = 1.70 m/sec.) portions of the soil column fully liquefied. The data suggest that a threshold level of earthquake shaking, as measured by Arias intensity, was required to trigger soil liquefaction at the Wildlife site.

---

[1] Research Civil Engineer, U.S. Geol. Survey, 345 Middlefield Road, Menlo Park, CA 94025
[2] Via Professor of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg VA 24061.
[3] Research Geologist, U.S Geol Survey, 345 Middlefield Road, Menlo Park, CA 94025

Introduction

The Wildlife liquefaction array (WLA) was established on the flood plain of the Alamo River in the Imperial Valley of California, 36 km north of the town of El Centro, to record the response of a liquefiable soil body, with the potential for lateral displacements, to earthquake motions (Figure 1). The Imperial Valley is situated south of the southerly end of the San Andreas Fault, in the vicinity of the Salton Sea and the Imperial Fault, and is one of the most earthquake-prone regions of the United States. As such, the Wildlife site is exposed to frequent strong motion events. The array, presented in Figure 2, is instrumented with piezometers and strong motion accelerometers at the surface and at 7.5 meters depth (Bennett et al., 1984, Holzer et al., 1989a). Numerous studies have documented the site characteristics and have presented analyses of the WLA, with regard to pore-water pressure response (Dobry, et al., 1989, Thilakaratne and Vucetic, 1989, Youd and Holzer, 1994); initial liquefaction (Holzer et al., 1989b, Elgamal and Zeghal, 1992); and ground deformations (Bazair et al., 1992, Youd and Bartlett, 1988, Holzer et al., 1989a, Dobry, et al., 1992).

The deposits that underlie the Wildlife site are underlain by a 2.3 meter thick fine-grained flood deposit (Figure 2); loose-to-moderately dense silty sand layer is found between 2.3 and 6.8 meters (units B1 and B2, Bennett, et al., 1984); below layer B are dense silty sands and sandy silts not subject to liquefaction. Sand boils found at the Wildlife site after the 1981 Westmorland Earthquake (M=5.9) are derived from material in both units B1 and B2 (Holzer et al., 1989). Fines corrected standard penetration tests (SPT) taken in layers B1 and B2 yield an average calculated $N_{1(60)}$ value of 12-14.

The instrumentation at WLA includes six Data Instruments model AB pore-pressure transducers placed in the soil column, in units B1 at 2.8 and 3.0 meters depth; in unit B2 at 4.0, 5.0, and 5.3 meters depth; and at 12.1 meters depth in the dense underlying soil. The boreholes for the pore pressure transducers were back-filled with bentonite-cement to seal the holes. The accelerometer instrumentation consists of two Kinemetrics model FBA-13 triaxial-accelerometers, one located at the surface, and the other at 7.5 meters depth within a PVC casing (designated FBA-13DH). The surface accelerometer is mounted to a concrete pad and housed within a fiberglass instrument box. The downhole accelerometer was placed at the base of the casing, which was then back-filled with sand.

Methods

We use the earthquake intensity measure Arias Intensity developed by Lange (1968) and Arias (1970) to characterize ground motion at the Wildlife site and investigate its relation to soil liquefaction. Arias intensity is defined by Arias (1970) as the total energy-per-unit-weight absorbed by evenly-spaced single-degree of freedom oscillators between the frequencies 0 and ∞. In practice, Arias intensity is calculated as proportional to the integral of the square of the recorded strong motion acceleration . The 2-component Arias intensity in the horizontal plane, I_h, is given by:

$$I_h = I_{xx} + I_{yy} = \frac{\pi}{2g} \int_0^{t_o} a_x^2(t)\,dt + \frac{\pi}{2g} \int_0^{t_o} a_y^2(t)\,dt$$

The two orthogonal single component Arias intensities, I_{xx} (intensity in the x-direction, integrated from the x-direction record) and I_{yy}, are integrated from acceleration time histories, where g is the gravitational acceleration, $a_x(t)$ is the acceleration at time-t recorded in the x-direction, and $a_y(t)$ is the acceleration recorded in the y-direction. Single-component of motion Arias intensity is commonly referred to as I_a. This intensity measure is relatively insensitive to the variation in the damping characteristics of liquefiable soils (Kayen, 1993) and has the advantage of incorporating the entire accelerogram record into the intensity measure, whereas for example, the peak ground acceleration (PGA) utilizes but one-point. Arias intensity is useful because it can be quantified and verified in an objective manner, as opposed to subjective psycho-physical intensity measures, such as the Modified Mercali Intensity (Arias, 1970).

Elmore Ranch and Superstition Hills Earthquake

The epicenter of the 23 November 1987 Elmore Ranch earthquake (***M***=6.2) was located approximately 23 kilometers to the west of the WLA. This earthquake triggered instruments that recorded modest earthquake motions but no elevated pore-water pressures. The peak ground-acceleration and surface-level two-component horizontal Arias intensity for the event were 0.13g and 0.44m/sec, respectively. The acceleration- and cumulative intensity-time histories for the two components of motion at the surface and at 7.5 meters depth are plotted in Figure 3.

On the following day, November 24, 1987, the Superstition Hills earthquake (*M*=6.6), centered 31 kilometers west-southwest of the site, triggered instruments at the Wildlife site that recorded strong motions and elevated pore-water pressures. Acceleration- and Arias intensity-time histories for the Superstition Hills event are plotted in Figure 4. During this event, excess pore-water pressures developed approximately 13.6 seconds (I_h = 0.54 m/sec) into the record. The sand layer began to soften, noted by the loss of phase coherence between the downhole and surface acceleration records (Holzer et al., 1989b). By 16 seconds ($I_{h,16secs}$ = 0.90 m/sec) the pore pressure ratio, r_u, in portions of layer B approached approximately 0.5. Between 27 seconds ($I_{h,27secs}$ = 1.37m/sec) and 40 seconds ($I_{h,40secs}$ = 1.70 cm/sec) portions of the soil column fully liquefied (Youd and Holzer, 1994).

Discussion

The Wildlife strong motion data indicate that the Arias intensity calculated from seismograms at the ground surface is typically greater than that measured at depth within the soil column. Amplification at the ground-level is expected due to the effects of double-amplification at the surface and interference of the upward and downward traveling shear waves within the soil column. To investigate the variation of Arias intensity with depth, we used the Wildlife data to normalize the cumulative Arias intensity at a depth of 7.5 meters with the surface measure of intensity. We define an intensity depth reduction parameter, r_b, as the ratio of the buried to surface cumulative Arias intensities.

$$r_b = \frac{I_{xx}\ (\text{depth})}{I_{xx}\ (\text{surface})}$$

The r_b parameter can be calculated for either the single- or double-component horizontal Arias intensity. The time-history of the cumulative Arias intensity depth reduction factor, r_b, is calculated for the single-components of the Elmore Ranch earthquake, and presented in figure 5. It can be seen that during the first seven seconds of the 360° record, during the period dominated by P-waves, the r_b ratio fluctuates significantly. This fluctuation is due to the influence of the intensity of incident waves on the very low value of the ratio, r_b, during the first 6 seconds of the acceleration time-history. After 7 seconds, when shear waves dominate the strong motion, the intensity ratio plateaus at approximately 0.28 until 13 seconds, and then climbs to 0.38. For the 090° component of motion, a similar response is calculated from the acceleration time histories.

For this record a generally noisy record persists up to 7 seconds, followed by a progressive increase in r_b to 0.33 at 30 seconds.

A noteworthy aspect of both of the above records is the relatively constant ratio of r_b during the principal portion of strong shaking. Holzer et al. (1989b) argued that under non-liquefaction conditions, a linear proportionality constant exists between the downhole and surface cumulative Arias intensity. The relatively flat r_b profiles in Figure 4 support their hypothesis.

Plotting the cumulative Arias intensity ratio, r_b, as a time-history for the Superstition Hills event (Figure 6) shows a strikingly different response, compared to that of the Elmore Ranch record (Figure 5). During the early seconds of shaking there is a high sensitivity to wave interference in the r_b signature, as noted in the Elmore Ranch records. After 7 seconds into the record the intensity ratio plateaus for a period of 5-6 seconds at a value of approximately 0.34 for the 360 record and 0.25 for the 090 record. At 13.5 seconds r_b begins to rise in a rapid and erratic manner until r_b reaches a value of approximately 0.44-0.46.

Accordingly, Holzer et al. (1989b) concluded that the divergence between a scaled-Arias intensity at depth and the surface intensity was due to the onset of strain-softening behavior and the absorption of energy by the intervening liquefied layer. Our observations of the erratic elevation in r_b during the Superstition Hills event support their findings. The rapid rise in r_b indicates a partial de-coupling of the surface layer from the soil beneath the liquefied layer, such that shear waves propagating upwards are attenuated, and perhaps partly reflected downwards, before reaching the surface accelerometer.

The depth reduction characteristics for Arias intensity, calculated from the Wildlife array data, are plotted as a triangle in Figure 7b; the left limb representing the Elmore Ranch Earthquake response, and the right limb representing the Superstition Hills earthquake response. A separate parametric study of the the attenuation of Arias intensity with depth (Figure 7a) was performed by integrating synthetic seismograms generated with the ground-response program SHAKE (Schnabel, et al., 1972) and normalizing the intensities calculated at depth by the surface Arias intensity (Kayen, 1993; Kayen and Mitchell, in progress). The lines in Figure 7a are the r_b profiles generated with SHAKE using a suite of soil-shear modulus profiles and input strong motion records. A statistical synthesis of these profiles are shown in Figure 7b as a mean and ± 1 standard deviation response. The empirical data from the Wildlife site fall below the mean response of the parametric study, but are in general agreement with those findings.

Liquefaction Response of Soil at the Wildlife liquefaction array

Acceleration time-histories recorded from the Elmore Ranch and Superstition Hills earthquakes are important in that they constrain the relation between shaking severity, as measured by Arias intensity, and liquefaction performance at the Wildlife site. To assess the liquefaction response, we coupled the depth factor, r_b, with surface-measured Arias intensity, I_h, to give an estimate of the energy-per-unit-weight absorbed by a specific soil layer at depth in the soil column, which we term the Arias intensity at depth, $\mathbf{I_{hb}}$. That is, we multiplied the surface intensities I_h measured at the surface accelerometer station at the Wildlife site by the depth-dependent reduction factor, r_b, interpolated between the surface and the measured value at 7.5 meter depth, to estimate Arias intensities within the soil column. In contrast, Egan and Rosidi (1991) have attempted to correlate the surface measure of Arias intensity with the field performance of potentially liquefiable sites. Their findings correctly indicate that the surface measure of Arias intensity correlates poorly with the liquefaction performance at depth in the soil column.

In Figure 8, we plot the intensity of earthquake shaking, $\mathbf{I_{hb}}$, estimated at the depth of soil layer B against the representative $(N_1)_{60}$ value for layer B (Bennett, et. al, 1984); having determined the fines- and effective overburden stress- corrected standard penetration resistance for that layer using the methods prescribed by Seed et al. (1984). The Elmore Ranch event, with a surface measured Arias intensity of 0.44 m/sec and an estimated intensity within layer B of 0.24 m/s, was insufficient to soften the sand layers B1 and B2. The Elmore Ranch event is marked on Figure 8 as no-liquefaction point below the boundary curves.

During the Superstition Hills earthquake, pore pressures developed at approximately 13.6 seconds, at which point the horizontal surface Arias intensity had reached 0.54 m/sec. Full liquefaction appears to have occurred after approximately 27 seconds (surface I_h = 1.37 m/sec) of instrument recording, as determined by the piezometer response (Dobry et al., 1989). The vertical band in Figure 8 represents the transition from a non-liquefied to liquefied soil state during the Superstition Hills event. The response of the Wildlife site is presented with a suite of points representing the field performance of other sites, investigated by Kayen (1993), observed during nine earthquakes in United States and Japan (magnitude range: $6.1 \leq \boldsymbol{M} \leq 7.9$). From this investigation, Arias intensity-based curves can be drawn which define a threshold boundary for liquefaction occurrence (Kayen and Mitchell, in progress). The integration of both acceleration amplitude and earthquake shaking duration in the parameter Arias intensity is such that these boundary curves are independent of earthquake magnitude . The liquefaction field performance observed at the Wildlife site during the Elmore Ranch and Superstition Hills events is consistent with that observed at the other sites, and supports the basis for a depth-dependent Arias intensity-based boundary in $(N_1)_{60}$-$\mathbf{I_{hb}}$ space defining limiting conditions for liquefaction occurrence.

Conclusions

We have analyzed the characteristics of strong motions of the Elmore Ranch and Superstition Hills Earthquakes, recorded at the WLA, in terms of their progressive Arias intensity build-up. The ratio of the downhole to surface cumulative Arias intensities was essentially a constant during the principal portion of ground shaking in the Elmore Ranch event, when no excess pore-water pressures were observed. The depth reduction factor, r_b, calculated for the two-components of motion for the Elmore Ranch event was 0.36. During the Superstition Hills event, the Arias intensity ratio climbed in an erratic manner in response to a partial de-coupling of the surface and downhole seismometers, between which was a liquefied layer. The Superstition Hills earthquake had a two-component depth reduction factor, r_b, of 0.45.

To assess the liquefaction response of the Wildlife site during the two earthquake events, we multiplied the surface intensities, I_h, by the depth-dependent reduction factor, r_b, interpolated between the surface and 7.5 meter depth. In doing so, we can compare the energy-per-unit-weight absorbed by a layer at depth, $\mathbf{I_{hb}}$, to the penetration resistance of that layer, $(N_1)_{60}$. The Elmore Ranch event had an estimated $\mathbf{I_{hb}}$ intensity within soil layer B of 0.24 m/sec. which was below the threshold required to elevate pore-water pressures within that layer. During the Superstition Hills earthquake, pore pressures began to develop at an $\mathbf{I_{hb}}$ intensity level of 0 27 m/sec. Full liquefaction appears to have occurred after approximately 27 seconds when the Arias intensity at the depth of layer B, $\mathbf{I_{hb}}$, was approximately 0.7 m/sec. The WLA data-set allow us to observe the transition of a site from a non-liquefied to a liquefied state in terms of Arias intensity buildup. This transition is consistent with an investigation of other sites in the United States and Japan where Arias intensity has been correlated with the liquefaction performance in the field.

Acknowledgments

We thank John C. Tinsley III and Michael J. Bennett for their thoughtful reviews of the manuscript.

References

Arias, A. (1970) A Measure of Earthquake Intensity, R.J. Hansen *ed.* Seismic Design for Nuclear Power Plants, The M.I.T. Press, Cambridge, Massachussetts.

Baziar, M.H., Dobry, R., and Alemi, M. (1992) Evaluation of Lateral Ground Deformation Using Sliding Block Model, Earthquake Engineering, Tenth World Conference, Balkema, Rotterdam, pp.1401-1406.

Bennett, M.J., Mc Laughlin, P.V., Sarmiento, J.S., and Youd, T.L., (1984) Geotechnical Investigation of Liquefaction Sites, Imperial Valley, California, USGS Open-File Report 84-252, U.S. Geological Survey, Menlo Park, CA.

Dobry, R., Elgamal, A.W., Baziar, M.H., and Vucetic, M. (1989) Pore Pressures and Acceleration Response of Wildlife Site During the 1987 Earthquake, Proceedings, Second U.S.-Japan Workshop on Liquefaction, Large Ground Deformation, and Effects on Buried Pipelines, Niagra Falls, New York, pp. 145-260.

Dobry, R., Baziar, M.H., O'Rourke, T.D., Roth, B.L., and Youd, T.L (1992) Liquefaction and Ground Failure in the Imperial Valley, Southern California during the 1979, 1981, and 1987 Earthquakes, U.S.-Japan Case Studies of Liquefaction and Pipeline Performance During Past Earthquakes, Vol. 2, U.S. Case Studies, NCEER Report 92-0002, pp.4-1 to 4-85.

Egan, J.A. and Rosidi, D. (1991) Assessment of Earthquake-Induced Liquefaction Using Ground-Motion Energy Characteristics, Proc. Pacific Conference on Earthquake Engineering, New Zealand.

Elgamal, A.-W. and Zeghal, M. (1992) Analysis of Wildlife Site Liquefaction During the 1987 Superstition Hills Earthquake, Proc. of the Fourth Japan - U.S.Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction, in M. Hamada and T.D. O'Rourke, eds. Technical Report NCEER-92-0019.

Holzer, T.L., Bennett, M.J., and Youd, T.L. (1989a) Lateral Spreading Experiments by the U.S. Geological Survey, Proceedings from the Second U.S.-Japan Workshop on Liquefaction, Large Ground Deformations and their Effects on Lifelines, *eds.* T.D. O'Rourke and M. Hamada, Technical Report NCEER-89-0032.

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

Kayen, R.E.(1993) Accelerogram-Energy Approach for Prediction of Earthquake-Induced Ground Liquefaction, unpublished Ph.D. dissertation, Department of Civil Engineering, University of California at Berkeley, 289 pp.

Kayen, R.E. and Mitchell, J.K., in progress, Ground-motion energy approach for assessment of earthquake-induced cyclic-liquefaction, J. Geotech. Engrg., ASCE.

Lange, G. (1968) Una Medida de Intensidad Sismica, unpublished Ph.D. Thesis, University of Chile, Santiago, Chile.

Schnabel, P., Lysmer, J., and Seed, H.B. (1972) SHAKE: A Computer Program for Earthquake Ground Response, Univ. Cal. Berkeley, EERC Report No. UCB/EERC-72-12.

Seed, H.B., Tokimatsu, K., Harder, L.F., and Chung, R.M., (1984) Influence of SPT procedures in soil liquefaction resistance evaluation, Earthquake Engineering Research Center Report No. UCB/EERC-84/15.

Thilakaratne, V. and Vucetic, M. (1989) Analysis of liquefaction occurrence at the Wildlife Site during 1987 Superstition Hills Earthquakes, Research Report, Dept. of Civil Engineering, University of California, Los Angeles, p.131.

Youd, T.L. and Bartlett, S.F., (1988) U.S. Case Histories of Liquefaction-Induced Ground Displacement, Proc. of the First Japan-U.S. Workshop on Liquefaction, Large Ground Deformations and their Effects on Lifeline Facilities, Tokyo, Japan.

Youd, T.L. and Holzer, T.L. (1994) Piezometer Performance at Wildlife Liquefaction Site, California. J. Geotech. Engrg., ASCE, 120(6).

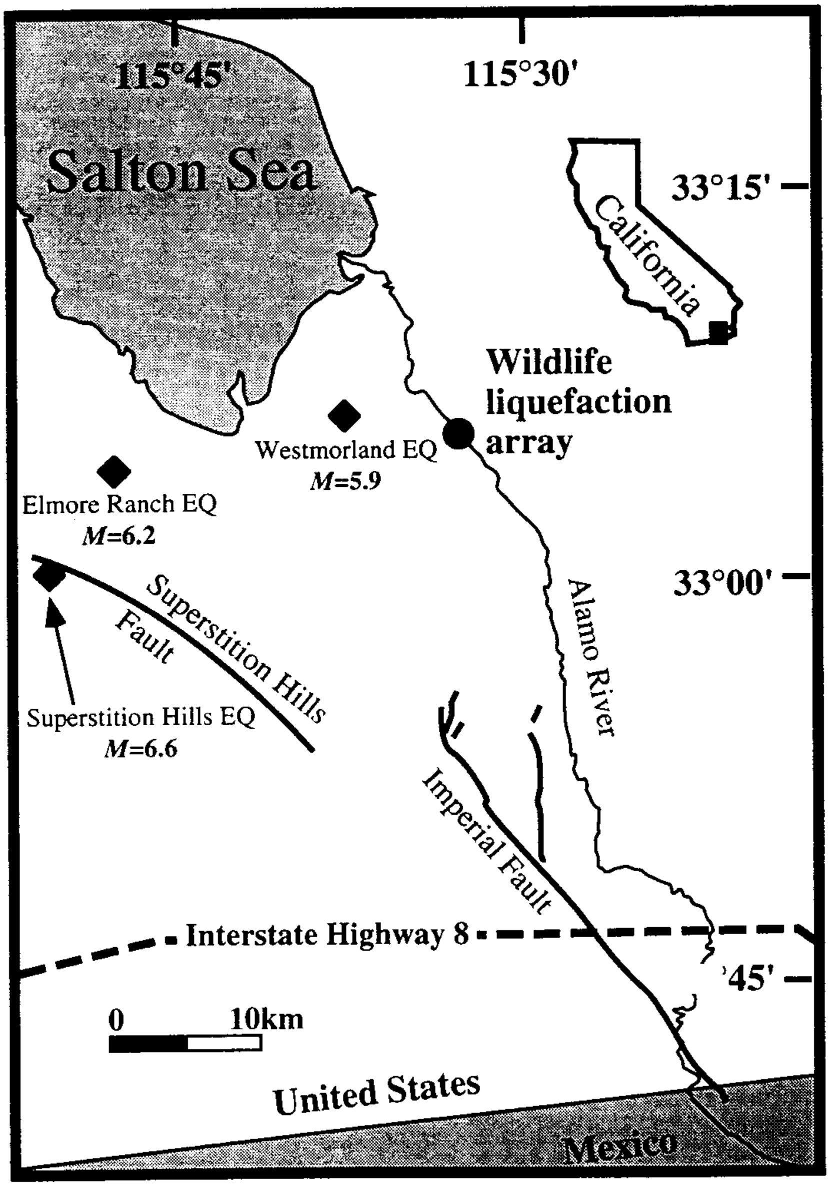


Figure 1. Location map of the WLA, Imperial Valley, Ca. Epicenters for the 1981 Westmorland; 1987 Elmore Ranch; and 1987 Superstition Hills earthquakes are starred.

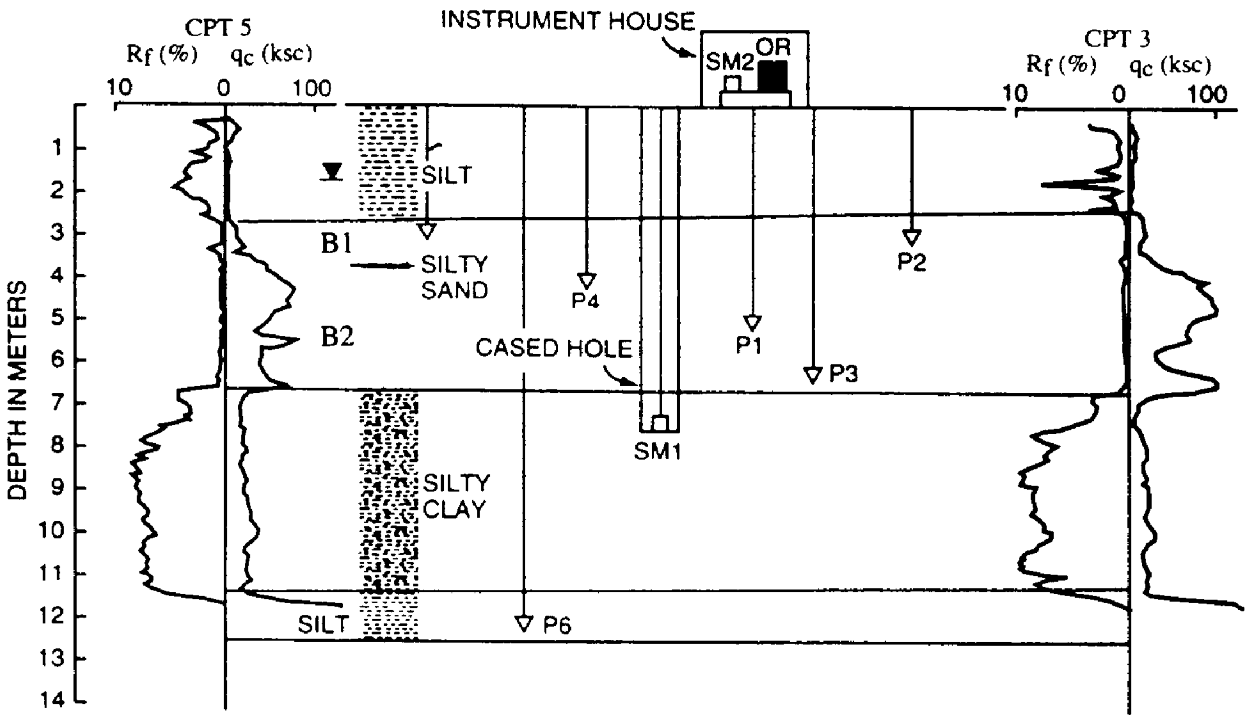


Figure 2. Profile of the Wildlife site with layers A-, from the surface, to-D at 12-meters, and cone penetration test (CPT) profiles (Bennett, et al , 1984). The parameters q_c (kg/cm^2) and r_f (%) are the cone-tip resistance and sleeve friction ratio, respectively Inverted triangles P1-P6 denotes the pore pressure piezometers, SM1 and SM2 denote the triaxial accelerometers; OR denotes the oscilloscope recorder.

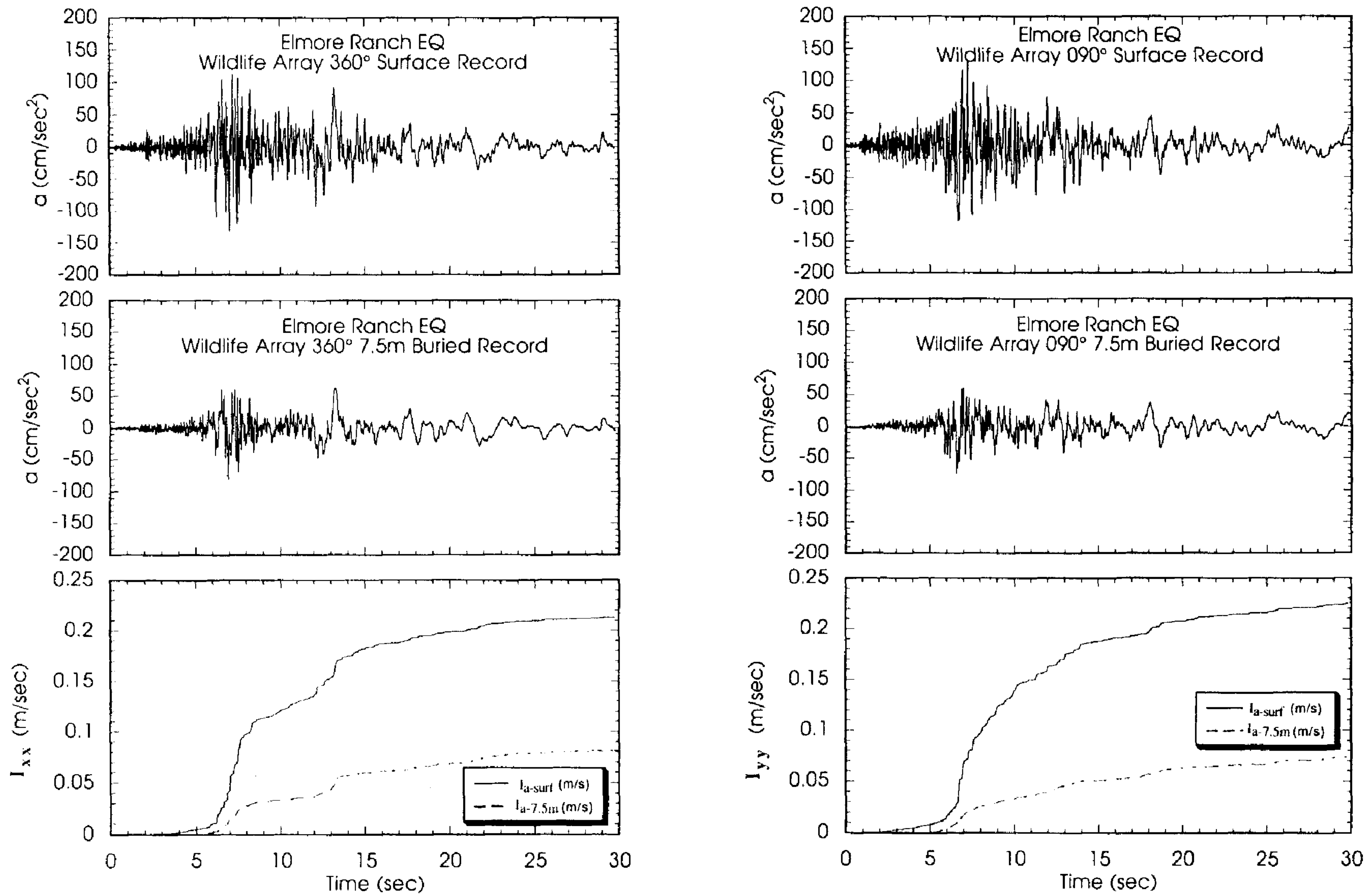


Figure 3. Ground surface and 7.5 m depth recordings from the WLA, recorded during the Elmore Ranch Earthquake. Plotted are accelerations and their computed cummulative Arias intensities for the 360° and 090° components. $I_{a\ top}$ and $I_{a\ mid}$ are the surface and 7.5 meter depth Arias intensities, respectively. Horizontal scaling is the first 30 seconds of recording.

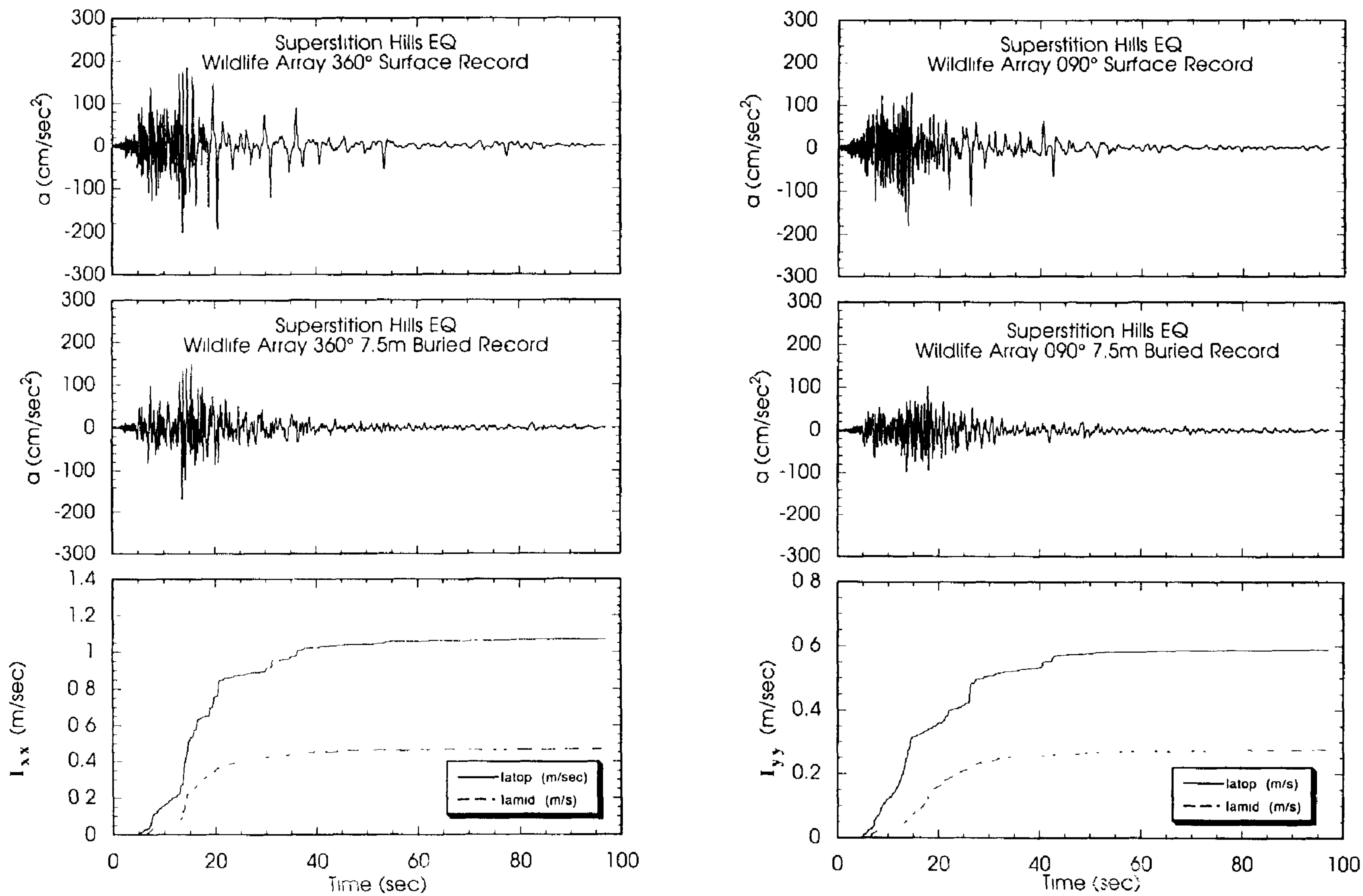
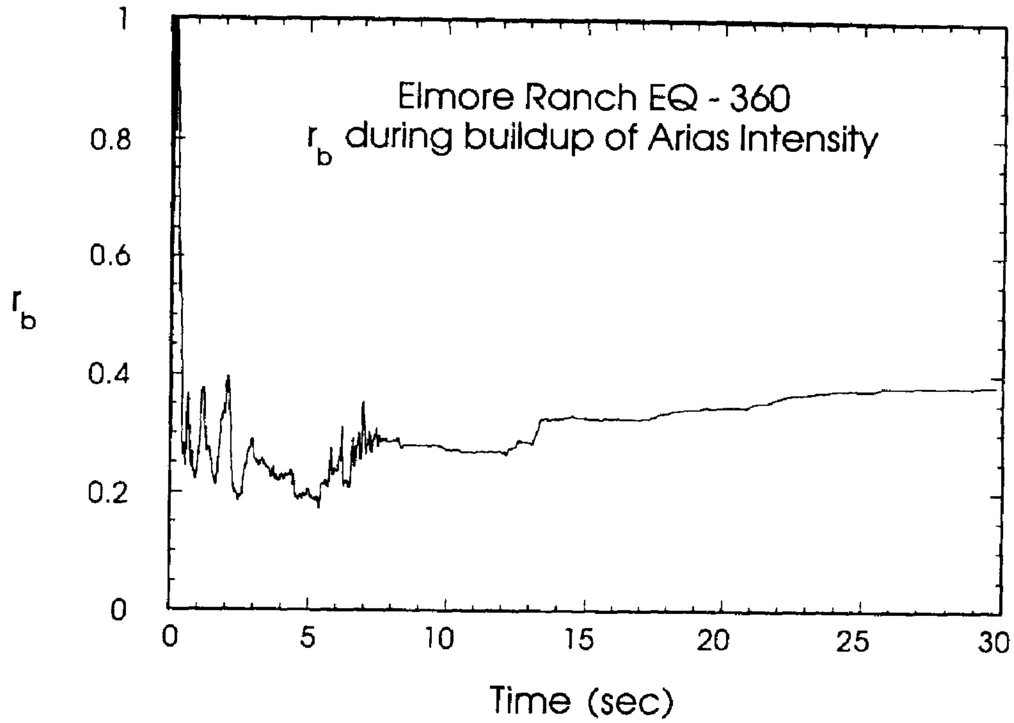


Figure 4 Ground surface and 7.5 m depth recordings from the WLA, recorded during the Superstition Hills Earthquake. Plotted are accelerations and their computed cumulative Arias intensities for the 360° and 090° components. Horizontal scaling is the first 100 seconds of recording.



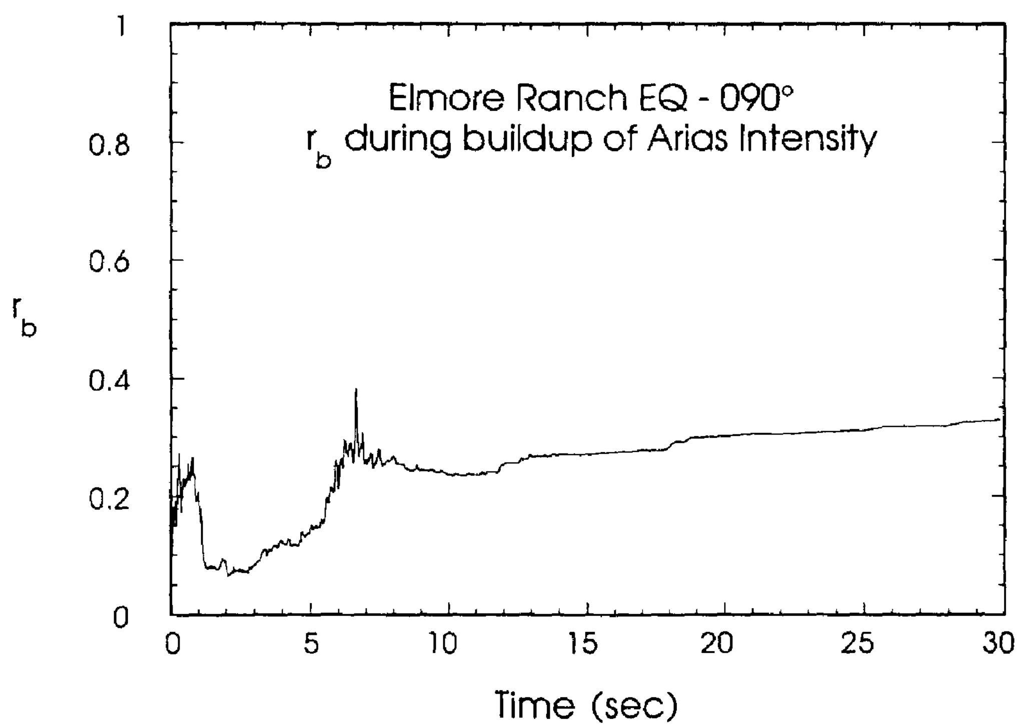
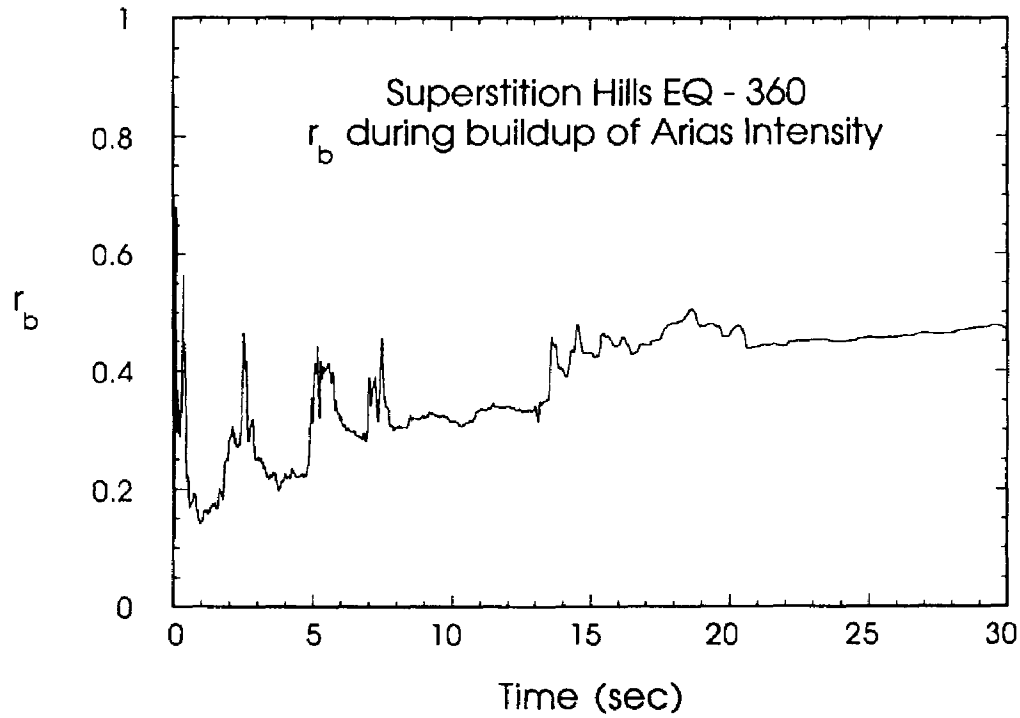


Figure 5. Cumulative r_b time-histories for the 360° and 090° components of the Elmore Ranch Earthquake records.



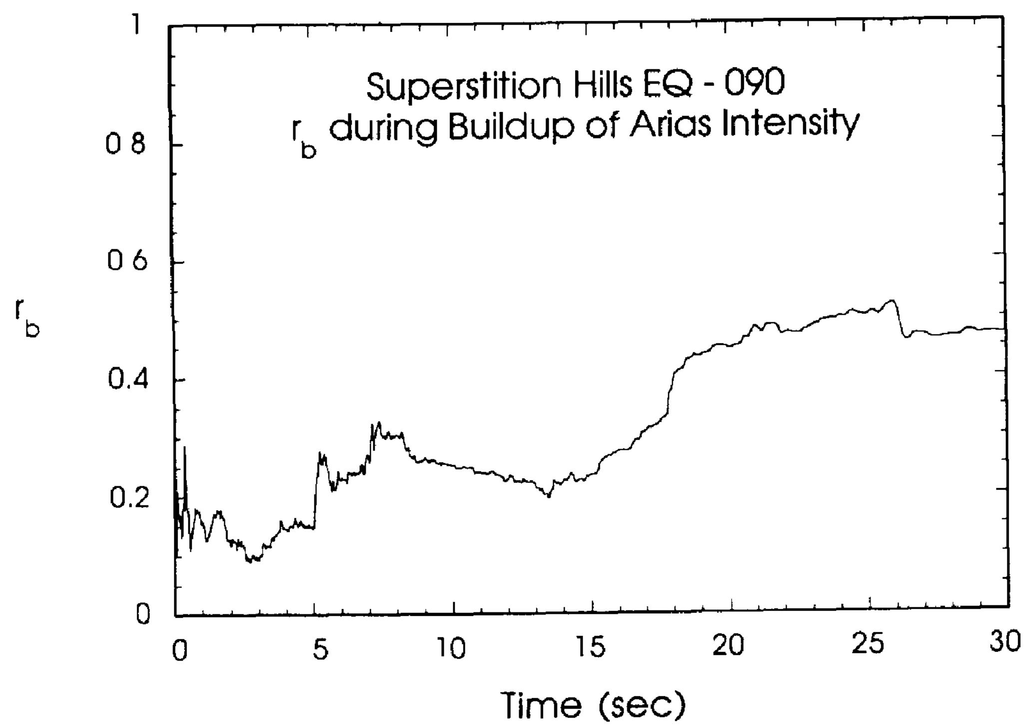


Figure 6. Cumulative r_b time-histories for the 360° and 090° components of the Superstition Hills Earthquake records.

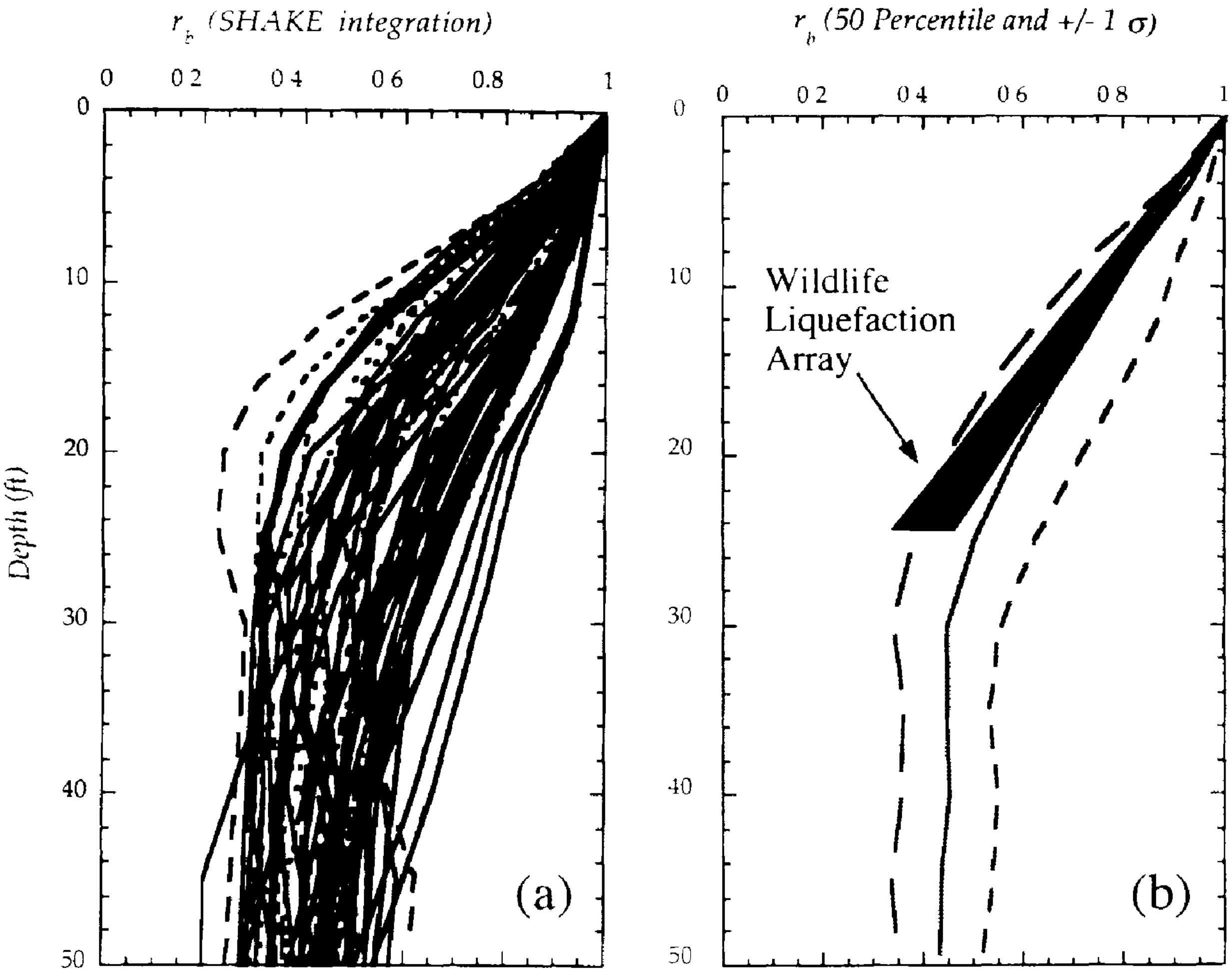


Figure 7 Arias intensity depth reduction profiles modeled using the ground response program SHAKE are presented in Figure 7a. A statistical synthesis of the SHAKE-study is presented in Figure 7b along with the empirical results from the WLA response during the Elmore Ranch and Superstition Hills earthquakes.

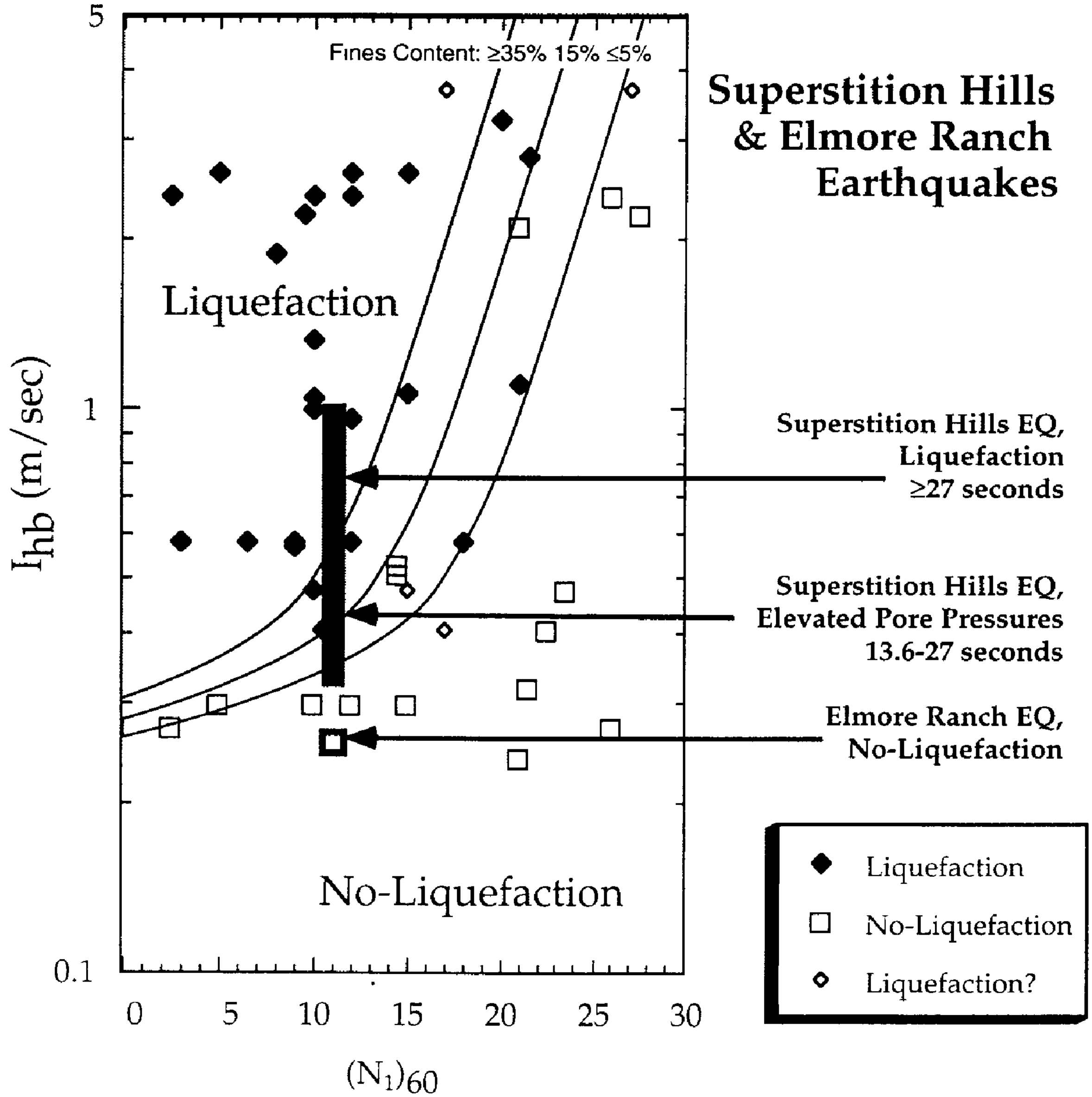


Figure 8. $\mathbf{I_{hb}}$ versus $(N_1)_{60}$ for the WLA site during the Elmore Ranch and Superstition Hills earthquakes. The boundary curves are constrained by field performance data from sites in Japan and United States, whose performance is identified in the legend (Kayen and Mitchell, in progress).