AHTD TRC TRANSPORTATION RESEARCH COMMITTEE

TRC0803

Shear Wave Velocity Profiling and Liquefaction Hazard Analysis

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Final Report

2008

SHEAR WAVE VELOCITY PROFILING AND LIQUEFACTION HAZARD ANALYSIS

TRC 0803

PRESENTED TO

TRANSPORATATION RESEARCH COMMITTEE STATE OF ARKANSAS HIGHWAY AND TRANSPORTATION DEPARTMENT

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Re.: Shear Wave Velocity Profiling and Liquefaction Hazard Analysis
TRC 0803 – Draft Report

Dear Mr. Maurer:

Please find enclosed the draft report of the referenced project.

We are pleased to be of service. If questions arise or if we can be of further assistance, please notify us at your convenience.

Respectfully Submitted,

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CHAPTER 1
INTRODUCTION

1.1. Background

Only a few states in the nation have areas with higher earthquake design acceleration coefficients than Northeast Arkansas. The area is prone to damage from earthquakes in the New Madrid seismic zone (NMSZ). The AASHTO LRFD Bridge Design Specification indicates the "liquefaction of foundation soil (has) contributed to much of the damage" to bridges in earthquakes. The code suggests that site-specific studies be performed at bridge locations to evaluate liquefaction hazards. It is well established that in-situ shear wave velocity (V_s) profiles of the subsurface, to a depth of at least 30-meters, are necessary for a site-specific seismic ground response analysis. Furthermore, site-specific V_s profiles can be used as a screening tool to evaluate the depth and thickness of potentially liquefiable soil layers.

1.2. Background and Significance of Work

Northeast Arkansas is located within the Upper Mississippi embayment. The embayment is a trough like depression that plunges southward along an axis that approximates the course of the Mississippi River (Figure 1.1 and Figure 1.2). It extends from Southern Illinois to the Gulf of Mexico. As shown in Figure 1.2, the embayment is filled with sediments of clay, silt, sand, and gravel to depths reaching to 1000 meters. According to Broughton *et al.* (2001), most of the study area has surficial deposits, which include Holocene artificial fill, alluvium Holocene deposits along river channels, Pleistocene Loess and Terrace deposits, Lafayette Gravel of Hilgard. Many of these deposits are susceptible to liquefaction (Rix and Romero-Hudock, 2006). Romero and Rix (2001) classified the soil in the embayment into Lowland (Holocene-age deposits) and Upland (Pleistocene-age deposits), as shown in Figure 1.3.

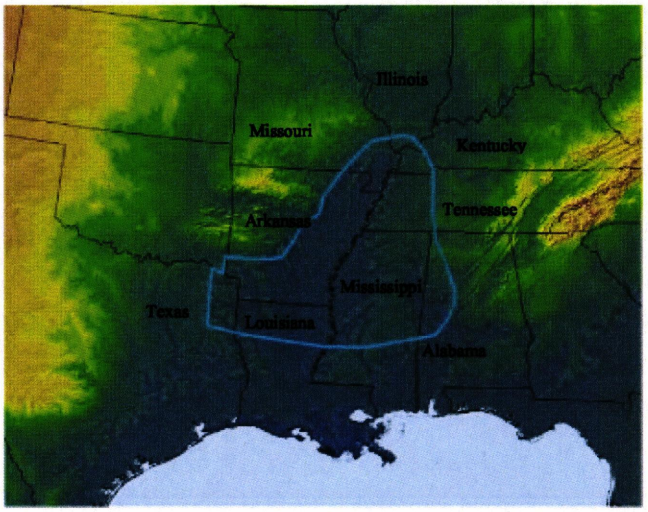

Figure 1.1 Plan View of the Mississippi embayment (after Ng *et al.*, 1989).

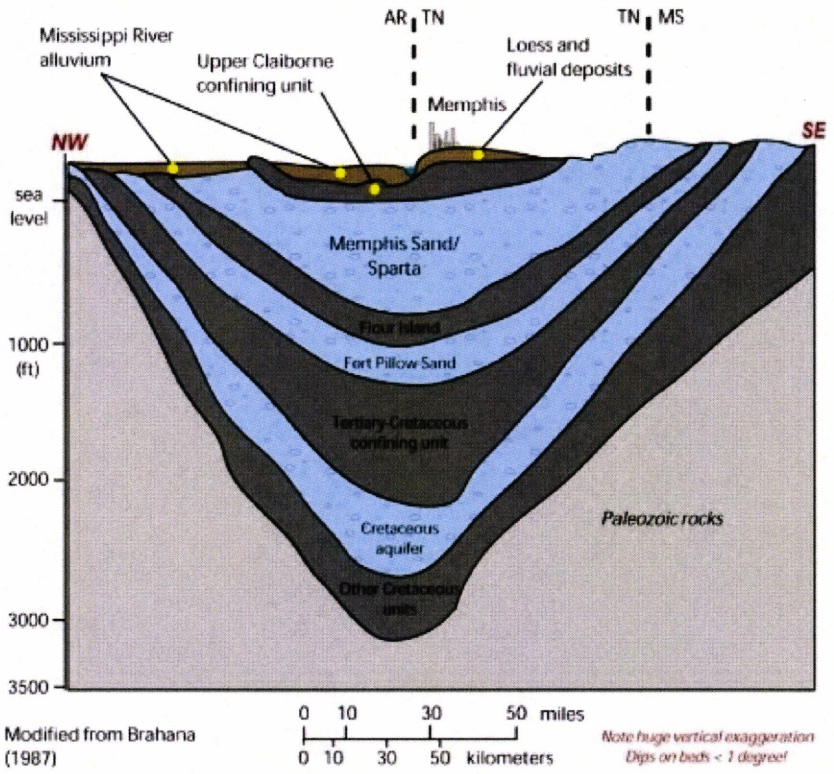

Figure 1.2 East-West profile view of the Mississippi embayment through Memphis and Shelby County (after Ng *et al.*, 1989).

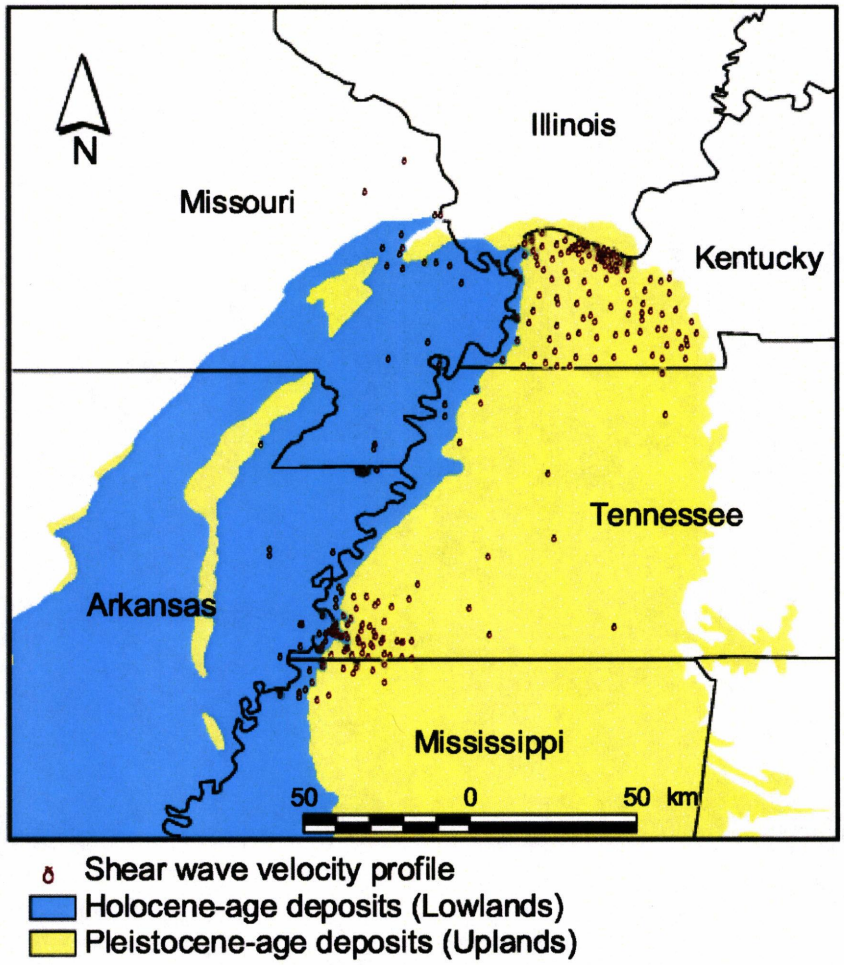

Figure 1.3 Lowlands and Uplands classification of Mississippi embayment (Romero and Rix, 2001).

The deep soil deposits of the Mississippi embayment have a pronounced yet not fully understood influence on the amplification and attenuation of ground motions associated with NMSZ. The NMSZ, which extends from southeastern Missouri to northwestern Tennessee and northeastern Arkansas, generated three large events in 1811-1812. According to Bakun and Hopper (2004), the best estimates of the moment magnitudes for the three large events range from 7.5 to 7.8. The recurrence interval for events similar to 1811-1812 is estimated by Tuttle *et al.* (2002) to be 500± 30 years based on geologic data.

1.3. Objective

The objective of this research, as set forth by the State of Arkansas Highway and Transportation Department (AHTD), was to obtain site-specific V_s profiles to depths of at least 30-meters at selected bridge locations in Northeast Arkansas. These bridges shall be considered as either "critical" or "essential" according to AASHTO, and were to be chosen in consultation with the AHTD. The V_s profiles were to be used to determine the soil liquefaction potential at each bridge location using a "Simplified Shear Wave Velocity Procedure". These V_s liquefaction evaluations were then to be compared with Standard Penetration Test (SPT) liquefaction evaluation procedures using blow count (N) and grain size distribution data already available from the AHTD.

1.4. Plan of Study

The plan of study was divided into specific tasks. They are listed below.

1.4.1. Task 1: Site Selection

Sixteen bridge sites were selected in conjunction with the AHTD. All bridge sites are located in Northeast Arkansas. The selection was limited to the sites where AHTD has existing SPT data to facilitate the liquefaction analysis using the simplified procedures (described later).

1.4.2. Task 2: Obtaining Site-Specific Shear Wave Velocity Profiles

Two nonintrusive (or noninvasive) techniques were utilized. They were Multichannel Spectral Analysis of Surface Waves (MSASW) and Refraction Microtremor (ReMi). Both MSASW and ReMi are non-invasive soil characterization methods using surface wave propagation. Both procedures utilize a linear array of vertically oriented sensors.

1.4.3. Task 3: AASHTO Site Classifications

The 16 sites were then classified in accordance with the latest American Association of State Highway Transportation Officials (AASHTO) guidelines. The classifications were performed using both the results of the field testing (shear wave velocity) and the SPT blow counts in the upper 100 feet below ground surface.

1.4.4. Task 4: Perform Liquefaction Analyses

The "simplified procedure" developed by Seed and Idriss (1971) and Youd *et al.* (2001) were used to determine safety against liquefaction. The simplified procedure uses available standard penetration test (SPT) and shear wave velocity, V_s, to derive liquefaction resistance. This procedure was based on evaluation of field observation and field and laboratory test data. The procedure uses two variables to evaluate the liquefaction potential of soils. These variables are the seismic demand placed on soil layer, expressed in terms of cyclic stress ratio (CSR), and the capacity of soil to resist liquefaction, expressed in terms of cyclic resistance ratio (CRR). The safety factor against liquefaction is defined according to Youd *et al.* (2001) as:

$$FS = \frac{CRR_{7.5}}{CSR} MSF \tag{1.1}$$

where *MSF* is the magnitude scaling factor to adjust the simplified curve to magnitudes smaller or larger than 7.5 (Seed and Idriss, 1982). Furthermore, liquefaction potential index (LPI) introduced by Iwasaki (1978; 1982) was used to evaluate the severity of liquefaction.

1.4.5. Task 5: Developing Correlation Relationships Between SPT Data and Shear Wave Velocity

The object of this part of the proposed study is to develop a procedure to obtain a set of empirical expressions to estimate the shear-wave velocity profile of a site, so that site response analyses can be performed and the site-dependent seismic amplification factor of a given site can be evaluated. Soil type, void ratio, effective confining stress, unconfined compression strength, energy corrected blow counts and depth factors were considered in the development of the empirical relationships (regression equations). The outcome of this objective is the development of a user-friendly computer program with graphics interface that will be provided to AHTD engineers to estimate shear-wave velocity of a soil profile using SPT data.

1.4.6. Task 6: Recommendations

The sixth and final task consists of the generation of the final report. The report includes recommendations and guidelines for future implementations upon evaluating proposed or existing bridge sites.

CHAPTER 2
SITE SELECTION

2.1 Initial Selection

AHTD Geotechnical Division provided boring logs for several bridge sites in the northeast Arkansas area. After evaluating the locations and subsurface conditions, the investigators prepared a list of potential test sites. These sites are listed below.

Table 2.1 Potential Sites.

PI Site No.	AHTD Site No.	County	Location Description
1	BR1108	CLAY	Cashe River Ditch 1 Str.&C. Rd. 53
2	BR1109	CLAY	Big Slough ditch St. & C. Road 82
3	BR1110	CLAY	Cashe River Ditch 1 Str.&C. Road 2
4	BR1907	CROSS	Prairie Creek Str. & C. Road 2
5	BR4706	MISSISSIPPI	National ditch St.& C. Road W 924
6	BR5607	POINSETT	Bayou DeView St. & C. Road 2
7	BR5609	POINSETT	Ditch No. 10 Str. & C. Road 48
8	110401	CRITTENDEN	I-55 / US 63 Interchange
9	110434	CRITTENDEN	US 63 / Gilmore Interchange
10	110463	CRITTENDEN	I-40-HWY 118 Interchange
11	110288	CROSS	St. Fran, River St. & US 64
12	110337	CRITTENDEN	I-55 / US 64 / HWY 147
13	110358	CRITTENDEN	I-40-HWY 118 Interchange Improve,
14	FA1904	CROSS	HWY 1 - HWY 284

Table 2.1 Potential Sites (Continued).

PI Site No.	AHTD Site No.	County	Location Description
15	R00059	CRAIGHEAD	US 63 / Washington Interchange
16	R10071	CROSSE	Colt Wynne – SH 1
17	100609	GREENE	US 49 / HWY 412-HWY 135
18	100570	GREENE	Hooker West Str. - SH 141
19	100569	CRAIGNHEAD	Big Creek Ditch St. - SH 349
20	100566	GREENE	Paragould/Big Slough Ditch-US412
21	100547	POINSETT	US63 &135 Interchange
22	100523	POINSETT	US63 &118 Interchange (Tyronza)
23	100522	POINSETT	US63 &149 Interchange (M. Tree)
24	100478	GREENE	S. Fra. River & St. - US 412
25	100395	CLAY	HWY 141N St. & SH 90
26	100381	POINSETT	Ditch 10 St. - SH 14
27	100126	CRAIGHEAD	Mud Creek Relief. St.- SH 141
28	100303	CRAIGHEAD	HYW 158 W & SH 18
29	100105	MISSISSIPPI	Tyronza River & Ditch 49

2.1. Selected Test Sites

AHTD project committee reviewed the list of potential sites and chose 15 sites for testing. They later added one additional site. The 16 test sites are listed in Table 2.2 below. All of these sites are north of Latitude 35.0° and west of Longitude 90.0°.

Table 2.2 Selected Test Sites.

PI Site No.	AHTD Site No.	County	Location Description
1	110288	CROSS	St. Fran, River St. & US 64
2	110358	CRITTENDEN	I-40-HWY 118 Interchange Improve,
3	110401	CRITTENDEN	I-55 / US 63 Interchange
4	100547	POINSETT	US63 &135 Interchange
5	110337	CRITTENDEN	I-55 / US 64 / HWY 147
6	110434	CRITTENDEN	US 63 / Gilmore Interchange
7	100523	POINSETT	US63 &118 Interchange (Tyronza)
8	100522	POINSETT	US63 &149 Interchange (M. Tree)
9	BR4706	MISSISSIPPI	National ditch St.& C. Road W 924
10	100105	MISSISSIPPI	Tyronza River & Ditch 49
11	R00059	CRAIGHEAD	US 63 / Washington Interchange
12	100303	CRAIGHEAD	HYW 158 W & SH 18
13	100153	CRAIGHEAD	SH 18 over St. Francis River
14	100478	GREENE	S. Fra. River & St. - US 412
15	BR1108	CLAY	Cashe River Ditch 1 Str.&C. Rd. 53
16	BR1110	CLAY	Cashe River Ditch 1 Str.&C. Road 2

CHAPTER 3
SHEAR WAVE VELOCITY DETERMINATION

The determination of shear wave velocities was accomplished by combining the results of two separate non-invasive methods, Multi-channel Spectral Analysis of Surface Waves (MSASW) and Refraction Microtremors (ReMi). The reason for combining the two methods was that it enabled the weakness of one method to be compensated by the strength of the other. The strengths and weaknesses of both methods are explained in their respective sections.

3.1. Multi-Channel Spectral Analysis of Surface Waves

MSASW is a non-invasive and economical seismic method used in the determination of velocity-depth profiles compared to the typical more expensive intrusive methods such as down-hole and cross-hole. The MSASW technique takes advantage of the dispersive nature of Rayleigh waves in a layered media in order to measure the phase velocity for a range of frequencies. This phase velocity vs. frequency is known as a dispersion curve which is then used in the calculation of a velocity-depth profile.

3.1.1. Dispersion of Rayleigh Waves

The wavelength of a particular Rayleigh wave is equal to:

$$\lambda_R = \frac{V_R}{f} \tag{3.1}$$

where λ_R is the Rayleigh wavelength, f is the frequency, and V_R is the Rayleigh phase velocity.

The properties of Equation (3.1) are illustrated in Figure 3.1. Rayleigh waves of lower frequency have longer wavelengths; therefore, they are able to penetrate deeper into the soil structure.

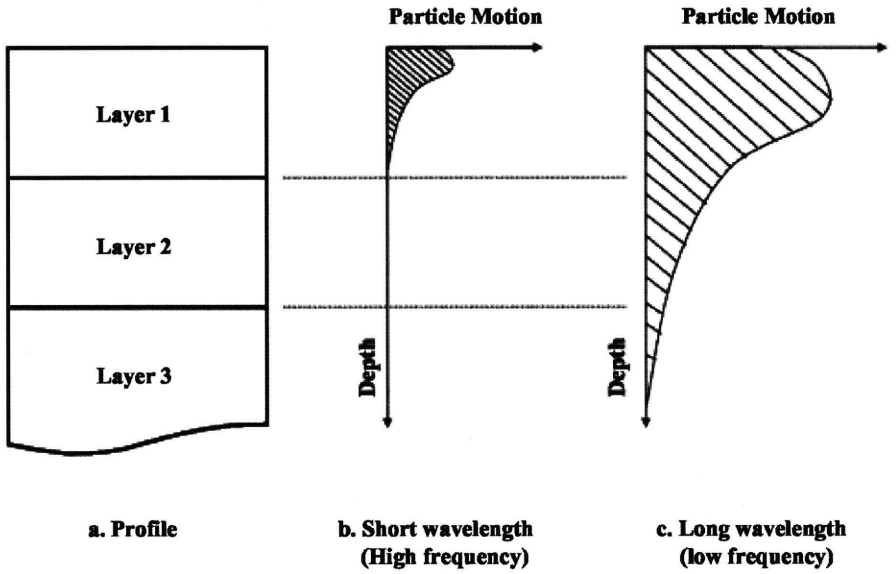

Figure 3.1 Relationship between frequency and Rayleigh wave travel depth.

3.1.2. Determination of Phase Velocity V_R

The determination of phase velocity is accomplished by placing a number of sensors (15 accelerometers were used in this study) in a linear array at spacing intervals of Δx_i (Figure 3.2) The spacing used is determined by an array smoothing function as outlined in Hebeler (2000). Sinusoidal waves are generated at a range of frequencies and recorded at each sensor.

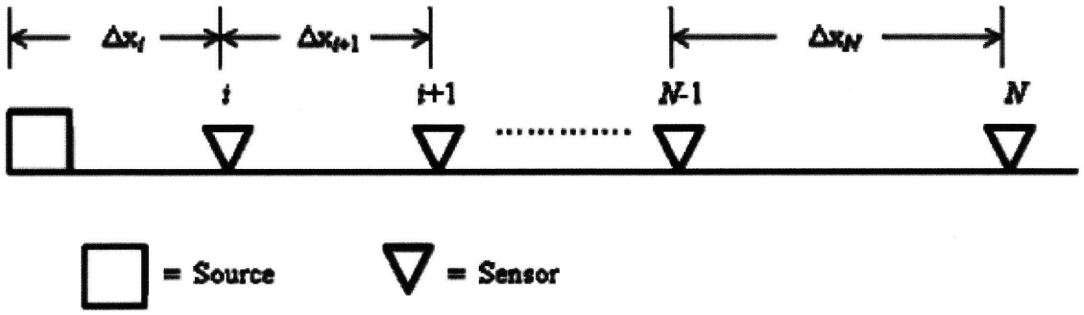

Figure 3.2 Linear array of sensors.

Once data for the entire range of frequencies are collected, the Fast Fourier Transform (FFT) is applied to the data to allow for frequency domain calculations. There are four

calculations needed in order to determine phase velocities. The first of which is the cross power spectrum:

$$G_{X_i X_j} = X_i(f)^* X_j(f) \tag{3.2}$$

where $G_{x_i x_j}$ is the cross power spectrum between sensors *i* and *j*, $X_i(f)^*$ is the complex conjugate of the Fourier spectrum of sensor *i*, and $X_j(f)$ is the Fourier spectrum of sensor *j*.

The cross power spectrum contains complex valued terms composed of magnitude and phase data. The phase shift between any two sensors can then be determined by:

$$\Delta\phi(f) = tan^{-1}\left[\frac{Im(G_{X_i X_j})}{Re(G_{X_i X_j})}\right] \tag{3.3}$$

where $Im(G_{x_i x_j})$ is the imaginary value of the complex cross power spectrum, and $\mathrm{Re}(G_{x_i x_j})$ is the real value.

The phase shifts for all sensors at a given frequency are plotted (Figure 3.3) in order to determine the wave number *k* as outlined in Zarrabi (2005):

$$k(f) = \frac{\Delta\phi(f)}{\Delta x_i} \tag{3.4}$$

where $k(f)$ is the wave number, $\Delta\phi(f)$ is the phase shift between sensors, and Δx_i is the spatial distance between each sensor.

Before Equation (3.4) can be used, the phase shifts must be unwrapped. The unwrapping process is depicted in Figure 3.3 through Figure 3.6. Figure 3.3 displays the unwrapped phase angles plotted versus distance to source as determined by Equation (3.3). If the wavelength λ is smaller than the distance between sensors, the phase shift must be unwrapped by a multiple of 2π times the number of wavelengths between sensors (Figure 3.4). Once the phase angles have been unwrapped (Figure 3.5), the slope of the line formed by the phase angles with respect to the spatial distance between sensors enables the determination of wave number *k(f* (Figure 3.6).

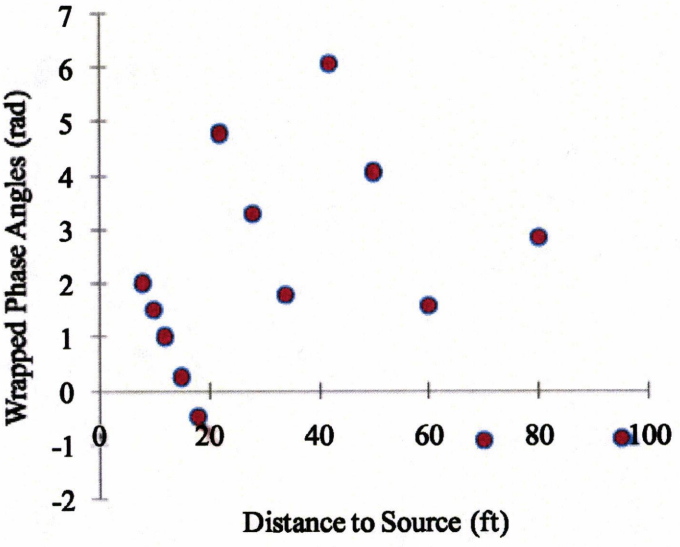

Figure 3.3 Unwrapped Phase Angles.

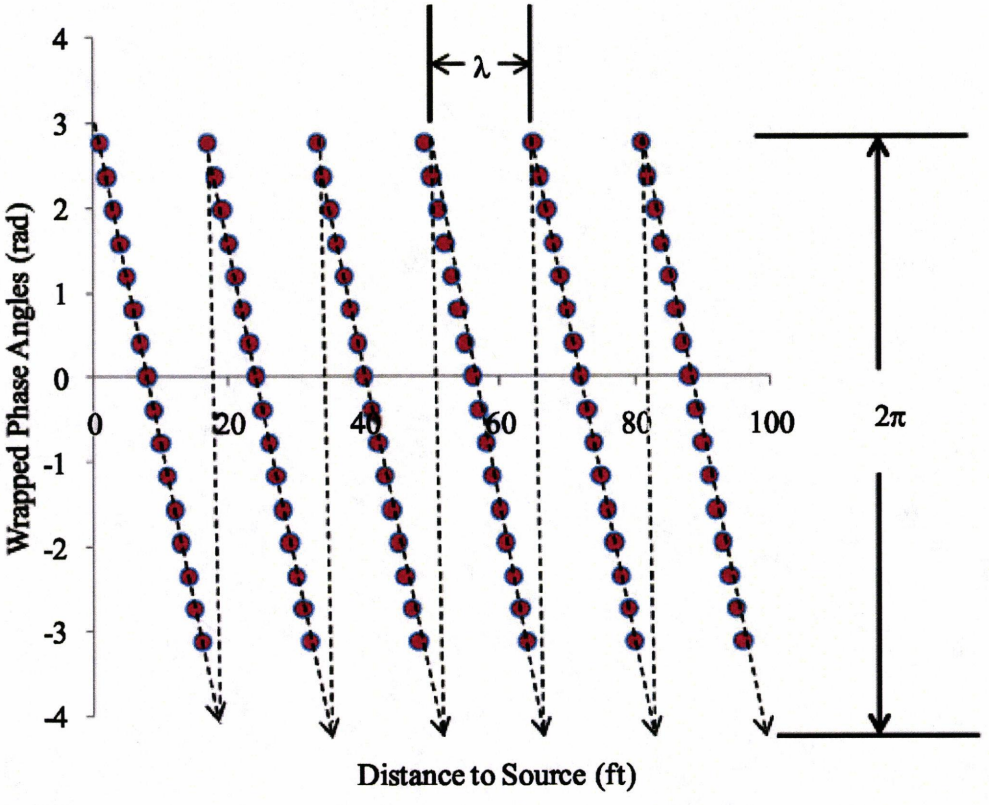

Figure 3.4 Depiction of unwraping process.

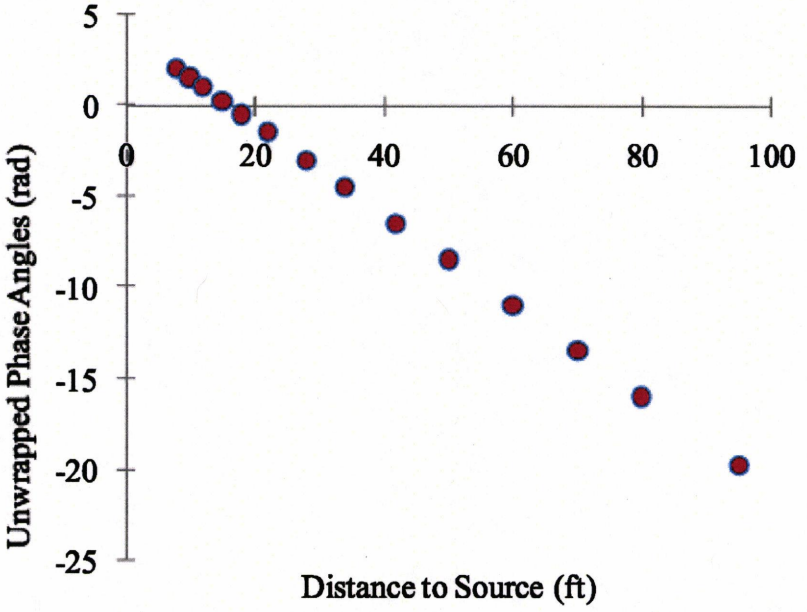

Figure 3.5 Unwrapped phase angles.

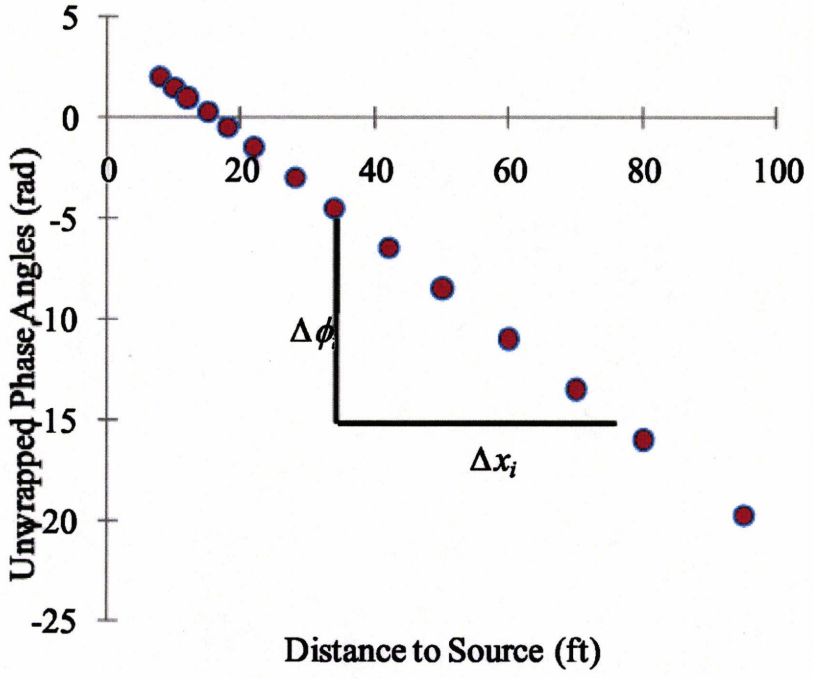

Figure 3.6 Determination of wave number $k(f)$ values.

The phase velocity can then be calculated by the following relationship:

$$V_R = f\lambda_R = \frac{2\pi f}{k} \tag{3.5}$$

By plotting the results of Equation (3.5), a dispersion curve is obtained as seen in Figure 3.7. The weakness of this method can be seen for frequencies of 8 Hz and lower. The scatter in the data can be contributed to low signal to noise ratio. The noise from ambient vibrations present in the soil contains amplitude close to or higher than that generated by the source resulting in apparent phase velocities approaching at angles oblique to the line of sensors. This will result in overestimating the true phase velocities. Due to low signal to noise ratio at low frequencies, MSASW is only able to produce quality results to depths of about 20 meters. This is due to the lightweight of the equipment used to generate the waves.

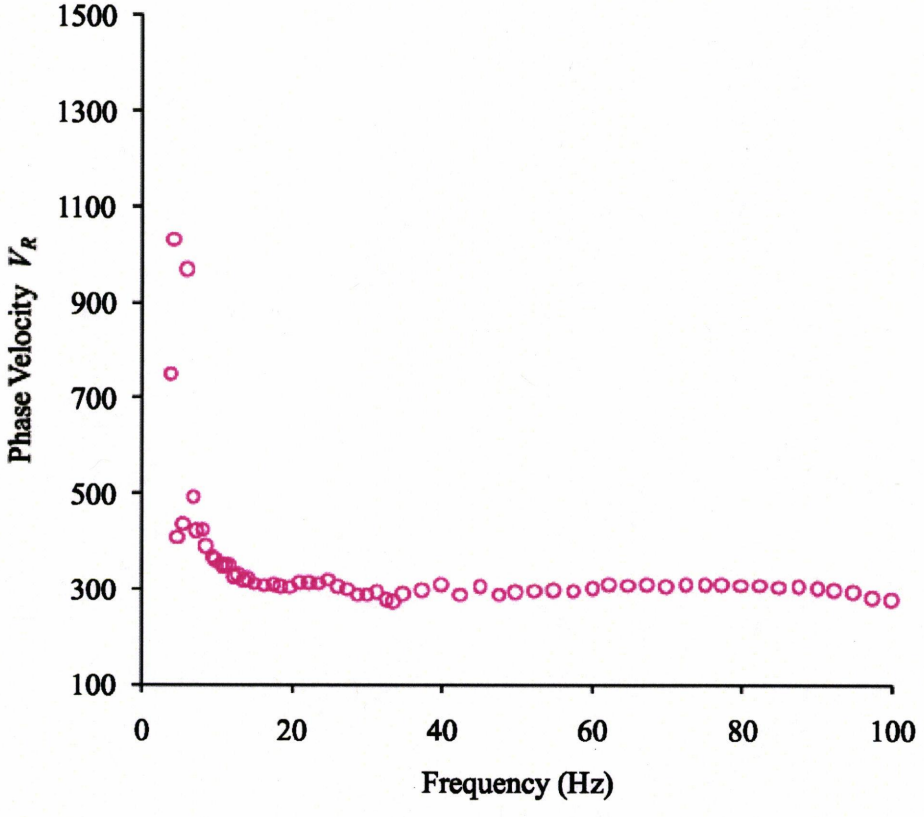

Figure 3.7 Dispersion curve.

3.1.3. Data Collection

For this project, impulsive Raleigh waves ranging from 3.75 to 100 Hz (Zarrabi 2005) were generated using the Agilent 15 MHz Function/Arbitrary Waveform Generator, model 33120A (Figure 3.8). The generated wave signals were then sent to the harmonic wave source, the APS Dynamics Electro-Seis 400 Shaker (Figure 3.9). The shaker is a long stroke, electrodynamic shaker, designed for the investigation of dynamic response characteristics for soil structures.

Figure 3.8 Agilent 15 MHz Function/Arbitrary Waveform Generator model 33120A.

Ground acceleration measurements were obtained using Wilcoxon 731A Seismic accelerometers (Figure 3.10). Each sensor rests on a metal base with a spiked bottom that is driven into the soil to ensure good coupling. A total of 15 sensors were used in this study as seen in Figure 3.11. Data were collected using the VT1432A 16 channel 24 bit digitizer (Figure 3.12) controlled with the VEE 6.2 signal processing software. Data were collected every 0.0015 sec for a total of 10 seconds per frequency. All data were analyzed using the methods described in Section 3.1.2 with computer programs written in the MATLAB software.

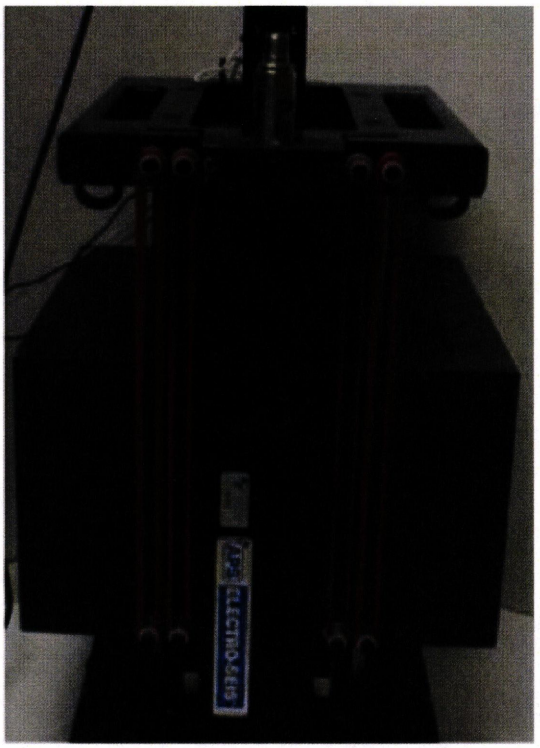

Figure 3.9 APS Dynamics Electro-Seis 400 Shaker.

Figure 3.10 Wilcoxon 731A Seismic accelerometers.

Figure 3.11 MSASW linear array.

Figure 3.12 VT1432A 16 channel 24 bit digitizer.

3.2. Refraction Microtremor (ReMi)

The Refraction Microtremor (ReMi) technique used in this research is based on the method described by Louie (2001). This method utilizes the recordings of background noise, or microtremors to separate Rayleigh waves from other seismic arrivals which allows for the determination of the true phase velocity compared to apparent velocity.

ReMi utilizes a velocity spectral (p-f) analysis in the determination of phase velocities for Rayleigh surface waves, the basis of which is the p-τ transformation or slanstack. This transformation takes multiple seismic records of amplitude relative to distance x, and time t and converts them to amplitudes relative to ray parameter p and intercept time τ. The p-τ transform is defined by:

$$A(p,\tau) = \int_x A(x, t = \tau + px)dx \tag{3.6}$$

where the slope of the line $p = dt/dx$ is the inverse of apparent velocity V_a in the x direction.

The next step is to compute the complex Fourier transform $F_A(p,\tau)$ in the τ intercept time direction:

$$F_A(p,\tau) = \int_\tau A(p,\tau)e^{-i2\pi ft}dt \tag{3.7}$$

The final step is to sum the energy from both the forward and reverse directions into one slowness axis that represents the absolute value of p. This is accomplished by first computing the Power spectrum $S_A(p,f)$:

$$S_A(p,f) = F^*_A(p,f)F_A(p,f) \tag{3.8}$$

where * denotes complex conjugate. The slowness axis is then folded and summed about $p = 0$:

$$S_A(|p|,f) = [S_A(p,f)]_{p\geq 0} + [S_A(-p,f)]_{p<0} \tag{3.9}$$

This completes the transformation from distance-time (x,t) into p-frequency (p,f) space.

3.2.1. Data Collection

Field data were collected using a linear array of 24, 4.5 Hz geophones (Figure 3.13), spaced evenly at 8 meter intervals (Figure 3.14).

Figure 3.13 4.5 Hz Geophone.

Figure 3.14 Linear array of geophones.

Data were recorded using the DAQLink II (Figure 3.15), a multiple channel 24 bit analog to digital acquisition system. The DAQLink II has 24 independent analog channels and uses standard 10/100 Base RJ45 network connection and standard TCP/IP network protocol.

Figure 3.15 DAQLink II.

The software SeisOpt ReMi was used in the organization and analysis of the data. Data were recorded every 2 milliseconds for a total of 32 seconds producing 16,000 data points per channel. On average a total of 20 separate recordings were collected for each site.

3.2.2. Dispersion Curve Determination

The determination of the Raleigh wave dispersion curve using the ReMi technique is accomplished by plotting the results from Equation (3.9), as illustrated in Figure 3.16, and by choosing points along the lower bound of the energy spectrum. The points along the lower bound of the energy spectrum represent the Raleigh waves traveling in a direction along the line of sensors which represents the true phase velocity. Raleigh waves approaching from angles oblique to the line of sensors produce higher apparent velocities thus picking points along the middle or upper bound of the energy spectrum would result in overestimated phase velocities. Figure 3.16 also depicts the spatial aliasing inherit to the ReMi method. Frequency resolution in and beyond the line of special aliasing is not certain and raises concern as to the accuracy of the method beyond such frequencies.

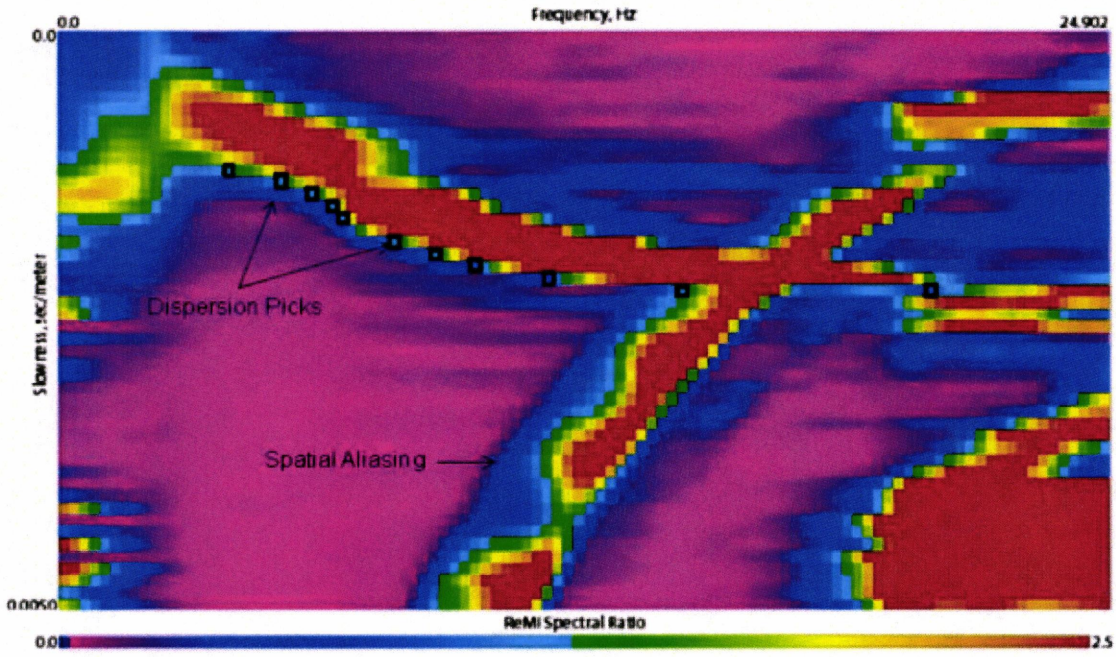

Figure 3.16 Plot of *p-f* spectrum

3.3. Combination of Methods

Both MASAW and ReMi techniques have their strengths and weaknesses. Fortunately, the weakness of one method is the strength of the other. As seen in Figure 3.17, in the low frequency range where MSASW would not provide quality results, ReMi fills the gap with good resolution at low frequencies and vice versa for high frequencies. The combination of both methods results in good quality data for the determination of Rayleigh phase velocities for a frequency range of 2 to 100 Hz providing the ability to determine shear wave velocities to depths of up to 100 meters.

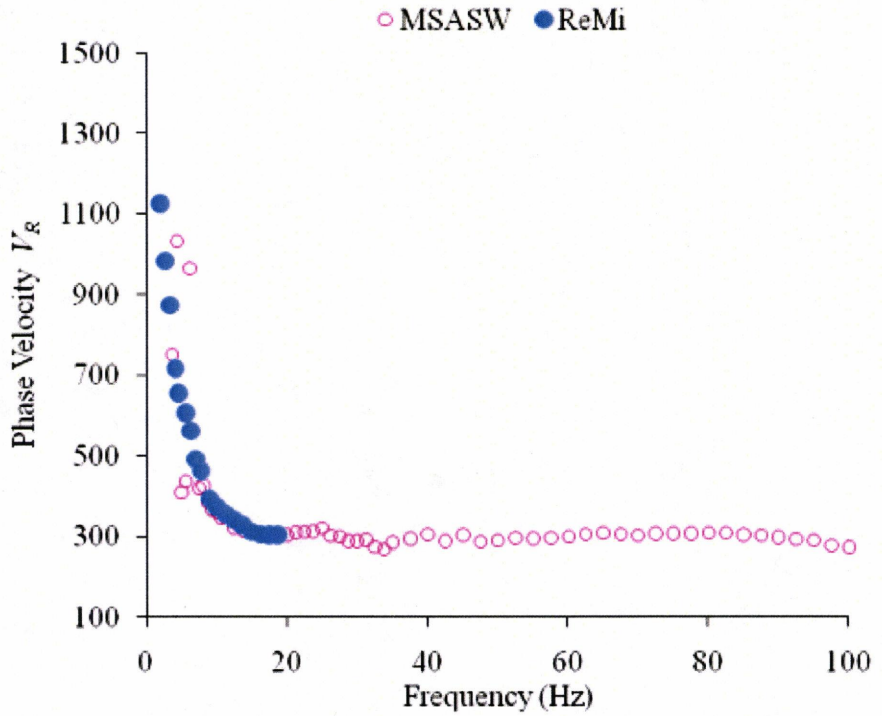

Figure 3.17 Combination dispersion curve from both MSASW and ReMi methods.

3.4. Inversion

The inversion process for all dispersion curves was accomplished through the utilization of a genetic algorithm (GA) for the solution of the Raleigh wave equation as outlined in Pezeshk and Zarrabi (2005). GAs are optimization and search techniques that simulate the natural evolution process and are based on a stochastic approach, which rely on strategy of survival of the best fit (Holland 1975). The procedure consists of randomly choosing an initial soil velocity profile to develop a theoretical dispersion curve using the forward method (Rix 1998). This theoretical dispersion curve is then compared to that of the experimental dispersion curve obtained from field testing (Figure 3.18). The difference between the two curves is calculated and the resulting profile is returned to the GA where offspring soil profiles, profiles with slight variations from the original, are generated and their resulting dispersion curves compared to that of the experimental (Figure 3.19). Then, this process continues by finding new and better sets of inputs through the processes that mimic the natural mating, selection, and mutation in each generation (Figure 3.20). The goal of the GA is to find the best match between the theoretical and the experimental dispersion curves. Therefore, with each new generation there is a better agreement between the

calculated output theoretical dispersion curve and the input experimental dispersion curve. The GA part of the procedure is fast, stable, and accurate, with several advantages compared to the traditional methods. The results for all sites of the project are displayed in Appendix A.

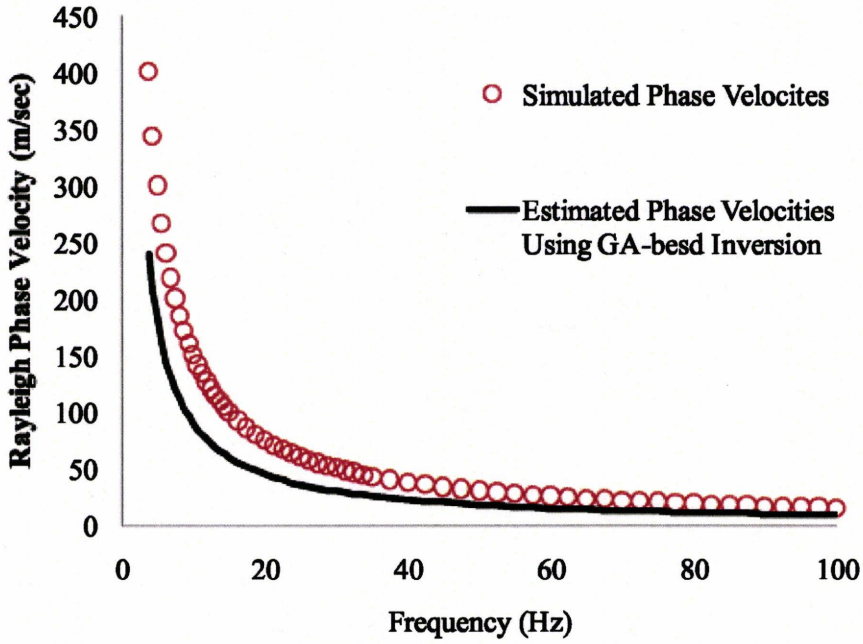

Figure 3.18 Theoretical vs. Experimental Dispersion Curve.

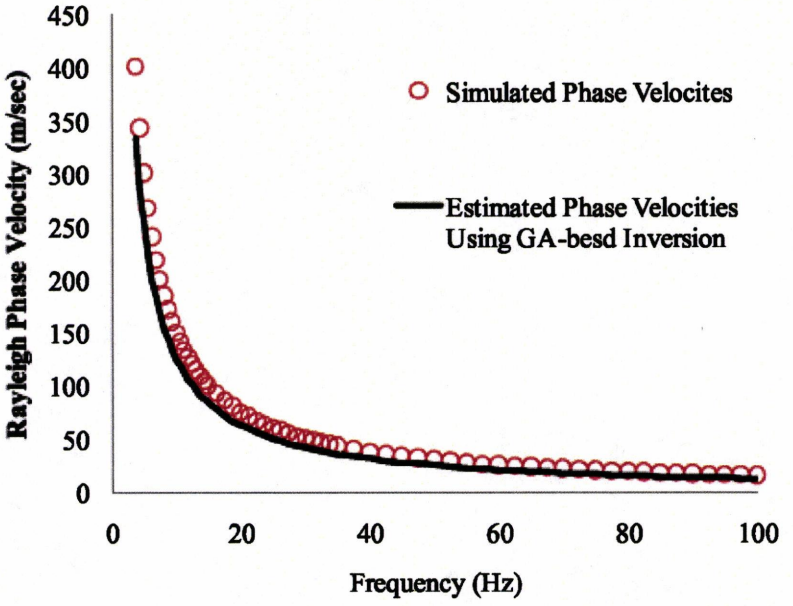

Figure 3.19 Theoretical vs. Experimental Dispersion Curve after new offspring.

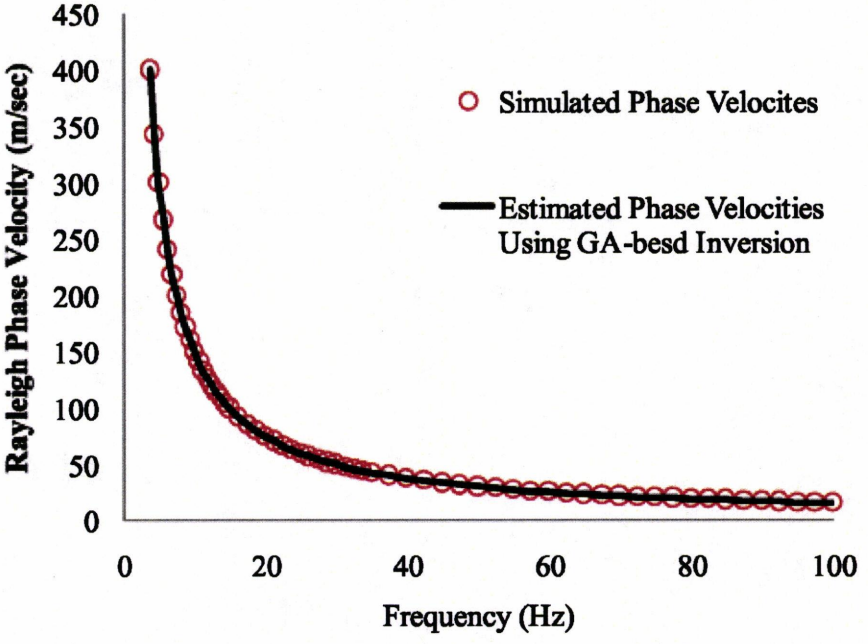

Figure 3.20 Experimental dispersion curve and the theoretical dispersion curve after convergence

CHAPTER 4
SITE CLASSIFICATIONS

4.1 Site Classification Definitions

According to the document titled "AASHTO Guideline Specifications for LRFD Seismic Bridge Deign," the Site Class Definitions are listed in Table 4.1 below.

Table 4.1 Site Class Definitions.

Site Class	Soil Type and Profile
A	Hard rock with measured shear wave velocity, V_s> 5,000 ft/sec.
B	Rock with 2,500 ft/sec < V_s < 5,000 ft/sec.
C	Very dense soil and soil rock with 1,200 ft/sec < V_s < 5,000 ft/sec. or with either N > 50 blows/ft. or S_u > 2000 psf
D	Stiff soil with 600 ft/sec < V_s < 1,200 ft/sec. or with either 15 < N > 50 blows/ft. or 2000 > S_u > 1000 psf
E	Soil profile with V_s < 600 ft/sec. or with either N < 15 blows/ft. or S_u < 1000 psf, or with any profile with more than 10 feet of soft clay defined with PI >20, w > 40 percent and S_u < 500 psf
F	Soil requiring site-specific evaluations, such as: Peats or highly organic clays (H > 10 ft of peat or highly organic clay, where H = thickness of soil) Very high plasticity clay (H > 25 ft with PI > 75) Very thick soft/medium stiff clay (H > 120 ft)

Exceptions:

Where the profile is not known in sufficient detail to determine the site class, a site investigation shall be undertaken sufficient to determine the site class. Site classes E or F should not be assumed unless the authority having jurisdiction determines that site classes E or F should be present at the site or in the event that site classes E or F are established by geotechnical data.

V_s = average shear wave velocity in the upper 100 feet of the soil profile
N = average Standard Penetration Test (SPT) blow count (blows/ft) (ASTM D 1586) for the upper 100 feet of the soil profile
S_u = average undrained shear strength in psf (ASTM D 2166 or D 2850) for the upper 100 feet of the soil profile
PI = plasticity index (ASTM D 4318)
w = moisture content (ASTM D2216)

Note: Site Class F includes soils vulnerable to potential failure or collapse under seismic loading, such as liquefiable soils, quick and highly sensitive clays, and collapsible weakly cemented soils.

4.2 Site Classification Based on Shear Wave Velocity Profiles

Based on the shear wave velocity profiles, the "Site Class" of each of the 16 bridge sites was determined. They are listed in Table 4.2 below.

Table 4.2 Site Class Based on Shear Wave Velocity Profiles.

PI Site No.	AHTD Site No.	Average Shear Wave Velocity in the Upper 100 ft, ft/sec.	Site Class
1	110288	849	D
2	110358	656	D
3	110401	712	D
4	100547	718	D
5	110337	575	E
6	110434	667	D
7	100523	1084	D
8	100522	736	D
9	BR4706	731	D
10	100105	692	D
11	R00059	721	D
12	100303	721	D
13	100153	754	D
14	100478	706	D
15	BR1108	693	D
16	BR1110	662	D

4.3 Site Classification Based on SPT Blow Counts

Based on the blow counts listed on the boring logs, the Site Class of the 16 bridge sites were determined. They are listed in Table 4.3 below.

Table 4.3 Site Class Based on SPT Blow Counts.

PI Site No.	AHTD Site No.	Average Field Blow counts in the Upper 100 ft, blows/ft.	Site Class
1	110288	15.5	D
2	110358	19.7	D
3	110401	15.0	E
4	100547	23.3	D
5	110337	15.3	D
6	110434	15.5	D
7	100523	22.5	D
8	100522	20.3	D
9	BR4706	20.9	D
10	100105	15.6	D
11	R00059	16.1	D
12	100303	20.6	D
13	100153	16.7	D
14	100478	16.0	D
15	BR1108	19.4	D
16	BR1110	18.0	D

Comparing the data from Table 4.1 and 4.3 indicate consistent results, except for sites 110337 and 110401. The results from these 2 sites were considered "borderline" between site classes D and E. It is imperative to recognize the difference between the 2 methods upon site class determination, as each of the 2 methods has its advantages, disadvantages, and sources of errors.

CHAPTER 5
LIQUEFACTION ANALYSIS

5.1. Introduction

The liquefaction analyses were performed using both shear wave velocity profiles and SPT blow counts as indicated on the boring logs provided by AHTD for each site. Each method required specific input data. The two methods, as well as their required input data, are discussed below.

5.2. Standard Penetration Testing Analysis

This section presents the procedure to perform liquefaction analyses using the standard penetration test (SPT).

5.2.1. Input Data

The following is a list of data needed to perform a liquefaction study.

5.2.1.1 Field Blow Counts

The ATHD Geotechnical Division provided boring logs that were prepared during the geotechnical investigations of the sites. Each log indicated the field blow counts (or N values) at specific depth intervals (typically 5 feet).

5.2.1.2 Depth to Groundwater

Most of the boring logs mentioned above indicated the depth to groundwater. In the cases where the depths to groundwater were not indicated on the logs, the soil descriptions were used to estimate the depth to the water table. For example, when the cohesive soil is described as "wet" or when the cohesionless soils were described as "wet to very wet, the depth to groundwater was taken as the top of such a layer.

5.2.1.3 Hammer Efficiency, Sampler Type, and Borehole Diameter

These data are required to correct the field blow counts to a hammer efficiency of 60% (N_{60}). The data were provided by the AHTD Geotechnical Division.

5.2.1.4 Soil Unit Weights

The unit weights were estimated using past experience, field blow counts, and typical values list in many soil mechanics text books (Bowles, 1993).

5.2.1.5 Peak Ground Acceleration

The peak ground acceleration is a significant input to the liquefaction analysis. According to the document titled "AASHTO Guide Specifications for LRFD Seismic Bridge Design," which was proposed by Roy Imbsen in May, 2007 and later approved, the 1000-year return period (approximately equivalent to a 7% probability of exceedance in 75 years) was recommended for the seismic design of highway bridges.

The United States Geological Survey (USGS) prepared two types of products for use by AASHTO. One of these products was a ground motion software tool to simplify the determination of the seismic design parameters. AHTD provided the PIs with a copy of the software (Figure 5.1). The software provides values for the design peak ground acceleration (A_s), short-period spectral acceleration (S_{DS}) and one-second spectral acceleration (S_{D1}) based on the site class and the location as documented by the zip code or the Latitude / Longitude.

The design peak ground acceleration for each of the test sites were determined using the Latitude / Longitude recorded during the fieldwork using hand-held global positioning system (GPS). These data are presented in Table 5.1 below.

Table 5.1 Site Geographic Locations and Design Peak Ground Accelerations (A_s), g.

AHTD Site No.	Geographic Location		Design Peak Ground Acceleration, A_s (g)
	Latitude	Longitude	
110288	35.27326	-90.55888	0.833
110358	35.16262	-90.22425	0.522
110401	39.39146	-90.27344	0.800
100547	35.4748	-90.33327	0.951
110337	35.19971	-90.24574	0.592
110434	35.41504	-90.28398	0.839
100523	35.48047	-90.35757	0.976
100522	35.51862	-90. 41266	1.035
BR4706	35.59755	-90.26931	1.038
100105	35.59754	-90.21449	1.030
R00059	35.84046	-90.75316	0.620
100303	35.82309	-90.5006	0.830
100153	35.82073	-90.43327	0.897
100478	36.05171	-90.36039	0.667
BR1108	36.39091	-90.39922	0.470
BR1110	36.45966	-90.35708	0.462

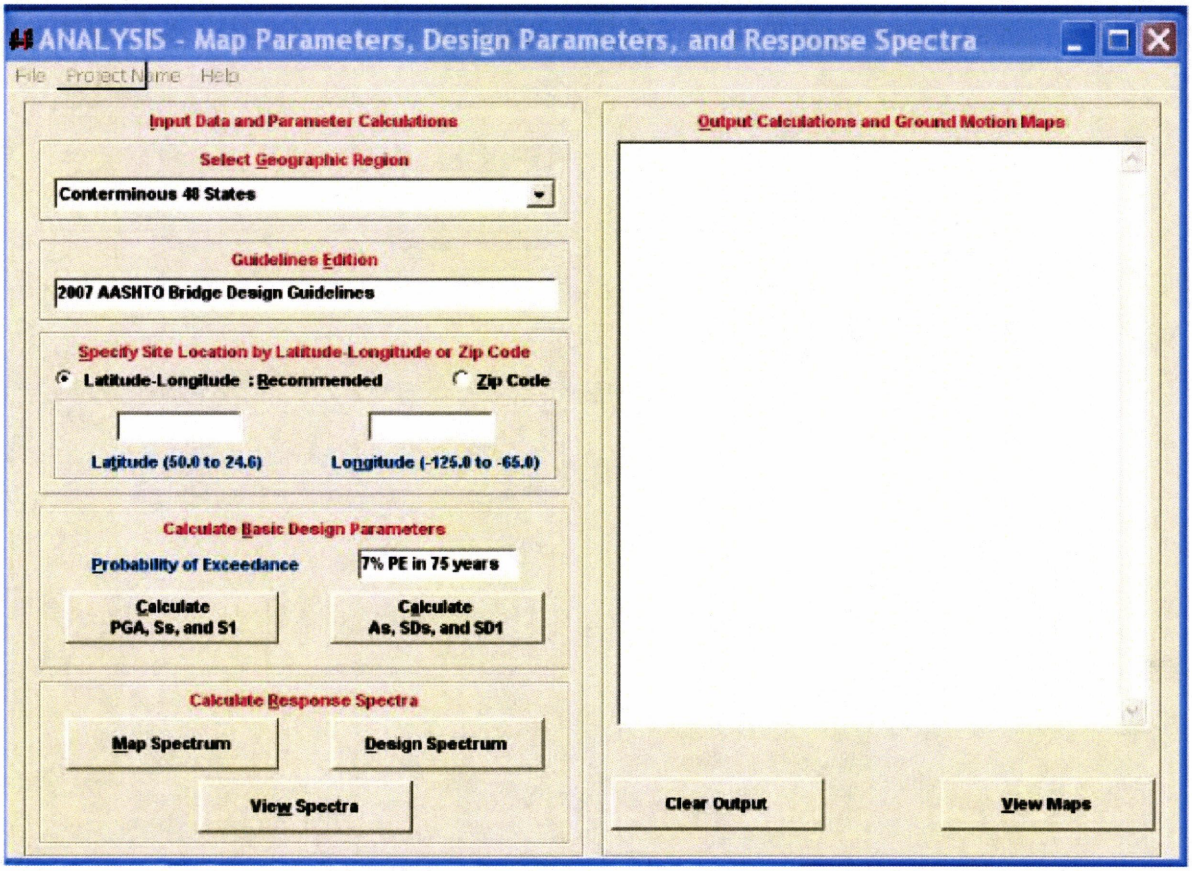

Figure 5.1 Screen shot of AASHTO Site Acceleration Program

5.2.1.6 Earthquake Magnitude

As previously mentioned, several researchers estimated the moment magnitudes of the 1811-1812 events to be in the range of 7.5 to 7.8 (Bakun & Hopper, 2004, Rix and Romero, 2005). After evaluating the available data, and based on the previous experience of the PIs in the study area, a decision was a made to utilize a moment magnitude (typically used in engineering practice) of 7.50 as the AASHTO-based event (probability of exceedance of 7% in 75 years).

5.2.1.7 Fine Contents and Soil Plasticity

The fine content is another significant input parameter needed for the analysis. The available AHTD data did not include any laboratory test results. Therefore, a decision was made to drill one borehole at each site to provide samples for fine content and Atterberg Limits determinations. The PI's provided a sampling sequence. Once the samples were collected, they

were transferred to the Arkansas State University (ASU) laboratory for testing. The laboratory test results are presented in Tables 5.2 through Table 5.9.

Table 5.2 Percent Fines and Atterberg Limits Data – Sites 110288/110358/110401.

AHTD Site No.	Depth, ft.	Percent Fines	Liquid Limit, %	Plasticity Index, %
110288	10	94	37	14
	20	10	-	-
	40	5	-	-
	70	5	-	-
	100	6	-	-
110358	25	66	34	16
	50	5	-	-
	70	5	-	-
	100	6	-	-
110401	20	93	47	26
	30	97	46	23
	50	8	-	-
	70	4	-	-
	100	5	-	-

Table 5.3 Percent Fines and Atterberg Limits Data – Sites 100547/110337/110434.

AHTD Site No.	Depth, ft.	Percent Fines	Liquid Limit, %	Plasticity Index, %
100547	20	30	-	-
	40	14	-	-
	70	4	-	-
	100	4	-	-
110337	20	95	34	15
	45	7	-	-
	70	8	-	-
	100	7	-	-
110434	10	78	45	25
	20	92	46	13
	40	74	-	-
	60	19	-	-
	100	13	-	-

Table 5.4 Percent Fines and Atterberg Limits Data – Sites 100523/100522/BR4706.

AHTD Site No.	Depth, ft.	Percent Fines	Liquid Limit, %	Plasticity Index, %
100523	10	62	31	16
	30	7	-	-
	50	8	-	-
	70	6	-	-
	100	6	-	-
100522	20	65	-	-
	30	11	-	-
	50	3	-	-
	70	5	-	-
	100	4	-	-
BR4706	20	88	68	35
	40	6	-	-
	70	6	-	-
	100	5	-	-

Table 5.5 Percent Fines and Atterberg Limits Data – Sites 100105/R0059/100303.

AHTD Site No.	Depth, ft.	Percent Fines	Liquid Limit, %	Plasticity Index, %
100105	10	70	50	34
	30	6	-	-
	50	5	-	-
	70	8	-	-
	100	5	-	-
R00059	20	89	36	18
	40	44	-	-
	60	37	-	-
100303	10	60	30	13
	20	7	-	-
	40	4	-	-
	70	5	-	-
	100	93	-	-

Table 5.6 Percent Fines and Atterberg Limits Data – Sites 00153/100478/BR1108/BR1110.

AHTD Site No.	Depth, ft.	Percent Fines	Liquid Limit, %	Plasticity Index, %
100153	10	36	-	-
	30	4	-	-
	60	4	-	-
	100	10	-	-
100478	15	42	26	12
	30	5	-	-
	50	4	-	-
	70	4	-	-
	100	4	-	-
BR1108	10	58	36	20
	20	19	-	-
	40	8	-	-
	70	5	-	-
	100	5	-	-
BR1110	20	58	27	5
	40	7	-	-
	50	4	-	-
	70	6	-	-
	100	4	-	-

5.2.2. Method of Analysis

Seed and Idriss (1971) developed a "simplified procedure" that can determine safety against liquefaction. The simplified procedure was developed from evaluation of field observation and field and laboratory test data. The procedure uses two variables to evaluate for liquefaction of soils. These variables are the seismic demand induced by the design earthquake and expressed in terms of cyclic stress ratio (*CSR*), and the capacity of soil to resist liquefaction, expressed in terms of cyclic resistance ratio (*CRR*). The *CRR* is proportional to the peak ground acceleration (a_{max}).

The CSR is calculated using the method introduced by Seed and Idriss (1971) as follows:

$$CSR = \frac{\tau_{av}}{\sigma'_{VD}} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{VD}}{\sigma'_{VD}}\right)r_d \tag{5.1}$$

where,

0.65: a weighing factor introduced by Seed to account for the average equivalent cyclic shear stress caused by the earthquake (assumed to be 0.65 of the maximum induced stress).

a_{max}: peak horizontal ground acceleration.

σ_{VD}: total vertical overburden pressure.

σ'_{VD}: effective vertical overburden pressure.

r_d: shear stress reduction coefficient to adjust for the flexibility of the soil profile.

Values of r_d are commonly estimated from a chart introduced by Seed and Idriss (1971). The 1996 NCEER participants recommended the following equations to estimate the average r_d values for noncritical projects (z is the depth below ground surface):

$$r_d = 1.0 - 0.000765 \cdot z \qquad z \le 9.15m \tag{5.2}$$

$$r_d = 1.174 - 0.0267 \cdot z \qquad 9.15m \le z \le 23m \tag{5.3}$$

$$r_d = 0.744 - 0.008 \cdot z \qquad 23m \le z \le 30m \tag{5.4}$$

$$r_d = 0.50 \qquad z \ge 30m \tag{5.5}$$

The first 2 equations were proposed by Liao and Whitman (1986), the third equation was proposed Robertson and Wride, and the fourth equation was proposed by William F. Marcuson. Revised average values were proposed by Idriss (1999) based on analytical work by Golesorkhi (1989). The revised values were magnitude dependent (Andrus and Stokoe, 1997).

It is important to note that the workshop participants indicated that the certainty with which CSR can be calculated decreases with depth when the mean r_d values are used to simplify the calculations. Moreover, the simplified procedure is not well verified with case history data

for depths greater than 15 m. However, they agreed that for convenience in programming, r_d values presented by Equations (5.2) through (5.5) above are suitable for routine engineering practice. Therefore, the method of calculating CSR introduced in this report represents the best available approach at this stage.

The CRR for a moment magnitude, M_w = 7.5 earthquake, $CRR_{7.5}$, can be determined using several field testing methods such as SPT, Cone Penetration Testing (CPT), Becker Penetration Testing (BPT), and Shear Wave Velocity, V_s.

To calculate the CRR using the SPT data, the equivalent clean sand standard penetration resistance defined as $(N_1)_{60cs}$, should first be determined. This can be done as follows:

$$(N_1)_{60cs} = N_f C_n C_a C_b C_r C_s \tag{5.6}$$

where,

$(N_1)_{60cs}$: corrected normalized standard Penetration *N*-value,

N_f: standard penetration value measured in the field,

C_n: depth (overburden stress) correction factor for an effective overburden pressure of 1 tsf (2000 pound per square foot),

C_e: hammer energy ratio correction factor for 60% hammer efficiency,

C_b: borehole diameter correction factor,

C_r: rod length correction factor, and

C_s: sampler correction factor (with or without a liner).

Fine content (% pass No. 200 sieve) factors were then applied to $(N_1)_{60cs}$ in order to account for the effect of the fines in the soil, thus calculate $(N_1)_{60f}$. Two approaches were adopted. The first one was to apply the fines correction using the method introduced by Stark and Olsen (1995). This method applies the correction for fines contents in the range of 0 to 35%. When this approach was taken, fine-grained soils with more 60 percent fines were assumed to be non-liquefiable. The second approach was to use the Modified Stark and Olsen, where the fines

content correction line is extended to fines of 100% instead of having a maximum correction factor (keeping the correction line flat) at 35%. For this approach, any soil layer with less than 100% fines was assumed to be liquefiable. When the soil type indicated that either approach can be taken, the analysis was denoted "ALT. A" and "ALT. B" for the first and second approaches, respectively. Otherwise, only the first approach was adopted and no denotation was used. This step was done for comparison only, as "ALT. A" is considered the most likely scenario.

The following equation, which was introduced by Blake (1997), was used to calculate $CRR_{7.5}$:

$$CRR_{7.5} = \frac{a + cx + ex^2 + gx^3}{1 + bx + dx^2 + fx^3 + hx^4} \tag{5.7}$$

where,

$x =$ $(N_1)_{60f}$

$a =$ 0.048

$b =$ -0.1248

$c =$ -0.004721

$d =$ 0.009578

$e =$ 0.0006136

$f =$ -0.0003285

$g =$ -1.673×10^{-5}

$h =$ 3.714×10^{-6}

The safety factor against liquefaction is defined according to Youd *et al.* (2001) as:

$$FS = \frac{CRR_{7.5}}{CSR} MSF \tag{5.8}$$

where *MSF* is the magnitude scaling factor to adjust the simplified curve to magnitudes smaller or larger than 7.5 (Seed and Idriss, 1982). Since the design earthquake was assumed to have a

moment magnitude of 7.5, the *MSF* had no impact on this analysis.

Correction factors for Equation (5.8) were introduced by Seed (1983) to account for high overburden stress (K_σ) and static shear due to sloping ground (K_α). The NCEER workshop participants, however, agreed that the effect of sloping ground is not well understood, although correction curves were available (Harder and Boulanger, 1997). They recommended that the evaluation is beyond routine application of the simplified procedure. The high overburden stress correction factor was also ignored as a partial compensation for the unquantified but substantial increase in the liquefaction resistance due to aging.

5.2.3. Method of Calculation

The computer program *Liquefy Pro* (Civiltech Software, 2007) was used to perform the SPT-based liquefaction analysis. The decision was made to use this software for the ease and speed of the calculation, as well as its graphic capability. In addition to the calculation of the safety factor against liquefaction, the program also calculates the estimated dynamic settlement due to the densification of the dry (above groundwater table) and wet (below groundwater table) cohesionless soils during the seismic event. The calculations are performed through 4 steps as follows:

- Establishing a relationship between $(N_1)_{60}$ and relative density, D_r.
- Calculating the fines corrections for settlement analysis purposes.
- Calculating of saturated soil settlement.
- Calculating of dry soil settlement.

5.2.4. Analysis Results

The analysis was performed using the available boring logs and soil data for each site. The results are summarized in Table 5.7 through Table 5.12 below. The results are also included in Appendix D.

Table 5.7 SPT-Based Liquefaction Analysis Results – Sites 110288 / 110358.

Site No.	Borehole No./Depth, ft.	Approach	Zones (ft. below Ground surface) that Indicated SF < 1.0	Est. Dynamic Settlement, in.
110288	B-1/100	ALT. A	15-65/74-99	13.9
		ALT. B	11-65/74-99	16.1
	B-2 / 100	-	17-33/58- >100	23.3
	B-3 / 70	ALT. A	10-18/33-50/55	6.1
		ALT. B	7-18/33-50/55	9.3
	B-4 / 66	ALT. A	10-20/21-28/32-42/55	5.3
		ALT. B	10-20/21-28/32-42/55	6.4
	B-5 / 100	ALT. A	35-45 55-65/80-82	7.2
		ALT. B	35-45/55-65/80-82	9.3
	B-6 / 76	ALT. A	28-38/43-57	4.4
		ALT. B	28-38/43-57	6.6
110358	B-1 / 100	ALT. A	55-65/78-99	4.5
		ALT. B	32-45/55-65/78-99	7.3
	B-2 / 100	ALT. A	31-40/ 46-81/95- > 100	6.4
		ALT. B	31-40/ 46-81/95- > 100	6.7
	B-4 / 100	ALT. A	31-40/ 45-81/95- > 100	8.6
		ALT. B	31-40/ 45-81/95- > 100	8.7
	B-5 / 100	ALT. A	31-35/ 45-67/73-95	8.1
		ALT. B	31-35/ 45-67/73-95	9.0
	B-6 / 100	ALT. A	50-54/57-63/70/78-84/87- >100	2.6
		ALT. B	40-54/57-63/70/78-84/87- >100	4.7
	B-7 / 100	ALT. A	36-95	13.0
		ALT. B	20-35/36-95	14.1
	B-8 / 100	ALT. A	41-95	7.5
		ALT. B	41-95	7.5
	B-9 / 100	-	35-38/45-68/73-88/93-96	6.3
	B-10 / 100	-	31-38/42-85/96-98	9.8

Table 5.8 SPT-Based Liquefaction Analysis Results – Sites 110401 / 110434.

Site No.	Borehole No./Depth, ft.	Approach	Zones (ft. below Ground surface) that Indicated SF < 1.0	Est. Dynamic Settlement, in.
110401	B-1 / 100	ALT. A	25-35/50-54/56-63/68-88/95->100	12.7
		ALT. B	25-35/50-54/56-63/68-88/95->100	13.6
	B-2 / 100	ALT. A	30-35/48-54/55-72/80->100	7.7
		ALT. B	30-35/48-54/55-72/80->100	7.9
	B-3 / 100	-	28-33/40-69/78-87/95->100	12.5
	B-4 / 100	-	30-32/47-64/77-91	7.4
	B-5 / 100	ALT. A	25-29/33-95	12.3
		ALT. B	20-29/33-95	14.1
	B-6 / 100	ALT. A	25-29/48-84/95->100	8.1
		ALT. B	25-29/48-84/95->100	8.4
	B-7 / 100	ALT. A	25-33/36-94/96->100	12.7
		ALT. B	25-33/36-94/96->100	13.7
	B-8 / 100	ALT. A	25-30/33-63/67-95	10.8
		ALT. B	25-30/33-63/67-95	11.4
	B-9 / 100	ALT. A	25-30/35-49/51-74/82->100	9.5
		ALT. B	24-30/35-49/51-74/82->100	11.7
	B-10 / 100	ALT. A	25-35/36-65/67->100	14.8
		ALT. B	25-35/36-65/67->100	15.0
	B-11 / 100	-	25-32/40->100	13.3
	B-12 / 100	-	25-65/66->100	12.3
	B-13 / 100	-	30-33/38->100	12.3
	B-14 / 100	-	25-53/57-99	12.6
110434	B-1 / 100	ALT. A	20-55/61-82/89-95	17.7
		ALT. B	20-55/61-82/89->100	18.4
	B-2 / 100	ALT. A	20-34/37-55/62-85/86-95	16.9
		ALT. B	20-34/37-55/62-85/86->100	18.3
	B-3 / 100	ALT. A	20-45/50-78/85-90	15.2
		ALT. B	20-78/85->100	18.2
	B-4 / 100	ALT. A	22-60/67-95	17.1
		ALT. B	21-95	20.4
	B-5 / 100	ALT. A	20-32/38-60/67-74/75-86/94-95	16.2
		ALT. B	20-32/38-60/67-74/75-86/94->100	16.6
	B-6 / 100	-	38-63/67-78/82-95	8.5
	B-7 / 100	-	21-22/48-64/67-73/87-92	5.8
	B-8 / 100	-	45-65/66-84/90->100	9.3
	B-9 / 100	-	29-30/45->100	10.1

Table 5.9 SPT-Based Liquefaction Analysis Results – Sites 100547/100523/100522.

Site No.	Borehole No./Depth, ft.	Approach	Zones (ft. below Ground surface) that Indicated SF < 1.0	Est. Dynamic Settlement, in.
100547	B-1 / 100	ALT. A	20-48/63-69/72-75/88-95	10.7
		ALT. B	20-48/63-69/72-75/88-95	12.8
	B-2 / 100	-	20-52/58-73/80-95	13.3
	B-3 / 100	-	23-66/76-90/91/99	15.0
	B-4 / 100	-	23-32/39-44/51-80/81-99	14.5
	B-5 / 100	-	23-25/32-49/51-62/73-76	8.3
	B-6 / 100	ALT. A	25-29	0.7
		ALT. B	25-29	2.2
	B-7 / 100	ALT. A	25-26/45-46	0.5
		ALT. B	25-26/45-46	1.4
100523	B-1 / 100	ALT. A	15-17/21-35/40-56/62-73/89->100	9.8
		ALT. B	15-17/21-56/62-73/89->100	12.4
	B-1NEW/ 100	ALT. A	15-20/30-36/48-52	2.7
		ALT. B	15-20/25-29/30-36/48-52	4.0
	B-2 / 100	ALT. A	30-33/37-42/50-61/90-94	3.7
		ALT. B	18-33/37-42/50-61/90-94	7.4
	B-2A / 100	ALT. A	15-51/58-76/81-93/96->100	11.3
	B-3 / 100	ALT. B	15-18/21-30/40-76/86->100	11.2
		ALT. A	15-18/21-76/86->100	11.7
	B-3NEW/ 100	ALT. B	25-35	1.8
		ALT. A	12-15/25-35	2.4
	B-4 / 100	ALT. B	15-29/33-66/73-80/81-93/97->100	11.4
	B-4NEW/ 100	ALT. A	25-37/45-48/80-85	3.8
		ALT. B	10-12/25-37/45-48/80-85	4.2
	B-5NEW/ 100	ALT. A	10-13/21-30	2.5
		ALT. B	10-13/21-3625-37/45-48/80-85	4.1
100522	B-1 / 100	ALT. A	30-33/39-90	8.0
		ALT. B	30-33/39-90	9.0
	B-2 / 100	-	25-75/84->100	9.6
	B-3 / 100	ALT. A	25-80	11.0
		ALT. B	22-80	14.3
	B-4 / 100	ALT. A	45-87	6.1
		ALT. B	22-24/45-87	6.5
	B-5 / 70	ALT. A	45-46/65-67	0.5
		ALT. B	45-46/65-67	1.4

Table 5.10 SPT-Based Liquefaction Analysis Results – Sites 100478/100303/100105/110337/BR1108/BR1110.

Site No.	Borehole No./Depth, ft.	Approach	Zones (ft. below Ground surface) that Indicated SF < 1.0	Est. Dynamic Settlement, in.
100478	B-1 / 100	-	20-24/25-48/65-95	11.1
	B-2 / 100	-	10-42/45-75/85-88	10.3
	B-3 / 100	-	16-74/75-83/93-99	11.7
	B-4 / 100	-	11-16/22-41/47-58/61-66/73-85/98->100	9.7
	B-5 / 100	-	35-50/60-69/90-91	4.0
	B-5A / 100	-	10-72/77-81/85->100	15.1
	B-6 / 100	-	9-43/53-75/76-80	10.8
	B-6A / 100	-	10-44/48-80/85-98	14.8
100303	B-1 / 100	-	15-39/48-73/75-80	9.3
	B-2 / 100	ALT. A	20-60/67-72/77-80	6.5
		ALT. B	20-60/67-72/77-80	6.7
	B-3 / 100	ALT. A	15-20/30-35/42-47/54-80	6.8
		ALT. B	7-20/30-35/42-47/54-80	8.7
	B-4 / 100	-	25-33/51-57/70-72	2.7
100105	B-1 / 60	-	58->60	0.2
	B-1A / 100	-	30-40/42/47/50-65/94-97	5.5
	B-2 / 100	-	None	3.2
	B-2A / 100	ALT. A	35-39	1.1
		ALT. B	30-39	4.4
	B-3 / 100	-	35-42	1.1
	B-3A / 100	ALT. A	30-36/44-55/80-90	5.7
		ALT. B	30-36/44-55/80-90	5.7
	B-4 / 100	-	40-50	2.2
	B-4A / 100	ALT. A	40-43/46-53	2.9
		ALT. B	15-30/40-43/46-53	6.9
110337	B-1 / 100	-	9-15/40-89/90-98	10.0
	B-2 / 100	-	50-90/98->100	7.9
	B-3 / 100	ALT. A	13-15/60-80/97->100	3.8
		ALT. B	13-30/40-50/55-80/97->100	9.4
BR1108	B-1 / 100	ALT. A	23-42/50-57/63-68/71-76	6.4
		ALT. B	23-42/50-57/63-68/71-76	6.6
	B-2 / 100	ALT. A	10-13/25-38/53-58/90-93	5.6
		ALT. B	9-13/25-38/53-58/90-93	5.9
BR1110	B-1 / 100	ALT. A	25-30/48-54/60->100	8.6
		ALT. B	15-30/48-54/60->100	11.7
	B-2 / 100	ALT. A	12-16/21-26/68-92	4.8
		ALT. B	12-26/68-92	5.8

Table 5.11 SPT-Based Liquefaction Analysis Results – Site 100153.

Site No.	Borehole No./Depth, ft.	Approach	Zones (ft. below Ground surface) that Indicated SF < 1.0	Est. Dynamic Settlement, in.
100153	B-1 / 75	ALT. A	17-28/48-55	3.1
		ALT. B	5-8/14/17-28/48-55	4.0
	B-2 / 65	ALT. A	10-16/39-44/51->65	3.9
		ALT. B	5-16/39-44/51->65	5.6
	B-3 / 75	ALT. A	10-14/17-28/36-61	6.7
		ALT. B	5-14/17-28/36-61	8.3
	B-4 / 75	ALT. A	10-36/49-53/60-64/70	6.7
		ALT. B	7-36/49-53/60-64/70	6.7
	B-5 / 100	ALT. A	10-45/46-60/67-72/78-81/91-99	10.6
		ALT. B	4-7/10-45/46-60/67-72/79-99	12.9
	B-6 / 65	ALT. A	12-44/50-51	6.2
		ALT. B	5-7/12-44/50-51	6.8
	B-7 / 60	ALT. A	10-24/33-39/55	5.5
		ALT. B	4-24/33-39/55	7.1
	B-8 / 100	ALT. A	15-16/23-27/40-43/48-72	5.9
		ALT. B	4-16/23-27/40-43/48-72	7.9
	B-9 / 65	ALT. A	15-40/63->65	4.5
		ALT. B	15-40/63->65	4.6
	B-10 / 75	ALT. A	10-28/40-53/63-68	7.8
		ALT. B	10-28/40-53/63-68	10.1
	B-11 / 75	-	25-37/48-54/58-73	5.6
	B-12 / 70	ALT. A	10-14/18-25/29-31/42-51/57-66	4.7
		ALT. B	4-14/18-25/29-31/42-51/57-66	6.6
	B-13 / 60	-	15-27/55	2.5
	B-14 / 80	-	25-37/55-60/63->80	5.5
	B-15 / 85	ALT. A	10-33/57-63	6.1
		ALT. B	2-33/57-63	8.1
	B-16 / 100	ALT. A	10-17/24-37/55-62/70-74/78->100	9.5
		ALT. B	3-17/24-37/55-62/70-74/78->100	11.5
	B-17 / 80	ALT. A	10-22/28-59/62->80	9.4
		ALT. B	5-22/28-59/62->80	11.2
	B-18 / 60	ALT. A	21-37	3.2
		ALT. B	21-37	4.2
	B-19 / 100	-	20-24/28-32/44-49/55-56/65-85	7.6
	B-20 / 60	ALT. A	25-30/31-35	2.3
		ALT. B	25-31/31-35	3.2

Table 5.12 SPT-Based Liquefaction Analysis Results – Sites R00059 / R4706.

Site No.	Borehole No./Depth, ft.	Approach	Zones (ft. below Ground surface) that Indicated SF < 1.0	Est. Dynamic Settlement, in.
R00059	B-1 / 100	ALT. A	60-63/73-76/85-87/95->100	2.3
		ALT. B	60-63/73-76/85-87/95->100	2.3
	B-2 / 100	ALT. A	37-40/63-71/80-90	4.1
		ALT. B	40-42/48-57/63-71/80->100	6.7
	B-3 / 100	ALT. A	35-40/73-75/90->100	3.1
		ALT. B	35-38/48-55/75-83/87->100	5.0
	B-4 / 100	ALT. A	40-41/88-95	2.4
		ALT. B	54-57/88->100	3.2
	B-5 / 100	ALT. A	40-41/76-97/93-97	0.7
		ALT. B	44-53/65-66/72-80/93-97	3.0
	B-6 / 100	ALT. A	65-71/78-87/95->100	3.0
		ALT. B	35-41/56-59/65-71/78-87/95->100	4.0
	B-7 / 100	ALT. A	28-31/42-46/71-77	2.7
		ALT. B	28-38/42-46/56-62/71-77	4.7
	B-8 / 100	ALT. A	61-67/76-80	2.7
		ALT. B	61-67/76->100	5.7
R4706	B-1 / 100	ALT. A	31-35/43-48/65-66	2.0
		ALT. B	31-35/43-48/65-66	3.2
	B-2 / 100	ALT. A	31-34/47-48	0.7
		ALT. B	31-34/47-48	1.9

5.3. Liquefaction Analysis Using Shear Wave Velocity

5.3.1. Input Data

The shear wave velocity-based liquefaction analysis, referred to herein as the V_s analysis, required the following information:

Peak Ground Acceleration and Earthquake Magnitude.

- Depth to groundwater.
- Soil unit weights, soil classifications, fine contents, and Plasticity Indices.
- Shear wave velocity profiles, which were determined using the field testing.

In addition, the following assumptions were made to perform the analysis:

- The slope of the ground surface is 6% or less. This assumption is accurate, since the area tested at each site were basically flat.
- The approximate age of the soil deposits at the test sites is 2000 years. This is considered a conservative assumption to some extent. The geologic maps of the sites indicated that the surficial soils are of Holocene age, which is measured in terms of thousands of years (< 10,000 years).

5.3.2. Method of Analysis

The method presented by Andrus and Stokoe (2000) was used to perform the analysis. First, the stress-based or normalized shear wave velocity was calculated as follows:

$$V_{s1} = V_s \left(\frac{P_a}{\sigma'_{vo}} \right)^{0.25} \tag{5.9}$$

where P_a is a reference stress of 100 kPa (2000 psf), approximately atmospheric pressure, and σ'_{vo} is effective overburden pressure in the same units. In applying the above equation, two assumptions were made (Andrus, Stokoe, and Juang, 2004). These assumptions were that the

initial effective horizontal stress is a constant factor of the effective vertical stress. The second assumption is the factor mention above is equal to 0.50. These assumptions were considered accurate for the level, normally consolidation deposits of the study area.

The *CRR* is calculated as follows (Andrus and Stokoe, 2000):

$$CRR = (a\,(K_{a1} V_{s1}/100)^2 + b\,\{1/(V^*_{s1} - V_{s1}) - 1/V^*_{s1}\}\,K_{a2})\,MSF \qquad (5.10)$$

where,

V^*_{s1}: limiting upper value of V_{s1} for liquefaction occurrence.

= 215 m/sec — for sands and gravels with fines contents ≤ 5%

= 215 – 0.5 (FC – 5) — for sands with 5% < FC <35%

= 200 m/sec — for sands and gravels with fines contents ≥35%

a,b: curve fitting parameters taken as 0.022 and 2.80, respectively. It is important to note, however, that initial 1996 NCEER workshop recommendations for *a* and *b* were 0.03 and 0.9, respectively.

MSF: magnitude scaling factor as previously described (equal to 1.0 in this study)

Andrus, Stokoe, and Juang (2004) introduced two the factors (K_{a1} and K_{a2}) to account for the effect of aging. The first factor is to correct for high V_{s1} caused by aging, and the second factor is to correct for the influence of aging on CRR. They stated that both factors are equal to 1.0 for uncemented deposits of Holocene age. Therefore, a value of 1.0 was assigned to both factors in this study.

It is of particular importance to recognize that the CRR – V_{s1} relationship was developed using observation data from 26 earthquakes in California, Japan, China, Taiwan, and Idaho. Only seven of the 26 earthquakes had a moment magnitude (M_w) larger than 7.0. It is not known how well this correlation would fit with an earthquake of magnitude of 7.5 in the NMSZ.

Since only one shear wave velocity profile was available per site, representative unit weight values were used to calculate the total and effective overburden stresses. The CSR values were calculated in the same manner as in the previous analysis. The parts of the soil profiles

where the classifications indicated clayey (CL or CH) or silty (ML) soils, it was assumed that these zones are non-liquefiable.

The safety factor against liquefaction was calculated as CRR/CSR. No additional corrections factor due to sloping ground or high overburden stress were applied due to the reasons mentioned in Section 5.2.2. For the convenience of graphical presentation, a safety factor of 2.0 was assigned when a particular layer was considered non-liquefiable or when the overburden stress corrected shear wave velocity exceeded the limiting value.

5.3.3. Method of Calculations

A spreadsheet was used to perform this analysis. The spreadsheet calculates the safety factor against liquefaction as described above and generates a plot of safety factor versus depth below ground surface. A copy of the spreadsheet is included in Appendix D.

5.3.4. Analysis Results

The analyses were performed using the available data and the determined shear wave velocity profile for each site. The results are summarized in

Table 5.13 below. The results are also included in Appendix D.

Table 5.13 Shear Wave Velocity-Based Liquefaction Analysis Results.

Site No.	Average Shear Wave Velocity in the Upper 100 ft, ft/sec.	Source of soil Information (Boring No.)	Zones (ft. below Ground surface) that Indicated SF < 1.0
110288	849	B-1	20 – more than 100
110358	656	B-1	55 - 90
110401	712	B-2	35 – 80
100547	718	B-7	35 – 75
110337	575	B-2	50 – 65
110434	667	B-9	20 – 90
100523	1084	B-1NEW	No Liquefaction
100522	736	B-3	25 – 80 / 100 -
BR4706	731	B-1	45 – 60

100105	692	B-4	30 - 55
R00059	721	B-6	No Liquefaction
100303	721	B-1	15 – 45 / 60 - 70
100153	754	B-9	25 – 35 / 85 – more than 100
100478	706	B-5	15 -45/ 55- 85
BR1108	693	B-1	20 40 / 50 - 65
BR1110	662	B-1	40 - 90

5.4. Liquefaction Potential Index

The liquefaction potential for the test sites was evaluated using the Liquefaction Potential Index (LPI) as proposed by Iwasaki *et al.* (1978, 1982), which can be calculated as follows:

$$LPI = \sum_{i=1}^{n} w_i S_i H_i \tag{5.11}$$

where

n: number of layers in the upper 20 m (66 feet).

w_i: depth-dependent weighting function for layer i.

$w_i(z) = 10 - 0.5z$ (z = depth below ground surface, m)

S_i: degree of severity for layer i defined as:

$S = 0$ for $FS > 1.0$

$S = 1 - FS$ for $FS < 1.0$

FS: factor of safety against liquefaction for layer i as previously defined.

H_i: thickness of layer i, m.

Iwasaki *et al.* (1982) identified LPI values of 5 and 15 as the lower bounds of "moderate" and "major" liquefaction, respectively. The parameter was used by Rix and Romero-Hudock (2005) to map the liquefaction potential for Shelby County, Tennessee. Moreover, Toprak and Holzer (2003) found that median values of LPI of 5 and 12 corresponded to occurrence of sand boils and lateral spreading, respectively. They also found that LPI correlated well with liquefaction effects.

LPI was calculated for each site using both the SPT (from a representative boring) and V_s liquefaction analyses. The results are summarized in Table 5.14.

Table 5.14 LPI Evaluation Results.

Site No.	SPT Analysis		V_s Analysis
	Boring No.	LPI Value	
110288	B-2	47.1	14.7
110358	B-7	15.5	2.3
110401	B-5	24.8	14.4
100547	B-3	22.3	19.5
110337	B-1	16.1	4.7
110434	B-3	31.1	39.9
100523	B-1	43.8	0
100522	B-3	29.3	28.0
BR4706	B-1	5.7	1.8
100105	B-4A	25.5	21.9
R00059	B-7	10.0	0
100303	B-1	27.5	29.4
100153	B-5	48.7	10.5
100478	B-5A	48.4	30.5
BR1108	B-1	11.8	23.9
BR1110	B-1	19.7	7.8

5.5. Evaluation of Analysis Results

The liquefaction analyses and the LPI calculations indicated the following:

- Both the SPT and V_s analyses indicated significant liquefaction may occur at the test sites during the design seismic event. This is due to the combined effect of the nature of the

soil deposits and the relatively large peak horizontal ground acceleration required by the latest AASHTO LRFD design guide.

- Significant variability was noted within each site using the SPT approach. This can be attributed to the nature of the soil deposits, as the alluvial materials are expected to vary in both the horizontal and vertical directions. Another source of variability is the test procedure. The SPT results are highly dependent on the equipment used, procedure, as well as the operator's experience and consistency, even when the test standard (ASTM D 1586) is closely followed. The variability in the soil conditions could not be verified in the V_s approach, as only one test was performed at each site.

- The potential for liquefaction, as indicated by the calculated LPI values from SPT analysis, is mostly major (13 of the 16 sites, or 81% indicated LPI values above 15). On the other hand, the V_s approach indicated that only 44% of the sites (7 of the 16 sites) have LPI values above 15.

- Comparing the two analysis approaches, in terms of the depth and thickness of the liquefiable layer and the LPI values, the V_s approach in general results in lower degree of liquefaction.

In spite of the analysis results, there are still uncertainties regarding the depth of liquefiable zones. The analysis indicated soil that may liquefy at significant depths (100 feet or deeper). The PIs do not have any knowledge of sites in the NMSZ that indicated liquefaction at such a significant depth. The lack of recent large earthquakes in the NMSZ adds to the uncertainty.

It is of particular importance to recognize that the CRR – V_{s1} relationship was developed using case history data from 26 earthquakes in California, Japan, China, Taiwan, and Idaho. Only seven of the 26 earthquakes had a moment magnitude (M_w) larger than 7.0 (Andrus and Stokoe, 2000). The data were limited to average depths of less than 10 m. It is not known how well this correlation would fit with an earthquake of magnitude of 7.5 in the NMSZ. Andrus and Stokoe advised that care should be exercised when applying this approach where site conditions are different from the general characteristics of the case history data. This also should be applied upon performing the analysis using the SPT method. It is not know how suitable the upper

(limiting) values for V_{s1} would be for the study area, as they were developed using data from shallower depths and mainly smaller earthquake magnitudes.

In the case of silts and silt-clay mixtures, not enough studies have been performed. Liquefaction of silt-clay mixtures were also observed in China and Japan (Prakash & Puri). Seed (1989) reported a slide failure of Lower San Fernando Dam during the San Fernando Earthquake due to liquefaction of silt-like fill sand. Youd et al (1985) reported liquefaction of silt-clay materials at the Whisky Spring during the 1983 Idaho earthquake. Although evidence of extensive liquefaction was reported in the Mississippi embayment during the 1811-1812 events, it is not know if liquefaction actually took place in slit-clay soils. Liquefaction of non-plastic silts has been observed in the laboratory and the field (Kramer, 1996). This indicates that plasticity characteristics rather grain size alone influence the liquefaction susceptibility of fine-grained soils. Coarse silts with bulky particles shapes (which are cohesionless and non-plastic) are fully susceptible to liquefaction (Kramer, 1996; Ishihara, 1993). Finer silts with flaky or plate like particles generally exhibit sufficient cohesion to inhibit liquefaction. According to the so-called "Chinese Criteria," fine-grained soils that satisfy each of the following conditions may be considered susceptible to significant strength loss (Seed et al 1983):

- Fraction finer than 0.005 mm $\leq$ 15%
- Liquid limit, LL $\leq$ 35%
- Natural water content $\geq$ 0.9 LL

The Chinese Criteria states that nonliquefiable clayey soils have clay content (% finer than 0.002 mm) $\geq$ 10% and liquid limits > 35%. Andrus, Stokoe, and Juang (2004) stated that some exceptions to these criteria have been observed in recent earthquake studies (Sancio et al., 2003). Based on all of the above, the PIs believe the assumption that the fine-grained soils at the test sites will not liquefy is fairly reasonable, based on the condition that index property testing is performed to verify the conditions above.

The shear wave velocity approach has the following advantages (NCEER Workshop):

- V_s can be accurately measured in situ using a number of techniques such as downhole seismic tests, the seismic cone penetration tests, spectral analysis of surface waves (SASW), or refraction microtremors (ReMi).

- V_s is directly related to small-strain shear modulus, a parameter required in analytical procedures for estimating dynamic soil response at small and intermediate shear strains (Youd *et al.,* 2001).

- V_s measurements are possible in soils that are difficult to penetrate and in sites where drilling may not be permitted.

The approach, however, still has the following limitations (NCEER Workshop):

- Seismic wave velocity measurements are made in small strain, where as liquefaction is a large strain phenomenon.

- The testing does not provide samples.

- The V_s analysis may indicate liquefaction potential in soft, non-liquefiable clay-rich deposits.

- The V_s analysis may indicate high safety factors in weekly-cemented that may be liquefiable.

Andrus, Stokoe, and Juang (2004) stated that site-specific liquefaction evaluation using only or mainly the V_s method should limited to situations where:

- Crosshole, downhole, suspension logger, or SASW tests are conducted such that high-quality V_s values are determined at intervals of at least ¼ of the critical layer (the layer most likely to liquefy).

- The limitations they stated in their paper regarding these methods are considered.

- Sufficient borings are conducted to identify materials type and to insure that thin, liquefiable strata are not present.

- The critical layer is of Holocene age and contains no or little carbonate (considered as a cementing agent).

Andrus, Piratheepan, Ellis, Zhang, and Juang (2004) compared the V_s-based CRR approach to the penetration-based one using data from 43 Holocene-age sand layers in

California, South Carolina, Canada, and Japan. They stated that the V_s-based CRR curves are more conservative than the SPT-based curves.

Andrus, Stokoe, and Juang (2004) stated that it is possible that liquefaction could occur when the safety factor is larger than 1.0 (outside the region of predicted liquefaction). Juang (2002) developed the concept of probability of liquefaction (P_L), which can be used to quantify and to establish an important link between the deterministic and probabilistic methods for determining the potential for liquefaction. According to Andrus, stoke, and Juang (2004), the CRR- V_s curves (Andrus and Stokoe, 2000) correspond to P_L of approximately 0.26, and the SPT-based procedure (Seed et a., 1985) corresponds to P_L of approximately 0.31. This means that if the safety factor against liquefaction is equal to 1.0, the probability of liquefaction will be 26% for the V_s method and 31% for the SPT-based method of analysis. Moreover, the Building Seismic Safety Council (BSSC, 2000) has suggested a safety factor of 1.20 to 1.50 when the simplified procedure is applied in engineering practice. These safety factors are equivalent to P_L values of 0.16 and 0.08 when applying the V_s-based procedure (Andrus, Stokoe, and Juang, 2004). This was taken into consideration upon making the recommendations presented in Chapter 7.

CHAPTER 6
SPT – SHEAR WAVE VELOCITY CORRELATION

6.1. Background

This portion of the project was an improvement on equations that predict shear wave velocity using standard penetration test (SPT) blow counts. Two different sets of equations with vastly different inputs and forms were used. The first equation was developed by Wei *et al.* (1995) and was later modified by Rojas (2004). The second equation was developed by Ohta and Goto (1978) and was further modified by Piratheepan (2002). In order to predict shear wave velocity, SPT blow counts were standardized using correction factors and effective stress information. This study uses combined data from 10 sites in West Tennessee with 16 sites in Northeastern Arkansas for a total of 369 data pairs, providing a representative sample of the southern portion of the New Madrid seismic zone (NMSZ).

The following sections provide historical background information about the development of relationships to predict shear wave velocity.

6.1.1 Wei et al. (1995)

Factors that influence shear wave velocity include soil type, shear strain/stress, confining pressure, void ratio and saturation state. In the NMSZ, the predominant soil types are sand and clay. Wei *et al.* (1995) used five soil classifications; two types of clay (C1, C2) and three types of sand (S1, S2, S3). Table 6.1 and Table 6.2 present these soil types.

Table 6.1 Sandy Soil Type Descriptions.

Soil Type	Description	Unified Soil Classification	e_{max}	e_{min}
S1	silt, poorly graded fine sand	ML, MH, SP-SM	0.88	0.47
S2	fine to medium sand	SM, SP, SP-SM	0.93	0.48
S3	fine to coarse sand	SP-SW-SM-GP	0.79	0.38

Table 6.2 Clay Soil Type Descriptions.

Soil Type	Description	Unified Soil Classification	Ip	LL
C1	high plasticity fat clay	CH, CL-CH	44	70
C2	silty to sandy clay	CL, CL-ML	14	33

The initial empirical equations for the estimation of shear wave velocity (V_s) were developed using laboratory tests and are provided below.

$$V_s = (207.0 - 132.8 \cdot e) \cdot \sigma_0^{0.25} \qquad \text{(Soil Type S1)} \tag{6.1}$$

$$V_s = (139.0 - 24.1 \cdot e) \cdot \sigma_0^{0.25} \qquad \text{(Soil Type S2)} \tag{6.2}$$

$$V_s = (183.0 - 110.8 \cdot e) \cdot \sigma_0^{0.25} \qquad \text{(Soil Type S3)} \tag{6.3}$$

where e is the void ratio and σ_0 is the average effective confining pressure (psi).

$$V_s = (387.0 - 793.0 \cdot q_u) \cdot \sigma_0^{0.17} \qquad \text{(Soil Type C1)} \tag{6.4}$$

$$V_s = (47.2 - 106.0 \cdot q_u) \cdot \sigma_0^{0.44} \qquad \text{(Soil Type C2)} \tag{6.5}$$

where q_u is the unconfined compressive strength (psi).

For clays, the shear wave velocity of the clay can be calculated as:

$$V_s = \sqrt{\frac{G}{\gamma}} \tag{6.6}$$

where γ is the unit weight (lb/ft^3)/(32.2 ft/sec^2) and G is the shear modulus (lb/ft^2).

The average effective confining pressure of the soil, σ_0, can be obtained by:

$$\sigma_0 = \frac{1+2}{3} \cdot K_0 \cdot \sigma_1 \tag{6.7}$$

where K_0 is the coefficient of horizontal earth pressure at rest and σ_1 is the effective overburden pressure (psi), which is calculated using unit weights and thicknesses of the soil layers above a certain depth. The parameter K_0 can be calculated as:

$$K_0 = 1 - \sin\phi \qquad \text{(Sandy Soils)} \tag{6.8}$$

The internal friction angle ϕ can be estimated using the standardized blow count (N') values provided in Table 6.3. N' can be taken as the $(N_1)_{60}$ value currently used. The relationship in Table 6.3 between blow counts and friction angle was introduced by Bowles (1988).

Table 6.3 Internal Friction Angle Estimation.

		Very Loose	**Loose**	**Medium**	**Dense**	**Very Dense**
		$D_r = 0$	$D_r = 0.15$	$D_r = 0.38$	$D_r = 0.65$	$D_r = 0.85$
	fine	1-2	3-6	7-15	16-30	
N'	medium	2-3	4-7	8-20	21-40	> 40
	coarse	3-6	5-9	10-25	26-45	> 45
	fine	26-28	28-30	30-34	33-38	< 50
ϕ	medium	27-28	30-32	32-36	36-42	
	coarse	28-30	30-34	33-40	40-50	

The void ratio of the cohesionless soils, e, is given by:

$$e = e_{max} - D_r(e_{max} - e_{min}) \tag{6.9}$$

where e_{max} and e_{min} are the maximum and minimum void ratios, respectively. D_r is the relative density of the soil, as indicated in Table 6.3.

Wei *et al.* (1995) considered the clay to be normally consolidated and calculated K_0 as follows:

$$K_0 = 0.4 + 0.007 \cdot I_p \qquad (0<I_p<40) \tag{6.10}$$

$$K_0 = 0.68 + 0.001 \cdot (I_p - 40) \qquad (40<I_p<80) \tag{6.11}$$

where I_p is the Plasticity Index of the clay.

The parameter N represents the field blow count (refer to ASTM D 1586 for details). In order to arrive at the standardized value, N', the field blow counts are corrected for the overburden pressure, sampler type, hammer efficiency, borehole diameter, and rod length. These corrections are applied as follows:

$$N' = C_N \cdot N \cdot \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 \tag{6.12}$$

where the η factors are defined in Table 6.4 and the overburden correction factor C_N is defined as:

$$C_N = \sqrt{\left(\frac{100 \quad kpa}{\sigma_1}\right)} \tag{6.13}$$

where σ_1 is effective overburden pressure in kPa.

Table 6.4 SPT Correction Factors (Wei, *et al.* 95).

Hammer for η_1				**Remarks**
Average energy ratio E_r				R-P = rope pulley or cathead
Donut		Safety		$\eta_1 = E_r / E_{70}$
R-P	Trip	R-P	Trip/Auto	For U.S. trip/auto w/ $E_r = 80$
45	---	70-80	80-100	$\eta_1 = 80 / 70 = 1.14$
Rod Length Correction η_2				
Length (m)			η_2	
> 10			1.00	
6 - 10			0.95	*N* is too high for $L < 10$ m
4 - 6			0.85	
0 - 4			0.75	
Sampler Correction η_3				
Type			η_3	
Without Liner			1.00	
With Liner: Dense Sand and Clay			0.80	*N* is too high with liner
With Liner: Loose Sand			0.90	
Borehole Diameter Correction η_4				
Hole Diameter (mm)			η_4	
60 - 120			1.00	
150			1.05	*N* is too low with oversize hole
200			1.15	

A computer program was written in FORTRAN to perform the calculations. The program requires an input file which includes depth, soil type, and N values, along with the four correction factors, and water table depth. An image of the file is in Figure 6.1.

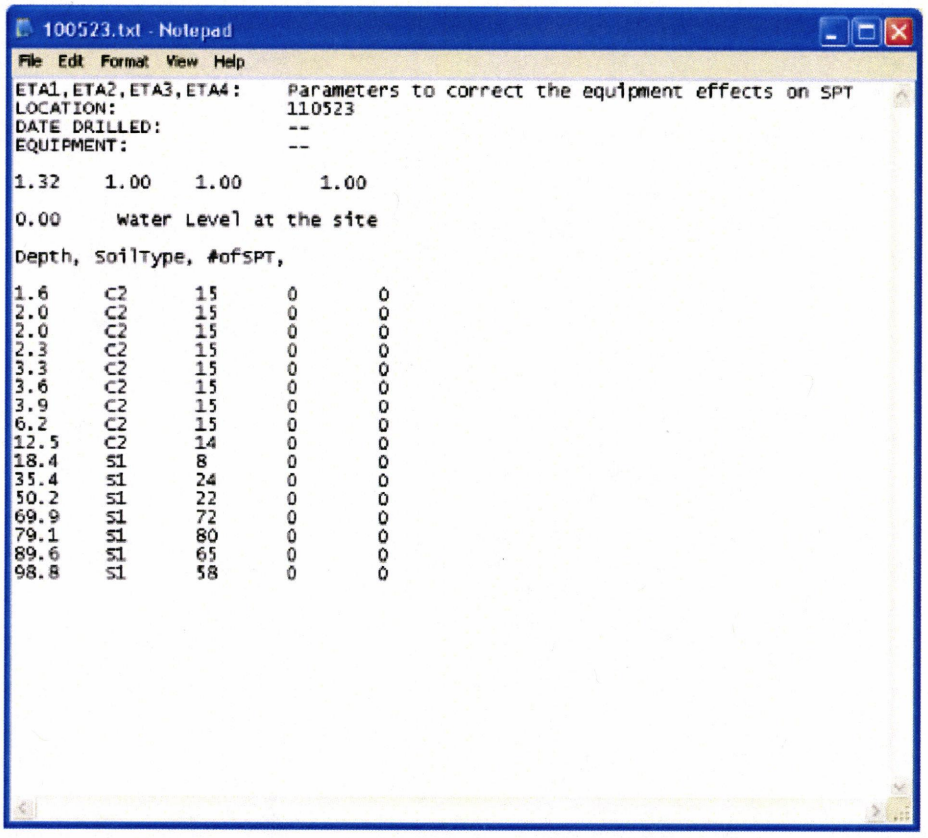

Figure 6.1 Wei Computer Program Input File

6.1.2 Rojas (2004)

Building on the work presented in Wei *et al.* (1995), Rojas (2004) evaluated 7 different forms of equations relating SPT blow count (N) to shear wave velocity (V_s). Using a genetic algorithm (GA), the coefficients of each equation were optimized to minimize the error. These equations are provided below. The sand equations utilize void ratios (e) and shear wave velocity (V_s), while the clay equations use the unconfined compressive strength (q_u) and calculate shear modulus (G_s).

Sandy Soil:

$$V_s = (C_1 + C_2 \cdot e) \cdot {\sigma_0}^{C3} \qquad (Model\#1) \tag{6.14}$$

$$V_s = (C_1 + C_2 \cdot e) \cdot {\sigma_0}^{C3} + C_4 \cdot Z^{C5} + C_6 \cdot N^{C7} \qquad (Model\#2) \tag{6.15}$$

$$V_s = C_1 \cdot N^{C2} \qquad (Model\#3) \tag{6.16}$$

$$V_s = C_1 \cdot N^{C2}\ Z^{C3} \qquad (Model\#4) \tag{6.17}$$

$$V_s = C_1 + C_2 \cdot {\sigma_0}^{C3} + C_4 \cdot e^{C5} + C_6 \cdot {\sigma_0}^{C7} \cdot e^{C8} \qquad (Model\#5) \tag{6.18}$$

$$V_s = C_1 + C_2 \cdot {\sigma_0}^{C3} + C_4 \cdot e^{C5} + C_6 \cdot {\sigma_0}^{C7} \cdot e^{C8} + C_9 \cdot (N \cdot Z) \qquad (Model\#6) \tag{6.19}$$

$$V_s = C_1 + {\sigma_0}^{C2} \cdot e^{C3} \cdot N^{C4} \cdot Z^{C5} \qquad (Model\#7) \tag{6.20}$$

Clay Soil:

$$G_s = (C_1 + C_2 \cdot q_u) \cdot {\sigma_0}^{C3} \qquad (Model\#1) \tag{6.21}$$

$$G_s = (C_1 + C_2 \cdot q_u) \cdot {\sigma_0}^{C3} + C_4 \cdot Z^{C5} + C_6 \cdot N^{C7} \qquad (Model\#2) \tag{6.22}$$

$$G_s = C_1 \cdot N^{C2} \qquad (Model\#3) \tag{6.23}$$

$$G_s = C_1 \cdot N^{C2}\ Z^{C3} \qquad (Model\#4) \tag{6.24}$$

$$G_s = C_1 + C_2 \cdot {\sigma_0}^{C3} + C_4 \cdot {q_u}^{C5} + C_6 \cdot {\sigma_0}^{C7} \cdot {q_u}^{C8} \qquad (Model\#5) \tag{6.25}$$

$$G_s = C_1 + C_2 \cdot {\sigma_0}^{C3} + C_4 \cdot {q_u}^{C5} + C_6 \cdot {\sigma_0}^{C7} \cdot {q_u}^{C8} + C_9 \cdot (N \cdot Z) \qquad (Model\#6) \tag{6.26}$$

$$G_s = C_1 + {\sigma_0}^{C2} \cdot {q_u}^{C3} \cdot N^{C4} \cdot Z^{C5} \qquad (Model\#7) \tag{6.27}$$

where e is the void ratio, σ_0 is the average effective confining pressure (psi), N is the uncorrected blow counts, Z is the depth (ft), and C_1 through C_{10} are the coefficients used by the GA for a least error optimization.

The GA procedure was performed by Rojas for all five soil types, and in each case, Model #6 had the best fit. The coefficients resulting from the GA procedure are as follow:

Soil Type S1:

$$V_s = 2.86 + 127.03 \cdot \sigma_0^{0.248} + 109.14 \cdot e^{-0.925} + 198.86 \cdot \sigma_0^{-0.256} \cdot e^{-1.978} - 178.99 \cdot (N \cdot Z)^{-0.142} \quad (6.28)$$

Soil Type S2:

$$V_s = 127.53 + 160.12 \cdot \sigma_0^{0.057} + 183.78 \cdot e^{-0.075} + 17.69 \cdot \sigma_0^{-0.235} \cdot e^{-0.965} - 109.12 \cdot (N \cdot Z)^{-0.999} \quad (6.29)$$

Soil Type S3:

$$V_s = 103.05 + 152.84 \cdot \sigma_0^{-0.722} + 235.64 \cdot e^{-0.085} + 288.98 \cdot \sigma_0^{0.187} e^{0.769} - 216.73 \cdot (N \cdot Z)^{-0.177} \quad (6.30)$$

Soil Type C1:

$$G_s = -60.14 + 275.67 \cdot \sigma_0^{0.252} + 230.57 \cdot q_u^{0.596} + 104.31 \cdot \sigma_0^{0.416} q_u^{0.873} + 276.30 \cdot (N \cdot Z)^{0.032} \quad (6.31)$$

Soil Type C2:

$$G_s = 13.42 - 350.68 \cdot \sigma_0^{0.337} - 453.87 \cdot q_u^{-0.735} + 362.96 \cdot \sigma_0^{0.181} q_u^{0.984} + 443.28 \cdot (N \cdot Z)^{0.547} \quad (6.32)$$

6.1.3 Piratheepan and Andrus (2002)

To develop regression equations relating SPT information and V_s, Piratheepan used the same form of equations that were first proposed by Ohta & Goto (1978). A total of 103 data pairs from Northern California, Southern California, Japan and Canada were considered. SPT information was gathered from within 5m of shear wave velocity test locations. V_s was obtained by either seismic CPT, cross-hole, suspension logger, or down-hole methods. The tested soils were of Holocene age (less than 10,000 years). The soil type was only available for 45% of the collected data. Only 8 out of 103 data pairs had fines content greater than 35%. A variety of

different equations were developed using the statistical software SPSS and Axum 5.0 C for Windows.

The variables used in the correlation were corrected blow count (N_{60}), depth (D), fines content (FC), median grain size (D_{50}), and coefficient of uniformity (C_u). Equations were developed for five different soil categories, divided according to their fines content. The categories were $FC < 10$ %, $10\% < FC < 35\%$, $FC > 35\%$, $0 < FC < 40\%$, and $0 < FC < 81\%$. The analysis revealed that the variables of fines content, median grain size and the coefficient of uniformity were not significant in the model. Because of the lack of data with fines content above 35%, the final relationship was given in terms of 3 fines content ranges and is given below:

$$V_s = 66.7 \cdot N_{60}^{0.248} \cdot D^{0.138} \qquad FC < 10\% \tag{6.33}$$

$$V_s = 72.3 \cdot N_{60}^{0.228} \cdot D^{0.152} \qquad 10\% < FC < 35\% \tag{6.34}$$

$$V_s = 72.9 \cdot N_{60}^{0.224} \cdot D^{0.130} \qquad FC < 40\% \tag{6.35}$$

where V_s is the shear wave velocity in m/s, N_{60} is the energy corrected SPT blow counts, and D is the depth in meters.

6.2. Data Analysis

6.2.1. Genetic Algorithm

Refer to Section 3.4 for a short description of the genetic algorithm used by Rojas (2004) and for this project.

6.2.2. Input Data

This study combines data from 10 sites in West Tennessee that were used in Rojas (2004), with the 16 sites from Northeastern Arkansas. The Tennessee data consisted of shear wave velocities at depth, soil types, SPT blow counts, and SPT correction factors. The shear wave velocity profiles were obtained from downhole testing. The soil types were as defined by Wei *et al.* (1995) and were determined from laboratory tests performed on soil samples collected during the

installation of the casings required for the downhole testing. The SPT blow counts were also obtained during the same operation. Refer to Chapters 2 through 5 for additional information.

6.2.3. Rojas (2004) Improvement

To improve the coefficients that were developed by Rojas (2004) and Piratheepan (2002), this study combined the West Tennessee data with the Northeastern Arkansas data from this project. This resulted in 95 zones of S1 soil, 148 zones of S2 soil, 20 zones of S3 soil, 21 zones of C1 soil, and 85 zones of C2 soil. Therefore, 369 total data sets were used. Each set contained information on depth, soil type, SPT blow counts, and shear wave velocity. Originally, 448 data sets were available. However, 79 sets were excluded from the correlation because of inconsistent relationships between SPT blow counts and shear wave velocity when compared with the rest of the data. Those 79 data sets were removed for correlation purposes, but included when evaluating the different regression models for each site.

The 369 data pairs were divided up into the five soil classes defined in Wei *et al.* (1995). The genetic algorithm was executed 14 times for each soil type and the GA run that had the least penalized fitness was selected to provide the improved coefficients for each soil type. The purpose of the GA was to optimize all 10 coefficients from the Rojas (2004) model.

For the 3 sandy soils, the following functional form was used:

$$V_s = C_1 + C_2 \cdot {\sigma_0}^{C3} + C_4 \cdot e^{C5} + C_6 \cdot {\sigma_0}^{C7} \cdot e^{C8} + C_9 \cdot (N \cdot Z)^{C10} \tag{6.36}$$

For the 2 clay soils, the following functional form was used:

$$G_s = C_1 + C_2 \cdot {\sigma_0}^{C3} + C_4 \cdot {q_u}^{C5} + C_6 \cdot {\sigma_0}^{C7} \cdot {q_u}^{C8} + C_9 \cdot (N \cdot Z)^{C10} \tag{6.37}$$

where V_s is the shear wave velocity (ft/sec), σ_0 is the average effective confining pressure (psi), e is the void ratio, q_u is the unconfined compressive strength (psi), and G_s is the shear modulus (lb/ft^2) and the shear wave velocity can be calculated as follows:.

$$V_s = \sqrt{\frac{G}{\gamma}} \tag{6.38}$$

where γ is the unit weight (lb/ft^3)/(32.2 ft/sec^2) and G is the shear modulus (lb/ft^2).

An example of the GA input file is shown in Figure 6.2.

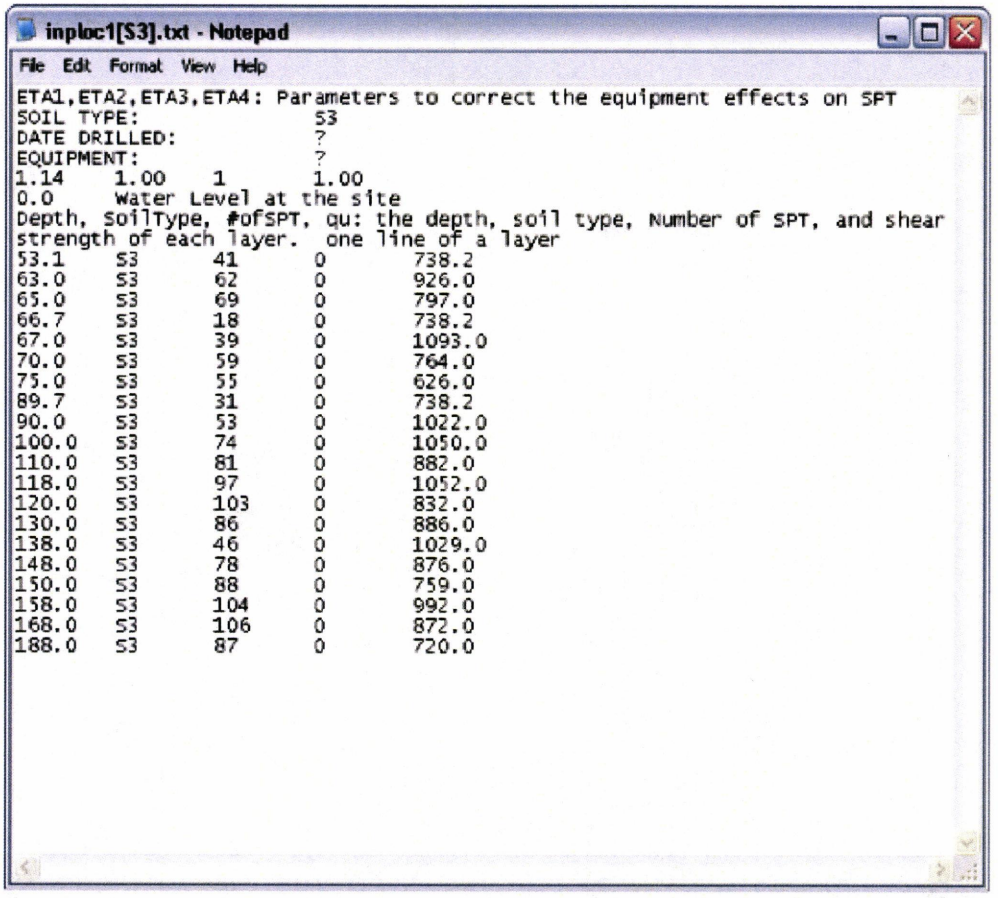

Figure 6.2 Input file for Genetic Algorithm to improve Rojas (2004)

The improved coefficients for all five soil types are presented in Table 6.5.

Table 6.5 Coefficients for Improved Rojas

Soil Type	Coefficients									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
S1	-22.3	176.4	-0.215	128.4	-0.918	164.3	-0.980	0.105	-176.0	-0.894
S2	86.5	177.8	-0.267	152.6	-0.101	47.0	-0.283	0.309	-114.4	-0.377
S3	68.6	196.5	-0.241	276.3	-0.075	312.6	0.321	0.105	-209.1	-0.115

C1	-39.9	229.8	0.281	278.1	0.984	144.6	0.944	0.273	270.1	0.381
C2	-13.2	-399.4	-0.165	-504.0	0.776	337.3	0.984	0.215	406.7	0.570

6.2.4. Piratheepan (2002) Improvement

The same genetic algorithm method that was used to improve the model proposed by Rojas (2004) was used to improve Piratheepan (2002) model. Although the equations produced by Piratheepan (2002) are only for soils with fines content of less than 40%, later analyses using data from Taiwan indicated that the equations can be used with soils that have more than 40% fine content. Accordingly, using the form of regression equation presented in Piratheepan (2002) to create a model to estimate V_s from SPT information is justified. Instead of breaking the data into the five different soil types, all 369 data sets were processed in one input file. In this case, the GA only optimized three coefficients instead of 10 for the Rojas (2004) model. The Piratheepan (2002) model is based only on depth and corrected SPT blow counts. The first coefficient (C1) was given a range from 0 to 200, and the second and third coefficients were given a range between zero and one. The form of the model can be found below:

$$V_s = C_1 \cdot N^{C_2} \cdot D^{C_3} \tag{6.39}$$

where V_s is the shear wave velocity in (m/sec), N is the corrected SPT blow counts, and D is the depth in meters.

The analysis resulted in the following equation:

$$V_s = 115.115 \cdot N_{60}{}^{0.102} \cdot D^{0.165} \tag{6.40}$$

The original equation provided by Piratheepan (2002) is as follows:

$$V_s = 72.9 \cdot N_{60}{}^{0.224} \cdot D^{0.130} \tag{6.41}$$

6.3. Summary of Results

To evaluate the effectiveness of both new models, they were compared against the models presented in Rojas (2004), and Piratheepan (2002) in two methods. The first method was to evaluate all of the data pairs from each of the five soil types (S1, S2, S3, C1, C2) using all three models. When comparing each of the five soil types with all four models, the Improved Rojas model estimated V_s with the least error in all five soil types. The plots of these soil type comparisons can be found in Appendix B.

The second evaluation method was to evaluate the shear velocity profile of each of the 16 sites using all three models. The difference between the measured shear wave velocity (SWVM) and the estimated shear wave velocity (V_s) was calculated. The error was computed as the square root sum of the squares (SRSS) of the difference between the two velocities.

Table 6.6 shows the calculated error for each model and site. The shaded cells indicate the model that had the least error for each site.

The computer program accompanying this report uses the Improved Rojas procedure. This computer program is developed in Visual Basic Application (VBA) as a Marco executable within the Microsoft Excel environment.

Table 6.6 SRSS Error for Each Site and Model.

AHTD Site No.	Rojas (2004)	Improved Rojas	Piratheepan (2002)	Improved Piratheepan
110288	1124	698	852	**611**
110358	1335	1364	1601	**1234**
110401	801	467	641	**364**
100547	688	**505**	524	584
110337	698	489	603	**422**
110434	1091	834	**646**	681
100523	**3232**	3619	3911	3630
100522	436	**303**	495	353
BR4706	**588**	786	901	822
100105	1481	1269	1269	**1190**
R00059	1543	1466	1106	**739**
100303	479	478	799	**455**
100153	353	**143**	302	167
100478	657	530	582	**478**
BR1108	1267	933	1026	**787**
BR1110	1087	778	**501**	538

The final versions of all four models used in this study can be found in

Table 6.7.

Table 6.7 Equations from all 4 V_s estimation models

Model	Regression Equation	Soil Type
Piratheepan (2002)	$V_s = 72.9 \cdot N_{60}^{0.224} \cdot D^{0.130}$	All Soils
Improved Piratheepan	$V_s = 115.115 * N_{60}^{0.102} * D^{0.165}$	All Soils
Rojas (2004)	$V_s = 2.86 + 127.03 \cdot \sigma_0^{0.248} + 109.14 \cdot e^{-0.925} + 198.86 \cdot \sigma_0^{-0.256} \cdot e^{-1.978} - 178.99 \cdot (N \cdot Z)^{-0.142}$	S1
	$V_s = 127.53 + 160.12 \cdot \sigma_0^{0.057} + 183.78 \cdot e^{-0.075} + 17.69 \cdot \sigma_0^{-0.235} \cdot e^{-0.965} - 109.12 \cdot (N \cdot Z)^{-0.999}$	S2
	$V_s = 103.05 + 152.84 \cdot \sigma_0^{-0.722} + 235.64 \cdot e^{-0.085} + 288.98 \cdot \sigma_0^{0.187} \cdot e^{0.769} - 216.73 \cdot (N \cdot Z)^{-0.177}$	S3
	$G_s = -60.14 + 275.67 \cdot \sigma_0^{0.252} + 230.54 \cdot q_u^{0.596} + .31 \cdot \sigma_0^{0.416} \cdot q_u^{0.873} + 276.30 \cdot (N \cdot Z)^{0.032}$	C1
	$G_s = 13.42 - 350.68 \cdot \sigma_0^{0.337} - 453.87 \cdot q_u^{-0.735} + 362.96 \cdot \sigma_0^{0.181} \cdot q_u^{0.984} + 443.28 \cdot (N \cdot Z)^{0.547}$	C2
Improved Rojas	$V_s = -22.28 + 176.40 \cdot \sigma_0^{-0.215} + 128.37 \cdot e^{-0.918} + 164.32 \cdot e^{-0.980} \cdot \sigma_0^{0.105} - 176.05 \cdot (N \cdot Z)^{-0.894}$	S1
	$V_s = 86.51 + 177.77 \cdot \sigma_0^{-0.267} + 152.62 \cdot e^{-0.101} + 46.98 \cdot e^{-0.283} \cdot \sigma_0^{0.309} - 114.36 \cdot (N \cdot Z)^{-0.377}$	S2
	$V_s = 68.62 + 196.49 \cdot \sigma_0^{-0.241} + 276.29 \cdot e^{-0.075} + 312.57 \cdot e^{0.321} \cdot \sigma_0^{0.105} - 209.14 \cdot (N \cdot Z)^{-0.115}$	S3
	$G_s = -39.93 + 229.80 \cdot \sigma_0^{0.281} + 278.10 \cdot q_u^{0.984} + 144.59 \cdot q_u^{0.944} \cdot \sigma_0^{0.273} + 270.14 \cdot (N \cdot Z)^{0.381}$	C1
	$G_s = -13.18 - 399.40 \cdot \sigma_0^{-0.165} - 504.00 \cdot q_u^{0.776} + 337.32 \cdot q_u^{0.984} \cdot \sigma_0^{0.215} + 406.71 \cdot (N \cdot Z)^{0.570}$	C2

CHAPTER 7
RECOMMENDATIONS

The results of the liquefaction analyses indicated that bridge sites in northeast Arkansas may experience significant liquefaction problems during a seismic event that approaches the magnitude of the AASHTO LRFD design earthquake. Therefore, the following steps are recommended upon conducting a liquefaction hazard analysis for bridge sites in Northeast Arkansas. These recommendations are based on the findings and the evaluations presented in Chapter 5. It is recommended that AHTD obtains a commercial software to perform SPT-based liquefaction analysis

A. Noncritical or Nonessential Bridges:

- Perform a geotechnical investigation at the bridge site. The investigation should include boreholes drilled to a minimum depth of 50 feet (100 feet is preferred). Perform in-situ testing (SPT or combination of SPT and CPT). Determine the location of groundwater table by installing Piezometers or monitoring wells.
- Perform a liquefaction analysis using the SPT approach. Use a minimum safety factor of 1.20 to determine the potential liquefiable zones.
- Using a deep foundation system is recommended if the liquefaction analysis indicate insufficient safety factors.

B. Critical or Essential Bridges:

- Prior to performing the geotechnical investigation, perform a sufficient number (a minimum of 2, depending on the total length of the bridge) of non-invasive testing, such as MSASW to determine the shear wave velocity profile along the route of the proposed bridge.
- Obtain the design peak horizontal ground acceleration using the USGS-AASHTO software for 7% probability of exceedance in 75 years and the latitude/longitude coordinates of the midpoint of the array. Perform preliminary liquefaction analyses using V_s-based approach. Make reasonable assumptions regarding the soil unit weights, fine contents, and depth to groundwater table based on past experience. Calculate the corresponding LPI values using the safety factors produced by the analysis. If the LPI values significantly exceed 15 on a

constant basis (25 or more), plan on installing PVC casings during the field exploration to perform invasive tests (such as downhole testing) and verify the profiles already obtained from the noninvasive tests.

- Perform a geotechnical investigation at the bridge site. The investigation should include boreholes at a minimum depth of 100 feet. Perform in-situ testing (SPT or combination of SPT and CPT). Determine the location of groundwater table by installing Piezometers or monitoring wells. The SPT intervals should not exceed 5 feet.
- Obtain representative samples and perform classification tests (particle size analysis, moisture contents, and Atterberg Limits) in the laboratory. Determine the unit weights of cohesive soils using undisturbed samples (such as Shelby tubes). Estimate the unit weights of cohesionless soils based on their classifications, grain size, and the SPT N-values. If the geotechnical investigation includes high quality sampling techniques (such as ground freezing or triple-tube core barrel sampling), use these samples to determine the unit weights of cohesionless soils. However, these techniques are not typically utilized due to the sampling difficulties and cost. Use the index property test results to determine the potential for liquefaction of silt-clay mixtures. This may require sedimentation (hydrometer) testing.
- Once the laboratory test results are available, re-run the V_s-based analysis and perform SPT-based liquefaction analysis to confirm the findings. Use a minimum safety factor of 1.20. Calculate the corresponding LPI values. If the significantly high LPI previously calculated from the preliminary V_s-based analyses are confirmed, proceed with the invasive testing. Otherwise, grout or abandon the PVC casings using appropriate techniques.
- Support the bridge by a deep foundation system. Use high displacement driven piles (such as precast concrete piles or steel pipe piles driven closed-ended) if possible. Extend the piles to a minimum of 5 pile diameters (or sizes) below the potential, lowermost liquefiable layer.
- If the liquefiable layer extends to a great depth (80 feet or more), perform a site-specific seismic study using the results of the invasive or the noninvasive tests. The invasive test results are preferred. This study consists of two parts; a site-specific hazard analysis, and a site-specific ground response analysis. Such a study may result in reducing the design seismic acceleration to 2/3 of their published values within a certain range of periods per the AASHTO design guide. This may result in significant cost saving in the seismic design, as

well as reducing the severity of the liquefaction. Revise the liquefaction analyses using the results of the site-specific study.

- The AASHTO Guideline Specifications for LRFD Seismic Bridge Design (Subcommittee for Seismic Effects on Bridges T-3) states that if liquefaction occurs, then the bridge shall be designed and analyzed in two configurations; Non-Liquefied Configuration, and Liquefied Configurations using the liquefied soil residual strength.
- Consider ground improvement for liquefaction mitigation. Techniques such as soil densification (using dynamic compaction, blasting, compaction piles), reinforcement (such as vibro-floatation), or deep mixing have been already used for liquefaction mitigation purposes. Refer to the FHWA document (Geotechnical Earthquake Engineering) for a list of possible ground improvement techniques.

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APPENDIX A
Shear Wave Velocity Profile Results

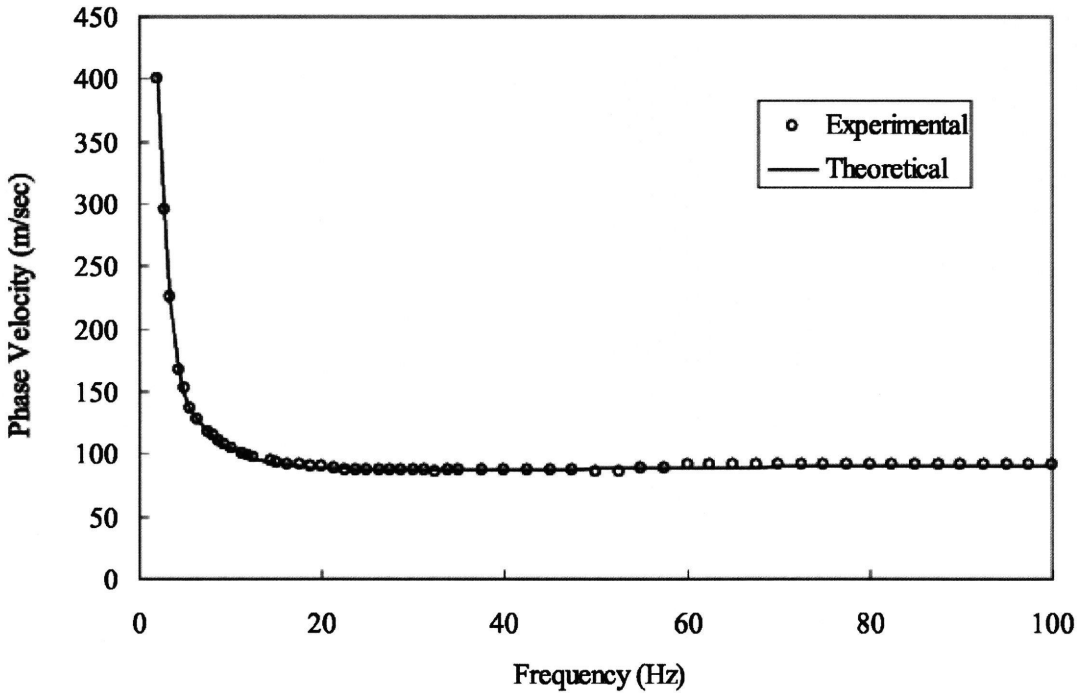


Figure A.1 Experimental vs. theoretical dispersion curve for site 110337

Table A.1 Velocities for site 110337

Depth (ft)	Velocity (ft/sec)
2.3	328
4.6	285
9.5	312
13.5	328
24.6	449
38.7	482
50.2	656
61.7	705
107.0	919
178.8	1394
336.0	1903

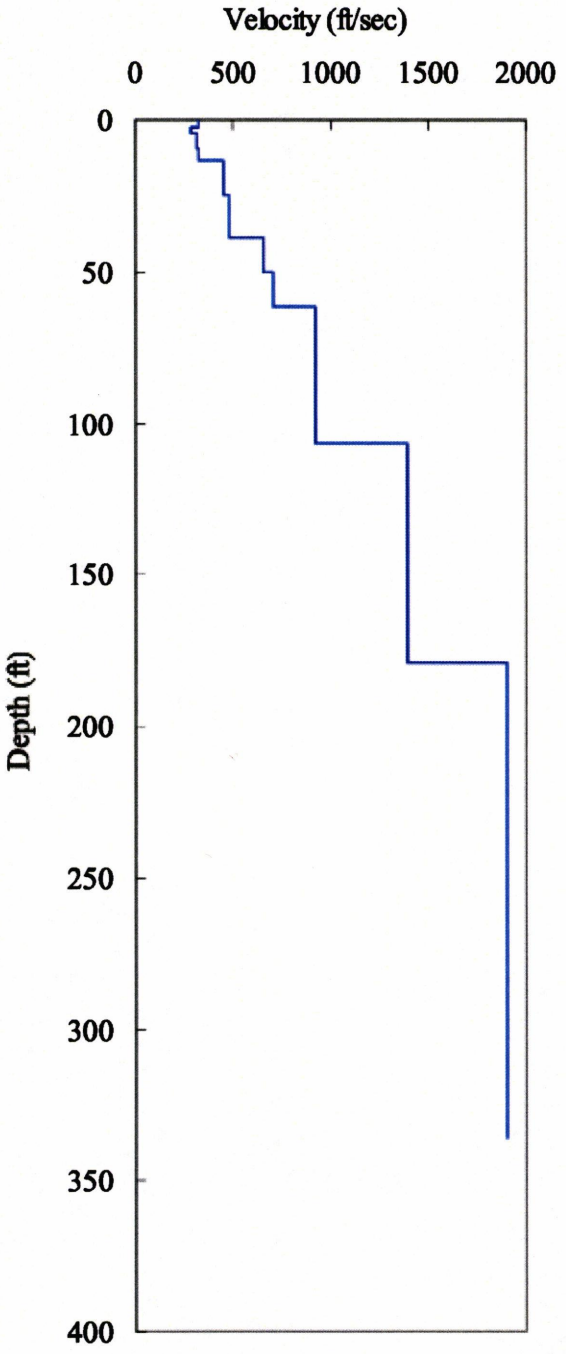


Figure A.2 Vertical Seismic Profile for Site 110337

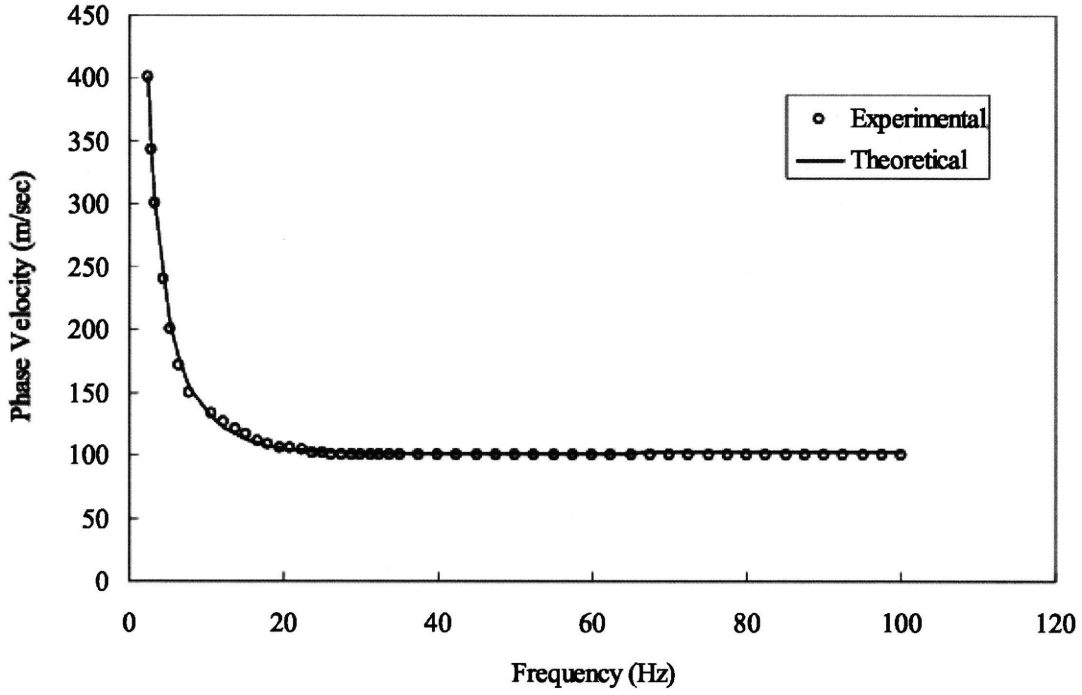


Figure A.3 Experimental vs. theoretical dispersion curve for site BR1108

Table A.2 Velocities for site BR1108

Depth (ft)	Velocity (ft/sec)
4.4	361
6.2	344
8.9	344
12.6	410
20.3	509
31.5	574
44.3	705
61.1	853
89.7	1033
144.1	1312
192.4	1558
268.7	1591

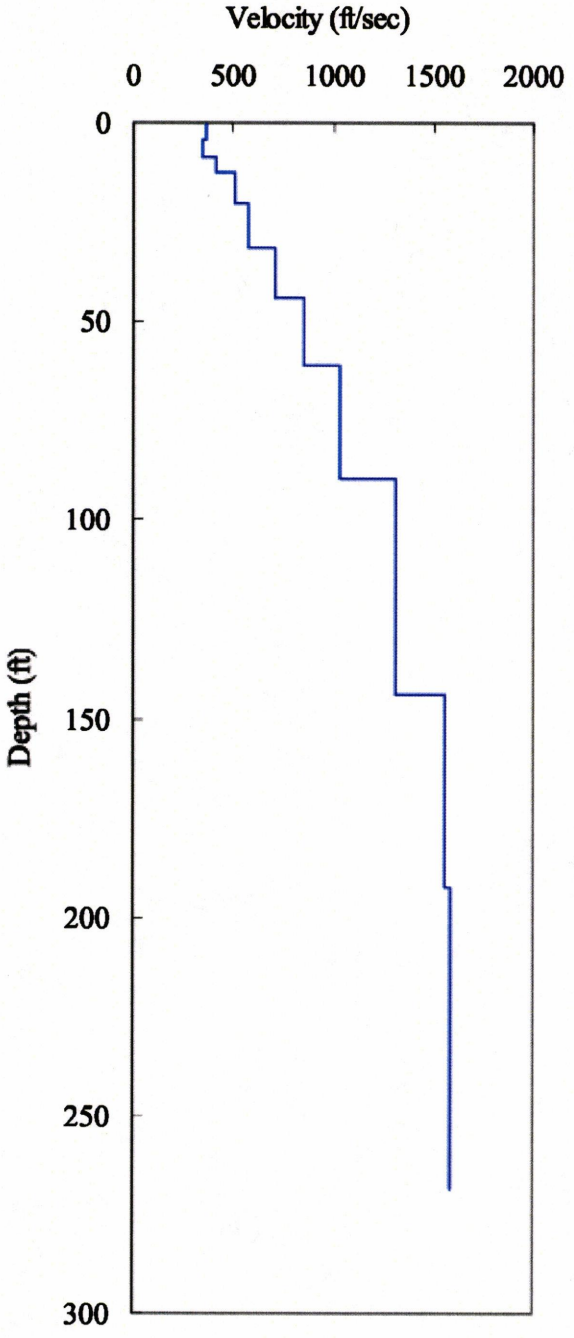


Figure A.4 Vertical Seismic Profile for Site BR1108

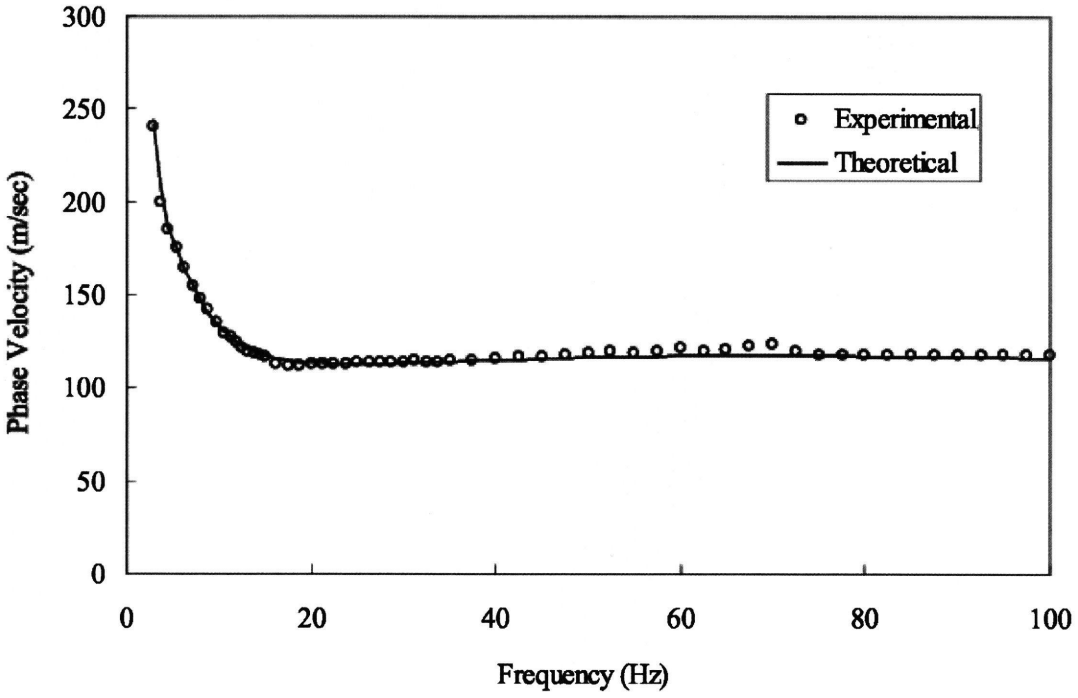


Figure A.5 Experimental vs. theoretical dispersion curve for site BR1110

Table A.3 Velocities for site BR1110

Depth (ft)	Velocity (ft/sec)
2.3	443
2.5	509
2.7	443
2.8	443
3.2	394
3.7	394
5.9	374
10.7	371
15.1	427
20.3	492
26.5	558
35.8	591
43.3	673
53.1	738
66.7	738
89.7	738
134.7	984

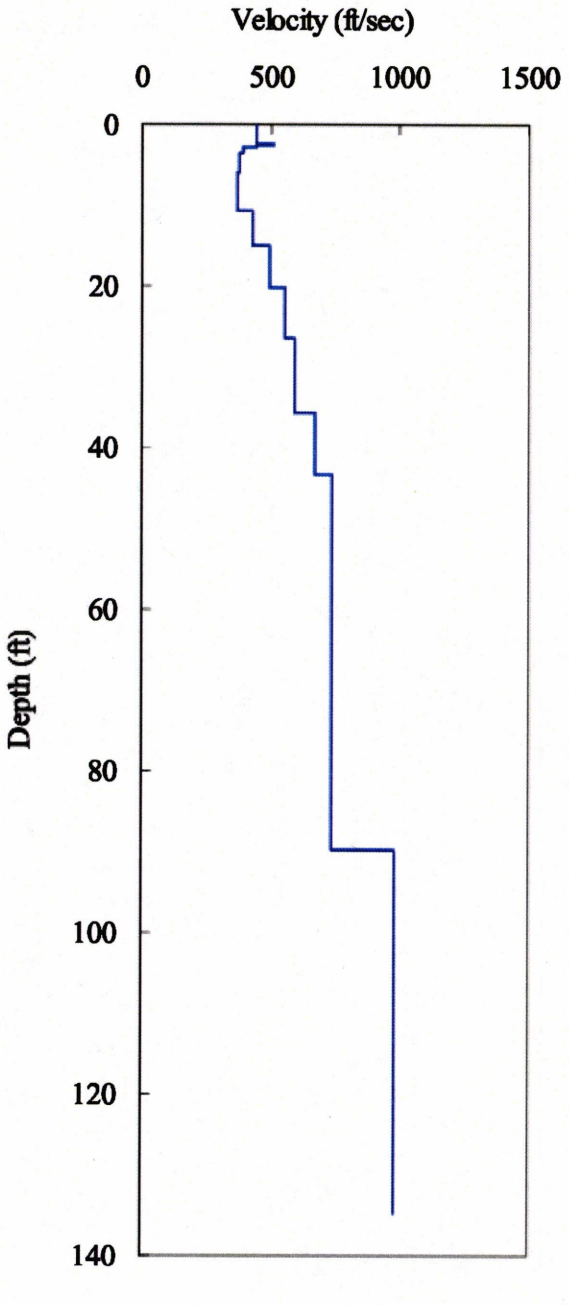


Figure A.6 Vertical Seismic Profile for Site BR1110

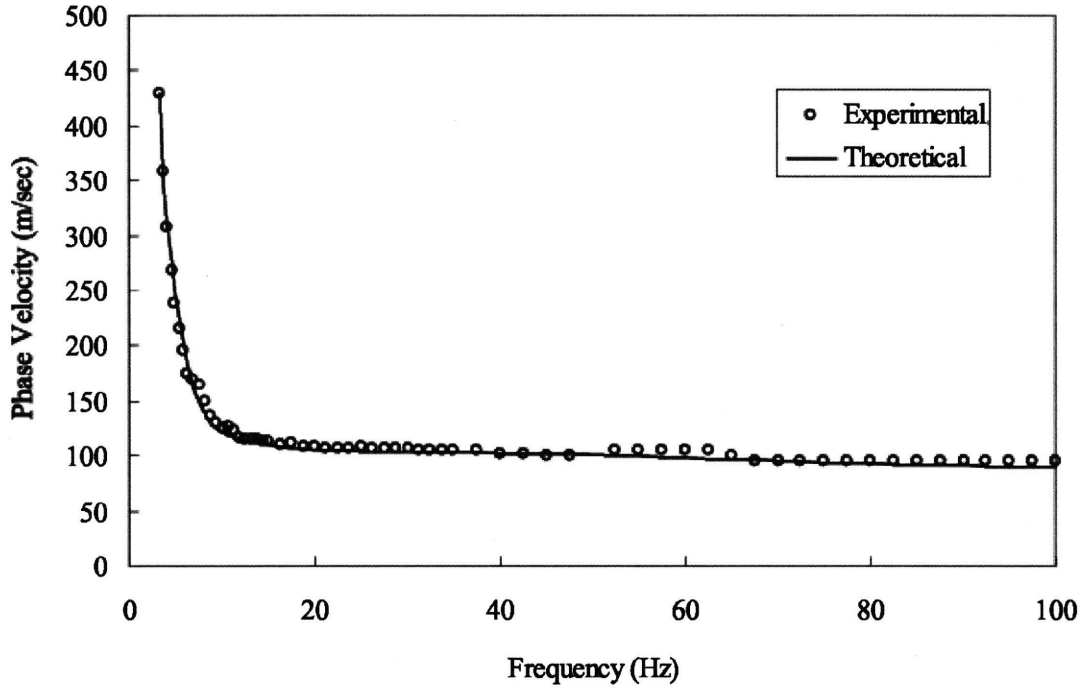


Figure A.7 Experimental vs. theoretical dispersion curve for site BR4706

Table A.4 Velocities for site BR4706

Depth (ft)	Velocity (ft/sec)
2.3	312
2.6	377
3.4	541
4.3	344
5.4	361
7.2	361
8.4	394
11.3	394
16.2	394
25.8	476
30.3	623
46.4	820
55.3	820
64.8	1181
79.6	1181
96.6	1345
25.5	1476
161.6	1969
215.7	2789

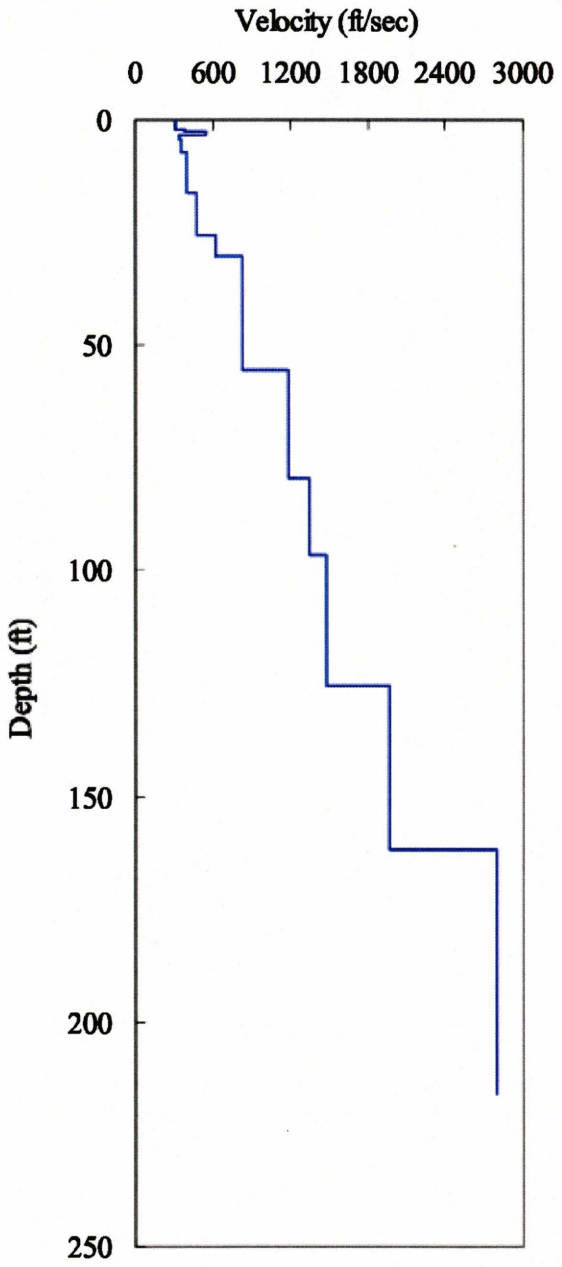


Figure A.8 Vertical Seismic Profile for Site BR4706

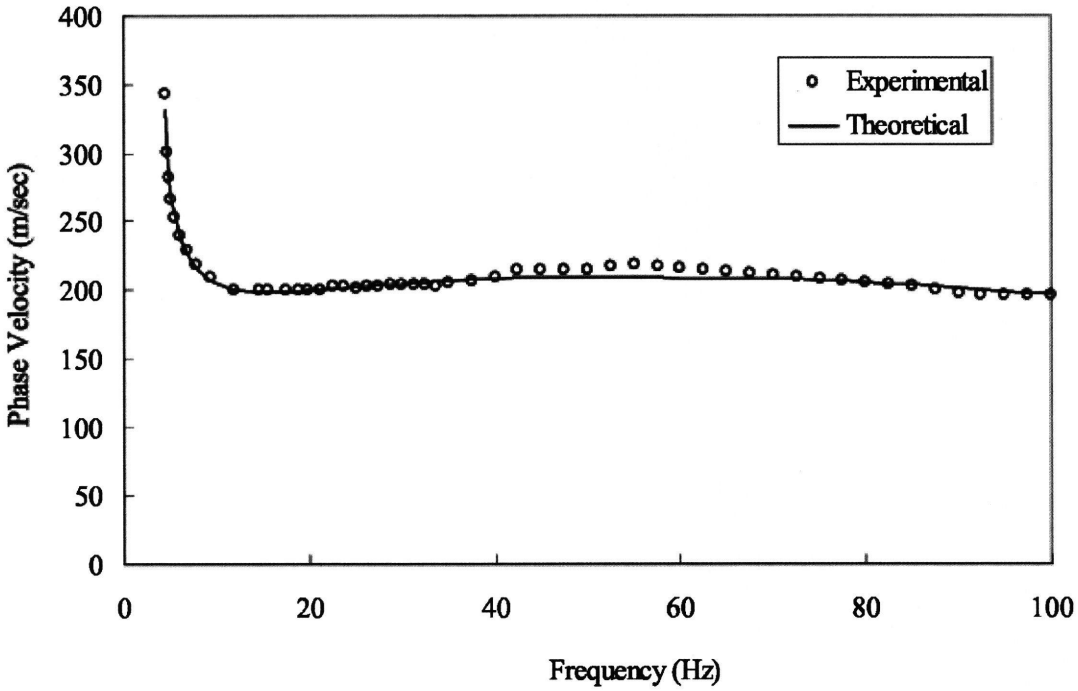


Figure A.9 Experimental vs. theoretical dispersion curve for site R00059

Table A.5 Velocities for site R00059

Depth (ft)	Velocity (ft/sec)
3.6	656
6.2	869
7.1	984
8.3	804
9.6	722
14.8	656
27.4	673
36.9	682
45.8	820
54.9	886
76.9	951
84.9	1017
94.5	1083
105.7	1214
127.8	1903

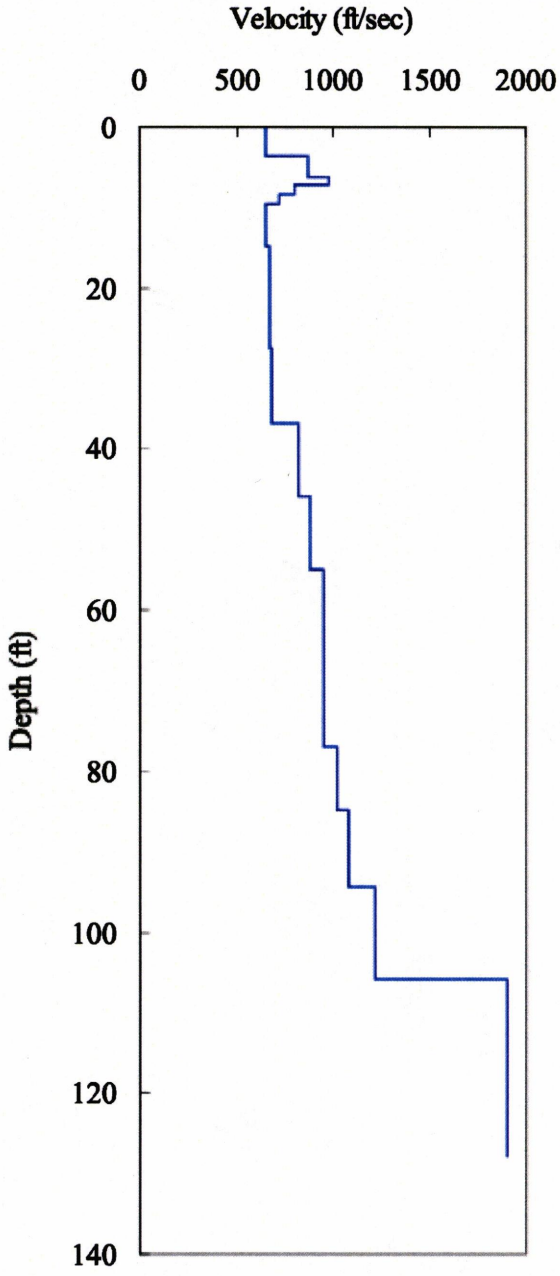


Figure A.10 Vertical Seismic Profile for Site R00059

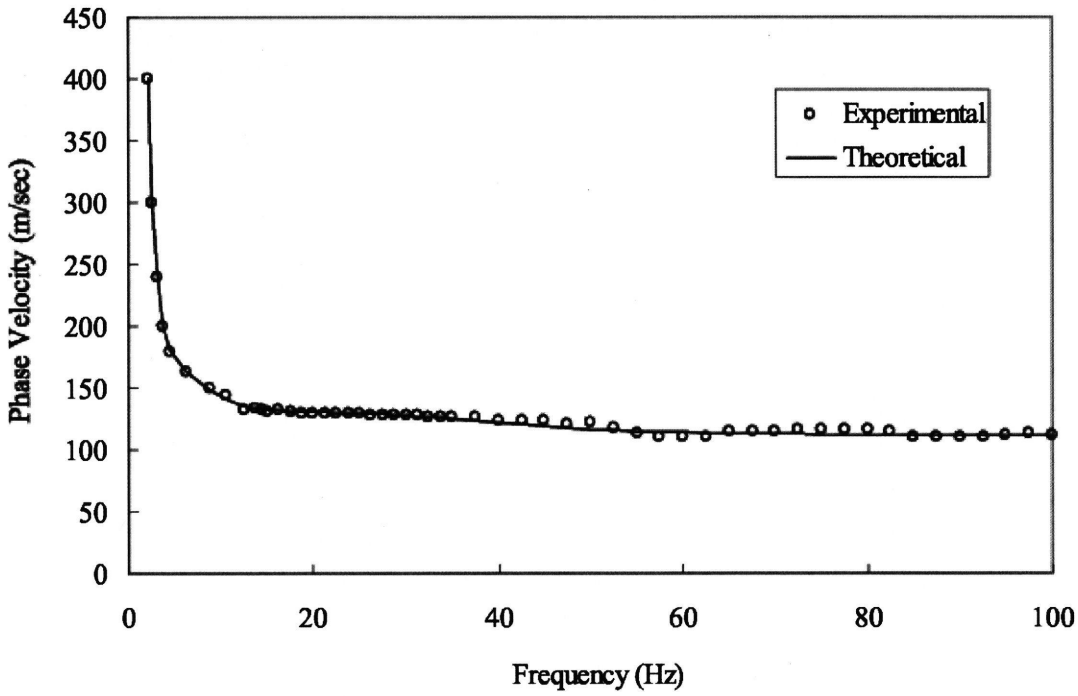


Figure A.11 Experimental vs. theoretical dispersion curve for site 110434

Table A.6 Velocities for site 110434

Depth (ft)	Velocity (ft/sec)
2.0	394
2.7	410
2.9	410
3.0	394
3.5	328
4.2	427
5.8	492
9.1	525
14.0	459
17.9	394
28.6	623
43.4	623
65.5	623
87.7	787
130.0	1050
193.1	1181
316.2	2100

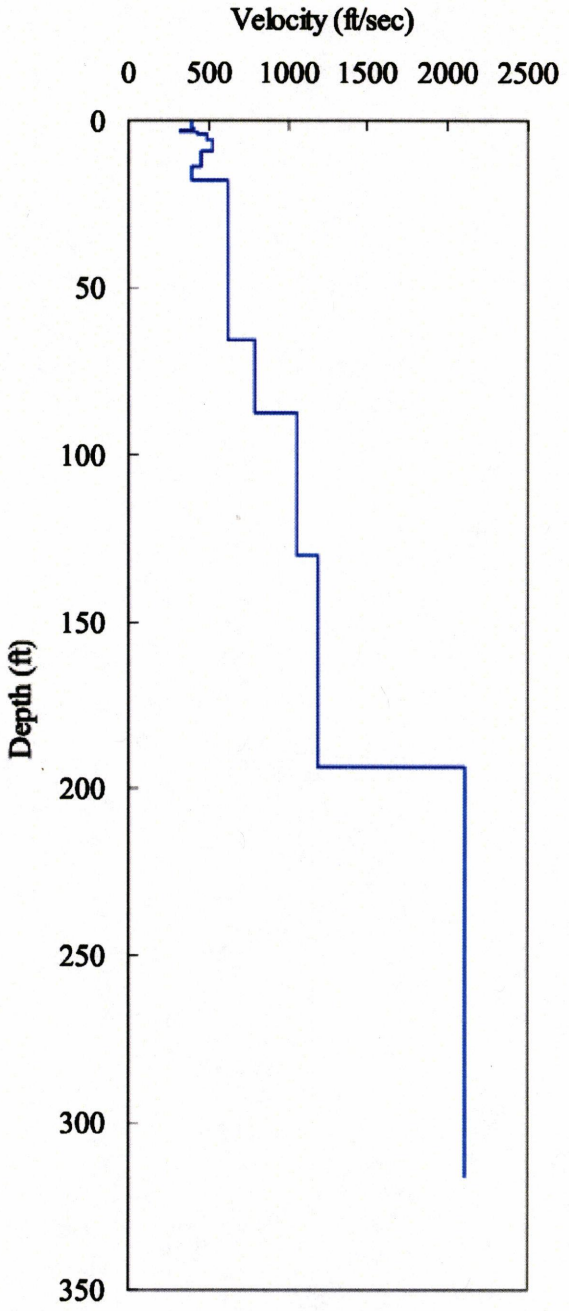


Figure A.12 Vertical Seismic Profile for Site 110434

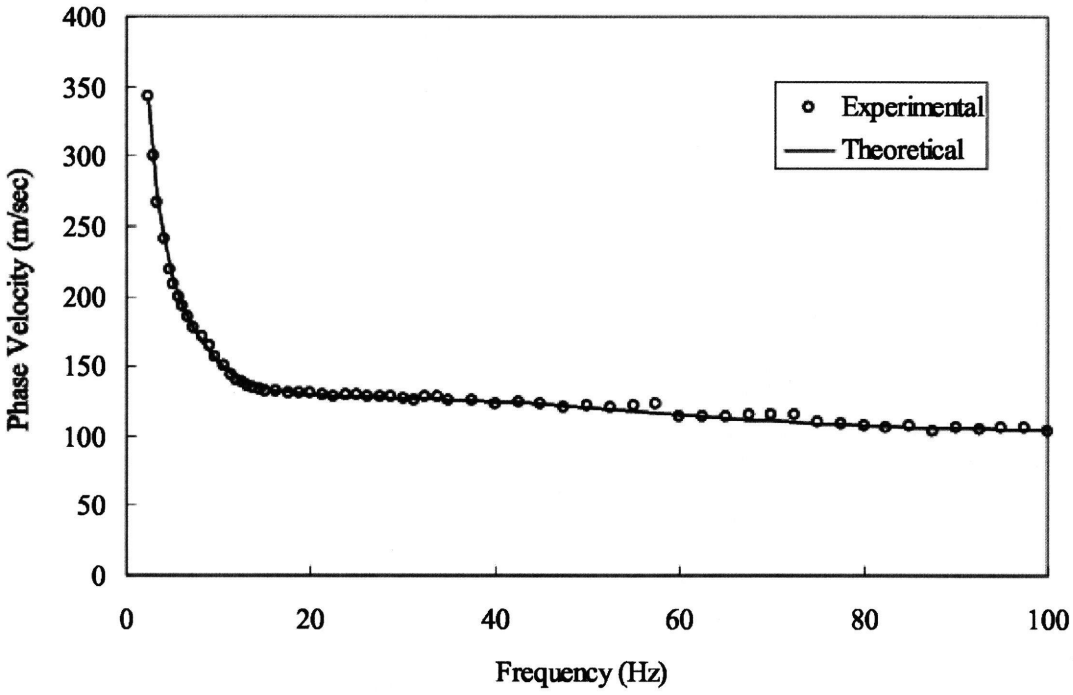


Figure A.13 Experimental vs. theoretical dispersion curve for site 110401

Table A.7 Velocities for site 110401

Depth (ft)	Velocity (ft/sec)
2.3	361
3.0	394
4.8	525
9.4	459
12.3	492
16.0	427
20.9	558
34.4	656
40.6	722
46.2	755
51.8	787
58.3	820
66.5	853
77.0	886
97.7	1017
127.9	1083
167.9	1296
230.6	1460

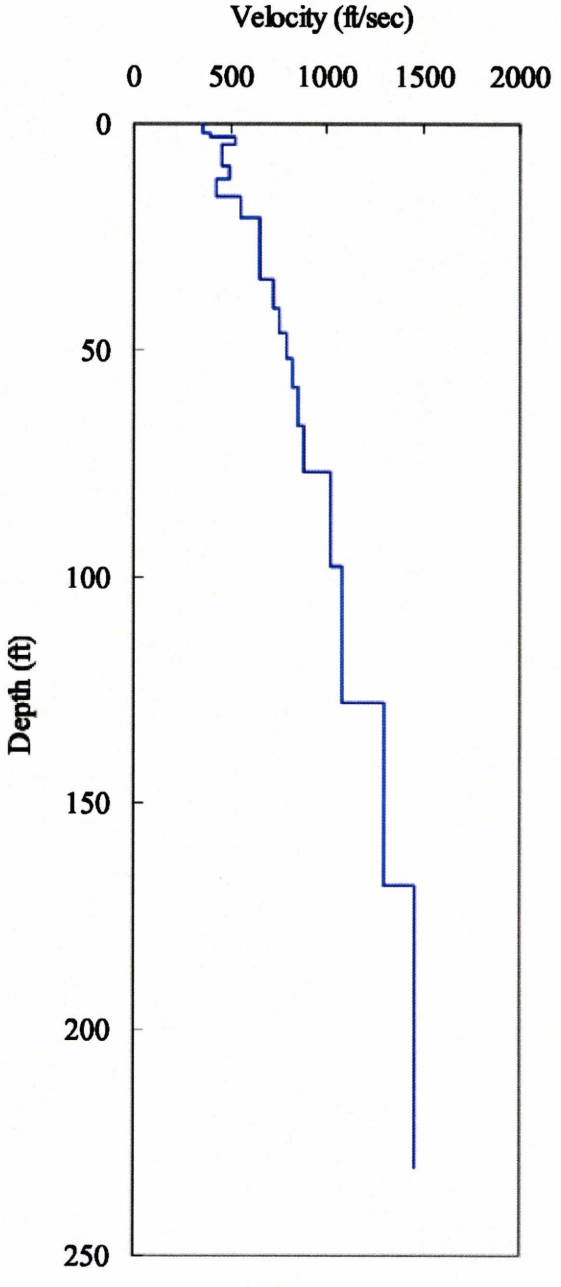


Figure A.14 Vertical Seismic Profile for Site 110401

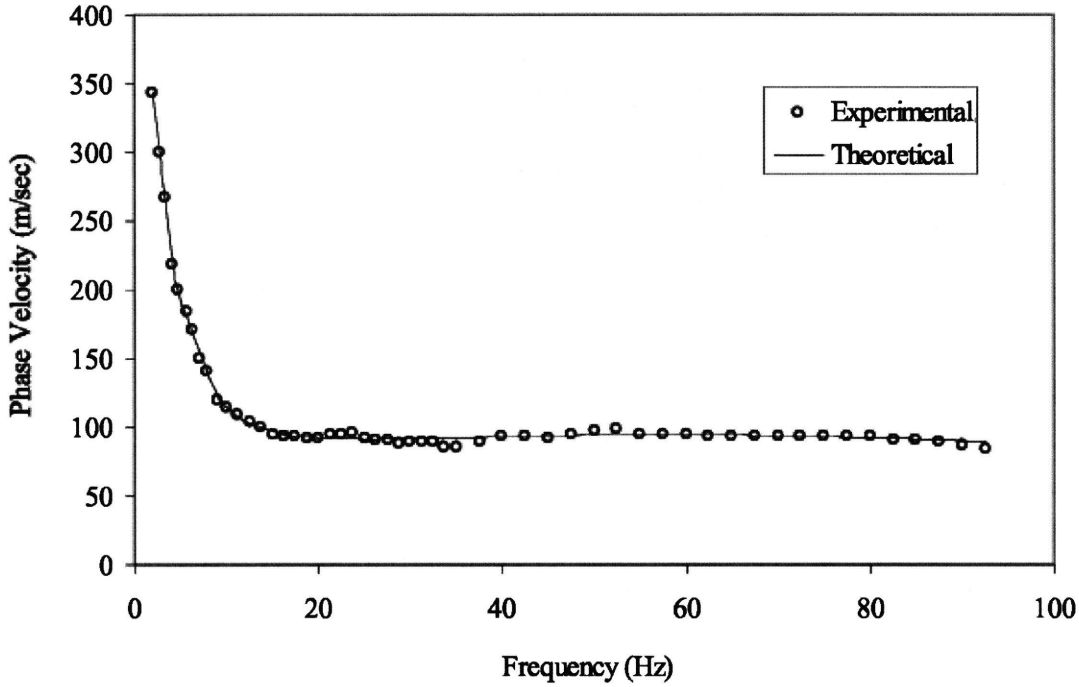


Figure A.15 Experimental vs. theoretical dispersion curve for site 110358

Table A.8 Velocities for site 110358

Depth (ft)	Velocity (ft/sec)
1.6	292
2.6	394
3.9	400
5.9	253
9.2	328
20.7	410
33.8	689
52.8	837
85.3	751
127.0	1453
182.1	1368
288.1	1243

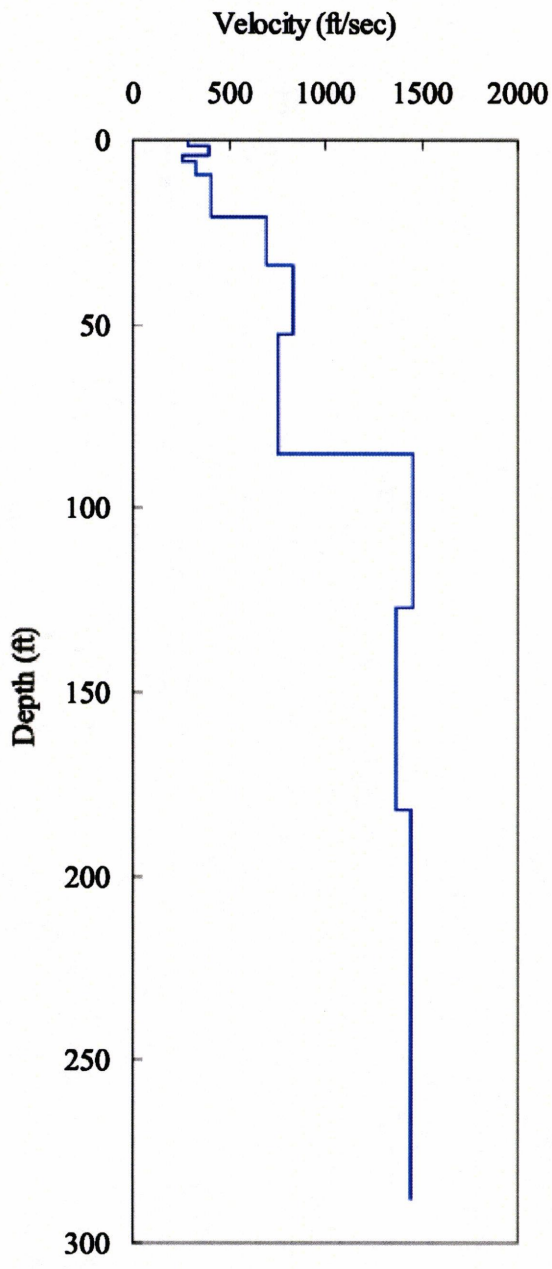


Figure A.16 Vertical Seismic Profile for Site 110358

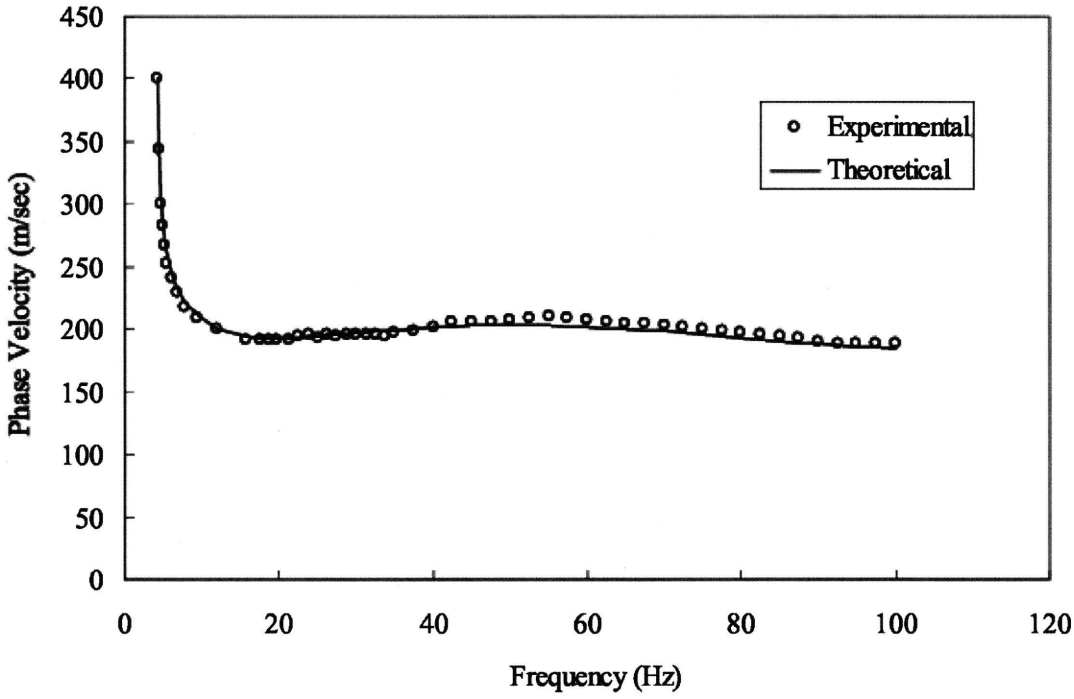


Figure A.17 Experimental vs. theoretical dispersion curve for site 110288

Table A.9 Velocities for site 110288

Depth (ft)	Velocity (ft/sec)
3.3	623
4.0	689
5.4	787
6.3	1312
6.8	1378
8.0	787
9.3	689
12.2	623
14.8	607
20.2	607
27.5	755
36.9	787
45.9	820
54.9	853
64.6	919
77.3	951
85.3	1017
94.9	1181
106.2	1312
118.4	1804
38.4	2133

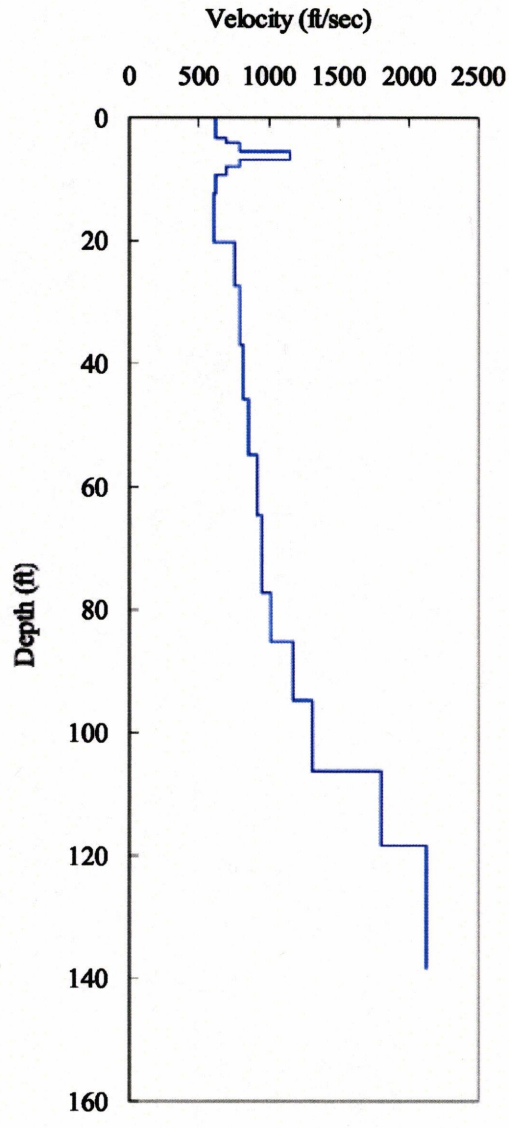


Figure A.18 Vertical Seismic Profile for Site 110288

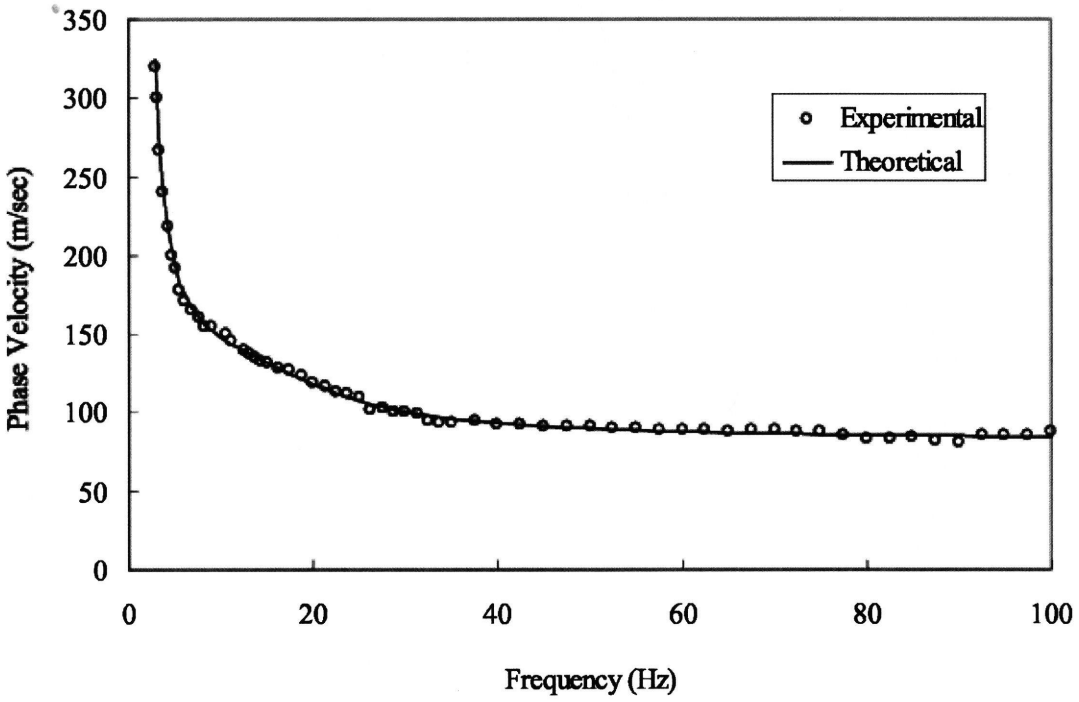


Figure A.19 Experimental vs. theoretical dispersion curve for site 100547

Table A.10 Velocities for site 100547

Depth (ft)	Velocity (ft/sec)
1.6	295
2.0	279
3.6	328
4.6	361
5.2	344
6.2	394
6.9	394
10.2	492
12.1	509
18.7	541
23.6	591
35.1	607
47.6	656
63.6	771
71.2	837
84.3	968
104.7	1050
128.3	1132
179.8	1558

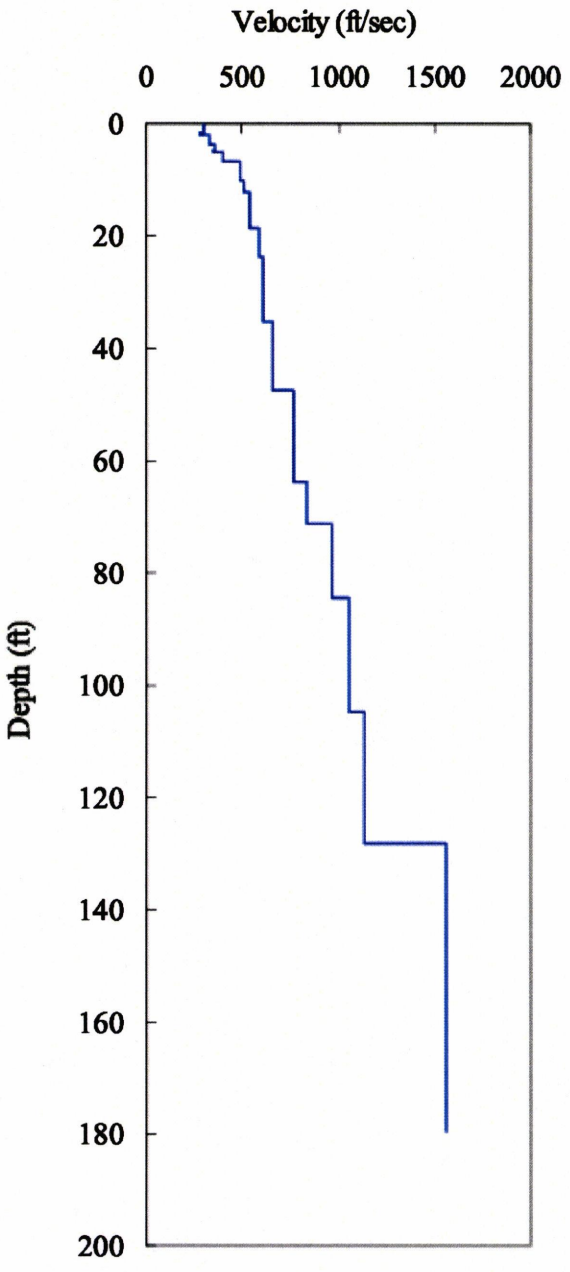


Figure A.20 Vertical Seismic Profile for Site 100547

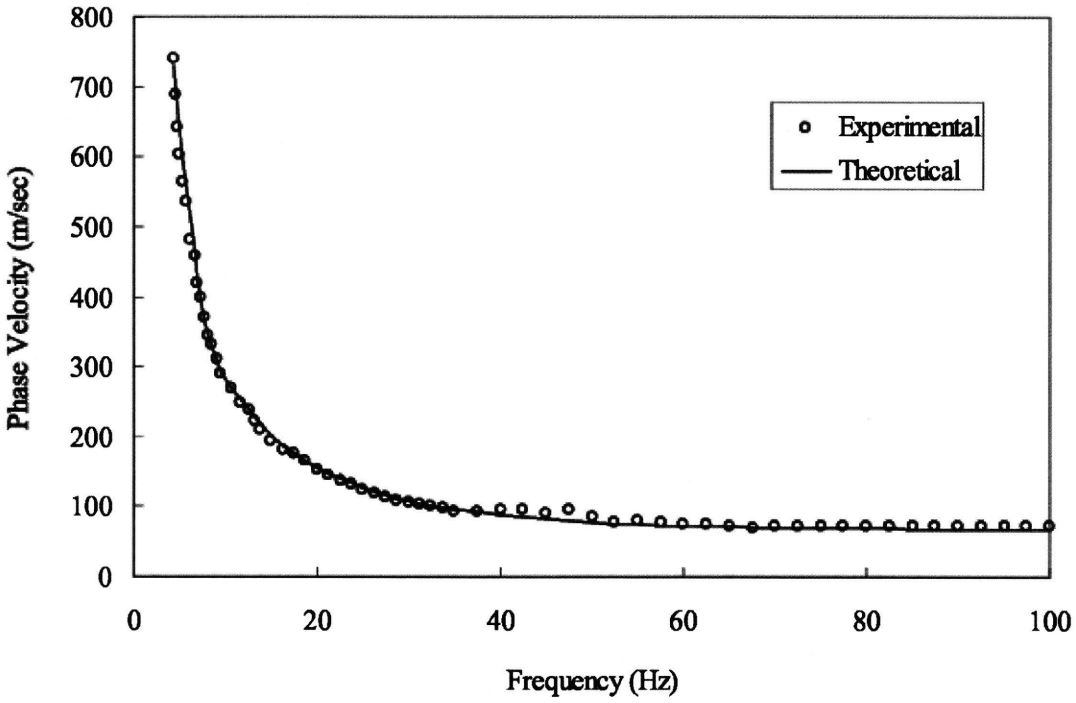


Figure A.21 Experimental vs. theoretical dispersion curve for site 100523

Table A.11 Velocities for site 1005

Depth (ft)	Velocity (ft/sec)
1.6	236
2.0	240
2.0	246
2.3	262
3.3	394
3.6	394
3.9	361
6.2	394
12.5	656
18.4	755
35.4	1129
50.2	1214
69.9	1444
79.1	1706
89.6	2297
98.8	2379
114.2	2543
130.6	2543
154.5	2707
174.5	2871
199.8	3035
220.8	3281
247.0	3445
276.6	3609

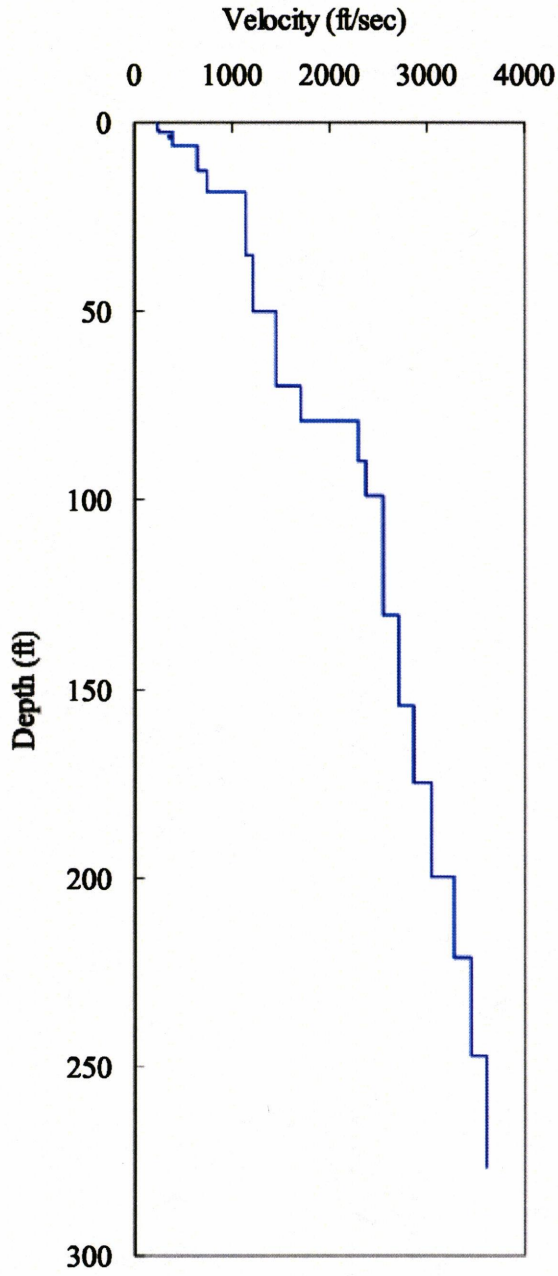


Figure A.22 Vertical Seismic Profile for Site 100523

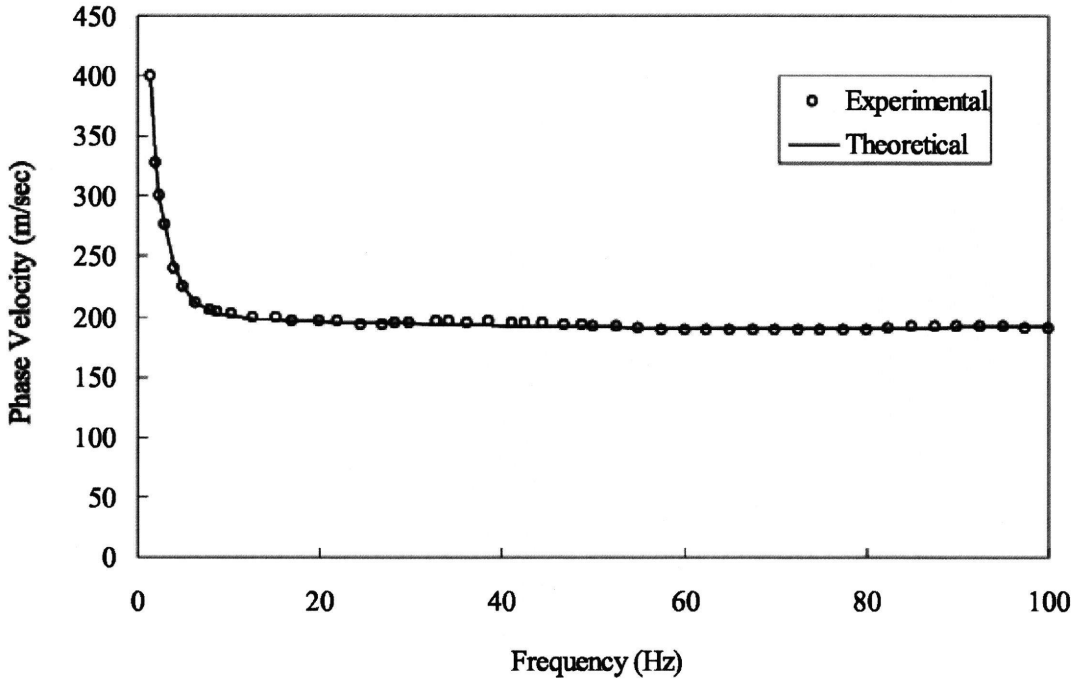


Figure A.23 Experimental vs. theoretical dispersion curve for site 100522

Table A.12 Velocities for site 100522

Depth (ft)	Velocity (ft/sec)
3.6	689
5.1	591
6.4	705
9.4	705
11.8	689
21.7	689
43.3	705
75.8	771
101.0	951
155.2	1083
201.8	1165
275.3	1247
449.1	1476

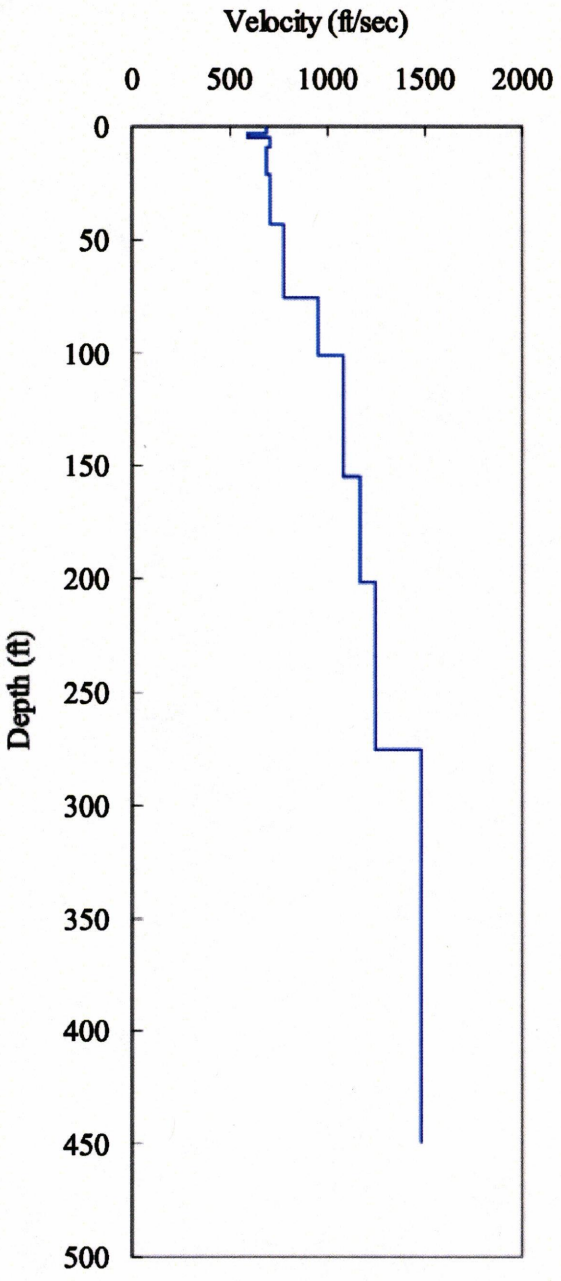


Figure A.24 Vertical Seismic Profile for Site 100522

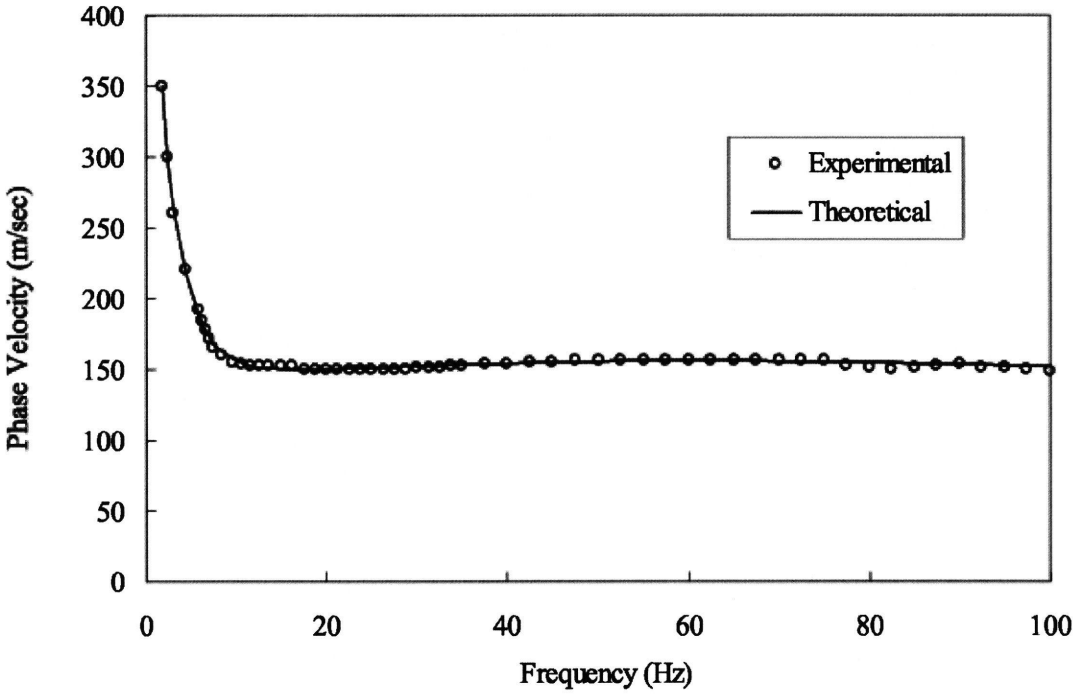


Figure A.25 Experimental vs. theoretical dispersion curve for site 100478

Table A.13 Velocities for site 100478

Depth (ft)	Velocity (ft/sec)
3	525
6	623
9	509
14	509
27	525
37	574
46	722
56	919
85	853
148	951
204	1411
338	1411

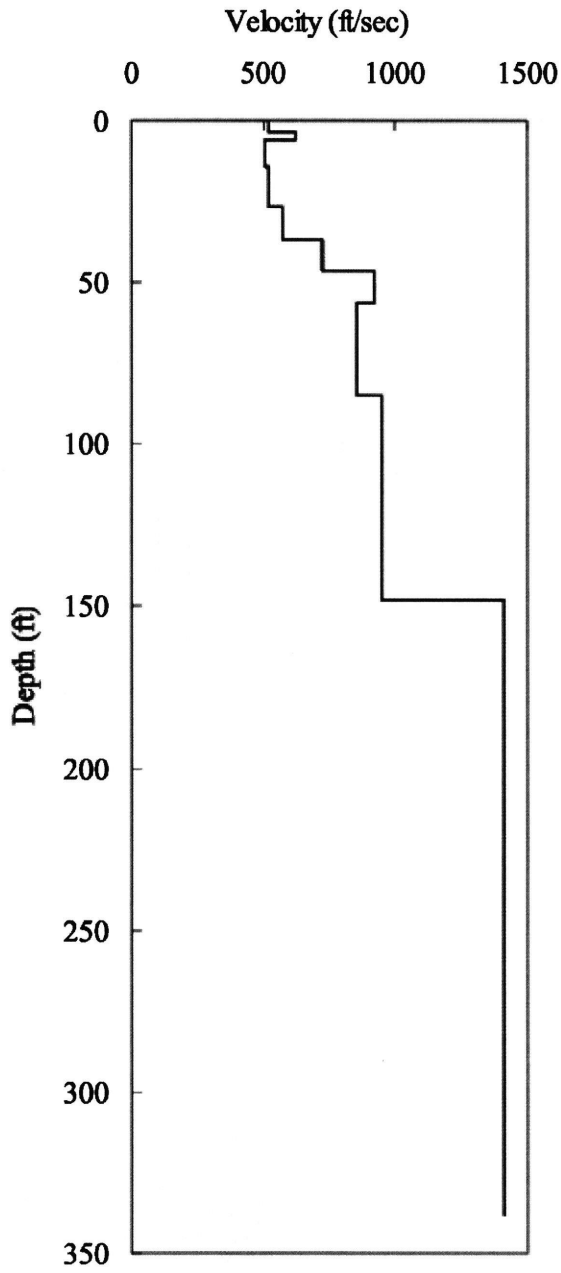


Figure A.26 Vertical Seismic Profile for Site 100478

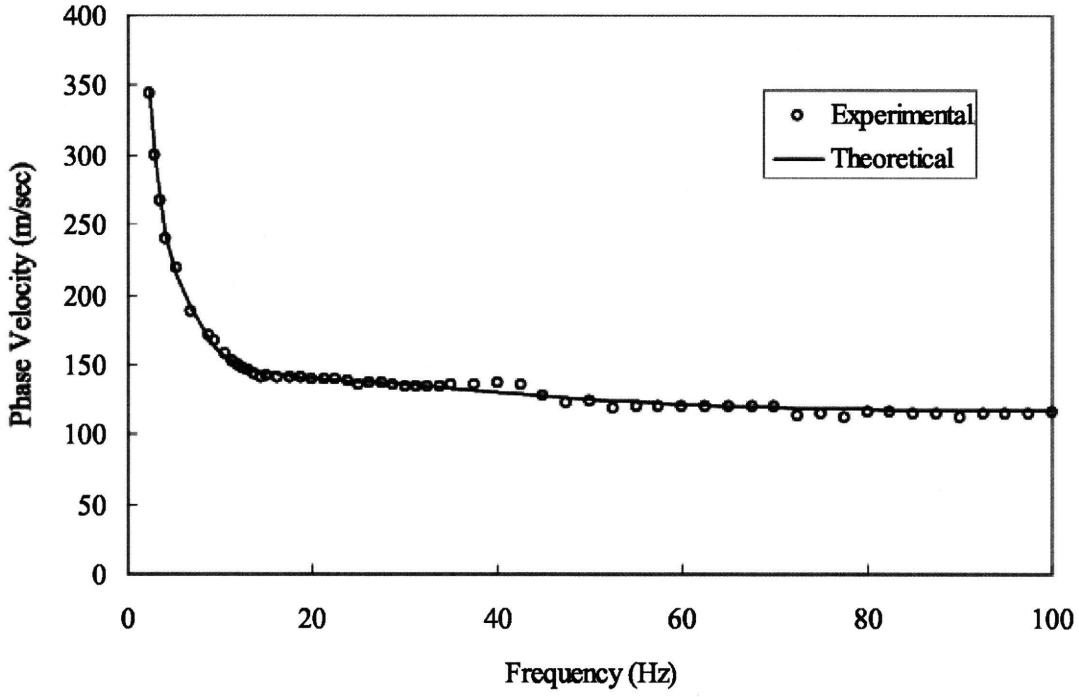


Figure A.27 Experimental vs. theoretical dispersion curve for site 100303

Table A.14 Velocities for site 100303

Depth (ft)	Velocity (ft/sec)
2.4	410
2.6	374
3.7	420
4.2	404
5.2	640
8.9	509
15.5	509
24.2	525
32.0	705
44.8	755
66.7	853
95.0	919
127.9	1083
168.1	1280
231.0	1444

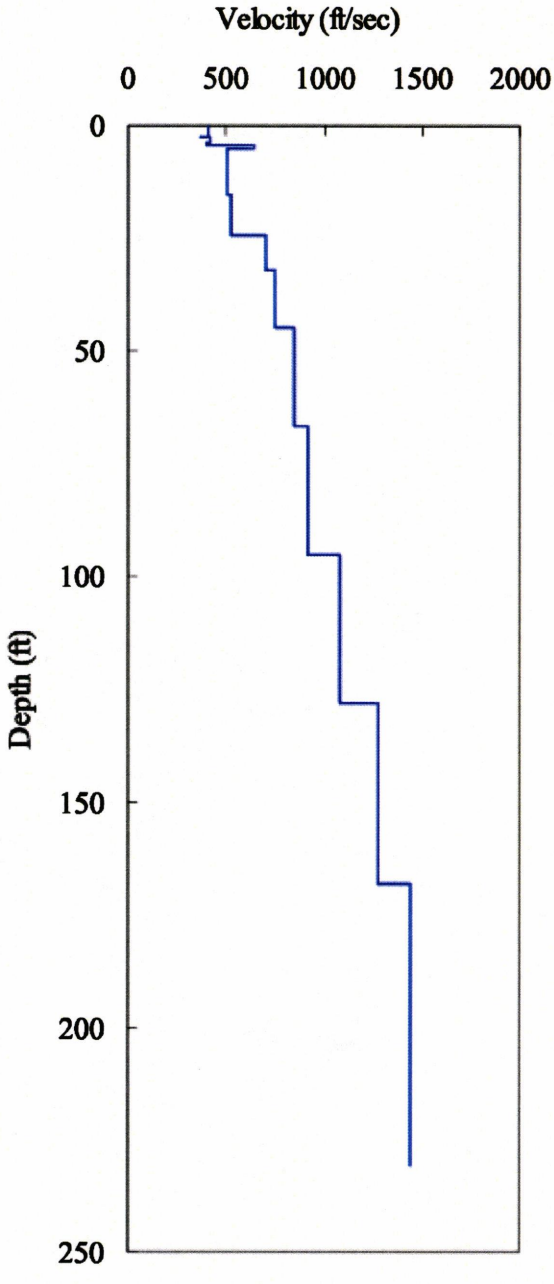


Figure A.28 Vertical Seismic Profile for Site 100303

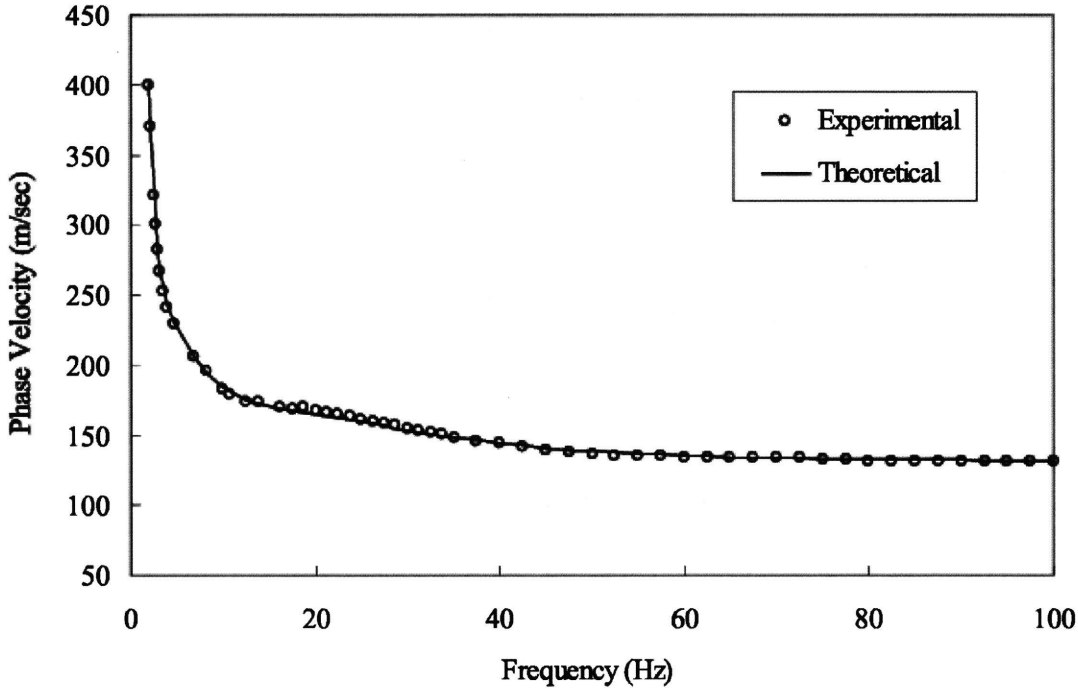


Figure A.29 Experimental vs. theoretical dispersion curve for site 100153

Table A.15 Velocities for site 100153

Depth (ft)	Velocity (ft/sec)
2.9	459
3.7	476
4.2	476
6.5	509
13.1	623
15.0	640
17.3	607
23.1	623
30.3	656
49.3	787
101.0	886
121.7	968
138.1	1050
158.1	1148
183.0	1378
215.5	1312
274.5	1886
334.9	1886

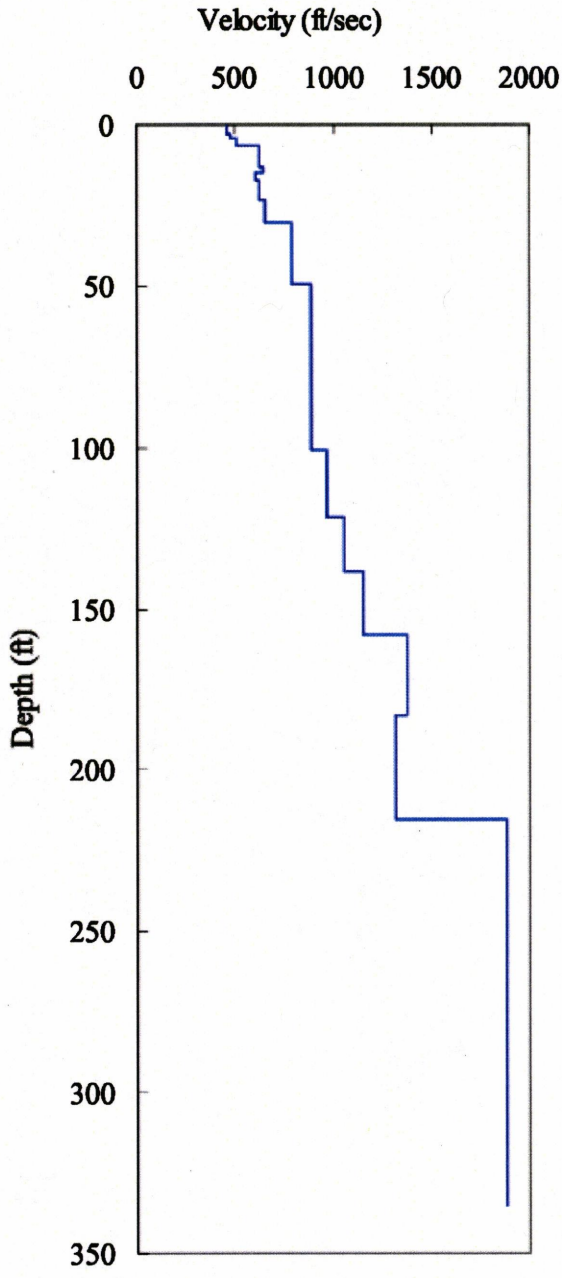


Figure A.30 Vertical Seismic Profile for Site 100153

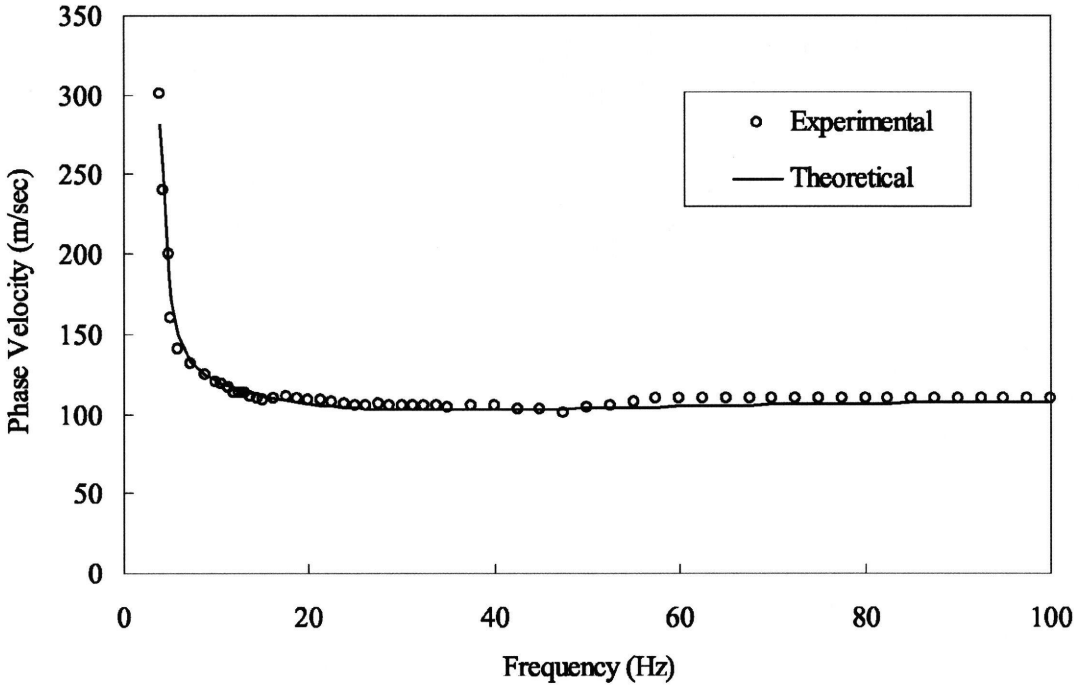


Figure A.31 Experimental vs. theoretical dispersion curve for site 100105.

Table A.16 Velocities for site 100105

Depth (ft)	Velocity (ft/sec)
3.3	394
3.8	213
4.4	361
5.2	361
7.4	377
13.0	394
20.8	443
40.6	492
52.4	820
55.6	919
65.5	919
85.2	1476

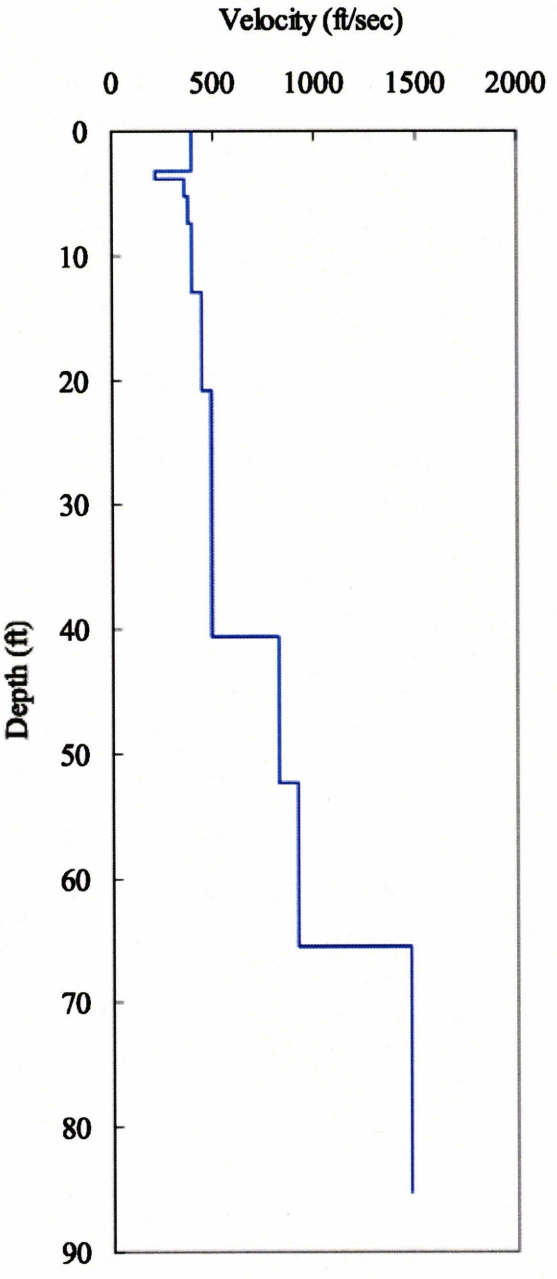


Figure A.32 Vertical Seismic Profile for Site 100105

APPENDIX B
V_s Estimation Model Comparison

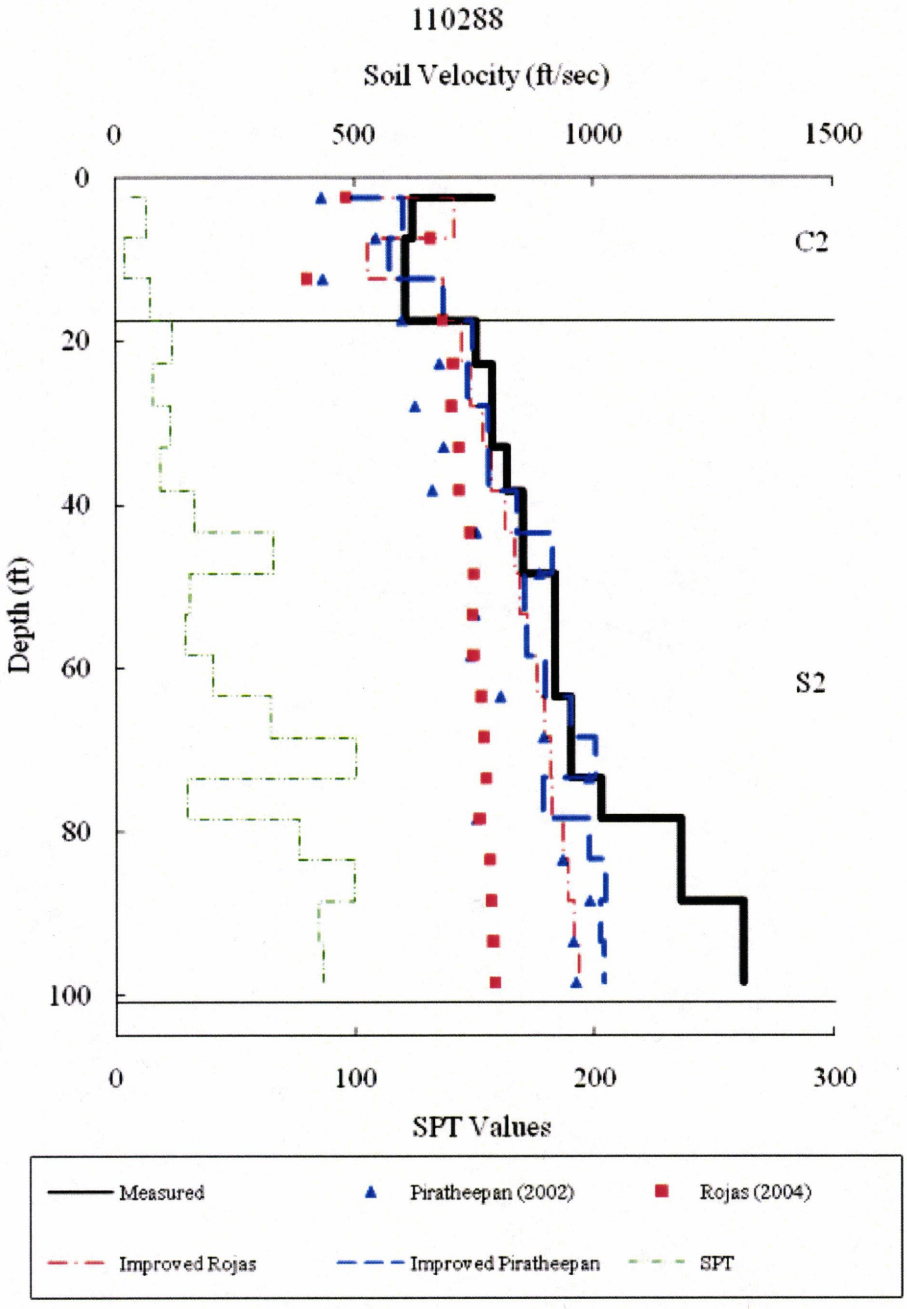


Figure B.1 110288 Model Comparison

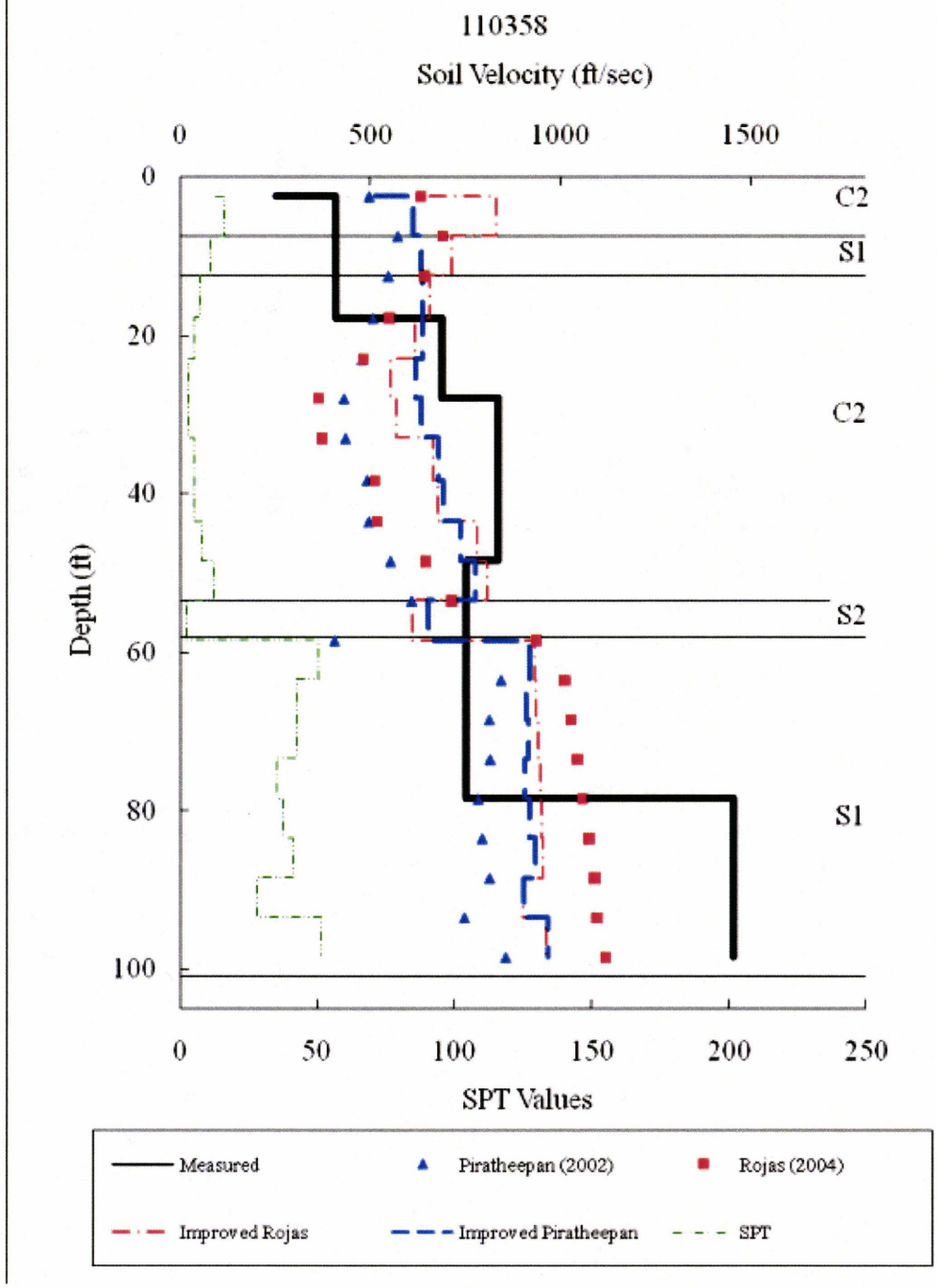


Figure B.2 110358 Model Comparison

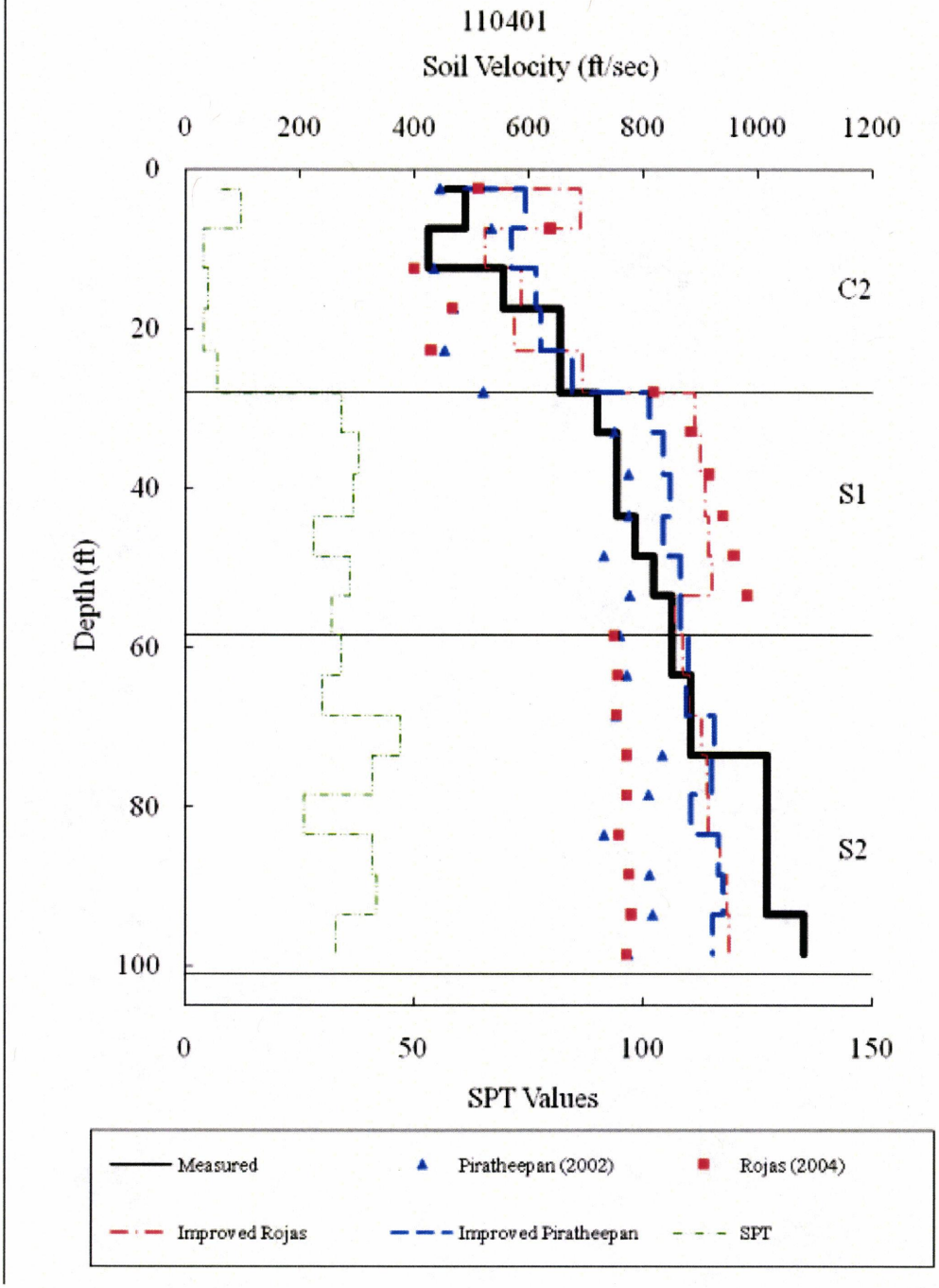


Figure B.3 110401 Model Comparison

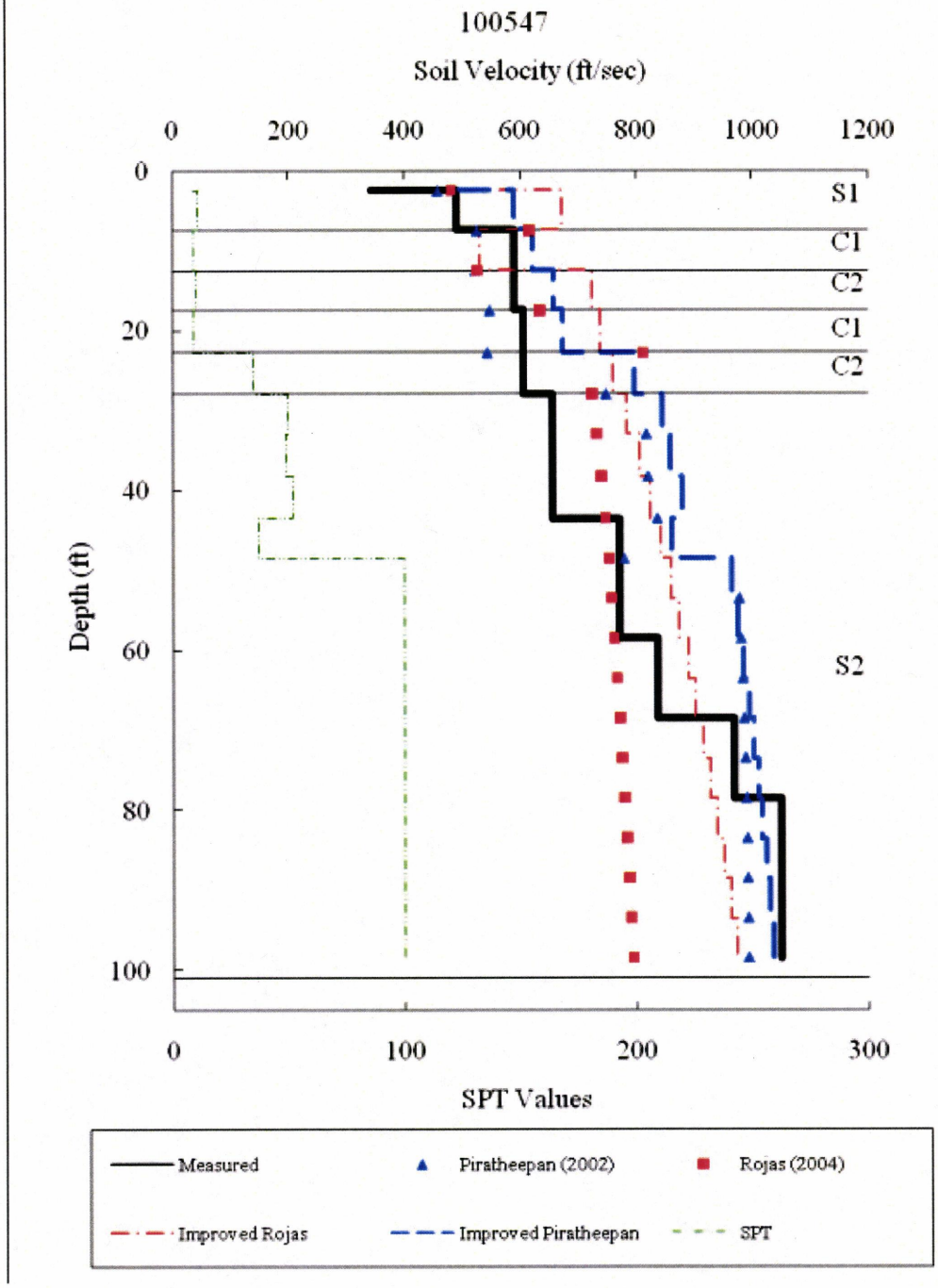


Figure B.4 100547 Model Comparison

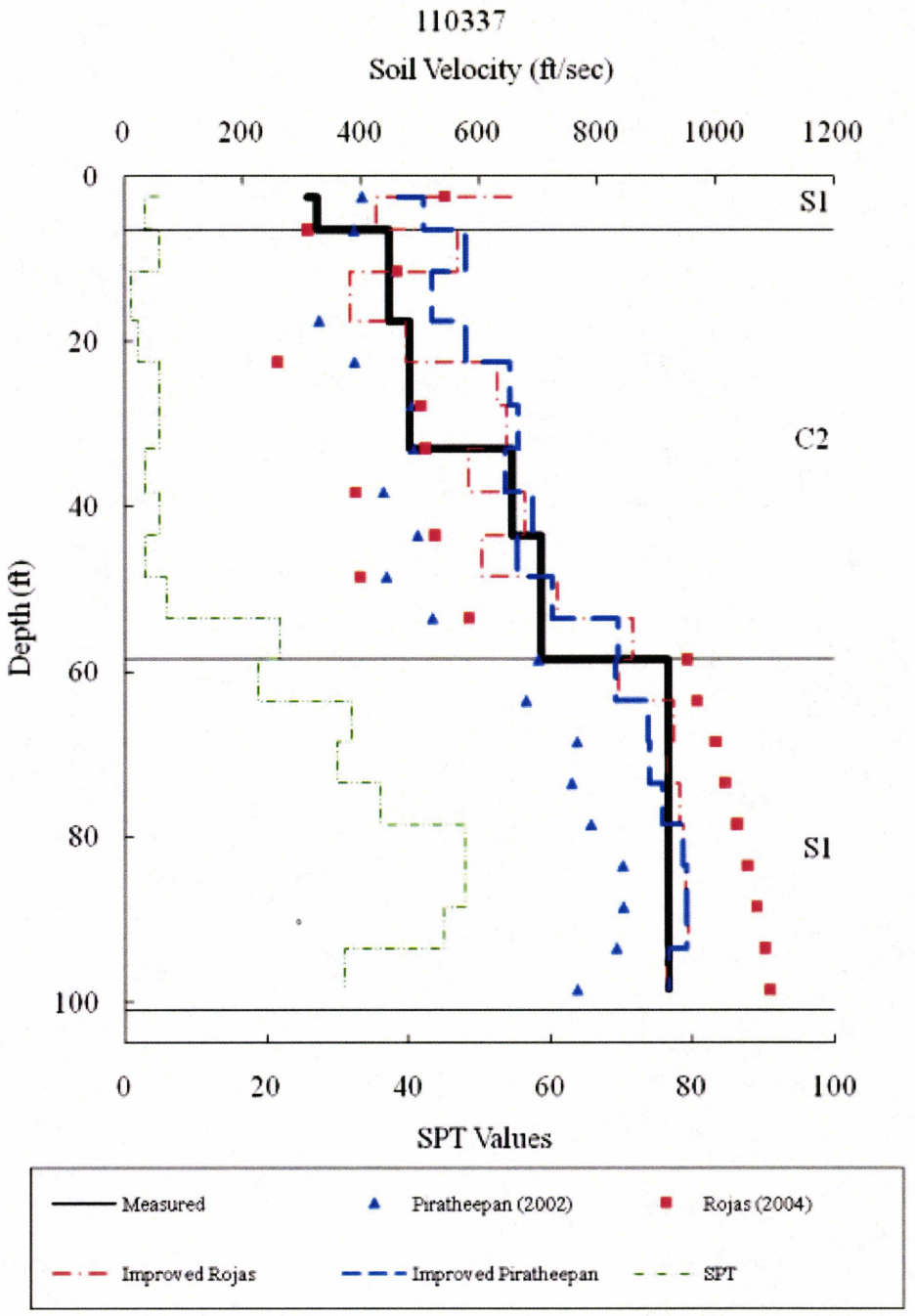


Figure B.5 110337 Model Comparison

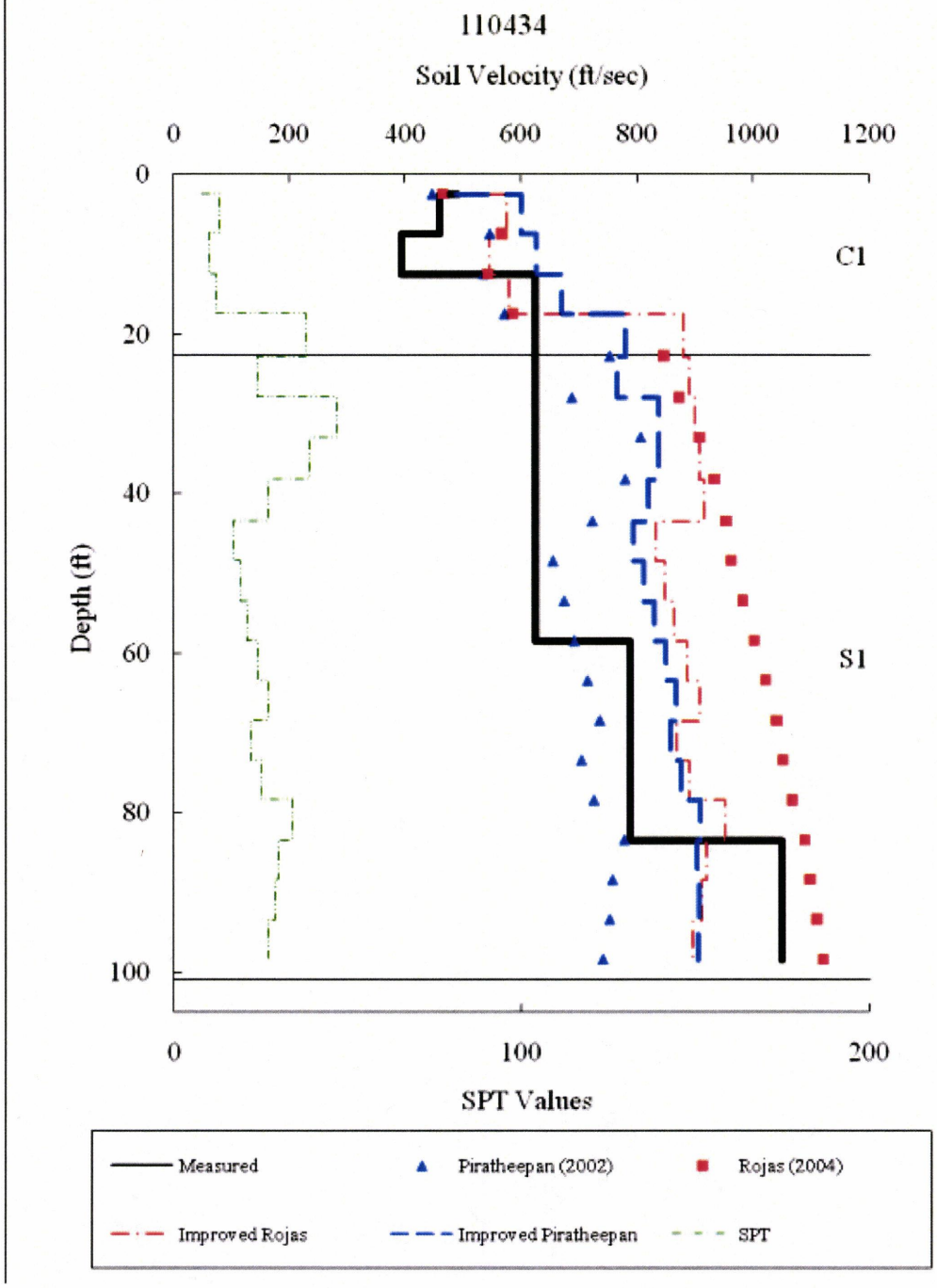


Figure B.6 110434 Model Comparison

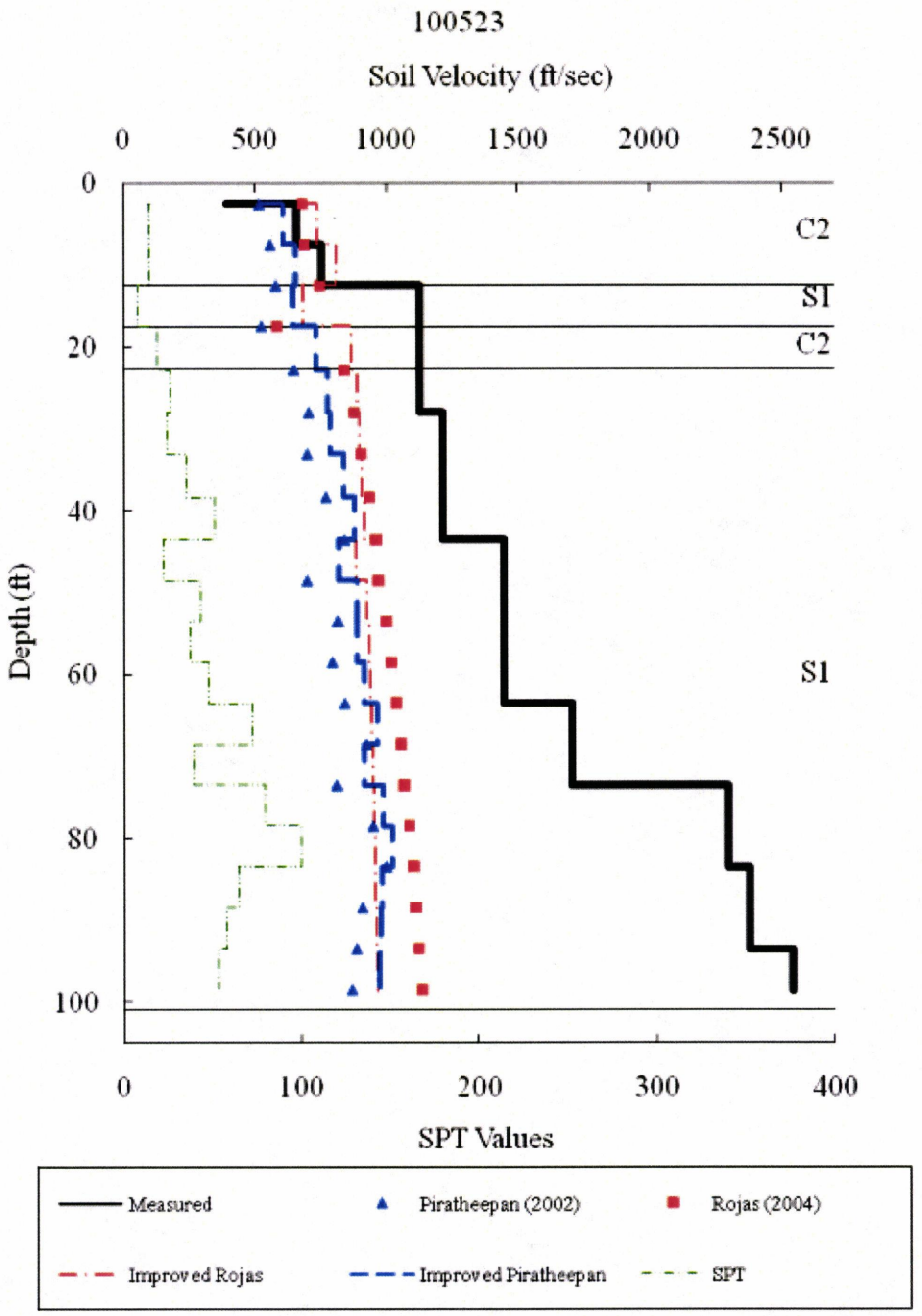


Figure B.7 100523 Model Comparison

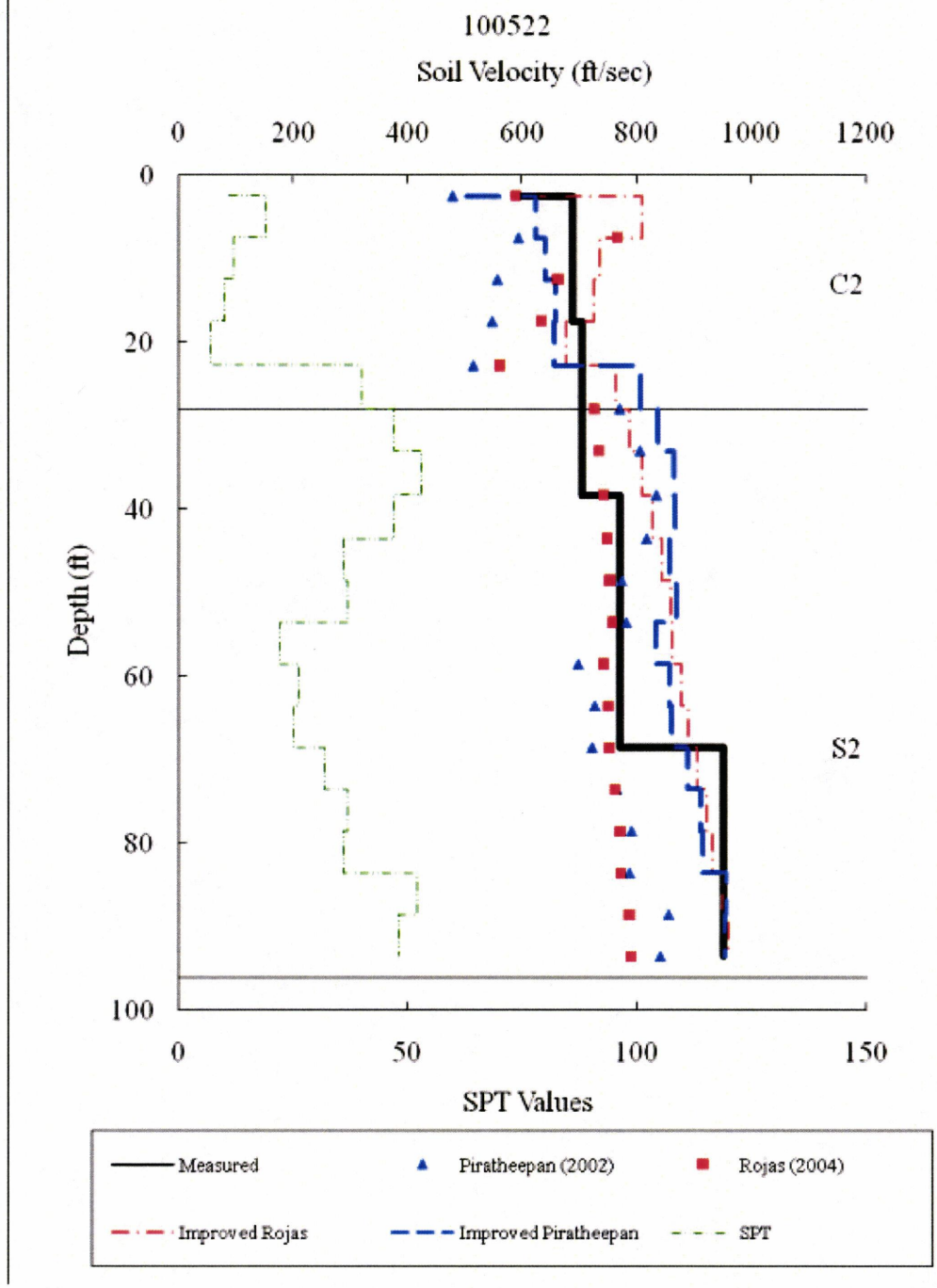


Figure B.8 100522 Model Comparison

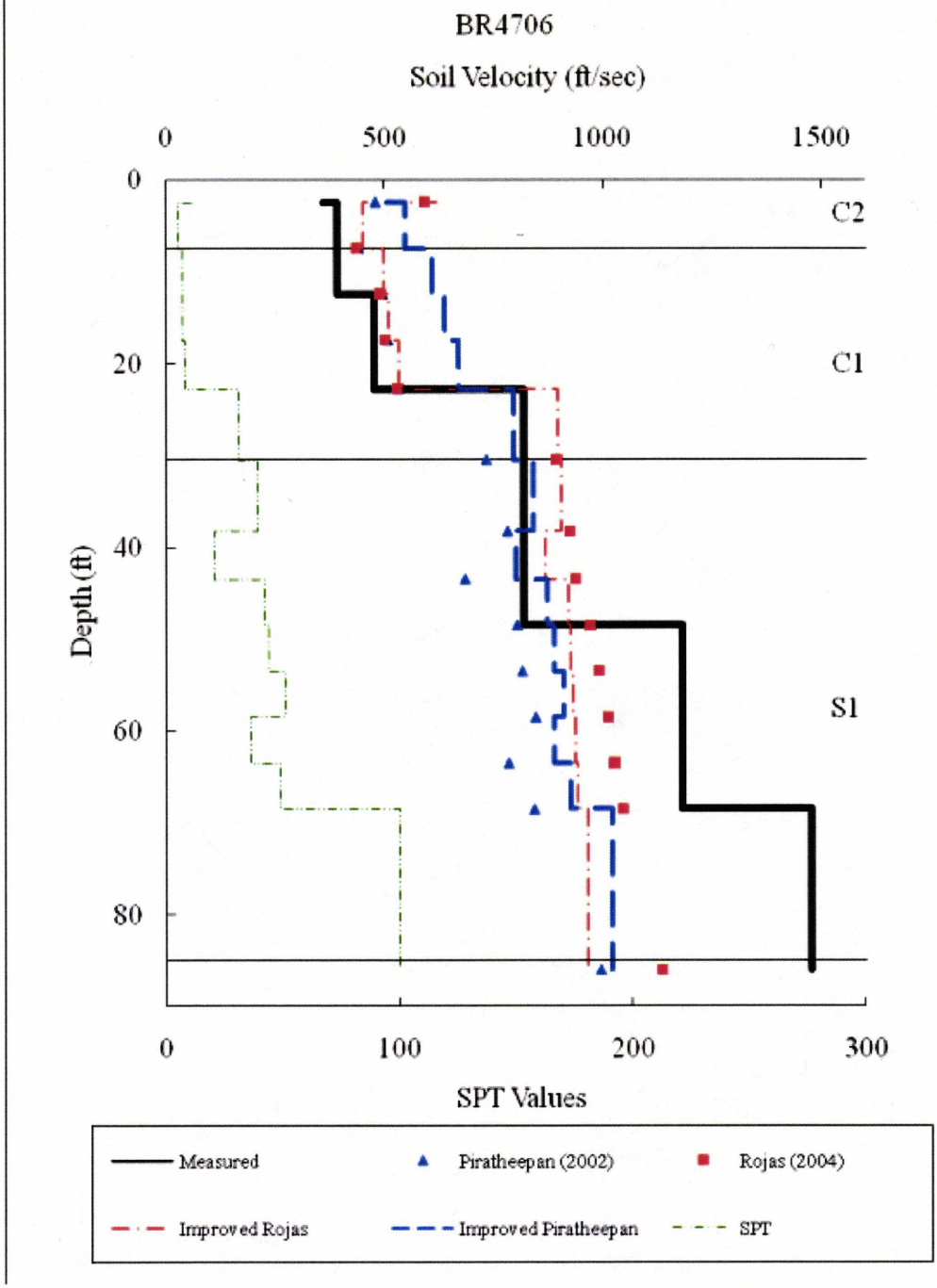


Figure B.9 BR4706 Model Comparison

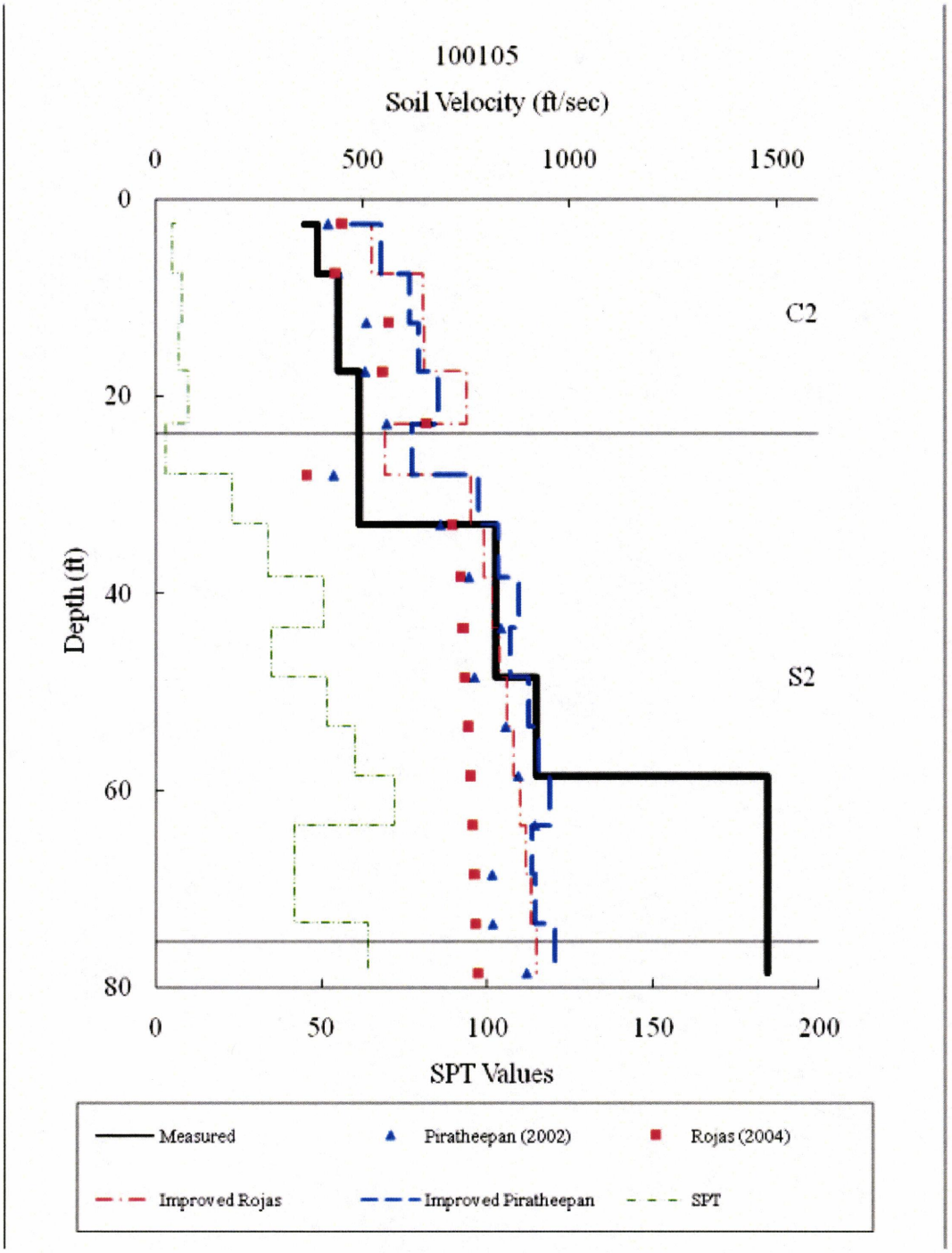


Figure B.10 100105 Model Comparison

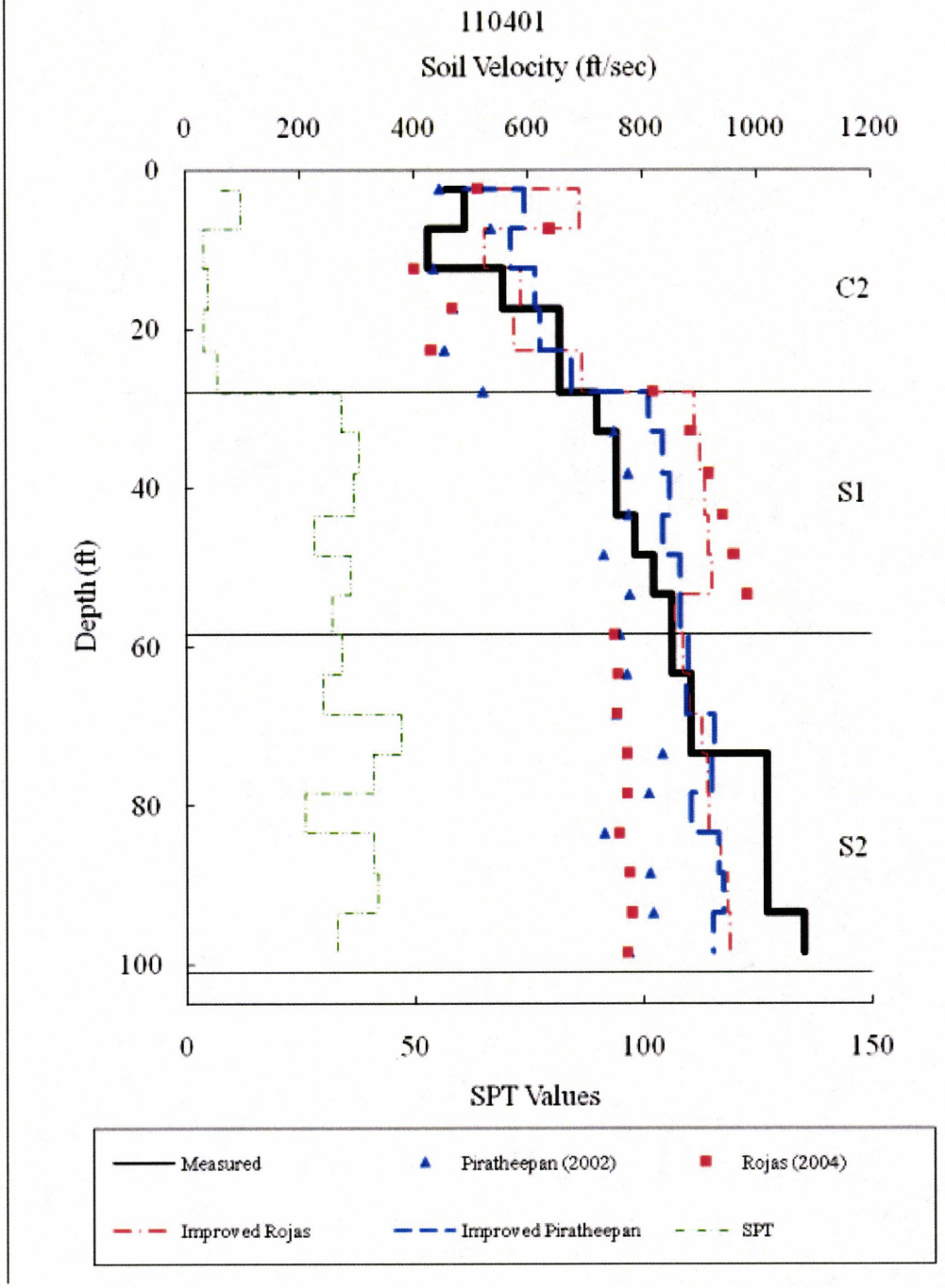


Figure B.11 110401 Model Comparison

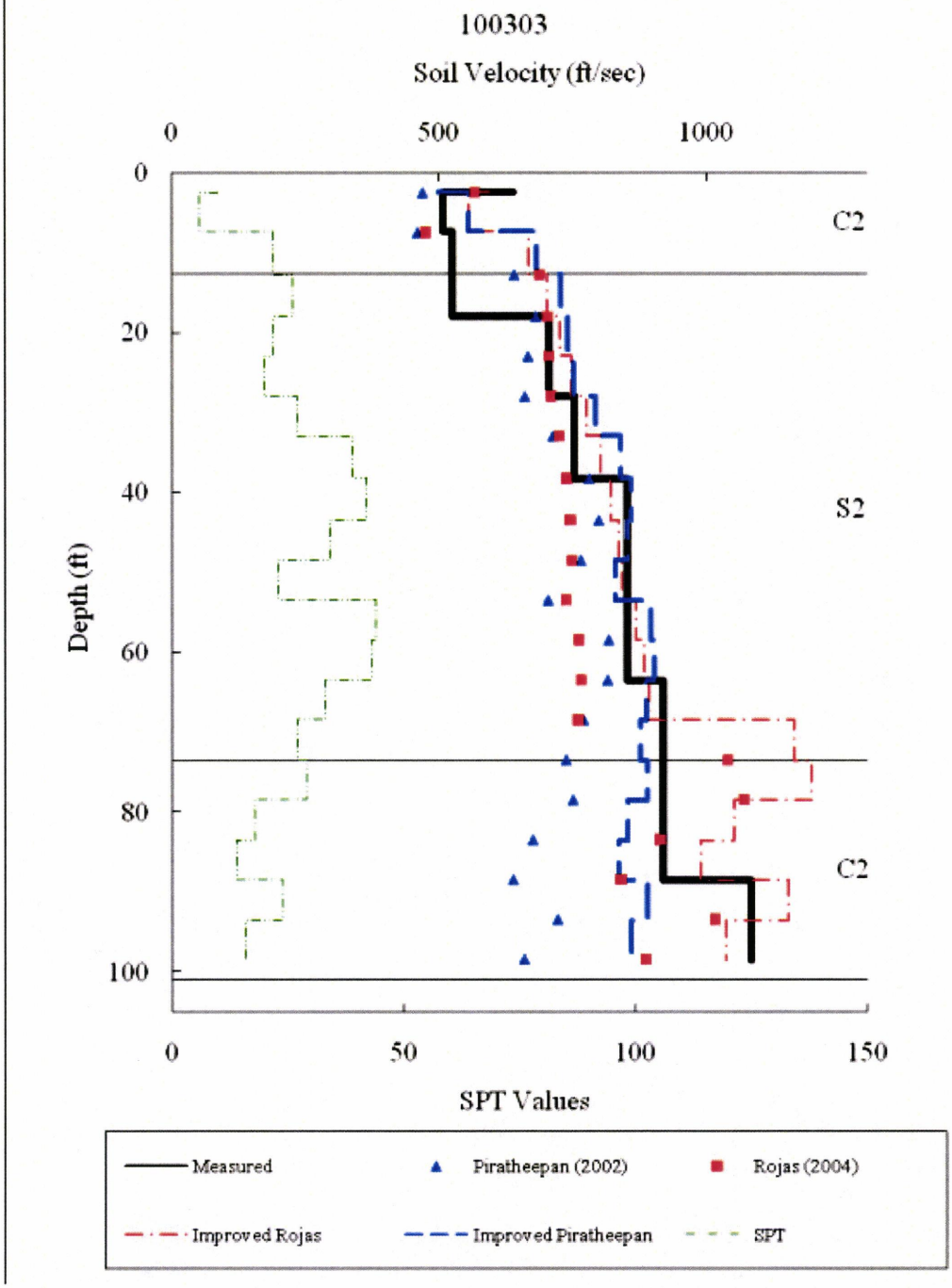


Figure B.12 100303 Model Comparison

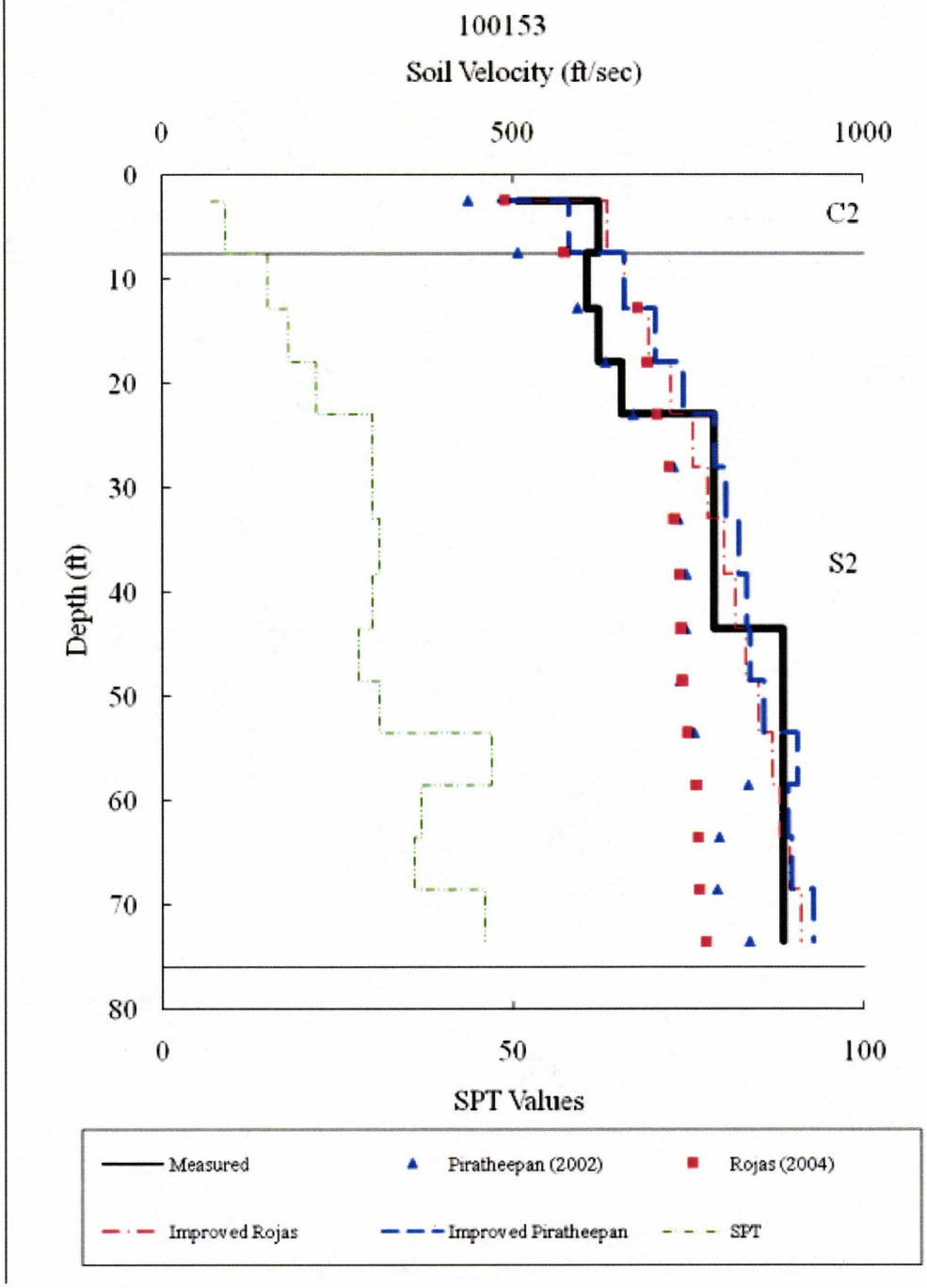


Figure B.13 100153 Model Comparison

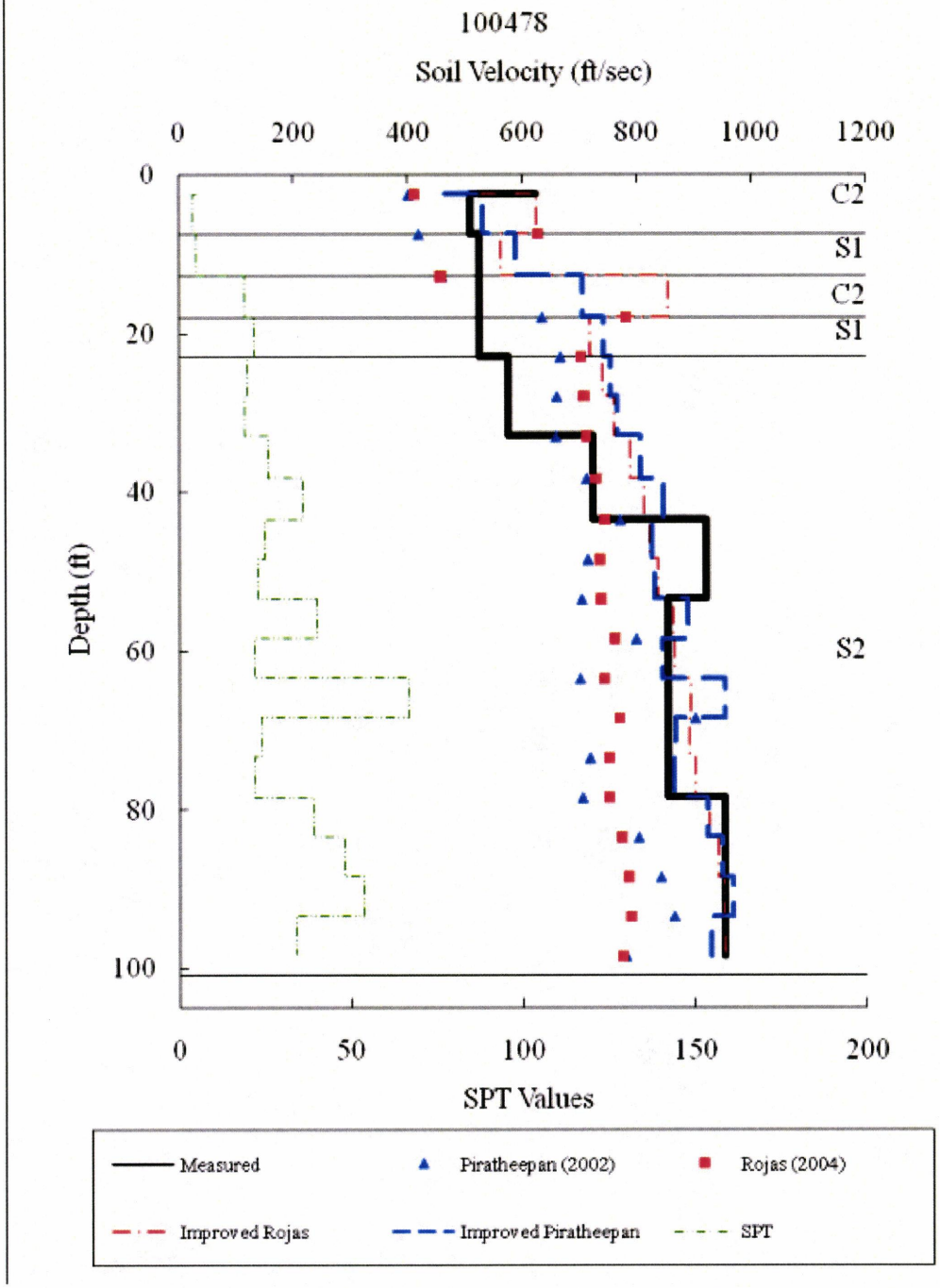


Figure B.14 100478 Model Comparison

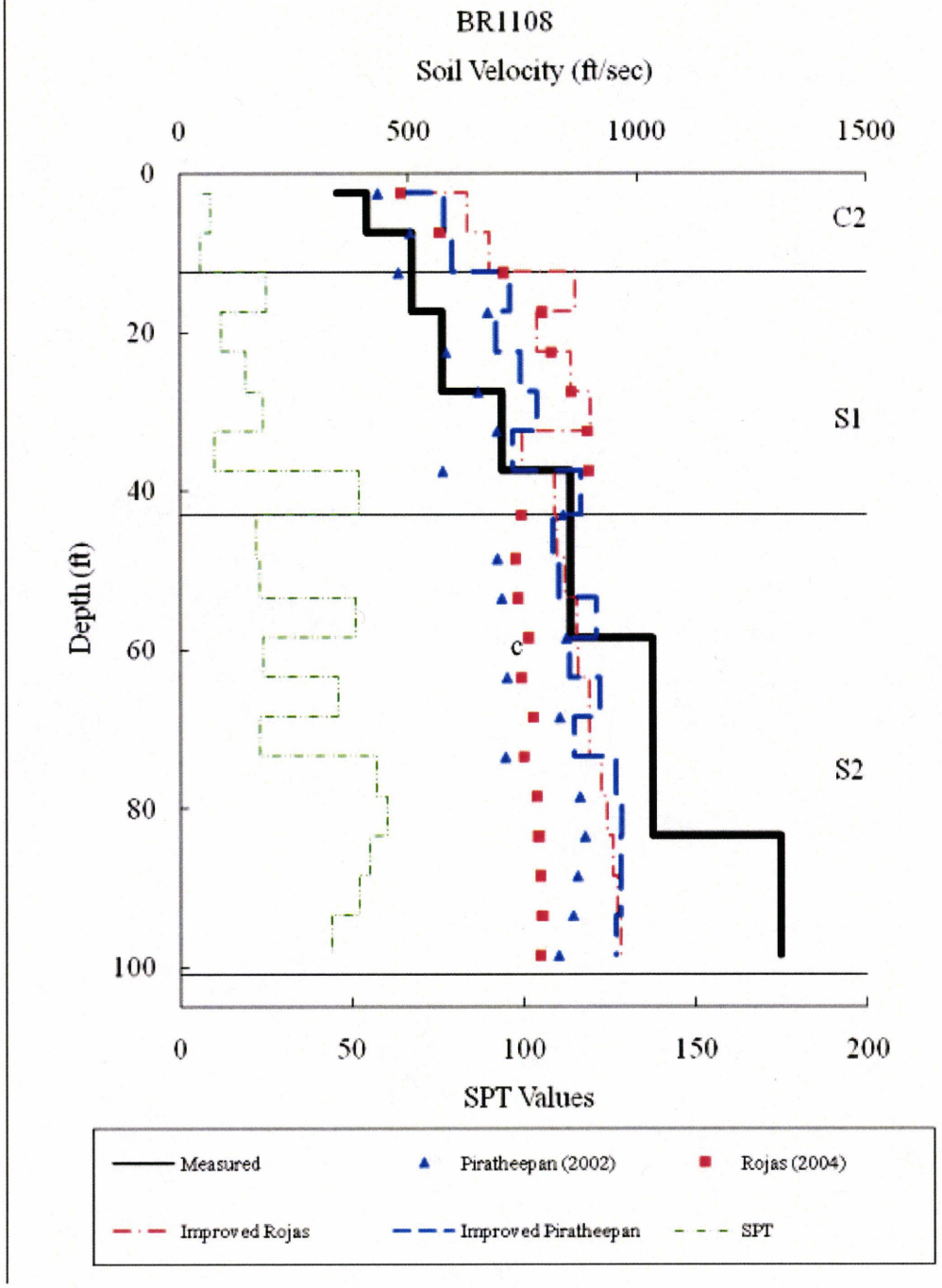


Figure B.15 BR1108 Model Comparison

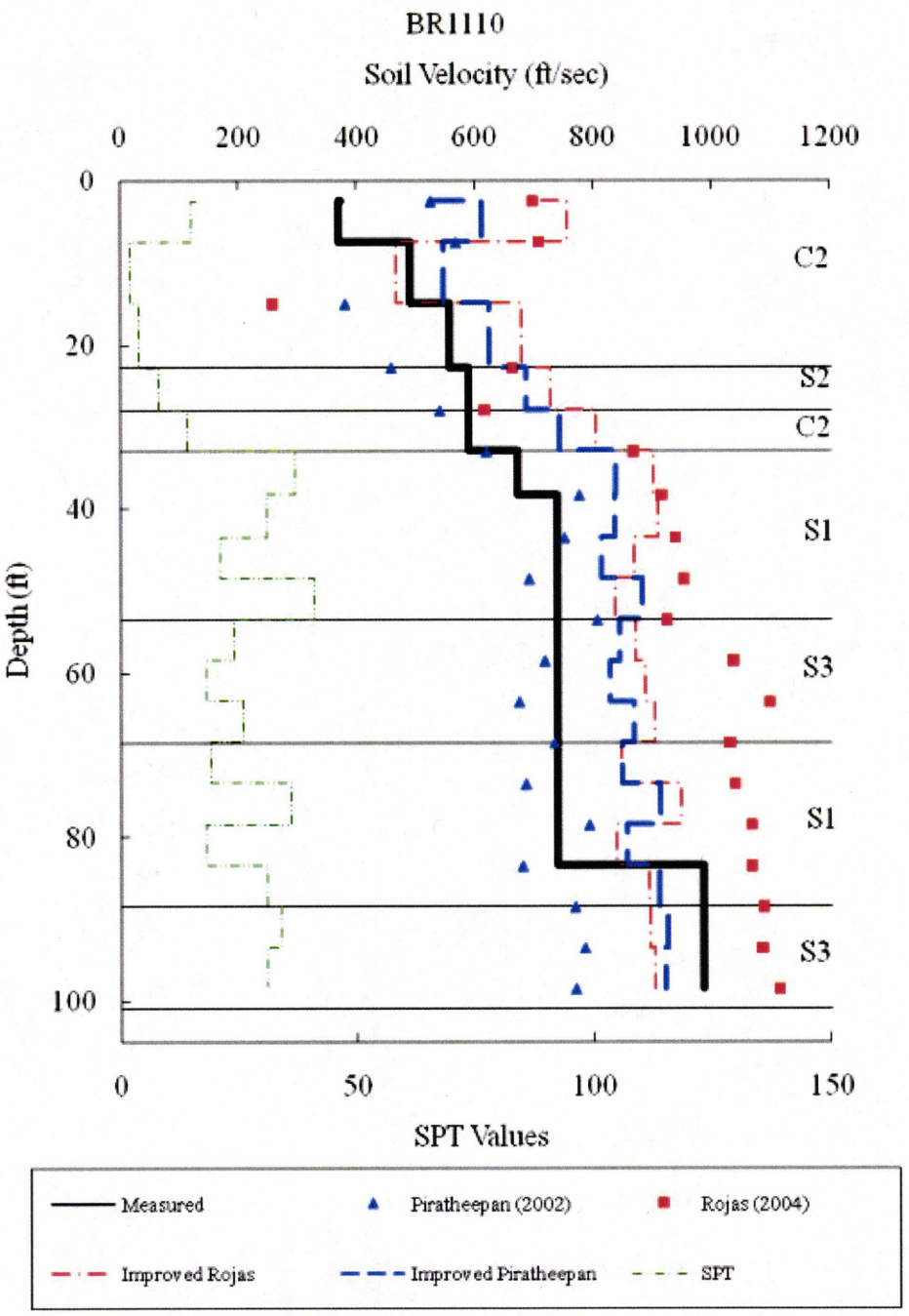


Figure B.16 BR1110 Model Comparison

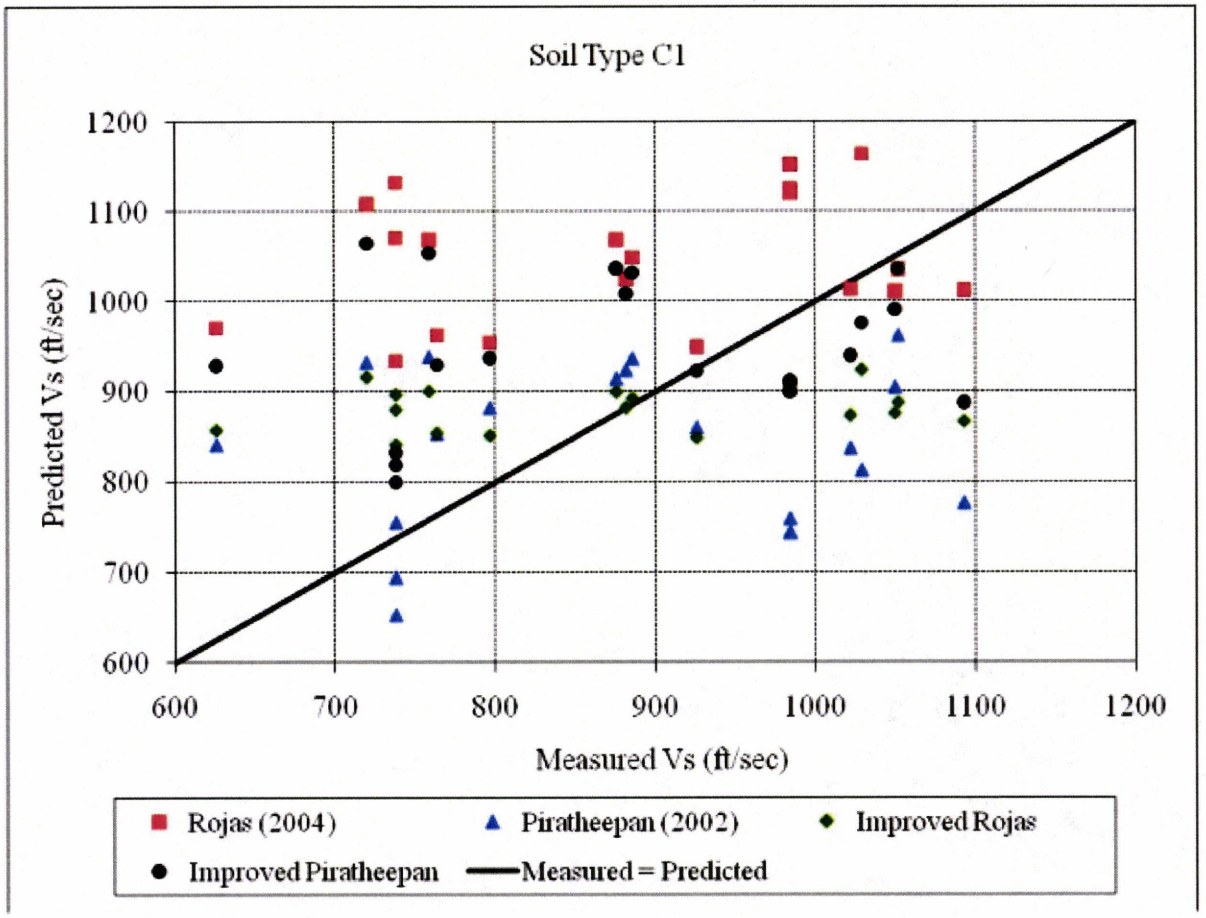


Figure B.17 Soil Type C1 Model Comparison

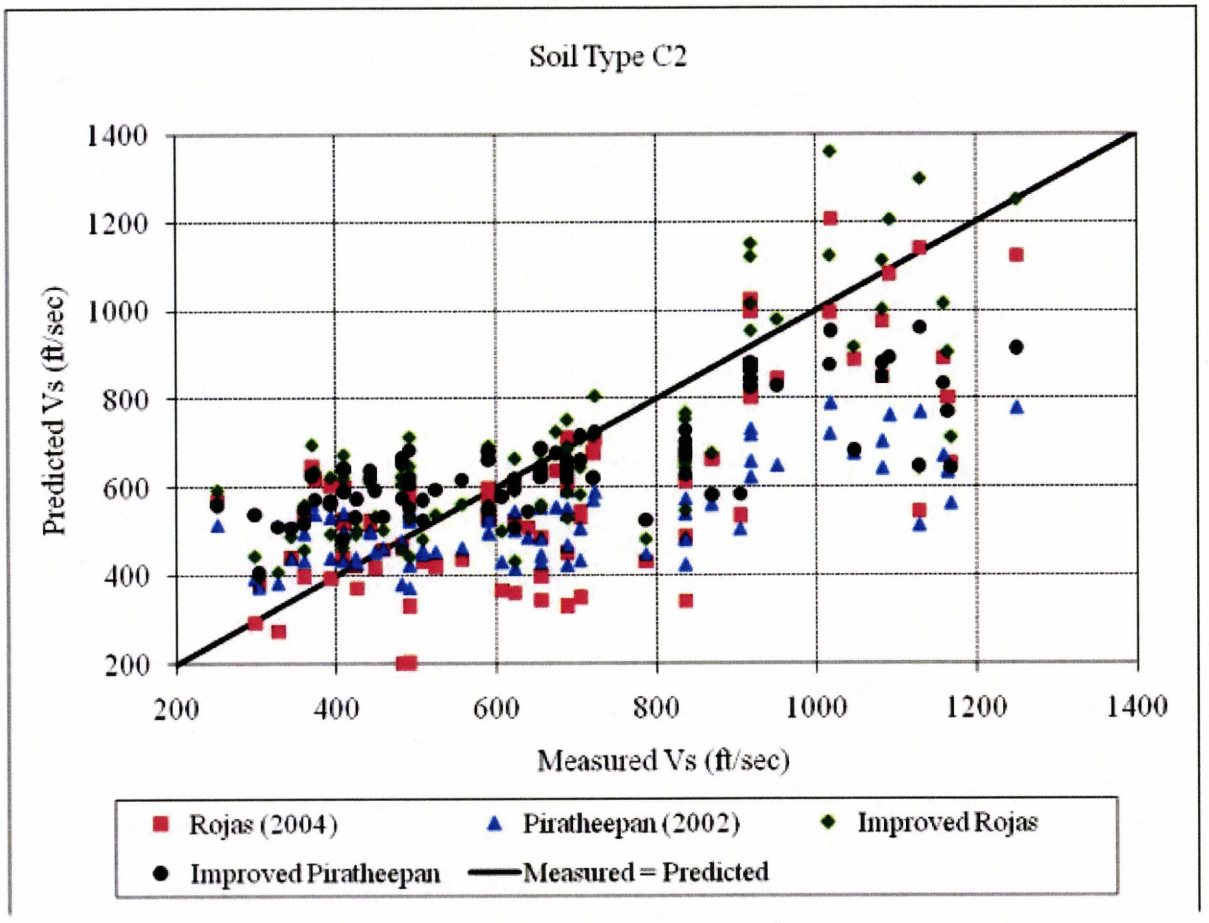


Figure B.18 Soil Type C2 Model Comparison

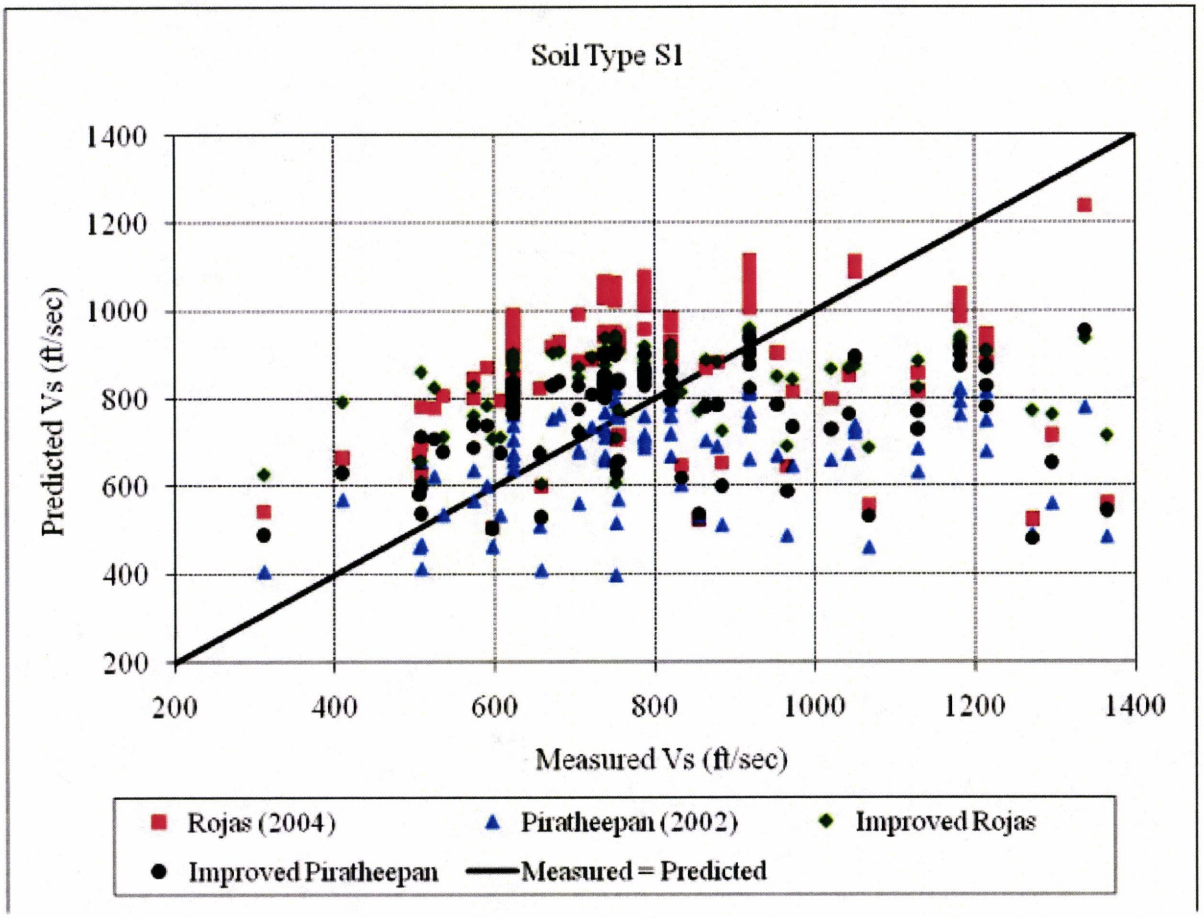


Figure B.19 Soil Type S1 Model Comparison

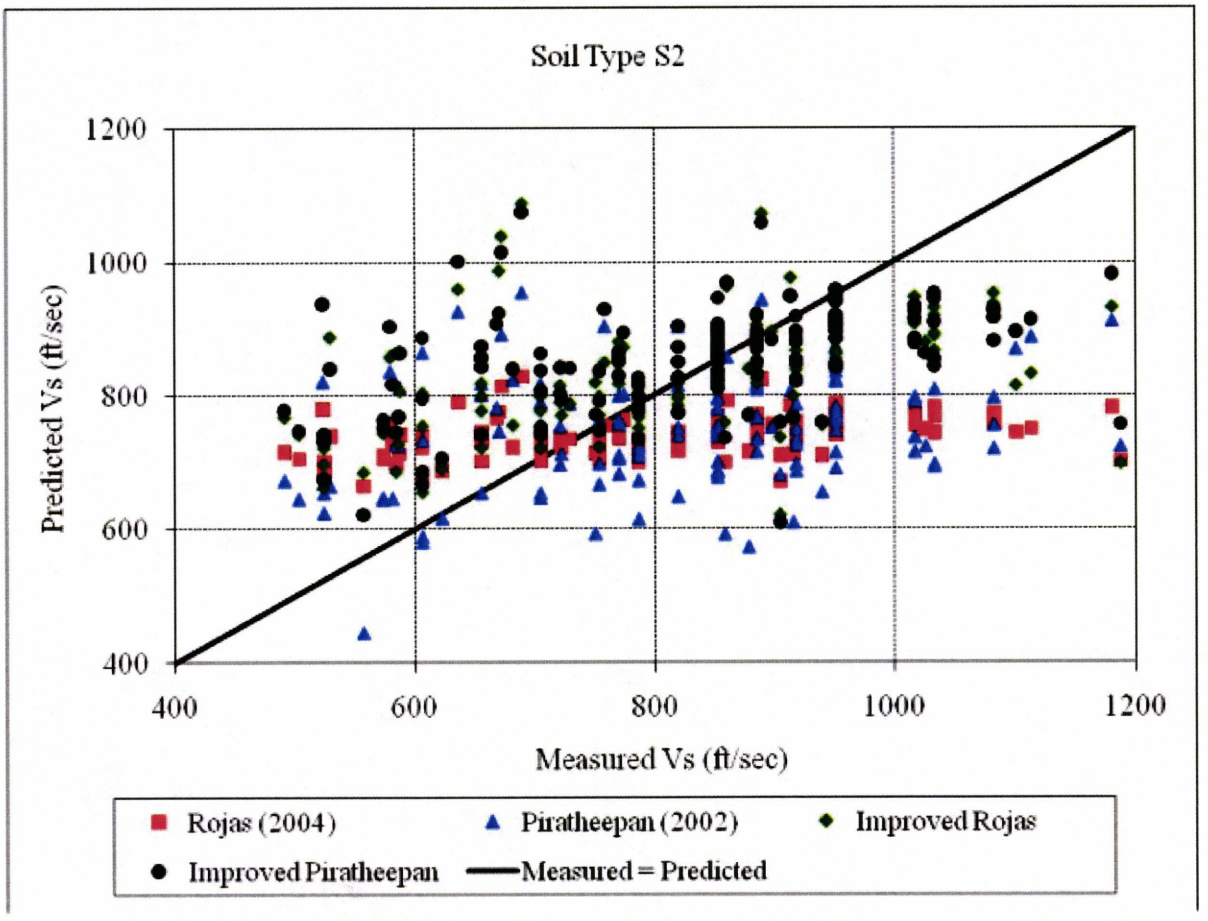


Figure B.20 Soil Type S2 Model Comparison

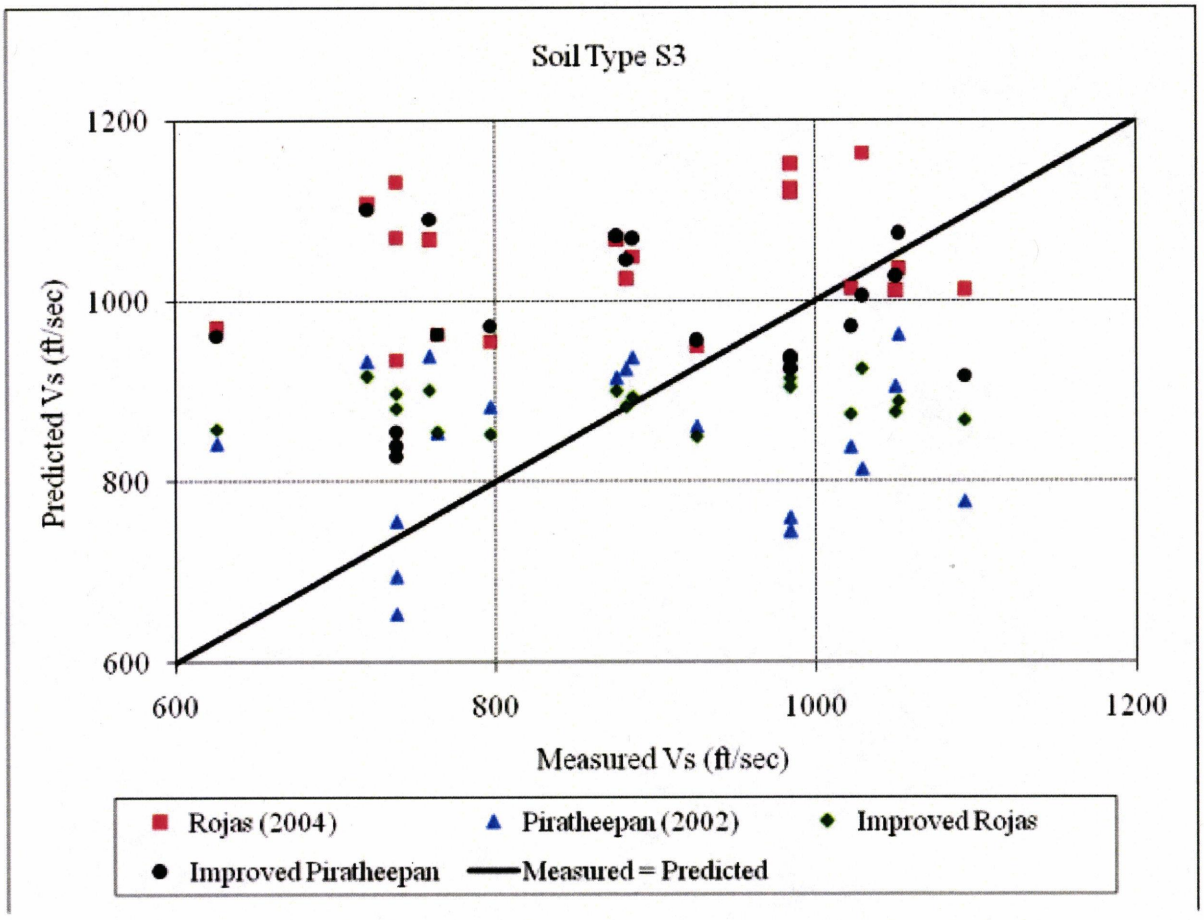


Figure B.21 Soil Type S3 Model Comparison

APPENDIX C
Satellite Images of test sites

Figure C.1 Satellite Image of all 16 test sites.

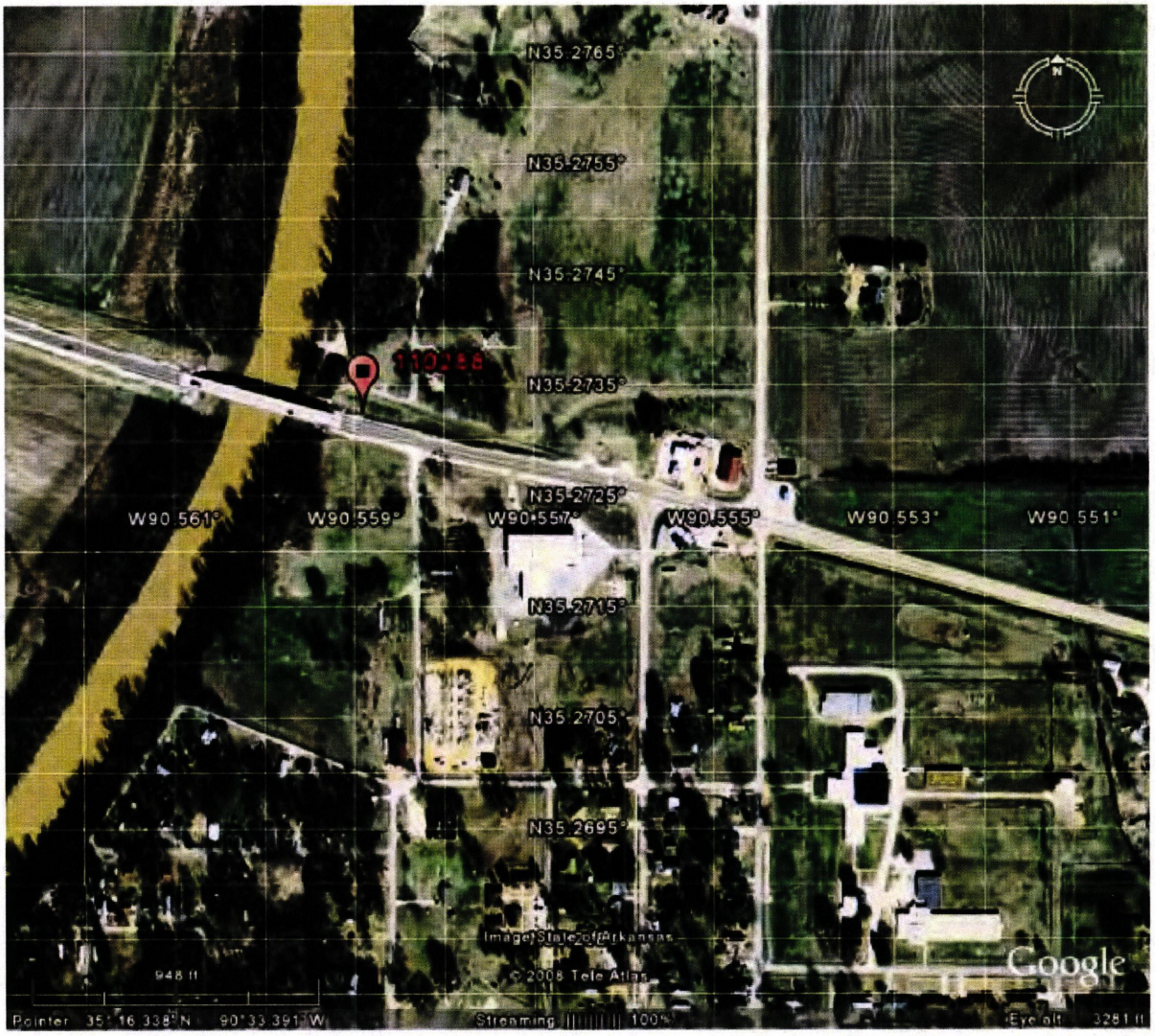


Figure C.2 Satellite view of Site # 110288

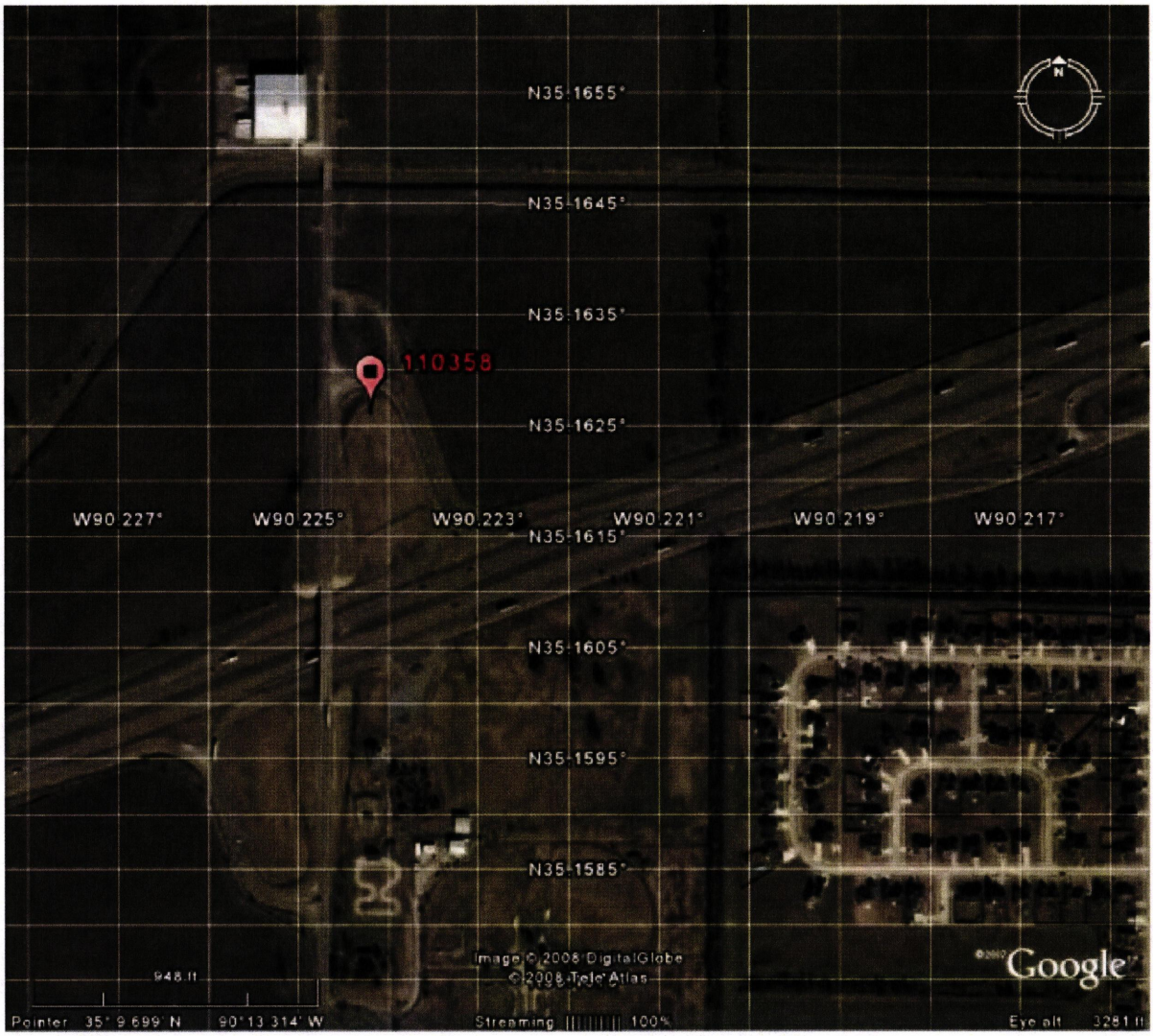


Figure C.3 Satellite view of Site # 110358

Figure C.4 Satellite view of Site # 110401

Figure C.5 Satellite view of Site # 100547

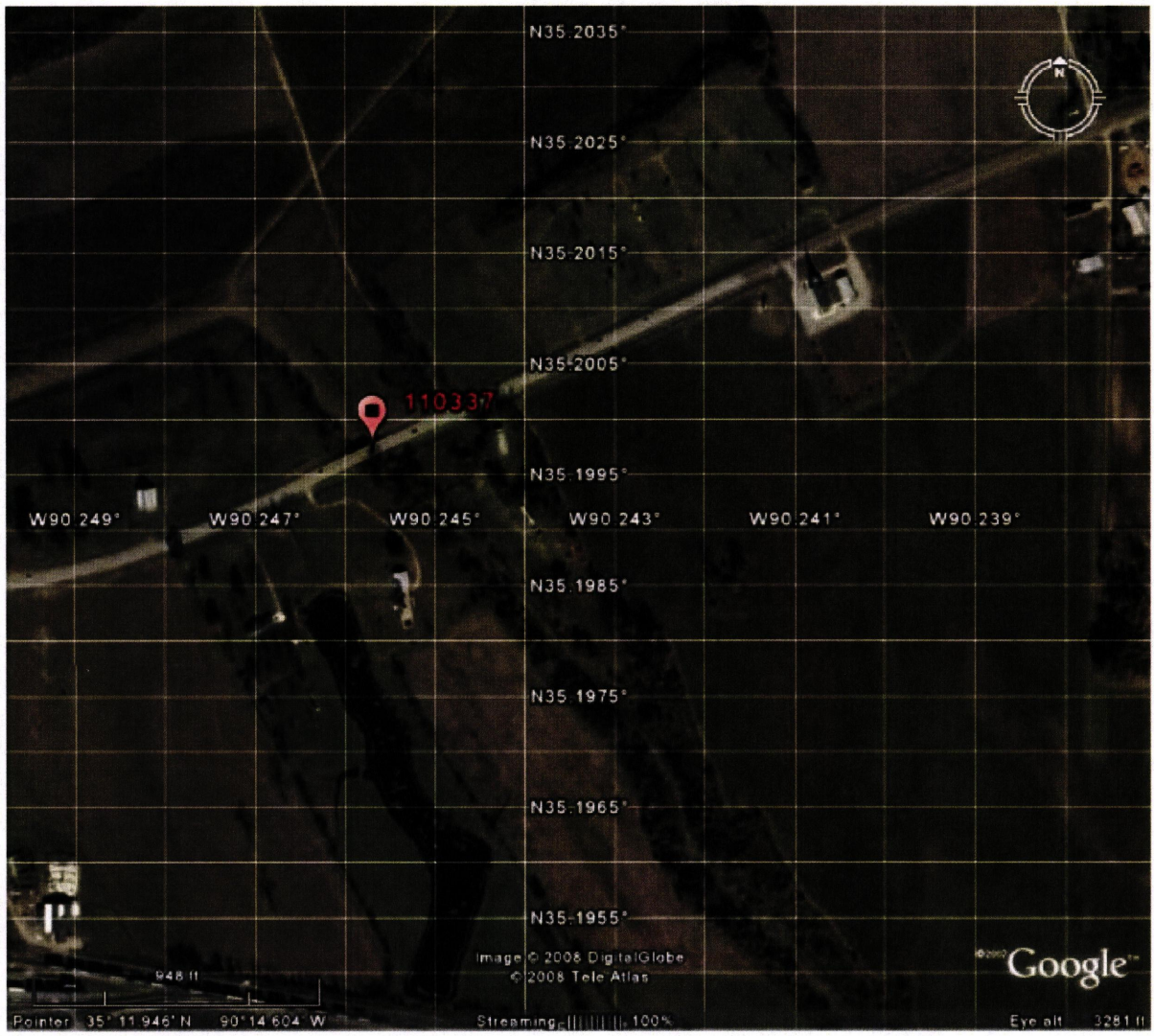


Figure C.6 Satellite view of Site # 110337

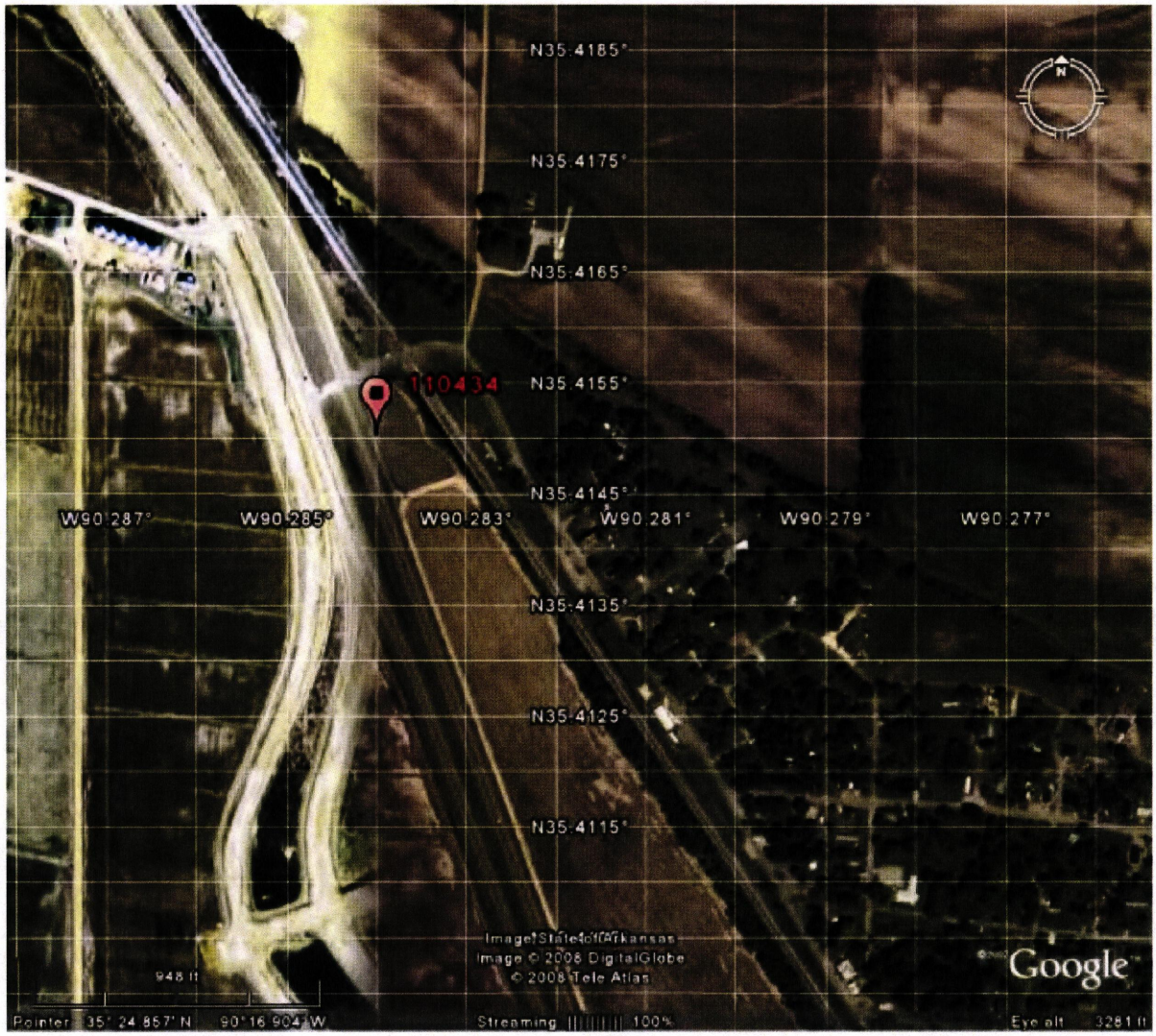


Figure C.7 Satellite view of Site # 110434

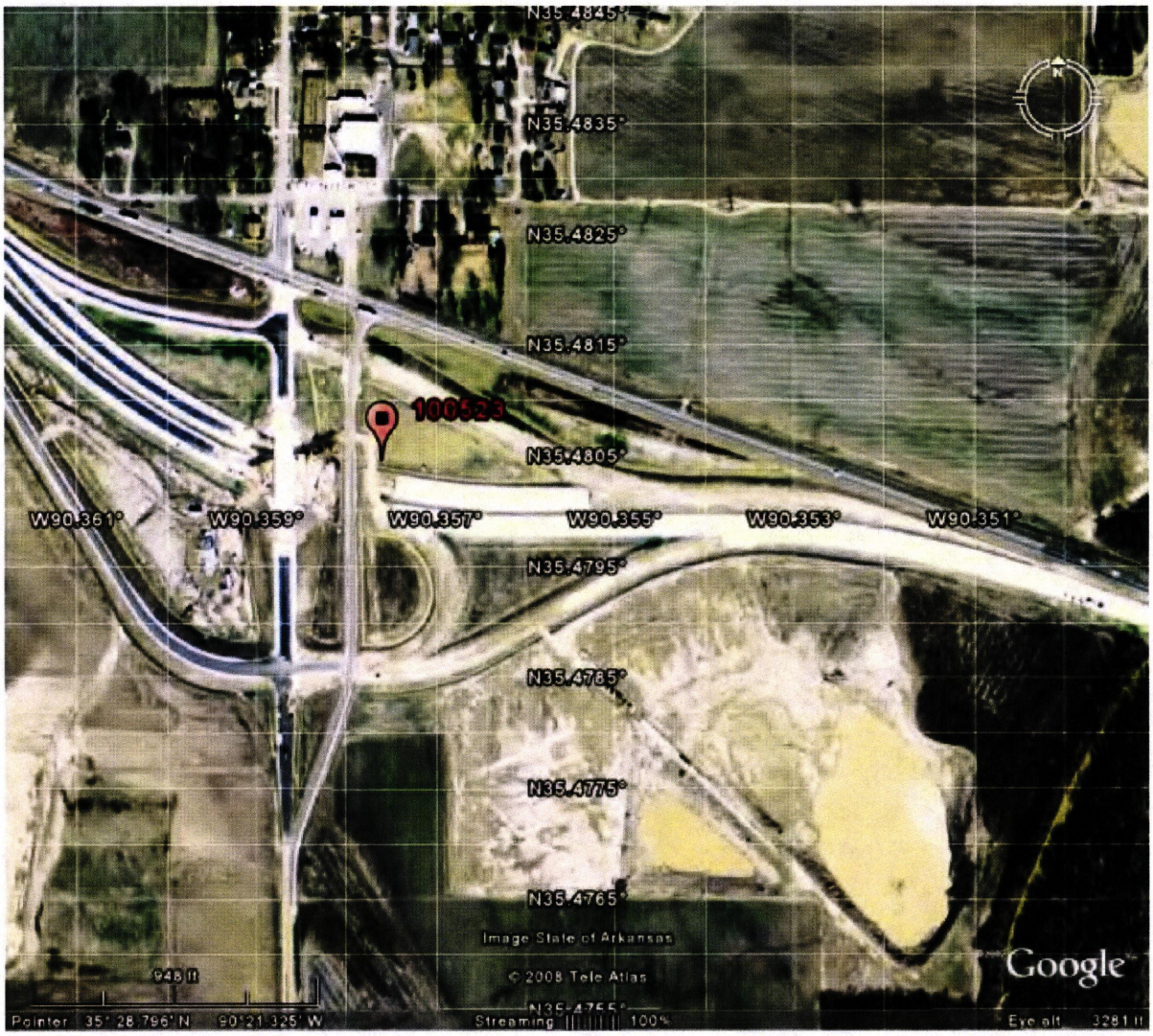


Figure C.8 Satellite view of Site # 100523

Figure C.9 Satellite view of Site # 100522

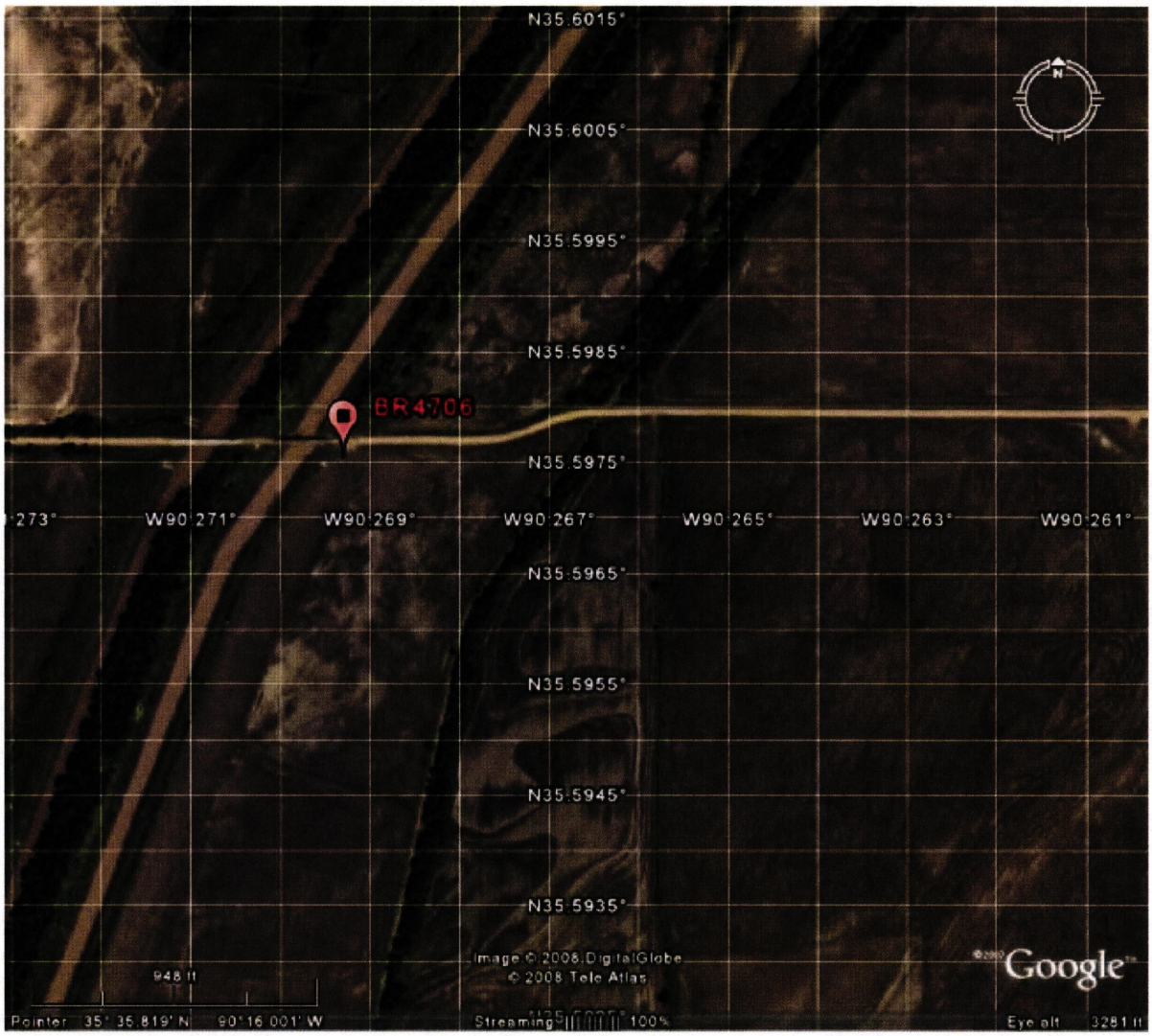


Figure C.10 Satellite view of Site # BR4706

Figure C.11 Satellite view of Site # 100105

Figure C.12 Satellite view of Site # R00059

Figure C.13 Satellite view of Site # 100303

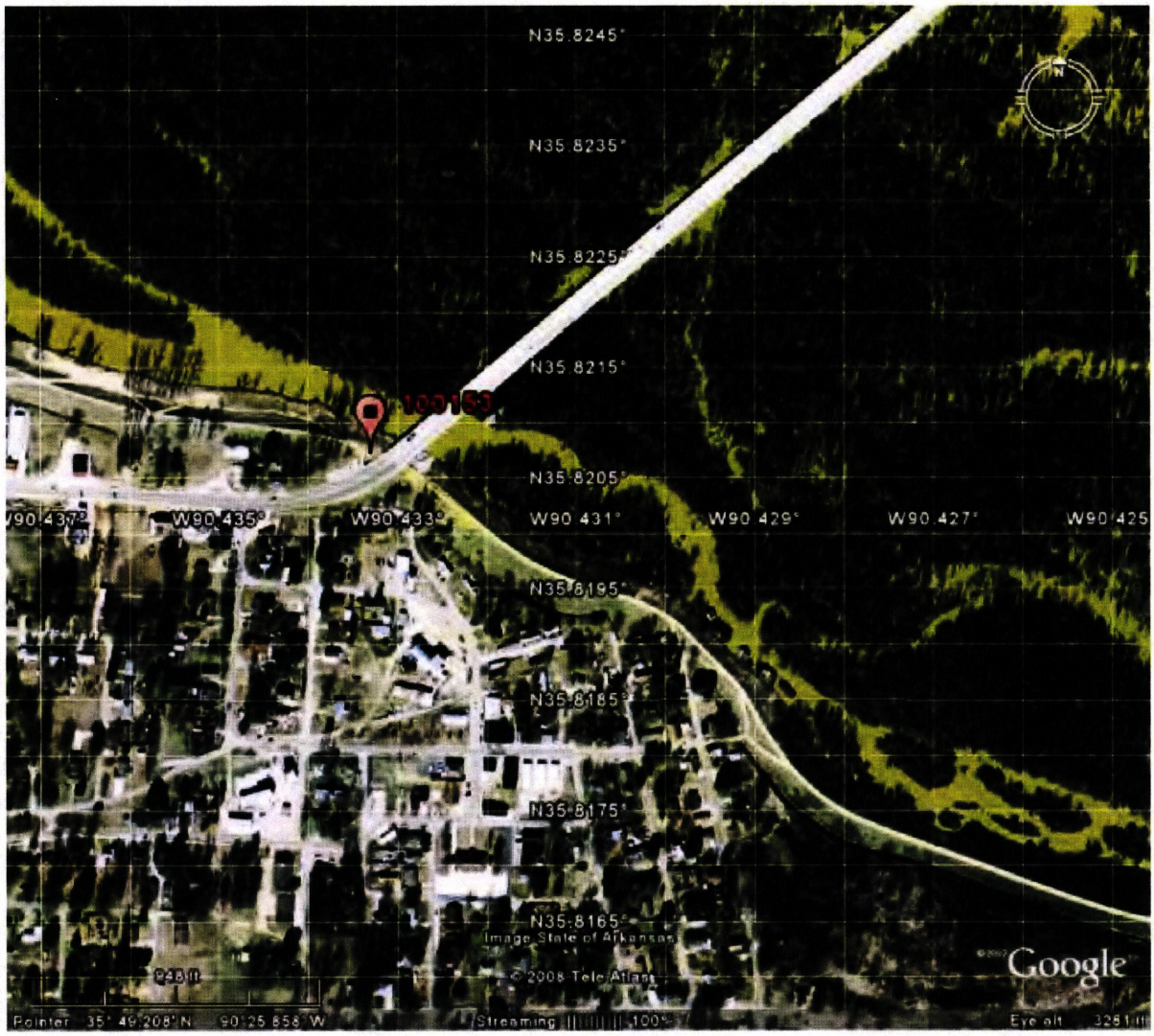


Figure C.14 Satellite view of Site # 100153

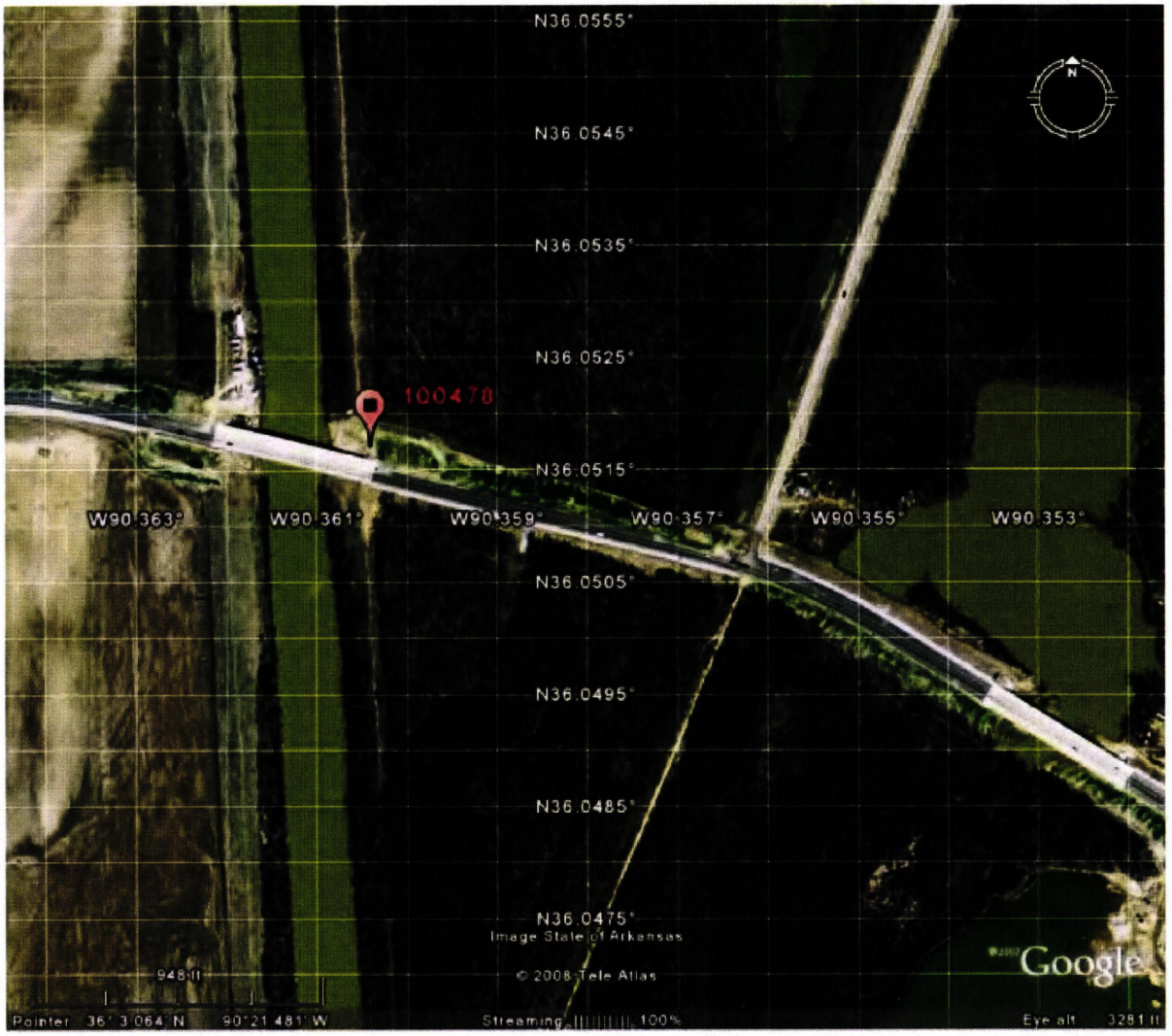


Figure C.15 Satellite view of Site # 100478

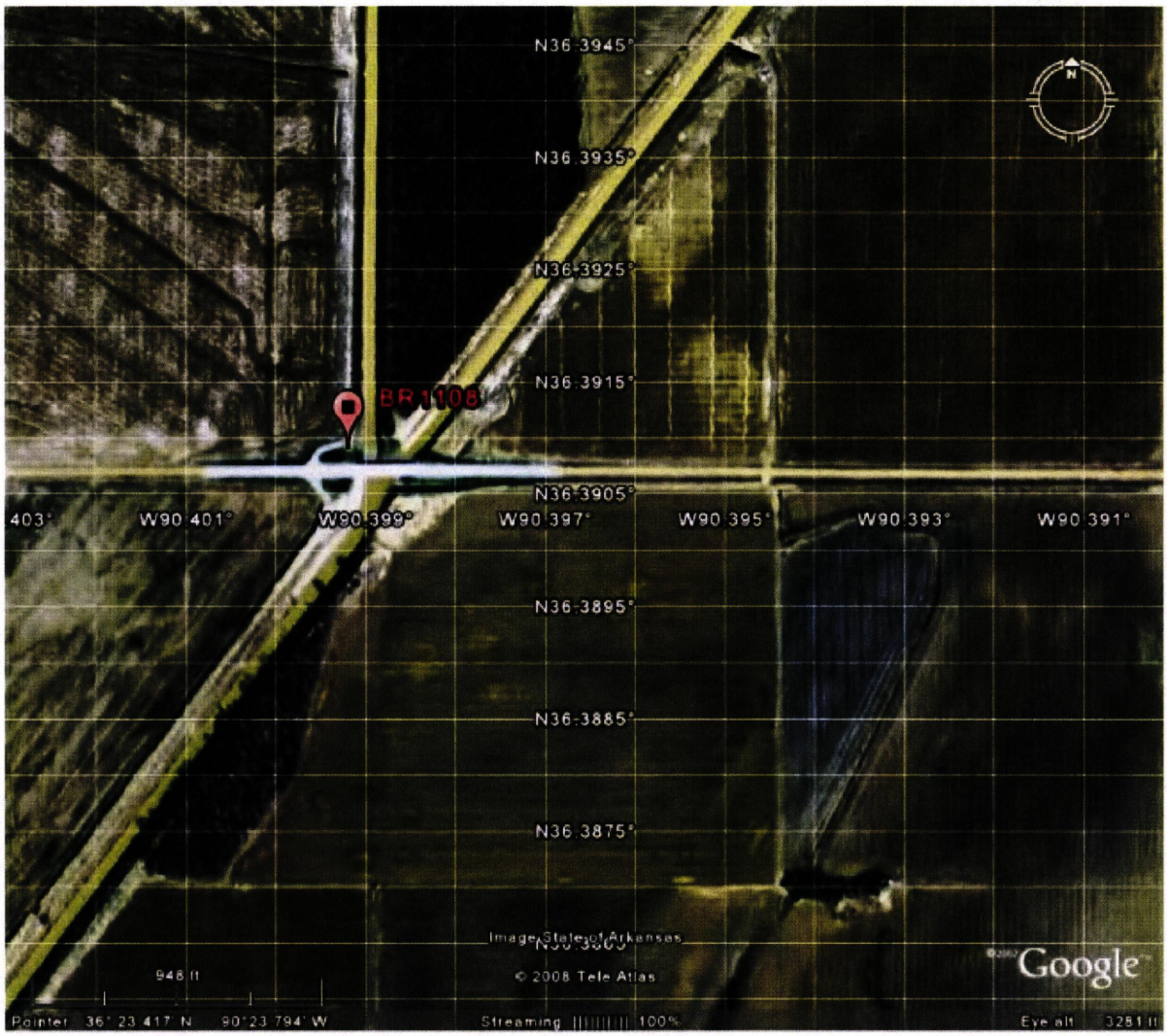


Figure C.16 Satellite view of Site # BR1108

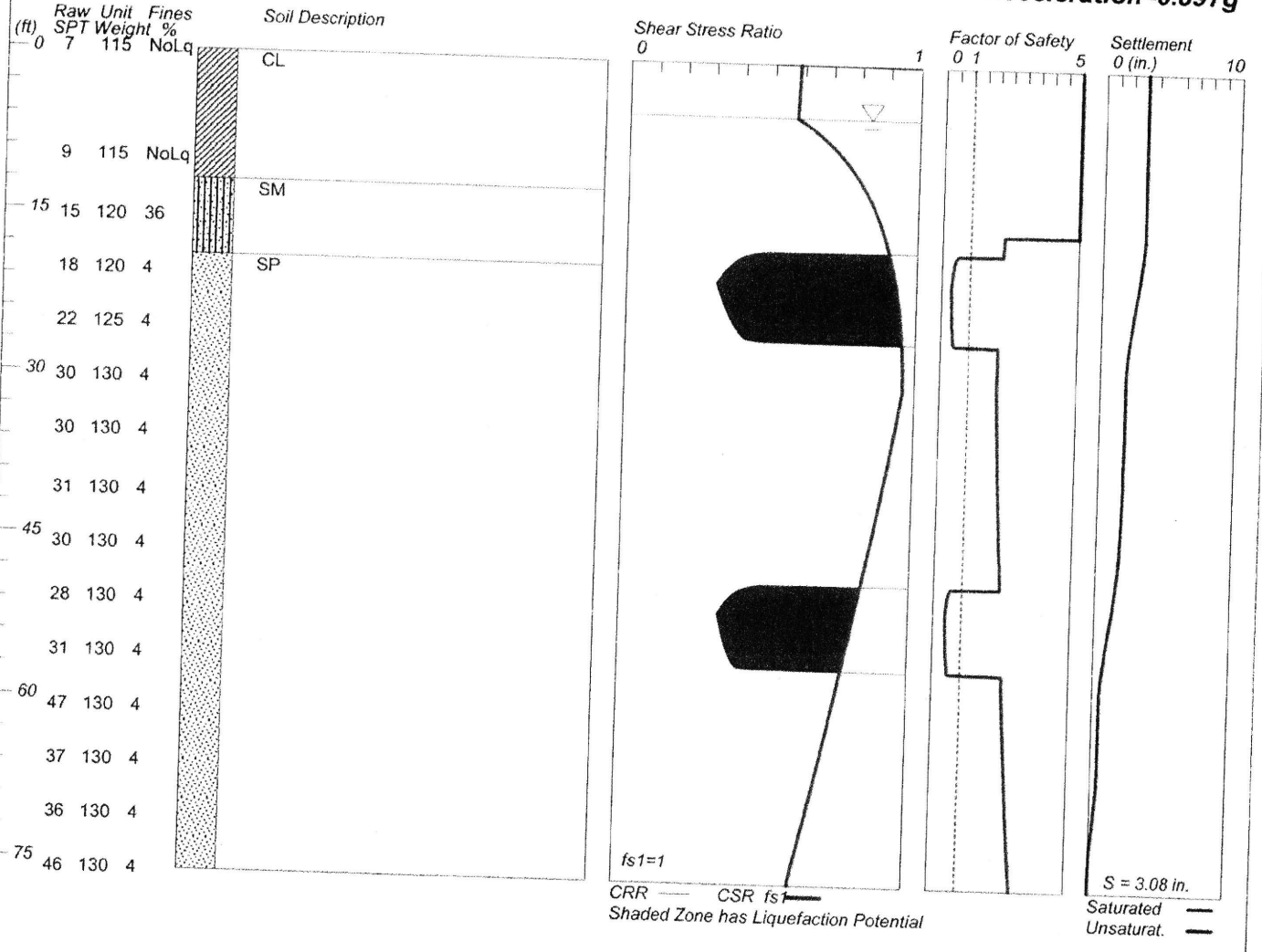
Figure C.17 Satellite view of Site # BR1110

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=1 Water Depth=5 ft Surface Elev.=226.1

Magnitude=7.5
Acceleration=0.897g



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BN-1, Craighead County

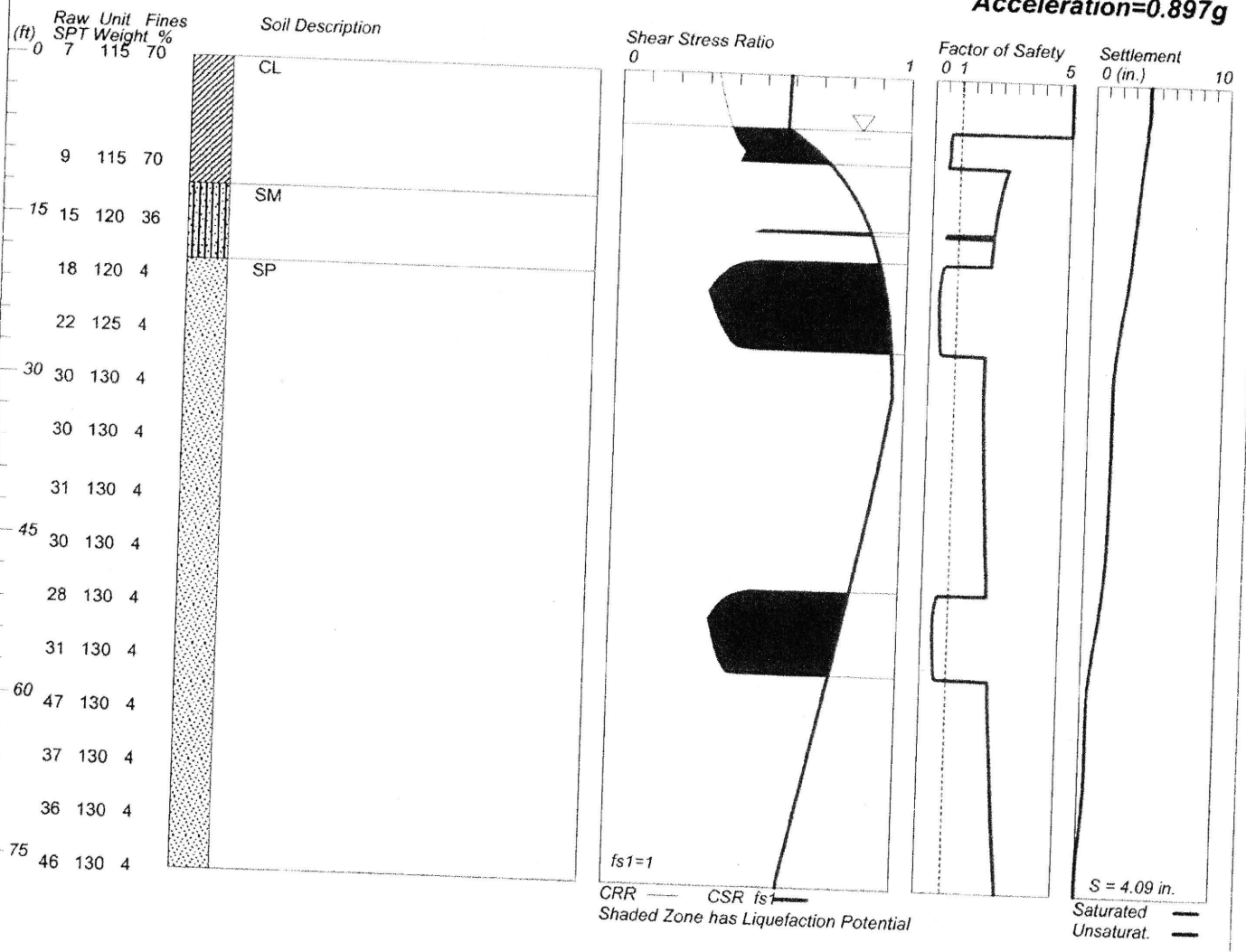
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=1 Water Depth=5 ft Surface Elev.=226.1

Magnitude=7.5
Acceleration=0.897g



BN-1, Craighead County

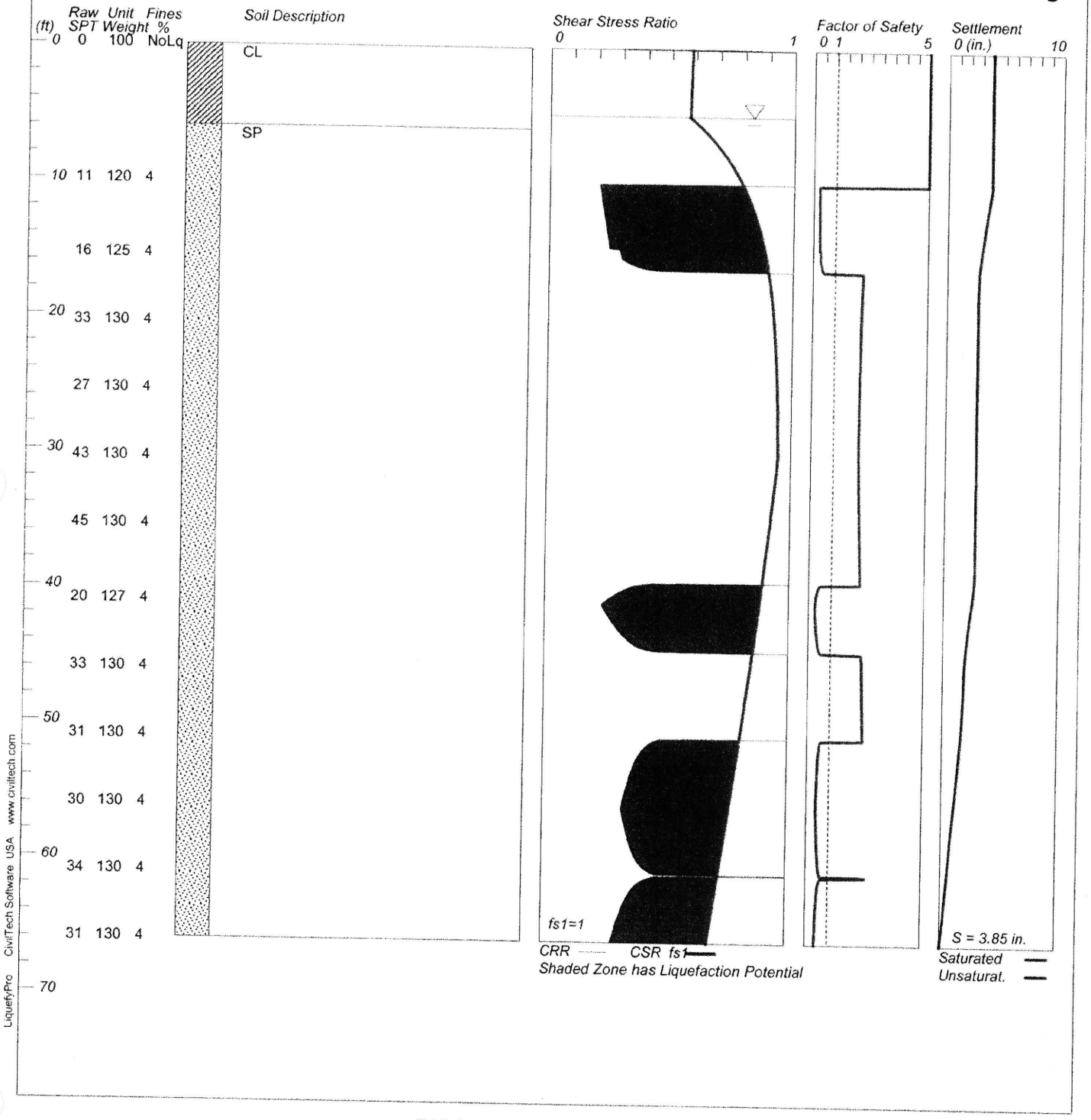
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=2 Water Depth=5 ft Surface Elev.=225.4

Magnitude=7.5
Acceleration=0.897g



BN-2, Craighead County

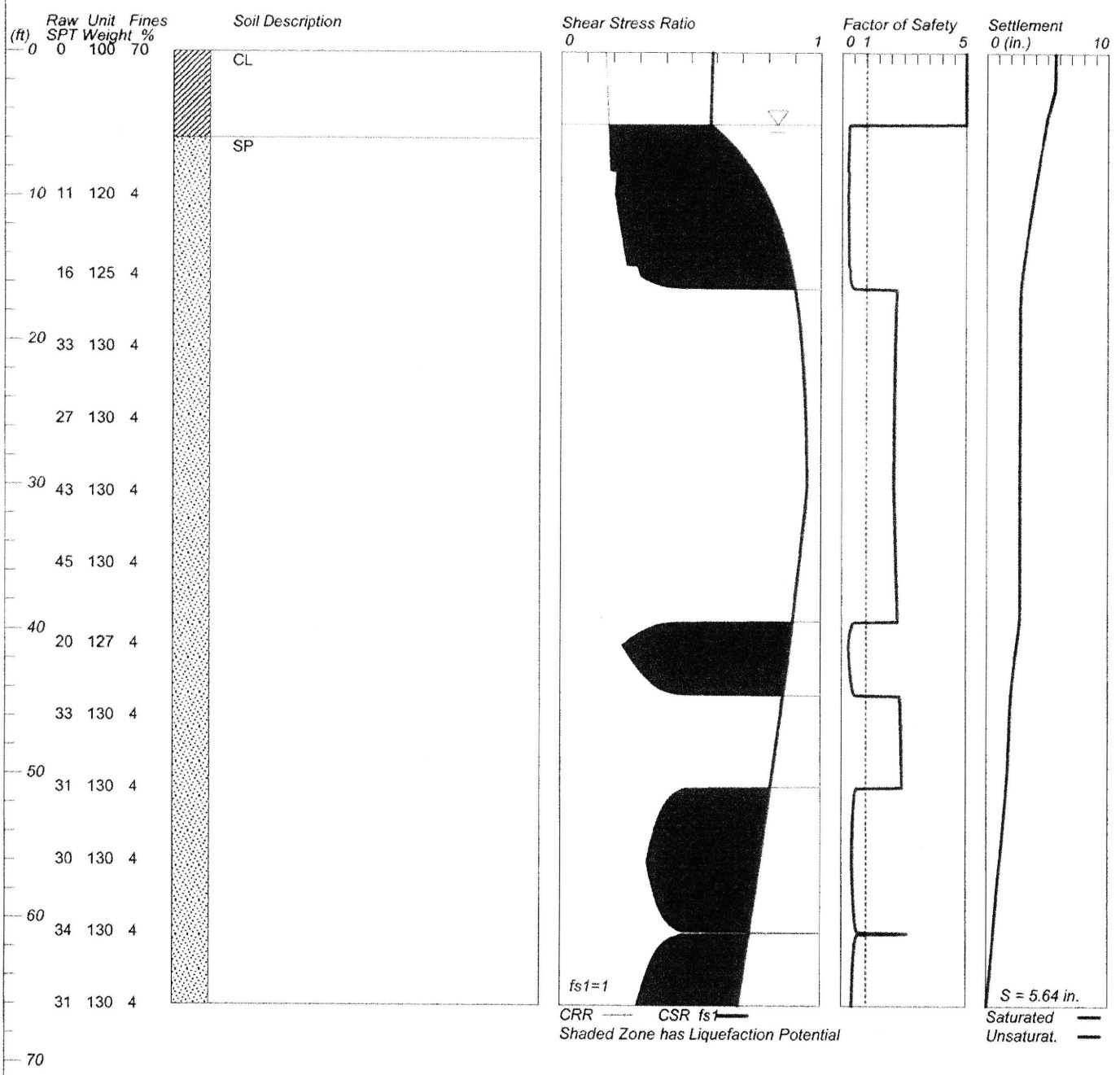
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=2 Water Depth=5 ft Surface Elev.=225.4

Magnitude=7.5
Acceleration=0.897g



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BN-2, Craighead County

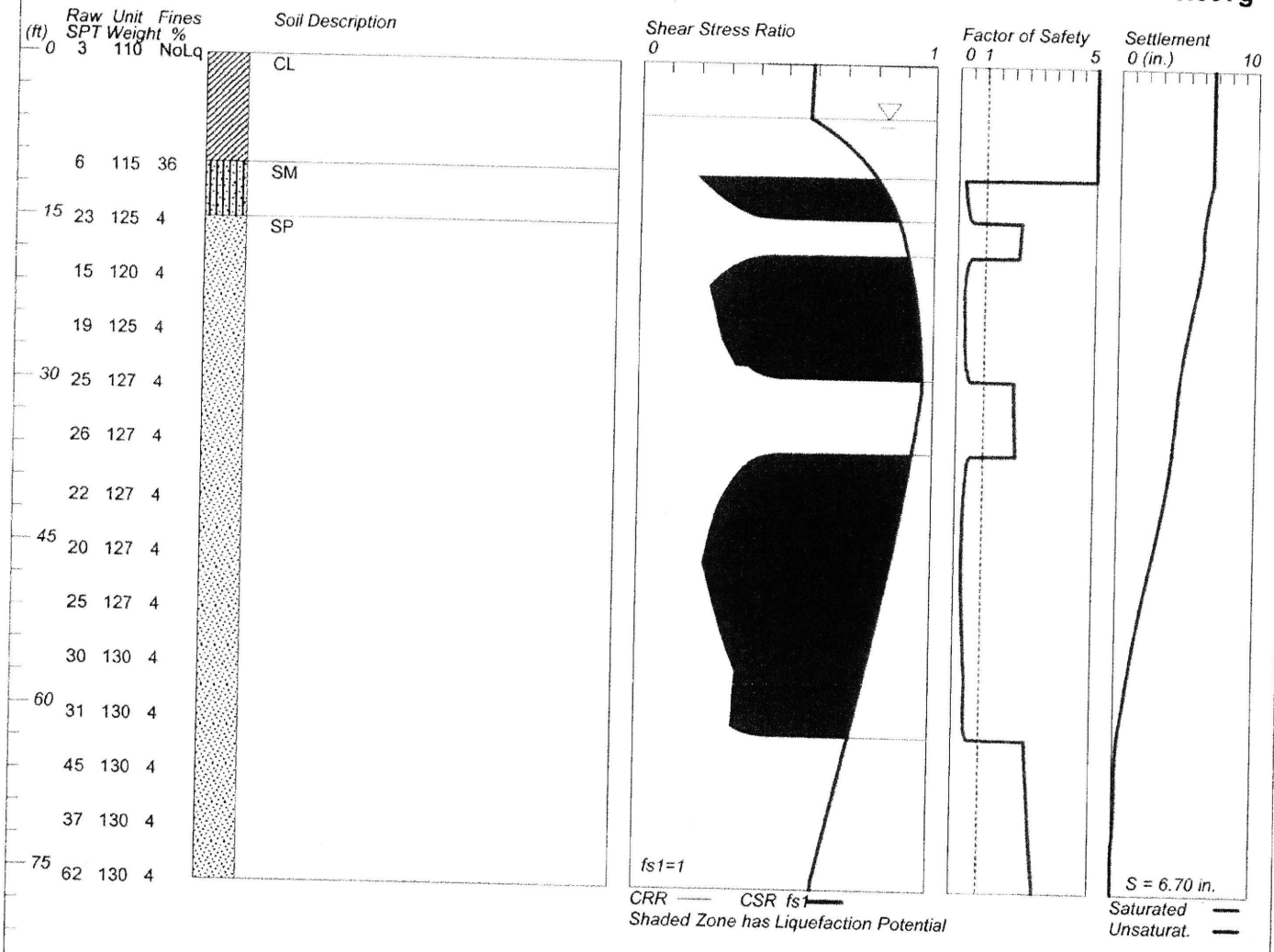
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=3 Water Depth=5 ft Surface Elev.=223.2

Magnitude=7.5
Acceleration=0.897g



BN-3, Craighead County

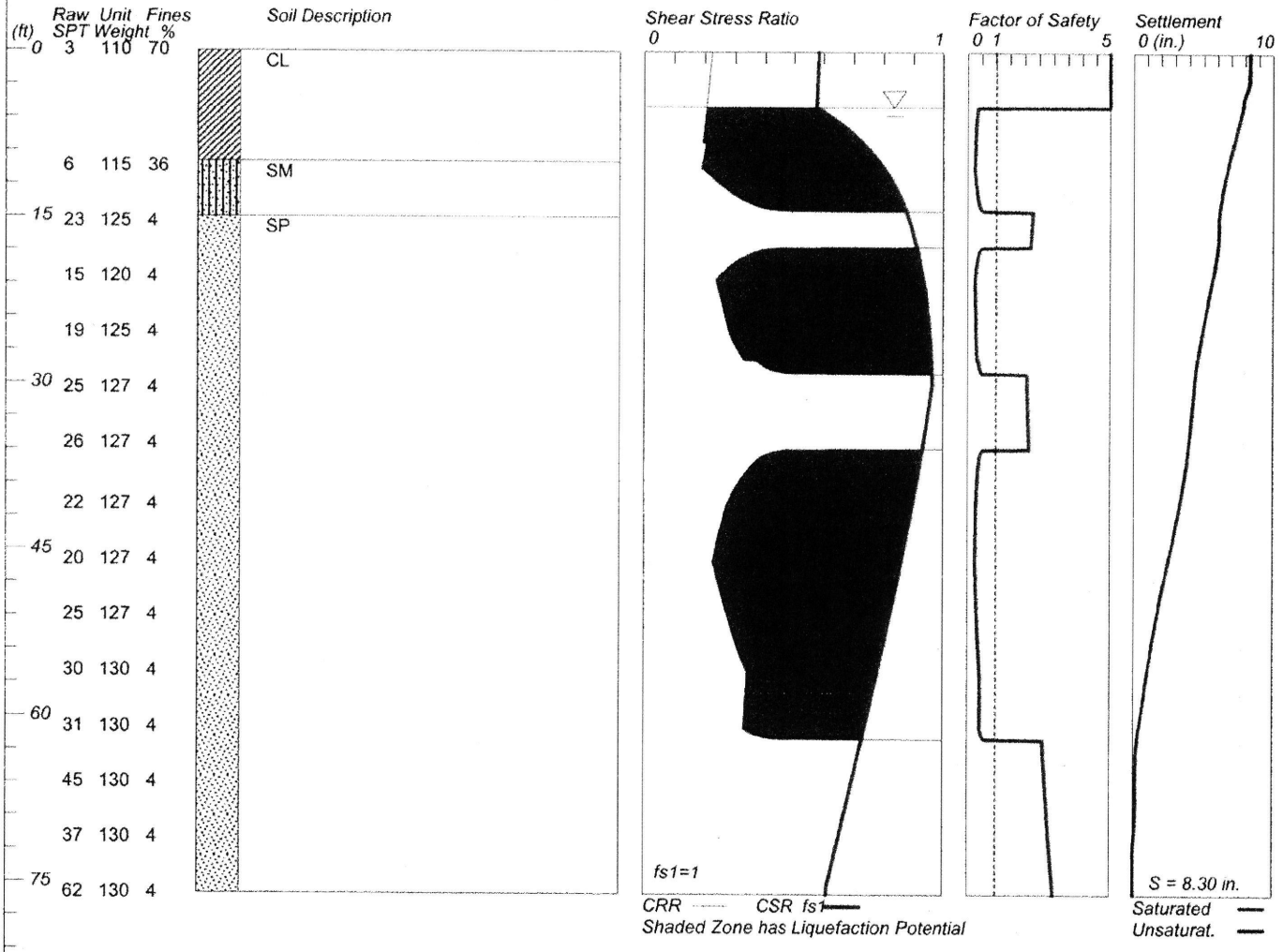
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=3 Water Depth=5 ft Surface Elev.=223.2

Magnitude=7.5
Acceleration=0.897g



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BN-3, Craighead County

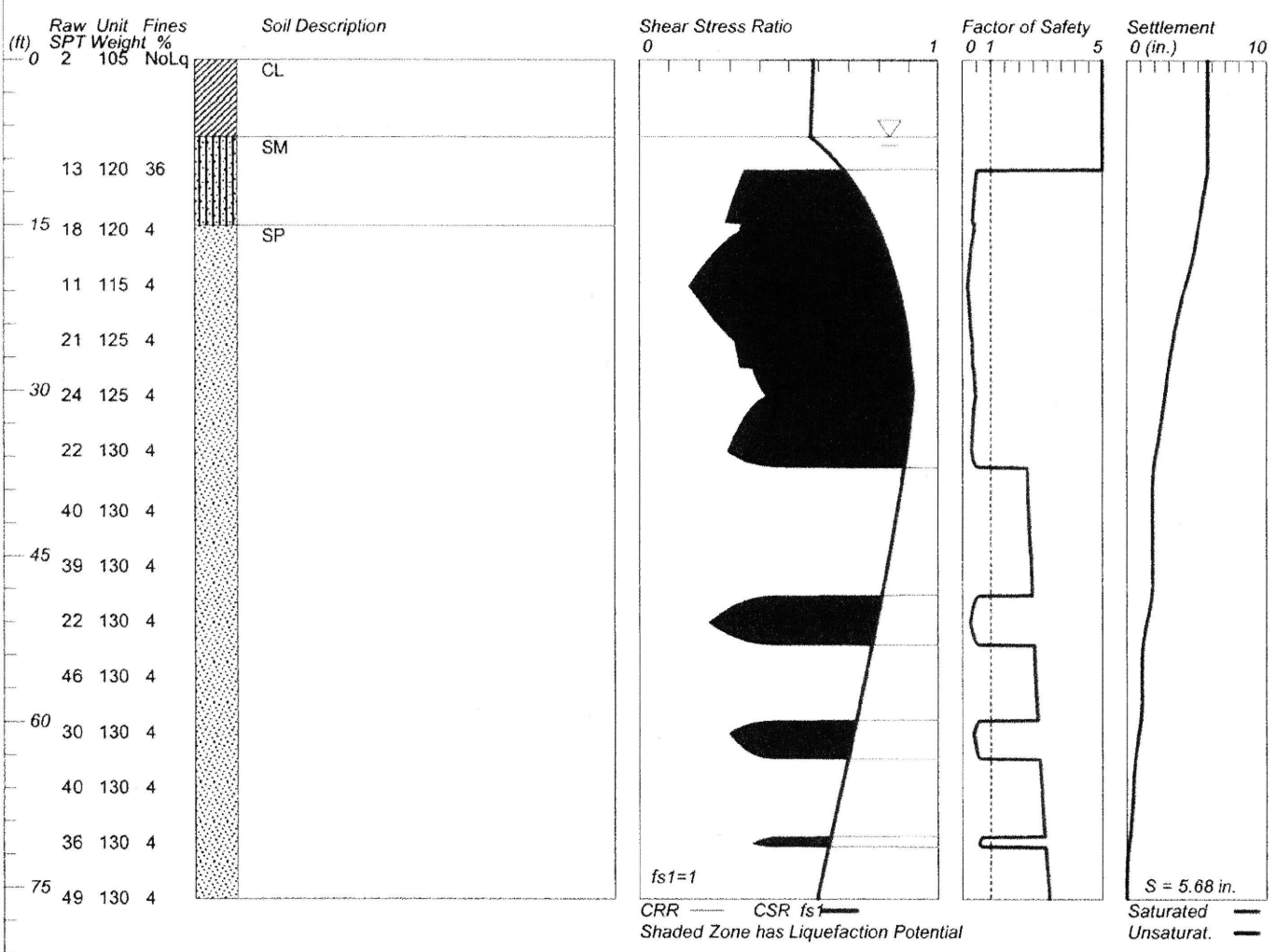
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=4 Water Depth=7 ft Surface Elev.=223.6

Magnitude=7.5
Acceleration=0.897g



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BN-4, Craighead County

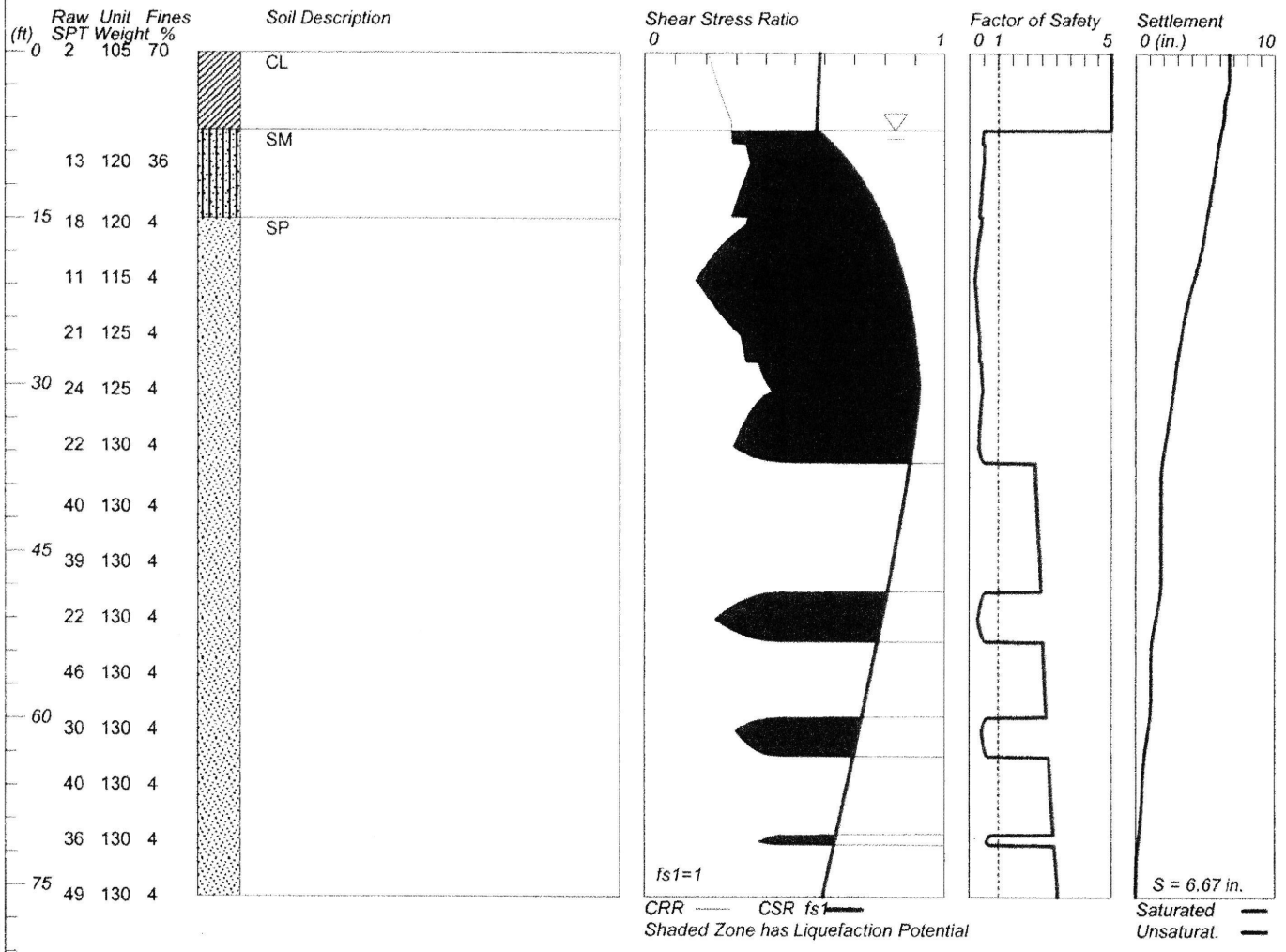
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=4 Water Depth=7 ft Surface Elev.=223.6

Magnitude=7.5
Acceleration=0.897g



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BN-4, Craighead County

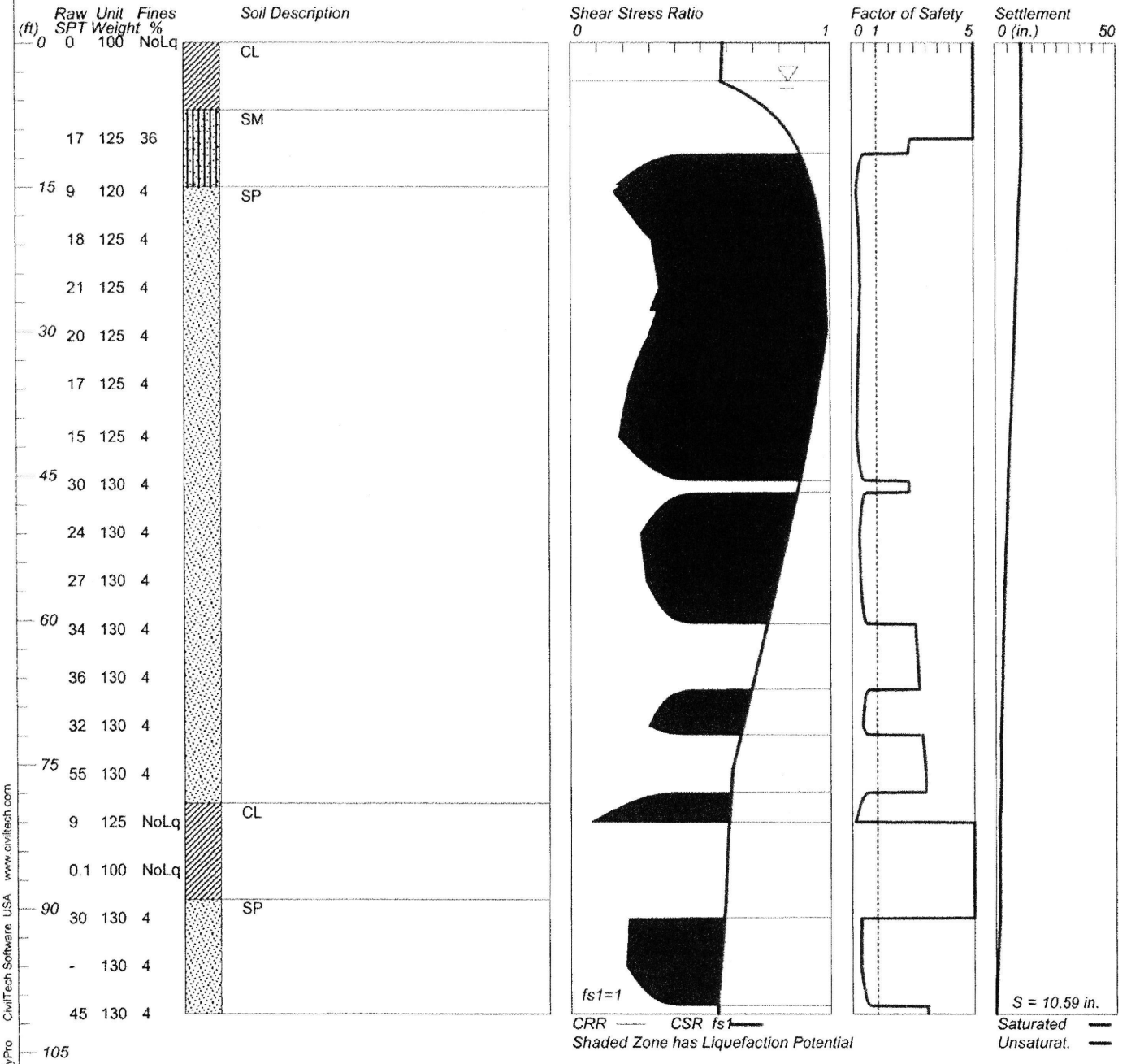
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=5 Water Depth=4 ft Surface Elev.=222.4

Magnitude=7.5
Acceleration=0.897g



BN-5, Craighead County

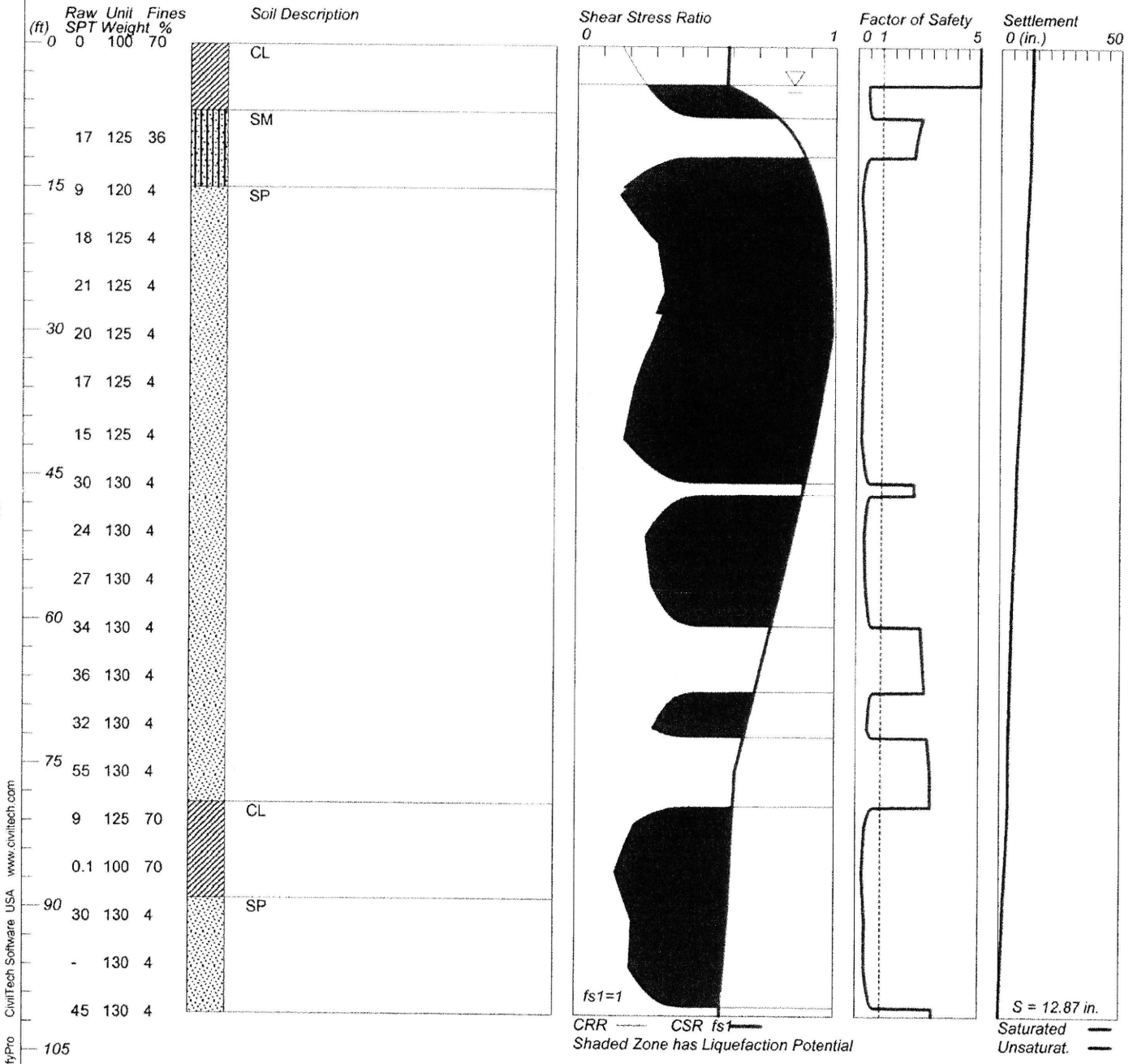
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=5 Water Depth=4 ft Surface Elev.=222.4

Magnitude=7.5
Acceleration=0.897g



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BN-5, Craighead County

Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=6 Water Depth=5 ft Surface Elev.=221.0

Magnitude=7.5
Acceleration=0.897g

BN-6, Craighead County

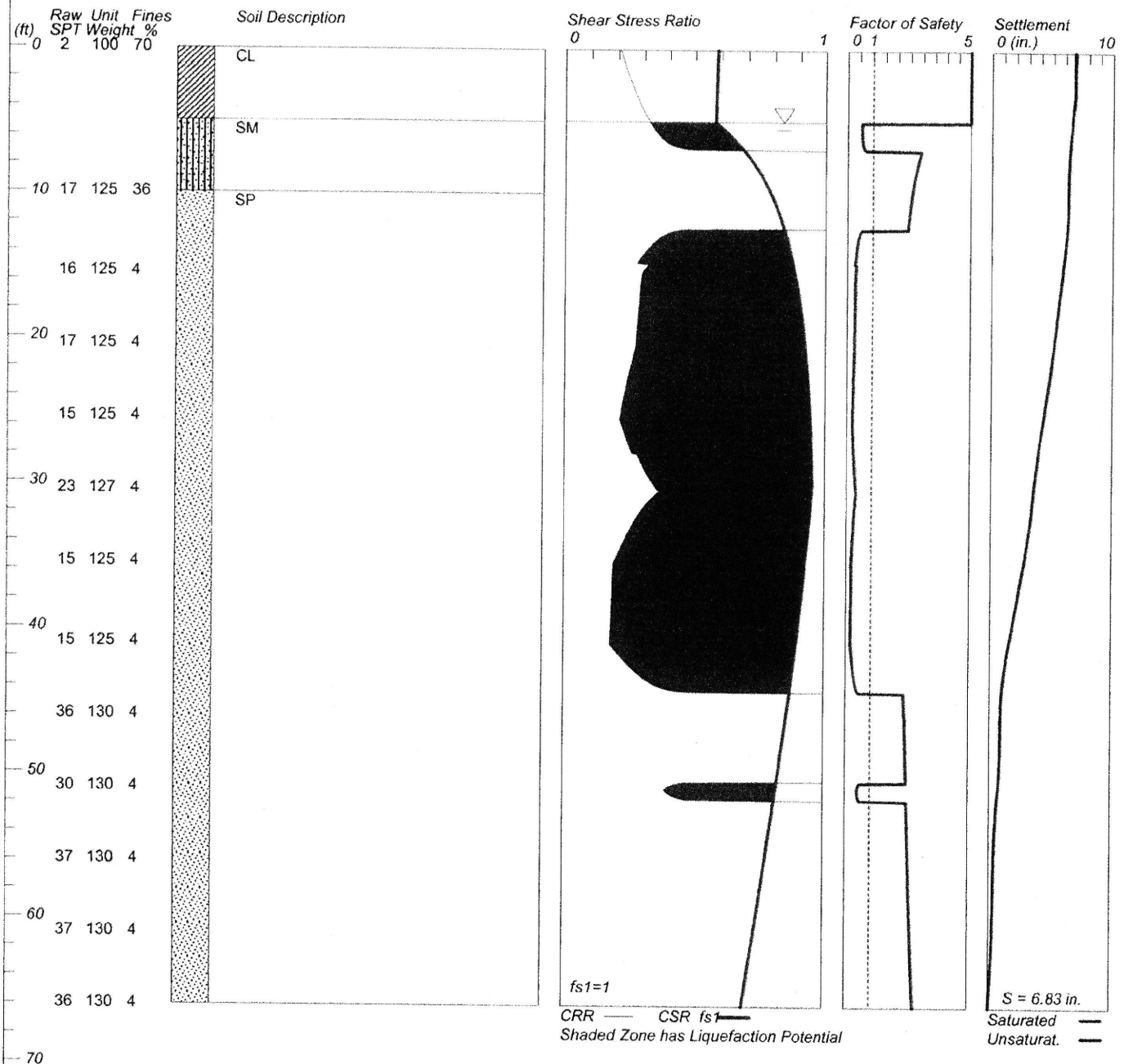
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=6 Water Depth=5 ft Surface Elev.=221.0

Magnitude=7.5
Acceleration=0.897g



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BN-6, Craighead County

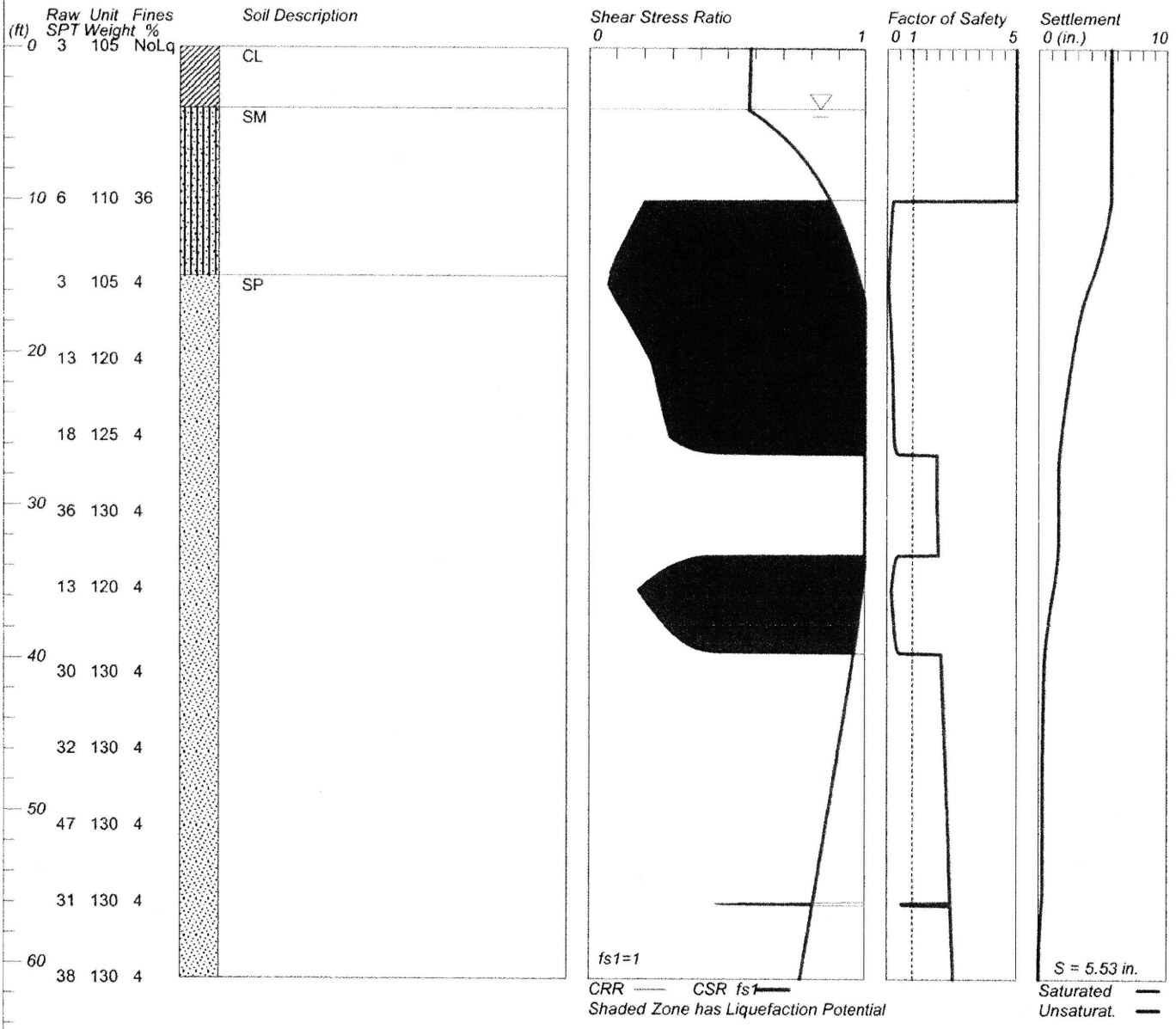
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=7 Water Depth=4 ft Surface Elev.=221.1

Magnitude=7.5
Acceleration=0.897g



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BN-7, Craighead County

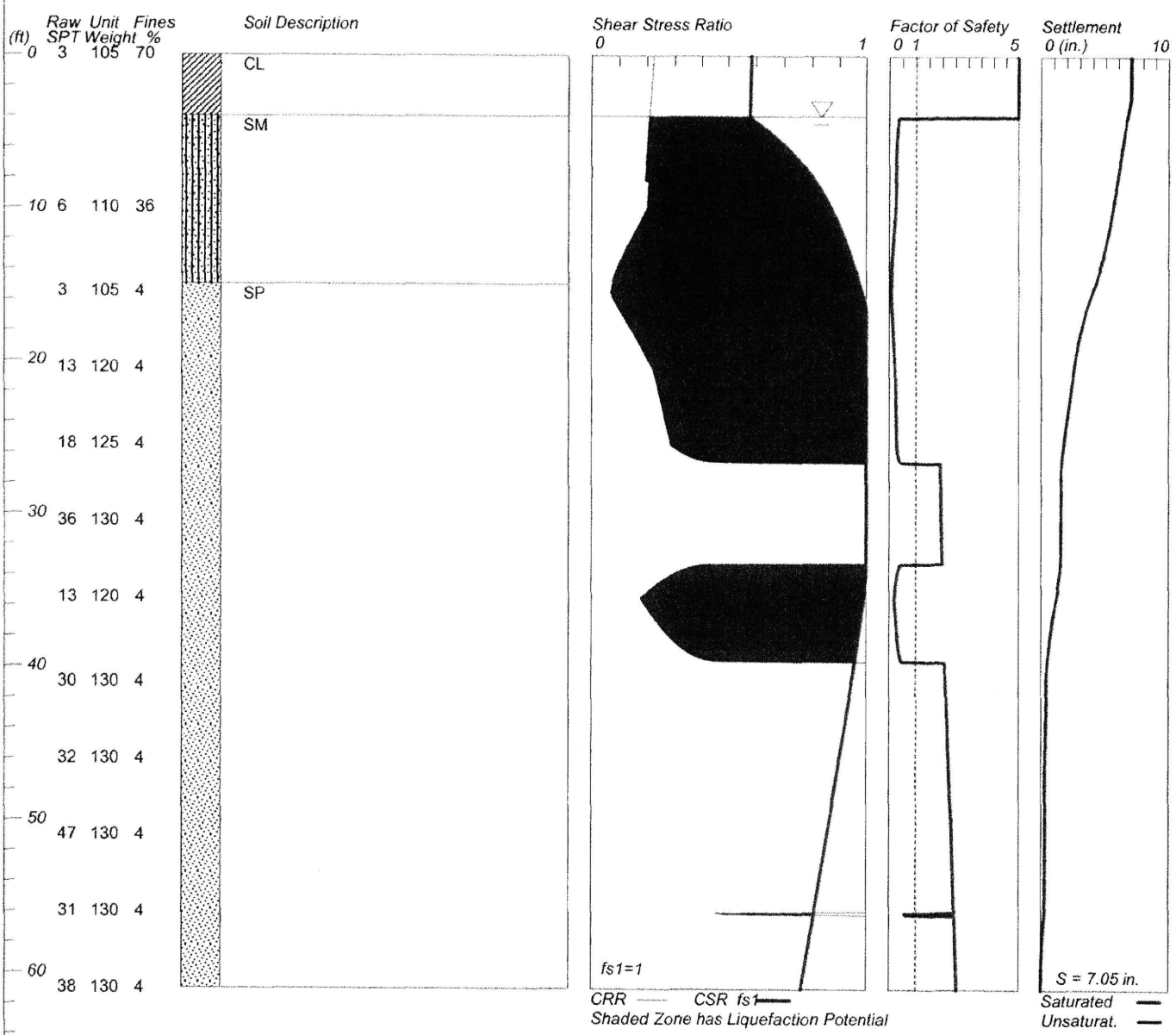
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=7 Water Depth=4 ft Surface Elev.=221.1

Magnitude=7.5
Acceleration=0.897g



BN-7, Craighead County

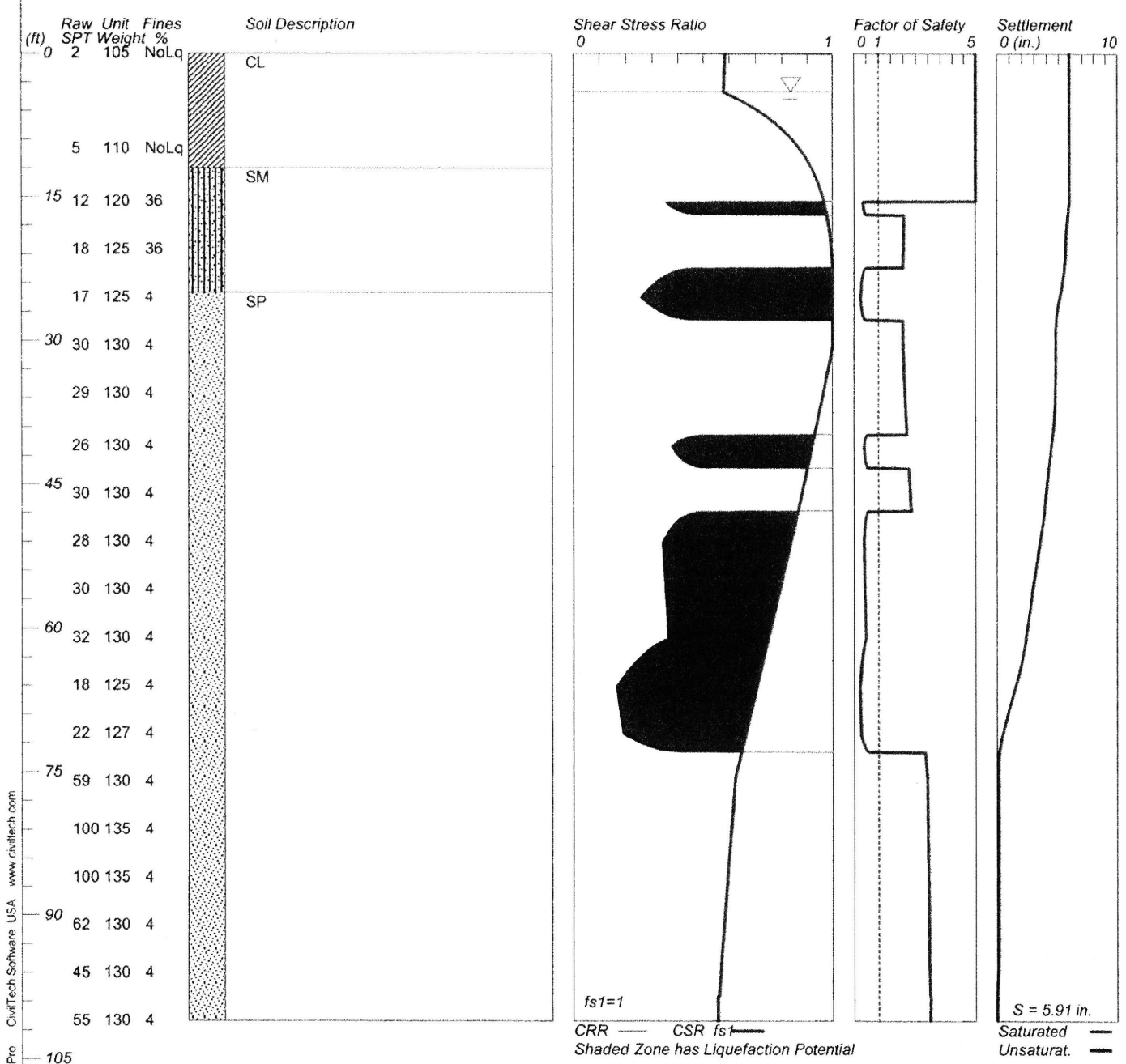
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=8 Water Depth=4 ft Surface Elev.=221.0

Magnitude=7.5
Acceleration=0.897g



BN-8, Craighead County

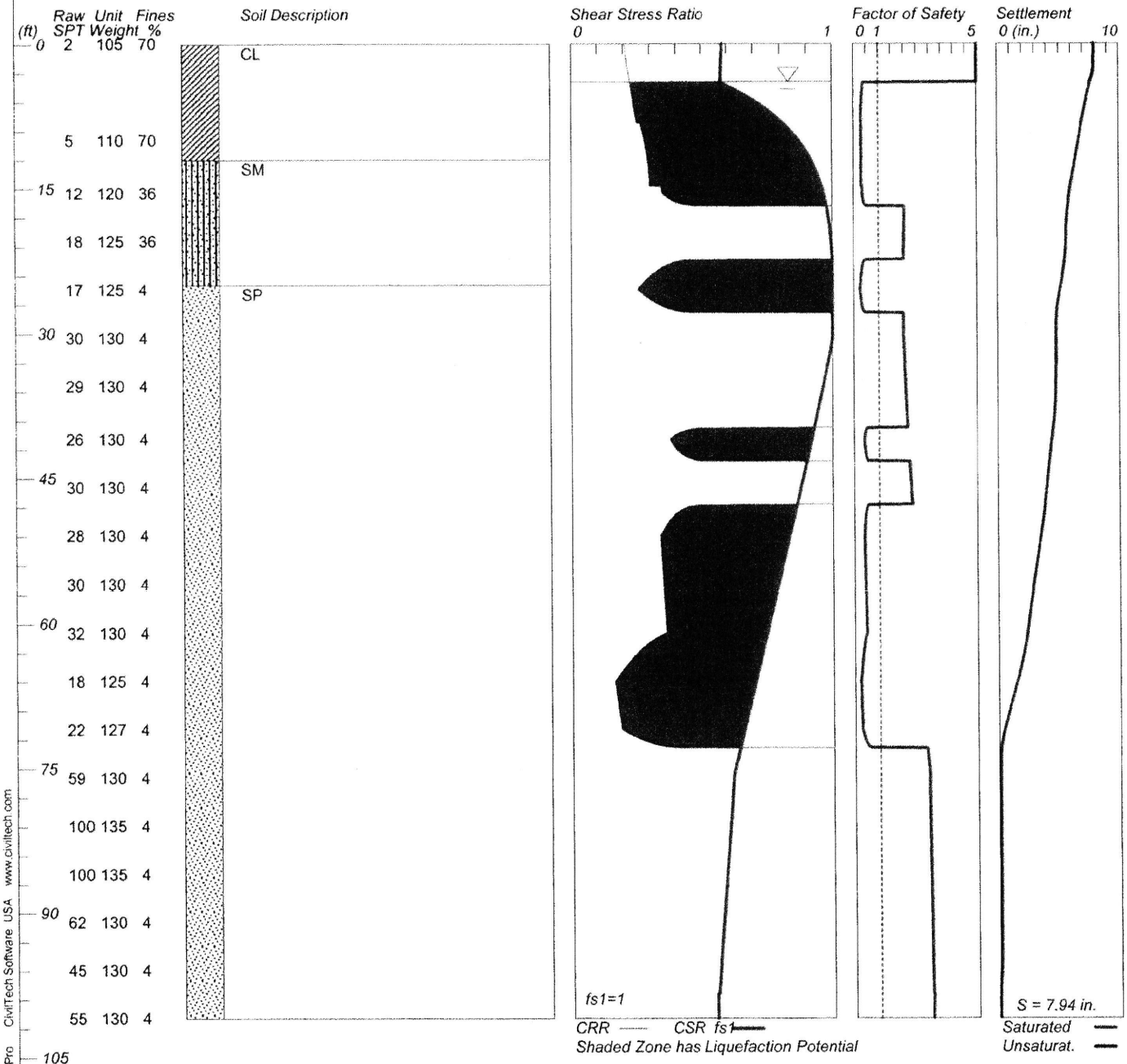
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=8 Water Depth=4 ft Surface Elev.=221.0

Magnitude=7.5
Acceleration=0.897g



BN-8, Craighead County

Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=9 Water Depth=4 ft Surface Elev.=220.8

Magnitude=7.5
Acceleration=0.897g

BN-9, Craighead County

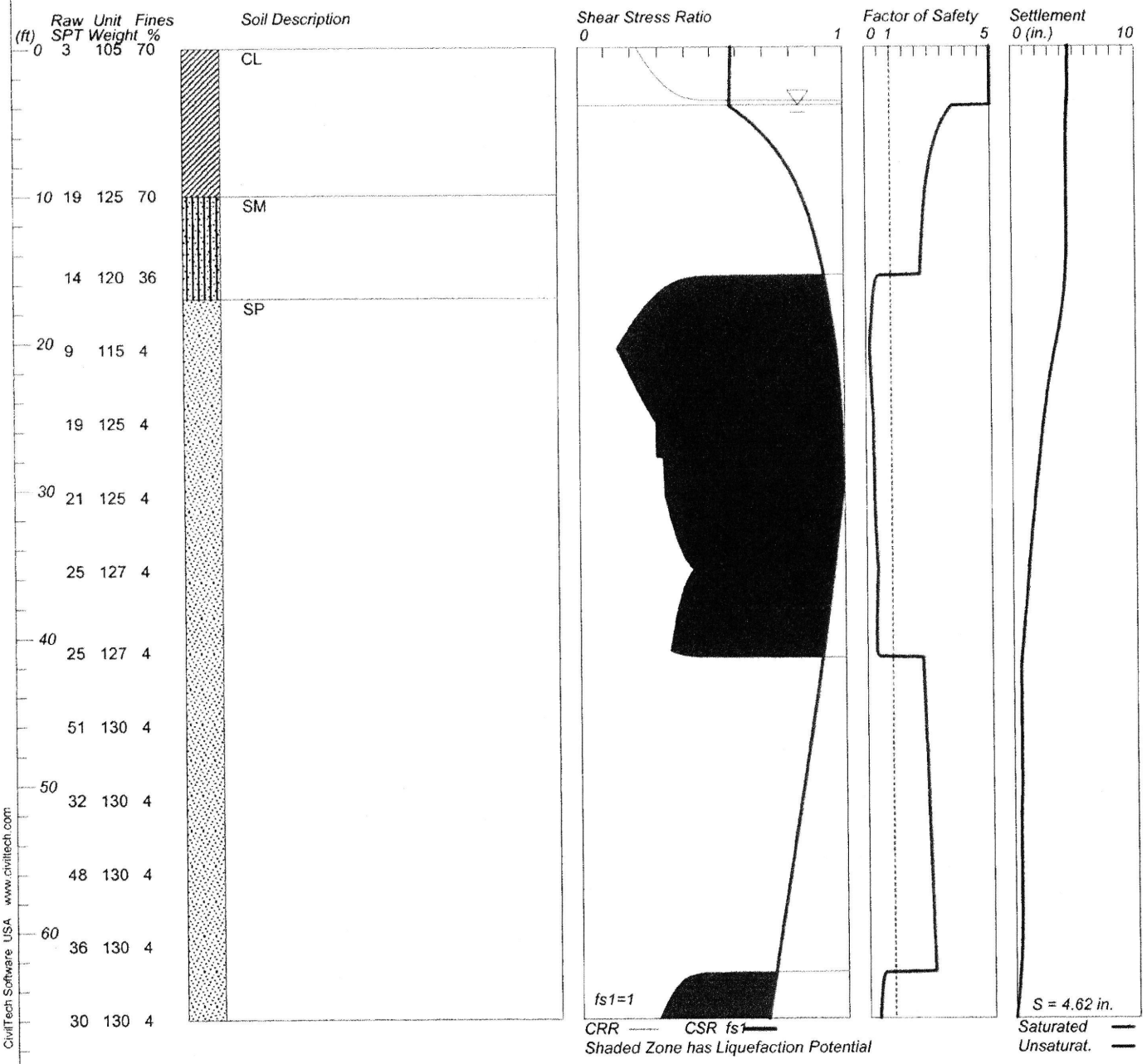
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=9 Water Depth=4 ft Surface Elev.=220.8

Magnitude=7.5
Acceleration=0.897g



BN-9, Craighead County

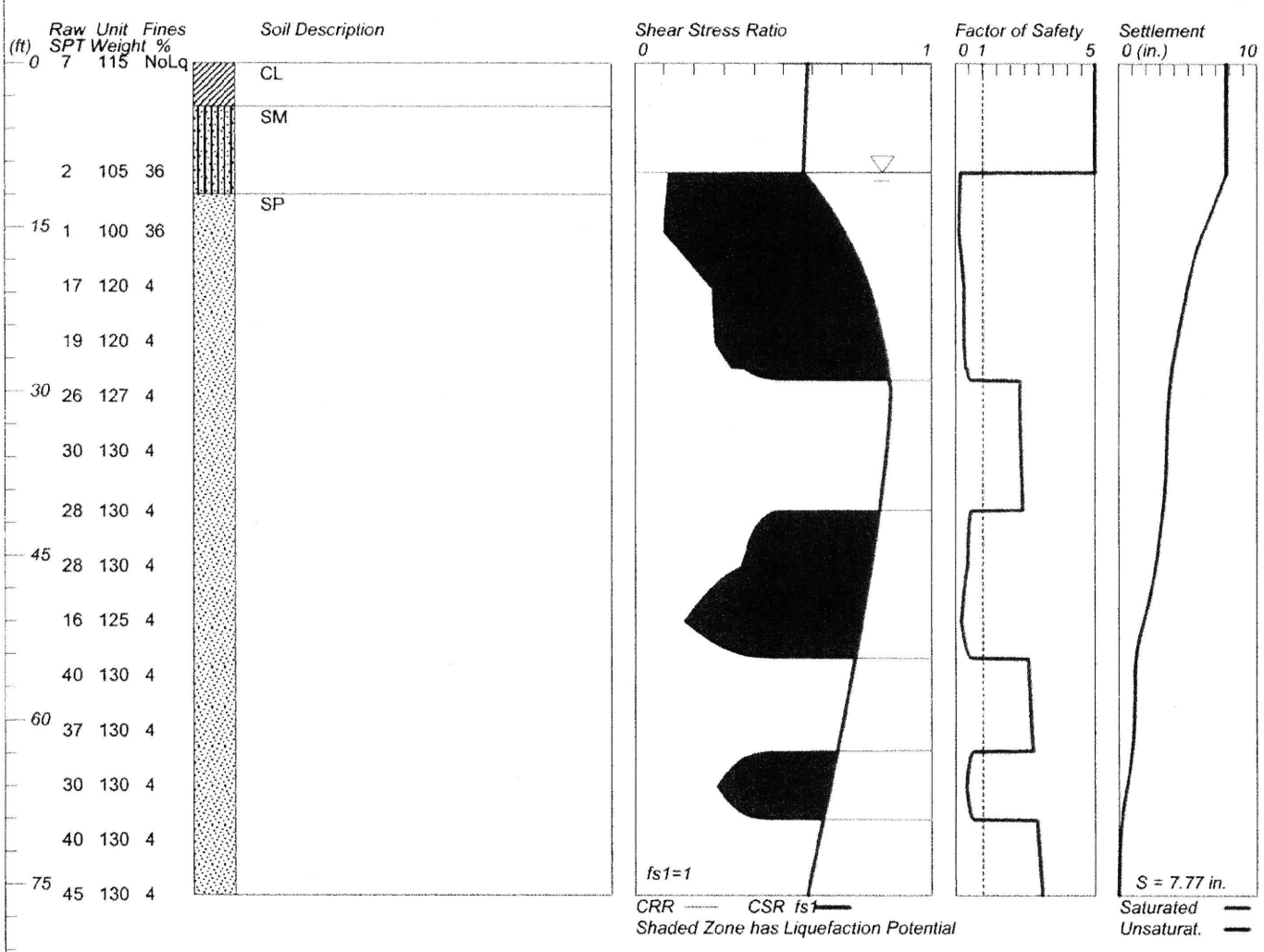
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=10 Water Depth=10 ft Surface Elev.=220.7

Magnitude=7.5
Acceleration=0.897g



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BN-10, Craighead County

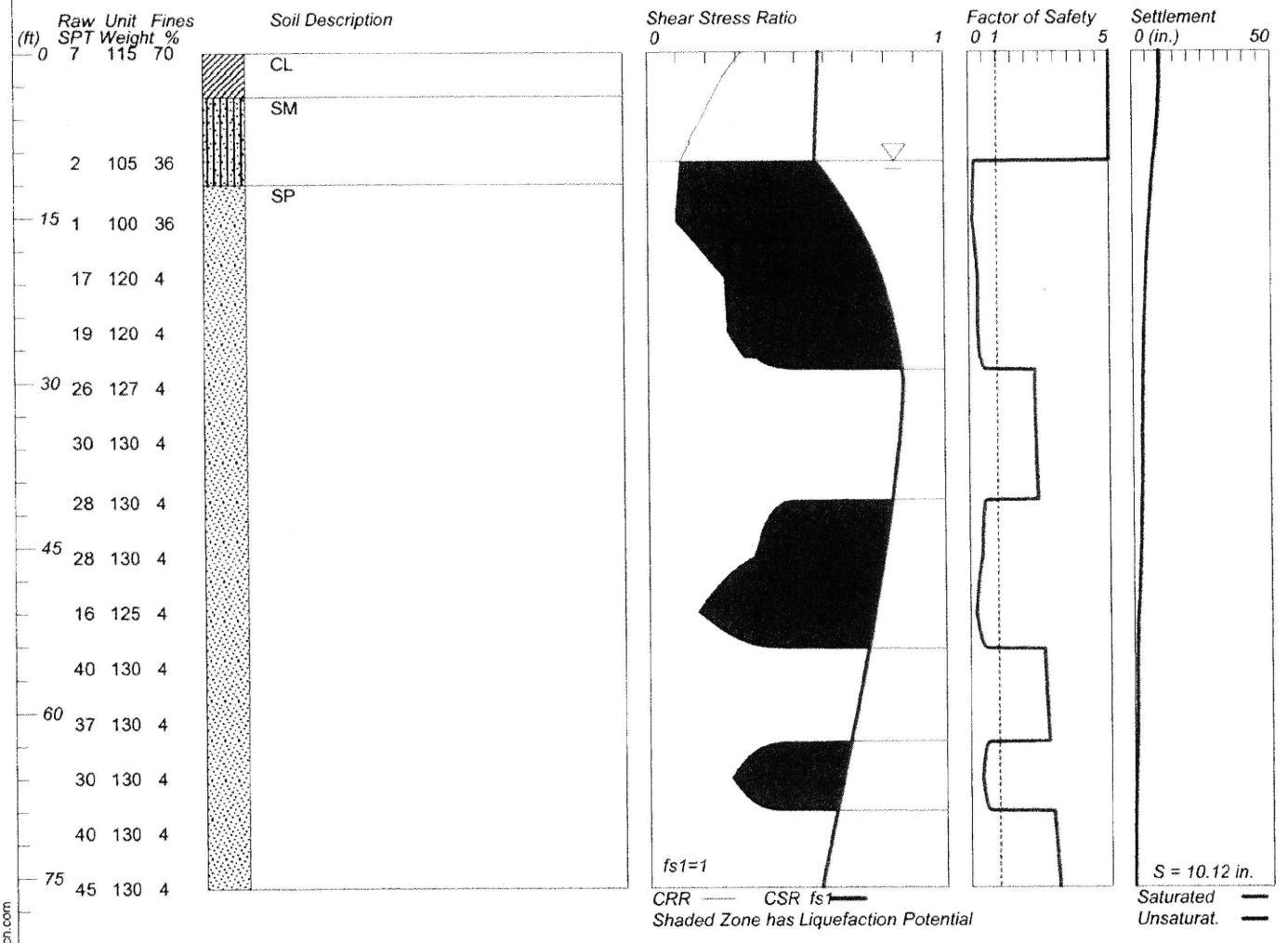
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=10 Water Depth=10 ft Surface Elev.=220.7

Magnitude=7.5
Acceleration=0.897g



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BN-10, Craighead County

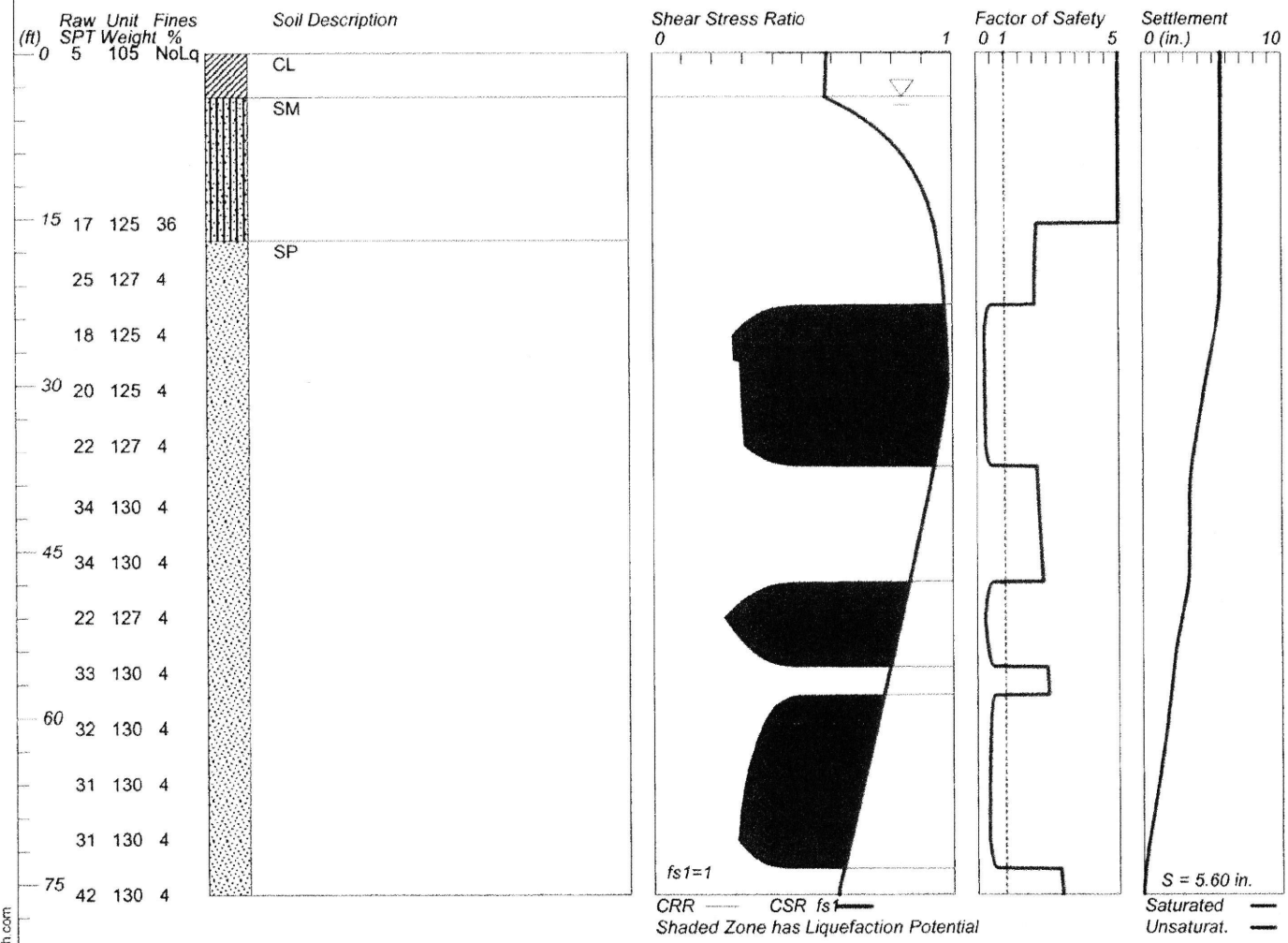
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100153

Hole No.=11 Water Depth=4 ft Surface Elev.=220.9

Magnitude=7.5
Acceleration=0.897g



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BN-11, Craighead County

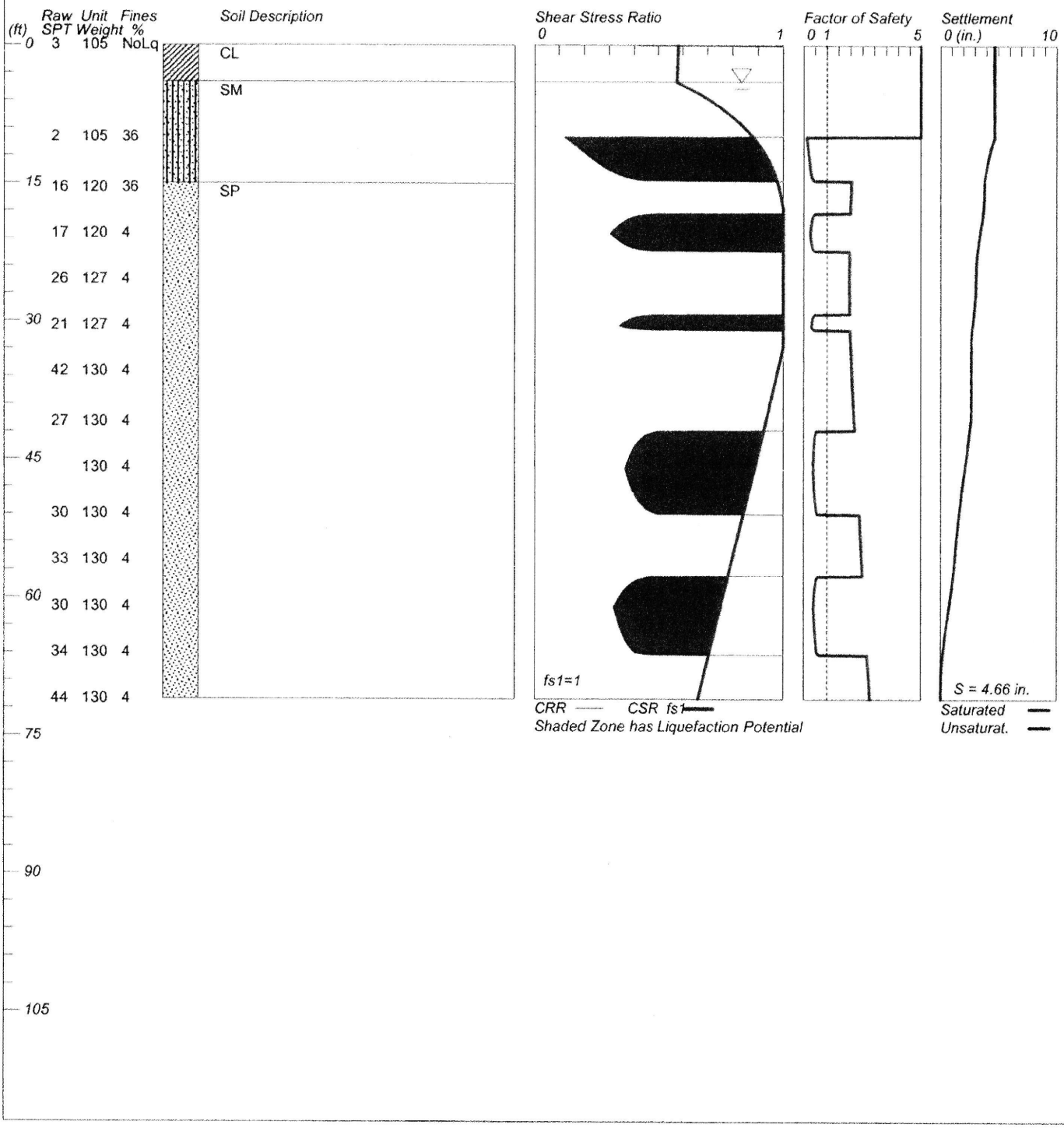
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=12 Water Depth=4 ft Surface Elev.=220.2

Magnitude=7.5
Acceleration=0.897g



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BN-12, Craighead County

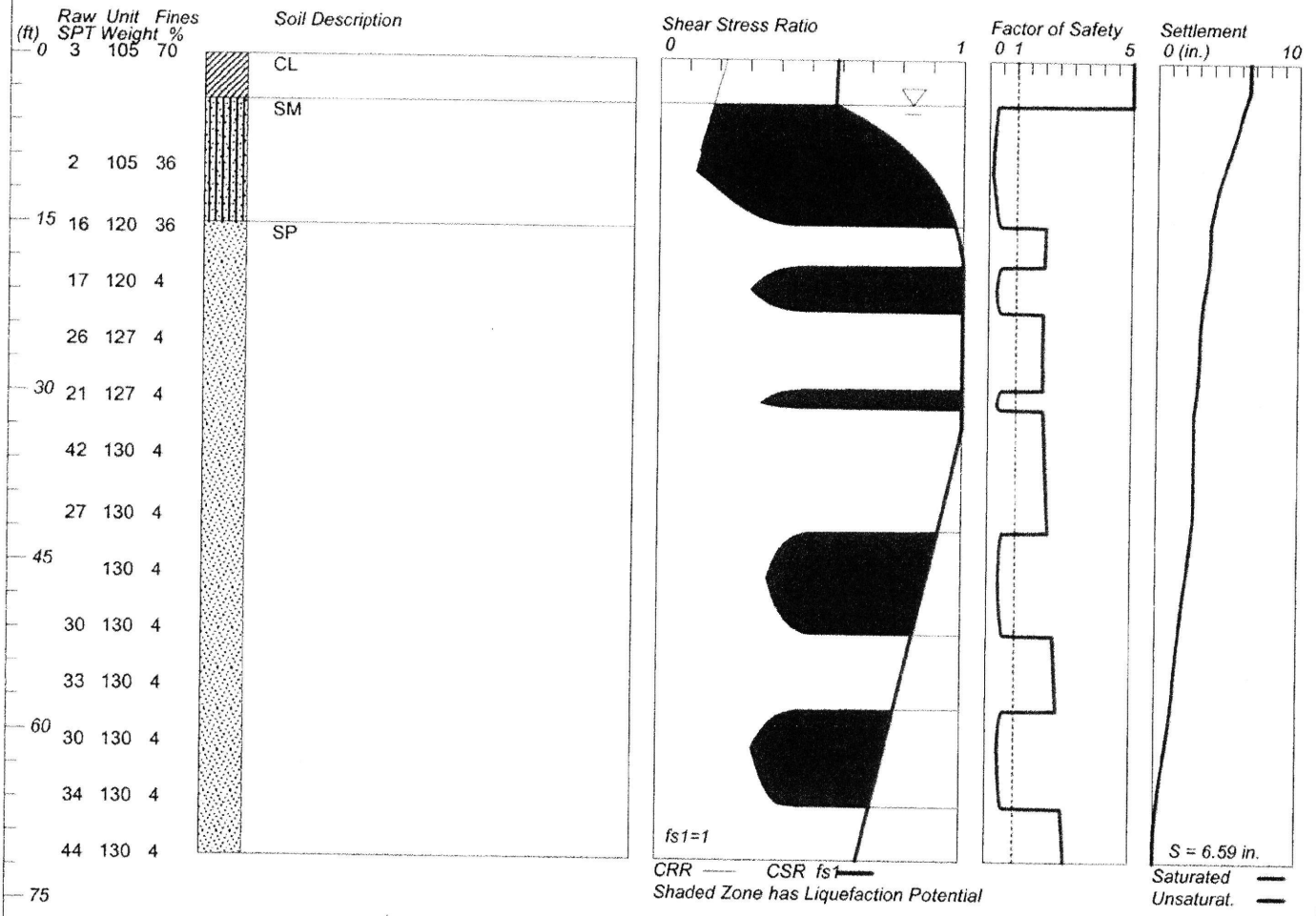
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=12 Water Depth=4 ft Surface Elev.=220.2

Magnitude=7.5
Acceleration=0.897g



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BN-12, Craighead County

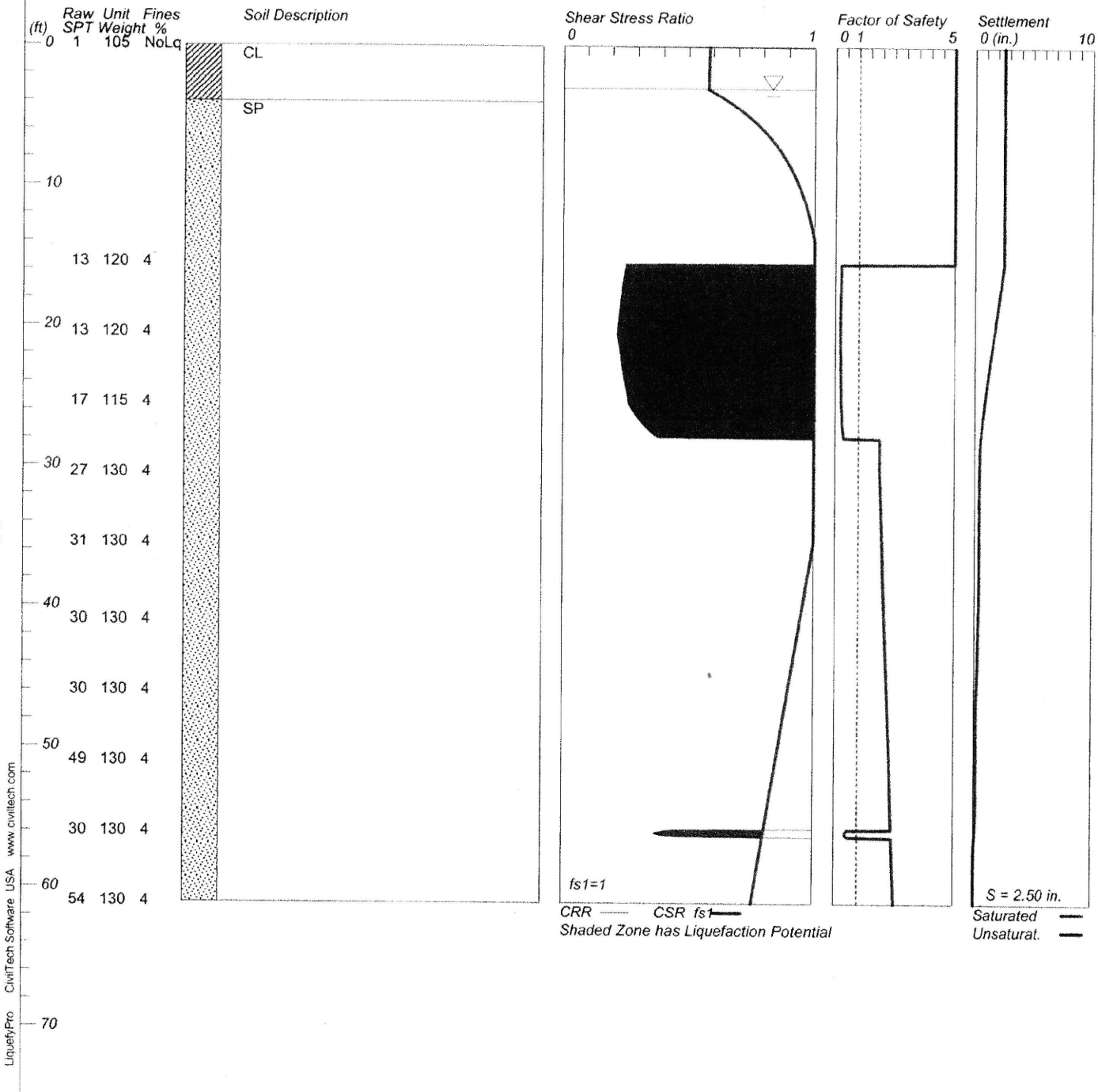
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100153

Hole No.=13 Water Depth=3 ft Surface Elev.=220.0

Magnitude=7.5
Acceleration=0.897g



BN-13, Craighead County

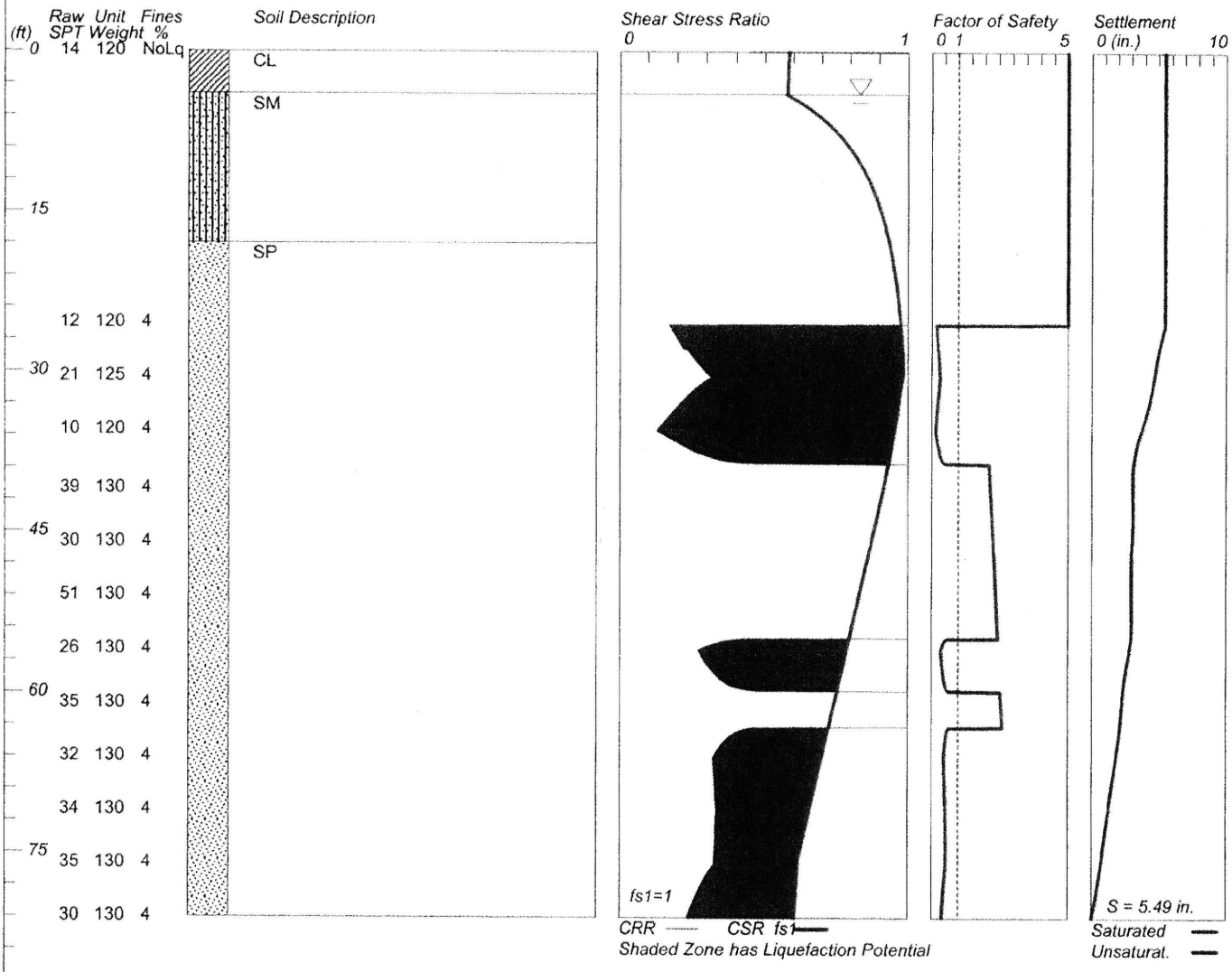
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100153

Hole No.=14 Water Depth=4 ft Surface Elev.=222

Magnitude=7.5
Acceleration=0.897g



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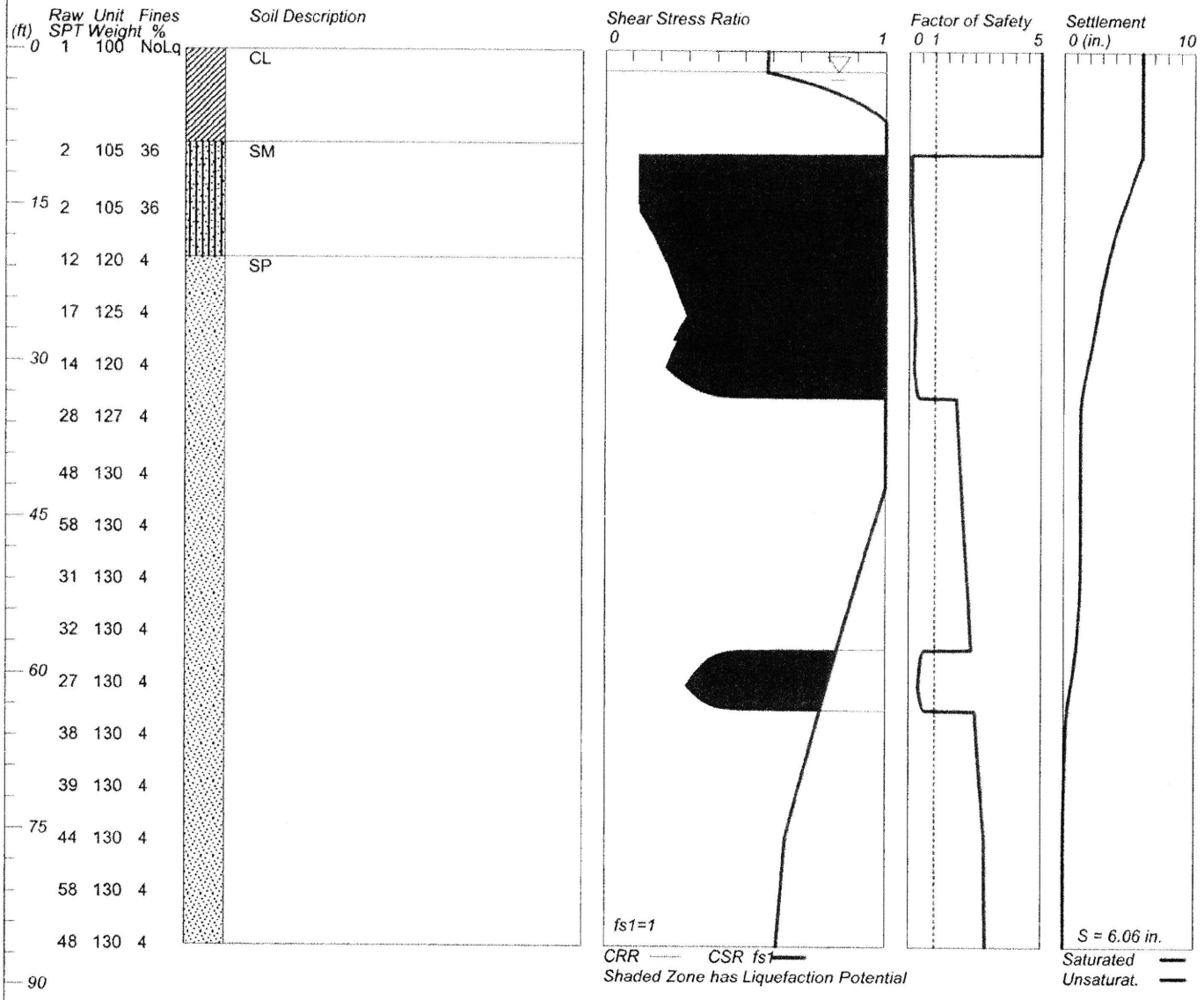
BN-14, Craighead County

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=15 Water Depth=2 ft Surface Elev.=220.4

Magnitude=7.5
Acceleration=0.897g



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BN-15, Craighead County

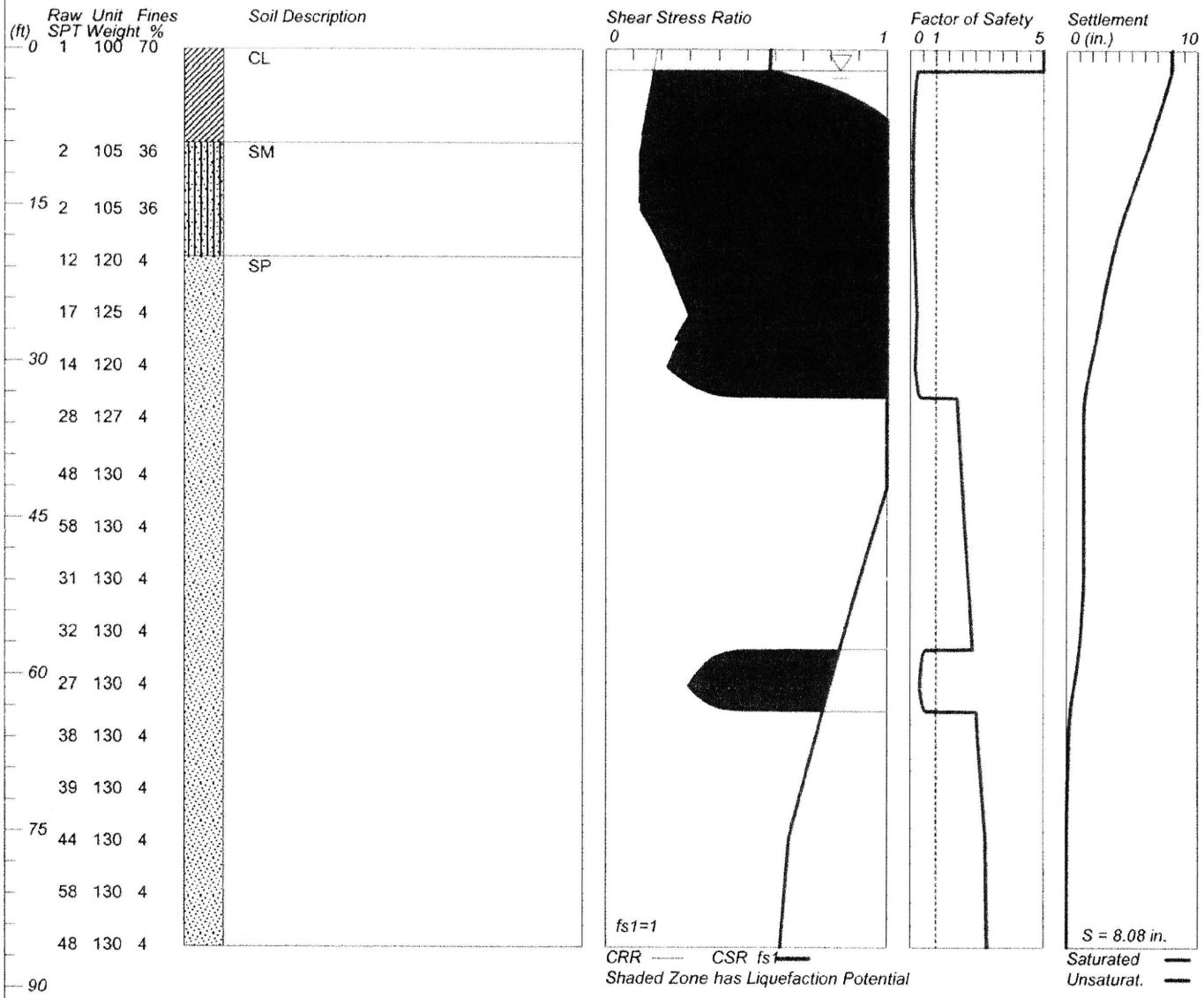
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=15 Water Depth=2 ft Surface Elev.=220.4

Magnitude=7.5
Acceleration=0.897g



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BN-15, Craighead County

Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=16 Water Depth=3 ft Surface Elev.=221.2

Magnitude=7.5
Acceleration=0.897g

BN-16, Craighead County

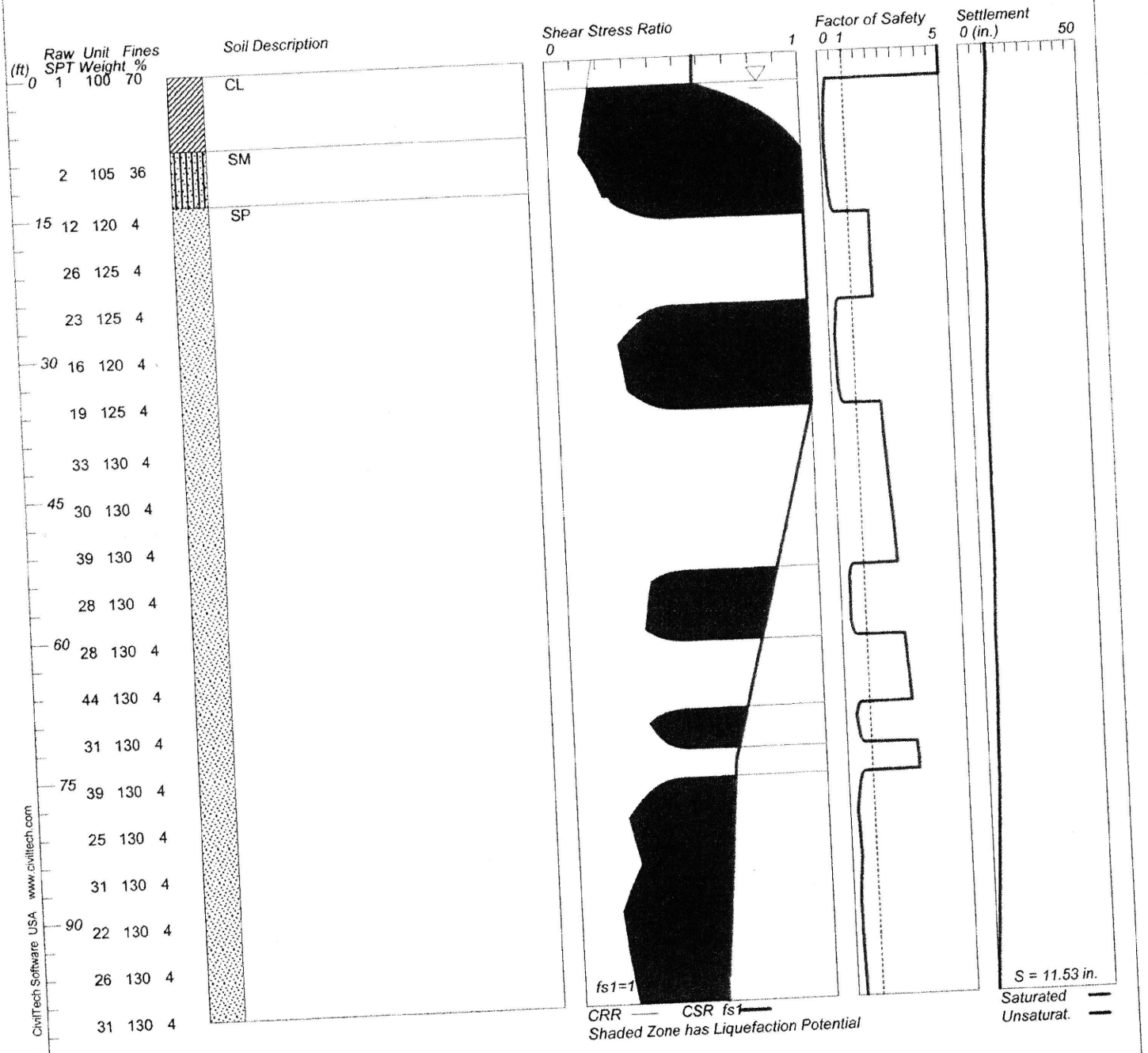
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=16 Water Depth=3 ft Surface Elev.=221.2

Magnitude=7.5
Acceleration=0.897g



BN-16, Craighead County

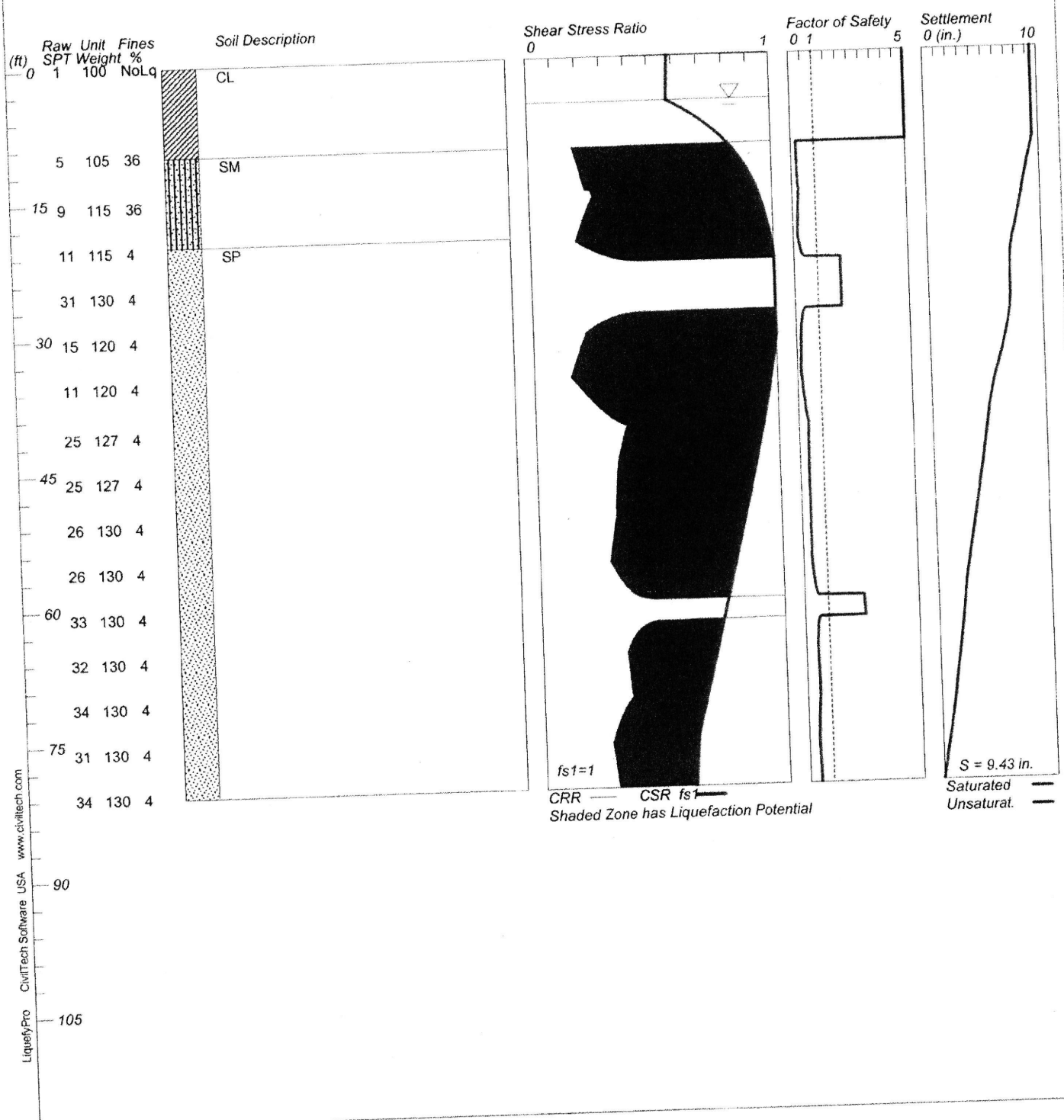
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=17 Water Depth=5 ft Surface Elev.=222

Magnitude=7.5
Acceleration=0.897g



BN-17, Craighead County

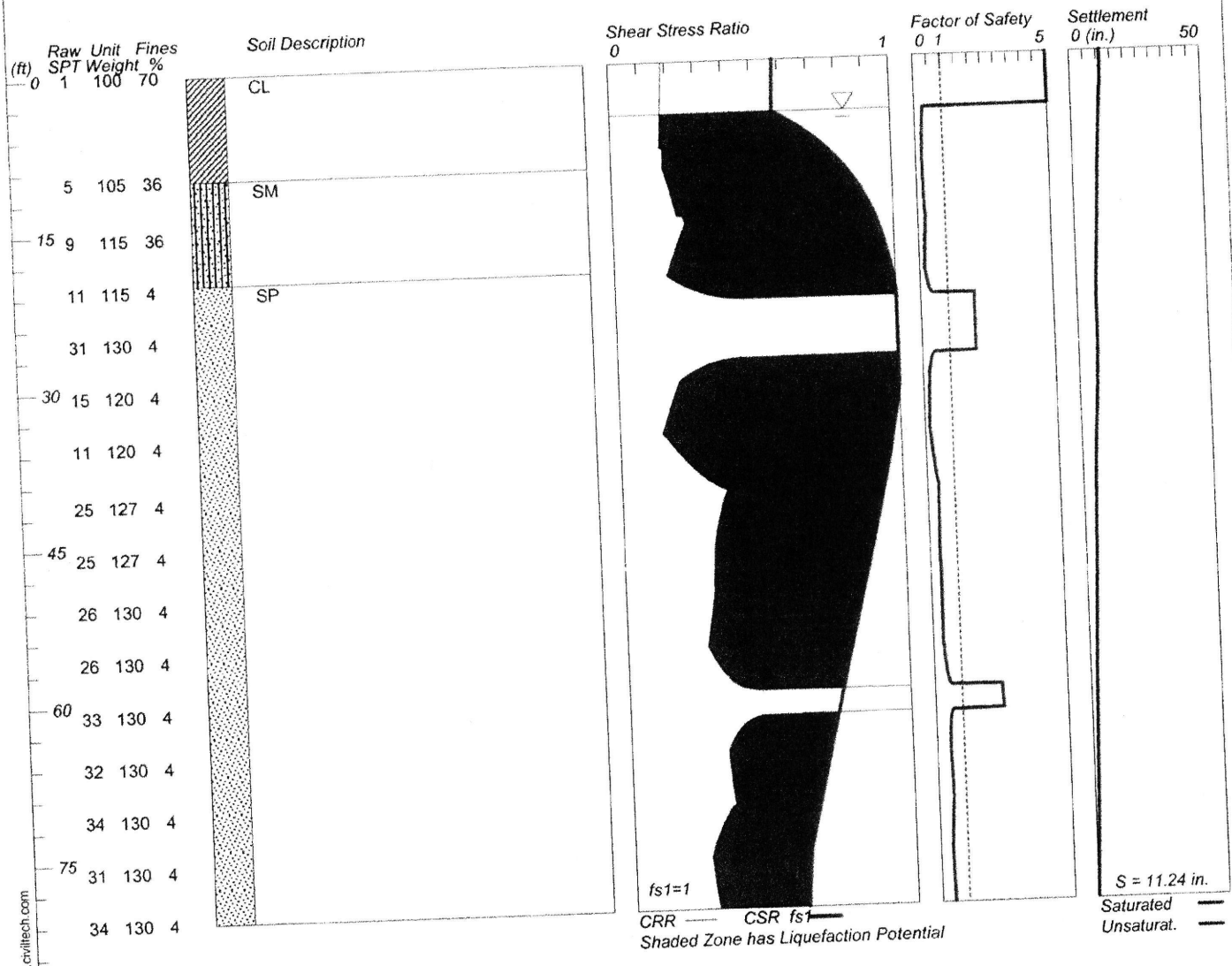
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=17 Water Depth=5 ft Surface Elev.=222

Magnitude=7.5
Acceleration=0.897g



BN-17, Craighead County

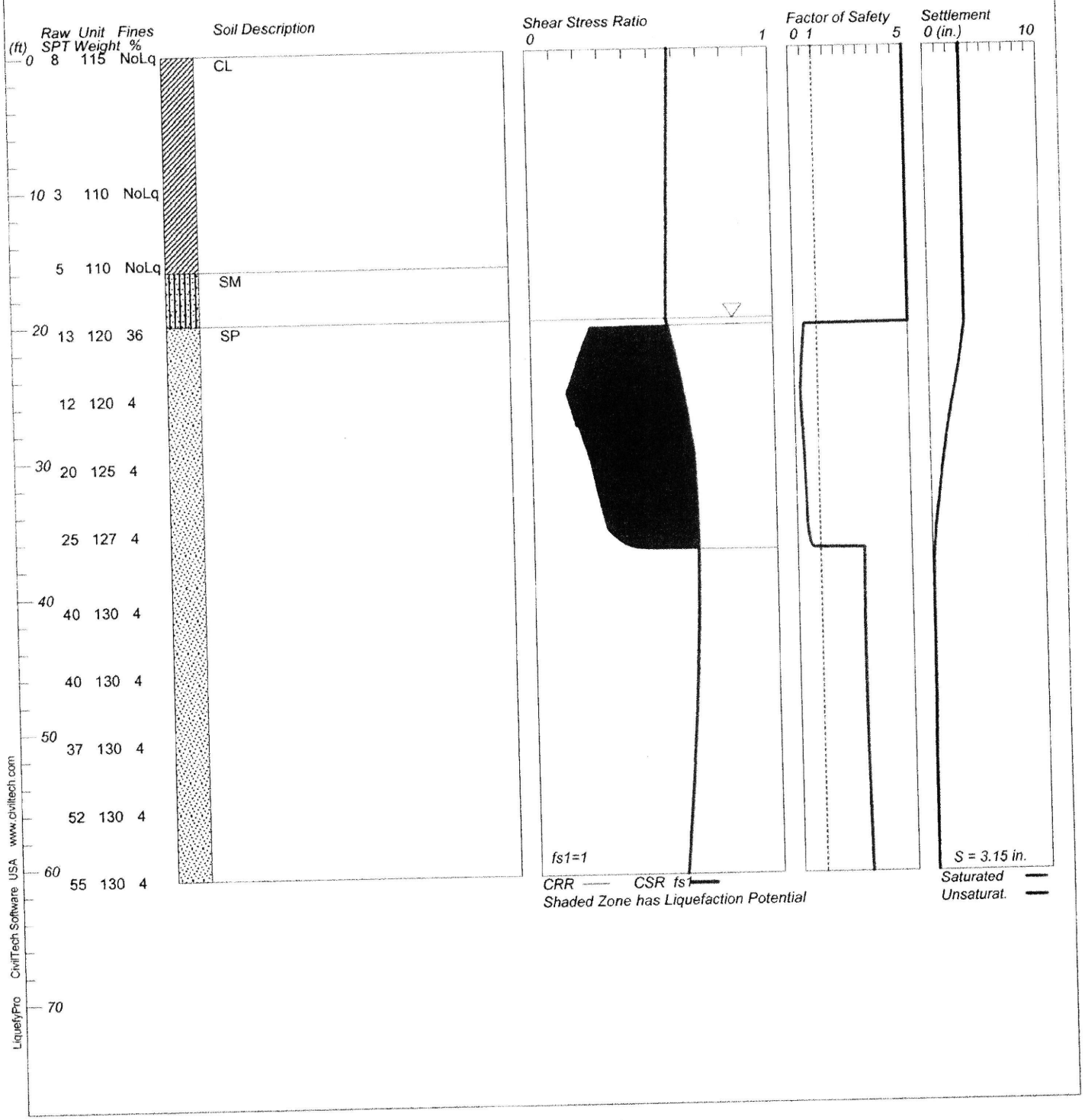
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=18 Water Depth=20 ft Surface Elev.=230.3

Magnitude=7.5
Acceleration=0.897g



BN-18, Craighead County

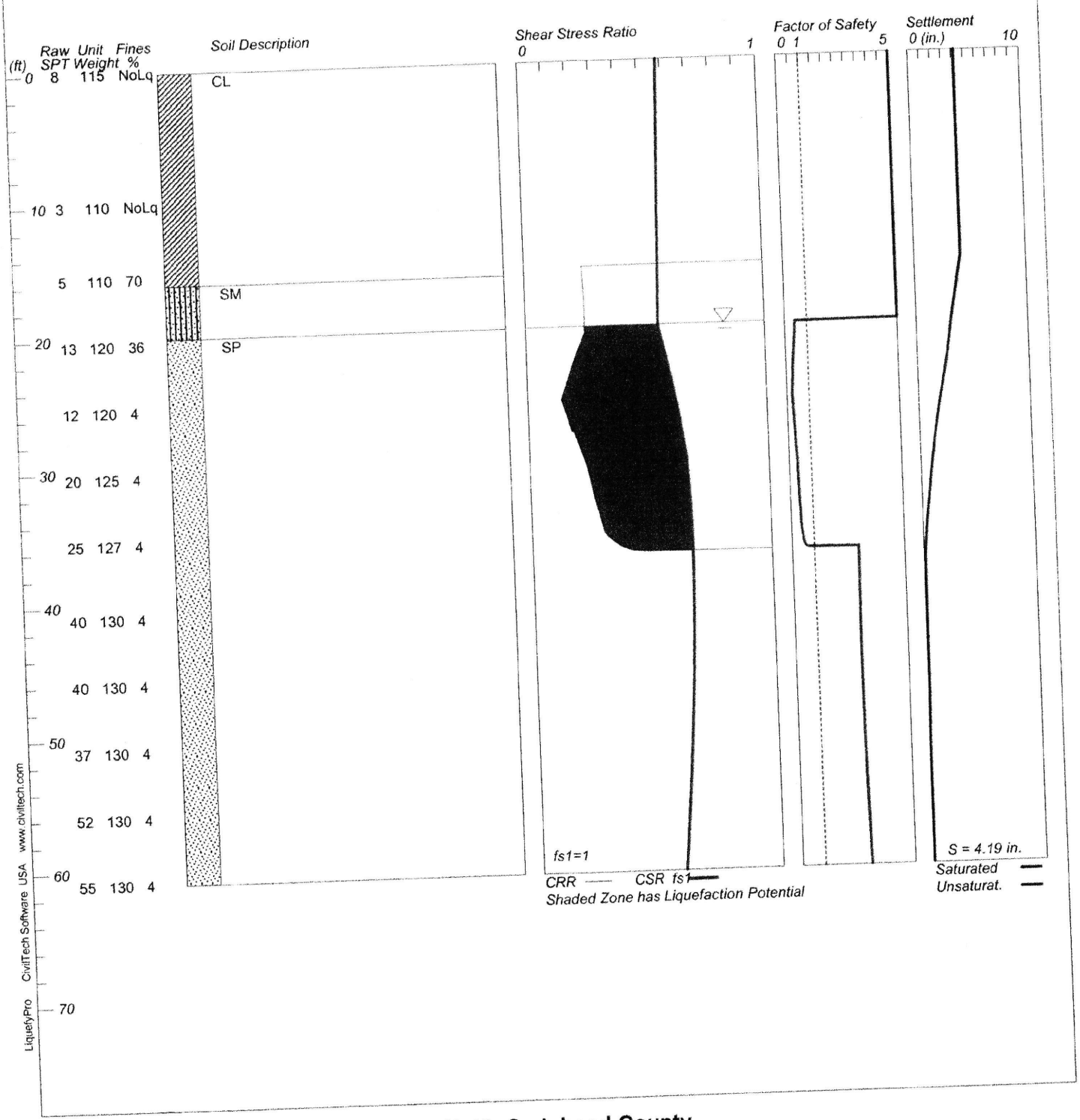
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=18 **Water Depth=20 ft** **Surface Elev.=230.3**

Magnitude=7.5
Acceleration=0.897g



BN-18, Craighead County

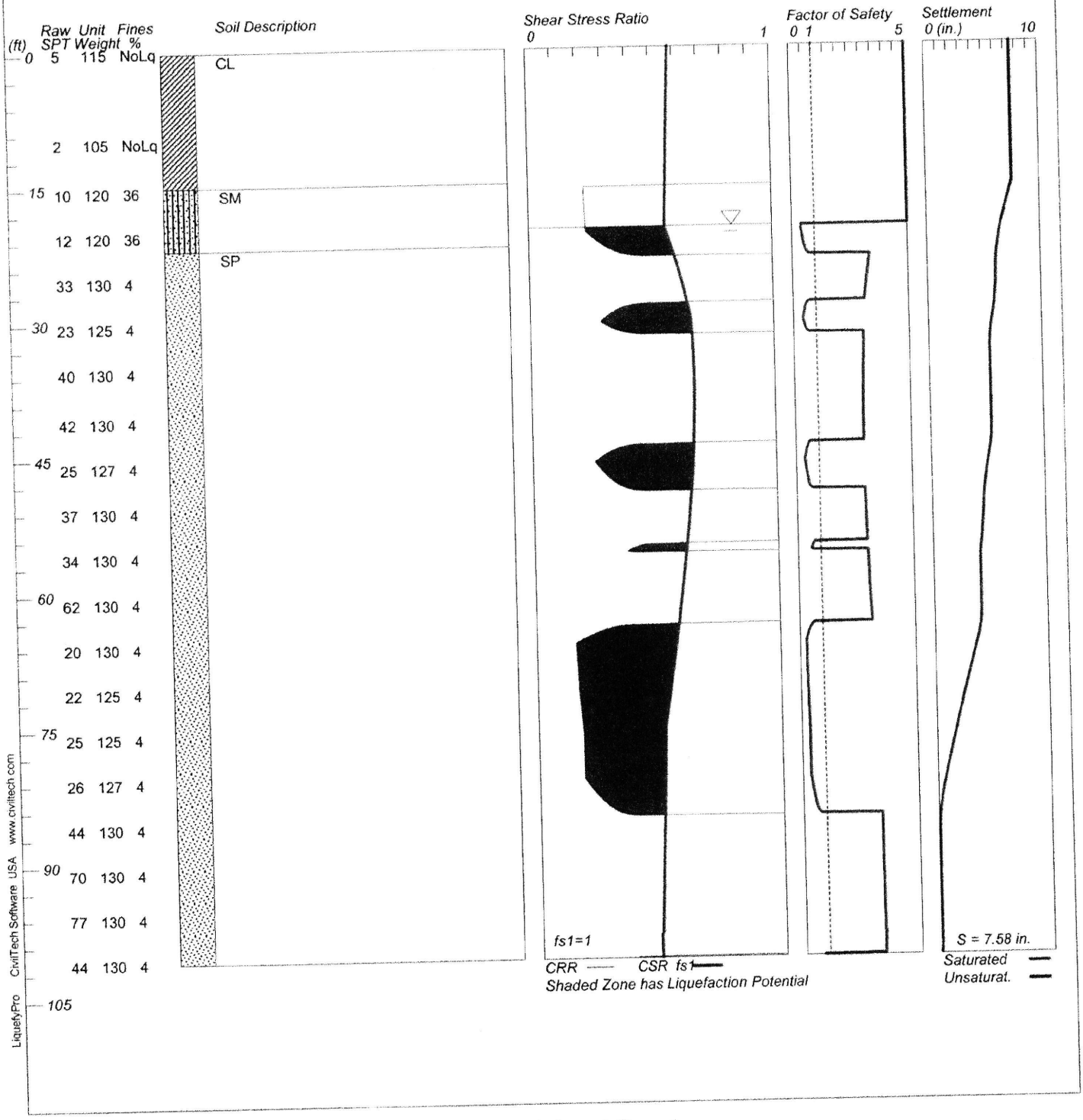
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100153

Hole No.=19 Water Depth=20 ft Surface Elev.=230

Magnitude=7.5
Acceleration=0.897g



BN-19, Craighead County

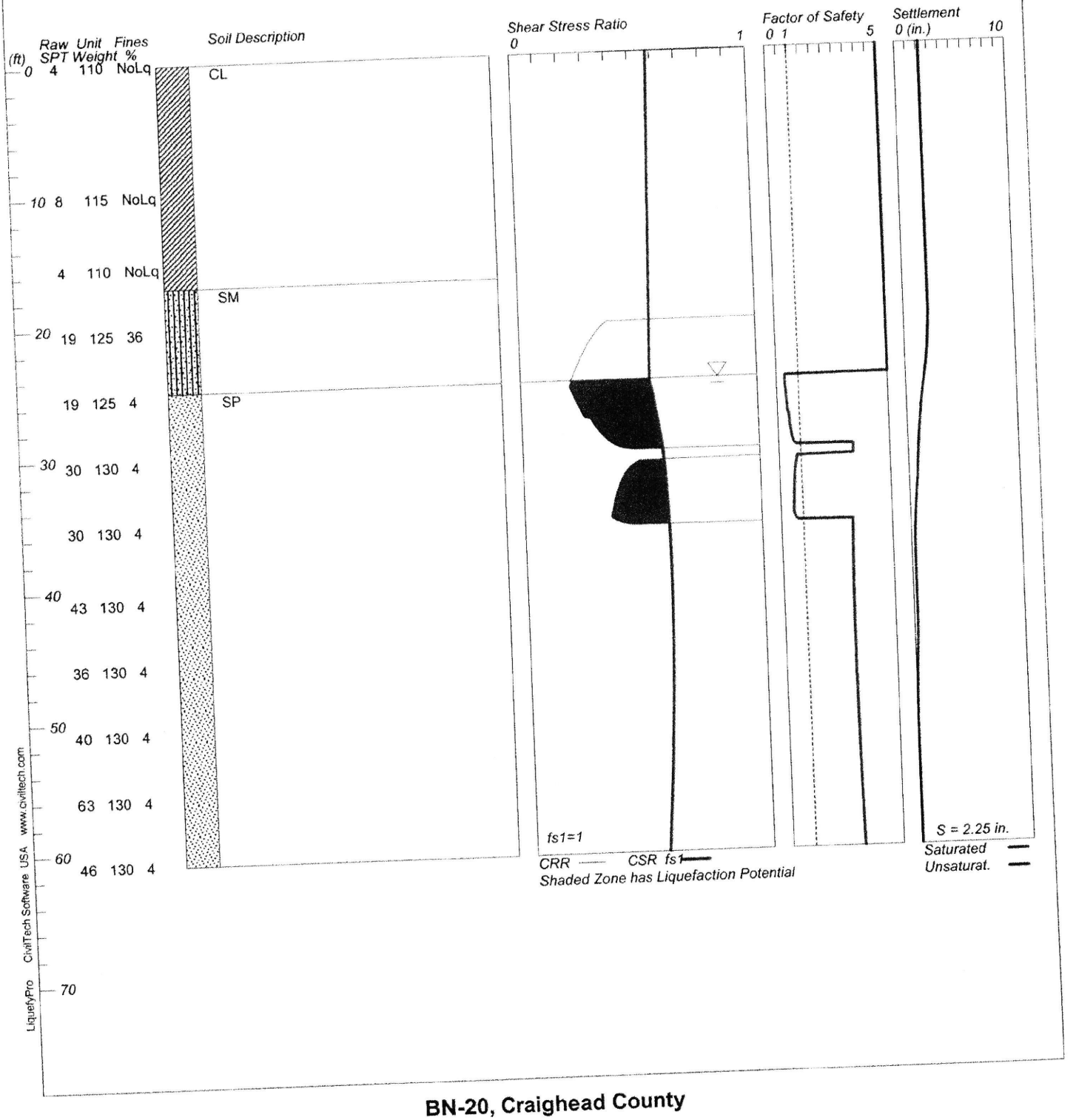
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100153

Hole No.=20 **Water Depth=25 ft** **Surface Elev.=233.8**

Magnitude=7.5
Acceleration=0.897g



BN-20, Craighead County

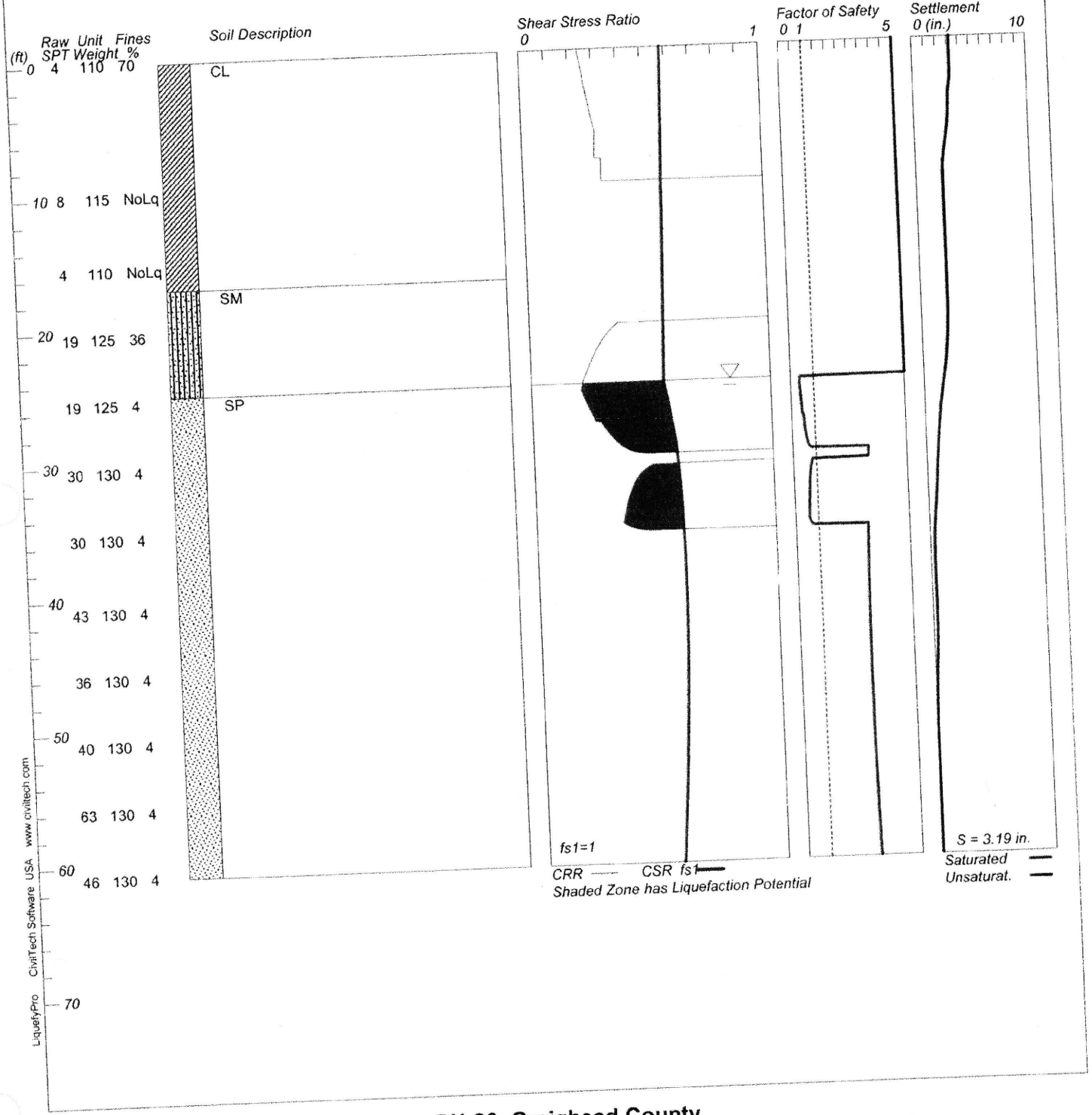
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100153

Hole No.=20 Water Depth=25 ft Surface Elev.=233.8

Magnitude=7.5
Acceleration=0.897g



BN-20, Craighead County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-100153

note applicible to sloping ground surfaces greater than about 6%

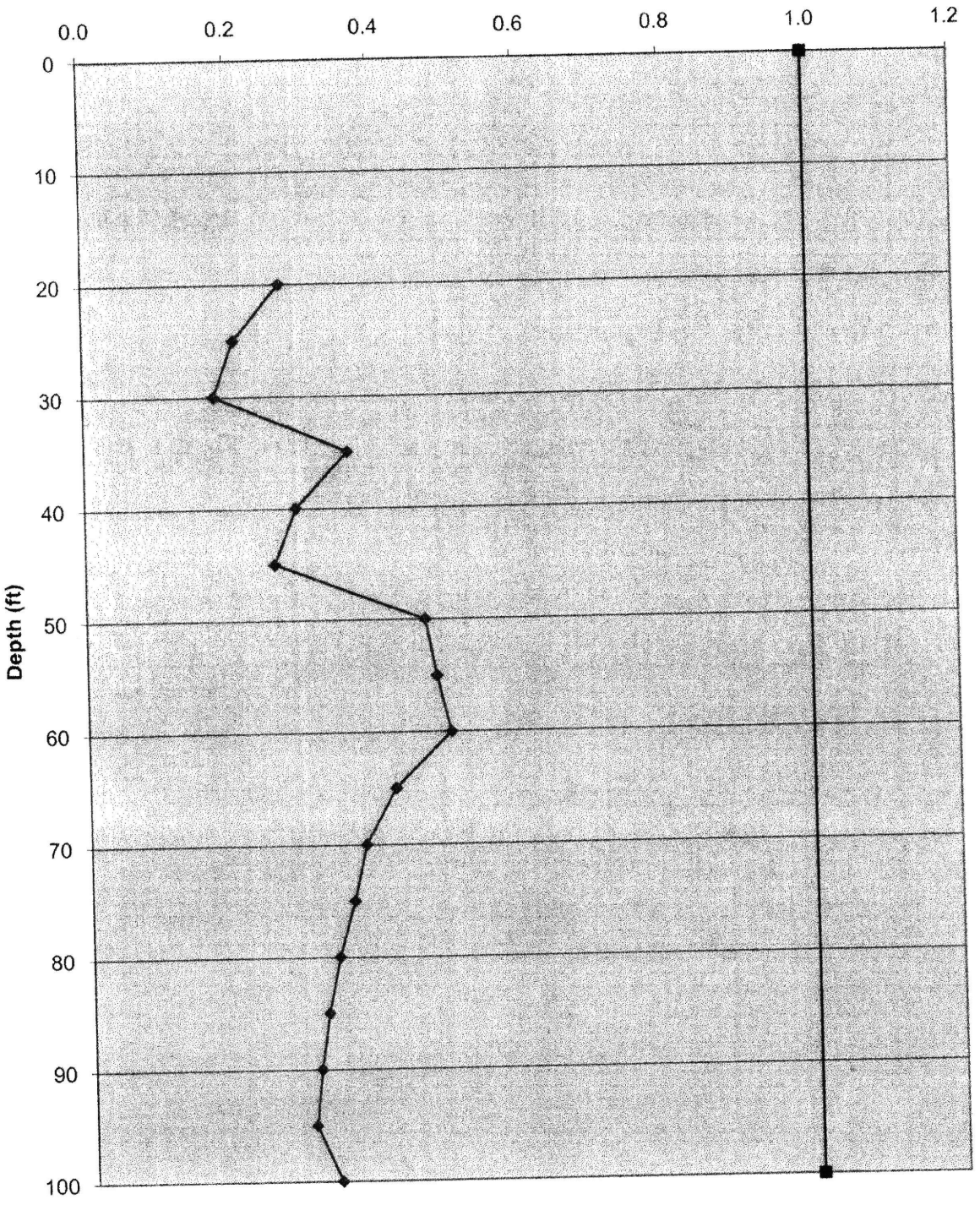
Moment Magnitude, M_w = 7.5
PGA = 0.897 g
depth to groundwater during drilling = 20 ft
estimated age of sand deposit = 2000 years

depth to finish floor = 0 ft
uniform floor load = 0 lb/ft^2
assumed depth to groundwater = 20 ft

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	115	509	80	0	575	575	575	0.988	0.5762	695	NA	1.00	1.00	NA	NA
10	1	105	623	80	0	1100	1100	1100	0.977	0.5694	723	NA	1.00	1.00	NA	NA
15	1	120	640	36	0	1700	1700	1700	0.965	0.5626	667	NA	1.00	1.00	NA	NA
20	2	120	623	36	0	2300	2300	2300	0.953	0.5558	602	0.1510	1.00	1.00	0.150993	0.3
25	2	130	656	4	0	2950	2638	2638	0.942	0.6140	612	0.1275	1.00	1.00	0.127482	0.2
30	2	125	656	4	0	3575	2951	2951	0.930	0.6569	595	0.1182	1.00	1.00	0.118157	0.2
35	2	130	787	4	0	4225	3289	3289	0.889	0.6658	695	0.2427	1.00	1.00	0.242677	0.4
40	2	130	787	4	0	4875	3627	3627	0.848	0.6648	678	0.1927	1.00	1.00	0.192644	0.3
45	2	127	787	4	0	5510	3950	3950	0.808	0.6568	664	0.1703	1.00	1.00	0.170244	0.3
50	2	130	886	4	0	6160	4288	4288	0.767	0.6423	732	0.3000	1.00	1.00	0.299946	0.5
55	2	130	886	4	0	6810	4626	4626	0.726	0.6232	718	0.3000	1.00	1.00	0.299946	0.5
60	2	130	886	4	0	7460	4964	4964	0.685	0.6006	706	0.3000	1.00	1.00	0.299946	0.5
65	2	125	886	4	0	8085	5277	5277	0.645	0.5759	695	0.2437	1.00	1.00	0.243636	0.4
70	2	125	886	4	0	8710	5590	5590	0.604	0.5487	685	0.2087	1.00	1.00	0.208698	0.4
75	2	127	886	4	0	9345	5913	5913	0.563	0.5190	676	0.1880	1.00	1.00	0.187946	0.4
80	2	130	886	4	0	9995	6251	6251	0.549	0.5116	666	0.1735	1.00	1.00	0.173485	0.3
85	2	130	886	4	0	10645	6589	6589	0.537	0.5055	658	0.1629	1.00	1.00	0.162918	0.3
90	2	130	886	4	0	11295	6927	6927	0.524	0.4986	649	0.1547	1.00	1.00	0.154666	0.3
95	2	130	886	4	0	11945	7265	7265	0.512	0.4910	642	0.1480	1.00	1.00	0.147926	0.3
100	2	130	886	10	0	12595	7603	7603	0.500	0.4829	635	0.1627	1.00	1.00	0.162684	0.3

Used Bore #9 for PI values & unit wt.

Vs Liquefaction Potential - Project 100153

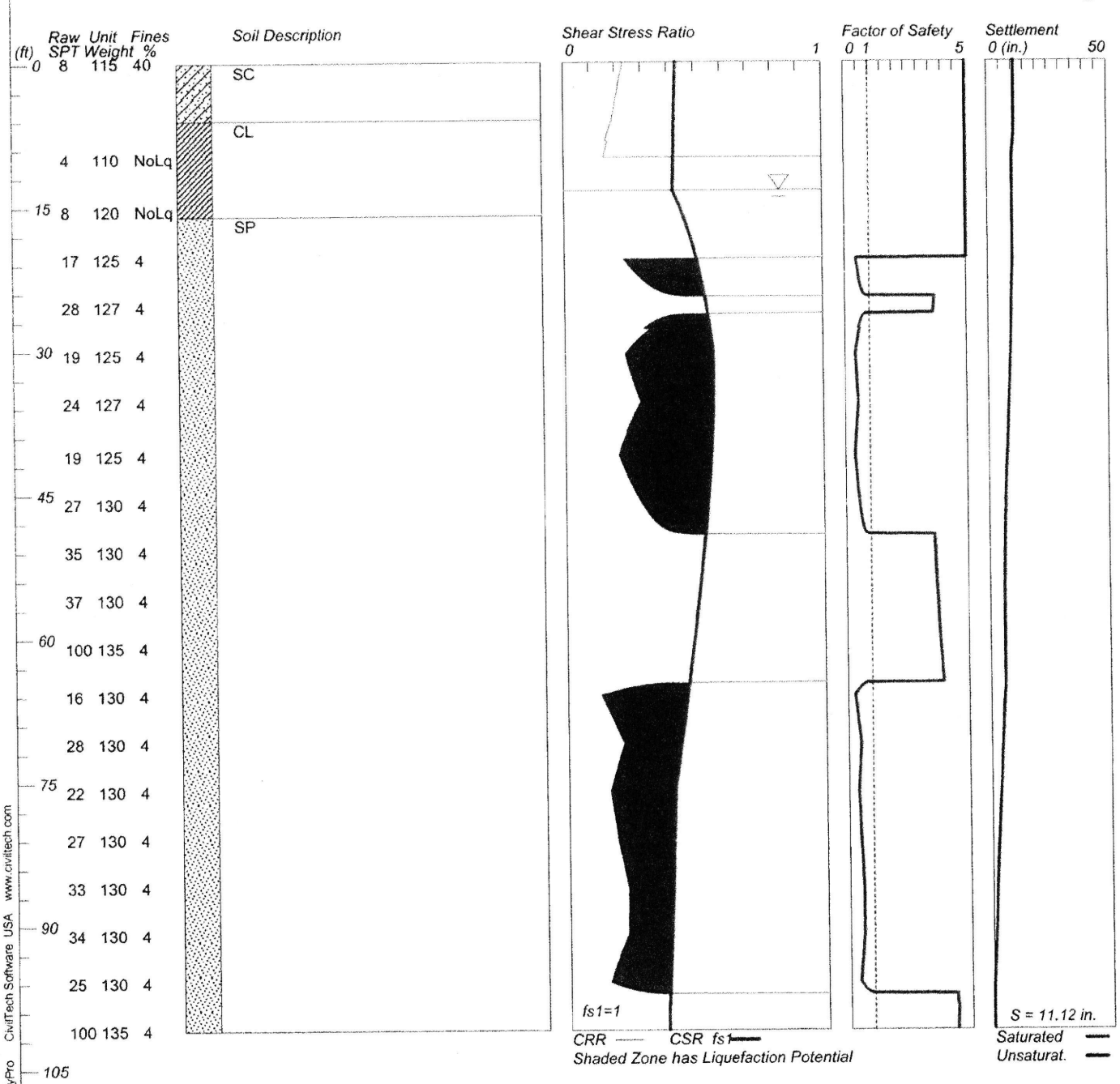


LIQUEFACTION ANALYSIS

100478

Hole No.=1 Water Depth=13.4 ft Surface Elev.=205.5

Magnitude=7.5
Acceleration=0.667g



BN-1, Greene County

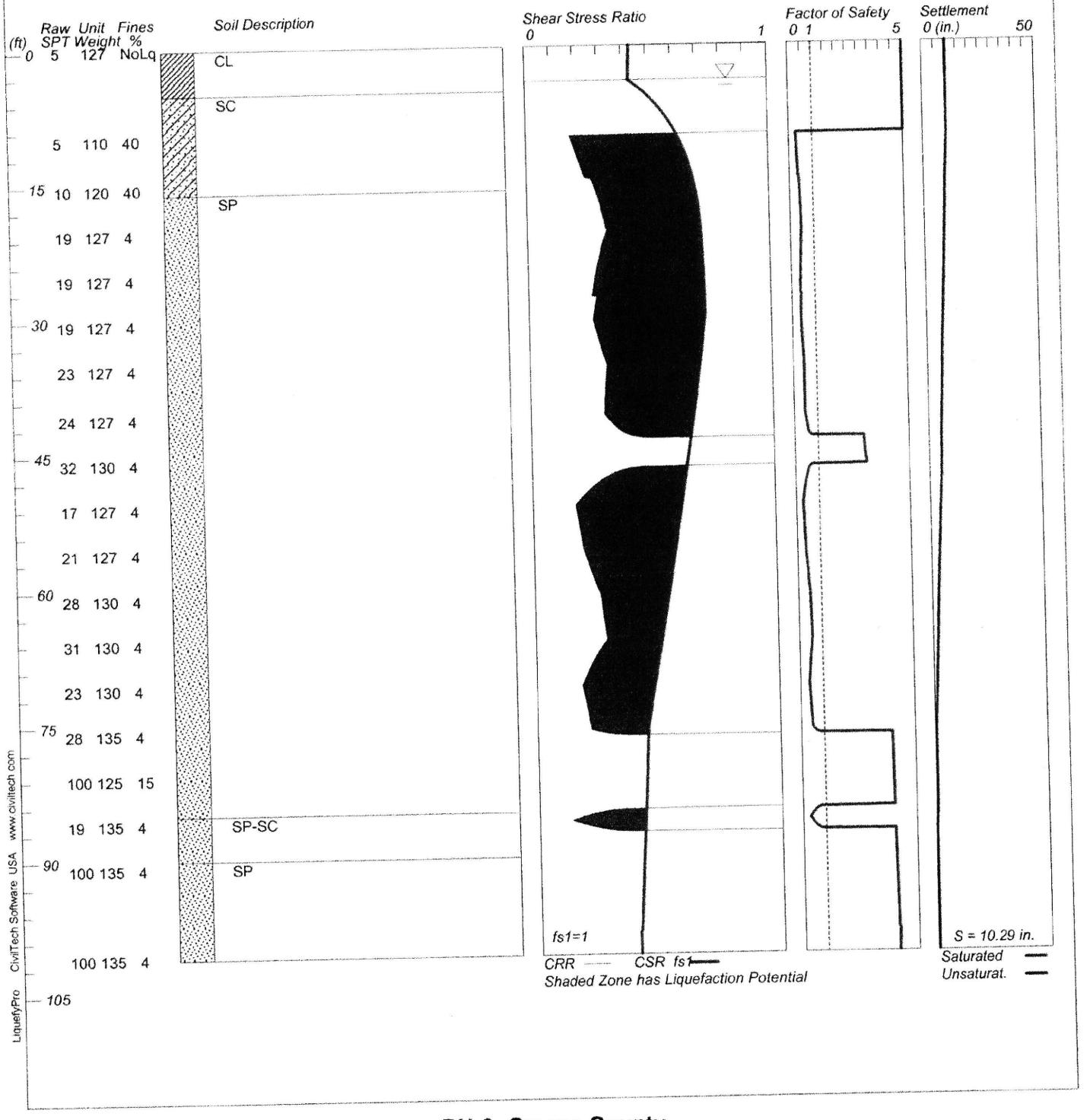
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100478

Hole No.=2 Water Depth=3.9 ft Surface Elev.=241.7

Magnitude=7.5
Acceleration=0.667g



BN-2, Greene County

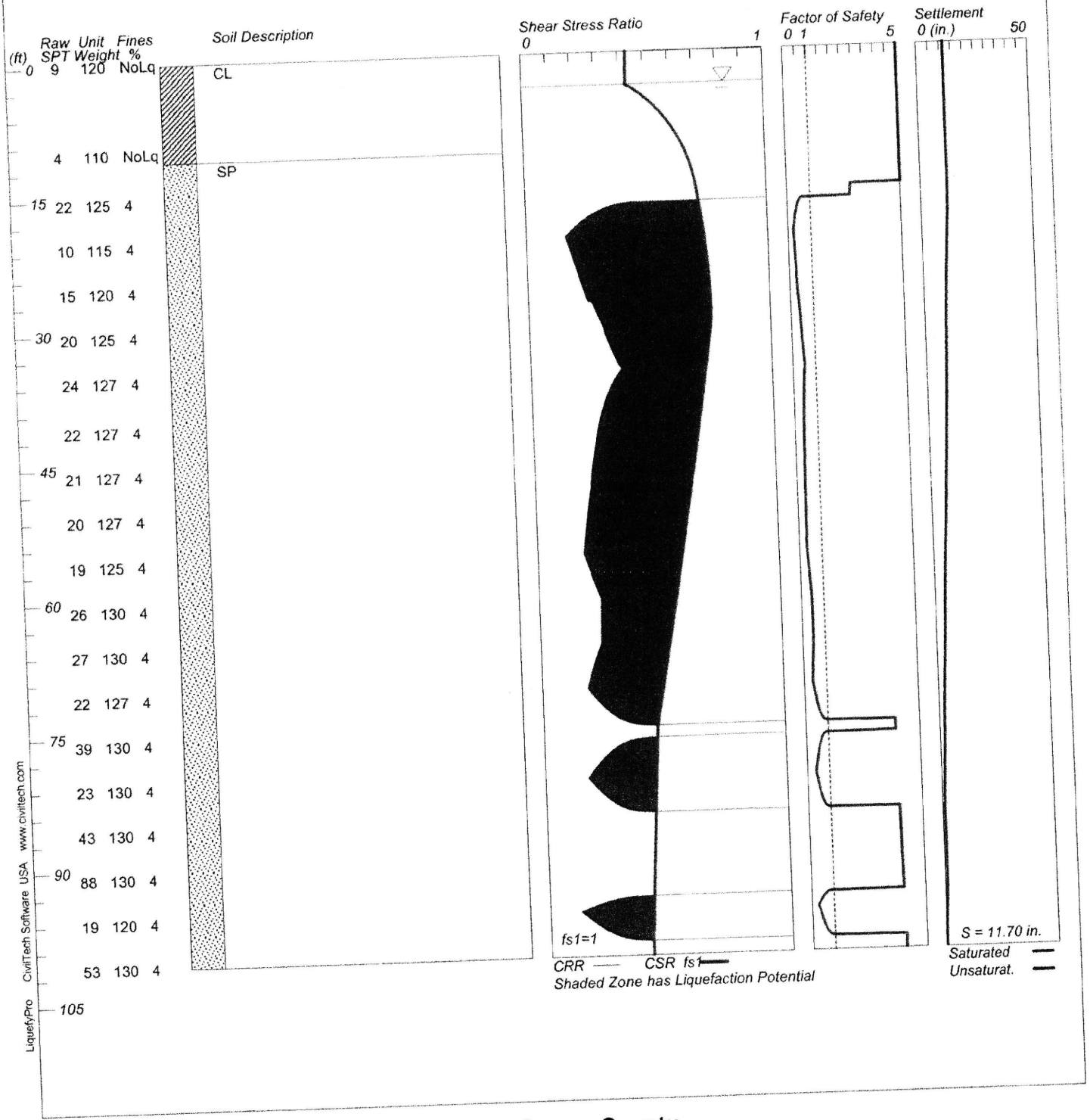
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100478

Hole No.=3 Water Depth=3.7 ft Surface Elev.=241.5

Magnitude=7.5
Acceleration=0.667g



BN-3, Greene County

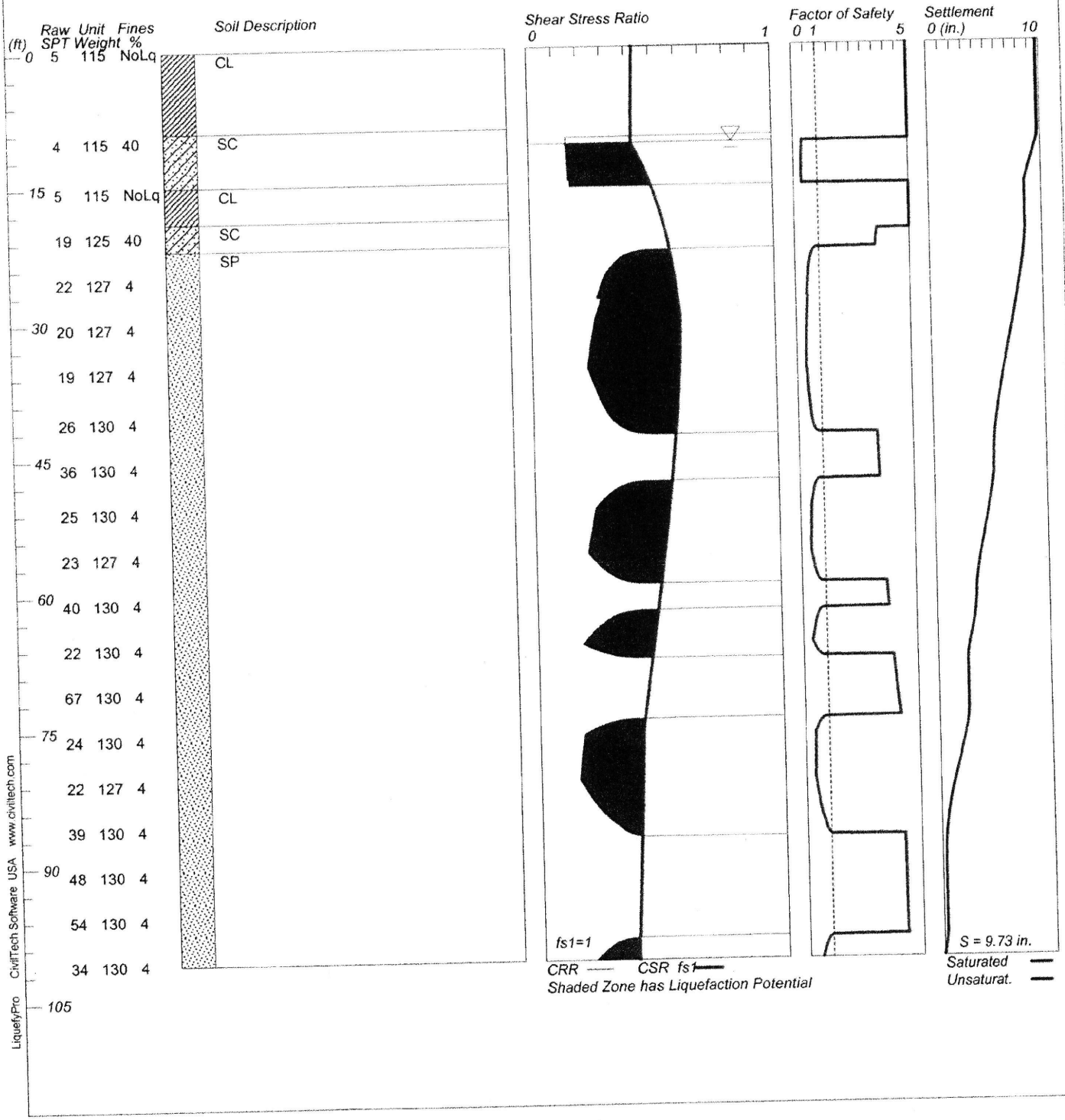
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100478

Hole No.=4 Water Depth=10.7 ft Surface Elev.=251.9

Magnitude=7.5
Acceleration=0.667g



BN-4, Greene County

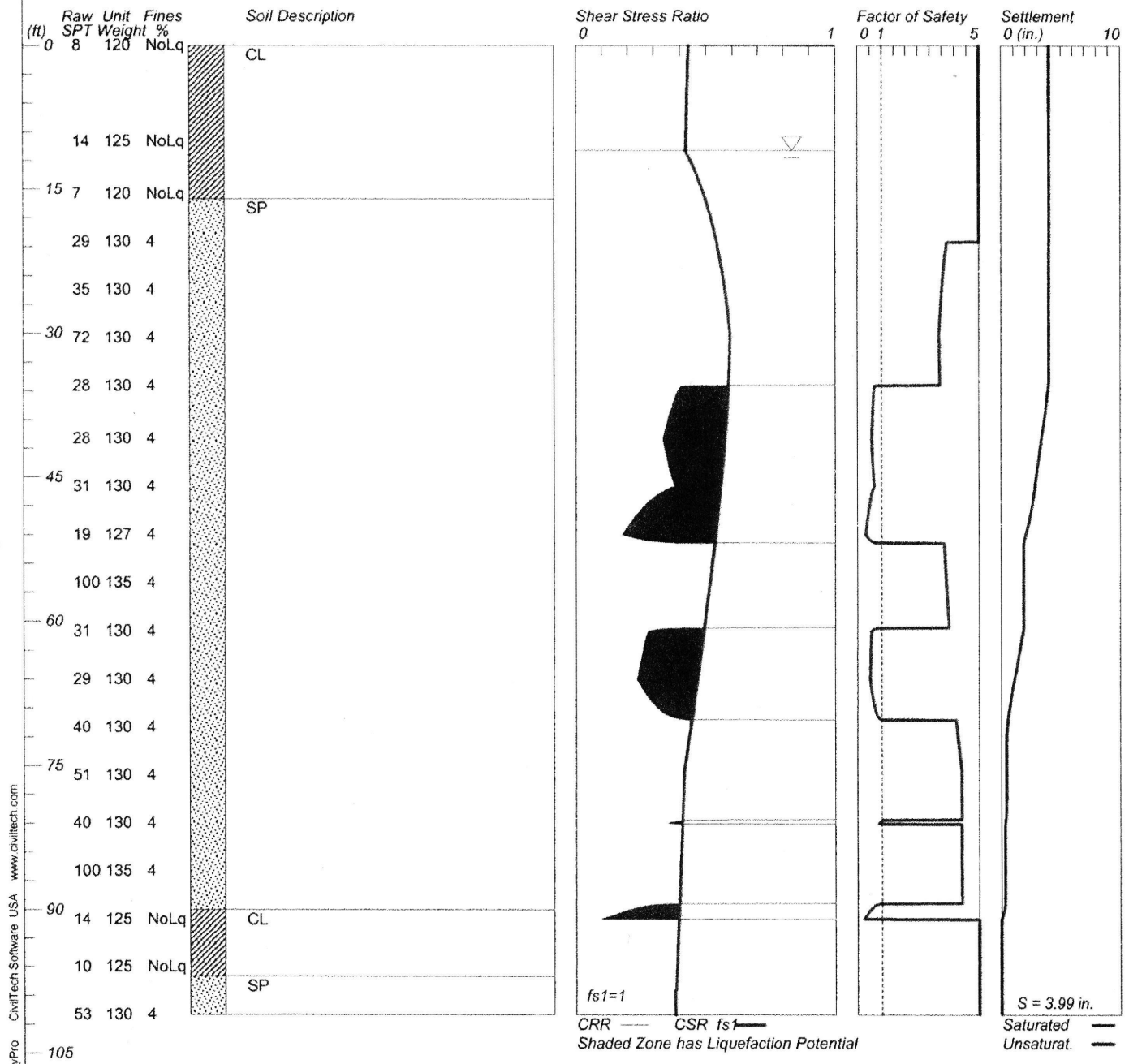
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100478

Hole No.=5 Water Depth=11 ft Surface Elev.=251.8

Magnitude=7.5
Acceleration=0.667g



BN-5, Greene County

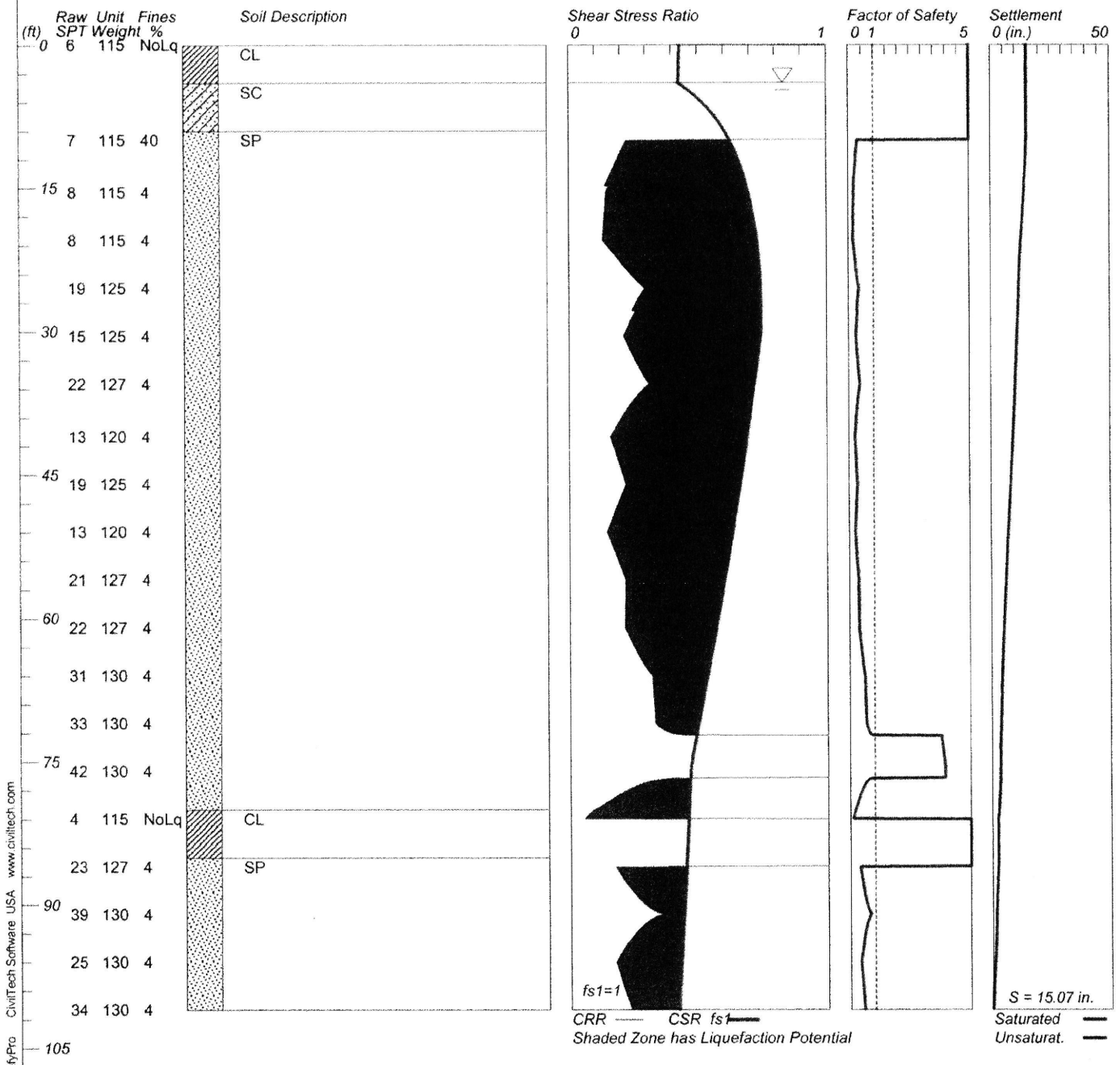
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100478

Hole No.=5A Water Depth=4 ft Surface Elev.=239.5

Magnitude=7.5
Acceleration=0.667g



BN-5A, Greene County

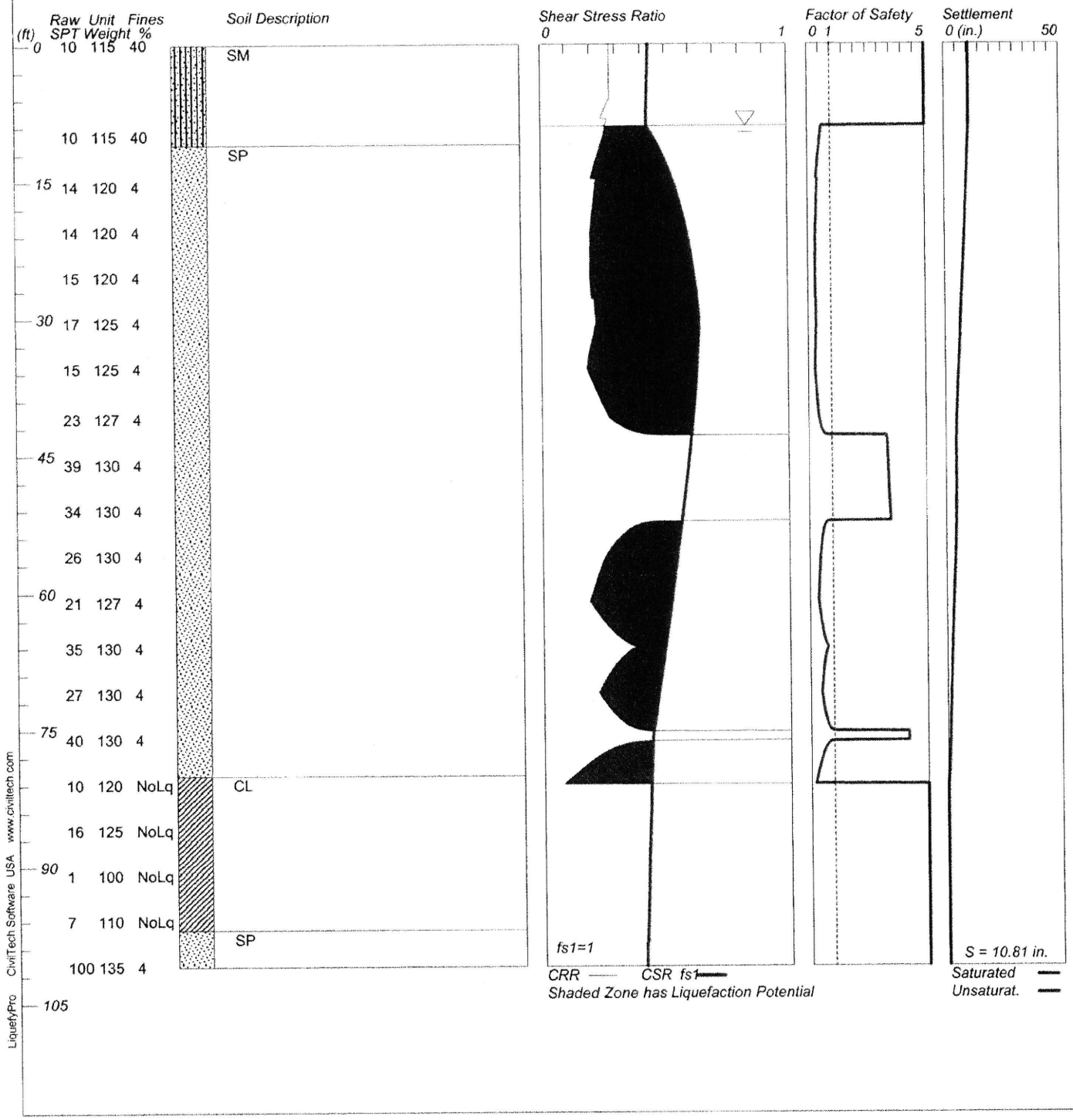
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100478

Hole No.=6 Water Depth=9 ft Surface Elev.=244.8

Magnitude=7.5
Acceleration=0.667g



BN-6, Greene County

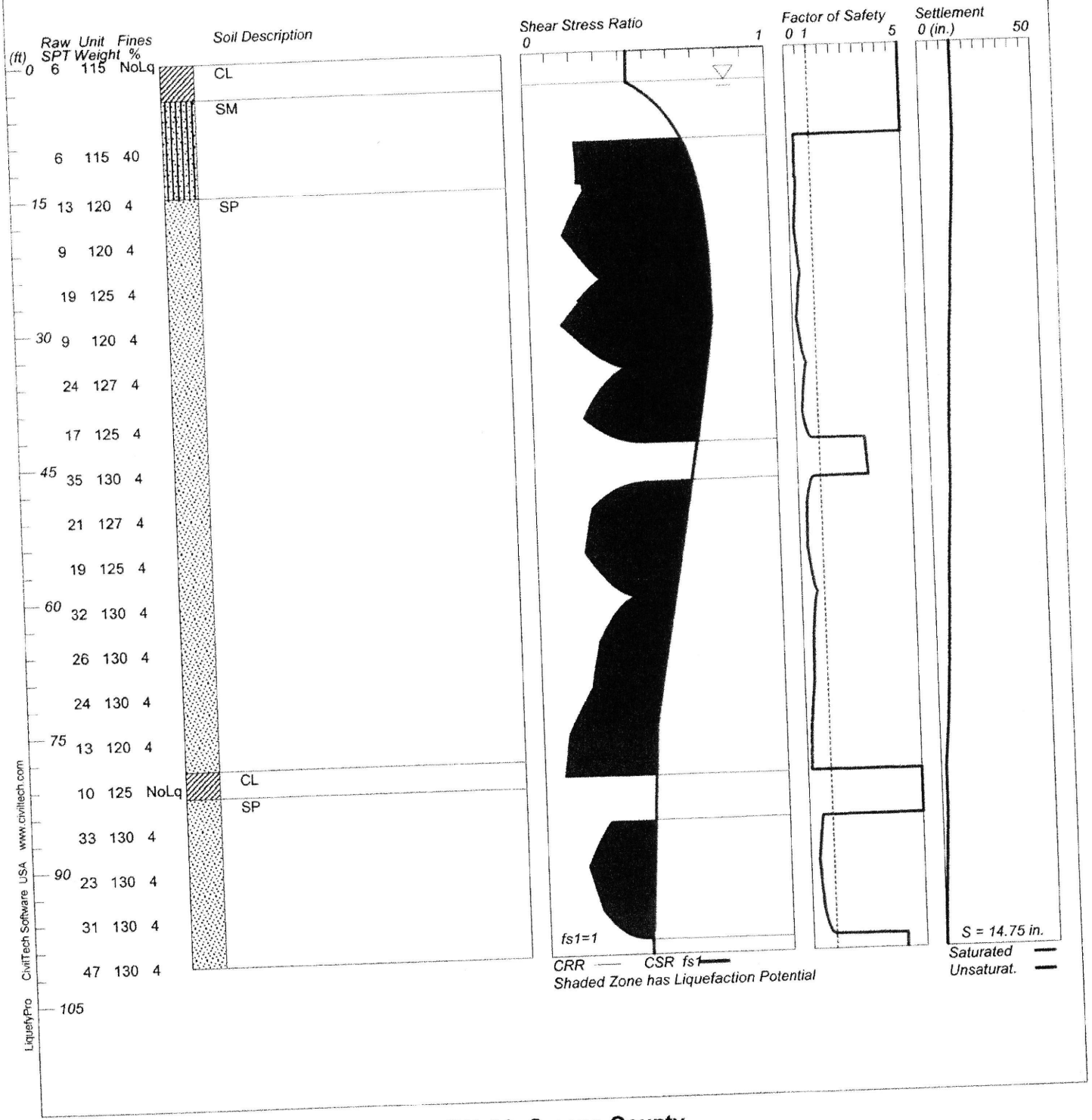
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100478

Hole No.=6A Water Depth=3.5 ft Surface Elev.=239.0

Magnitude=7.5
Acceleration=0.667g



BN-6A, Greene County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-100478

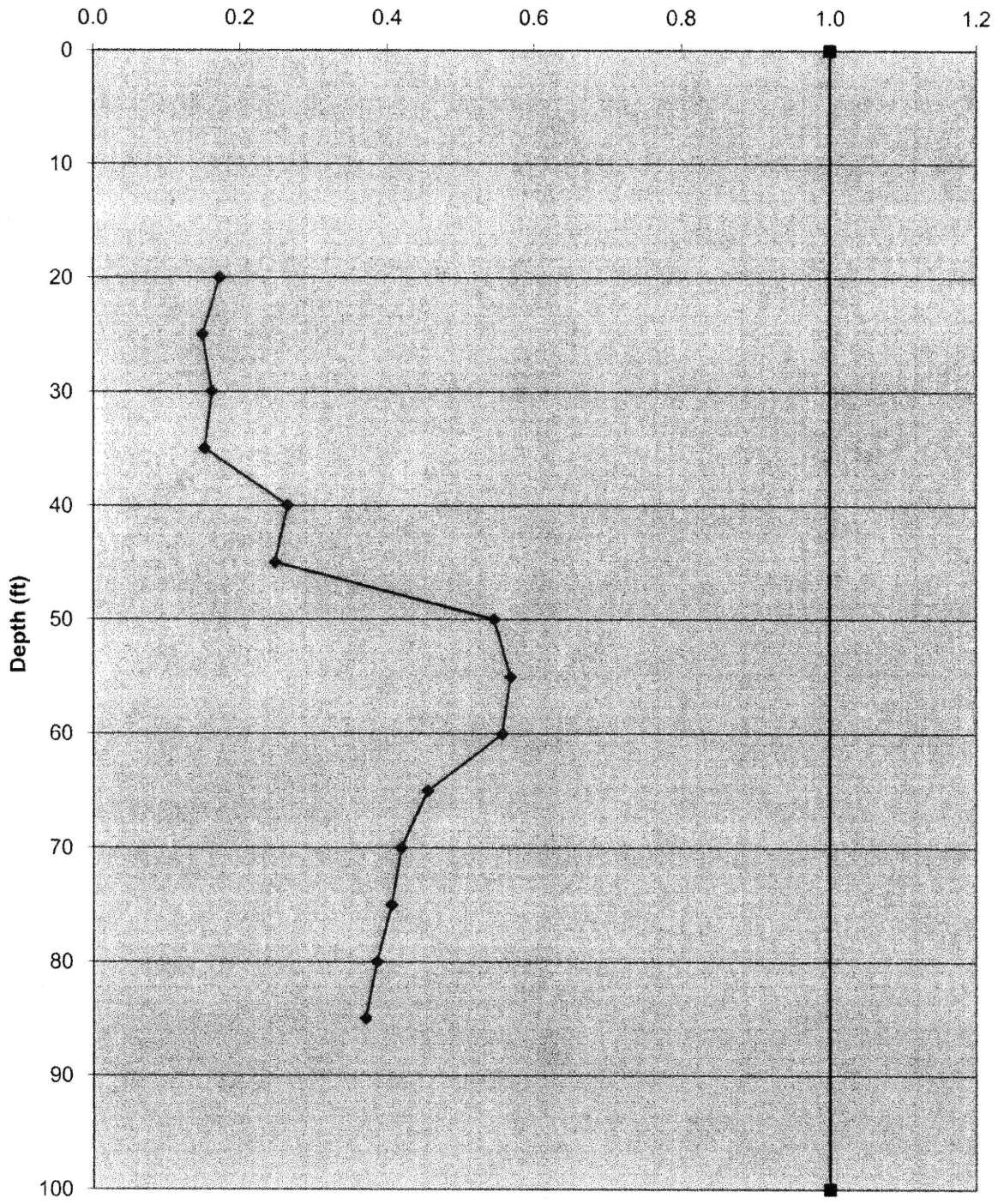
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	0.667	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	11	ft	assumed depth to groundwater =	11	ft
estimated age of sand deposit =	2000	years			

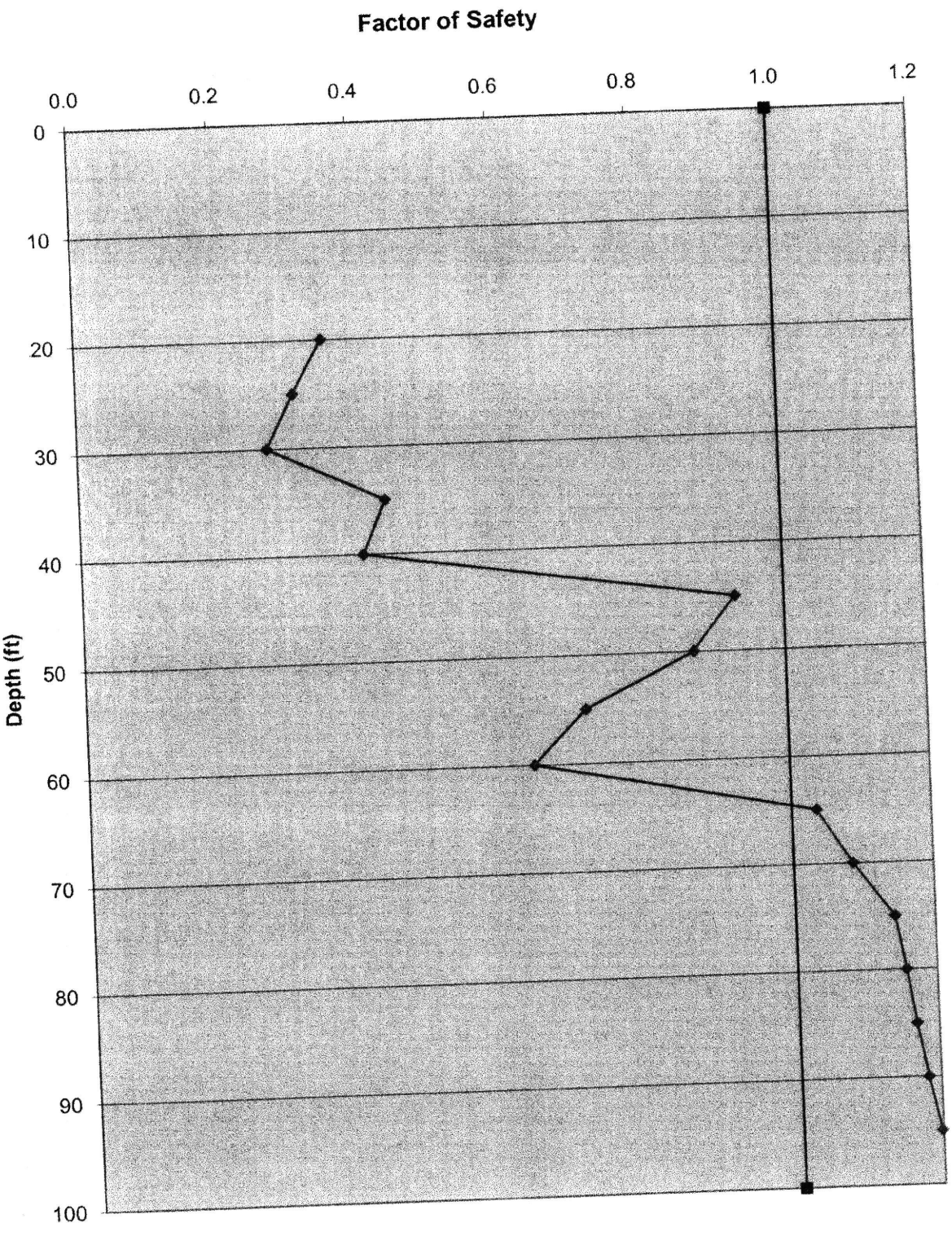
	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	120	623	60	12	600	600	600	0.988	0.4285	842	NA	1.00	1.00	NA	NA
10	1	120	509	60	12	1200	1200	1200	0.977	0.4234	578	NA	1.00	1.00	NA	NA
15	1	115	525	60	12	1775	1525	1525	0.965	0.4868	562	NA	1.00	1.00	NA	NA
20	2	115	525	5	0	2350	1788	1788	0.953	0.5431	540	0.0935	1.00	1.00	0.0935	0.2
25	2	120	525	5	0	2950	2076	2076	0.942	0.5800	520	0.0861	1.00	1.00	0.086051	0.1
30	2	125	574	5	0	3575	2389	2389	0.930	0.6033	549	0.0972	1.00	1.00	0.097143	0.2
35	2	125	574	5	0	4200	2702	2702	0.889	0.5990	532	0.0906	1.00	1.00	0.090614	0.2
40	2	130	722	5	0	4850	3040	3040	0.848	0.5867	650	0.1554	1.00	1.00	0.15538	0.3
45	2	130	722	5	0	5500	3378	3378	0.808	0.5700	633	0.1414	1.00	1.00	0.141348	0.2
50	2	127	919	4	0	6135	3701	3701	0.767	0.5510	788	0.3000	1.00	1.00	0.299946	0.5
55	2	139	919	4	0	6785	4039	4039	0.726	0.5288	771	0.3000	1.00	1.00	0.299946	0.6
60	2	130	853	4	0	7435	4377	4377	0.685	0.5047	701	0.2806	1.00	1.00	0.280553	0.6
65	2	130	853	4	0	8085	4715	4715	0.645	0.4792	688	0.2178	1.00	1.00	0.217712	0.5
70	2	130	853	4	0	8735	5053	5053	0.604	0.4526	677	0.1896	1.00	1.00	0.189567	0.4
75	2	130	853	4	0	9385	5391	5391	0.563	0.4251	666	0.1726	1.00	1.00	0.172618	0.4
80	2	130	853	4	0	10035	5729	5729	0.549	0.4167	656	0.1608	1.00	1.00	0.160799	0.4
85	2	130	853	4	0	10685	6067	6067	0.537	0.4097	646	0.1518	1.00	1.00	0.151819	0.4
90	1	130	951	60	12	11335	6405	6405	0.524	0.4023	711	NA	1.00	1.00	NA	NA
95	1	130	951	60	12	11985	6743	6743	0.512	0.3947	702	NA	1.00	1.00	NA	NA
100	2	130	951	4	0	12635	7081	7081	0.500	0.3868	693	0.2353	1.00	1.00	0.235266	0.6

Used Bore #5 for PI values, water depth, & unit wt.

Vs Liquefaction Potential - Project 100478



Vs Liquefaction Potential - Project BR1108

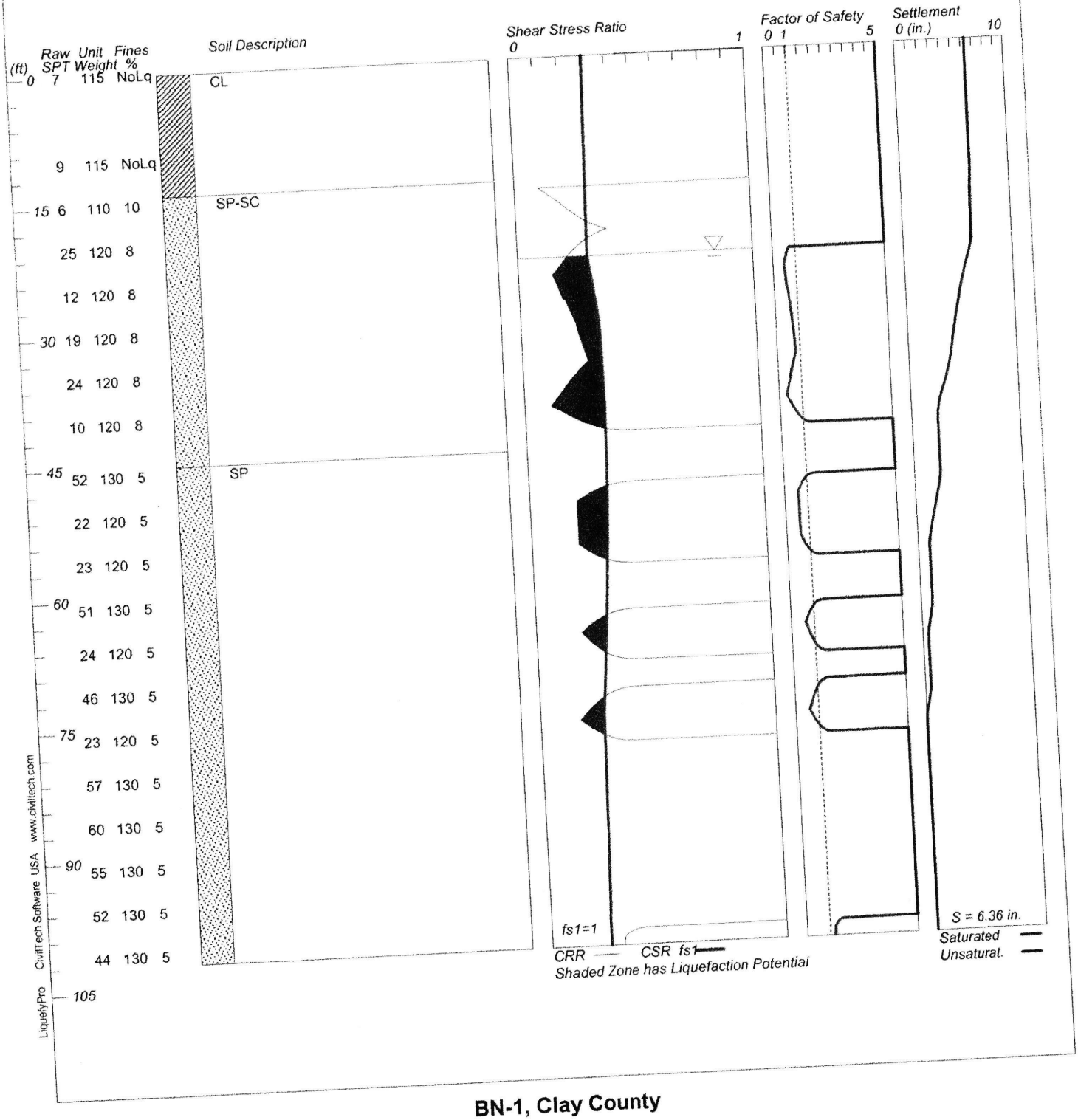


LIQUEFACTION ANALYSIS (ALT.A)

BR1108

Hole No.=1 **Water Depth=23 ft** **Surface Elev.=294.9**

Magnitude=7.5
Acceleration=0.470g



BN-1, Clay County

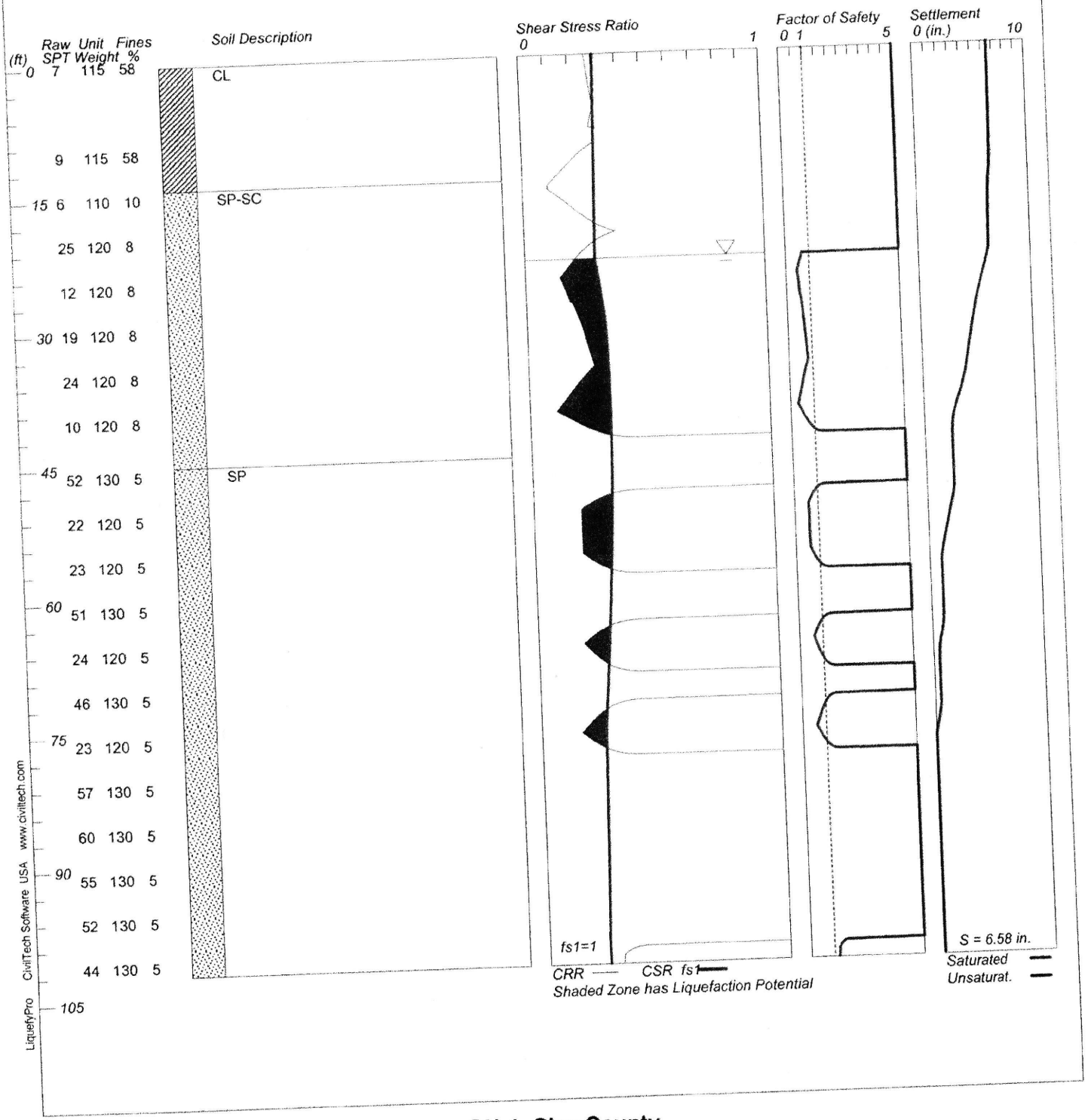
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

BR1108

Hole No.=1 **Water Depth=23 ft** **Surface Elev.=294.9**

Magnitude=7.5
Acceleration=0.470g



BN-1, Clay County

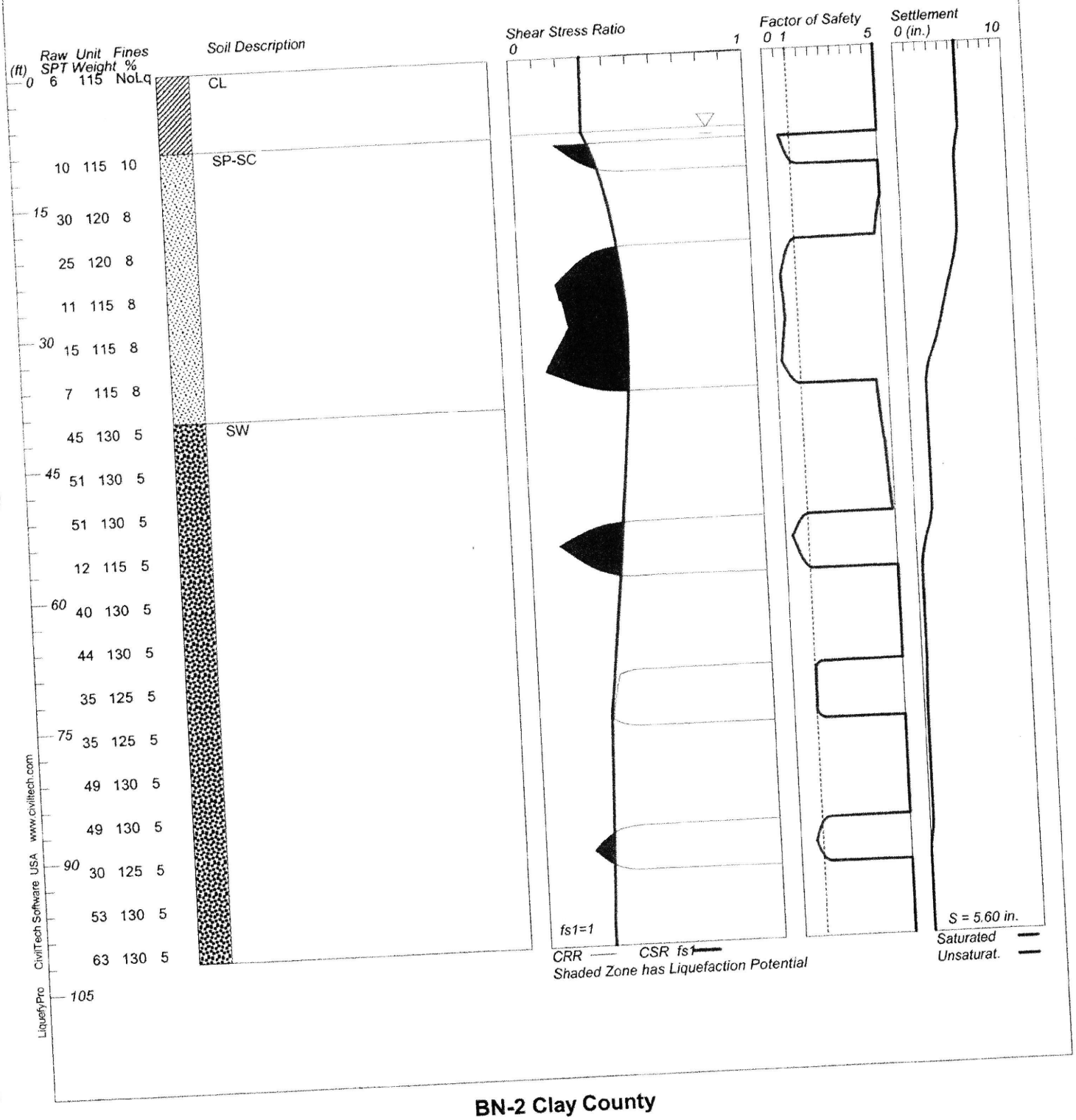
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

BR1108

Hole No.=2 **Water Depth=8.67 ft** **Surface Elev.=288.9**

Magnitude=7.5
Acceleration=0.470g



BN-2 Clay County

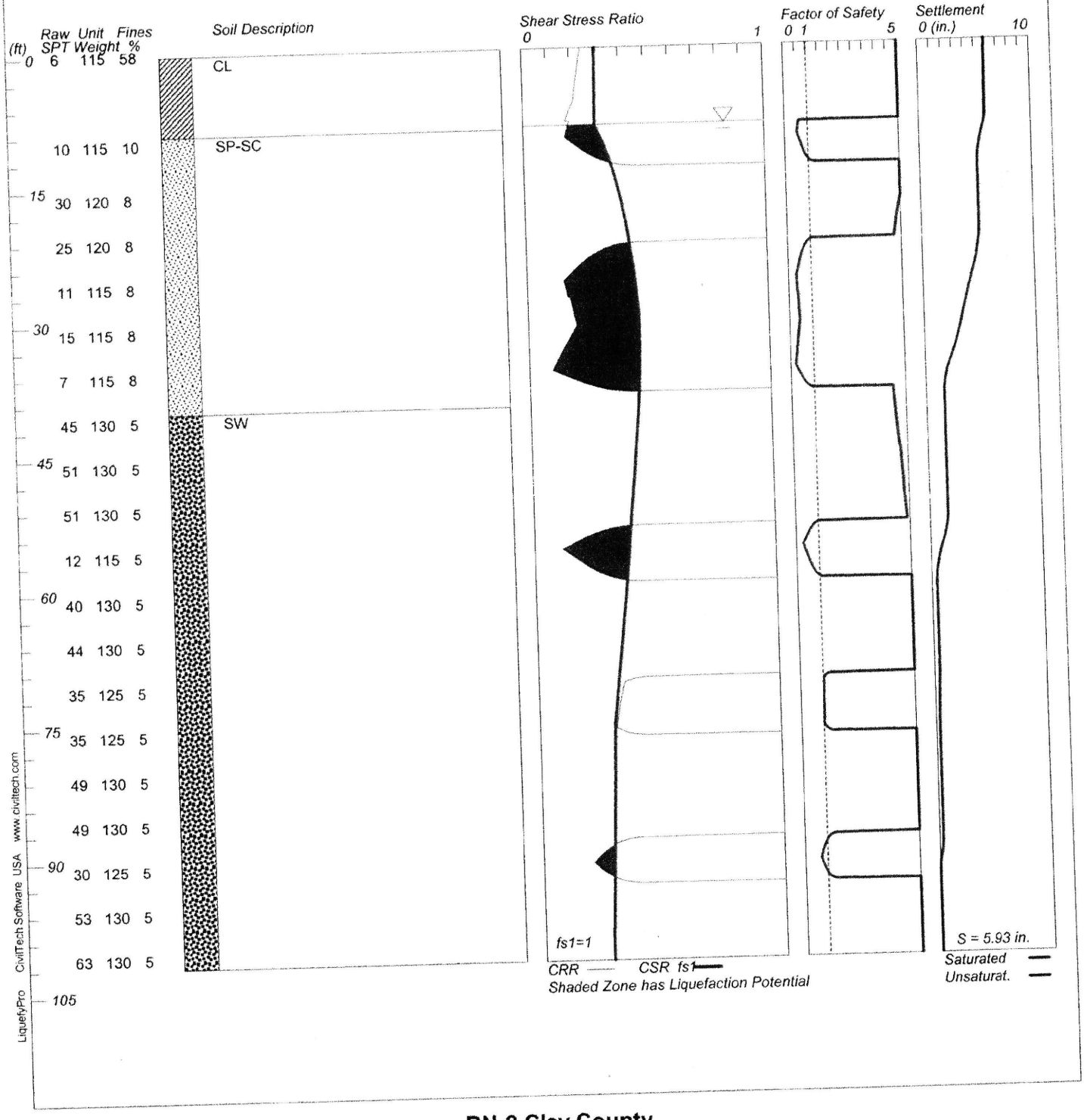
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

BR1108

Hole No.=2 Water Depth=8.67 ft Surface Elev.=288.9

Magnitude=7.5
Acceleration=0.470g



BN-2 Clay County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-BR1108

note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5	depth to finish floor =	0 ft
PGA =	0.47 g	uniform floor load =	0 lb/ft^2
depth to groundwater during drilling =	25 ft	assumed depth to groundwater =	25 ft
estimated age of sand deposit =	2000 years		

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	115	344	58	20	575	575	575	0.988	0.3019	470	NA	1.00	1.00	NA	NA
10	1	115	410	58	20	1150	1150	1150	0.977	0.2984	471	NA	1.00	1.00	NA	NA
15	1	110	509	58	20	1700	1700	1700	0.965	0.2948	530	NA	1.00	1.00	NA	NA
20	2	120	574	10	20	2300	2300	2300	0.953	0.2912	554	0.1034	1.00	1.00	0.103421	0.4
25	2	120	574	8	0	2900	2900	2900	0.942	0.2877	523	0.0899	1.00	1.00	0.089893	0.3
30	2	120	574	8	0	3500	3188	3188	0.930	0.3119	511	0.0852	1.00	1.00	0.085135	0.3
35	2	120	705	8	0	4100	3476	3476	0.889	0.3203	614	0.1405	1.00	1.00	0.140505	0.4
40	2	120	705	8	0	4700	3764	3764	0.848	0.3236	602	0.1309	1.00	1.00	0.130869	0.4
45	2	130	853	5	0	5350	4102	4102	0.808	0.3218	713	0.3000	1.00	1.00	0.299946	0.9
50	2	120	853	5	0	5950	4390	4390	0.767	0.3175	701	0.2768	1.00	1.00	0.276736	0.9
55	2	120	853	5	0	6550	4678	4678	0.726	0.3106	690	0.2222	1.00	1.00	0.222133	0.7
60	2	130	853	5	0	7200	5016	5016	0.685	0.3006	678	0.1920	1.00	1.00	0.191949	0.6
65	2	120	1033	5	0	7800	5304	5304	0.645	0.2896	809	0.3000	1.00	1.00	0.299946	1.0
70	2	130	1033	5	0	8450	5642	5642	0.604	0.2763	797	0.3000	1.00	1.00	0.299946	1.1
75	2	120	1033	5	0	9050	5930	5930	0.563	0.2626	787	0.3000	1.00	1.00	0.299946	1.1
80	2	130	1033	5	0	9700	6268	6268	0.549	0.2595	776	0.3000	1.00	1.00	0.299946	1.2
85	2	130	1033	5	0	10350	6606	6606	0.537	0.2568	766	0.3000	1.00	1.00	0.299946	1.2
90	2	130	1312	5	0	11000	6944	6944	0.524	0.2538	961	0.3000	1.00	1.00	0.299946	1.2
95	2	130	1312	5	0	11650	7282	7282	0.512	0.2503	950	0.3000	1.00	1.00	0.299946	1.2
100	2	130	1312	5	0	12300	7620	7620	0.500	0.2466	939	0.3000	1.00	1.00	0.299946	1.2

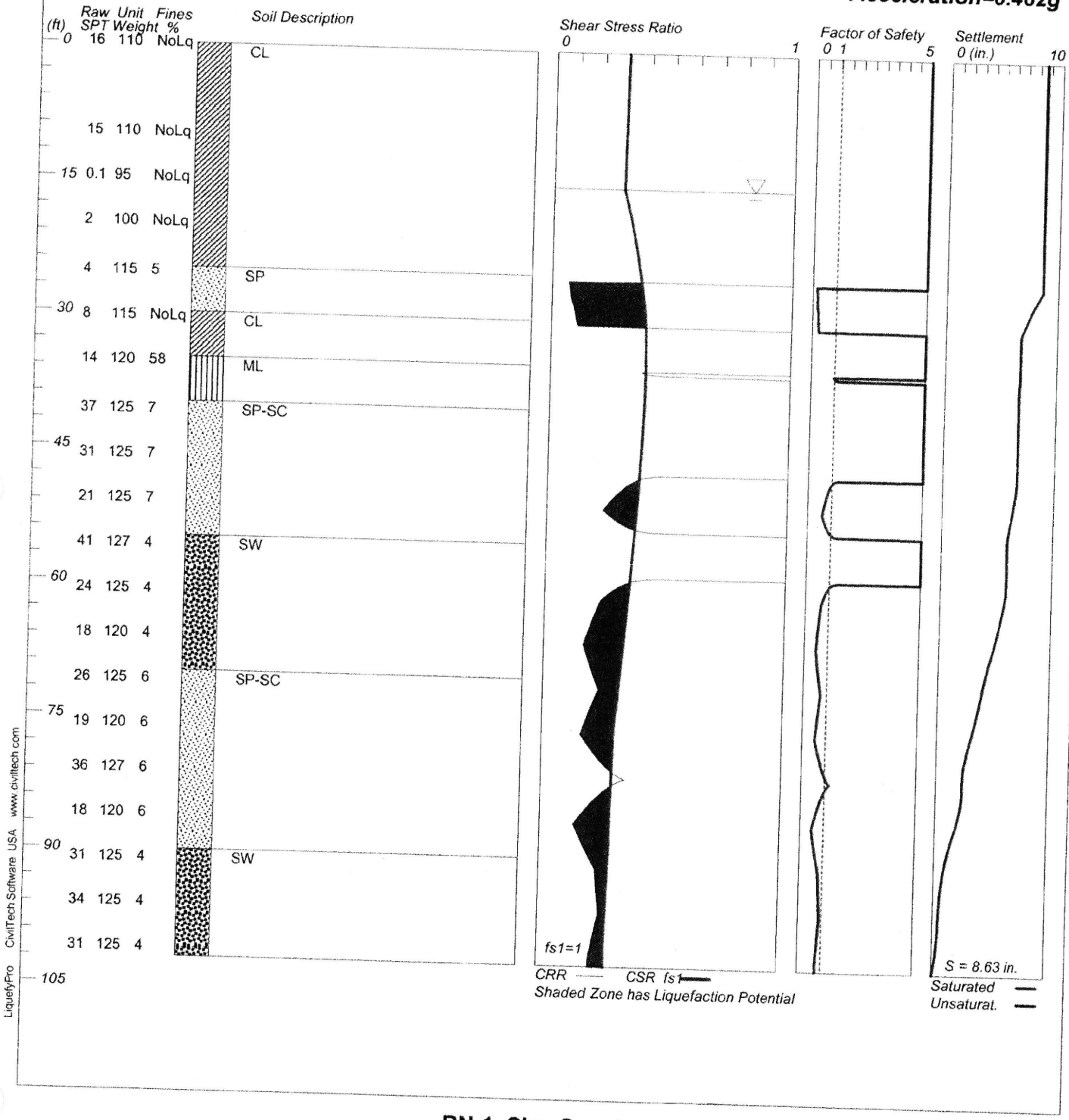
Used Bore #1 for PI values & unit wt.

LIQUEFACTION ANALYSIS (ALT.A)

BR1110

Hole No.=1 Water Depth=15.2 ft Surface Elev.=298.6

Magnitude=7.5
Acceleration=0.462g



BN-1, Clay County

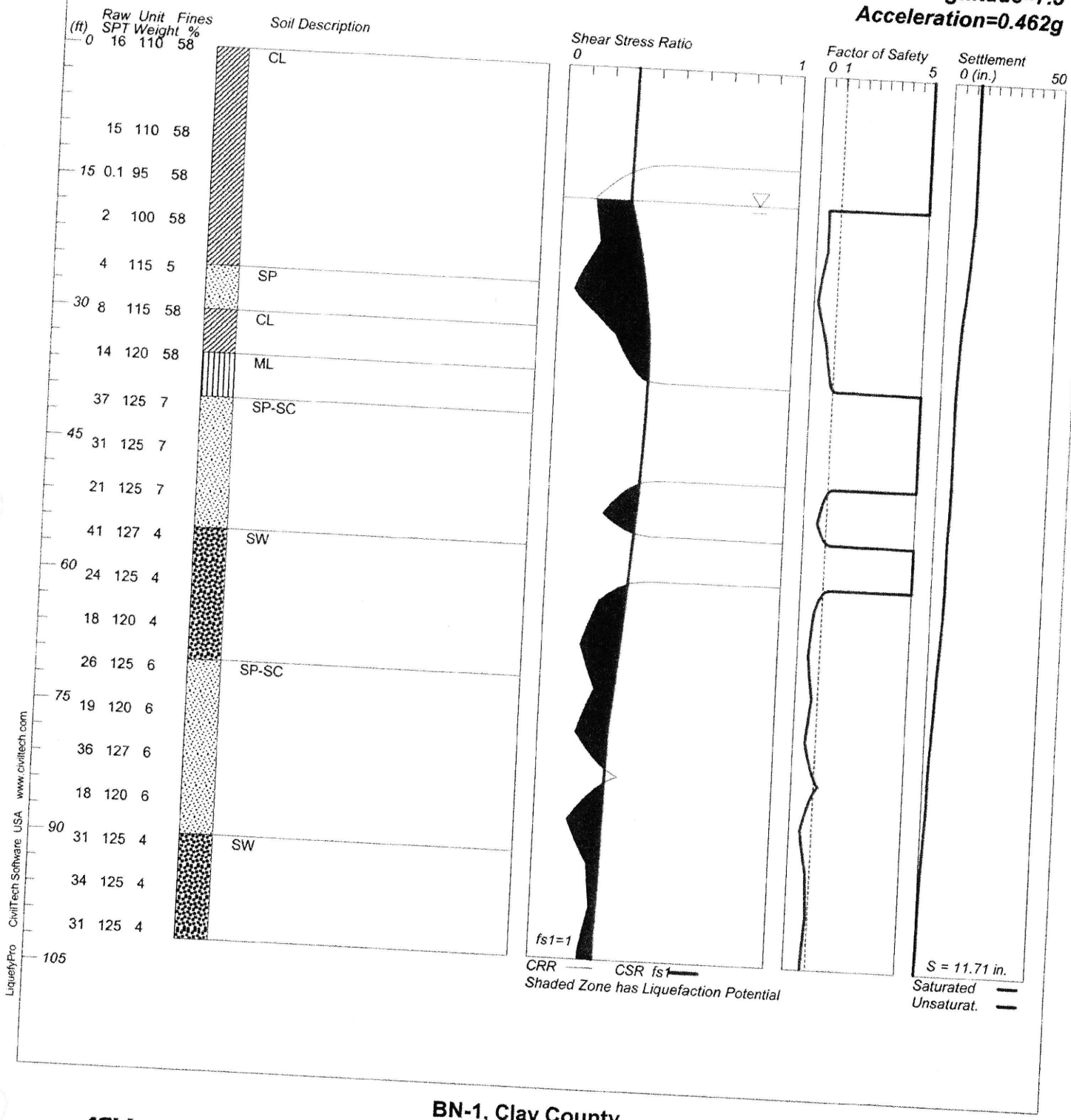
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

BR1110

Hole No.=1 Water Depth=15.2 ft Surface Elev.=298.6

Magnitude=7.5
Acceleration=0.462g



BN-1, Clay County

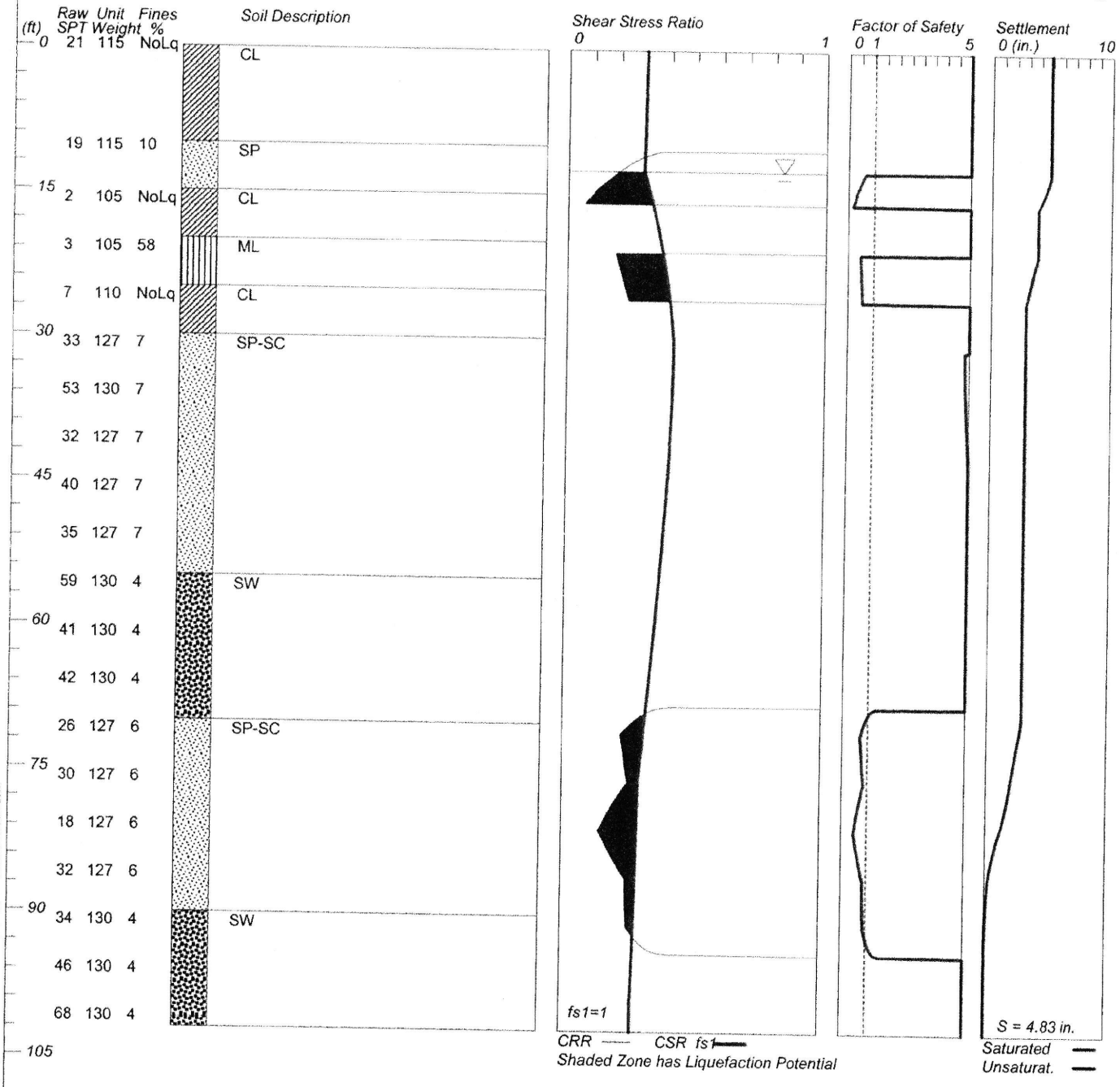
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

BR1110

Hole No.=2 Water Depth=12.6 ft Surface Elev.=296.0

Magnitude=7.5
Acceleration=0.462g



BN-2, Clay County

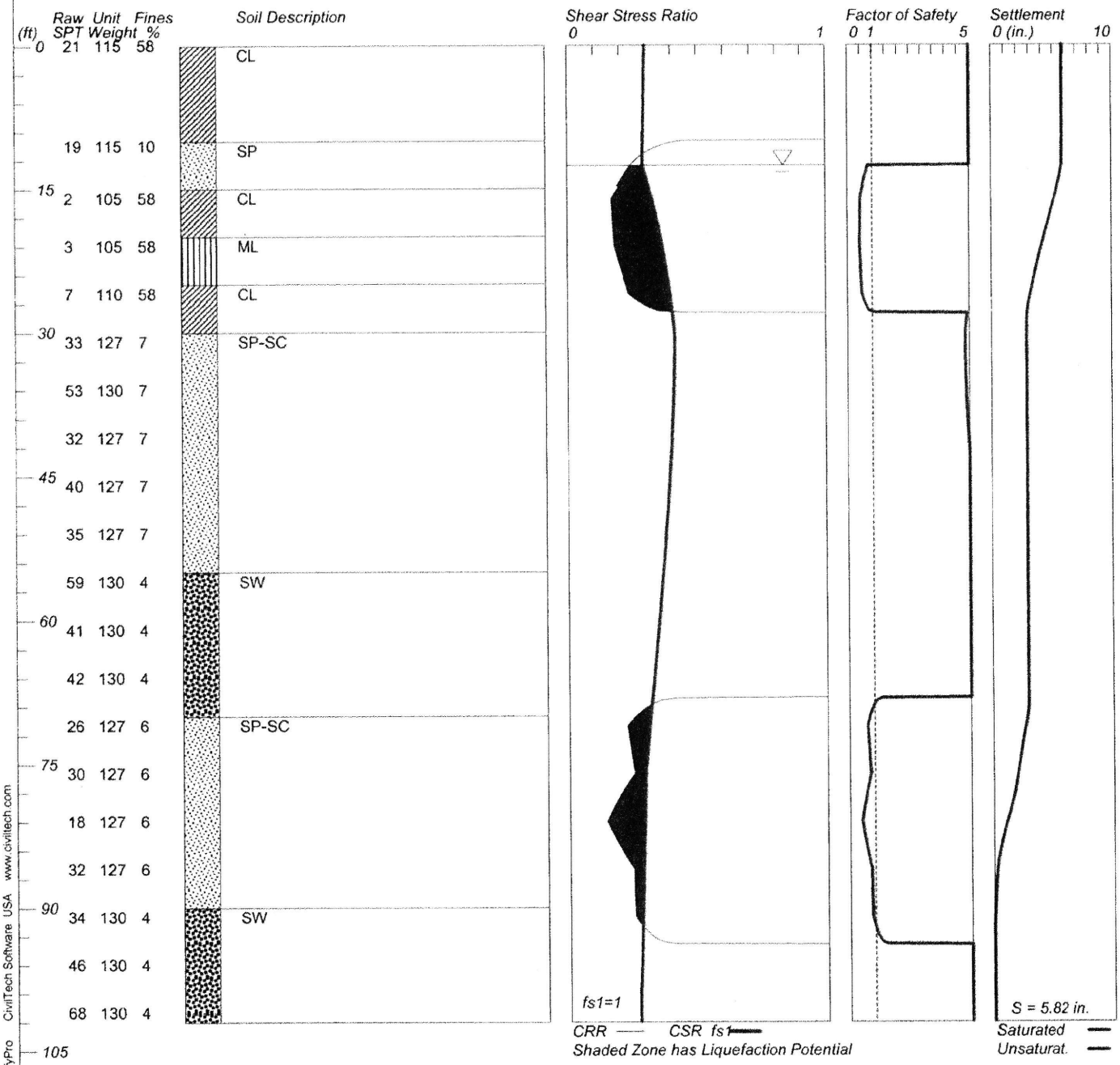
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

BR1110

Hole No.=2 Water Depth=12.6 ft Surface Elev.=296.0

Magnitude=7.5
Acceleration=0.462g



BN-2, Clay County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-BR1110

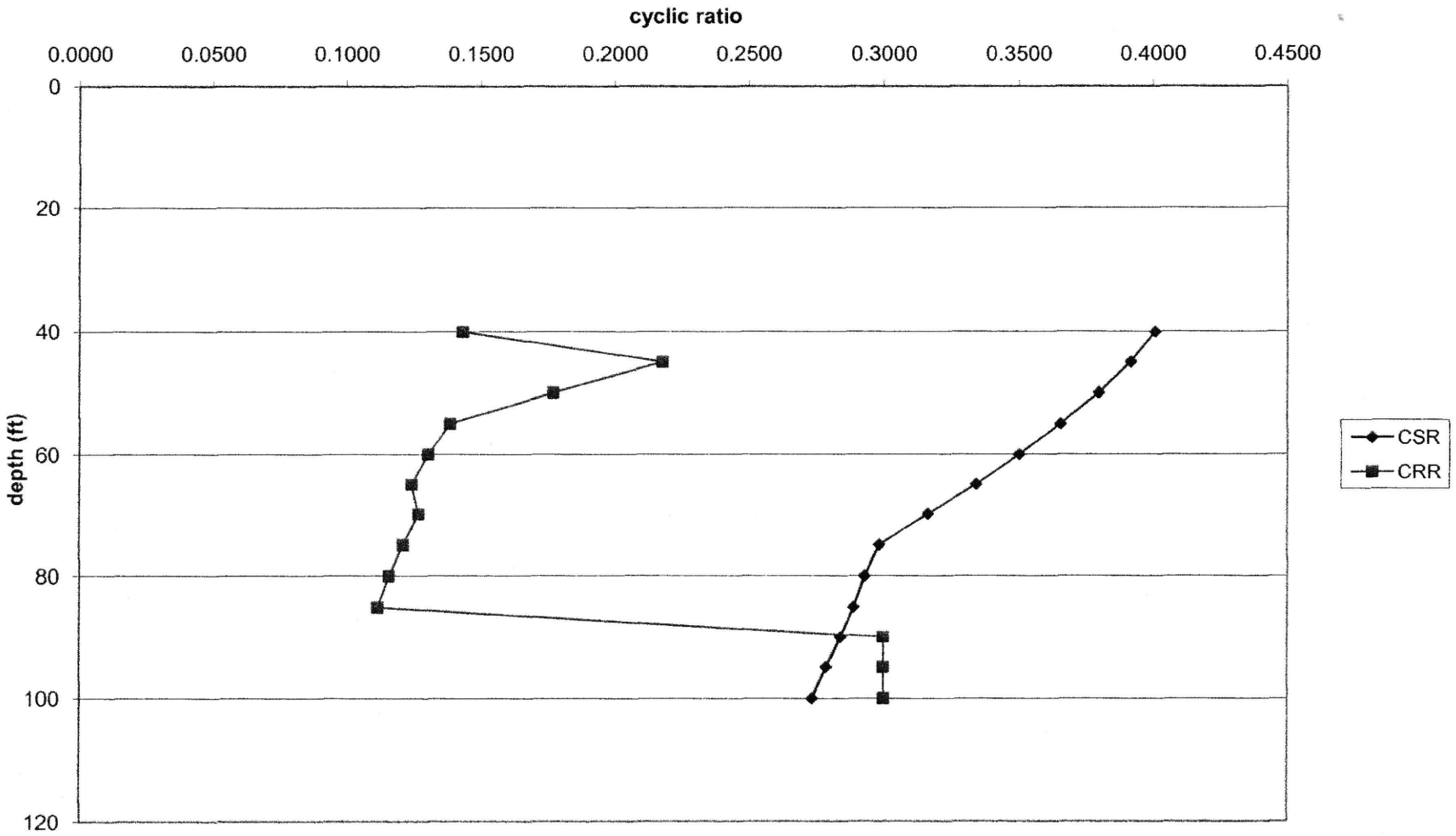
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	0.462	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	14	ft	assumed depth to groundwater =	14	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	110	374	58	5	550	550	550	0.988	0.2968	516	NA	1.00	1.00	NA	NA
10	1	110	371	58	5	1100	1100	1100	0.977	0.2933	431	NA	1.00	1.00	NA	NA
15	1	95	427	58	5	1575	1513	1513	0.965	0.3017	458	NA	1.00	1.00	NA	NA
20	1	100	492	58	5	2075	1701	1701	0.953	0.3493	512	NA	1.00	1.00	NA	NA
25	1	115	558	58	5	2650	1964	1964	0.942	0.3816	561	NA	1.00	1.00	NA	NA
30	1	115	591	58	5	3225	2227	2227	0.930	0.4045	575	NA	1.00	1.00	NA	NA
35	1	120	591	58	5	3825	2515	2515	0.889	0.4061	558	NA	1.00	1.00	NA	NA
40	2	125	673	7	0	4450	2828	2828	0.848	0.4009	617	0.1434	1.00	1.00	0.143359	0.4
45	2	125	738	7	0	5075	3141	3141	0.808	0.3919	659	0.2179	1.00	1.00	0.217823	0.6
50	2	125	738	7	0	5700	3454	3454	0.767	0.3801	644	0.1773	1.00	1.00	0.177316	0.5
55	2	127	738	4	0	6335	3777	3777	0.726	0.3658	630	0.1387	1.00	1.00	0.138657	0.4
60	2	125	738	4	0	6960	4090	4090	0.685	0.3503	617	0.1305	1.00	1.00	0.13051	0.4
65	2	120	738	4	0	7560	4378	4378	0.645	0.3343	607	0.1244	1.00	1.00	0.12438	0.4
70	2	125	738	6	0	8185	4691	4691	0.604	0.3165	596	0.1270	1.00	1.00	0.126958	0.4
75	2	120	738	6	0	8785	4979	4979	0.563	0.2985	588	0.1213	1.00	1.00	0.12125	0.4
80	2	127	738	6	0	9420	5302	5302	0.549	0.2928	578	0.1159	1.00	1.00	0.11584	0.4
85	2	120	738	6	0	10020	5590	5590	0.537	0.2889	571	0.1117	1.00	1.00	0.111675	0.4
90	2	125	984	6	0	10645	5903	5903	0.524	0.2840	751	0.3000	1.00	1.00	0.299946	1.1
95	2	125	984	4	0	11270	6216	6216	0.512	0.2789	741	0.3000	1.00	1.00	0.299946	1.1
100	2	125	984	4	0	11895	6529	6529	0.500	0.2736	732	0.3000	1.00	1.00	0.299946	1.1

Used Bore #1 for PI values & unit wt.

Cyclic Stress Ratio vs. Cyclic Resistance Ratio
Project BR1110: Shear Wave Velocity Analysis

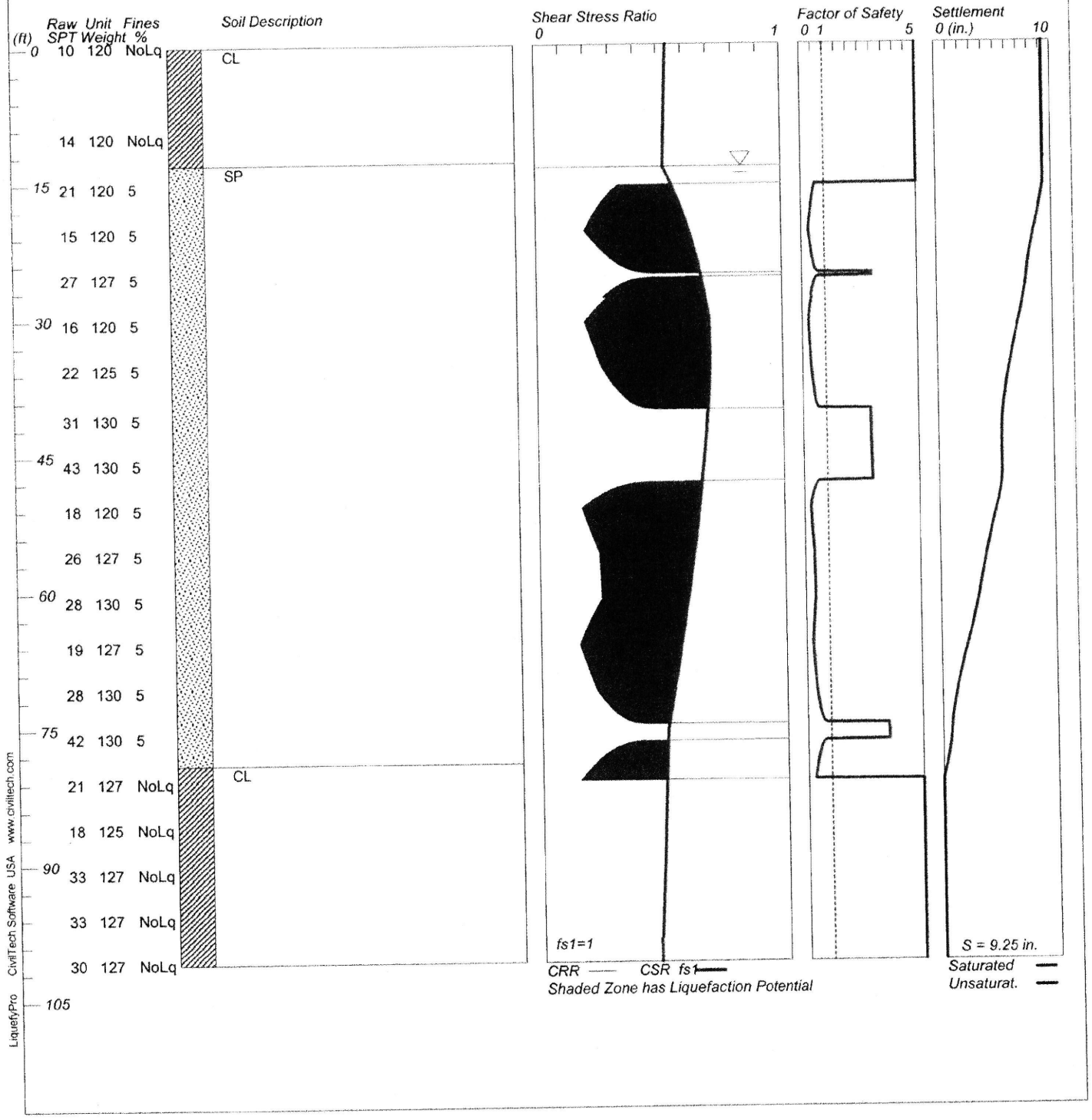


LIQUEFACTION ANALYSIS

100303

Hole No.=1 Water Depth=13.5 ft Surface Elev.=236.8

Magnitude=7.5
Acceleration=0.830g



BN-1, Craighead County

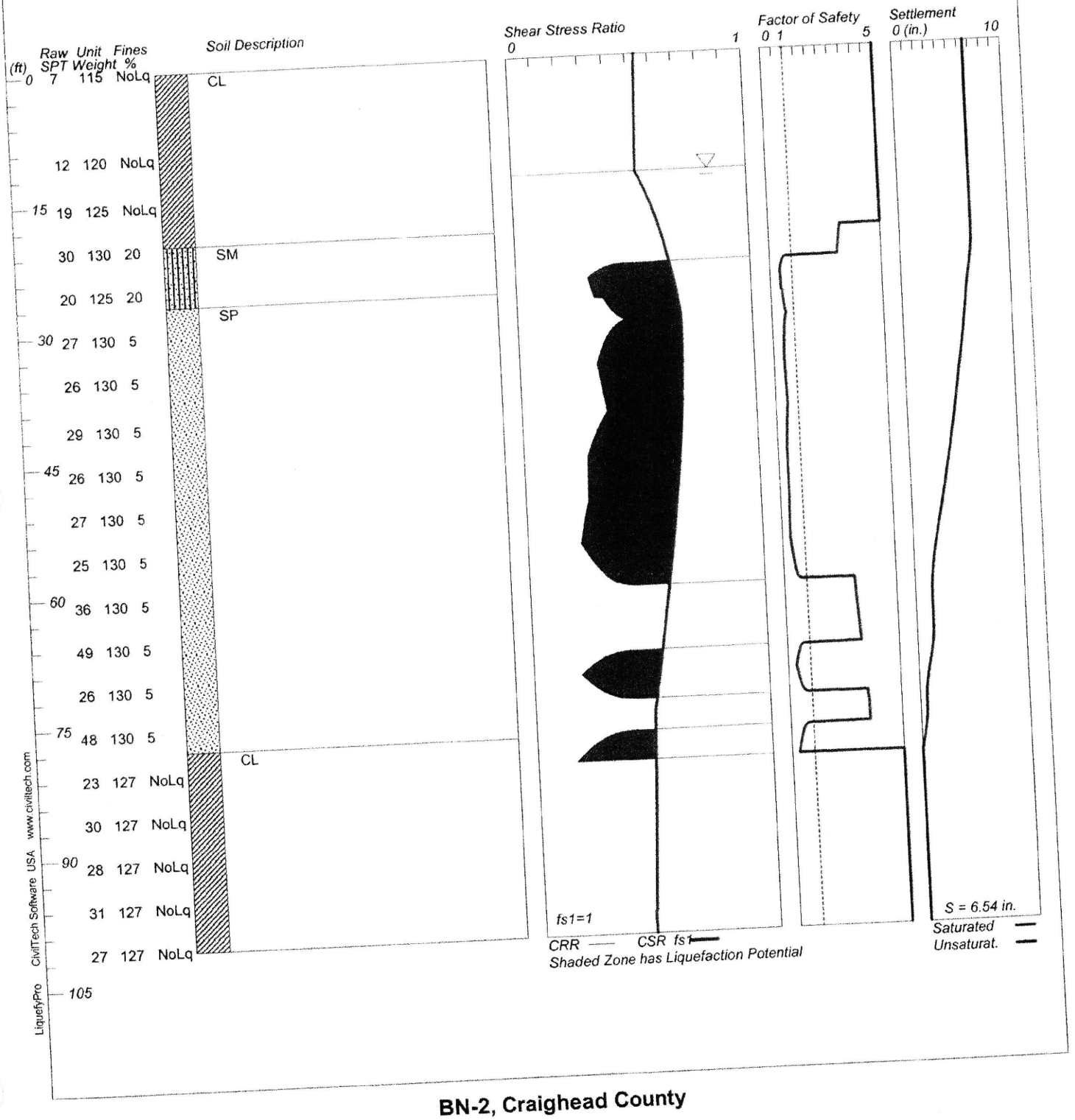
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100303

Hole No.=2 **Water Depth=13.5 ft** **Surface Elev.=236.8**

Magnitude=7.5
Acceleration=0.830g



BN-2, Craighead County

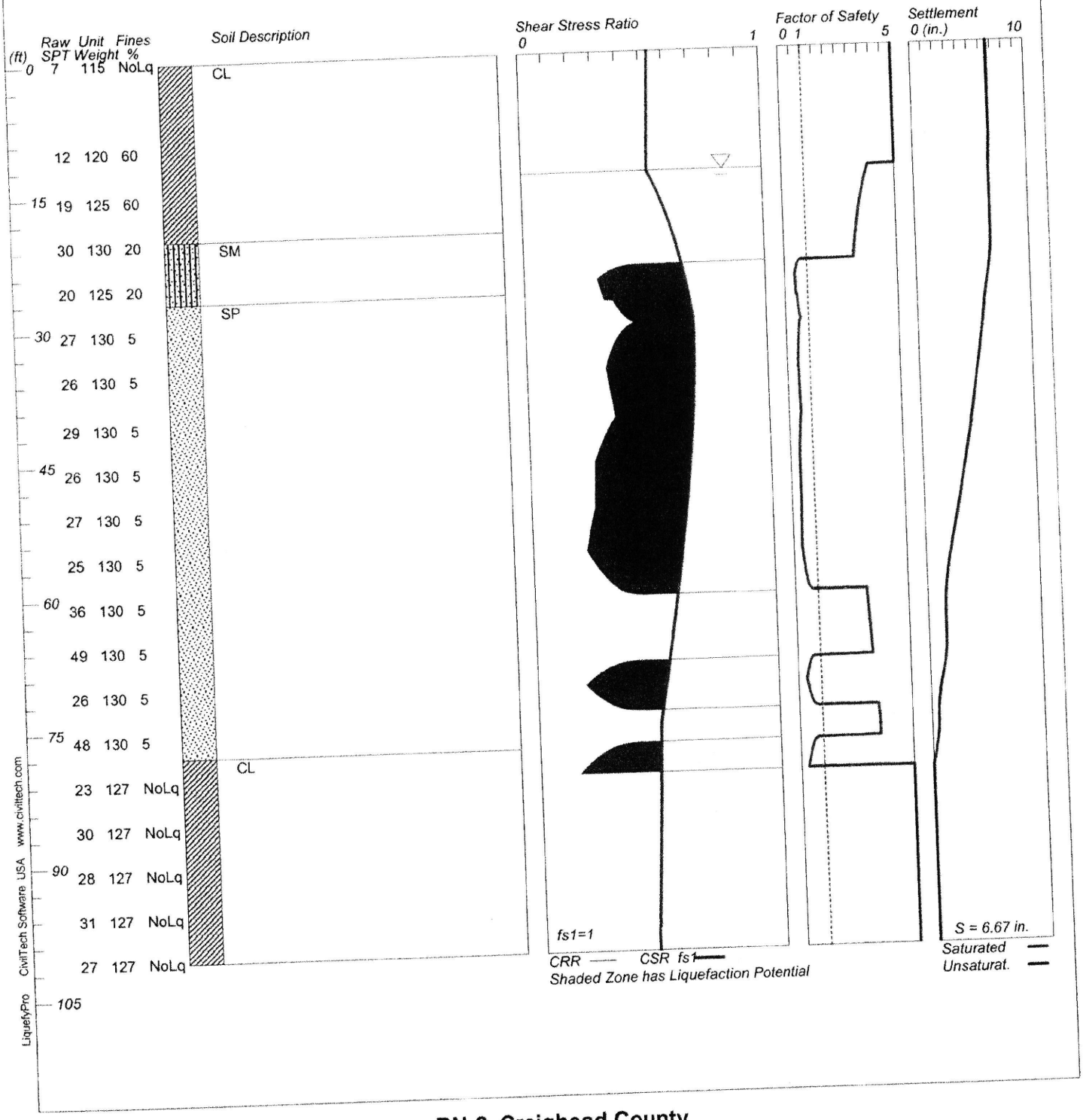
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100303

Hole No.=2 Water Depth=13.5 ft Surface Elev.=236.8

Magnitude=7.5
Acceleration=0.830g



BN-2, Craighead County

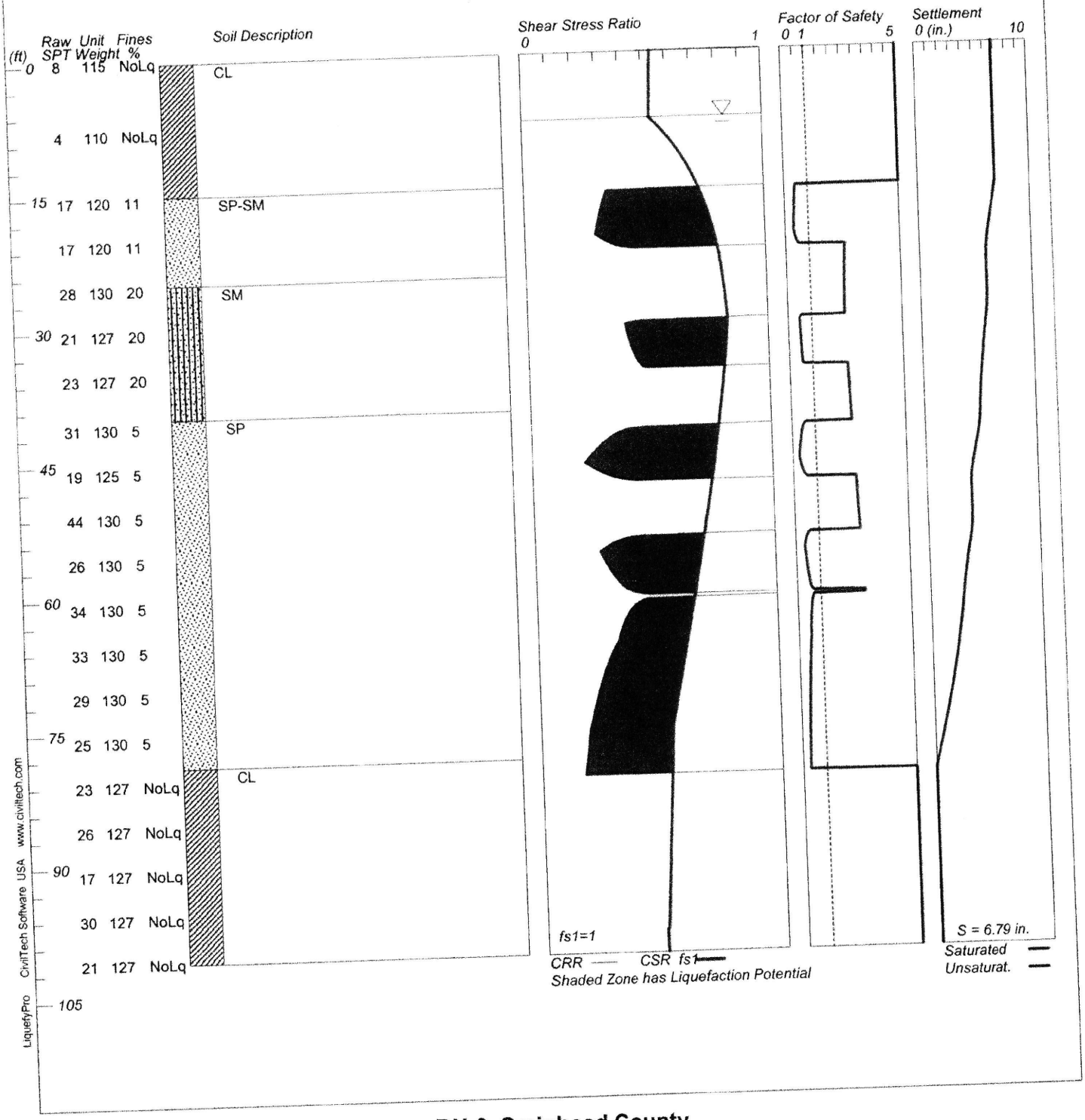
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100303

Hole No.=3 Water Depth=7.5 ft Surface Elev.=231.4

Magnitude=7.5
Acceleration=0.830g



BN-3, Craighead County

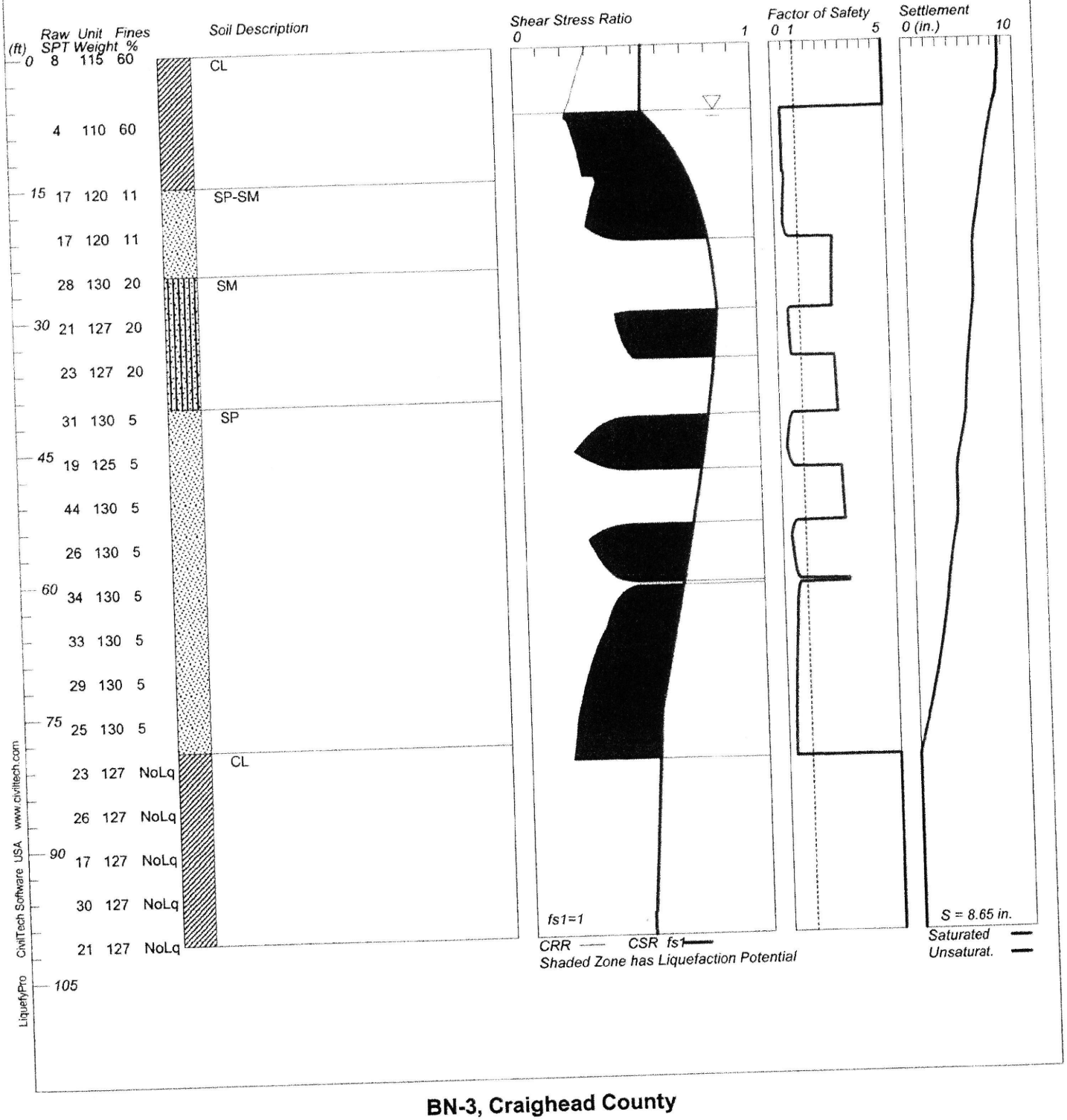
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100303

Hole No.=3 Water Depth=7.5 ft Surface Elev.=231.4

Magnitude=7.5
Acceleration=0.830g



BN-3, Craighead County

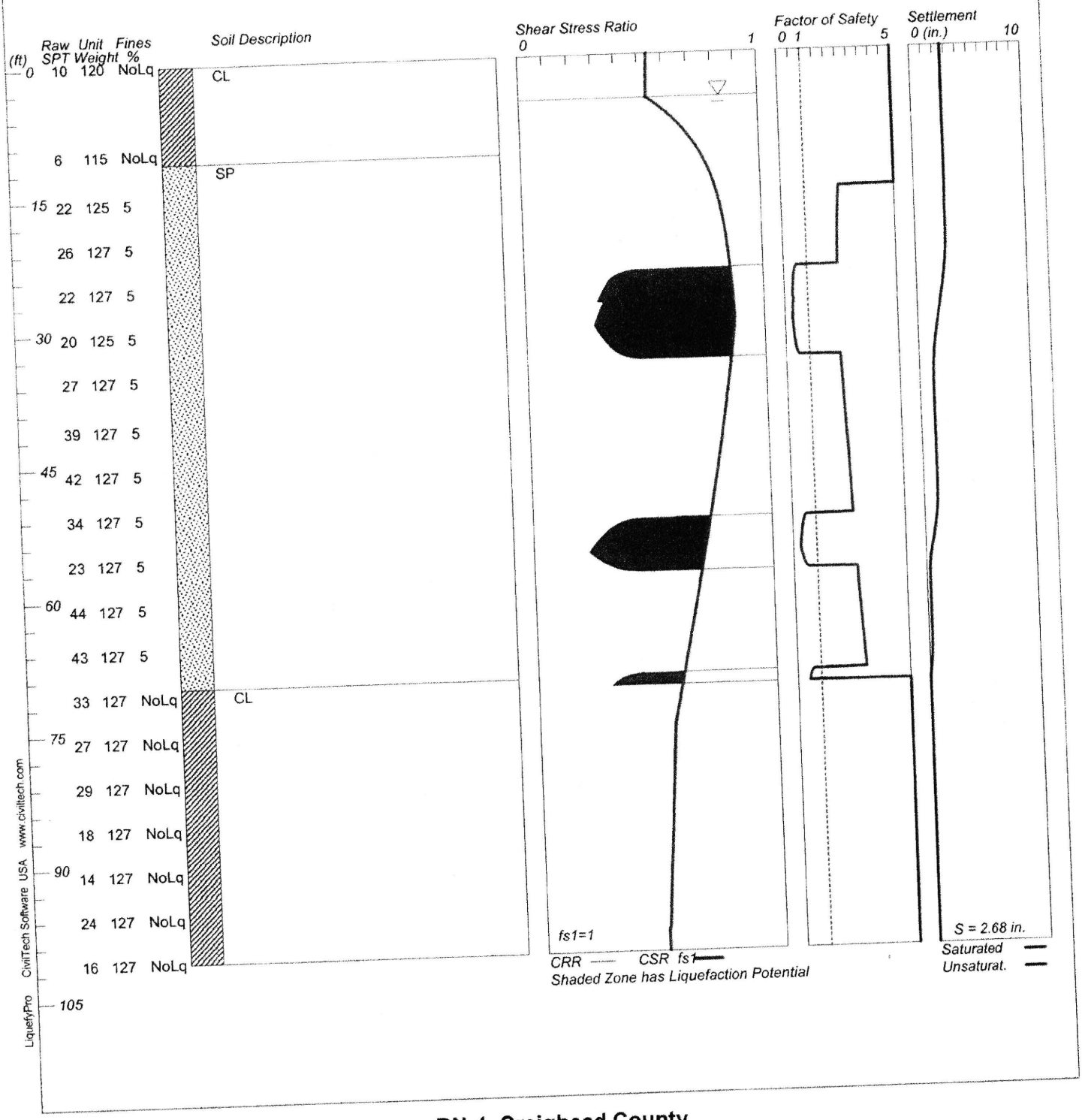
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100303

Hole No.=4 Water Depth=5 ft Surface Elev.=230.9

Magnitude=7.5
Acceleration=0.830g



BN-4, Craighead County

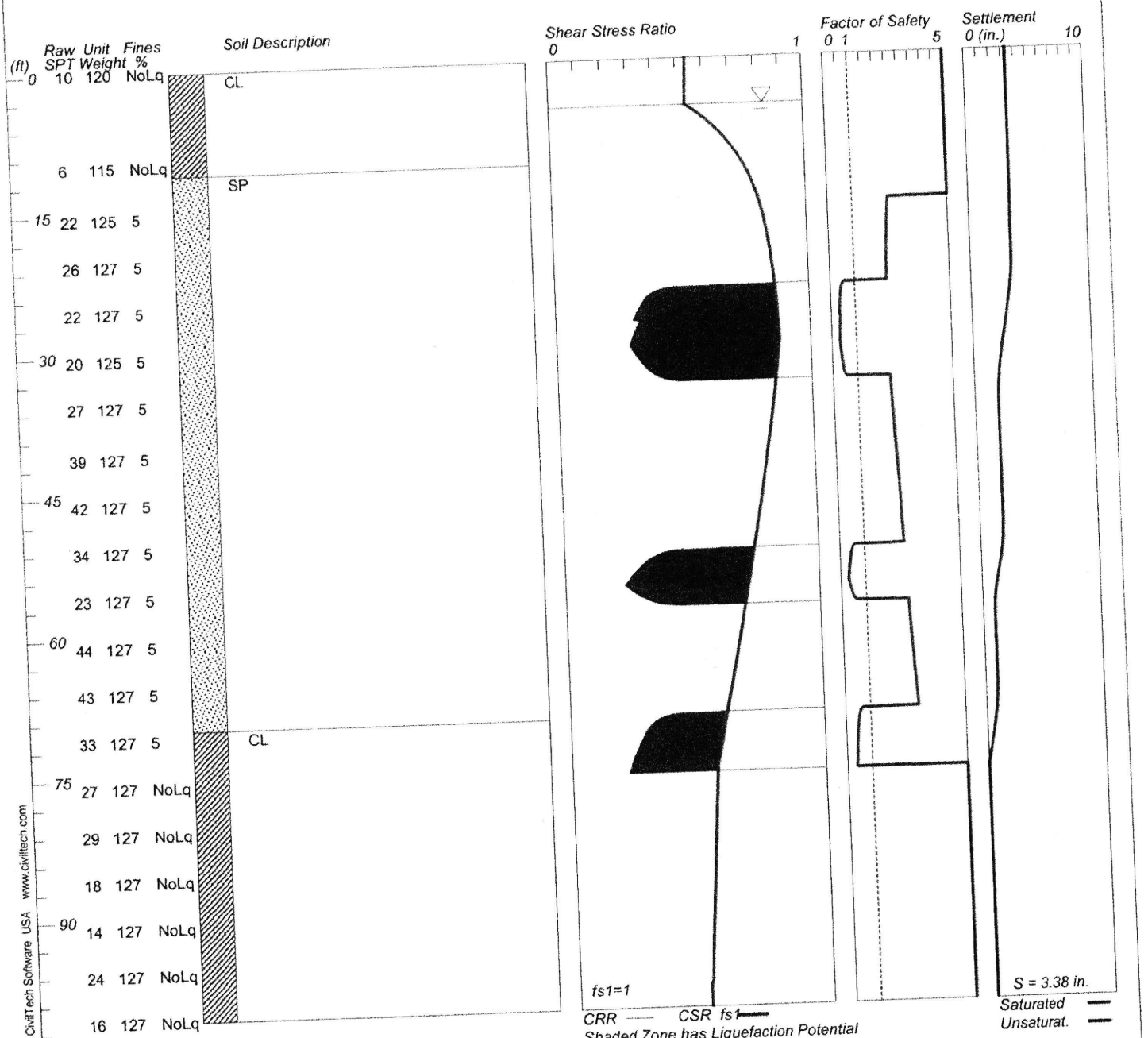
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100303

Hole No.=4 Water Depth=5 ft Surface Elev.=230.9

Magnitude=7.5
Acceleration=0.830g



BN-4, Craighead County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-100303

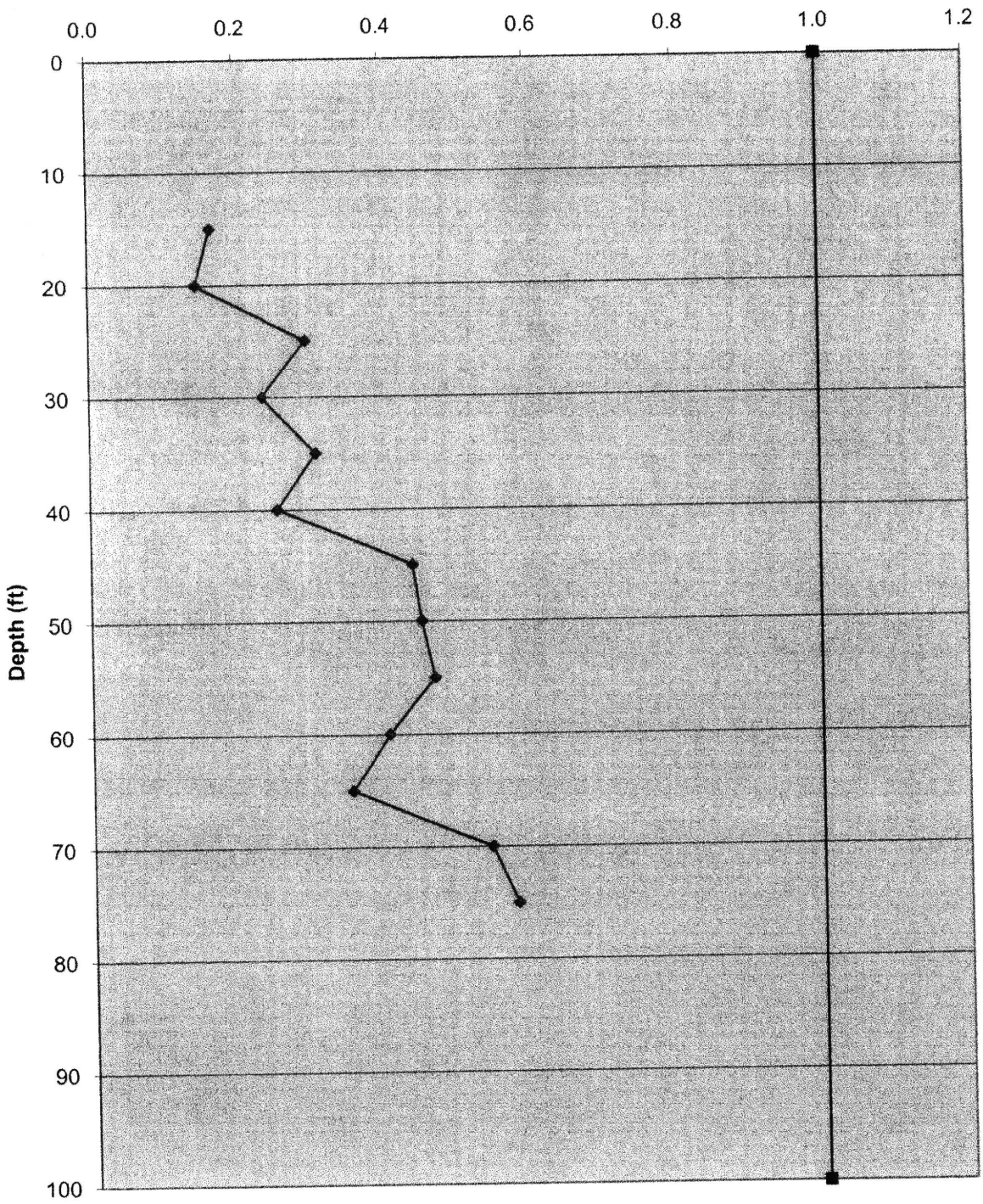
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	0.83	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	13	ft	assumed depth to groundwater =	13	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	120	640	60	13	600	600	600	0.988	0.5332	865	NA	1.00	1.00	NA	NA
10	1	120	509	60	13	1200	1200	1200	0.977	0.5269	578	NA	1.00	1.00	NA	NA
15	2	120	509	7	0	1800	1675	1675	0.965	0.5594	532	0.0936	1.00	1.00	0.093558	0.2
20	2	120	525	7	0	2400	1963	1963	0.953	0.6288	527	0.0917	1.00	1.00	0.091654	0.1
25	2	127	705	4	0	3035	2286	2286	0.942	0.6744	682	0.2004	1.00	1.00	0.200323	0.3
30	2	120	705	4	0	3635	2574	2574	0.930	0.7085	662	0.1678	1.00	1.00	0.167801	0.2
35	2	125	755	4	0	4260	2887	2887	0.889	0.7076	689	0.2190	1.00	1.00	0.218998	0.3
40	2	130	755	5	0	4910	3225	3225	0.848	0.6967	670	0.1787	1.00	1.00	0.17864	0.3
45	2	130	853	5	0	5560	3563	3563	0.808	0.6798	738	0.3000	1.00	1.00	0.299946	0.4
50	2	120	853	5	0	6160	3851	3851	0.767	0.6617	724	0.3000	1.00	1.00	0.299946	0.5
55	2	127	853	5	0	6795	4174	4174	0.726	0.6377	710	0.3000	1.00	1.00	0.299946	0.5
60	2	130	853	5	0	7445	4512	4512	0.685	0.6101	696	0.2477	1.00	1.00	0.247635	0.4
65	2	127	853	5	0	8080	4835	4835	0.645	0.5812	684	0.2057	1.00	1.00	0.20571	0.4
70	2	130	919	5	0	8730	5173	5173	0.604	0.5499	725	0.3000	1.00	1.00	0.299946	0.5
75	2	130	919	5	0	9380	5511	5511	0.563	0.5172	713	0.3000	1.00	1.00	0.299946	0.6
80	1	127	919	93	13	10015	5834	5834	0.549	0.5082	703	NA	1.00	1.00	NA	NA
85	1	125	919	93	13	10640	6147	6147	0.537	0.5011	694	NA	1.00	1.00	NA	NA
90	1	127	919	80	13	11275	6470	6470	0.524	0.4930	685	NA	1.00	1.00	NA	NA
95	1	127	919	93	13	11910	6793	6793	0.512	0.4845	677	NA	1.00	1.00	NA	NA
100	1	127	1083	93	13	12545	7116	7116	0.500	0.4755	789	NA	1.00	1.00	NA	NA

Used Bore #1 for PI values, water depth, & unit wt.

Vs Liquefaction Potential - Project 100303

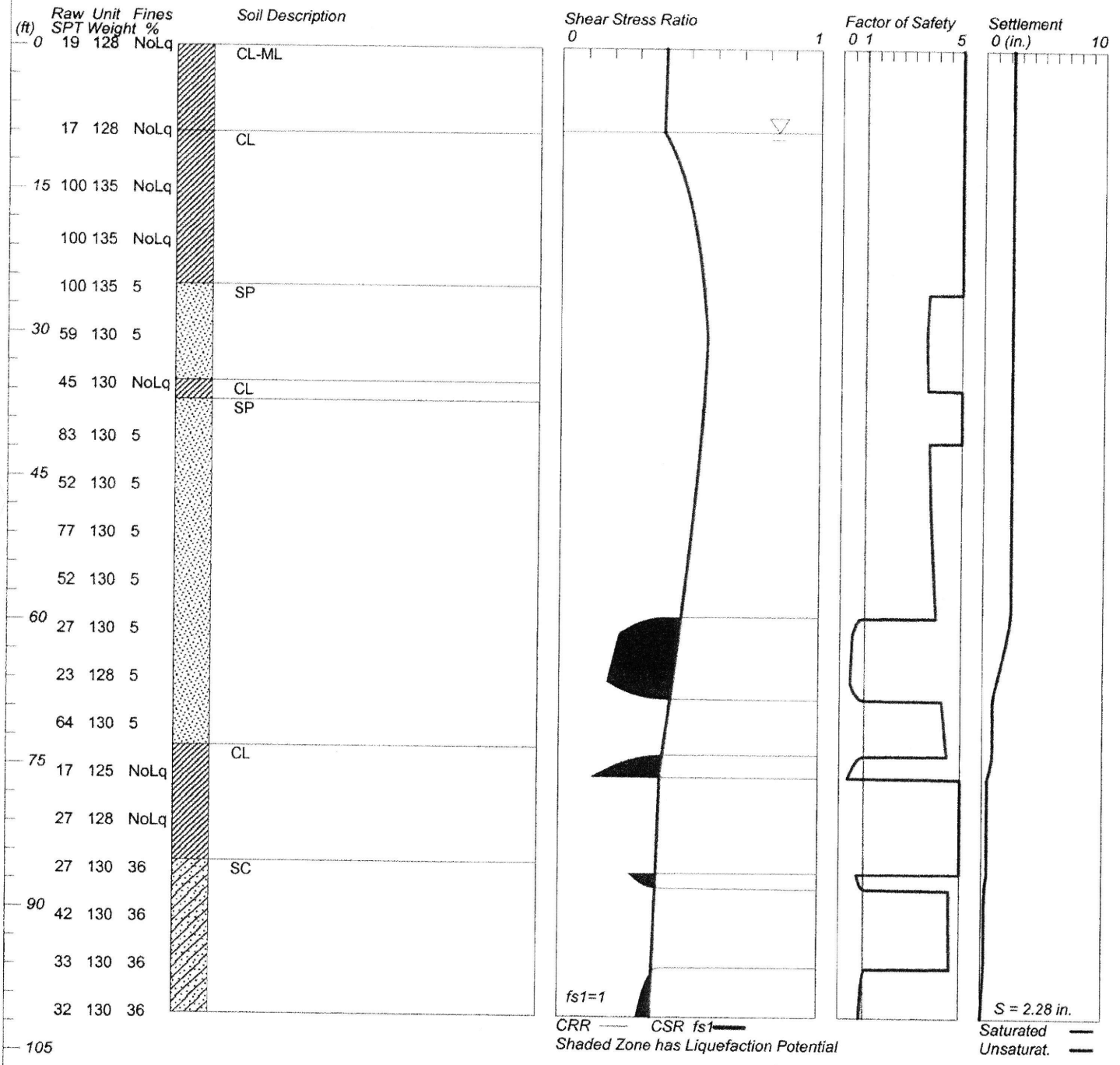


LIQUEFACTION ANALYSIS (ALT.A)

R00059

Hole No.=1 Water Depth=8.7 ft Surface Elev.=300.1

Magnitude=7.5
Acceleration=0.620g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Craighead County

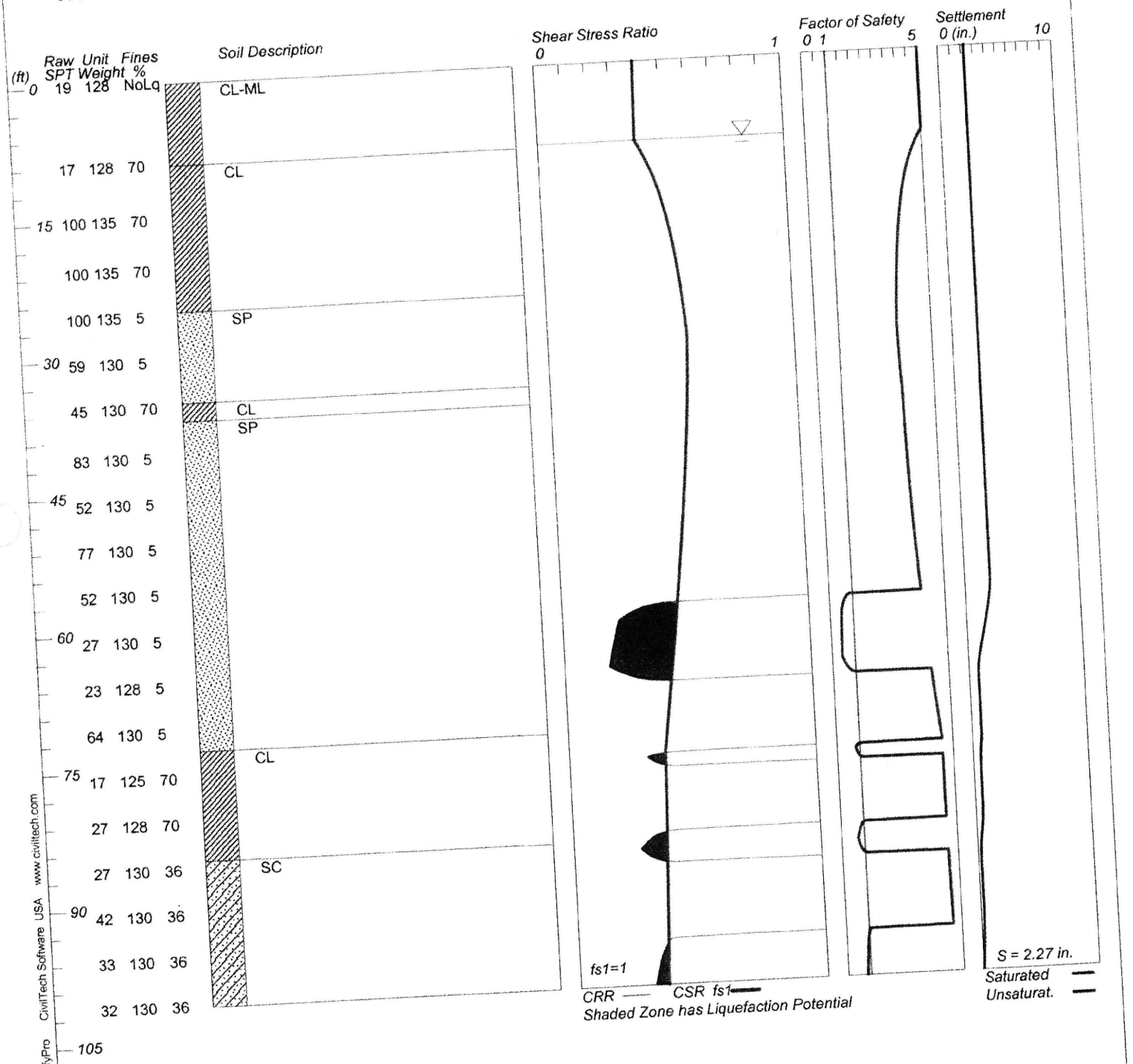
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

R00059

Hole No.=1 **Water Depth=8.7 ft** **Surface Elev.=300.1**

Magnitude=7.5
Acceleration=0.620g



BN-1, Craighead County

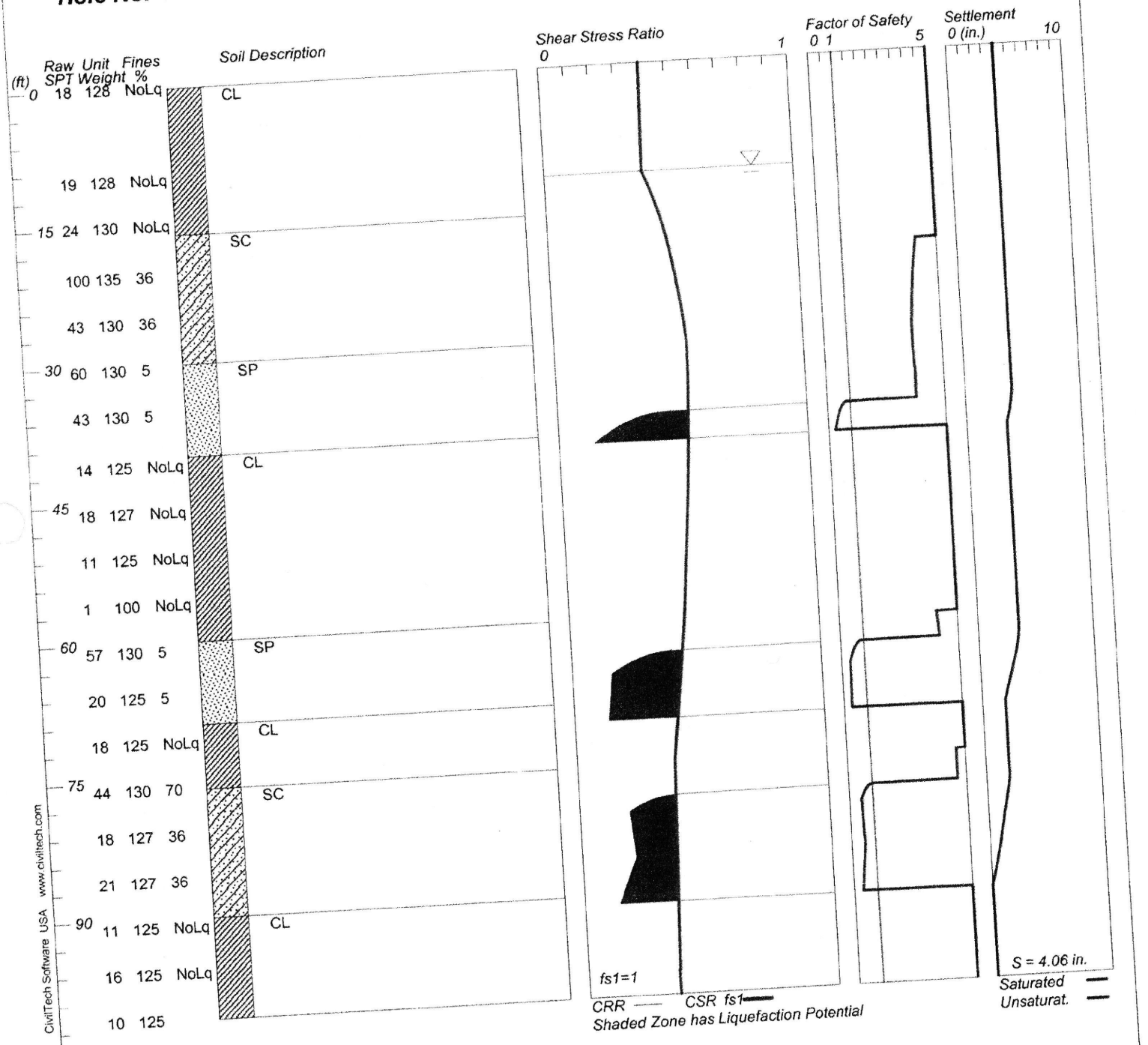
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

R00059

Hole No.=2 **Water Depth=11.8 ft** **Surface Elev.=303.3**

Magnitude=7.5
Acceleration=0.620g



BN-2, Craighead County

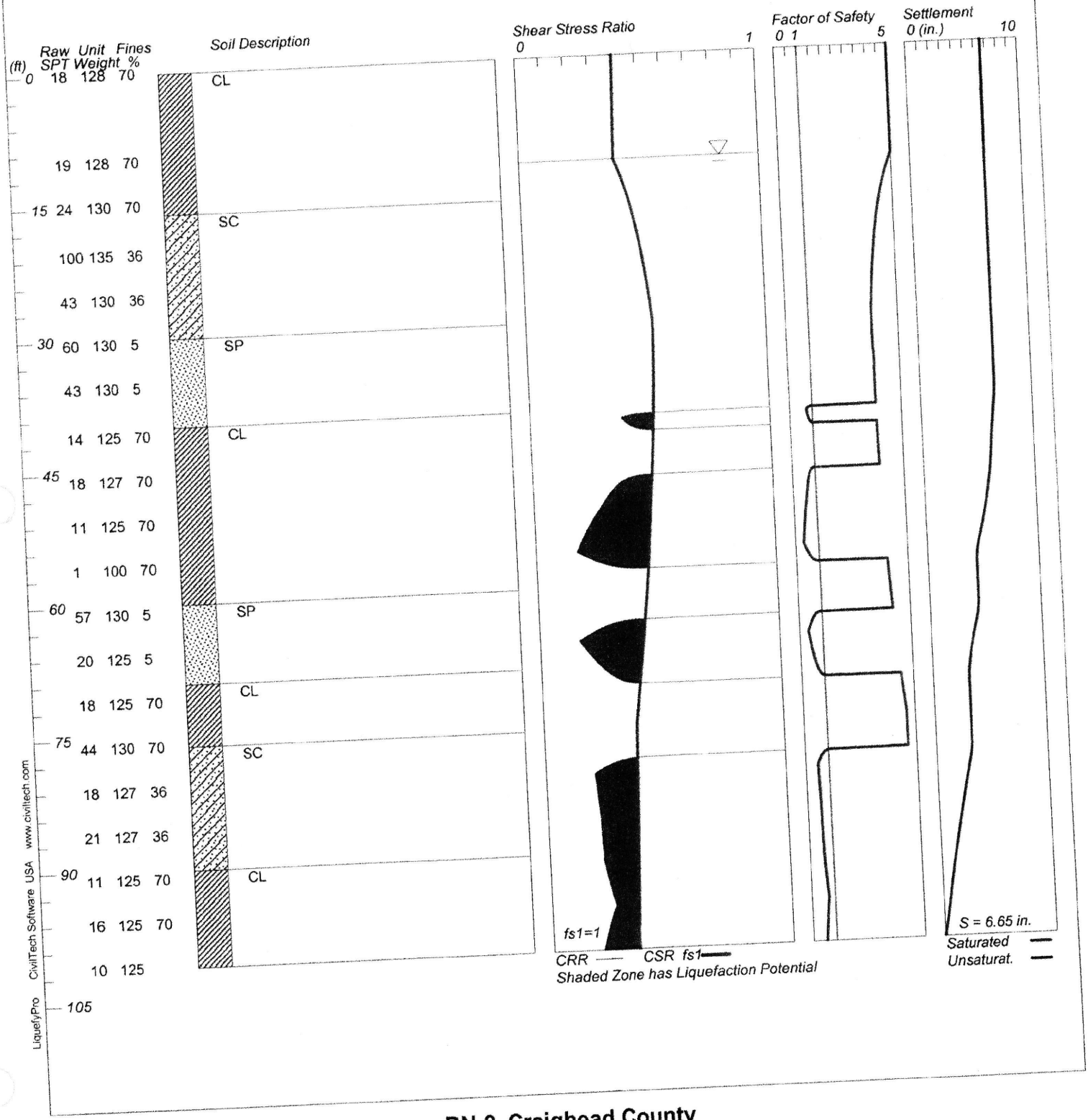
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

R00059

Hole No.=2 ***Water Depth=11.8 ft*** ***Surface Elev.=303.3***

Magnitude=7.5
Acceleration=0.620g



BN-2, Craighead County

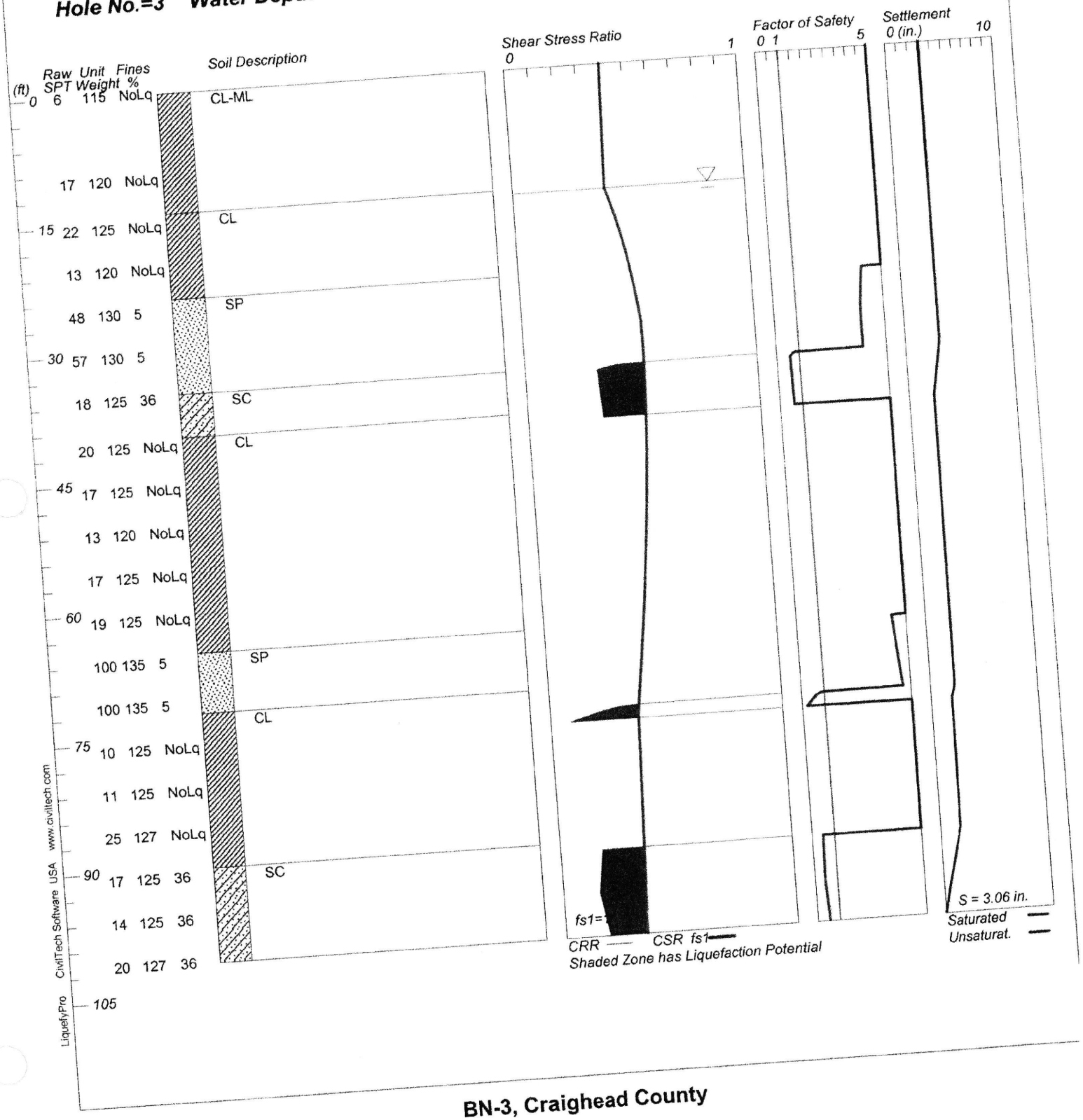
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

R00059

Hole No.=3 **Water Depth=14.5 ft** **Surface Elev.=306.3**

Magnitude=7.5
Acceleration=0.620g



BN-3, Craighead County

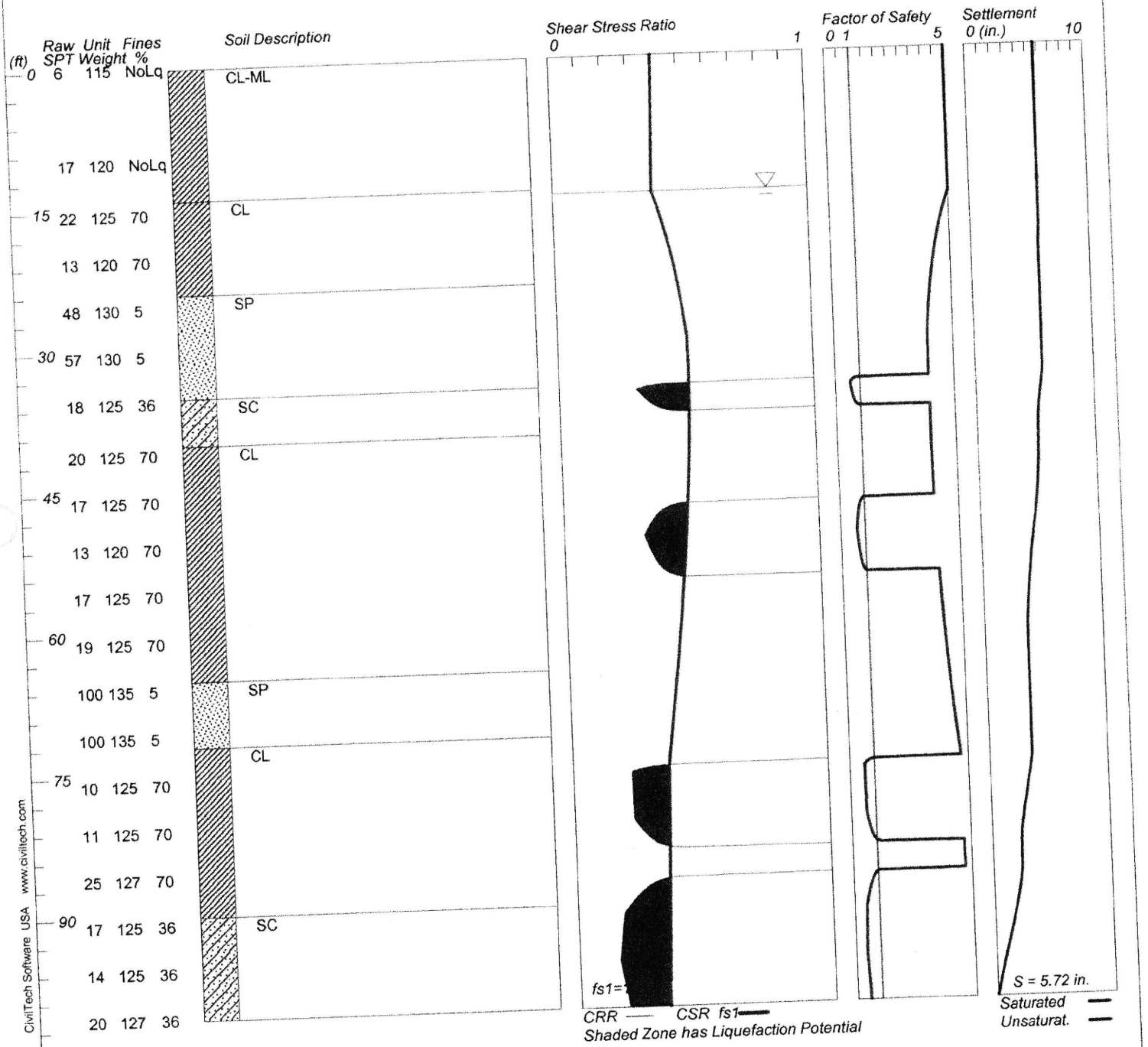
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

R00059

Hole No.=3 **Water Depth=14.5 ft** **Surface Elev.=306.3**

Magnitude=7.5
Acceleration=0.620g



BN-3, Craighead County

Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

R00059

Hole No.=4 **Water Depth=17 ft** **Surface Elev.=303.6**

Magnitude=7.5
Acceleration=0.620g

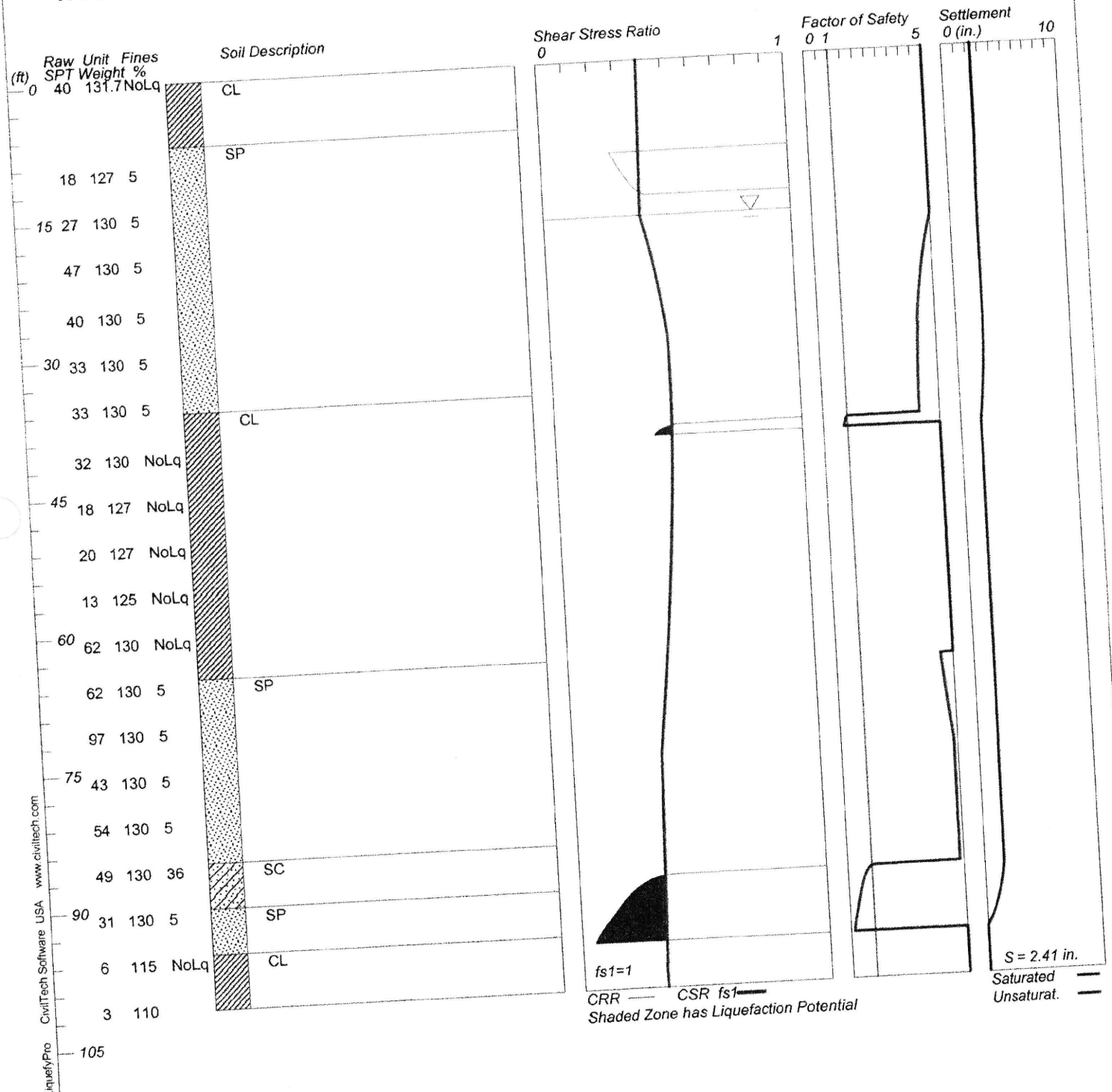


Plate A-1

BN-4, Craighead County

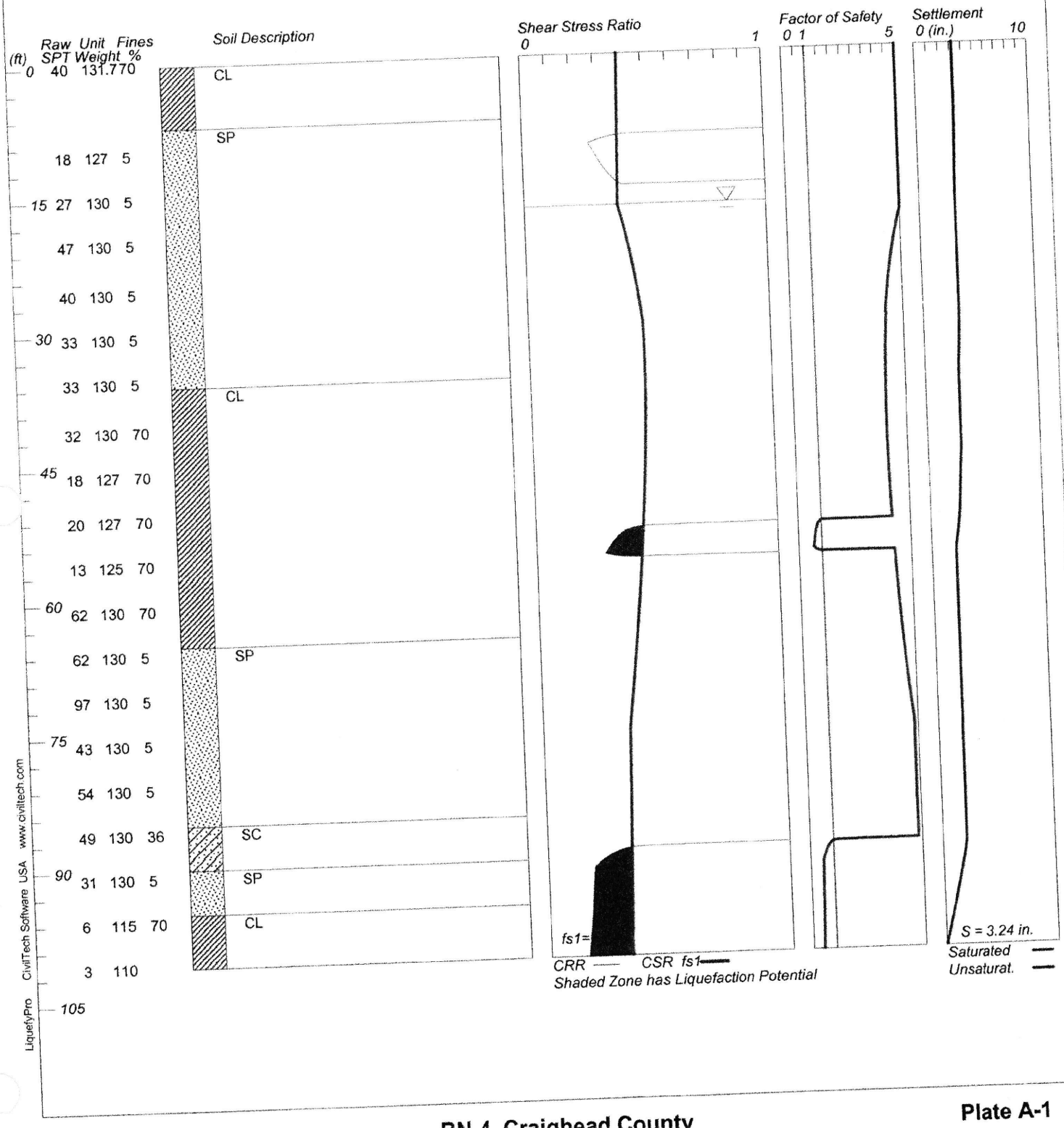
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

R00059

Hole No.=4 **Water Depth=17 ft** **Surface Elev.=303.6**

Magnitude=7.5
Acceleration=0.620g



BN-4, Craighead County

Plate A-1

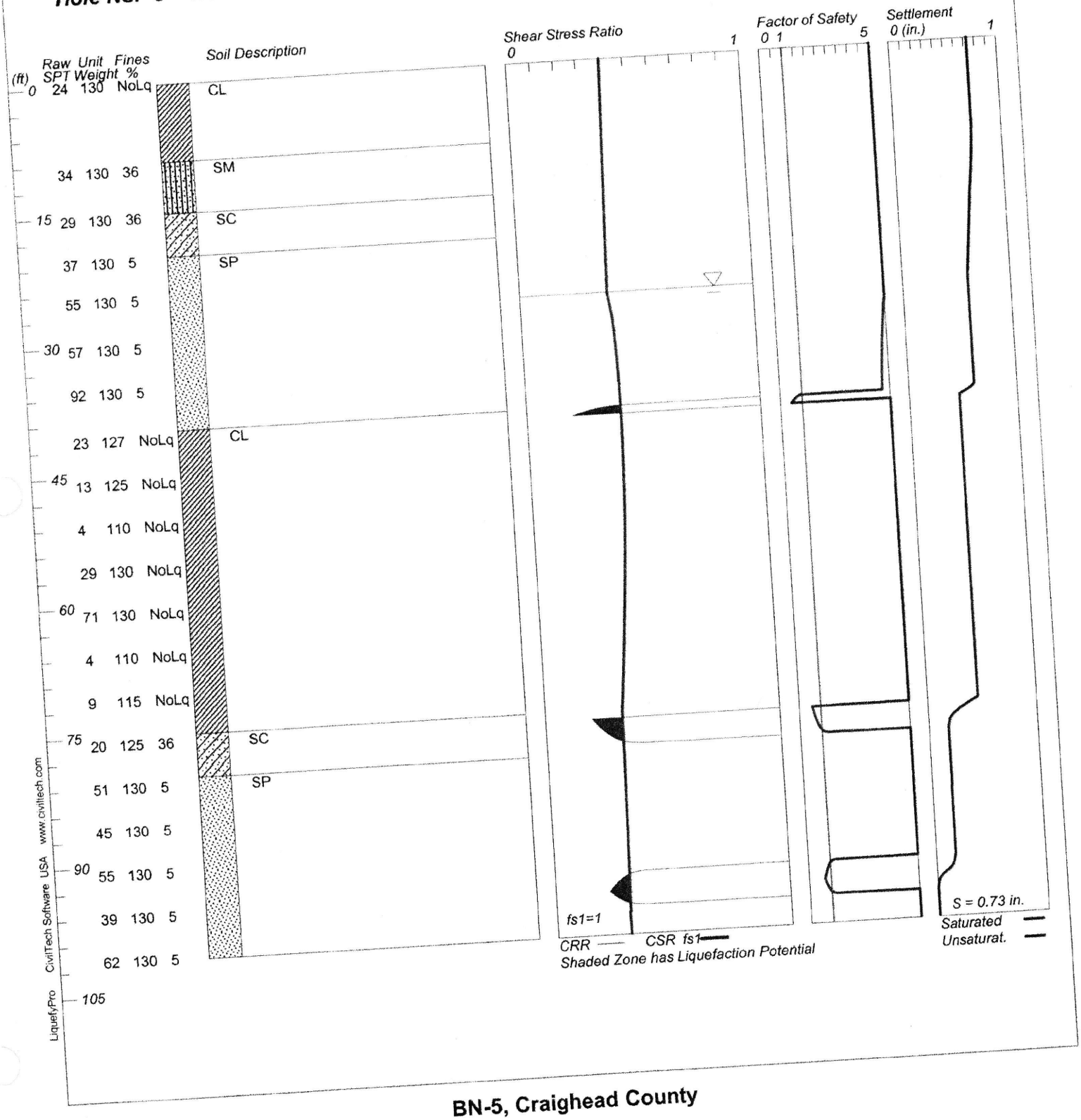
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

R00059

Hole No.=5 **Water Depth=27 ft** **Surface Elev.=313.4**

Magnitude=7.5
Acceleration=0.620g



BN-5, Craighead County

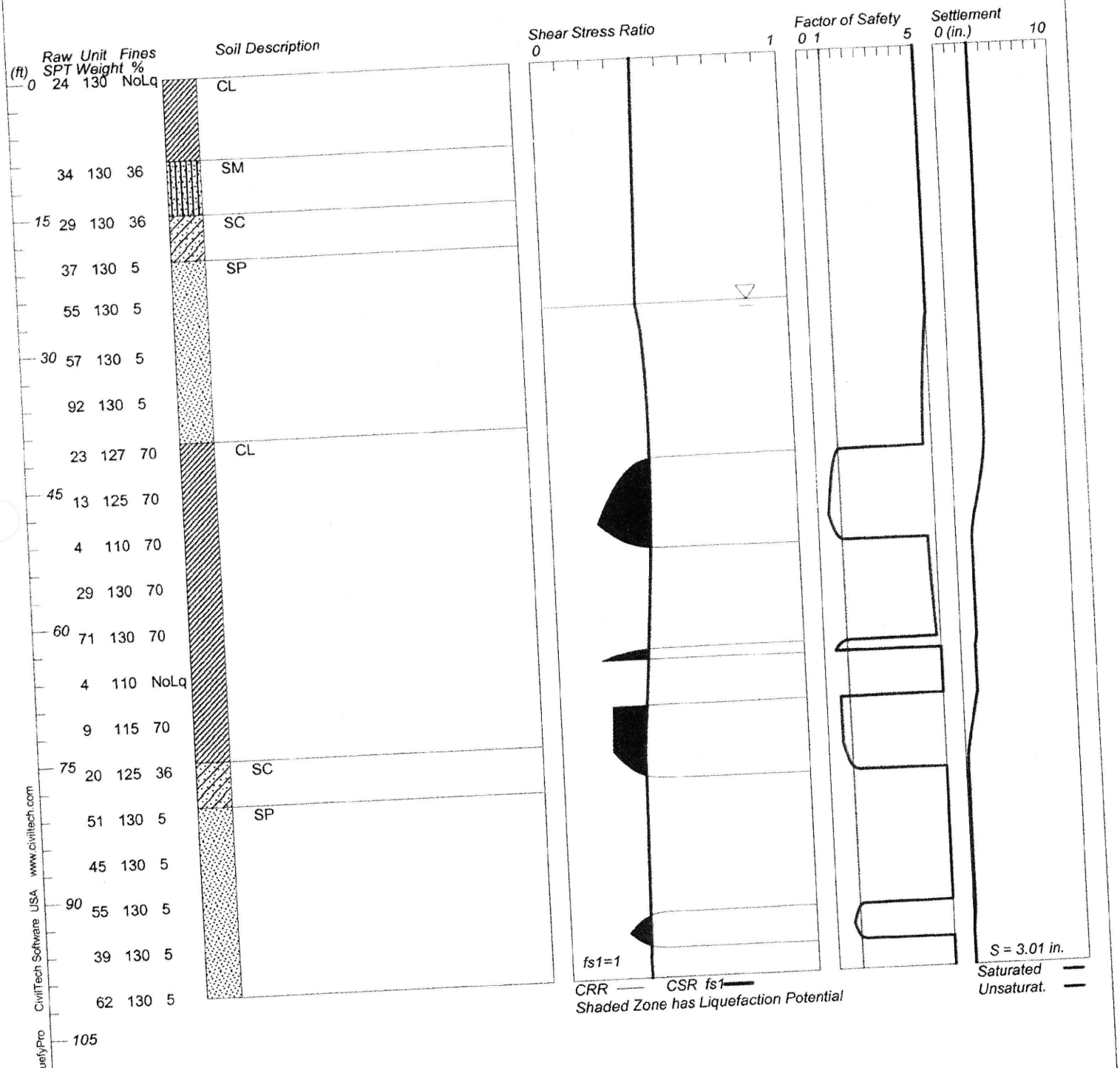
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

R00059

Hole No.=5 **Water Depth=27 ft** **Surface Elev.=313.4**

Magnitude=7.5
Acceleration=0.620g



BN-5, Craighead County

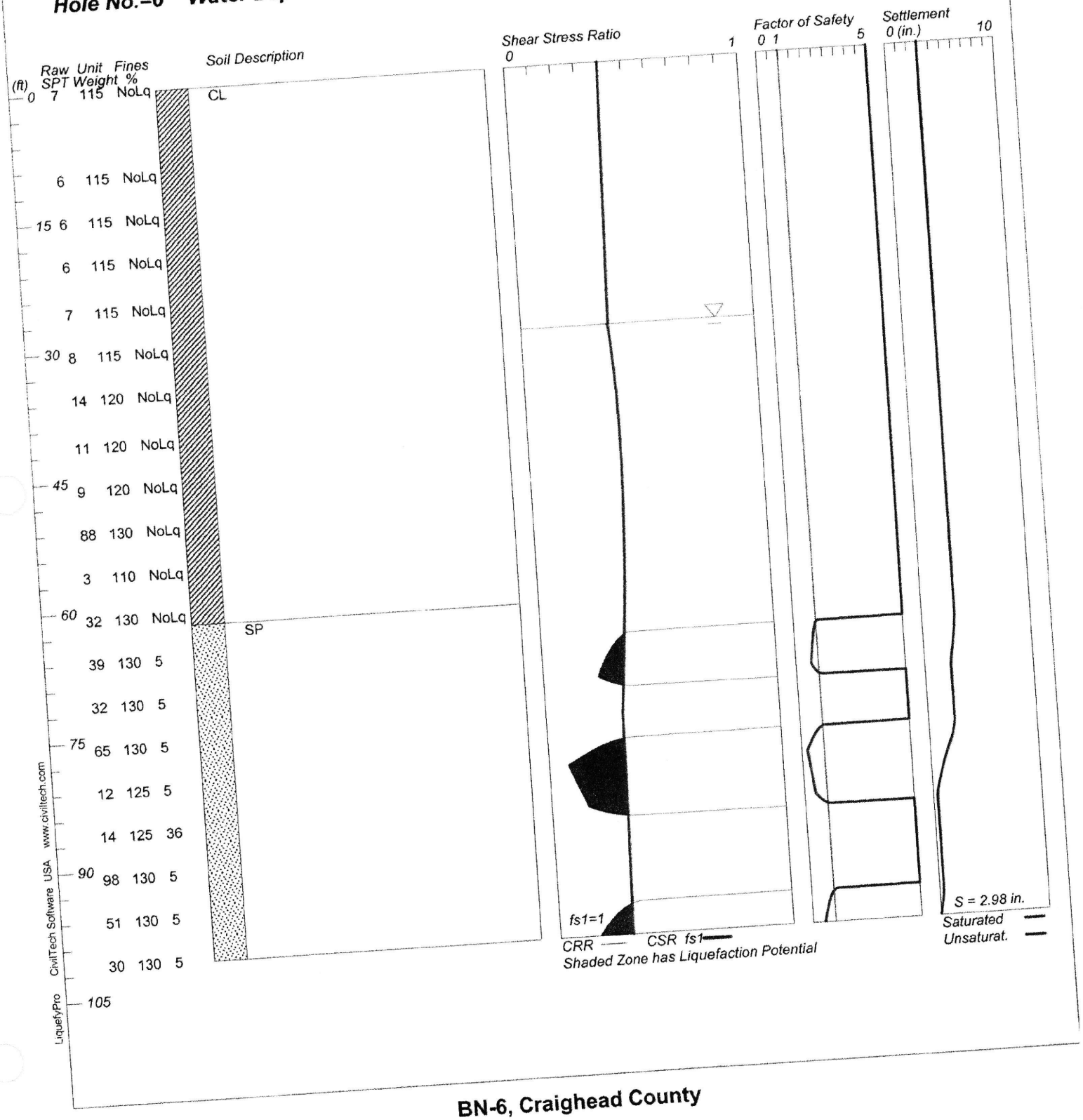
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

R00059

Hole No.=6 **Water Depth=30.4 ft** **Surface Elev.=316.8**

Magnitude=7.5
Acceleration=0.620g



BN-6, Craighead County

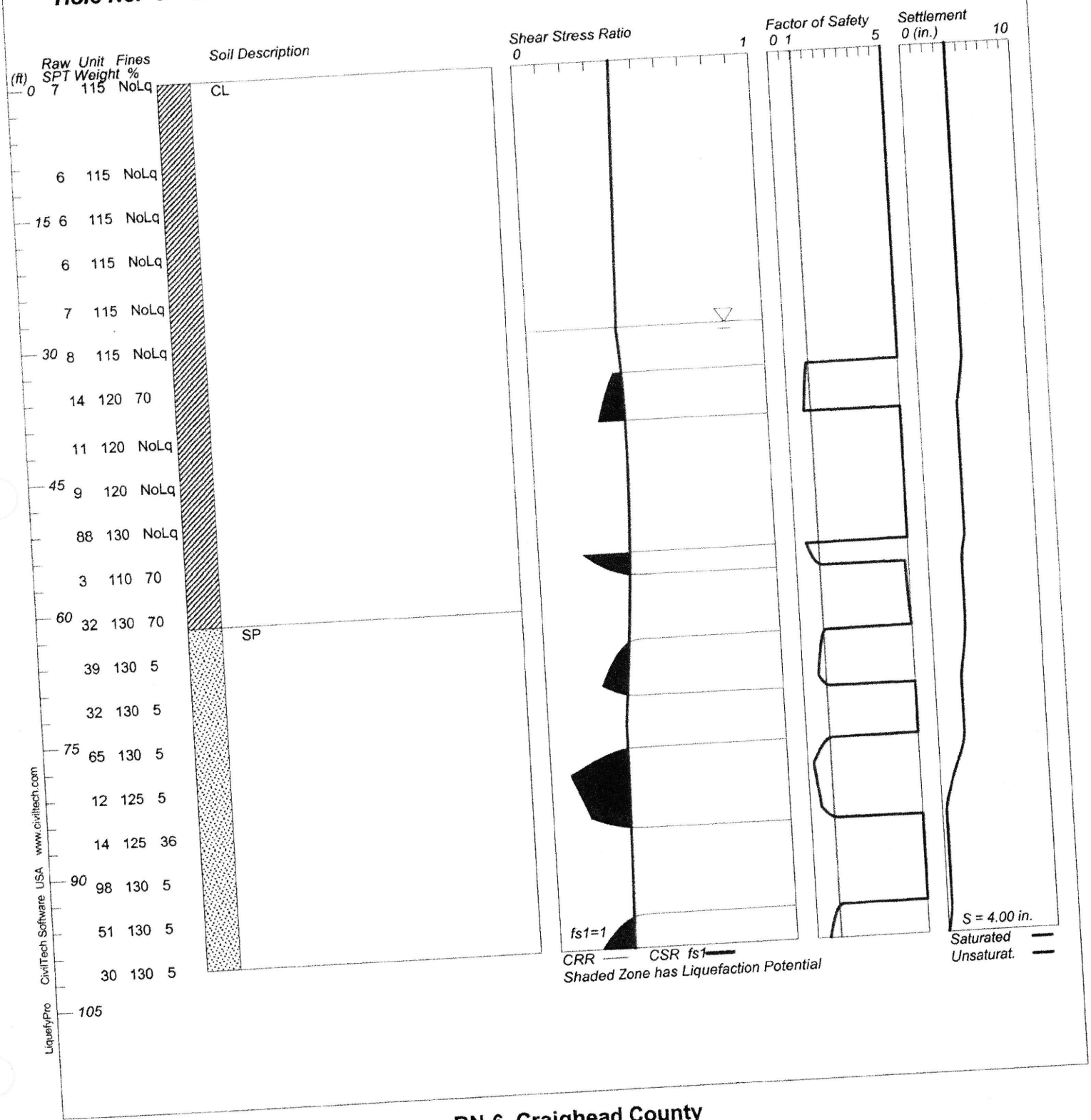
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

R00059

Hole No.=6 **Water Depth=30.4 ft** **Surface Elev.=316.8**

Magnitude=7.5
Acceleration=0.620g



BN-6, Craighead County

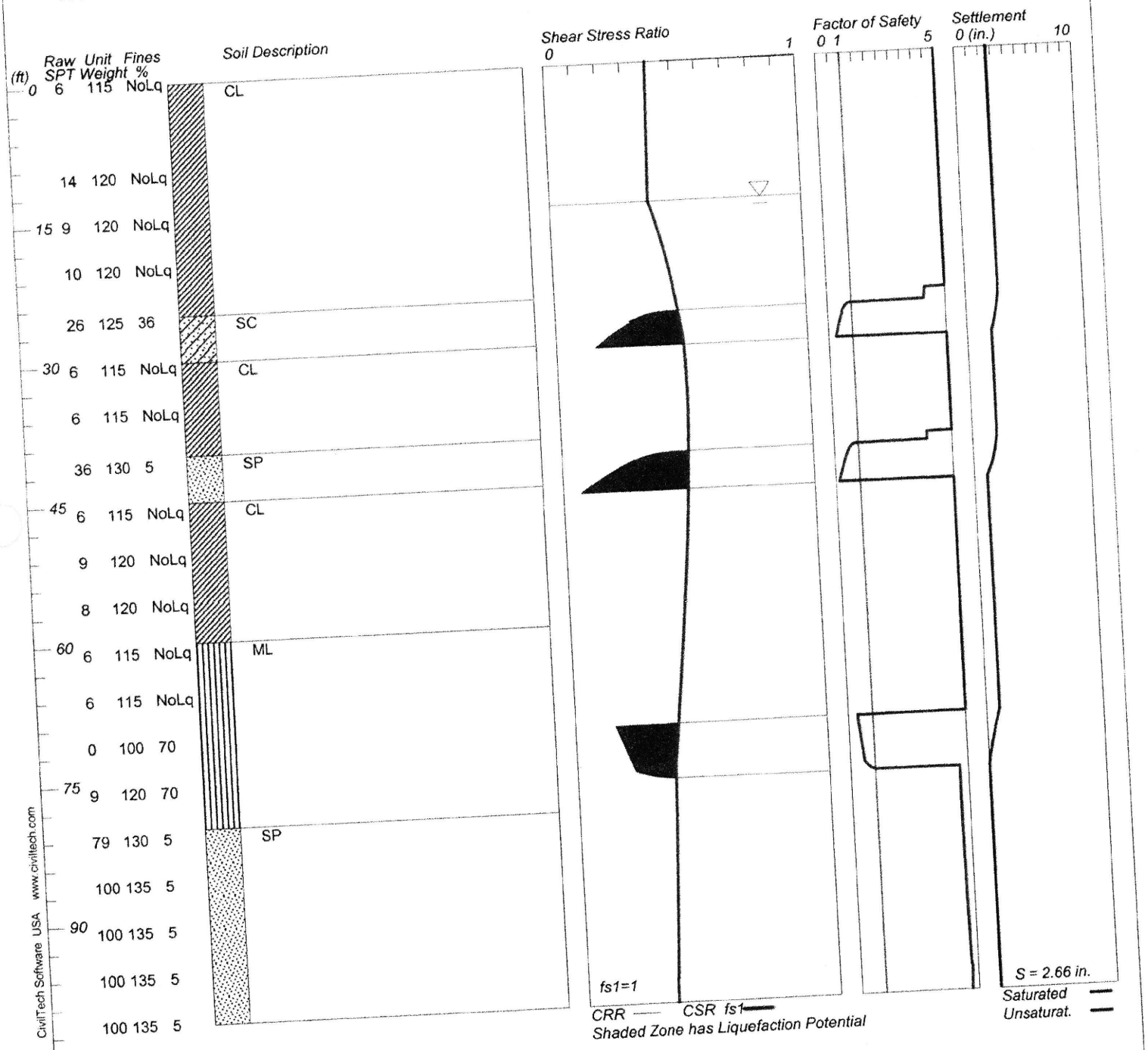
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

R00059

Hole No.=7 **Water Depth=15.0 ft** **Surface Elev.=287.0**

Magnitude=7.5
Acceleration=0.620g



BN-7, Craighead County

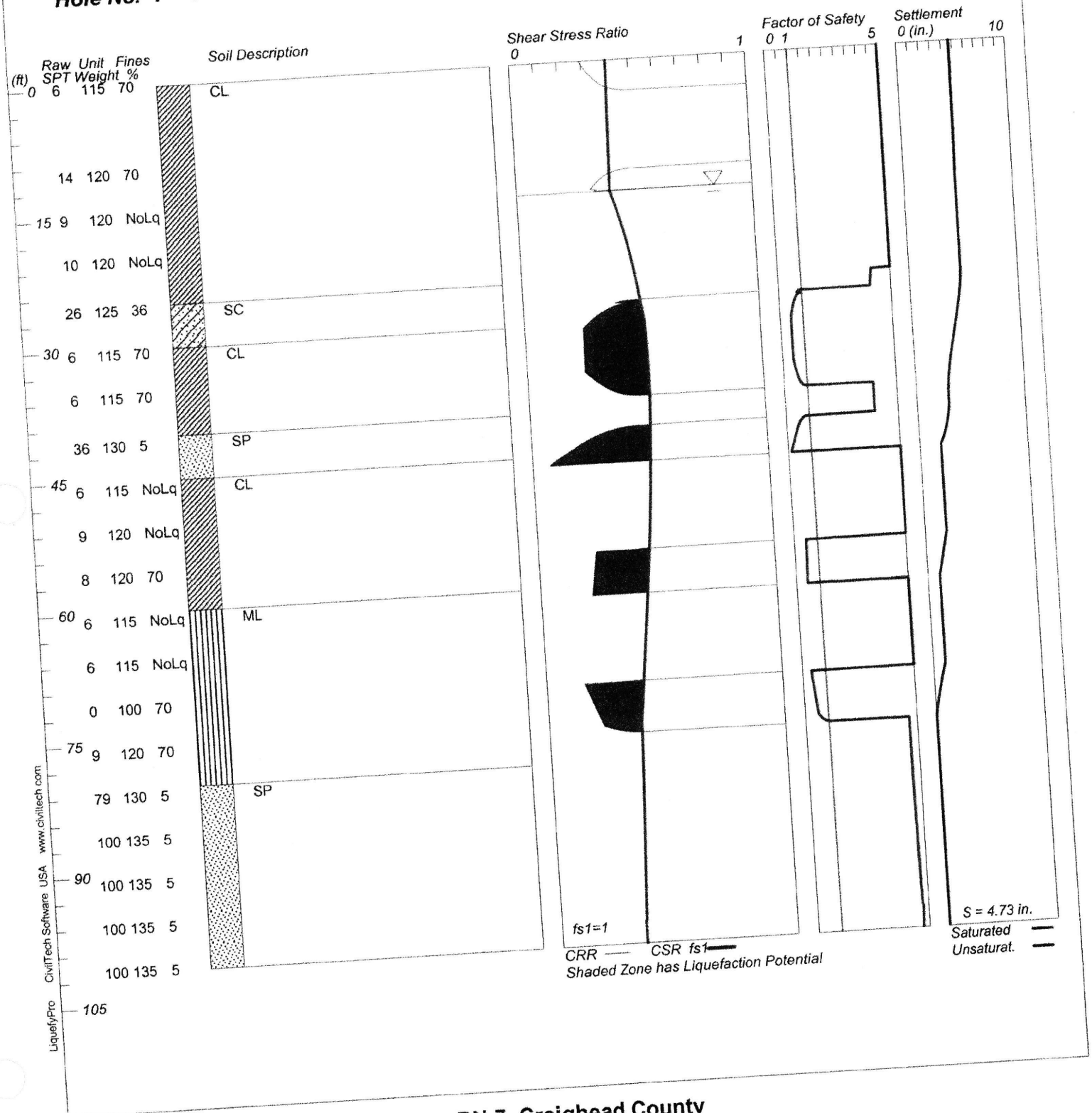
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

R00059

Hole No.=7 **Water Depth=15.0 ft** **Surface Elev.=287.0**

Magnitude=7.5
Acceleration=0.620g



BN-7, Craighead County

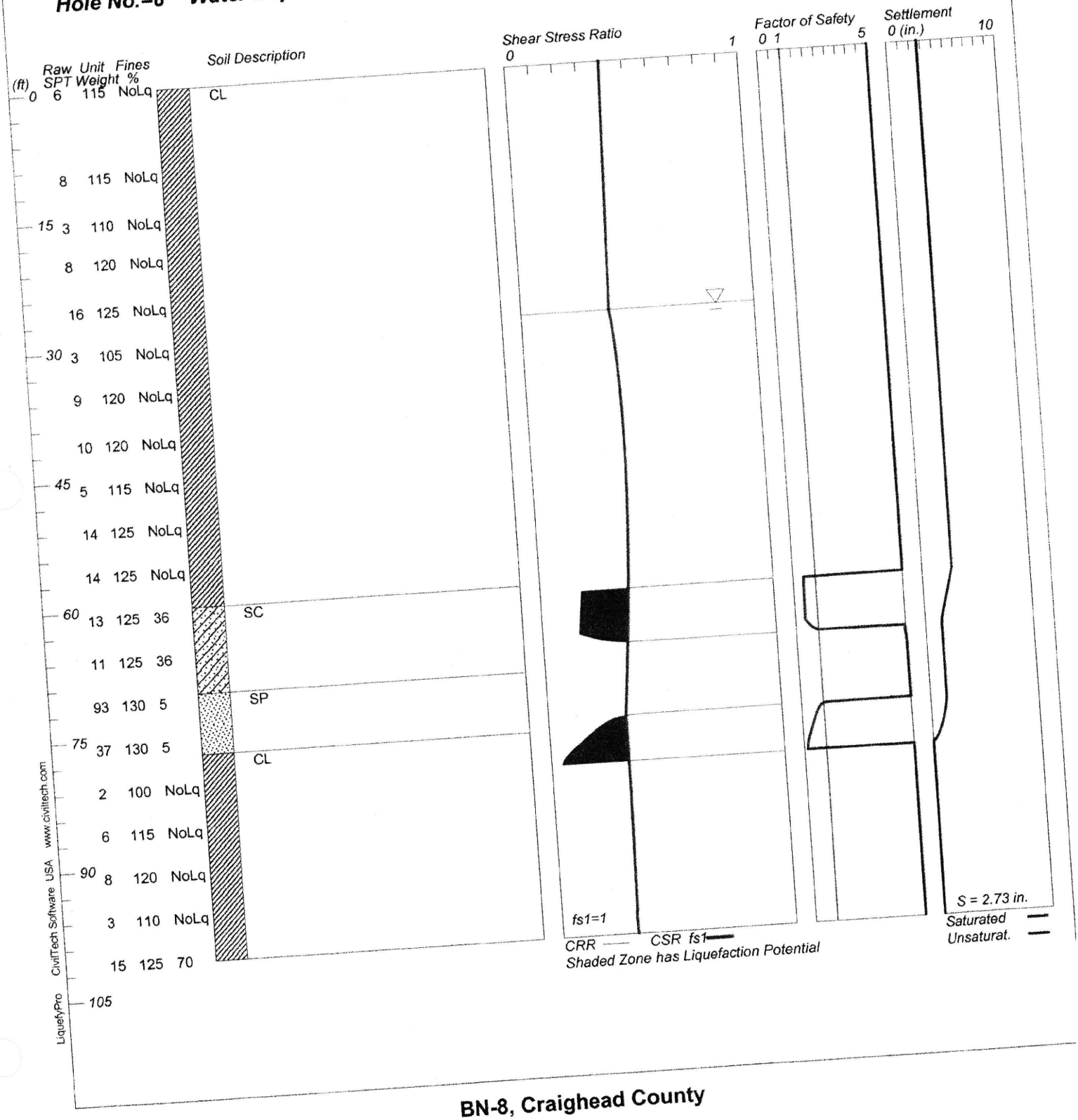
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

R00059

Hole No.=8 **Water Depth=28.8 ft** **Surface Elev.=316.3**

Magnitude=7.5
Acceleration=0.620g



BN-8, Craighead County

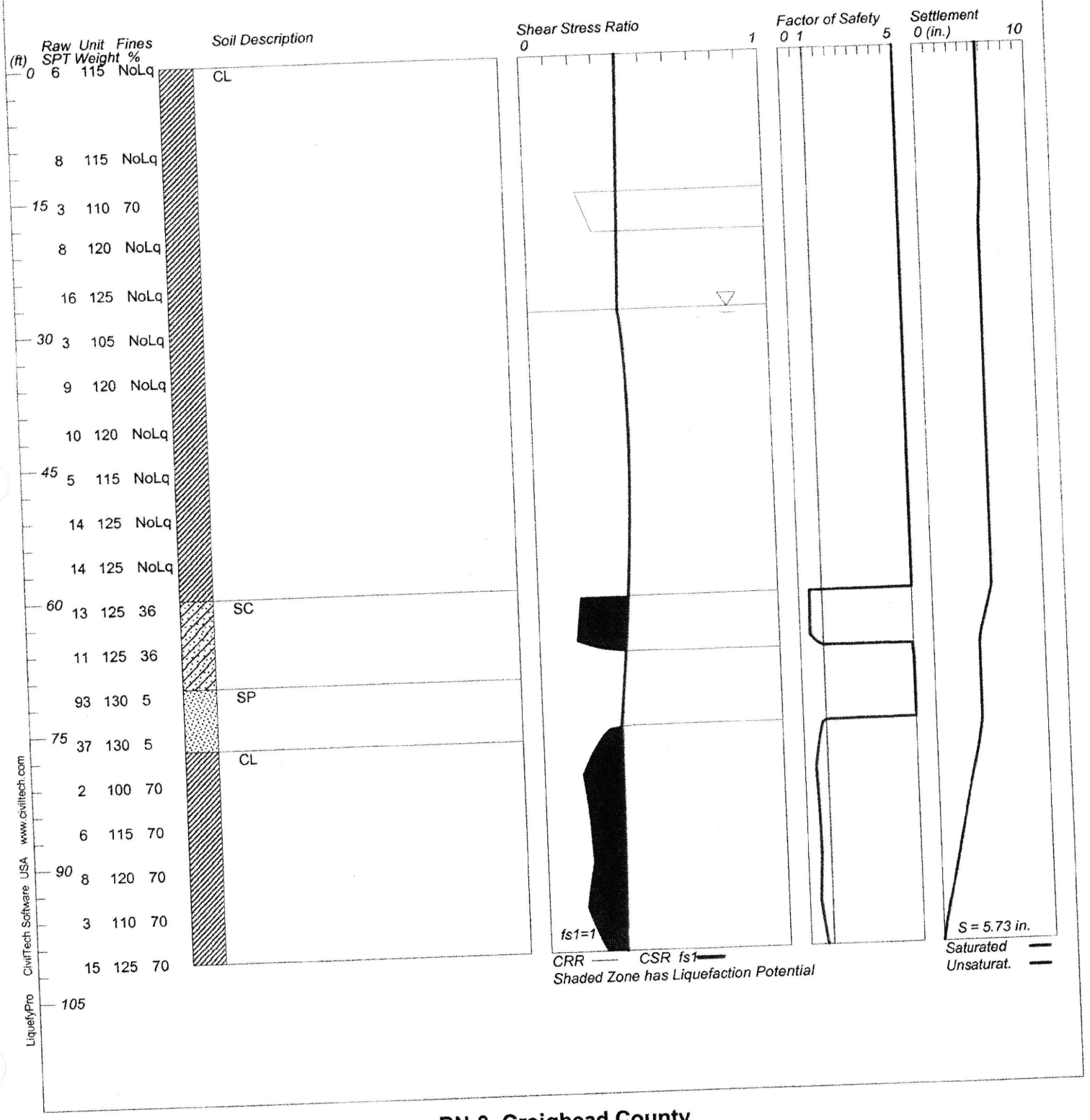
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

R00059

Hole No.=8 Water Depth=28.8 ft Surface Elev.=316.3

Magnitude=7.5
Acceleration=0.620g



BN-8, Craighead County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-R00059

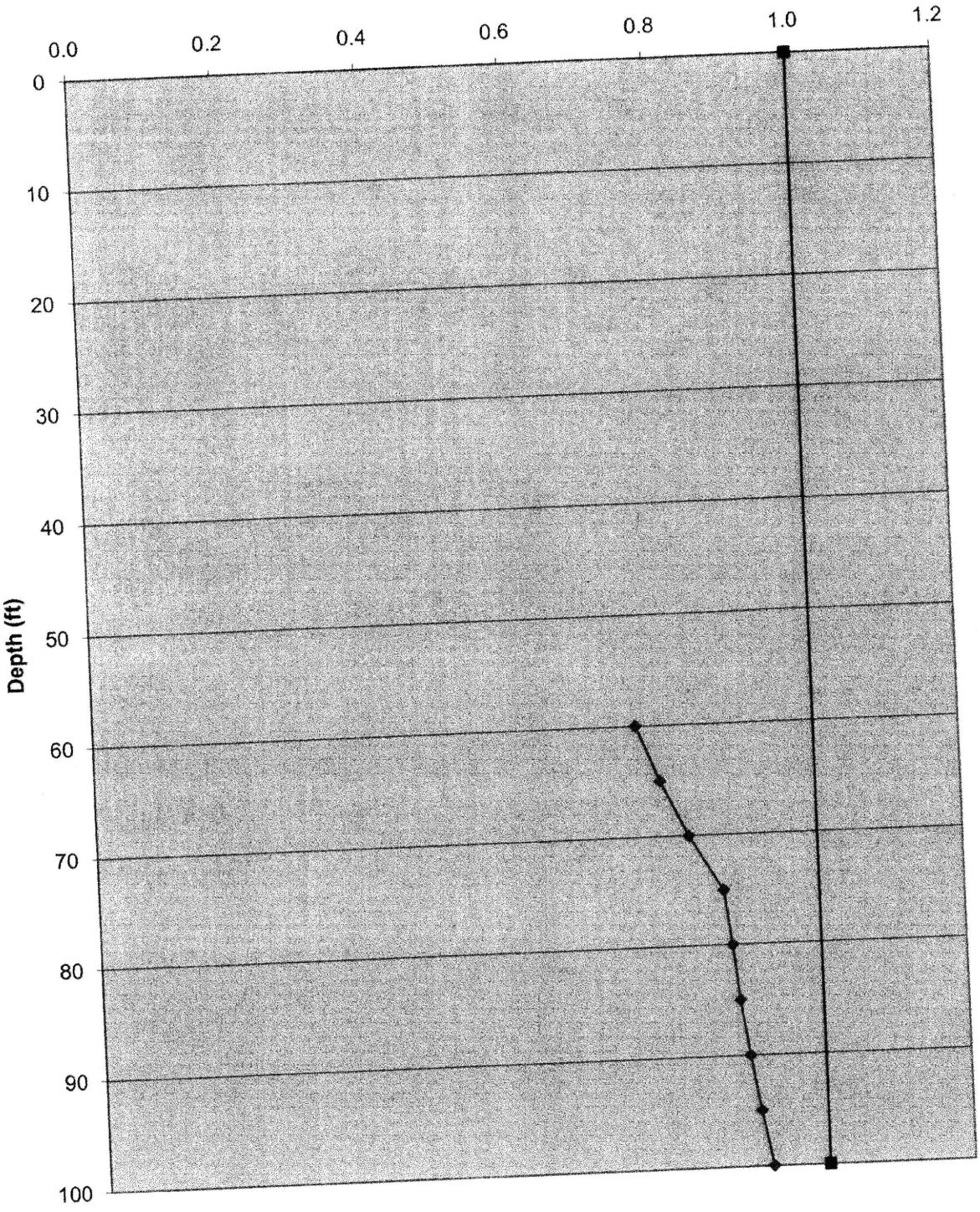
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	0.62	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	25	ft	assumed depth to groundwater =	25	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	115	869	89	18	575	575	575	0.988	0.3983	1187	NA	1.00	1.00	NA	NA
10	1	115	656	89	18	1150	1150	1150	0.977	0.3936	753	NA	1.00	1.00	NA	NA
15	1	115	673	89	18	1725	1725	1725	0.965	0.3889	698	NA	1.00	1.00	NA	NA
20	1	115	673	89	18	2300	2300	2300	0.953	0.3842	650	NA	1.00	1.00	NA	NA
25	1	115	673	89	18	2875	2875	2875	0.942	0.3795	615	NA	1.00	1.00	NA	NA
30	1	120	682	44	18	3475	3163	3163	0.930	0.4118	608	NA	1.00	1.00	NA	NA
35	1	120	682	44	18	4075	3451	3451	0.889	0.4230	595	NA	1.00	1.00	NA	NA
40	1	120	820	44	18	4675	3739	3739	0.848	0.4274	701	NA	1.00	1.00	NA	NA
45	1	120	820	44	18	5275	4027	4027	0.808	0.4263	688	NA	1.00	1.00	NA	NA
50	1	130	886	44	18	5925	4365	4365	0.767	0.4195	729	NA	1.00	1.00	NA	NA
55	1	110	951	37	18	6475	4603	4603	0.726	0.4116	772	NA	1.00	1.00	NA	NA
60	2	130	951	37	0	7125	4941	4941	0.685	0.3983	759	0.3000	1.00	1.00	0.299946	0.8
65	2	130	951	37	0	7775	5279	5279	0.645	0.3826	746	0.3000	1.00	1.00	0.299946	0.8
70	2	130	951	5	0	8425	5617	5617	0.604	0.3651	735	0.3000	1.00	1.00	0.299946	0.8
75	2	130	951	5	0	9075	5955	5955	0.563	0.3459	724	0.3000	1.00	1.00	0.299946	0.9
80	2	125	1017	5	0	9700	6268	6268	0.549	0.3423	764	0.3000	1.00	1.00	0.299946	0.9
85	2	125	1083	5	0	10325	6581	6581	0.537	0.3393	804	0.3000	1.00	1.00	0.299946	0.9
90	2	130	1083	5	0	10975	6919	6919	0.524	0.3352	794	0.3000	1.00	1.00	0.299946	0.9
95	2	130	1214	5	0	11625	7257	7257	0.512	0.3307	880	0.3000	1.00	1.00	0.299946	0.9
100	2	130	1214	5	0	12275	7595	7595	0.500	0.3257	870	0.3000	1.00	1.00	0.299946	0.9

Used Bore #6 for PI values & unit wt.

Vs Liquefaction Potential - Project R00059

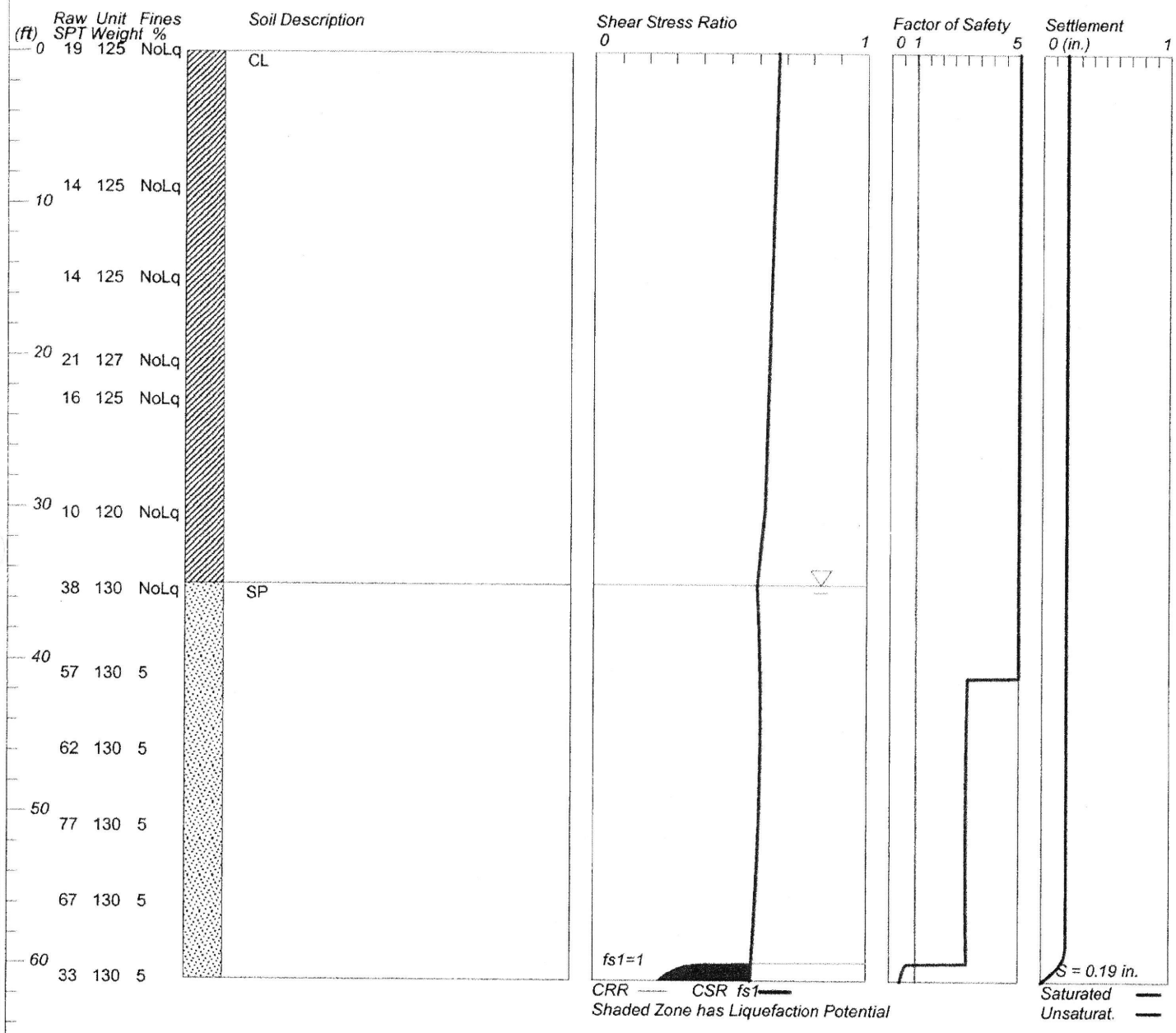


LIQUEFACTION ANALYSIS

100105

Hole No.=1 Water Depth=35 ft Surface Elev.=221.1

Magnitude=7.5
Acceleration=1.030g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Mississippi County

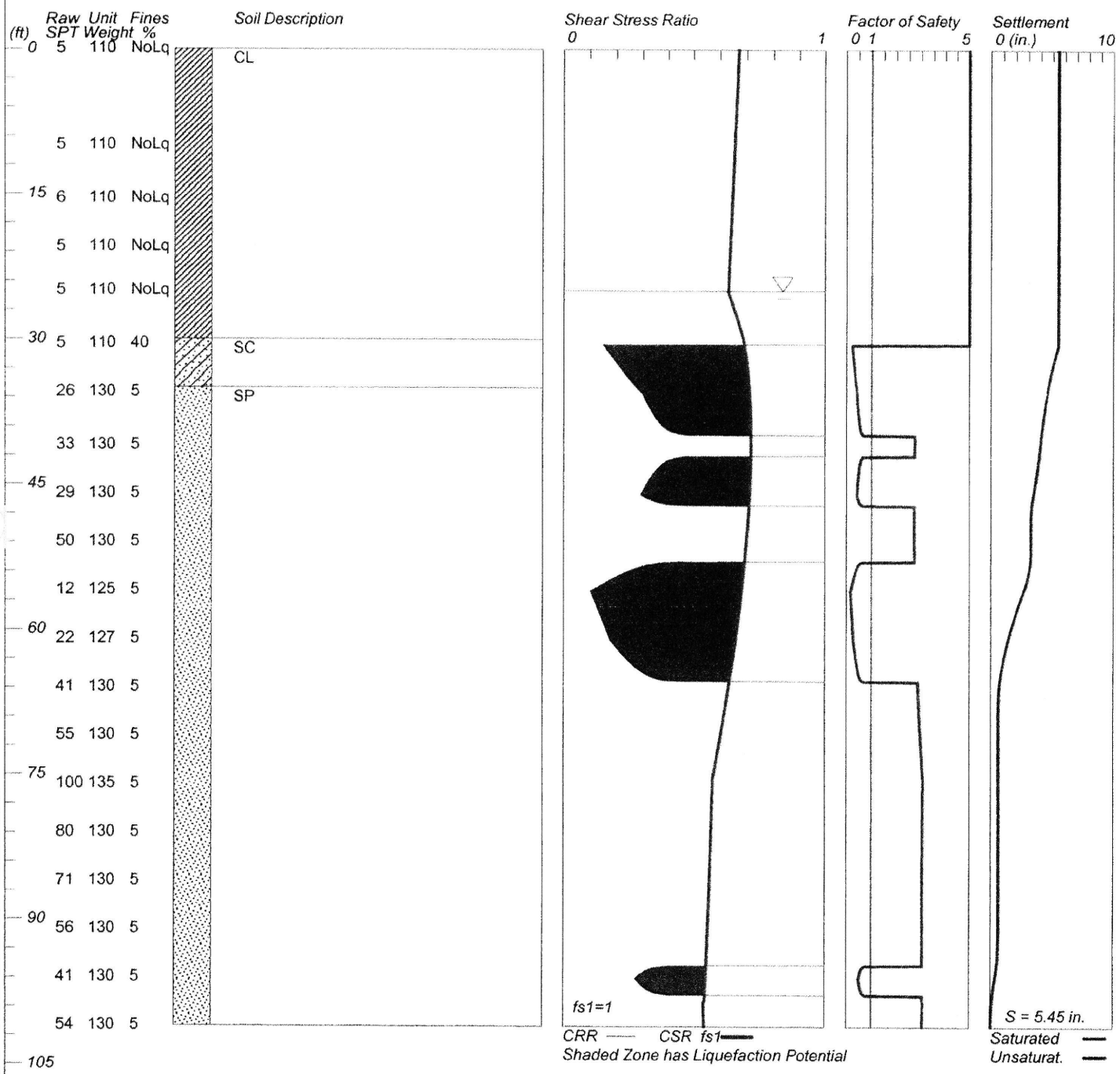
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100105

Hole No.=1A Water Depth=25 ft Surface Elev.=222.5

Magnitude=7.5
Acceleration=1.030g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1A, Mississippi County

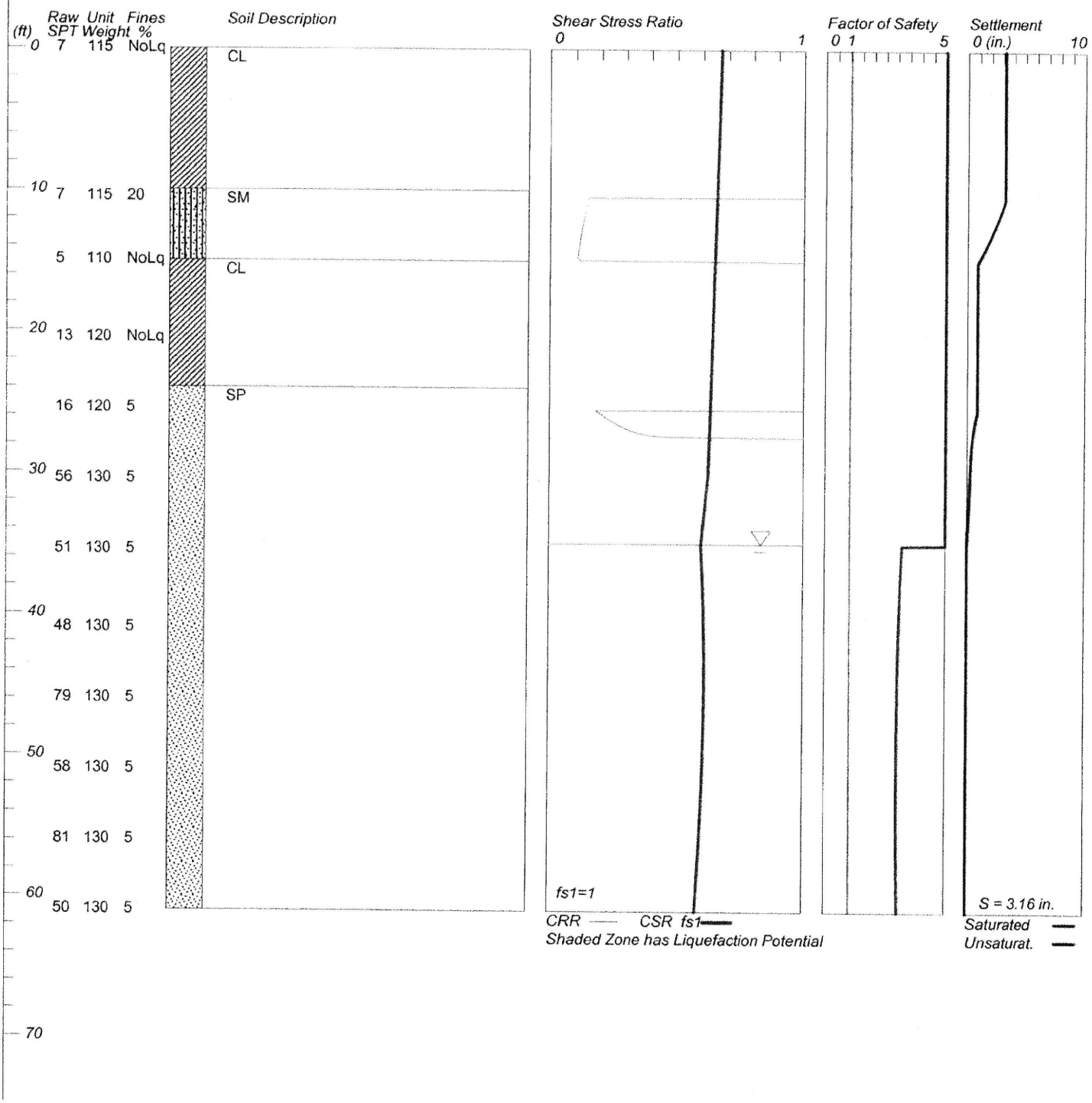
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100105

Hole No.=2 Water Depth=35 ft Surface Elev.=222.3

Magnitude=7.5
Acceleration=1.030g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-2, Mississippi County

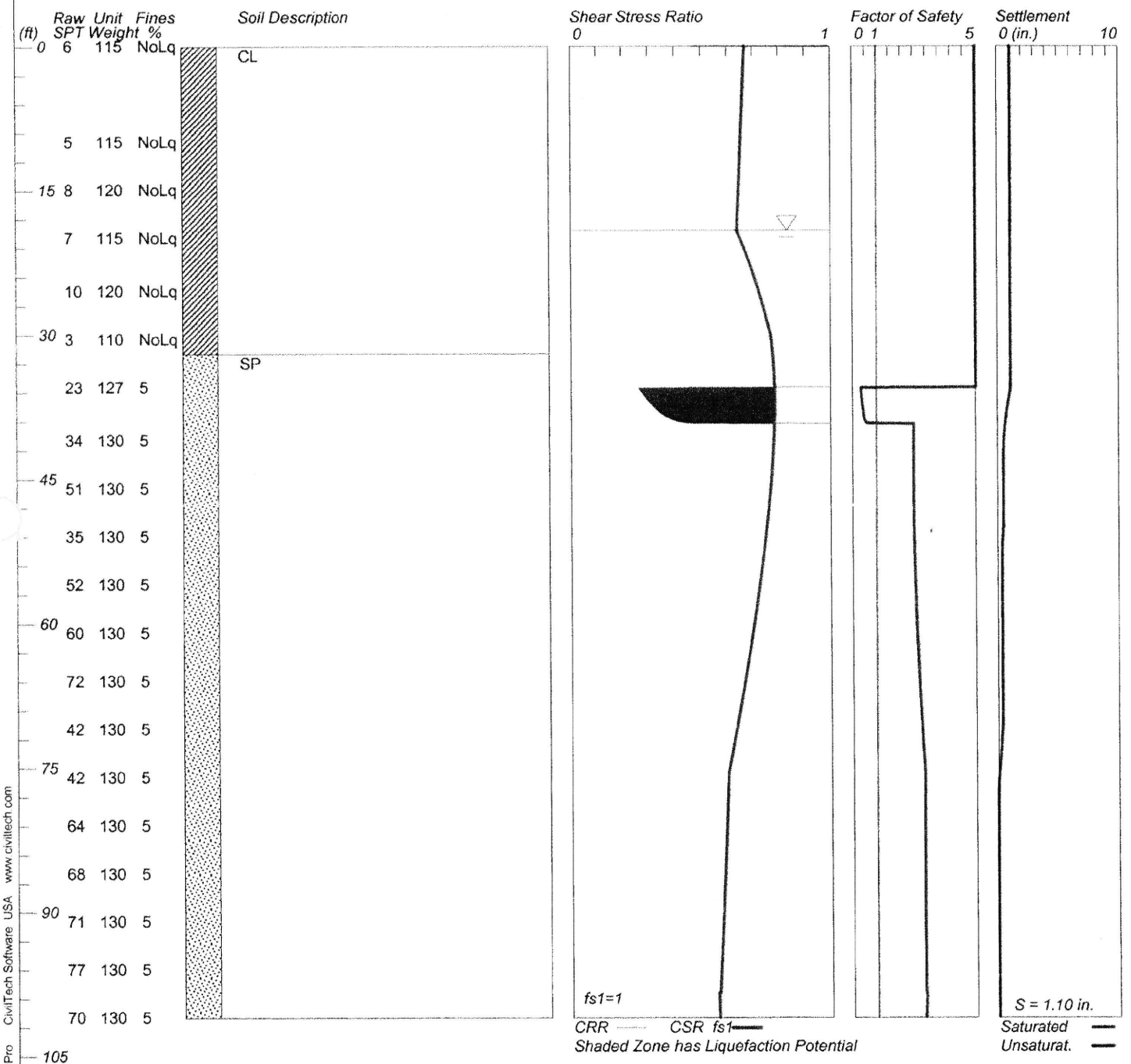
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100105

Hole No.=2A Water Depth=19.2 ft Surface Elev.=224.1

Magnitude=7.5
Acceleration=1.030g



BN-2A, Mississippi County

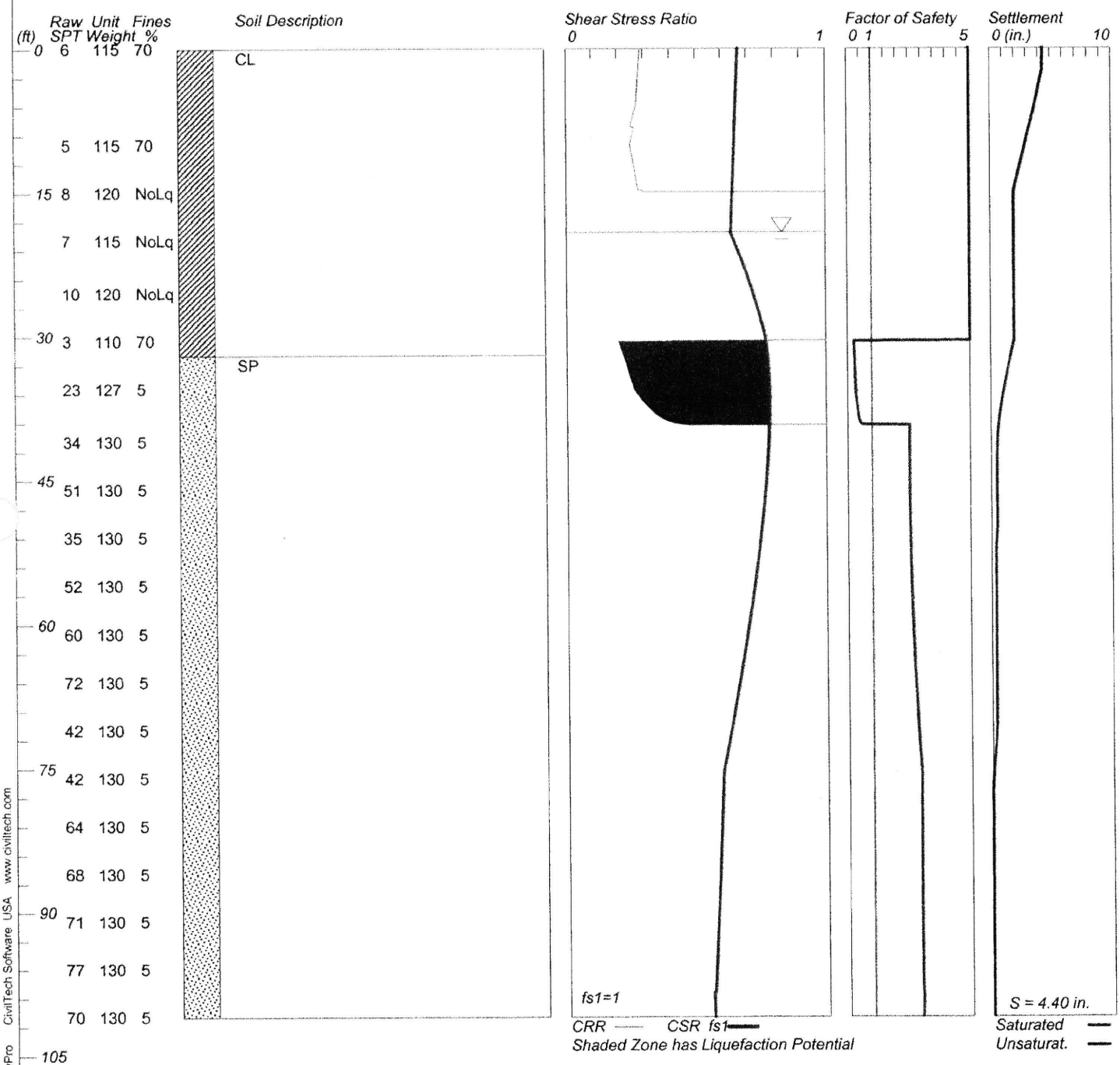
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100105

Hole No.=2A Water Depth=19.2 ft Surface Elev.=224.1

Magnitude=7.5
Acceleration=1.030g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-2A, Mississippi County

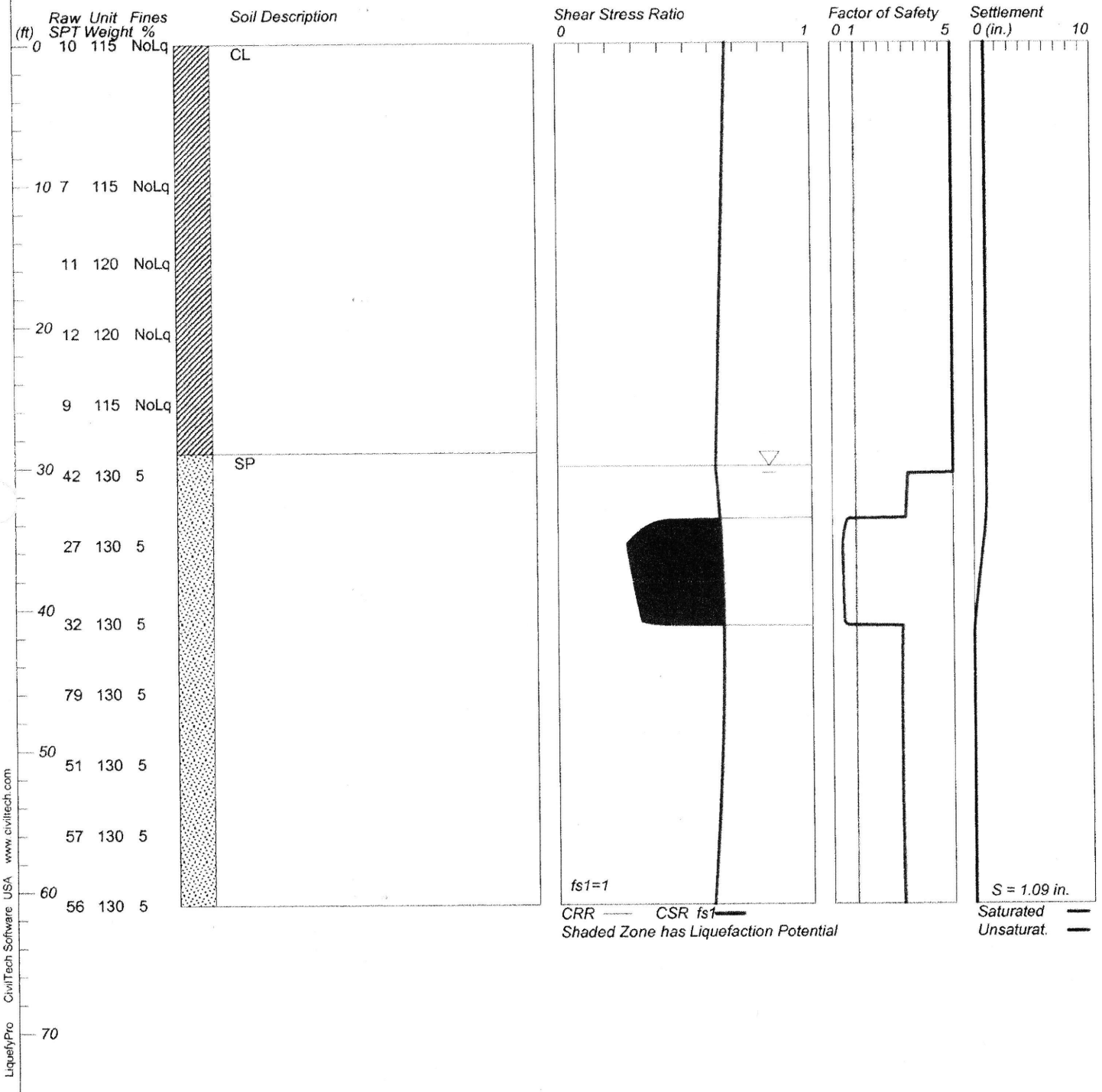
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100105

Hole No.=3 Water Depth=30 ft Surface Elev.=222.1

Magnitude=7.5
Acceleration=1.030g



BN-3, Mississippi County

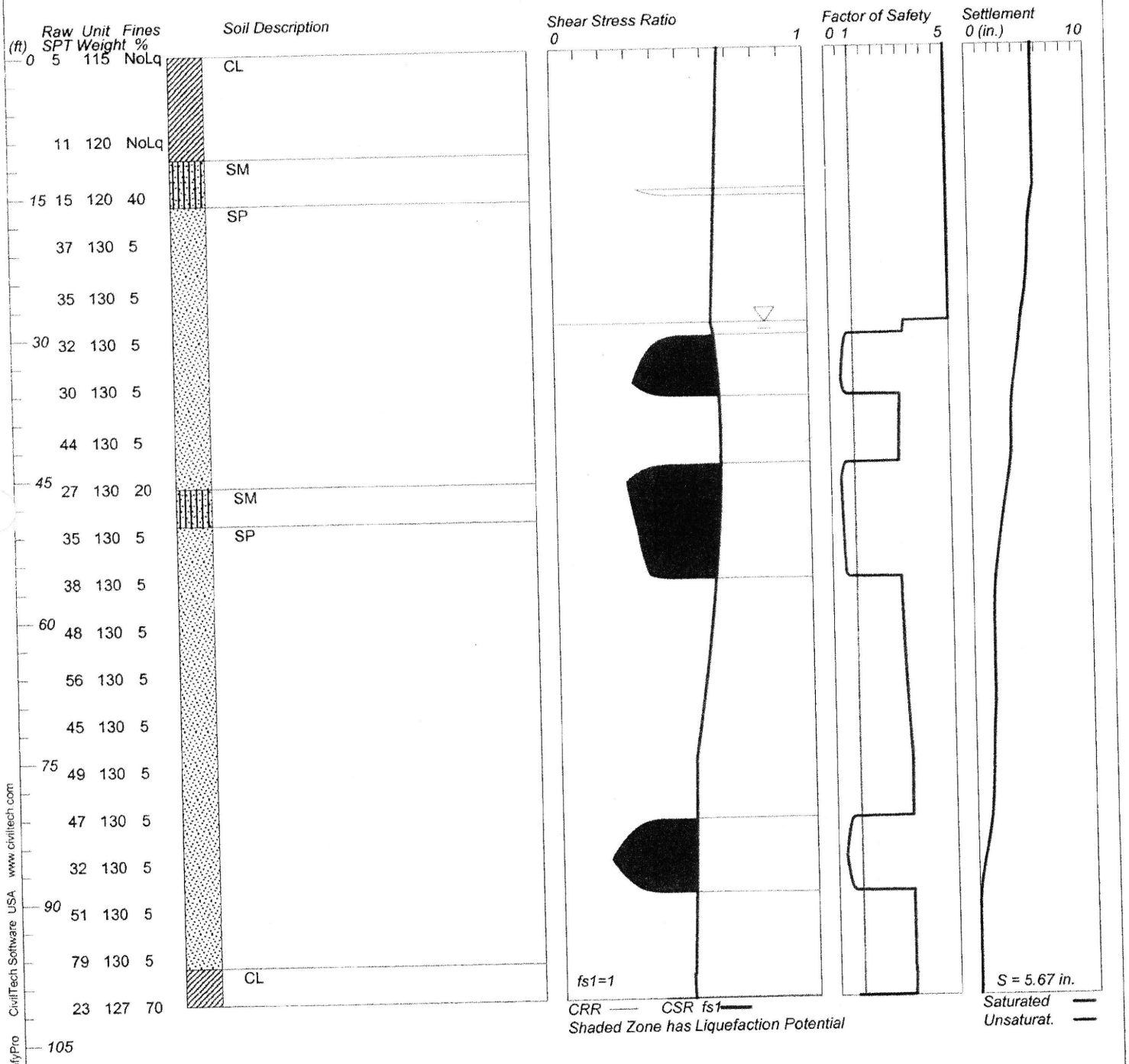
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100105

Hole No.=3A Water Depth=29.2 ft Surface Elev.=213.8

Magnitude=7.5
Acceleration=1.030g



BN-3A, Mississippi County

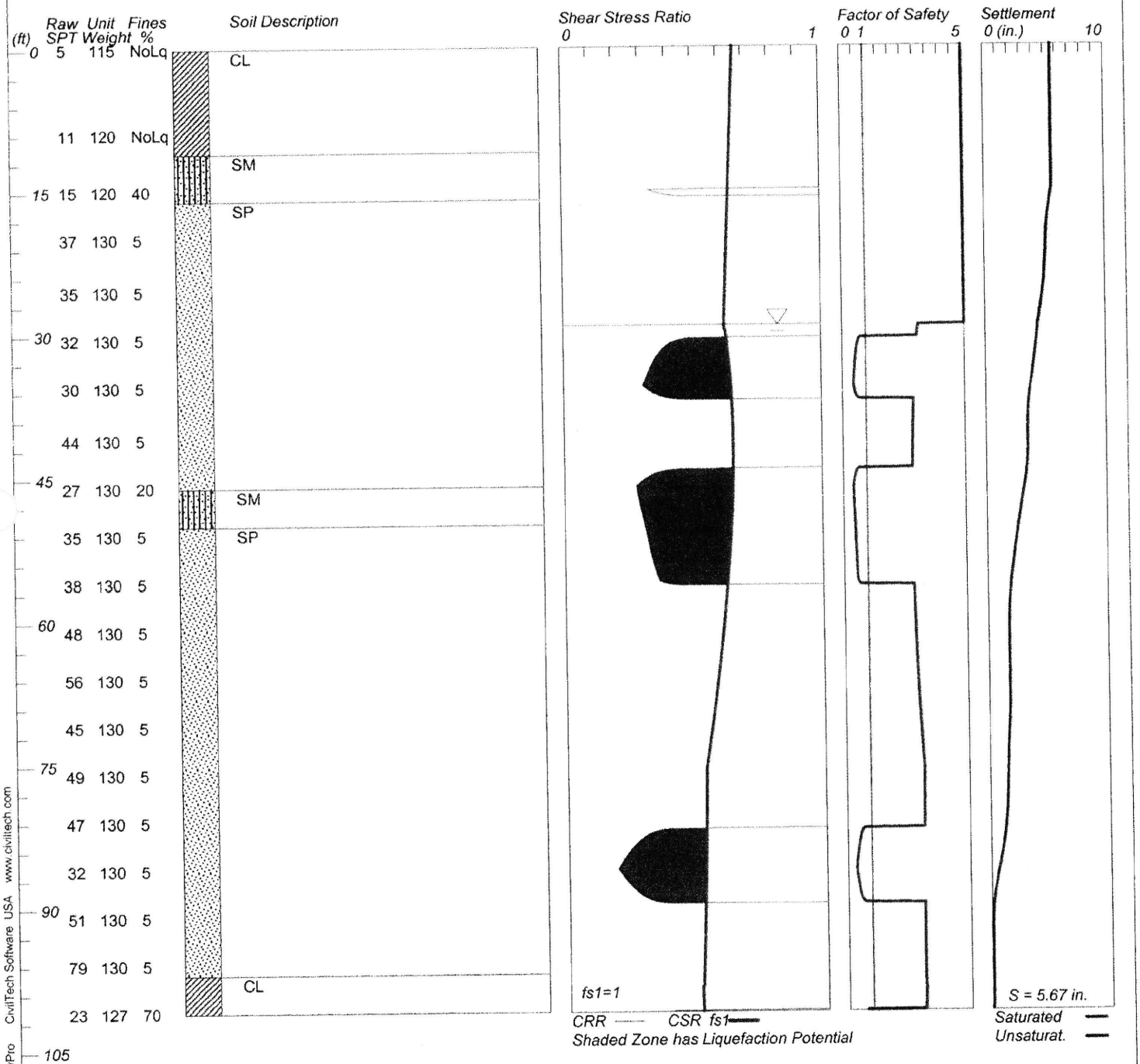
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100105

Hole No.=3A Water Depth=29.2 ft Surface Elev.=213.8

Magnitude=7.5
Acceleration=1.030g



BN-3A, Mississippi County

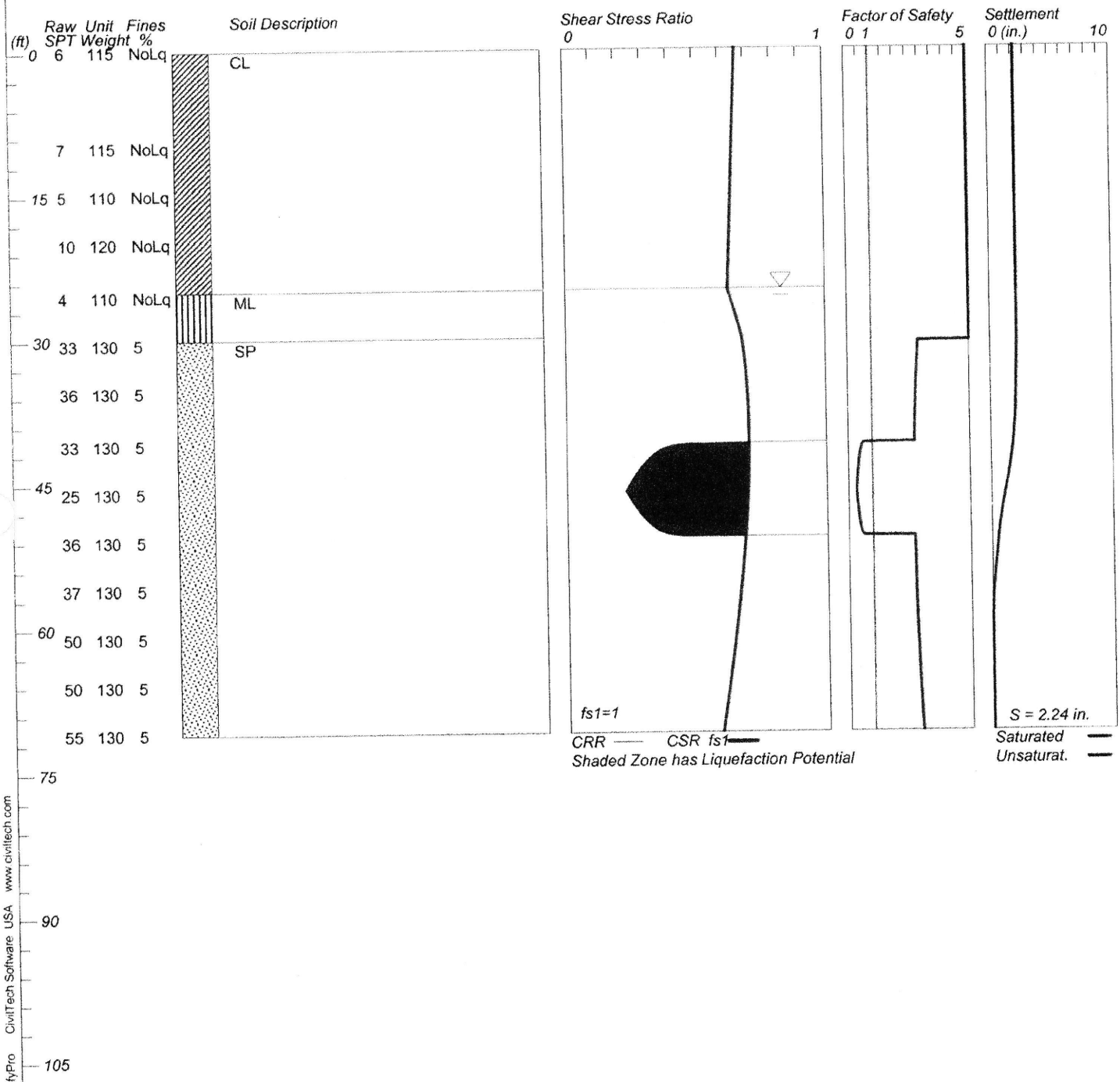
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100105

Hole No.=4 Water Depth=25 ft Surface Elev.=222.5

Magnitude=7.5
Acceleration=1.030g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-4, Mississippi County

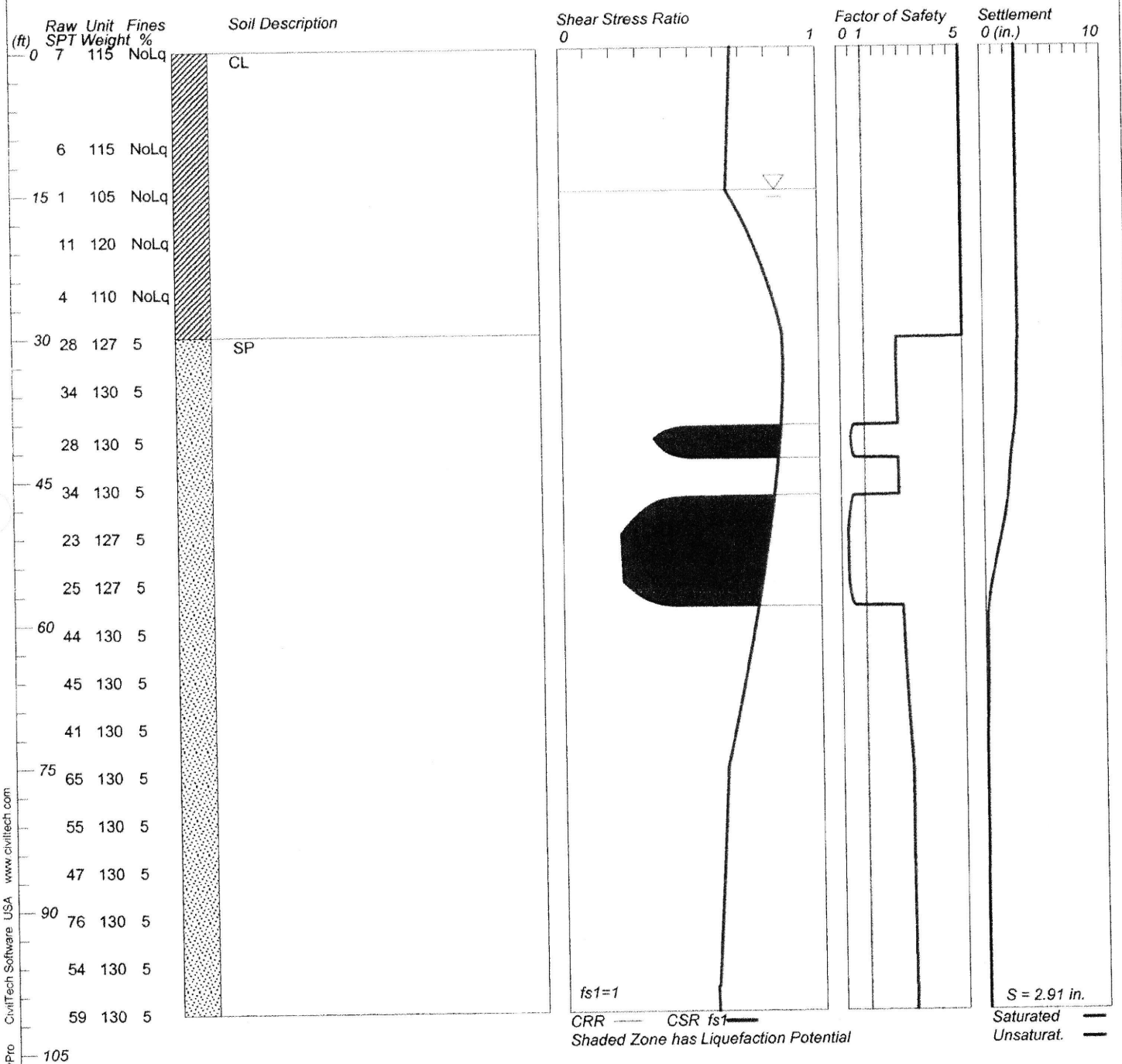
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100105

Hole No.=4A Water Depth=15 ft Surface Elev.=222.8

Magnitude=7.5
Acceleration=1.030g



BN-4A, Mississippi County

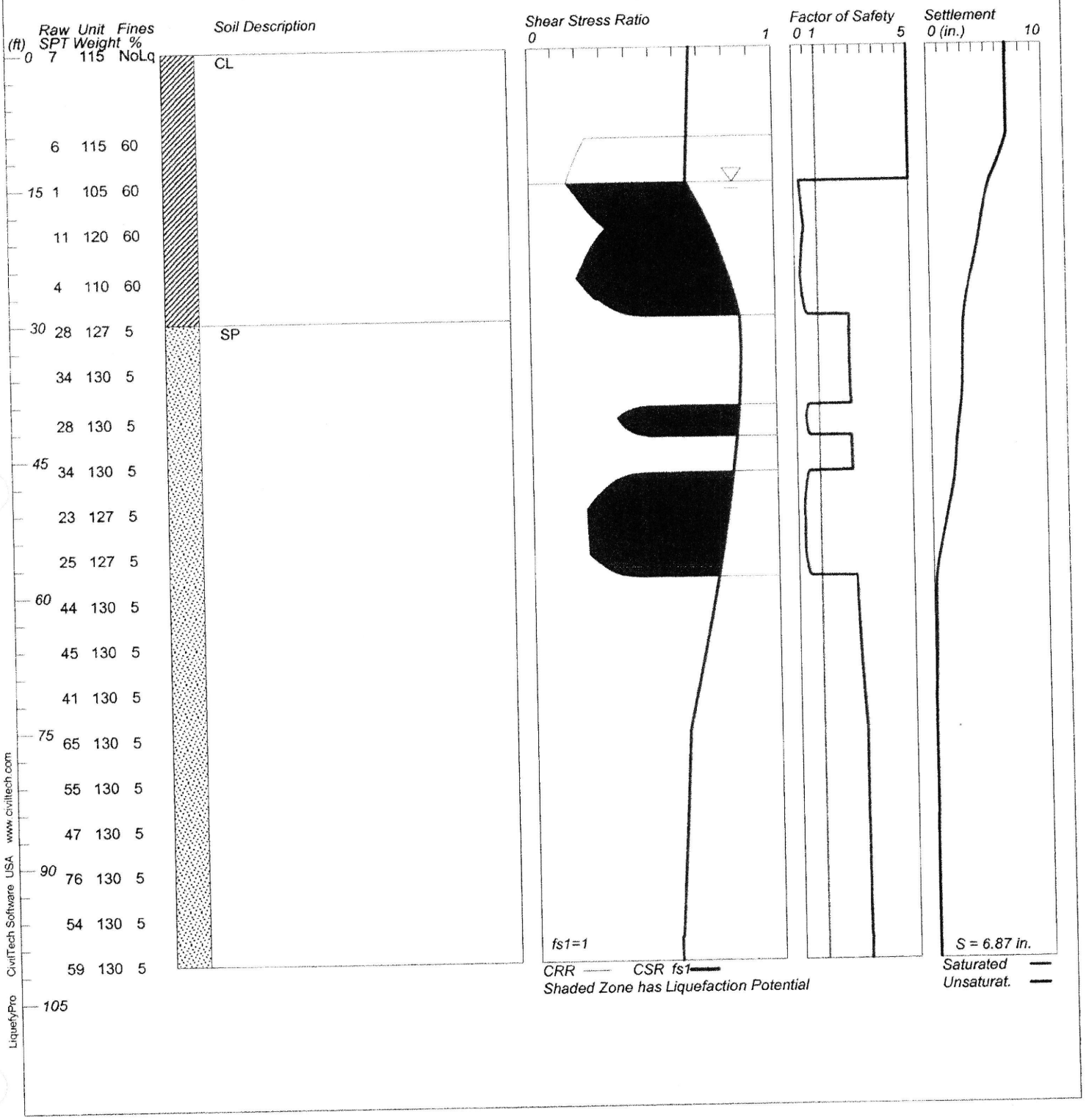
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100105

Hole No.=4A Water Depth=15 ft Surface Elev.=222.8

Magnitude=7.5
Acceleration=1.030g



BN-4A, Mississippi County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-100105

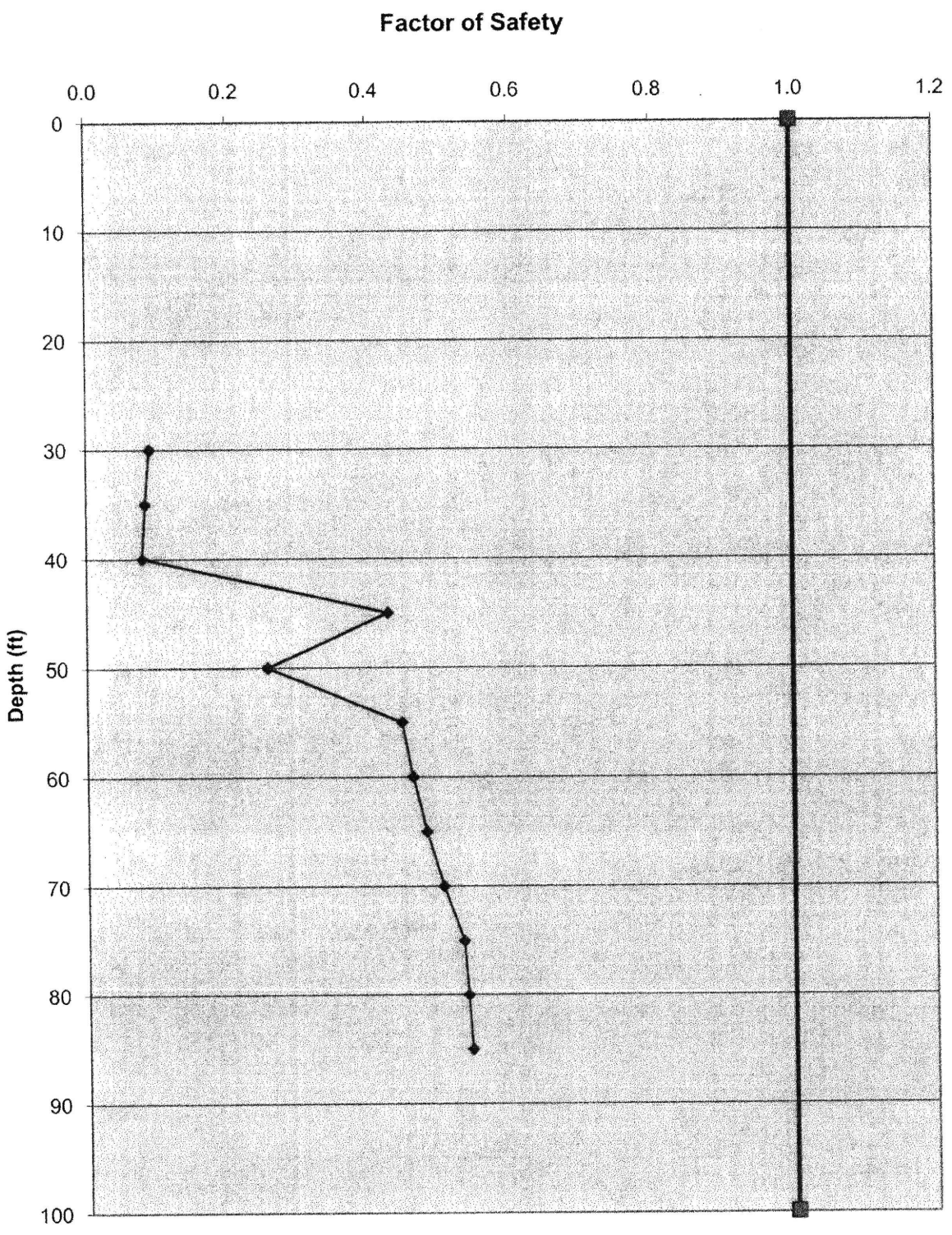
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	1.030	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	25	ft	assumed depth to groundwater =	25	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	115	361	71	34	575	575	575	0.988	0.6617	493	NA	1.00	1.00	NA	NA
10	1	115	394	71	34	1150	1150	1150	0.977	0.6539	452	NA	1.00	1.00	NA	NA
15	1	110	443	71	34	1700	1700	1700	0.965	0.6461	461	NA	1.00	1.00	NA	NA
20	1	120	443	71	34	2300	2300	2300	0.953	0.6383	428	NA	1.00	1.00	NA	NA
25	1	110	492	71	0	2850	2850	2850	0.942	0.6304	450	NA	1.00	1.00	NA	NA
30	2	130	492	6	0	3500	3188	3188	0.930	0.6836	438	0.0610	1.00	1.00	0.060982	0.1
35	2	130	492	6	0	4150	3526	3526	0.889	0.7005	427	0.0579	1.00	1.00	0.057863	0.1
40	2	130	492	6	0	4800	3864	3864	0.848	0.7055	417	0.0552	1.00	1.00	0.055186	0.1
45	2	130	820	6	0	5450	4202	4202	0.808	0.7012	681	0.3000	1.00	1.00	0.299946	0.4
50	2	130	820	5	0	6100	4540	4540	0.767	0.6898	668	0.1759	1.00	1.00	0.175825	0.3
55	2	130	919	5	0	6750	4878	4878	0.726	0.6727	735	0.3000	1.00	1.00	0.299946	0.4
60	2	130	919	5	0	7400	5216	5216	0.685	0.6510	723	0.3000	1.00	1.00	0.299946	0.5
65	2	130	919	5	0	8050	5554	5554	0.645	0.6256	712	0.3000	1.00	1.00	0.299946	0.5
70	2	130	1476	8	0	8700	5892	5892	0.604	0.5971	1127	0.3000	1.00	1.00	0.299946	0.5
75	2	130	1476	8	0	9350	6230	6230	0.563	0.5659	1111	0.3000	1.00	1.00	0.299946	0.5
80	2	130	1476	8	0	10000	6568	6568	0.549	0.5594	1096	0.3000	1.00	1.00	0.299946	0.5
85	2	130	1476	8	0	10650	6906	6906	0.537	0.5540	1083	0.3000	1.00	1.00	0.299946	0.5

Used Bore #4 for PI values, water depth, & unit wt.

Vs Liquefaction Potential - Project 100105

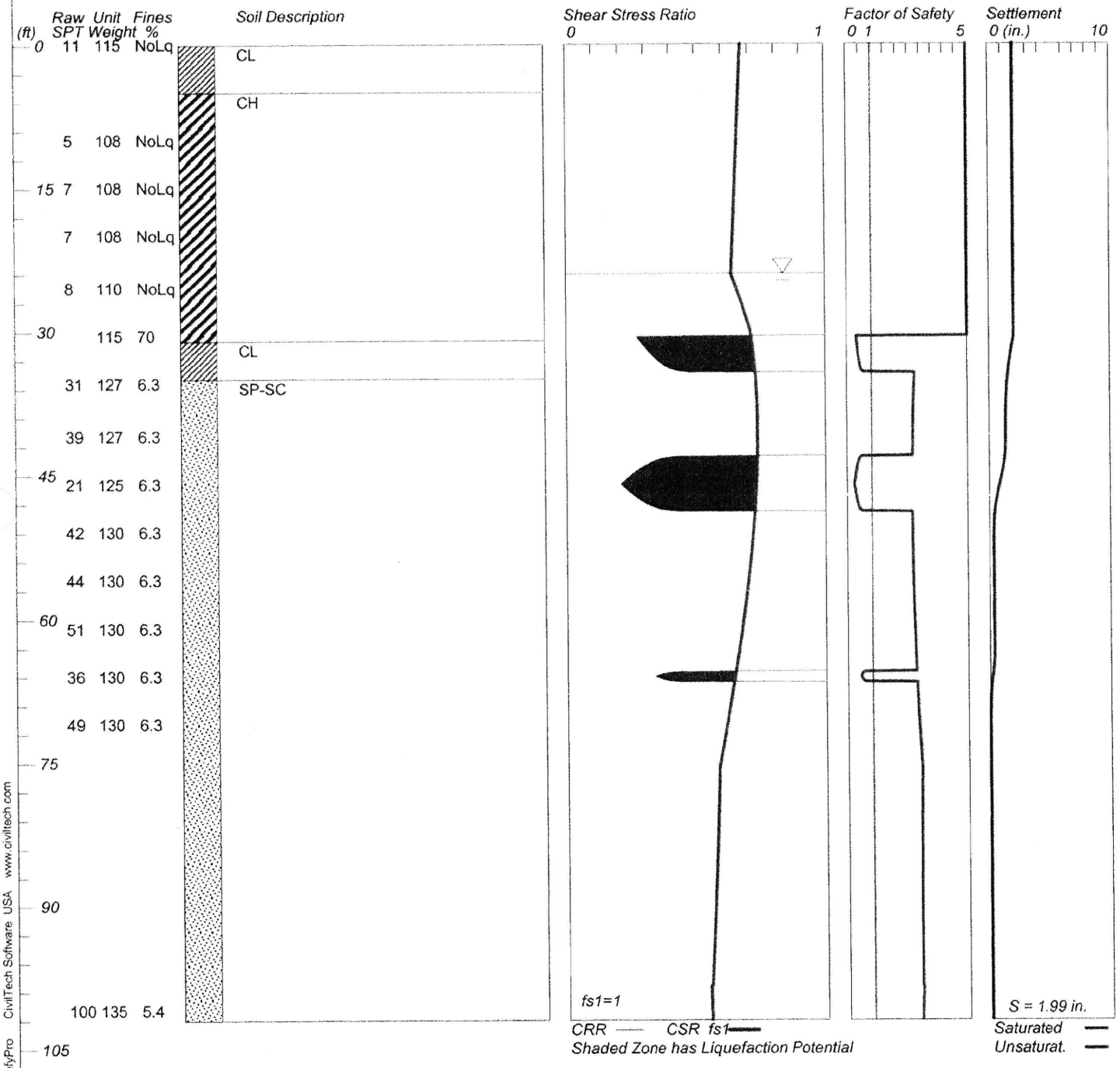


LIQUEFACTION ANALYSIS (ALT.A)

BR4706

Hole No.=1 Water Depth=24.0 ft Surface Elev.=227.7

Magnitude=7.5
Acceleration=1.038g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Mississippi County

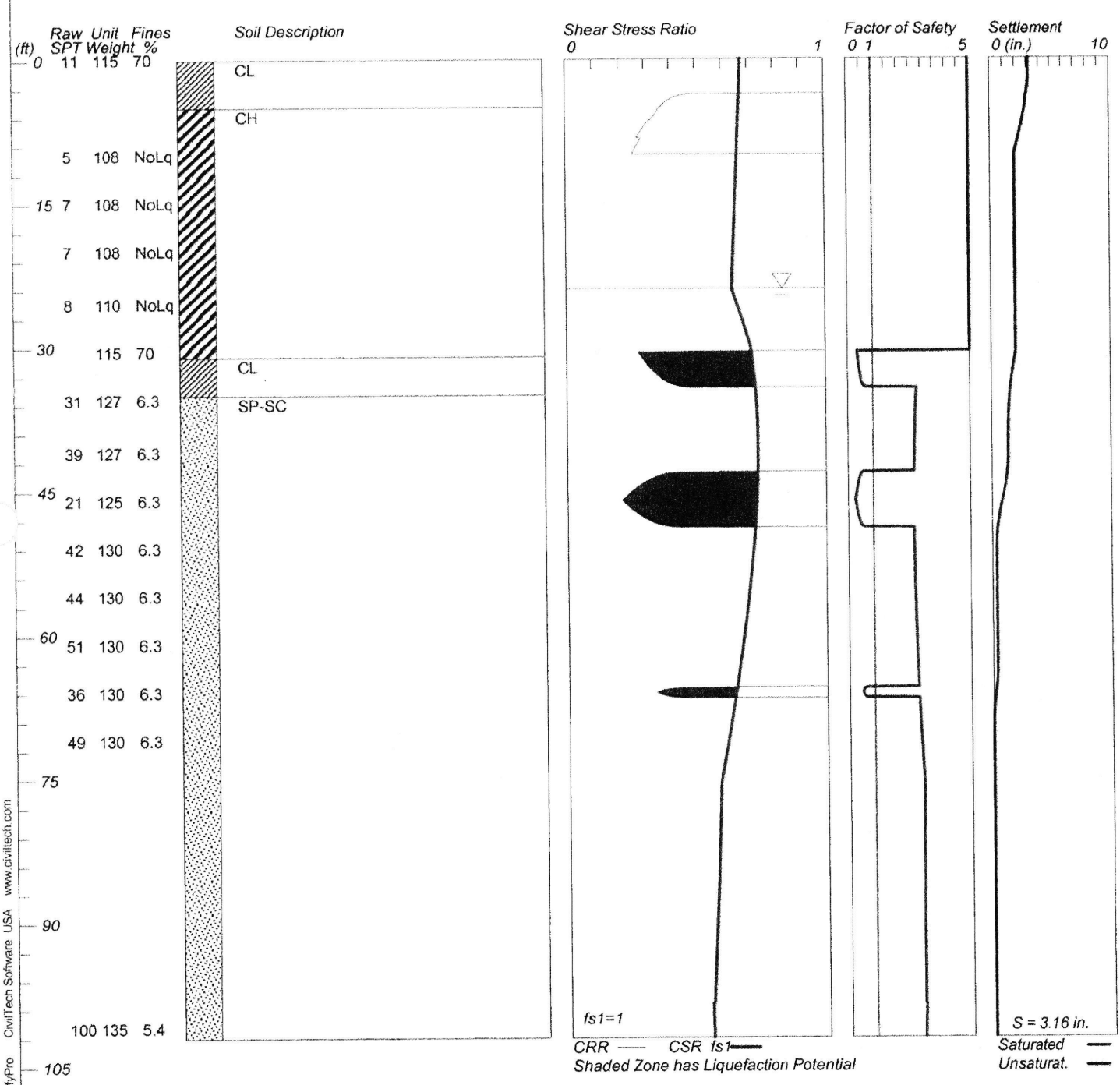
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

BR4706

Hole No.=1 Water Depth=24.0 ft Surface Elev.=227.7

Magnitude=7.5
Acceleration=1.038g



BN-1, Mississippi County

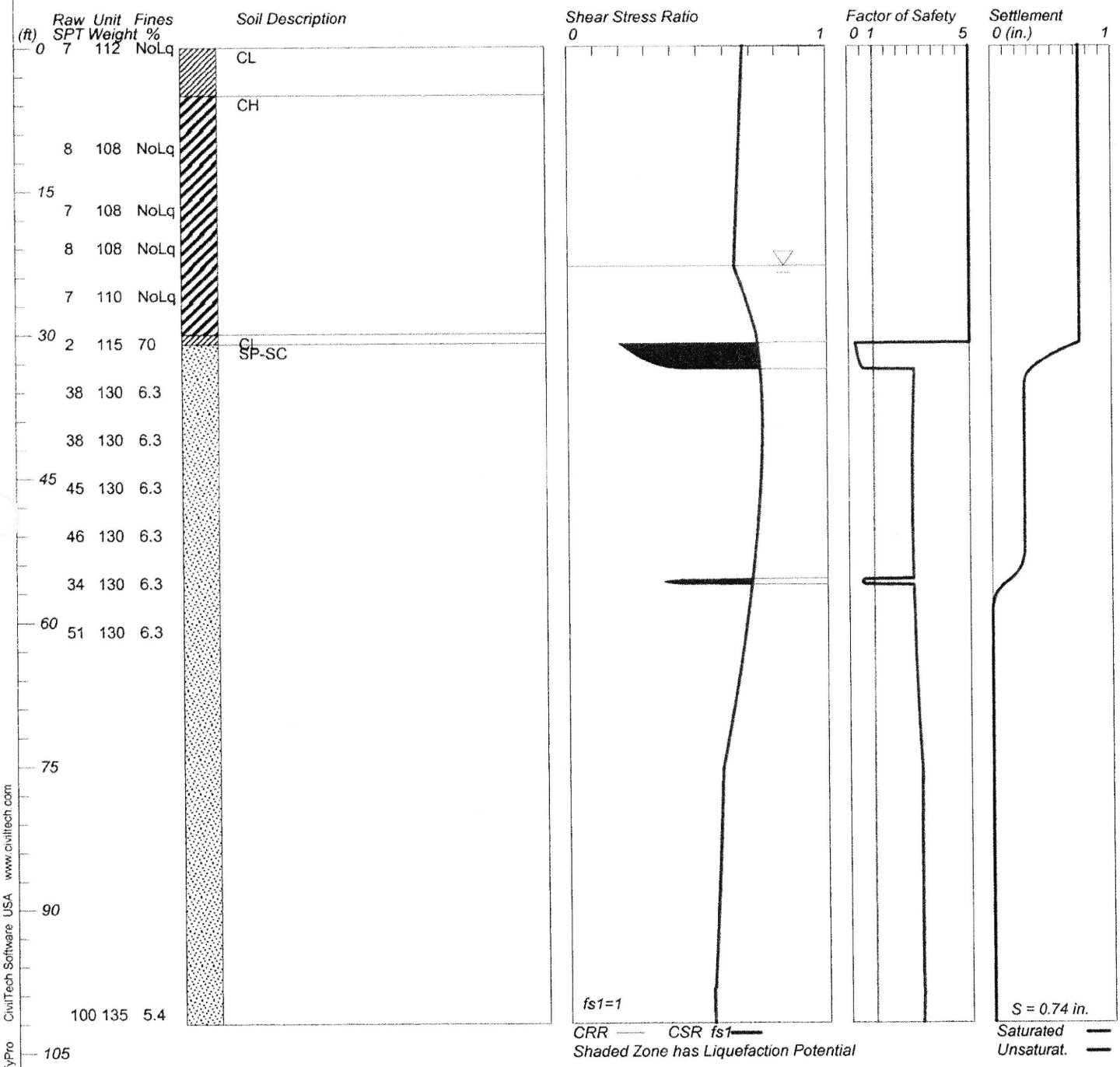
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

BR4706

Hole No.=2 Water Depth=23 ft Surface Elev.=226.9

Magnitude=7.5
Acceleration=1.038g



BN-2, Mississippi County

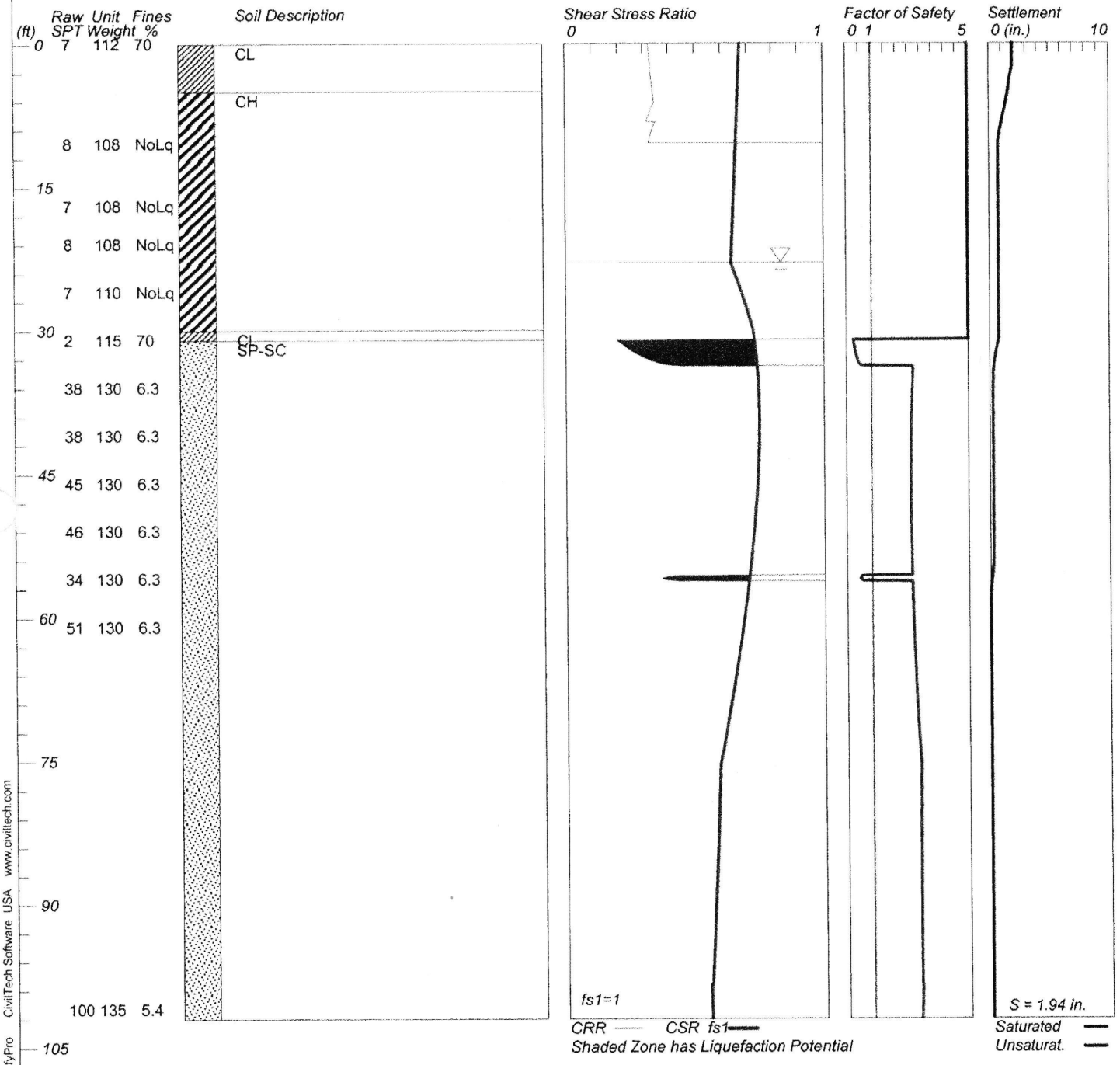
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

BR4706

Hole No.=2 Water Depth=23 ft Surface Elev.=226.9

Magnitude=7.5
Acceleration=1.038g



BN-2, Mississippi County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-BR4706

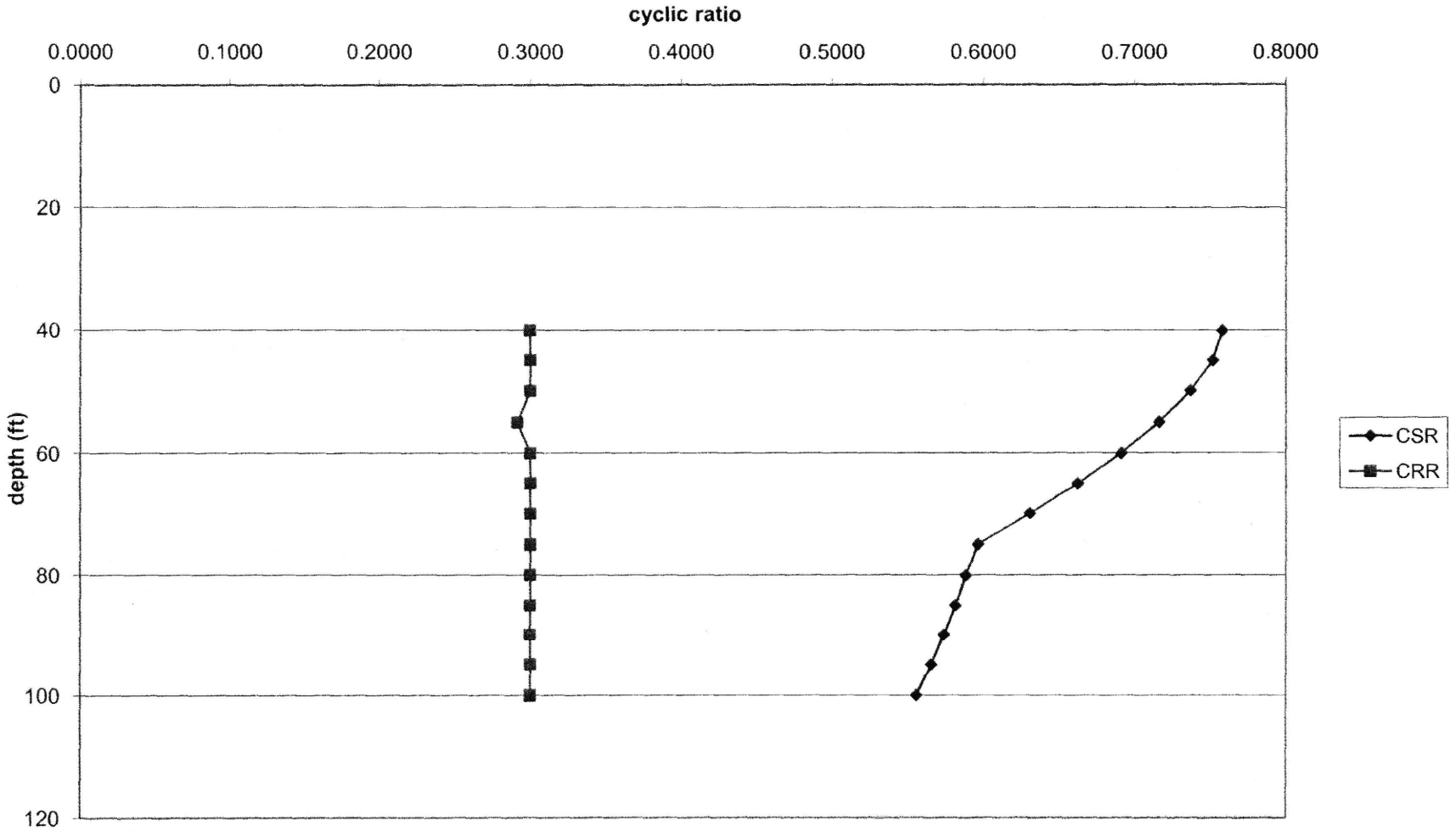
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	1.038	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	22	ft	assumed depth to groundwater =	22	ft
estimated age of sand deposit =	2000	years			

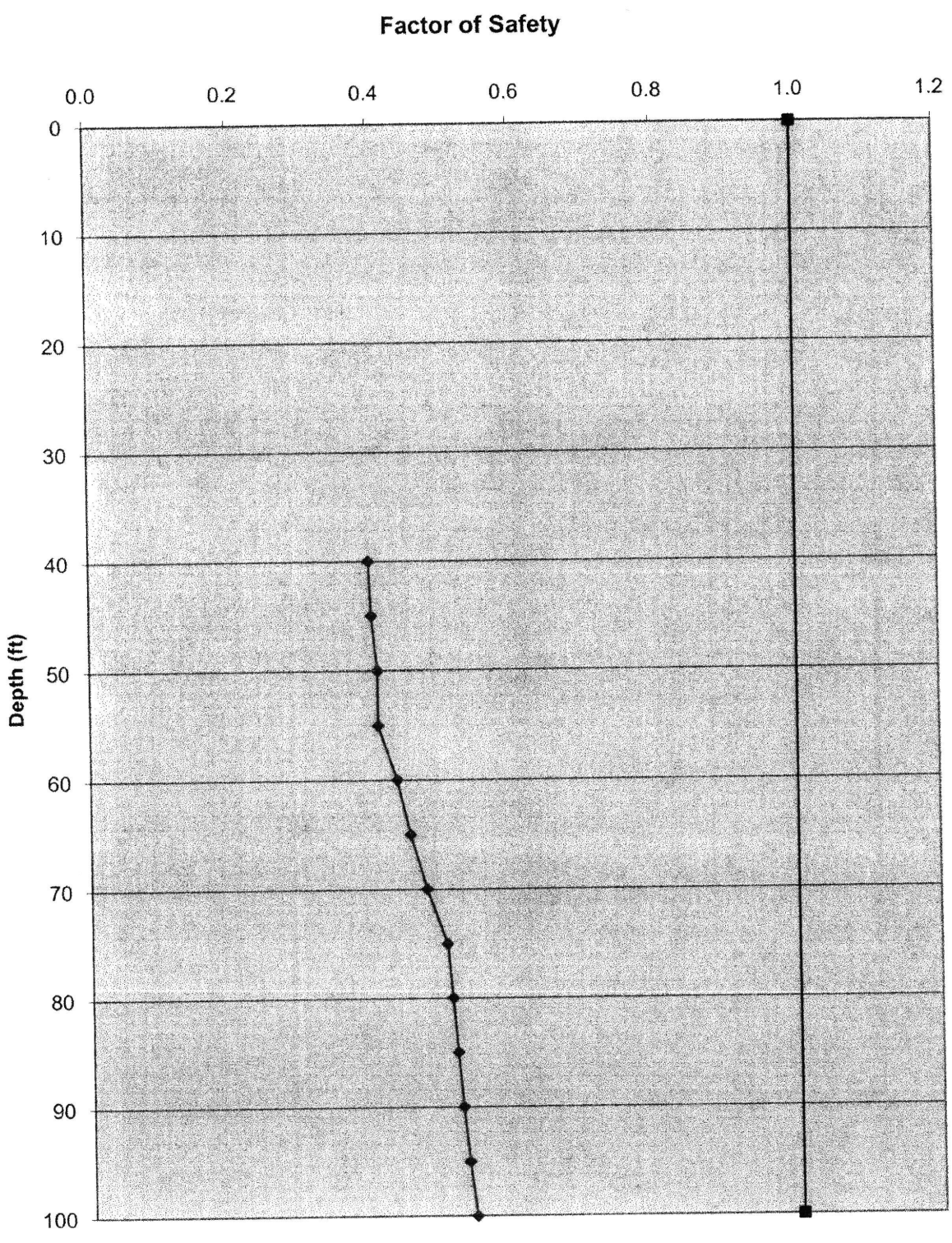
	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	115	361	70	35	575	575	575	0.988	0.6668	493	NA	1.00	1.00	NA	NA
10	1	108	394	88.5	35	1115	1115	1115	0.977	0.6590	456	NA	1.00	1.00	NA	NA
15	1	108	394	88.5	35	1655	1655	1655	0.965	0.6511	413	NA	1.00	1.00	NA	NA
20	1	108	476	88.5	35	2195	2195	2195	0.953	0.6432	465	NA	1.00	1.00	NA	NA
25	1	110	476	88.5	35	2745	2558	2558	0.942	0.6818	448	NA	1.00	1.00	NA	NA
30	1	115	623	70	35	3320	2821	2821	0.930	0.7385	572	NA	1.00	1.00	NA	NA
35	1	127	820	6	35	3955	3144	3144	0.889	0.7546	732	NA	1.00	1.00	NA	NA
40	2	127	820	6	0	4590	3467	3467	0.848	0.7577	715	0.3000	1.00	1.00	0.299946	0.4
45	2	125	820	6	0	5215	3780	3780	0.808	0.7517	699	0.3000	1.00	1.00	0.299946	0.4
50	2	130	820	6	0	5865	4118	4118	0.767	0.7369	685	0.3000	1.00	1.00	0.299946	0.4
55	2	130	820	6	0	6515	4456	4456	0.726	0.7163	671	0.2916	1.00	1.00	0.291524	0.4
60	2	130	1181	6	0	7165	4794	4794	0.685	0.6912	949	0.3000	1.00	1.00	0.299946	0.4
65	2	130	1181	6	0	7815	5132	5132	0.645	0.6624	933	0.3000	1.00	1.00	0.299946	0.5
70	2	130	1181	6	0	8465	5470	5470	0.604	0.6306	918	0.3000	1.00	1.00	0.299946	0.5
75	2	130	1181	6	0	9115	5808	5808	0.563	0.5964	905	0.3000	1.00	1.00	0.299946	0.5
80	2	130	1345	6	0	9765	6146	6146	0.549	0.5883	1016	0.3000	1.00	1.00	0.299946	0.5
85	2	130	1345	6	0	10415	6484	6484	0.537	0.5816	1002	0.3000	1.00	1.00	0.299946	0.5
90	2	130	1345	6	0	11065	6822	6822	0.524	0.5739	990	0.3000	1.00	1.00	0.299946	0.5
95	2	130	1345	6	0	11715	7160	7160	0.512	0.5654	978	0.3000	1.00	1.00	0.299946	0.5
100	2	135	1476	5	0	12390	7523	7523	0.500	0.5556	1060	0.3000	1.00	1.00	0.299946	0.5

Used Bore #1 for PI values & unit wt.

Cyclic Stress Ratio vs. Cyclic Resistance Ratio
Project BR4706: Shear Wave Velocity Analysis



Vs Liquefaction Potential - Project BR4706



LIQUEFACTION ANALYSIS (ALT.A)

100522

Hole No.=1 Water Depth=17.5 ft Surface Elev.=216.5

Magnitude=7.5
Acceleration=1.035g

LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Poinsett County

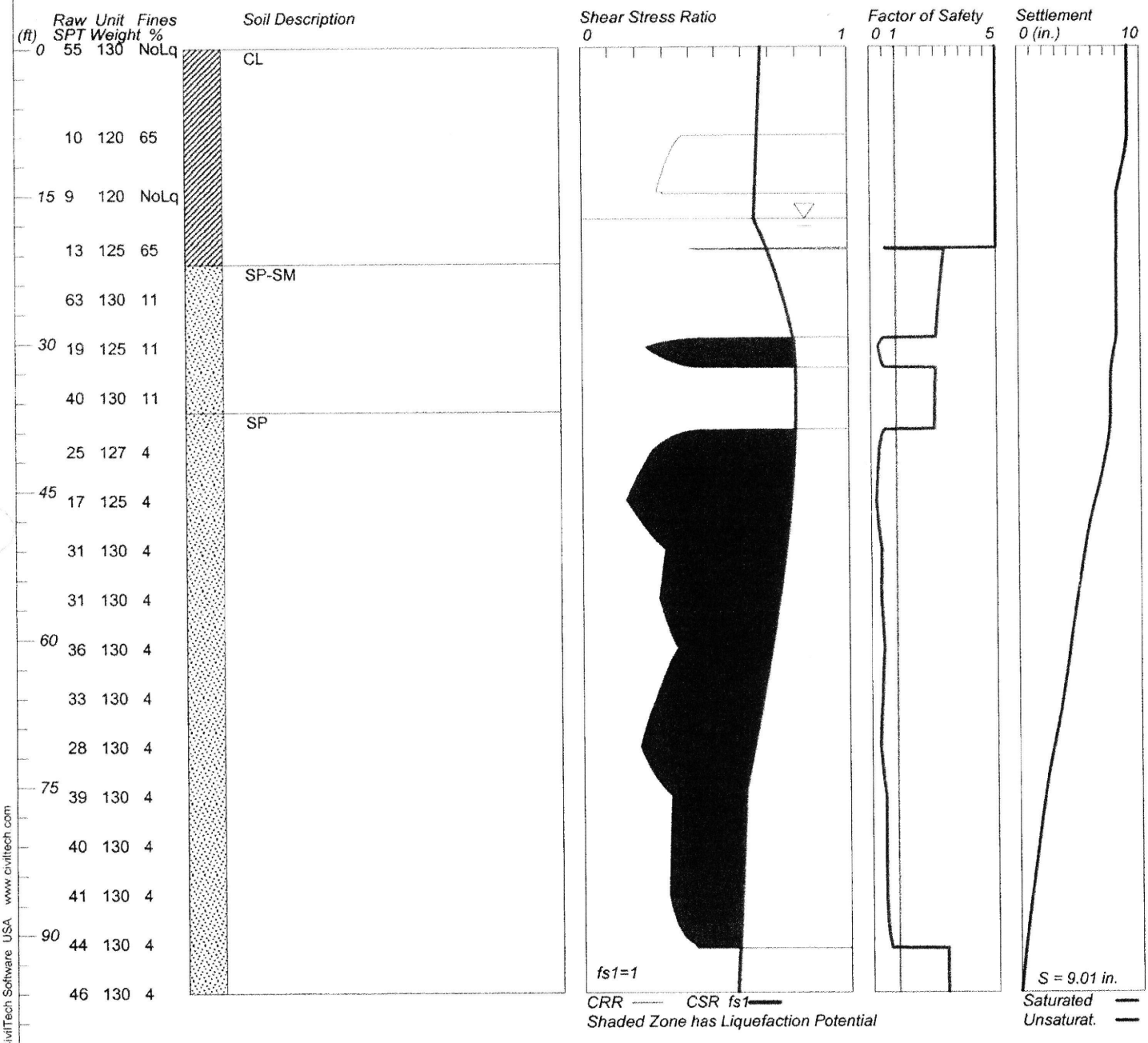
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100522

Hole No.=1 Water Depth=17.5 ft Surface Elev.=216.5

Magnitude=7.5
Acceleration=1.035g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Poinsett County

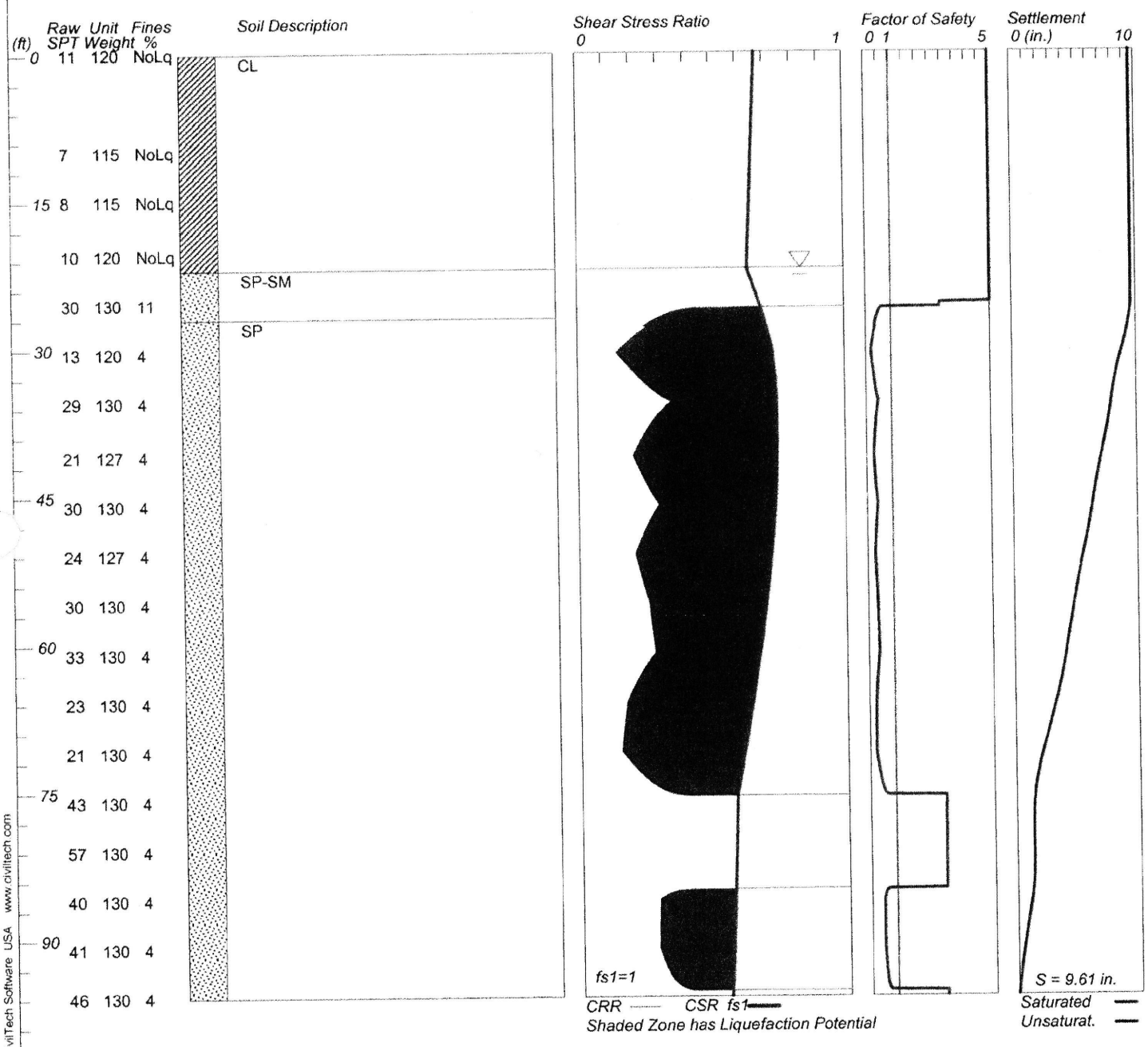
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100522

Hole No.=2 Water Depth=22 ft Surface Elev.=220.0

Magnitude=7.5
Acceleration=1.035g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-2, Poinsett County **Plate A-1**

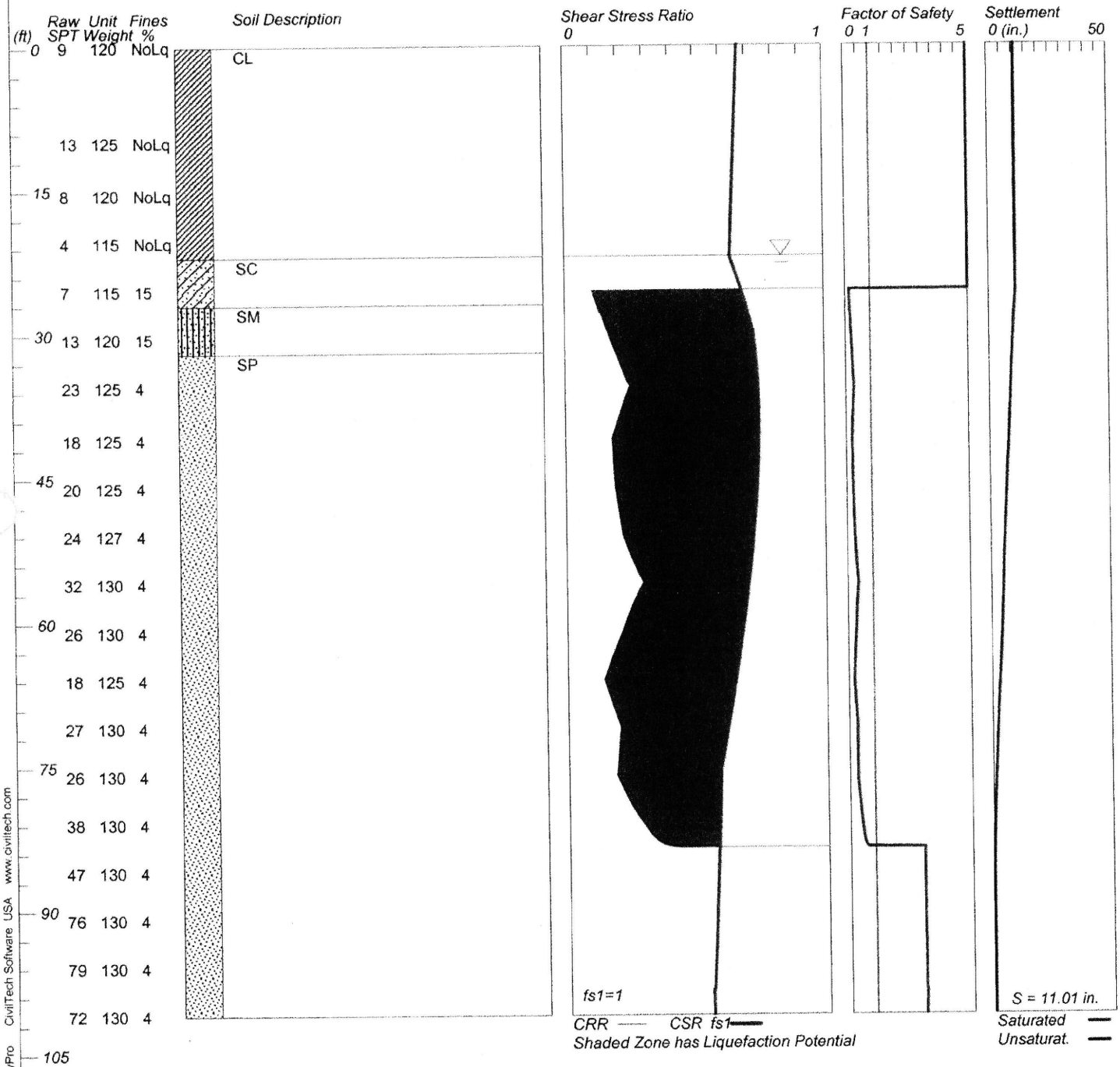
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100522

Hole No.=3 Water Depth=22 ft Surface Elev.=220

Magnitude=7.5
Acceleration=1.035g



BN-3, Poinsett County

Plate A-1

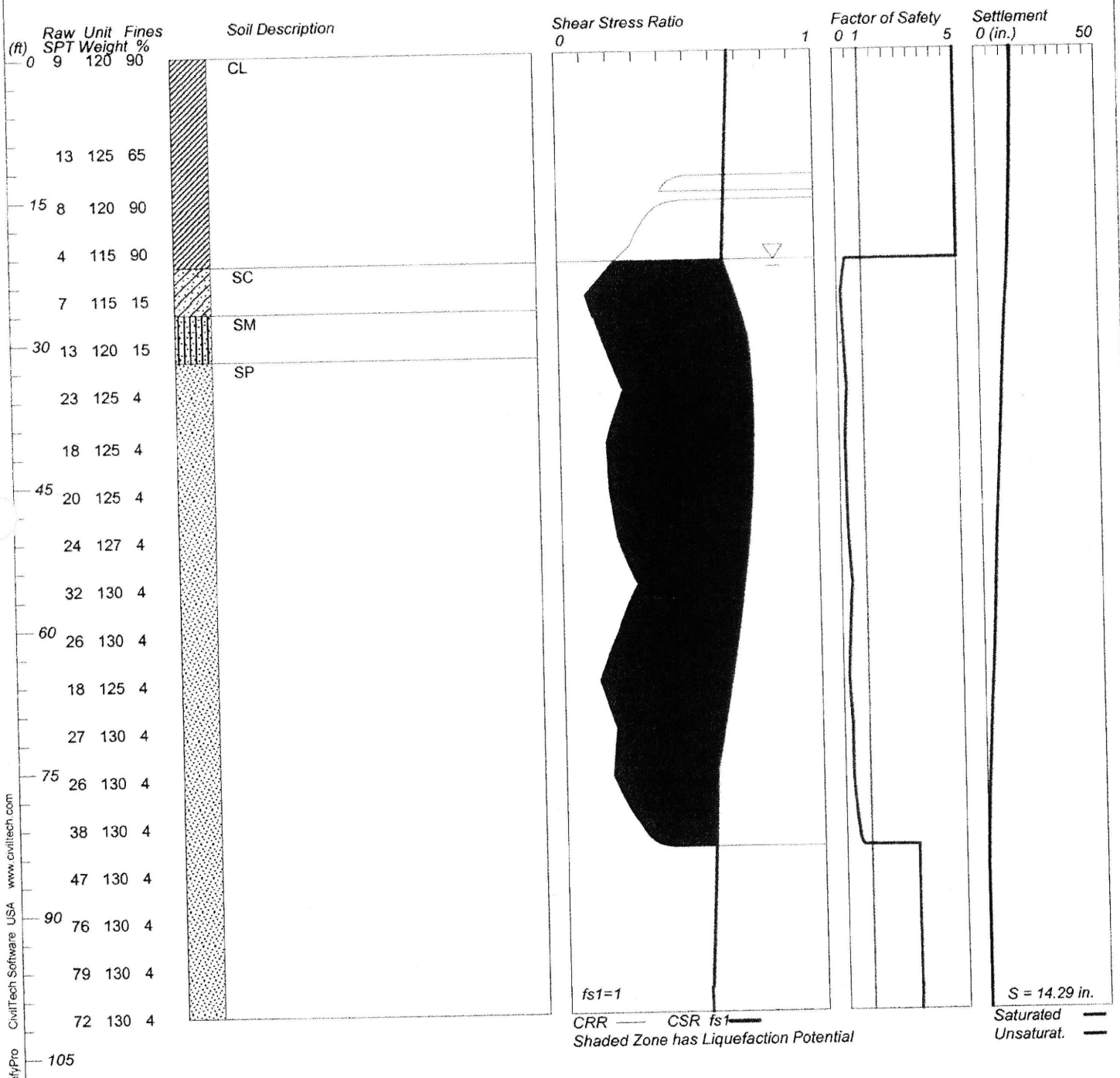
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100522

Hole No.=3 Water Depth=22 ft Surface Elev.=220

Magnitude=7.5
Acceleration=1.035g



BN-3, Poinsett County

Plate A-1

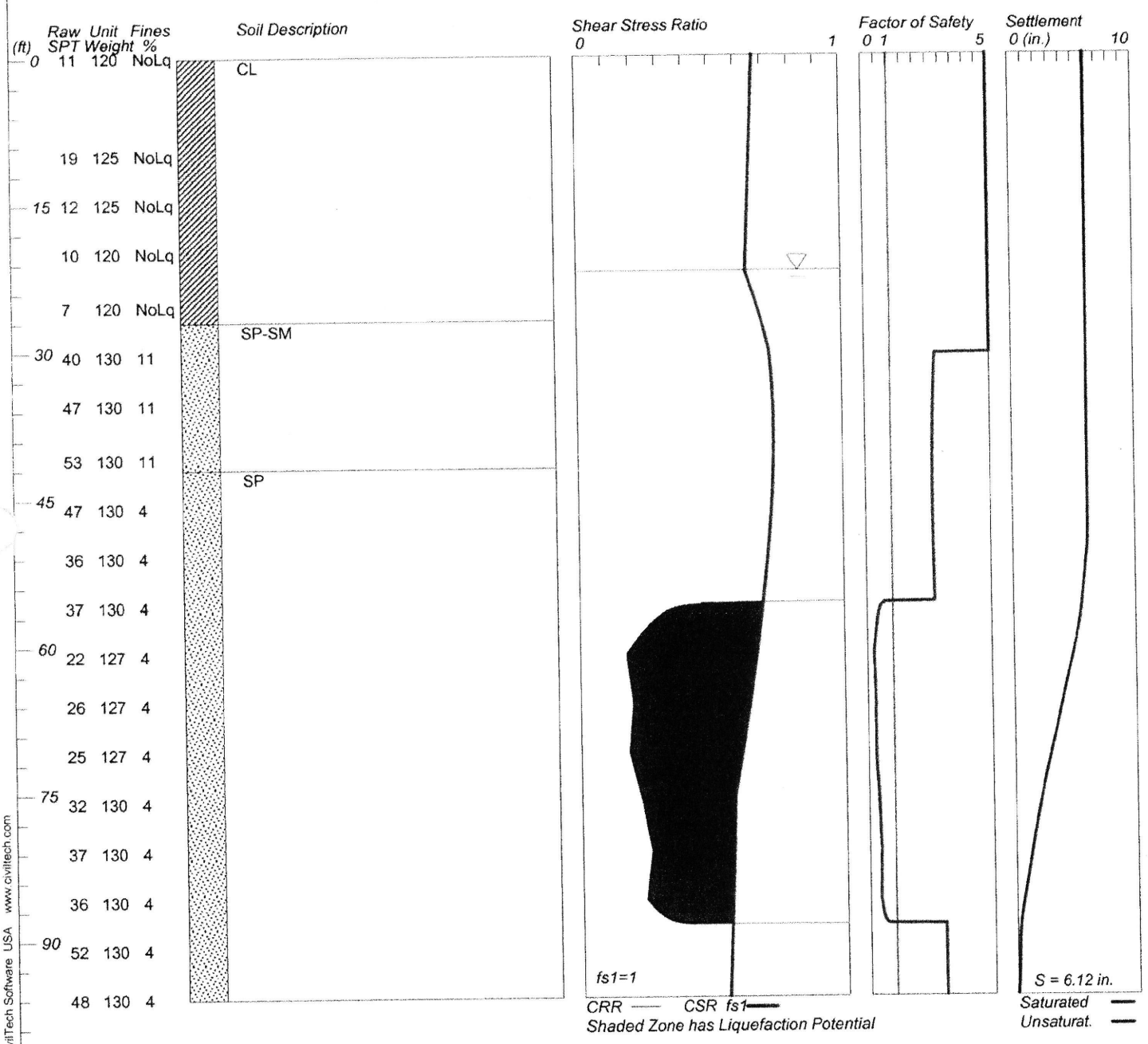
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100522

Hole No.=4 Water Depth=22 ft Surface Elev.=219.5

Magnitude=7.5
Acceleration=1.035g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-4, Poinsett County

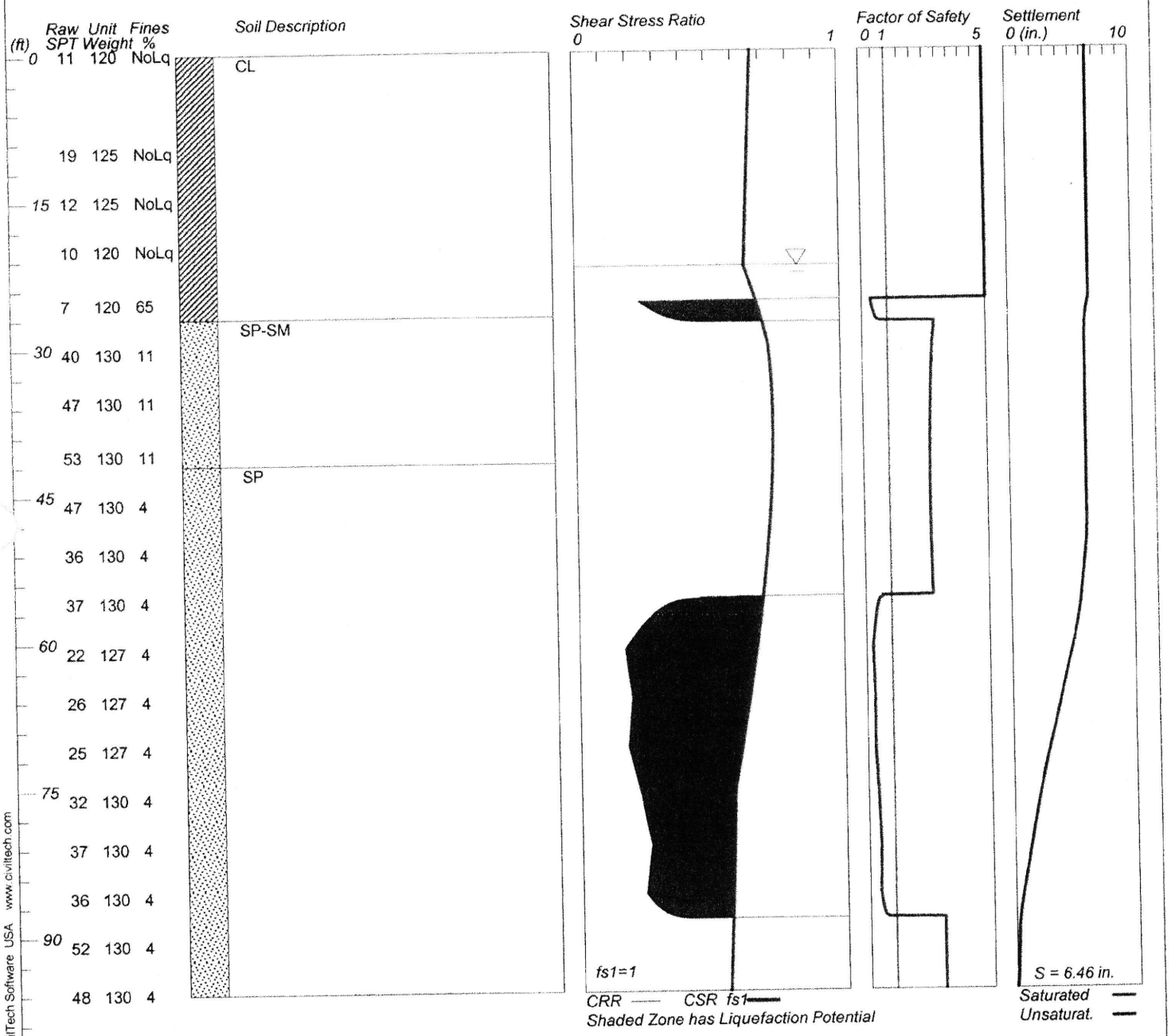
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100522

Hole No.=4 Water Depth=22 ft Surface Elev.=219.5

Magnitude=7.5
Acceleration=1.035g



BN-4, Poinsett County

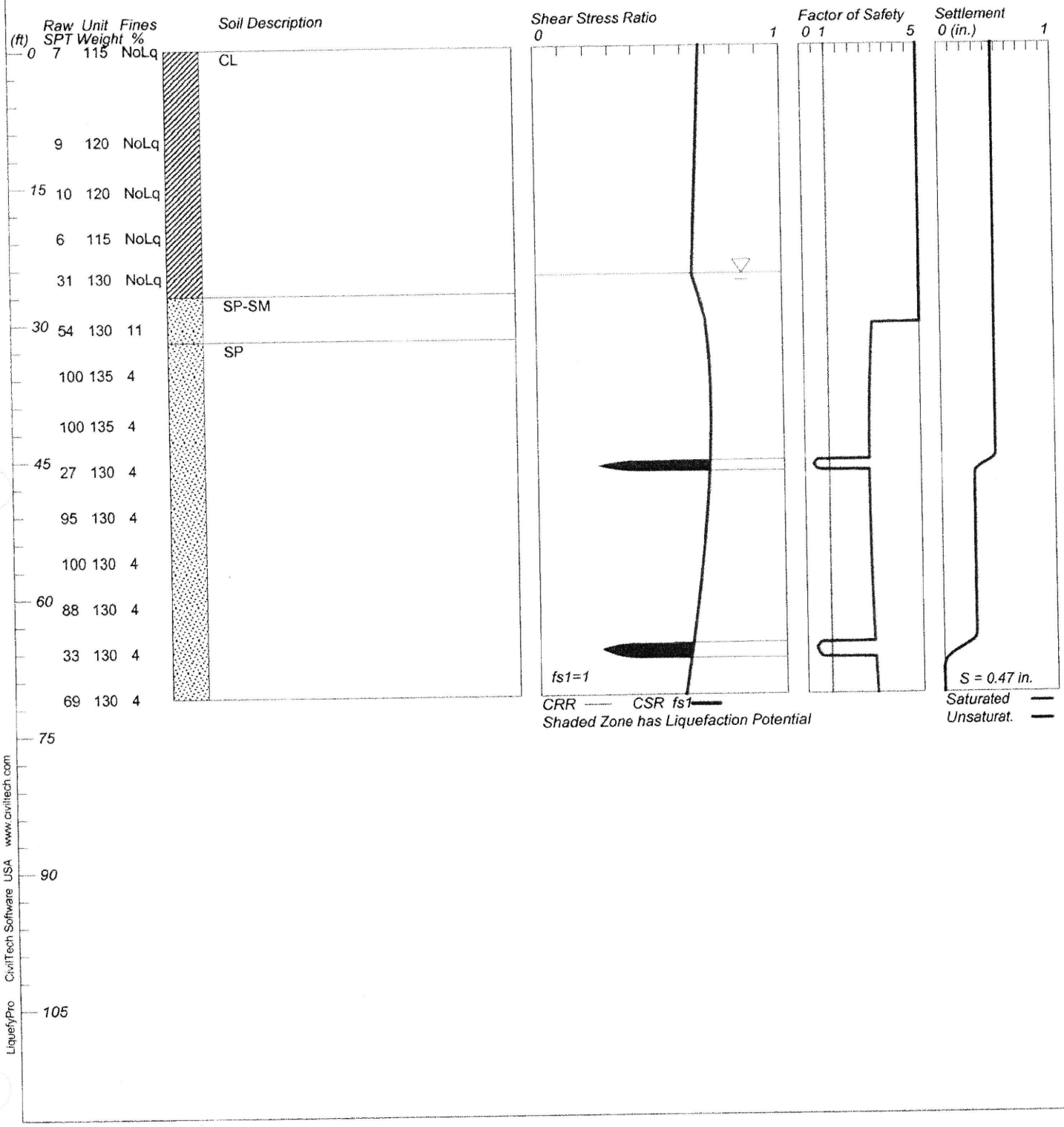
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100522

Hole No.=5 Water Depth=25 ft Surface Elev.=217

Magnitude=7.5
Acceleration=1.035g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-5, Poinsett County

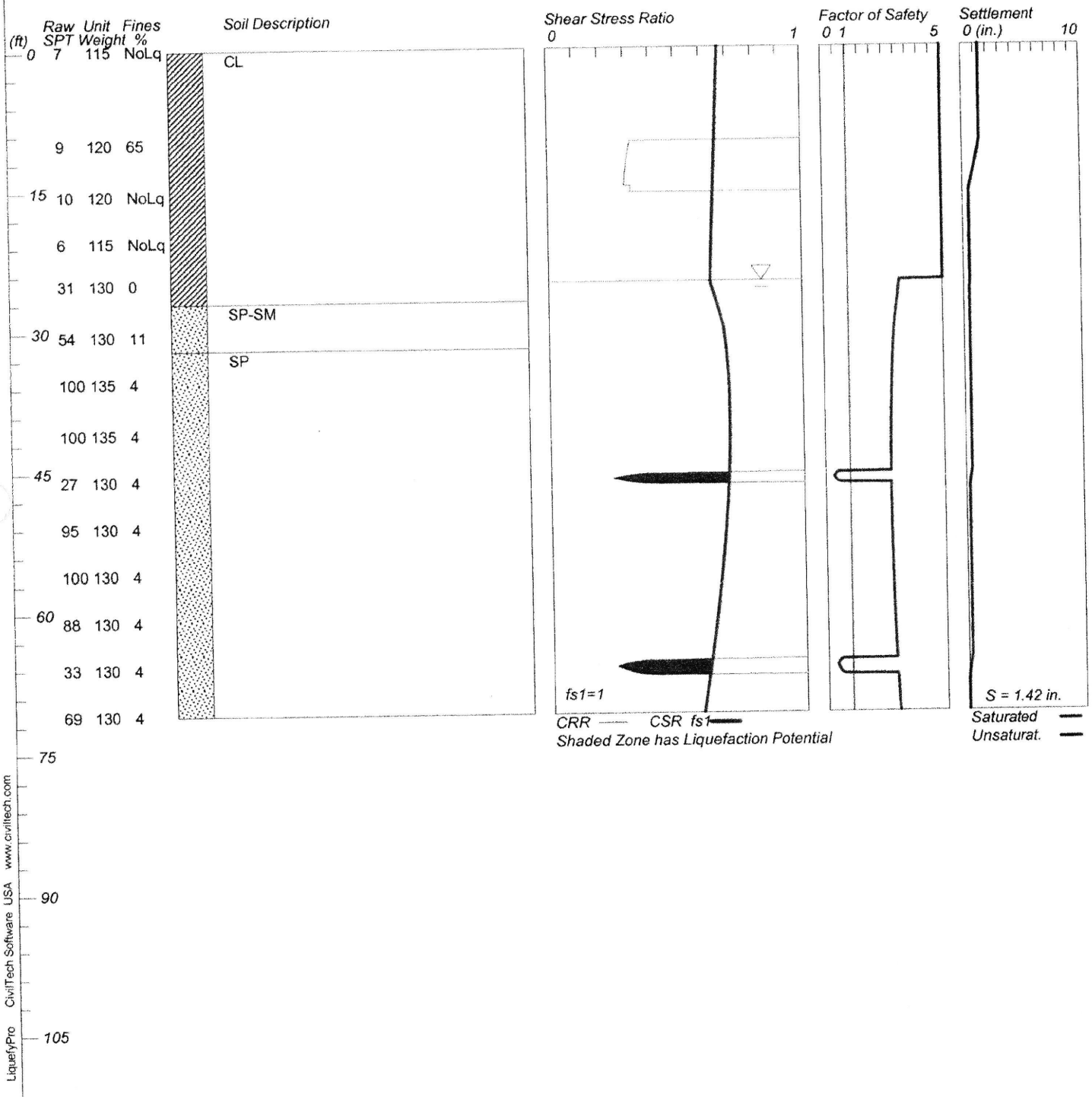
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100522

Hole No.=5 Water Depth=25 ft Surface Elev.=217

Magnitude=7.5
Acceleration=1.035g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-5, Poinsett County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-100522

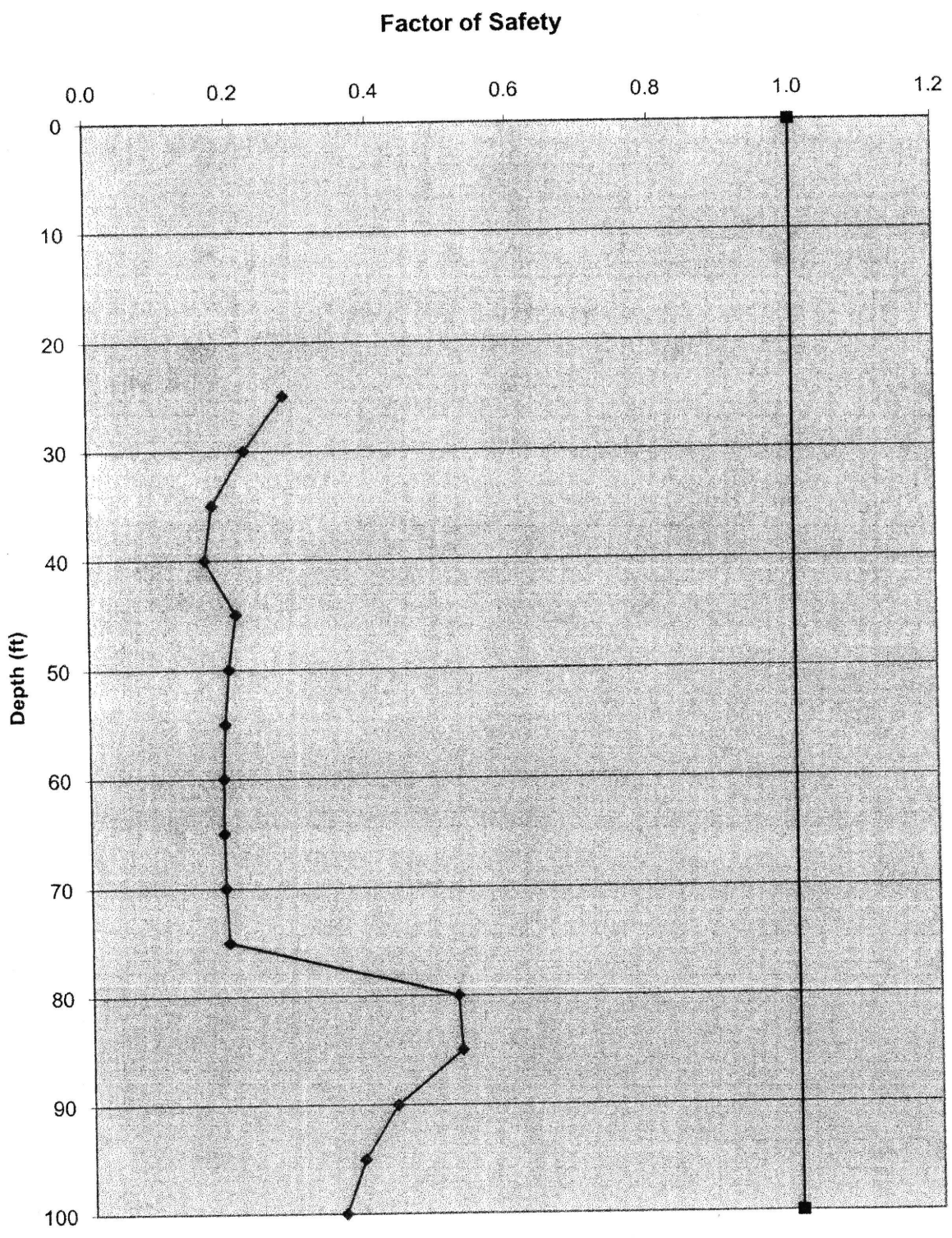
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	1.035	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	22	ft	assumed depth to groundwater =	22	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	120	691	90	15	600	600	600	0.988	0.6649	799	NA	1.00	1.00	NA	NA
10	1	125	689	85	15	1225	1225	1225	0.977	0.6571	779	NA	1.00	1.00	NA	NA
15	1	120	689	90	15	1825	1825	1825	0.965	0.6492	705	NA	1.00	1.00	NA	NA
20	1	115	689	90	15	2400	2400	2400	0.953	0.6414	658	NA	1.00	1.00	NA	NA
25	2	115	705	15	0	2975	2788	2788	0.942	0.6760	649	0.1875	1.00	1.00	0.187505	0.3
30	2	120	705	15	0	3575	3076	3076	0.930	0.7272	633	0.1608	1.00	1.00	0.160754	0.2
35	2	125	705	4	0	4200	3389	3389	0.889	0.7412	618	0.1310	1.00	1.00	0.130986	0.2
40	2	125	705	4	0	4825	3702	3702	0.848	0.7438	604	0.1231	1.00	1.00	0.123087	0.2
45	2	125	771	4	0	5450	4015	4015	0.808	0.7375	648	0.1531	1.00	1.00	0.153074	0.2
50	2	127	771	4	0	6085	4338	4338	0.767	0.7237	635	0.1429	1.00	1.00	0.142844	0.2
55	2	130	771	4	0	6735	4676	4676	0.726	0.7036	624	0.1346	1.00	1.00	0.134555	0.2
60	2	130	771	4	0	7385	5014	5014	0.685	0.6792	613	0.1279	1.00	1.00	0.127838	0.2
65	2	125	771	4	0	8010	5327	5327	0.645	0.6522	604	0.1226	1.00	1.00	0.12259	0.2
70	2	130	771	4	0	8660	5665	5665	0.604	0.6211	594	0.1177	1.00	1.00	0.117695	0.2
75	2	130	771	4	0	9310	6003	6003	0.563	0.5877	586	0.1134	1.00	1.00	0.113415	0.2
80	2	130	951	4	0	9960	6341	6341	0.549	0.5799	713	0.3000	1.00	1.00	0.299946	0.5
85	2	130	951	4	0	10610	6679	6679	0.537	0.5735	703	0.2997	1.00	1.00	0.299631	0.5
90	2	130	951	4	0	11260	7017	7017	0.524	0.5661	695	0.2423	1.00	1.00	0.242211	0.4
95	2	130	951	4	0	11910	7355	7355	0.512	0.5580	687	0.2129	1.00	1.00	0.212853	0.4
100	2	130	951	4	0	12560	7693	7693	0.500	0.5492	679	0.1945	1.00	1.00	0.194429	0.4

Used Bore #3 for PI values & unit wt.

Vs Liquefaction Potential - Project 100522

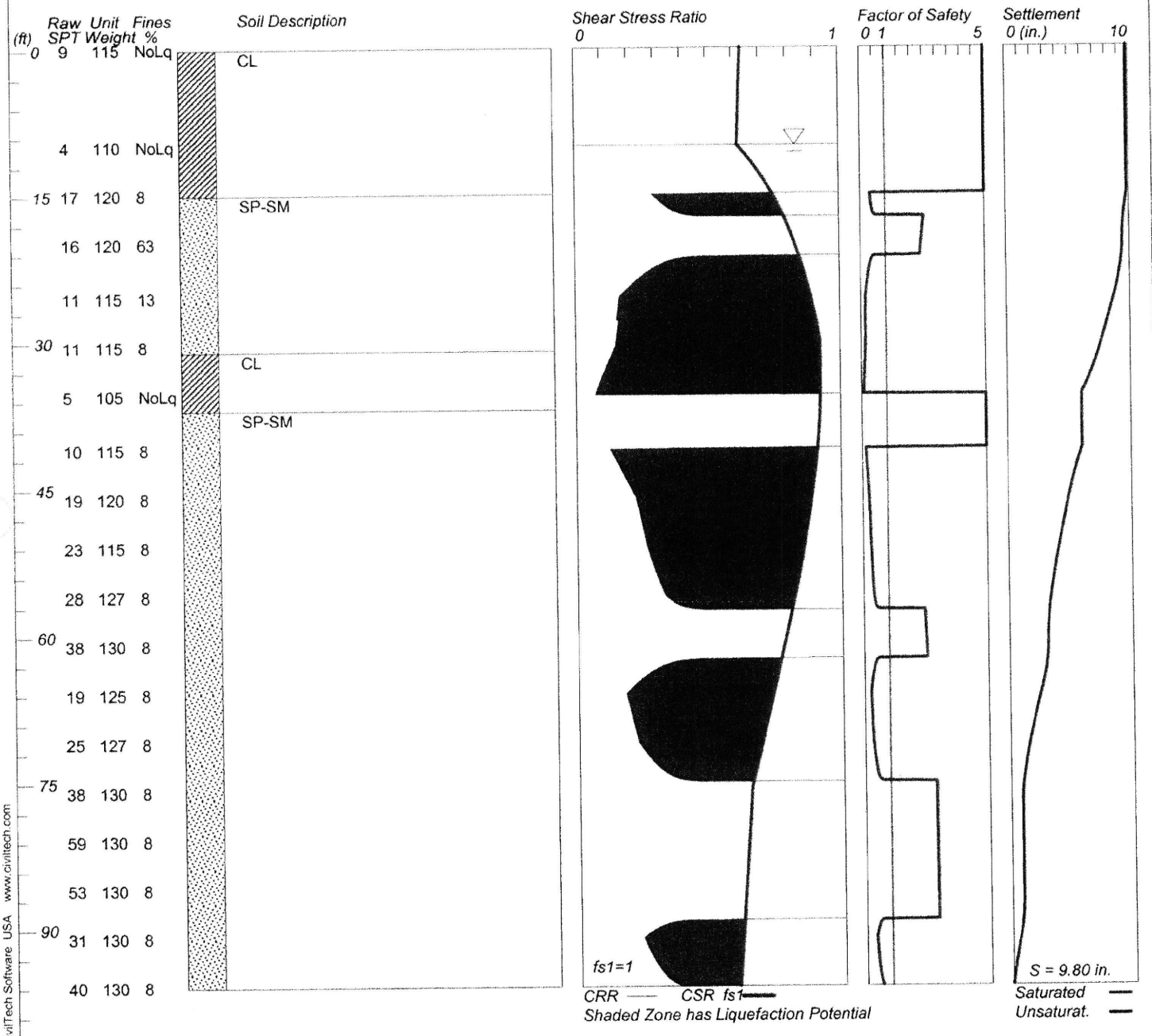


LIQUEFACTION ANALYSIS (ALT.A)

100523

Hole No.=1 Water Depth=10 ft Surface Elev.=218.8

Magnitude=7.5
Acceleration=0.976g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Poinsett County

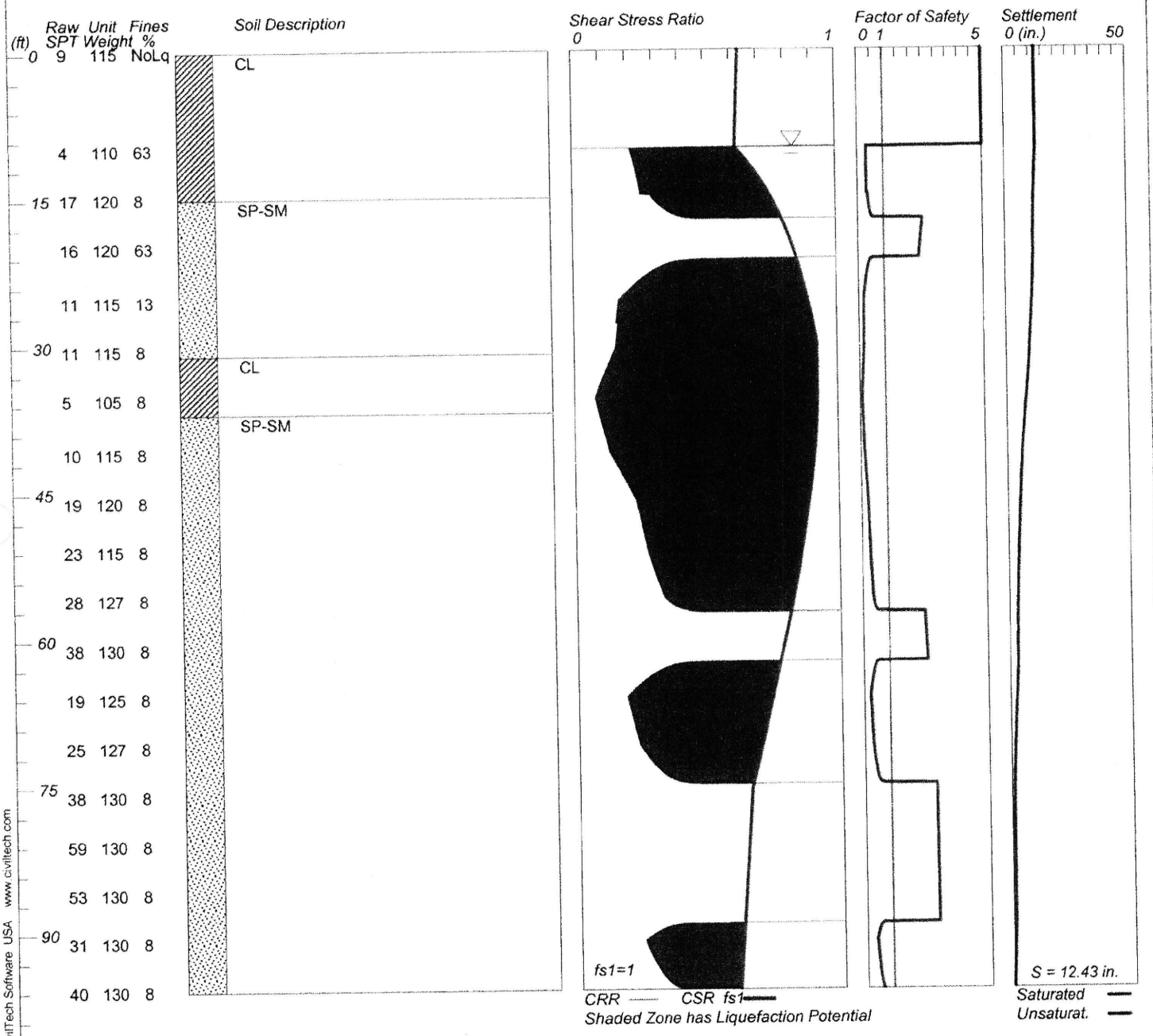
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100523

Hole No.=1 Water Depth=10 ft Surface Elev.=218.8

Magnitude=7.5
Acceleration=0.976g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Poinsett County

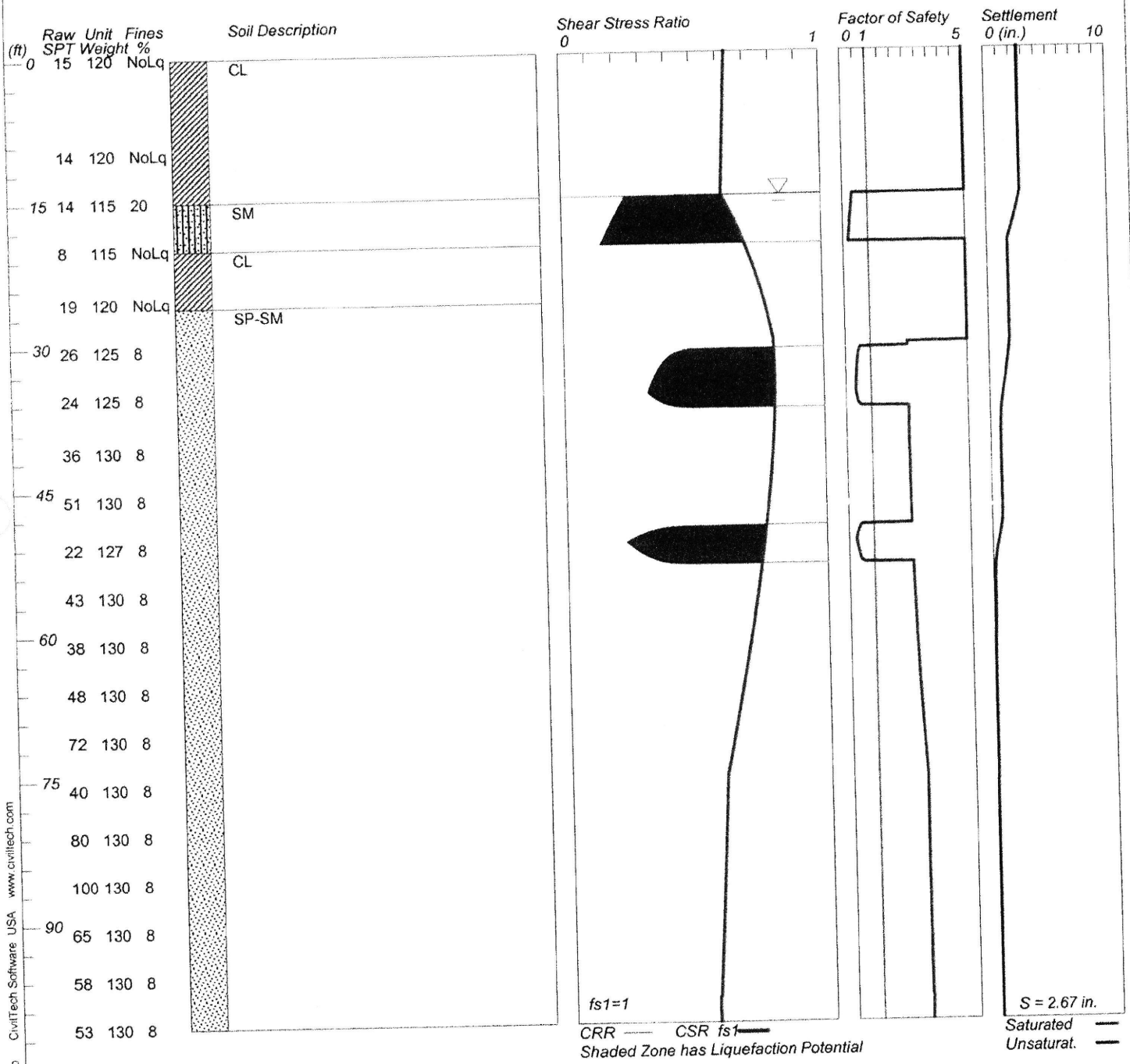
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100523

Hole No.=1NEW Water Depth=15.0 ft Surface Elev.=220.3

Magnitude=7.5
Acceleration=0.976g



BN-1NEW, Poinsett County

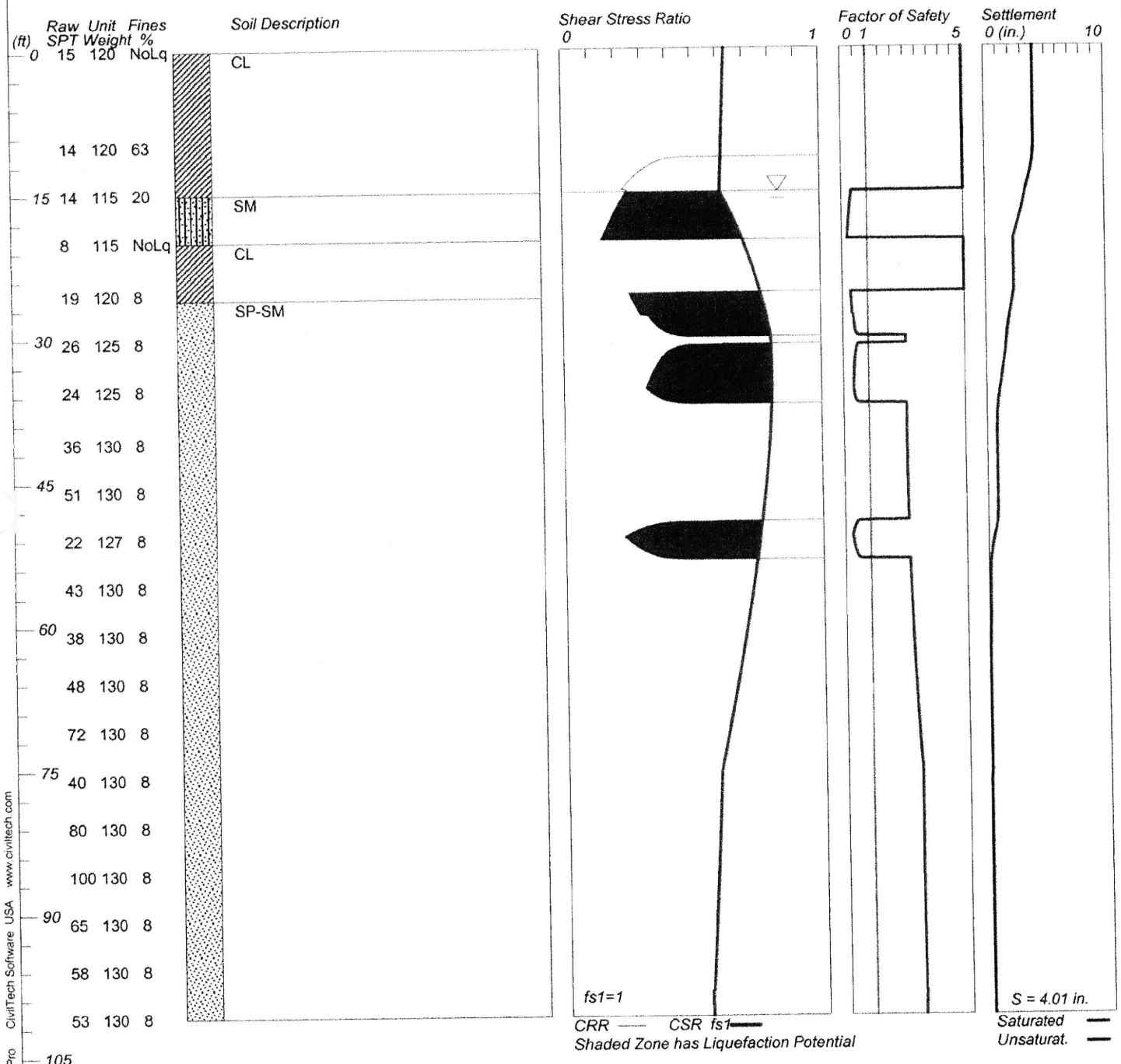
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100523

Hole No.=1NEW Water Depth=15.0 ft Surface Elev.=220.3

Magnitude=7.5
Acceleration=0.976g



BN-1NEW, Poinsett County

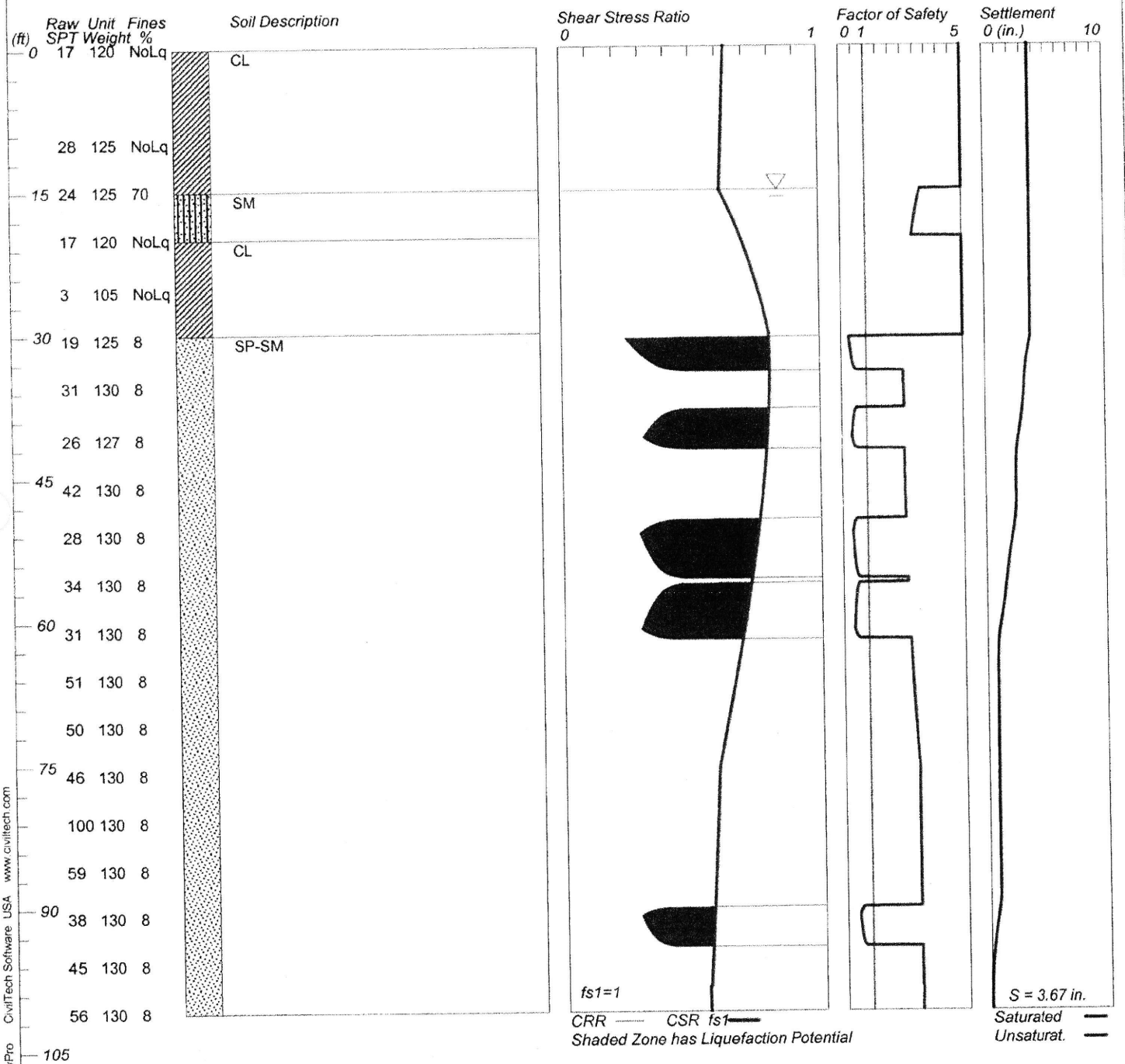
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100523

Hole No.=2 Water Depth=15.1 ft Surface Elev.=220.4

Magnitude=7.5
Acceleration=0.976g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-2, Poinsett County

Plate A-1

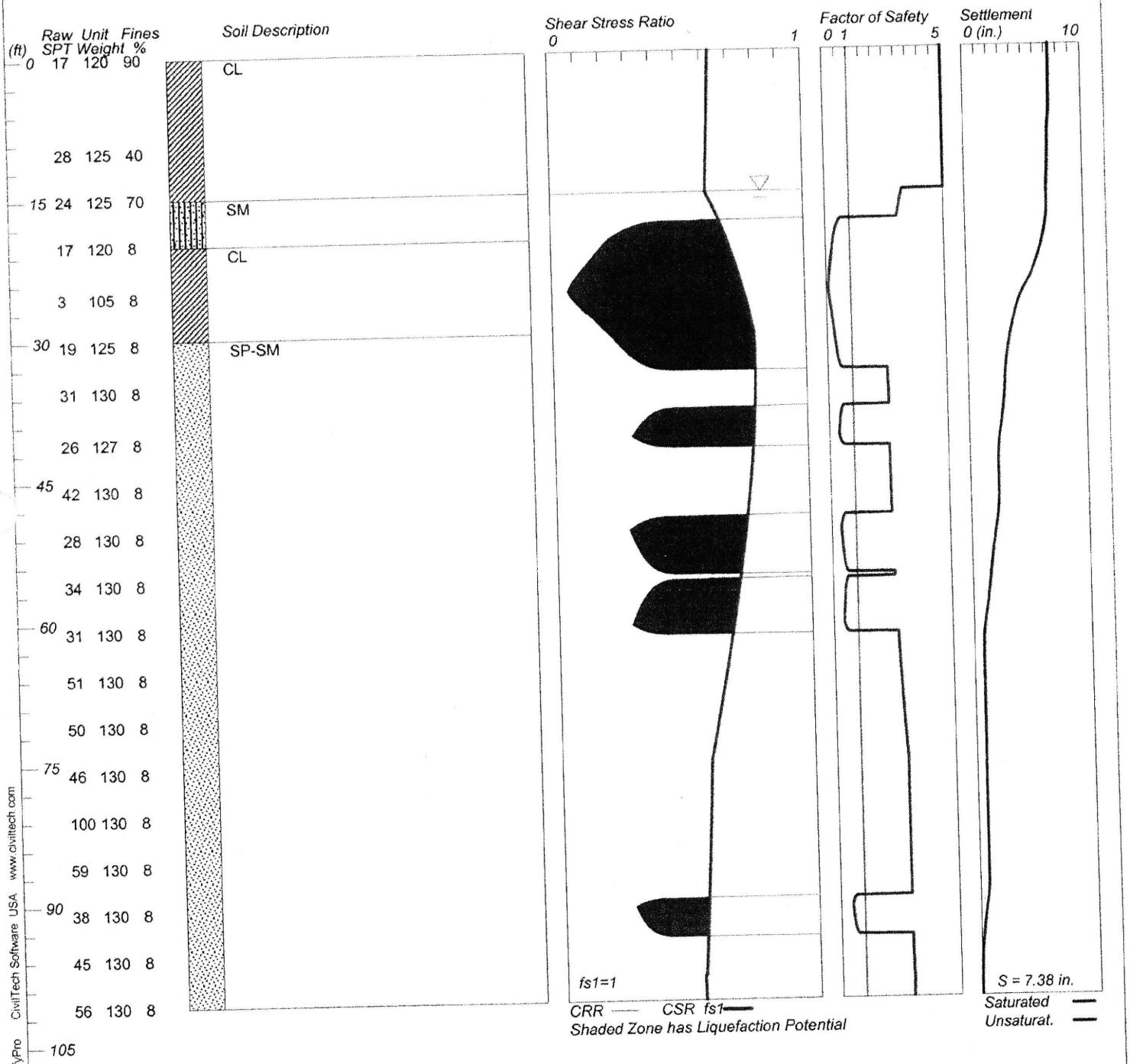
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100523

Hole No.=2 Water Depth=15.1 ft Surface Elev.=220.4

Magnitude=7.5
Acceleration=0.976g



BN-2, Poinsett County

Plate A-1

Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100523

Hole No.=2A Water Depth=9 ft Surface Elev.=219.2

Magnitude=7.5
Acceleration=0.976g

BN-2A, Poinsett County

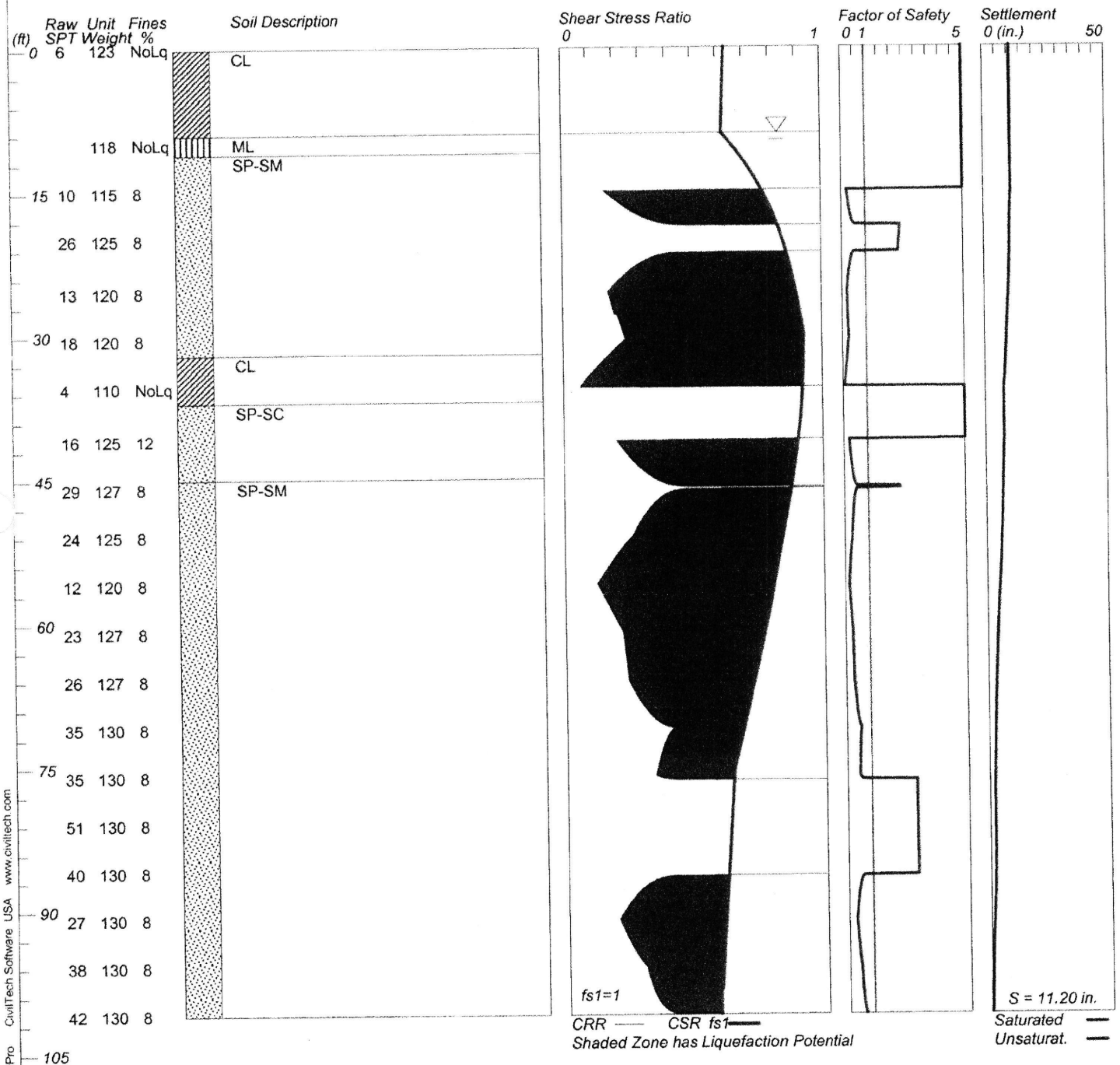
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100523

Hole No.=3 Water Depth=9.0 ft Surface Elev.=218.2

Magnitude=7.5
Acceleration=0.976g



BN-3, Poinsett County

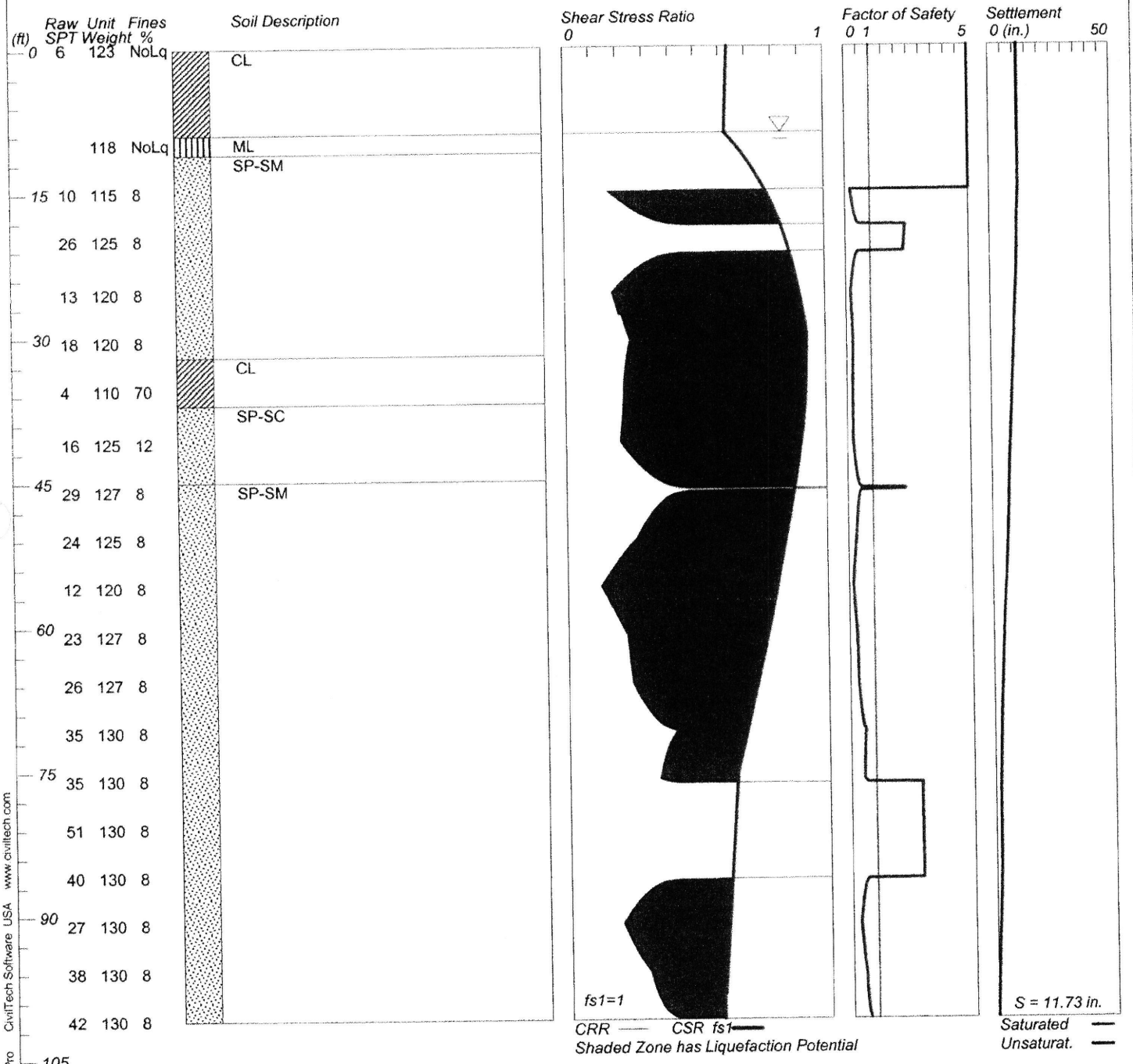
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100523

Hole No.=3 Water Depth=9.0 ft Surface Elev.=218.2

Magnitude=7.5
Acceleration=0.976g



BN-3, Poinsett County

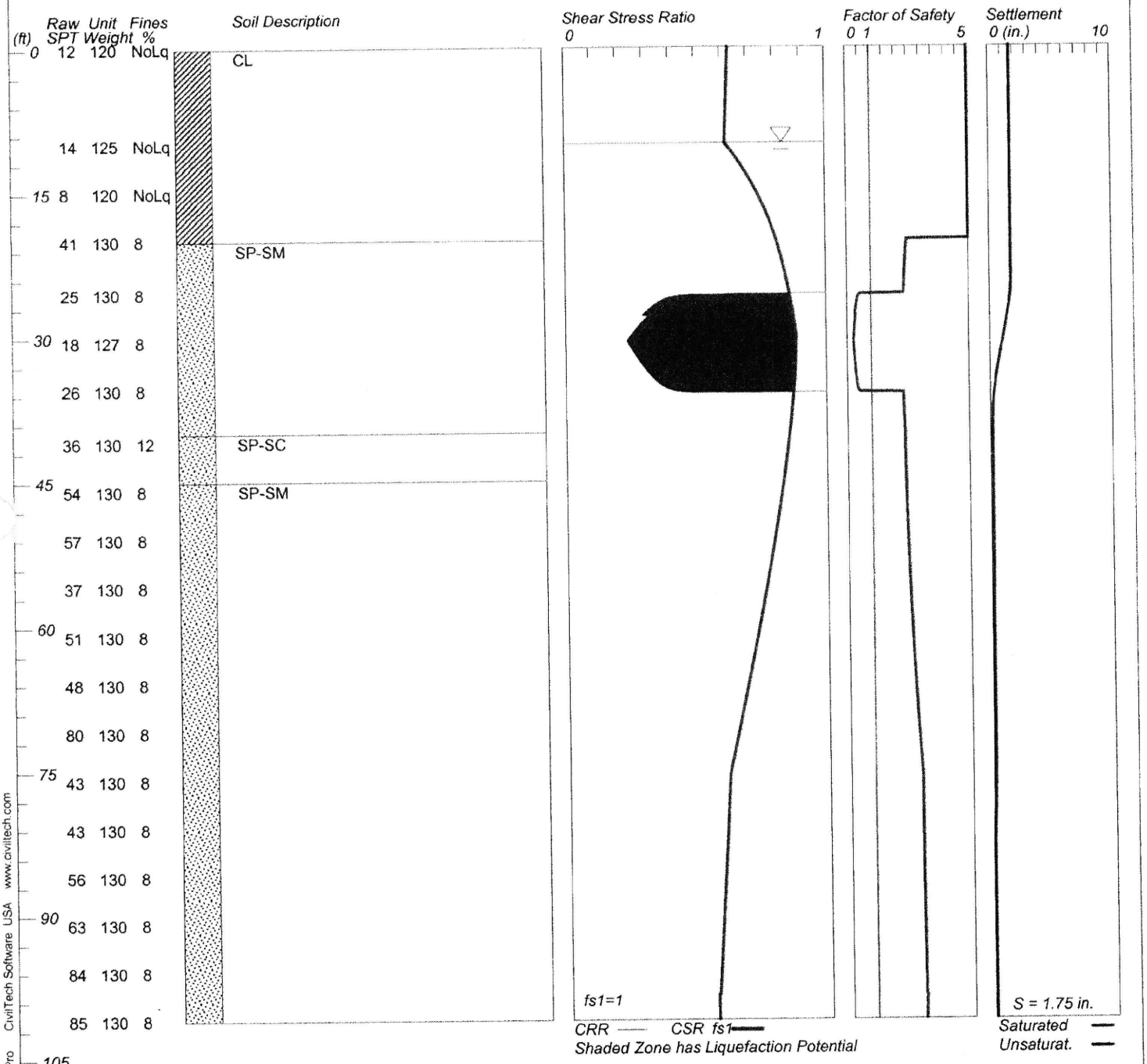
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100523

Hole No.=3NEW Water Depth=10 ft Surface Elev.=220.5

Magnitude=7.5
Acceleration=0.976g



BN-3NEW, Poinsett County

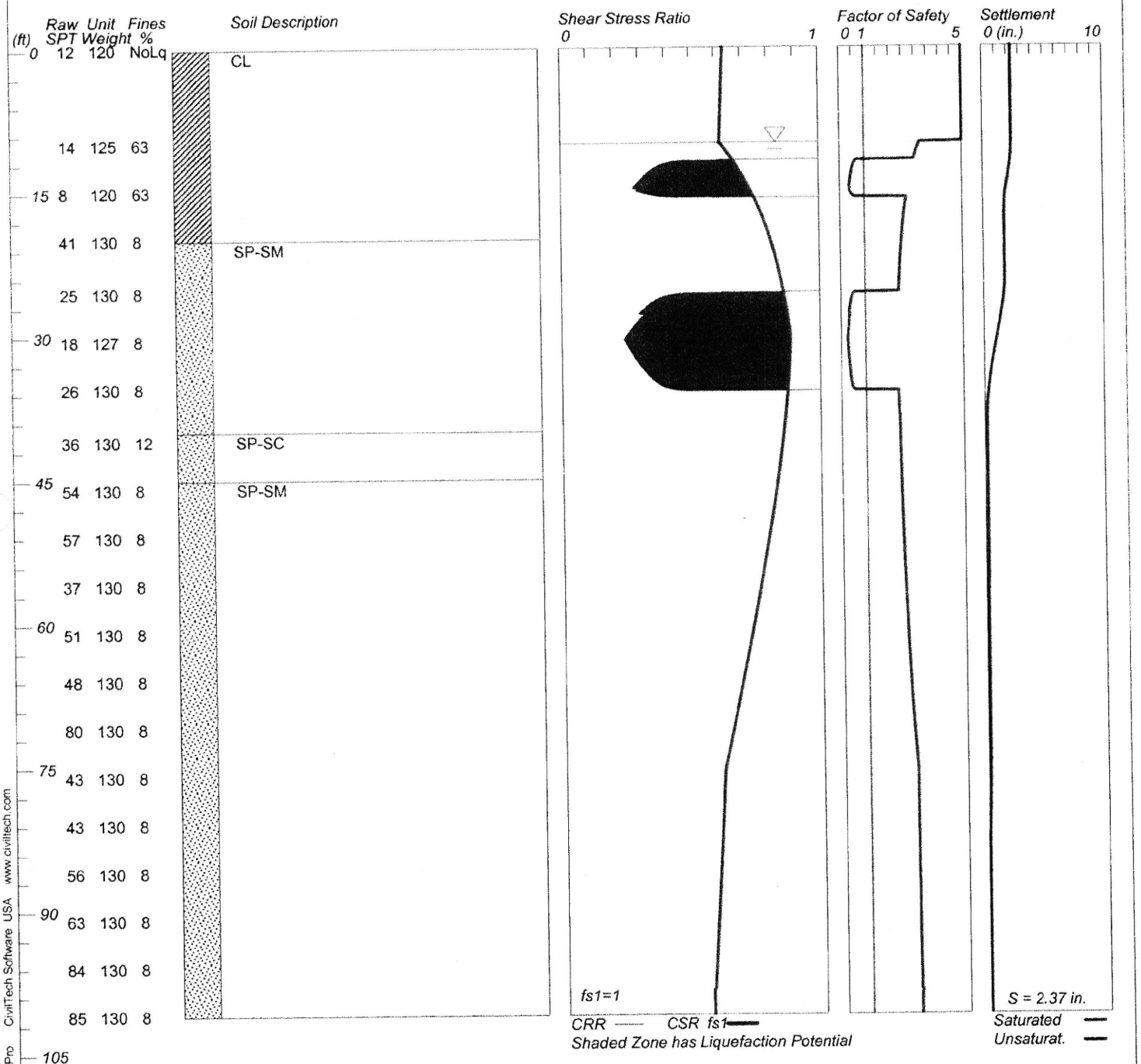
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100523

Hole No.=3NEW Water Depth=10 ft Surface Elev.=220.5

Magnitude=7.5
Acceleration=0.976g



BN-3NEW, Poinsett County

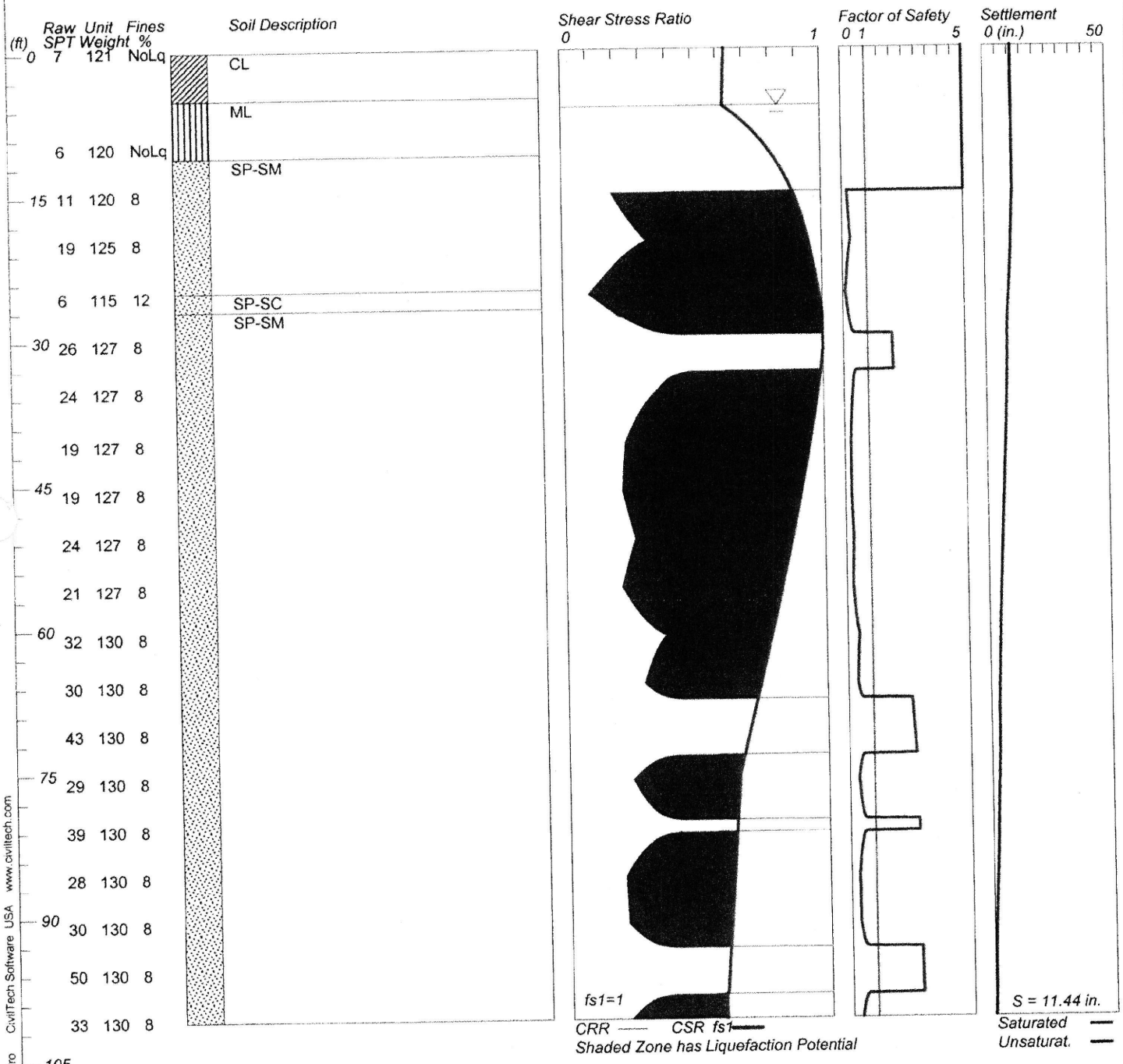
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100523

Hole No.=4 Water Depth=6.0 ft Surface Elev.=217.2

Magnitude=7.5
Acceleration=0.976g



BN-4, Poinsett County

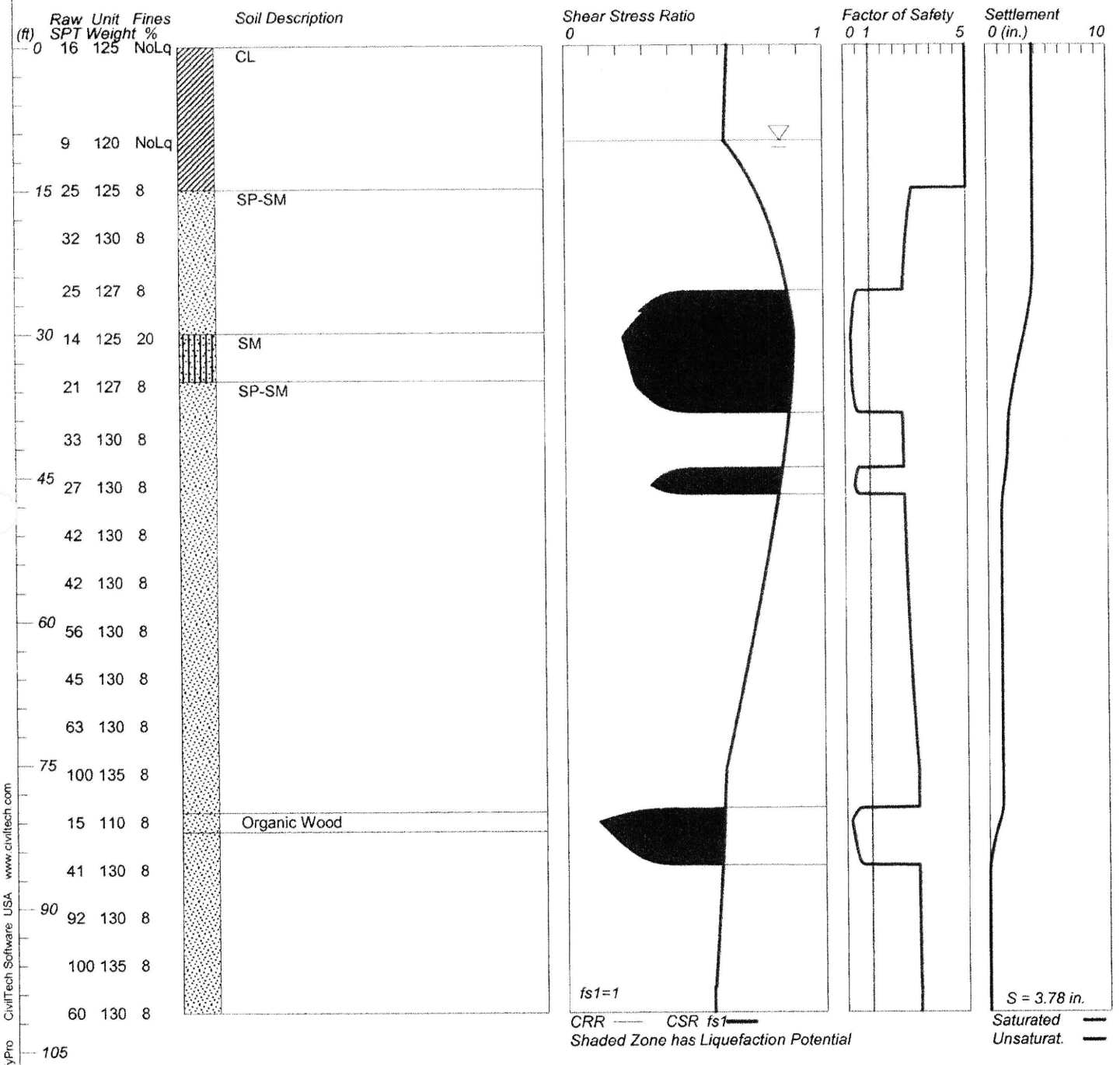
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100523

Hole No.=4NEW Water Depth=10 ft Surface Elev.=220.5

Magnitude=7.5
Acceleration=0.976g



BN-4NEW, Poinsett County

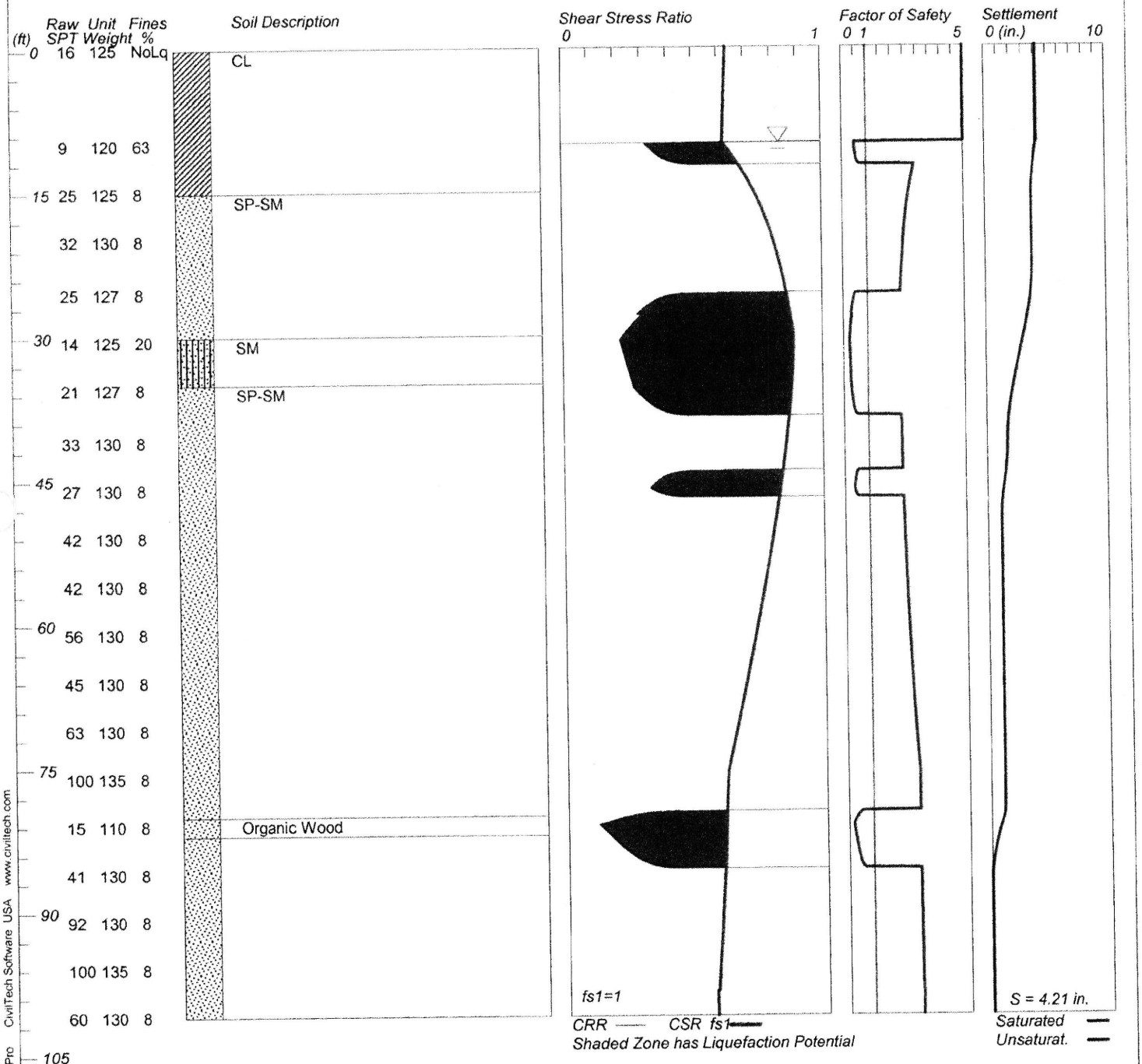
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100523

Hole No.=4NEW Water Depth=10 ft Surface Elev.=220.5

Magnitude=7.5
Acceleration=0.976g



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BN-4NEW, Poinsett County

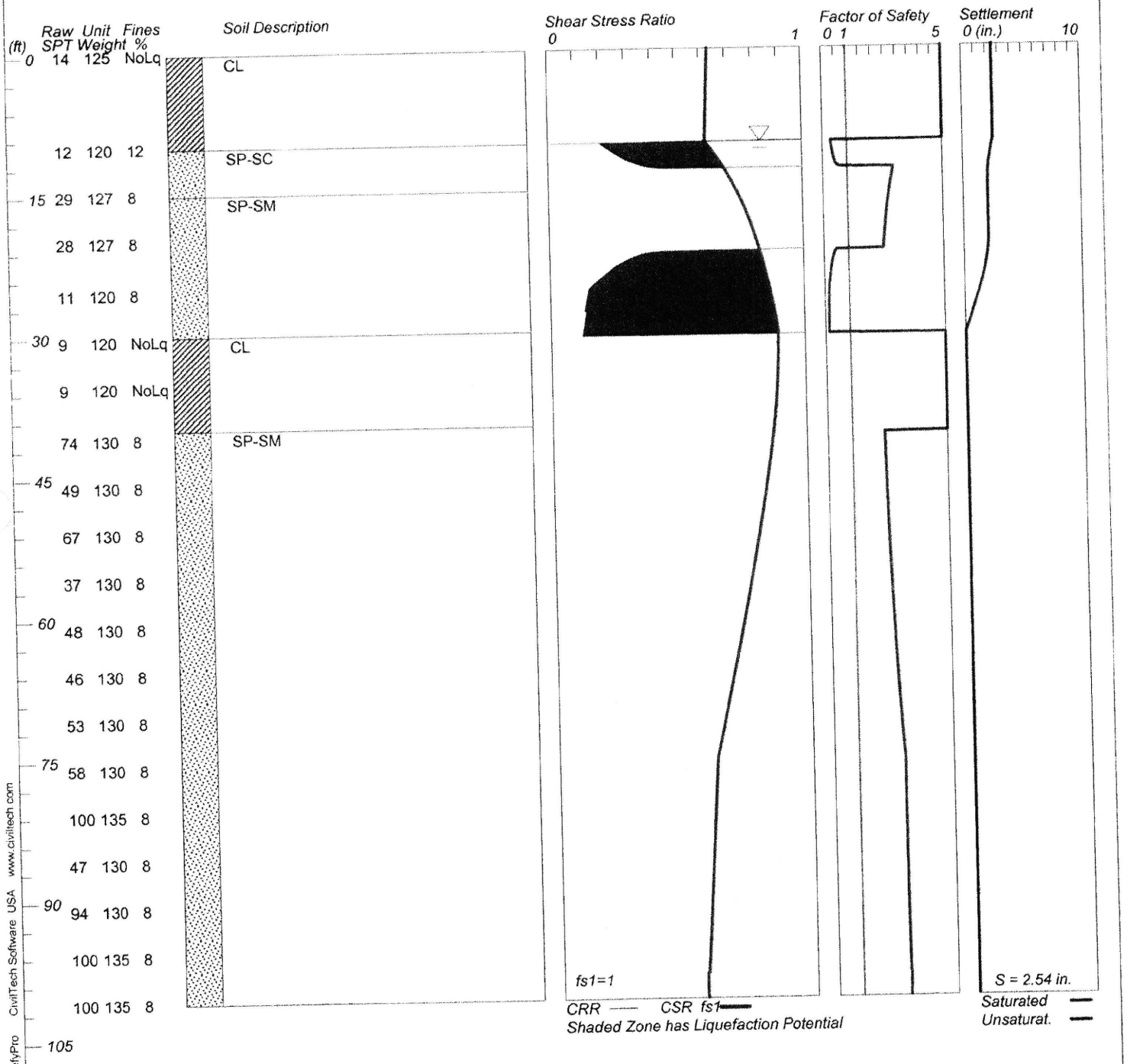
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100523

Hole No.=5NEW Water Depth=10.0 ft Surface Elev.=220.9

Magnitude=7.5
Acceleration=0.976g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-5NEW, Poinsett County

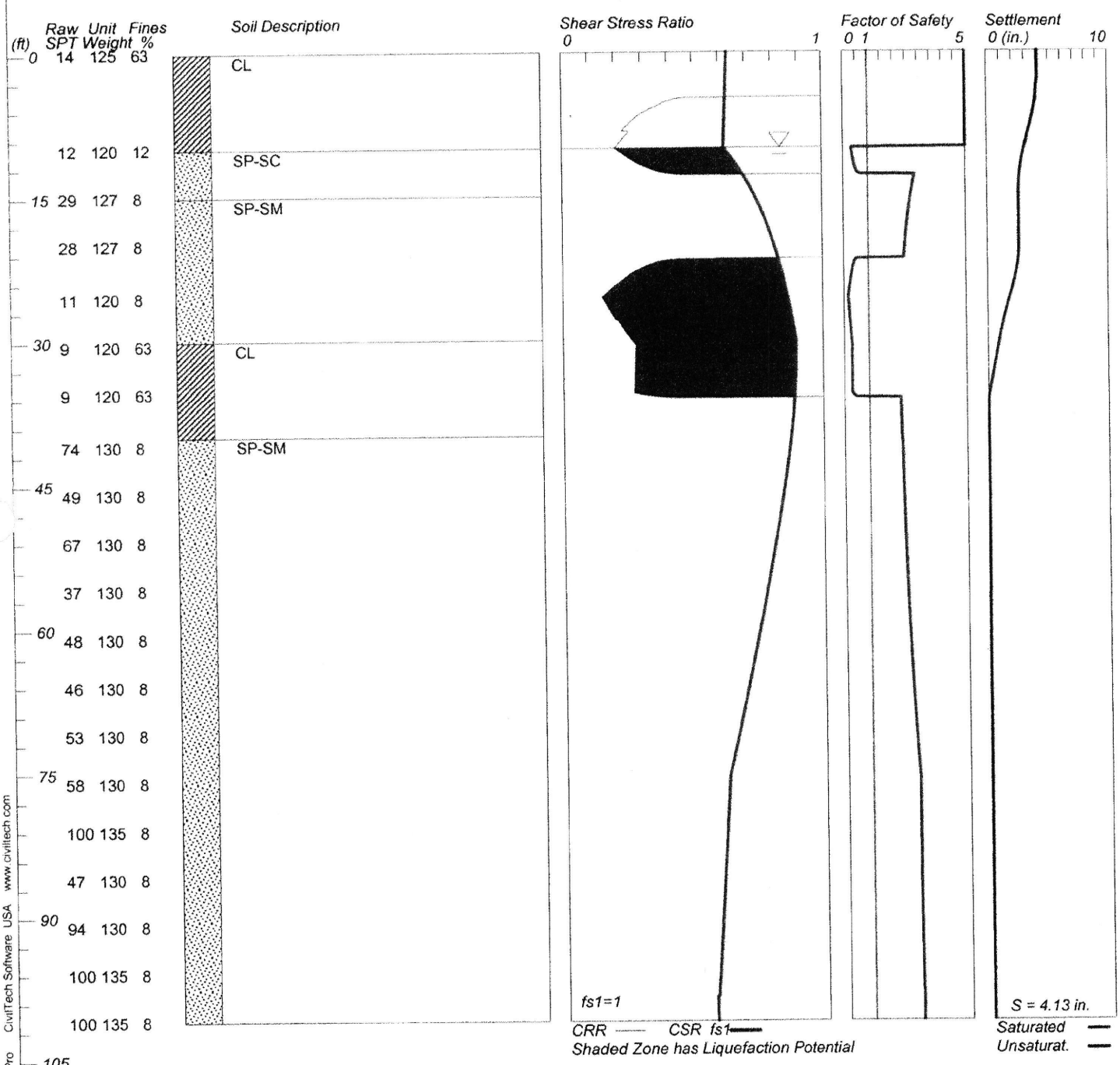
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100523

Hole No.=5NEW Water Depth=10.0 ft Surface Elev.=220.9

Magnitude=7.5
Acceleration=0.976g



BN-5NEW, Poinsett County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-100523

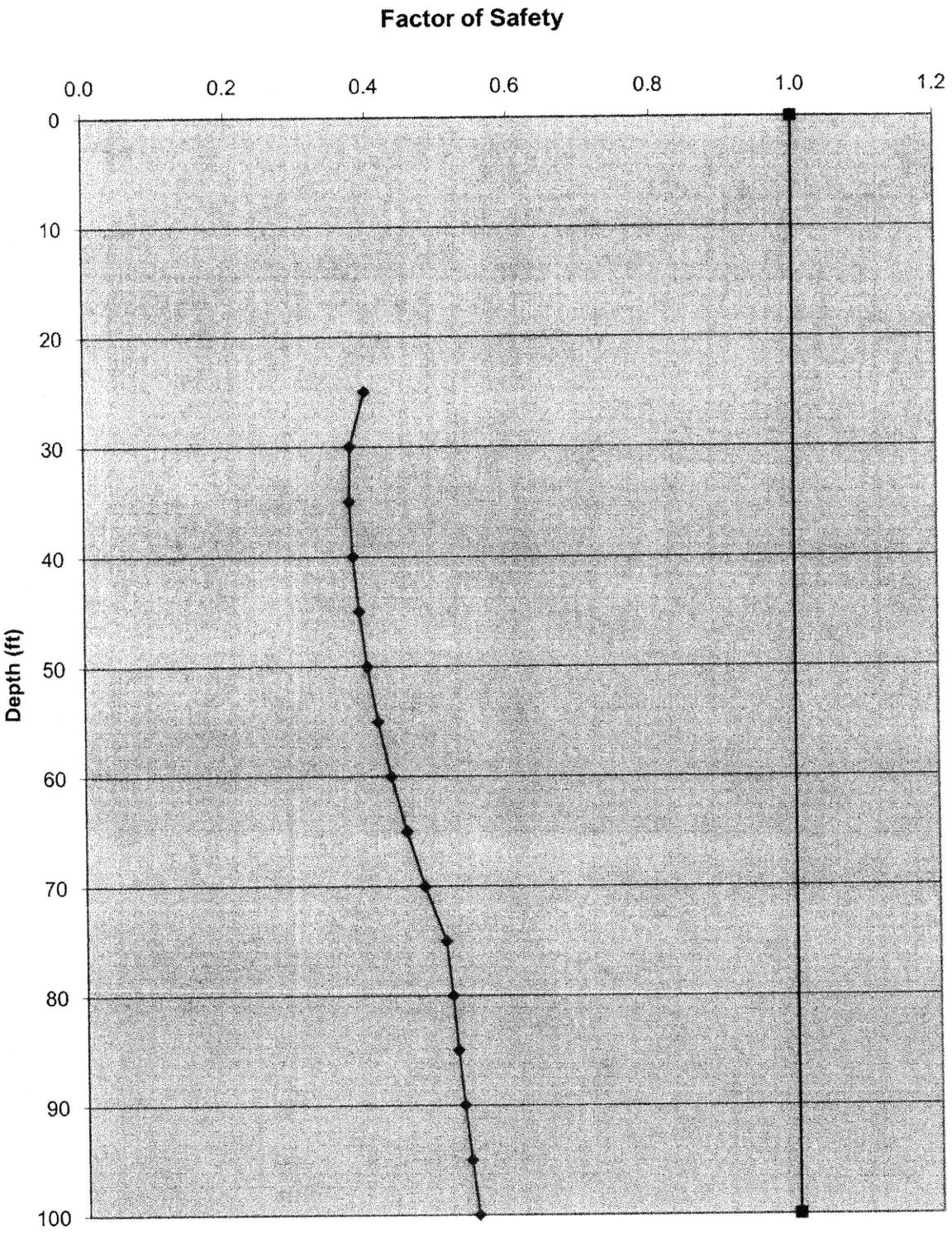
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	0.975	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	15	ft	assumed depth to groundwater =	15	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	120	394	63	15	600	600	600	0.988	0.6270	532	NA	1.00	1.00	NA	NA
10	1	120	656	63	15	1200	1200	1200	0.977	0.6196	745	NA	1.00	1.00	NA	NA
15	1	115	755	63	15	1775	1775	1775	0.965	0.6122	778	NA	1.00	1.00	NA	NA
20	1	115	1129	63	15	2350	2038	2038	0.953	0.6974	1124	NA	1.00	1.00	NA	NA
25	2	120	1129	8	0	2950	2326	2326	0.942	0.7577	1087	0.3000	1.00	1.00	0.299946	0.4
30	2	125	1129	8	0	3575	2639	2639	0.930	0.7993	1053	0.3000	1.00	1.00	0.299946	0.4
35	2	125	1129	8	0	4200	2952	2952	0.889	0.8024	1024	0.3000	1.00	1.00	0.299946	0.4
40	2	130	1214	8	0	4850	3290	3290	0.848	0.7933	1072	0.3000	1.00	1.00	0.299946	0.4
45	2	130	1214	8	0	5500	3628	3628	0.808	0.7766	1046	0.3000	1.00	1.00	0.299946	0.4
50	2	127	1214	8	0	6135	3951	3951	0.767	0.7554	1024	0.3000	1.00	1.00	0.299946	0.4
55	2	130	1444	8	0	6785	4289	4289	0.726	0.7287	1193	0.3000	1.00	1.00	0.299946	0.4
60	2	130	1444	6	0	7435	4627	4627	0.685	0.6987	1171	0.3000	1.00	1.00	0.299946	0.4
65	2	130	1444	6	0	8085	4965	4965	0.645	0.6660	1150	0.3000	1.00	1.00	0.299946	0.5
70	2	130	1706	6	0	8735	5303	5303	0.604	0.6311	1337	0.3000	1.00	1.00	0.299946	0.5
75	2	130	1706	6	0	9385	5641	5641	0.563	0.5945	1316	0.3000	1.00	1.00	0.299946	0.5
80	2	130	2297	7	0	10035	5979	5979	0.549	0.5843	1747	0.3000	1.00	1.00	0.299946	0.5
85	2	130	2297	7	0	10685	6317	6317	0.537	0.5758	1723	0.3000	1.00	1.00	0.299946	0.5
90	2	130	2379	7	0	11335	6655	6655	0.524	0.5666	1761	0.3000	1.00	1.00	0.299946	0.5
95	2	130	2379	7	0	11985	6993	6993	0.512	0.5569	1740	0.3000	1.00	1.00	0.299946	0.5
100	2	130	2543	7	0	12635	7331	7331	0.500	0.5467	1838	0.3000	1.00	1.00	0.299946	0.5

Used Bore #1-N for PI values & unit wt.

Vs Liquefaction Potential - Project 100523

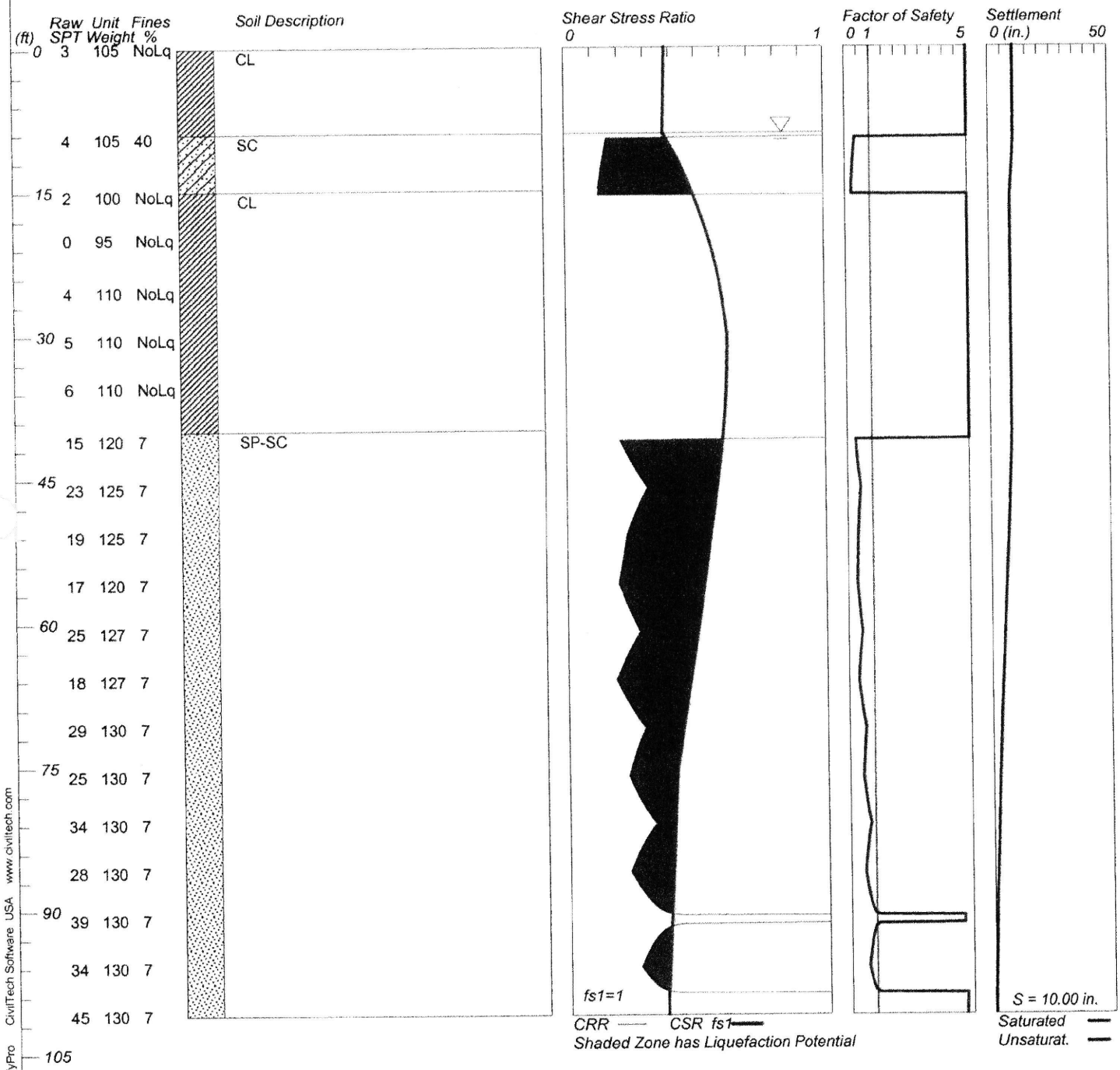


LIQUEFACTION ANALYSIS

110337

Hole No.=1 Water Depth=9 ft Surface Elev.=212.6

Magnitude=7.5
Acceleration=0.592g



BN-1, Crittenden County

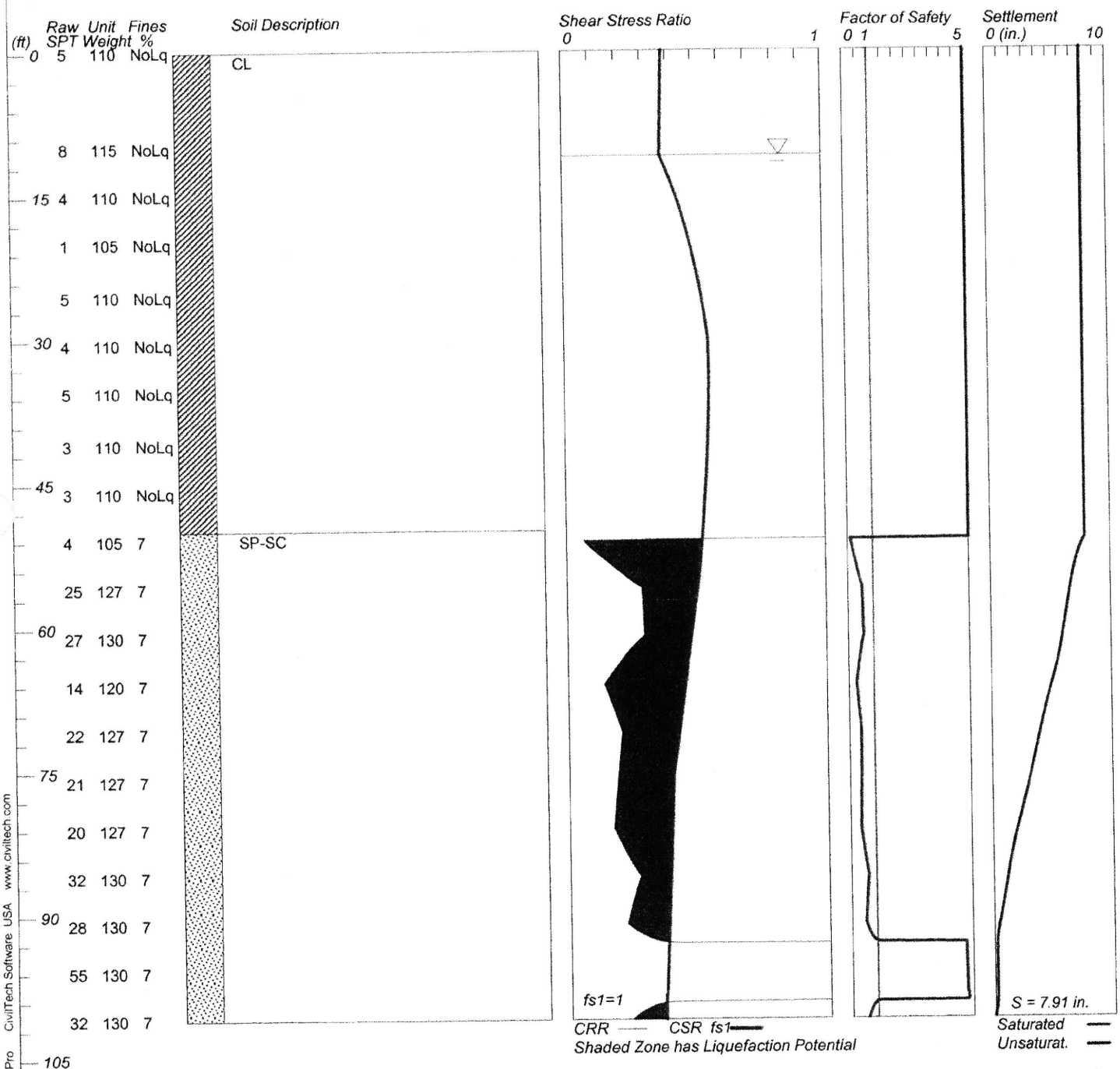
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110337

Hole No.=2 Water Depth=11.0 ft Surface Elev.=214.9

Magnitude=7.5
Acceleration=0.592g



BN-2, Crittenden County

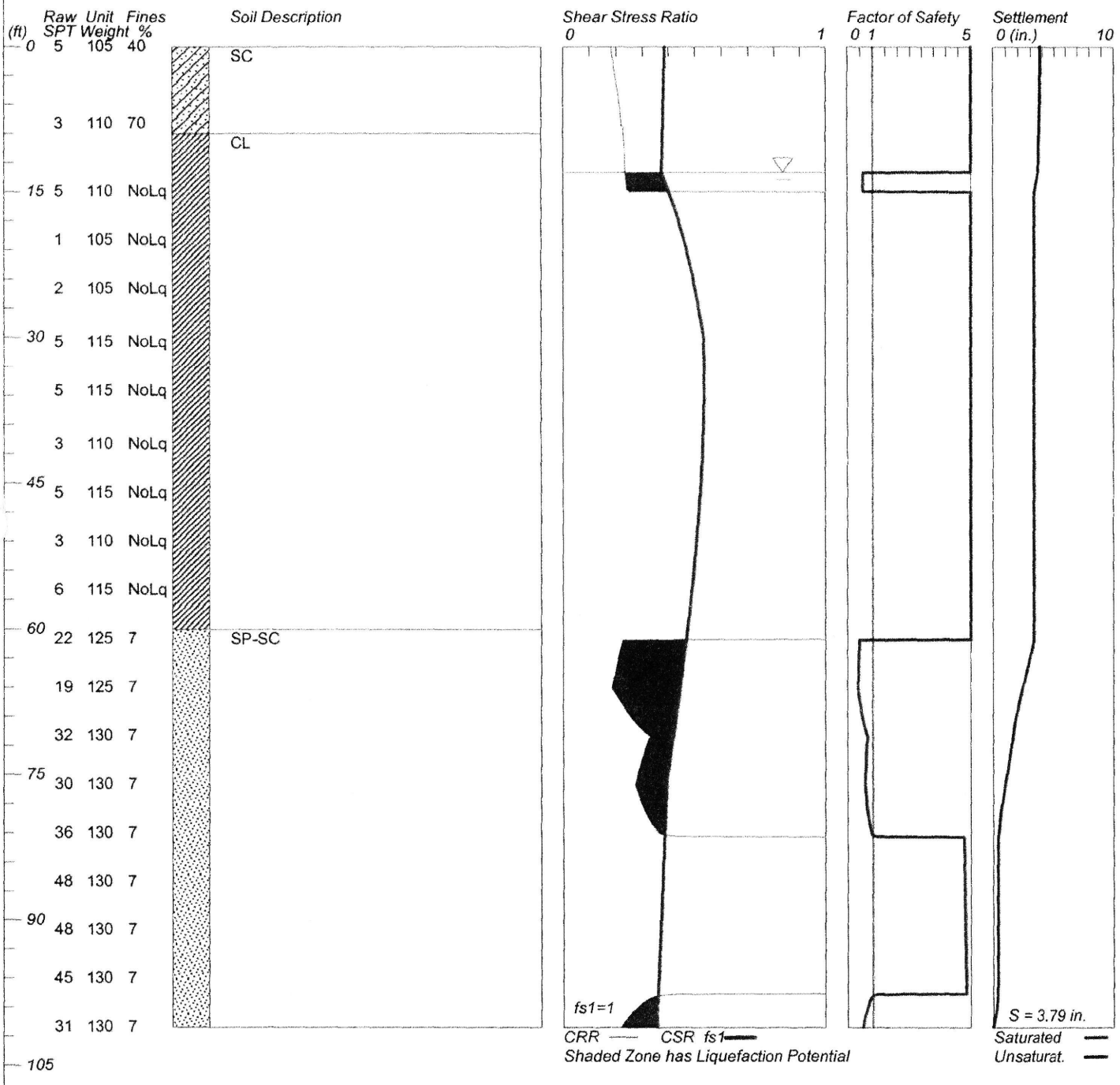
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110337

Hole No.=3 Water Depth=13 ft Surface Elev.=216.8

Magnitude=7.5
Acceleration=0.592g



BN-3, Crittenden County

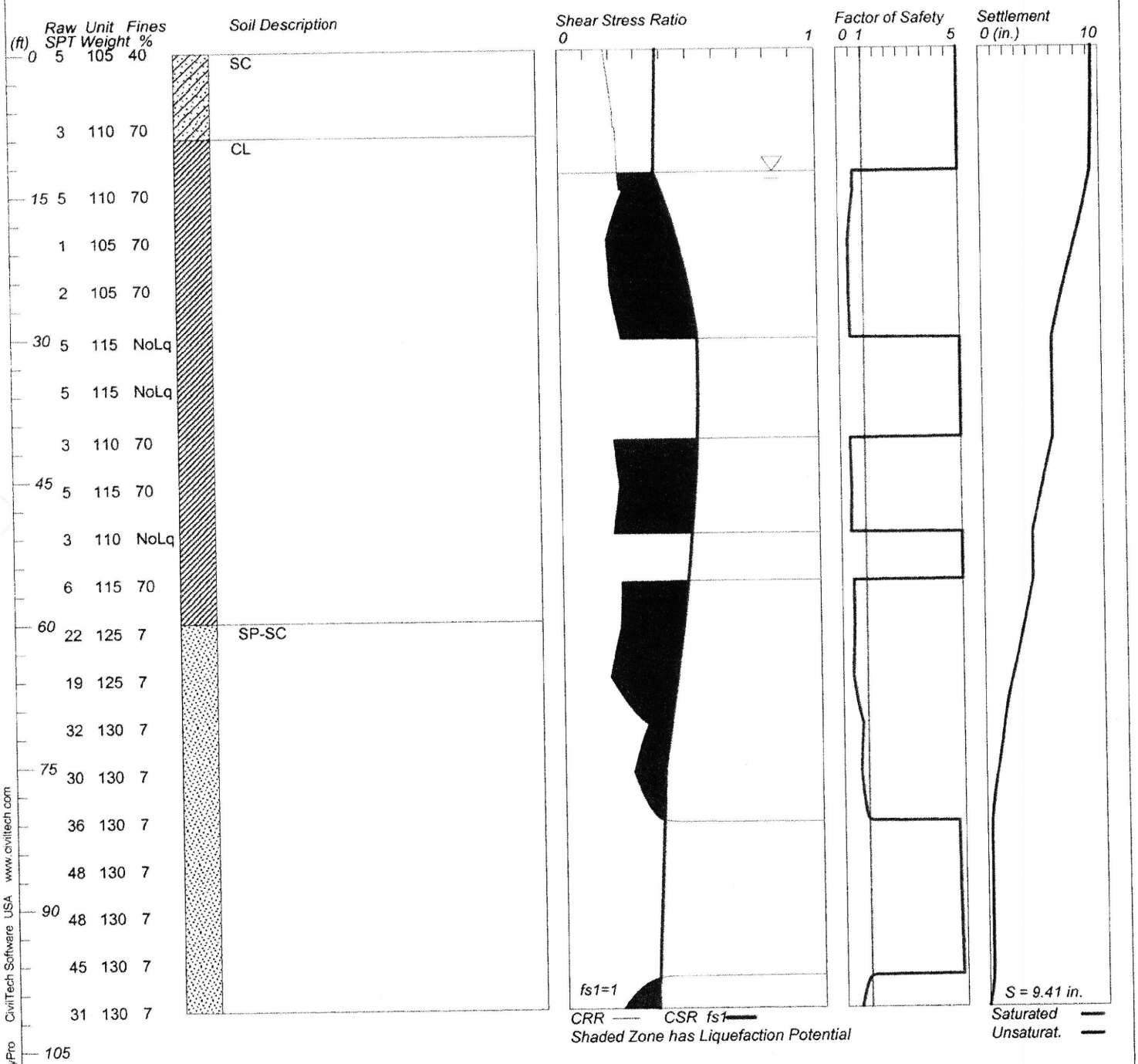
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110337

Hole No.=3 Water Depth=13 ft Surface Elev.=216.8

Magnitude=7.5
Acceleration=0.592g



BN-3, Crittenden County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-110337

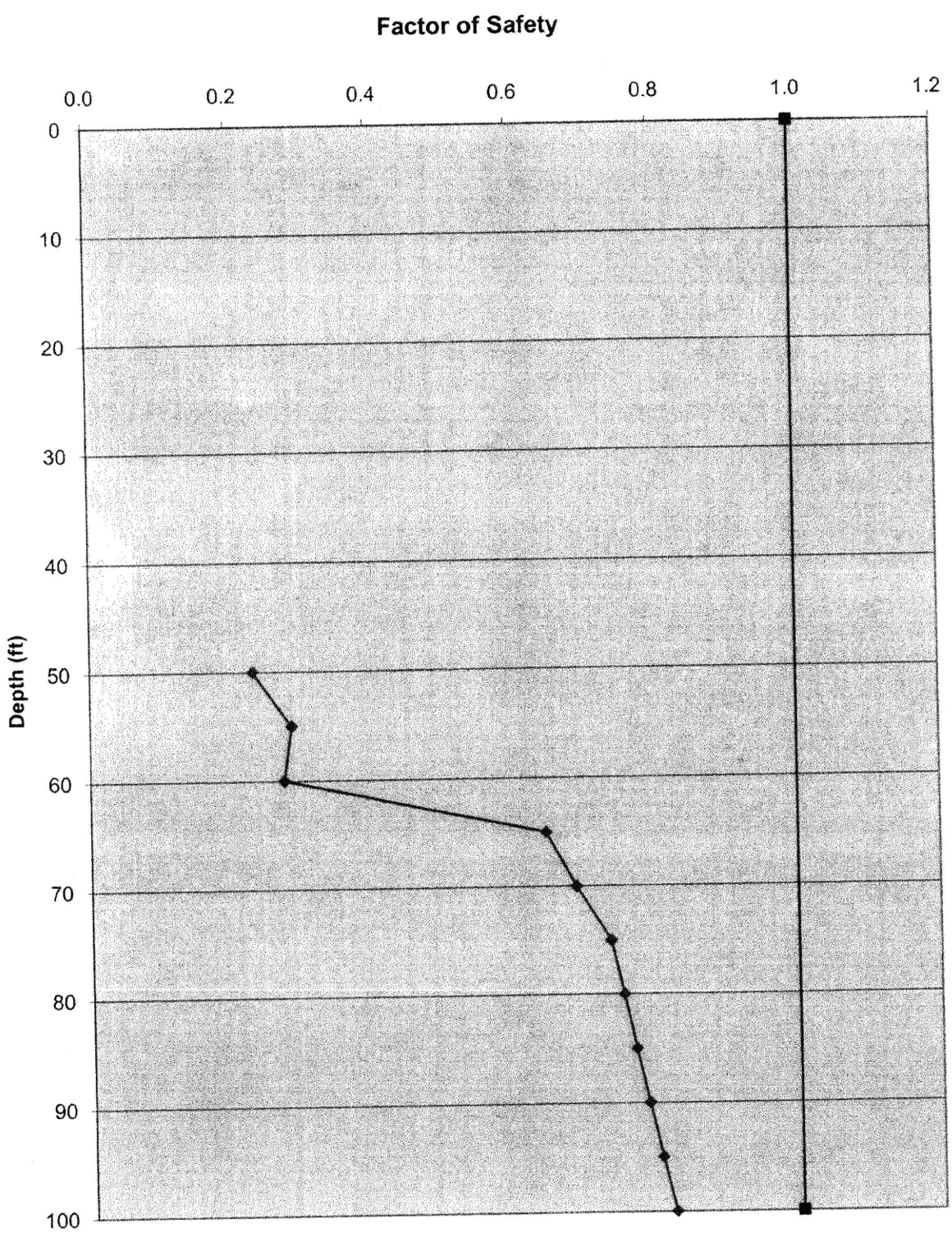
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	0.592	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	10	ft	assumed depth to groundwater =	10	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	110	312	95	15	550	550	550	0.988	0.3803	431	NA	1.00	1.00	NA	NA
10	1	115	328	95	15	1125	1125	1125	0.977	0.3758	379	NA	1.00	1.00	NA	NA
15	1	110	449	95	15	1675	1363	1363	0.965	0.4563	494	NA	1.00	1.00	NA	NA
20	1	105	449	95	15	2200	1576	1576	0.953	0.5121	477	NA	1.00	1.00	NA	NA
25	1	110	482	95	15	2750	1814	1814	0.942	0.5493	494	NA	1.00	1.00	NA	NA
30	1	110	482	95	15	3300	2052	2052	0.930	0.5755	479	NA	1.00	1.00	NA	NA
35	1	110	482	95	15	3850	2290	2290	0.889	0.5751	466	NA	1.00	1.00	NA	NA
40	1	110	656	95	15	4400	2528	2528	0.848	0.5681	619	NA	1.00	1.00	NA	NA
45	1	110	656	95	15	4950	2766	2766	0.808	0.5561	605	NA	1.00	1.00	NA	NA
50	2	105	656	7	0	5475	2979	2979	0.767	0.5423	594	0.1253	1.00	1.00	0.125248	0.2
55	2	127	705	7	0	6110	3302	3302	0.726	0.5170	622	0.1480	1.00	1.00	0.147959	0.3
60	2	130	705	7	0	6760	3640	3640	0.685	0.4898	607	0.1347	1.00	1.00	0.134691	0.3
65	2	120	919	7	0	7360	3928	3928	0.645	0.4648	776	0.3000	1.00	1.00	0.299946	0.6
70	2	127	919	7	0	7995	4251	4251	0.604	0.4371	761	0.3000	1.00	1.00	0.299946	0.7
75	2	127	919	7	0	8630	4574	4574	0.563	0.4089	747	0.3000	1.00	1.00	0.299946	0.7
80	2	127	919	7	0	9265	4897	4897	0.549	0.3995	735	0.3000	1.00	1.00	0.299946	0.8
85	2	130	919	7	0	9915	5235	5235	0.537	0.3911	723	0.3000	1.00	1.00	0.299946	0.8
90	2	130	919	7	0	10565	5573	5573	0.524	0.3825	711	0.3000	1.00	1.00	0.299946	0.8
95	2	130	919	7	0	11215	5911	5911	0.512	0.3739	701	0.3000	1.00	1.00	0.299946	0.8
100	2	130	919	7	0	11865	6249	6249	0.500	0.3653	691	0.3000	1.00	1.00	0.299946	0.8

Used Bore #2 for PI values & unit wt.

Vs Liquefaction Potential - Project 110337

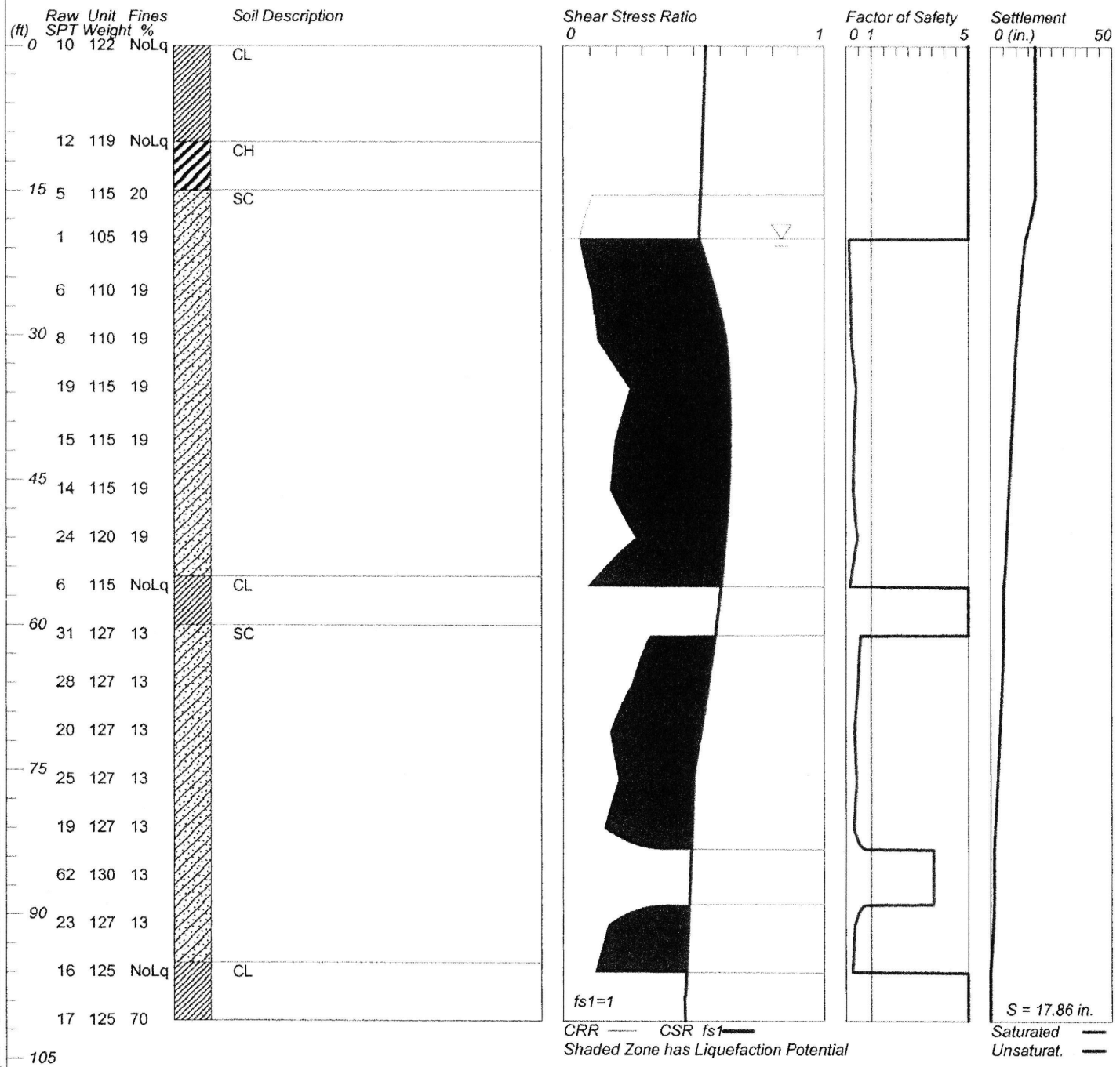


LIQUEFACTION ANALYSIS (ALT.A)

110434

Hole No.=1 Water Depth=20 ft Surface Elev.=221

Magnitude=7.5
Acceleration=0.839g



CivilTech Software USA www.civiltech.com
LiquefyPro

BN-1, Crittenden County

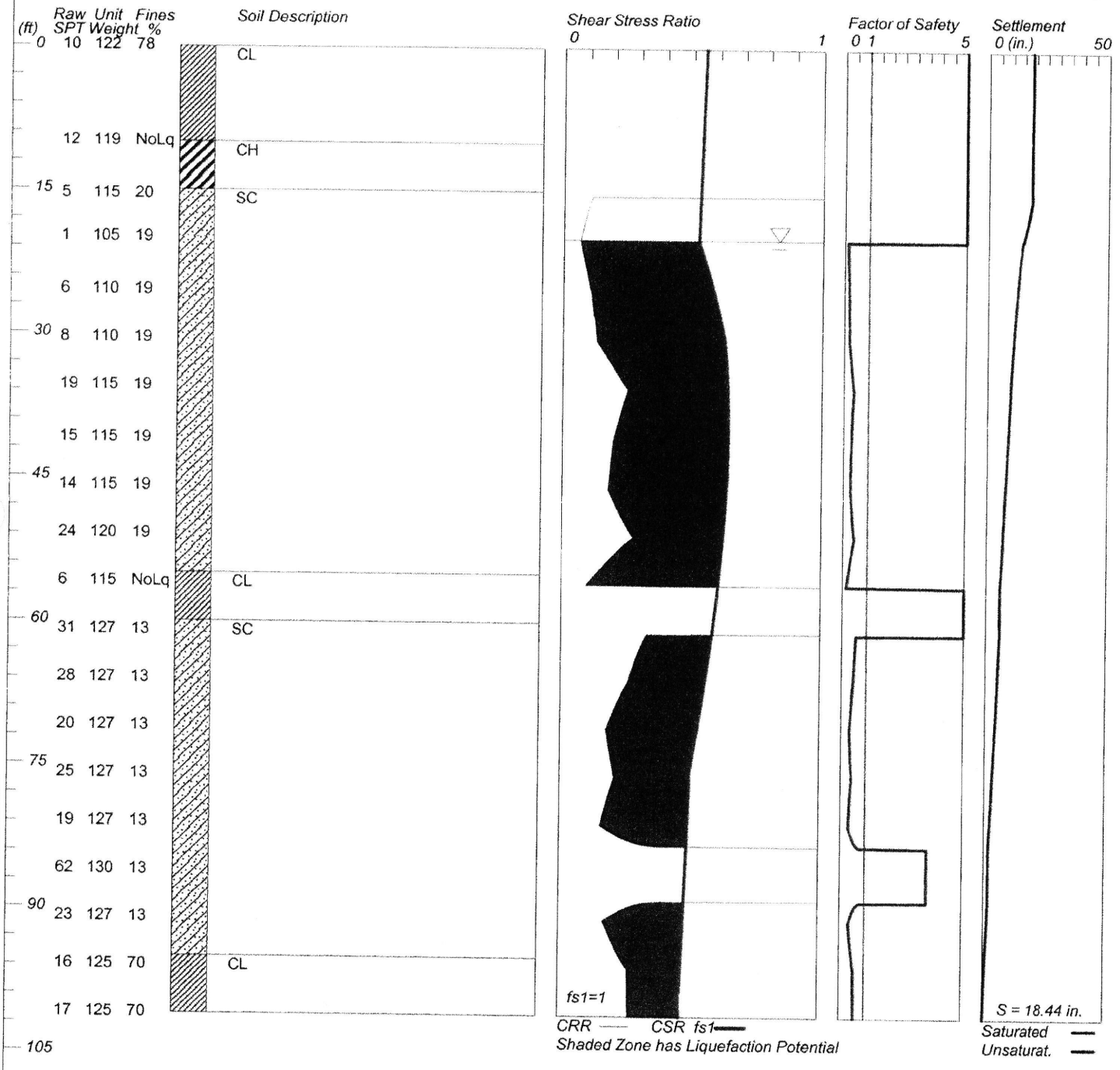
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110434

Hole No.=1 Water Depth=20 ft Surface Elev.=221

Magnitude=7.5
Acceleration=0.839g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Crittenden County

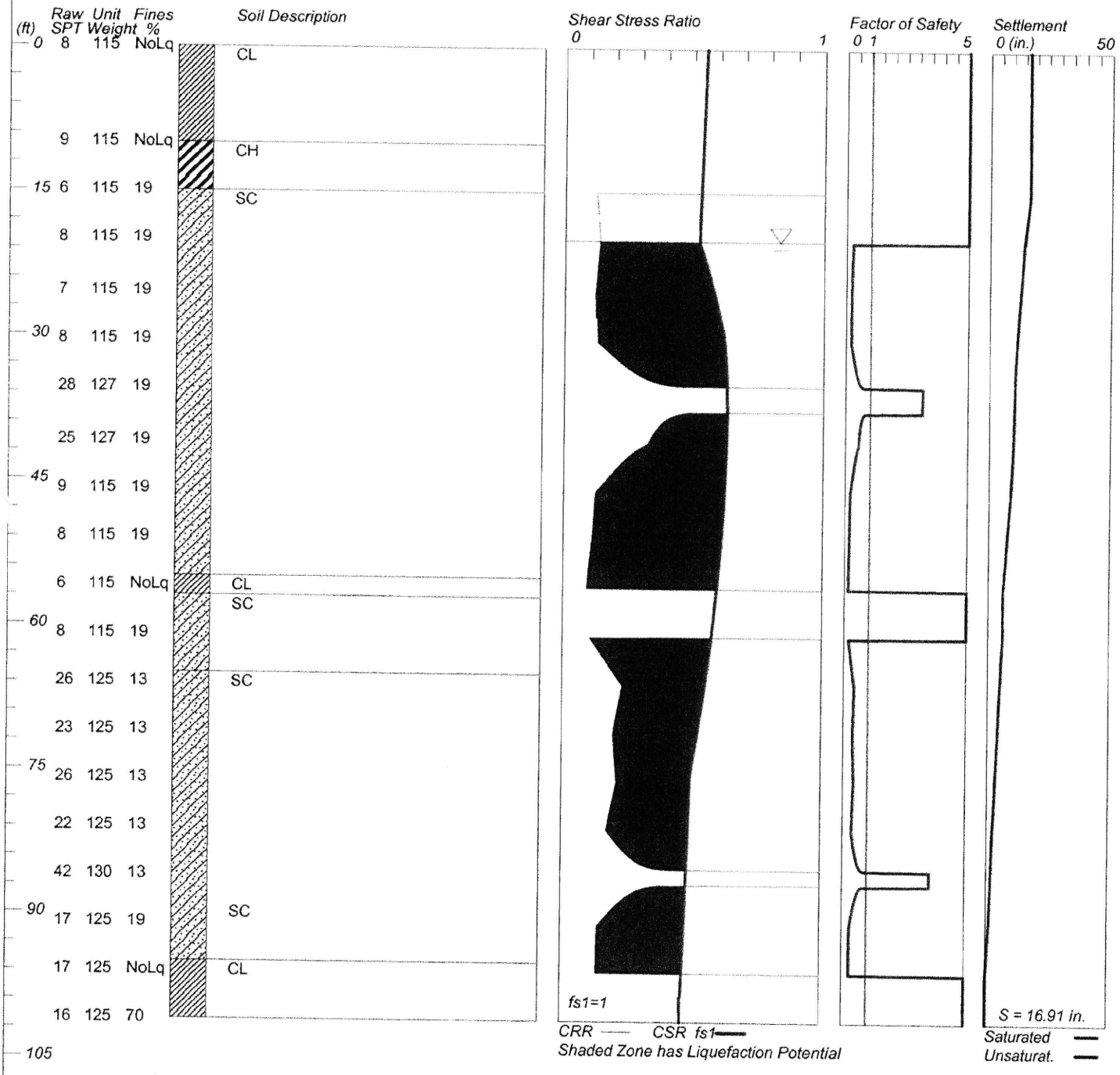
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110434

Hole No.=2 Water Depth=20.0 ft Surface Elev.=221

Magnitude=7.5
Acceleration=0.839g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-2, Crittenden County

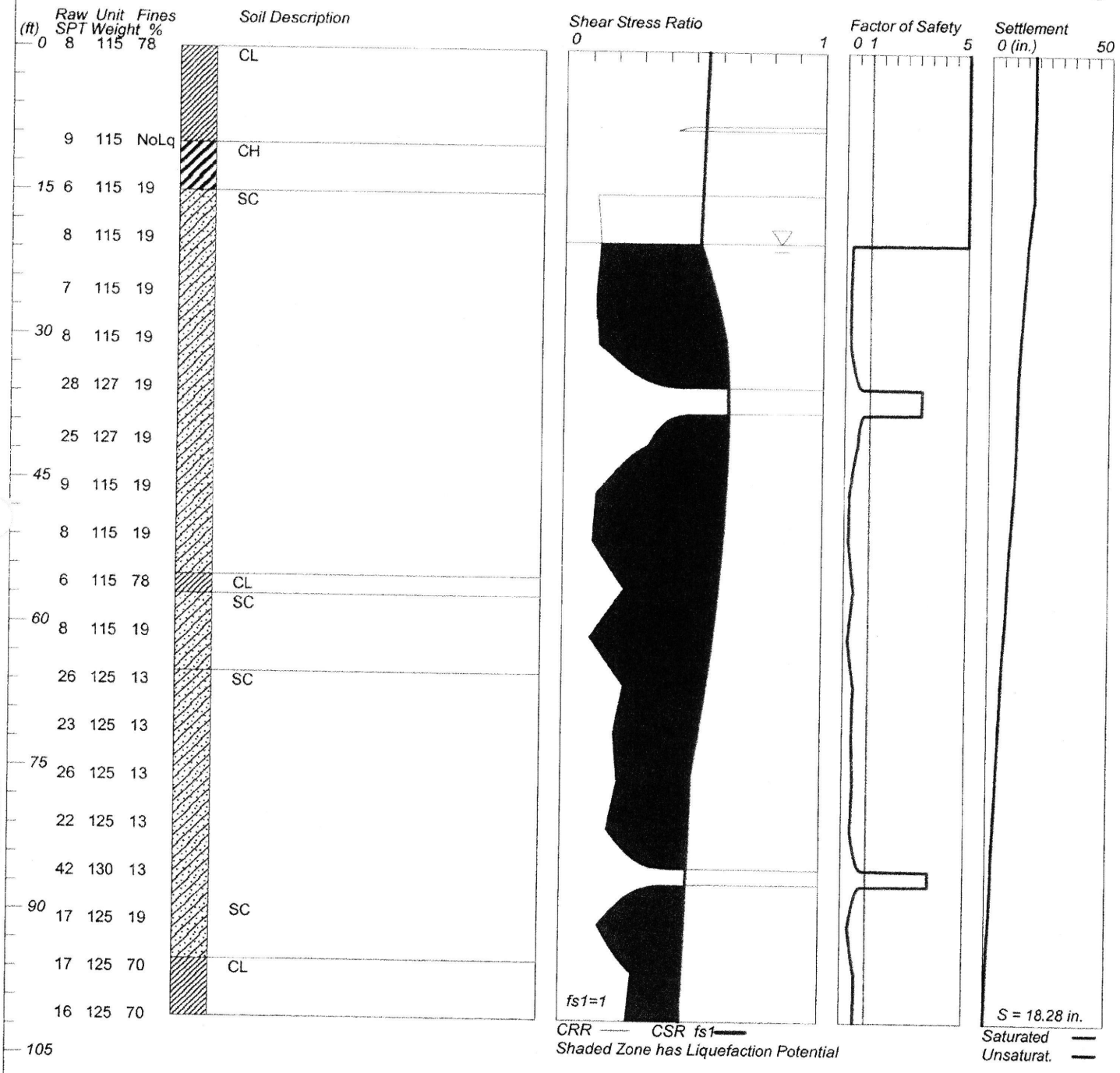
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110434

Hole No.=2 Water Depth=20.0 ft Surface Elev.=221

Magnitude=7.5
Acceleration=0.839g



BN-2, Crittenden County

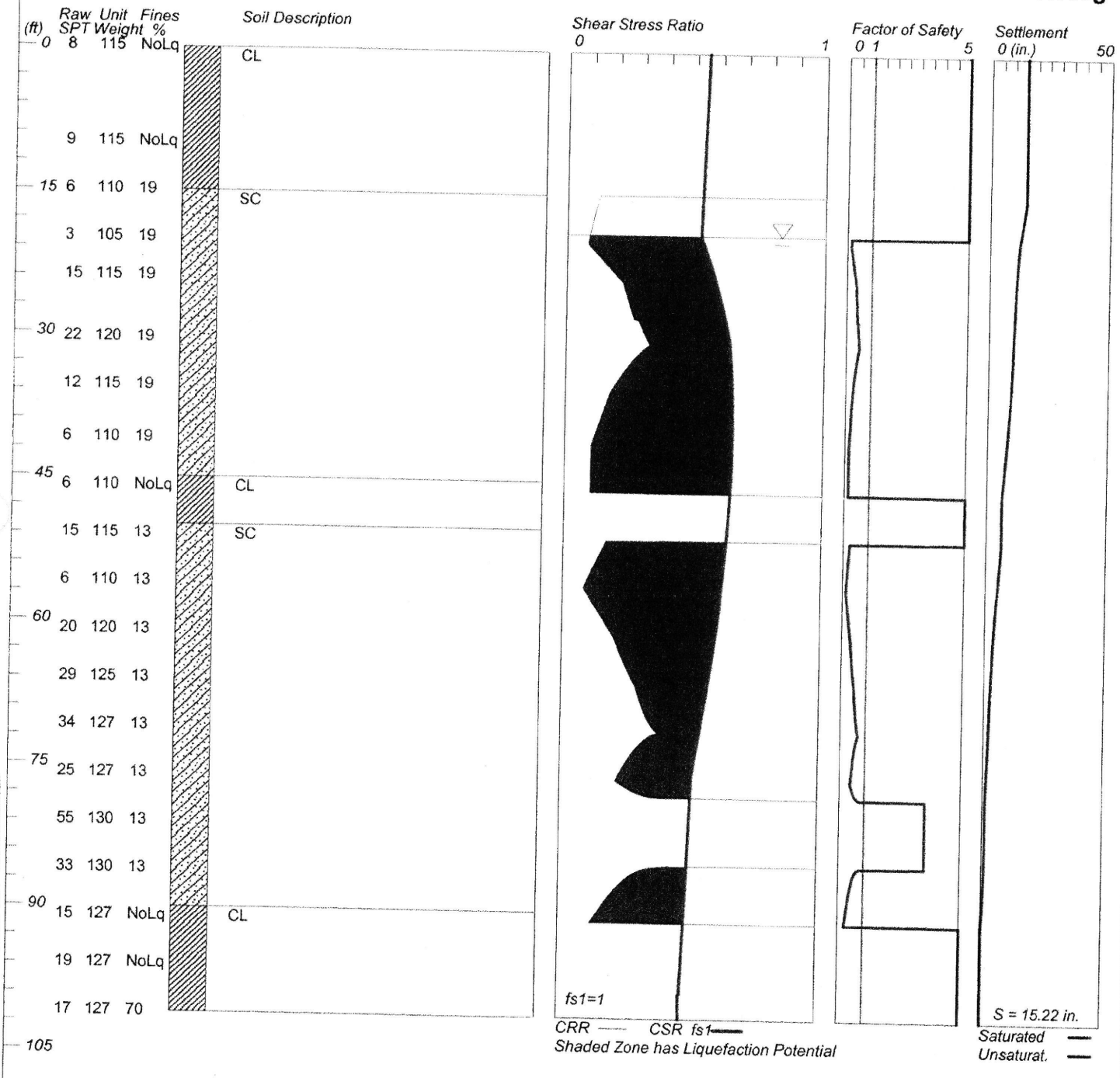
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110434

Hole No.=3 Water Depth=19.1 ft Surface Elev.=219.5

Magnitude=7.5
Acceleration=0.839g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-3, Crittenden County

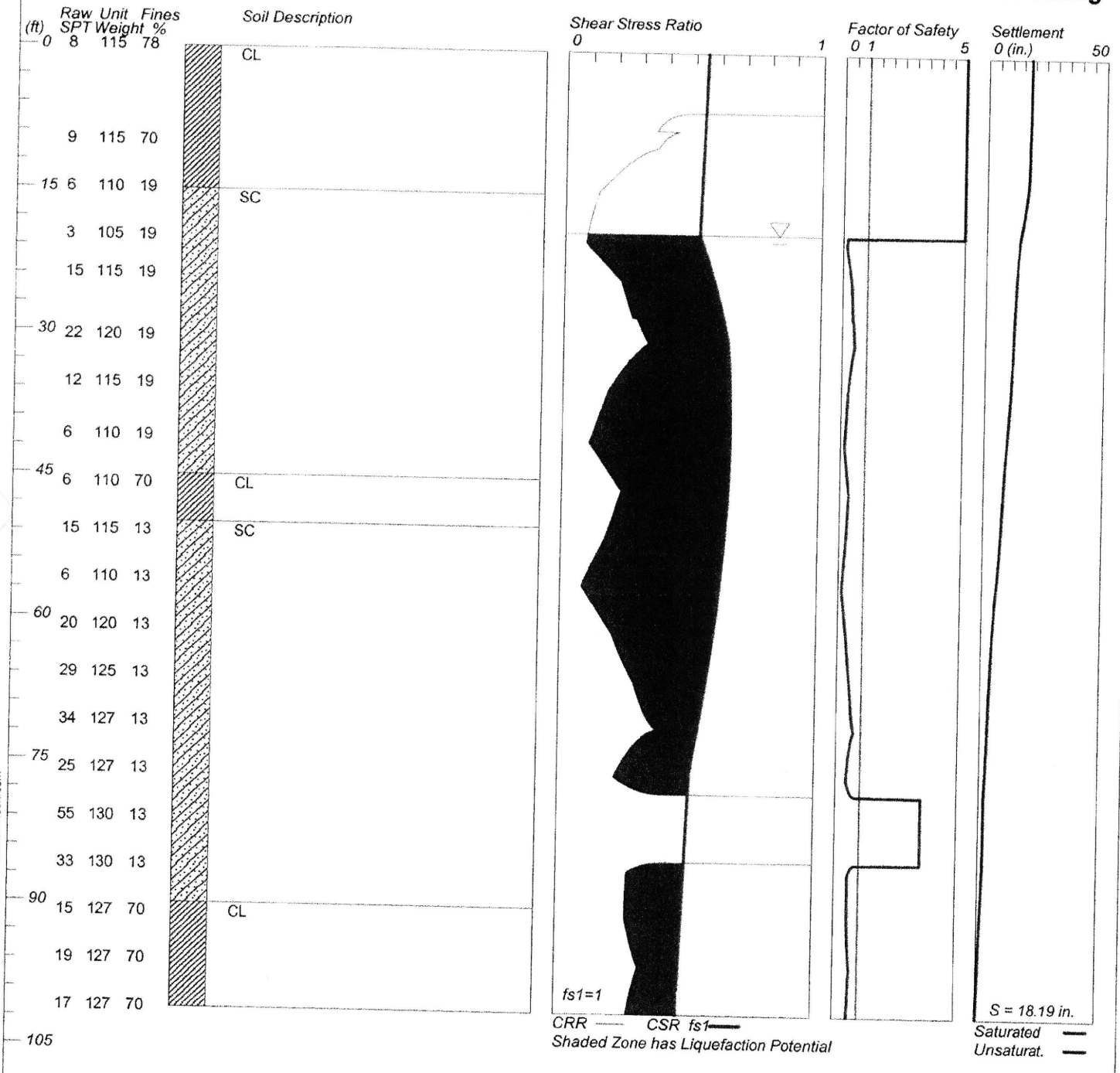
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110434

Hole No.=3 Water Depth=19.1 ft Surface Elev.=219.5

Magnitude=7.5
Acceleration=0.839g



BN-3, Crittenden County

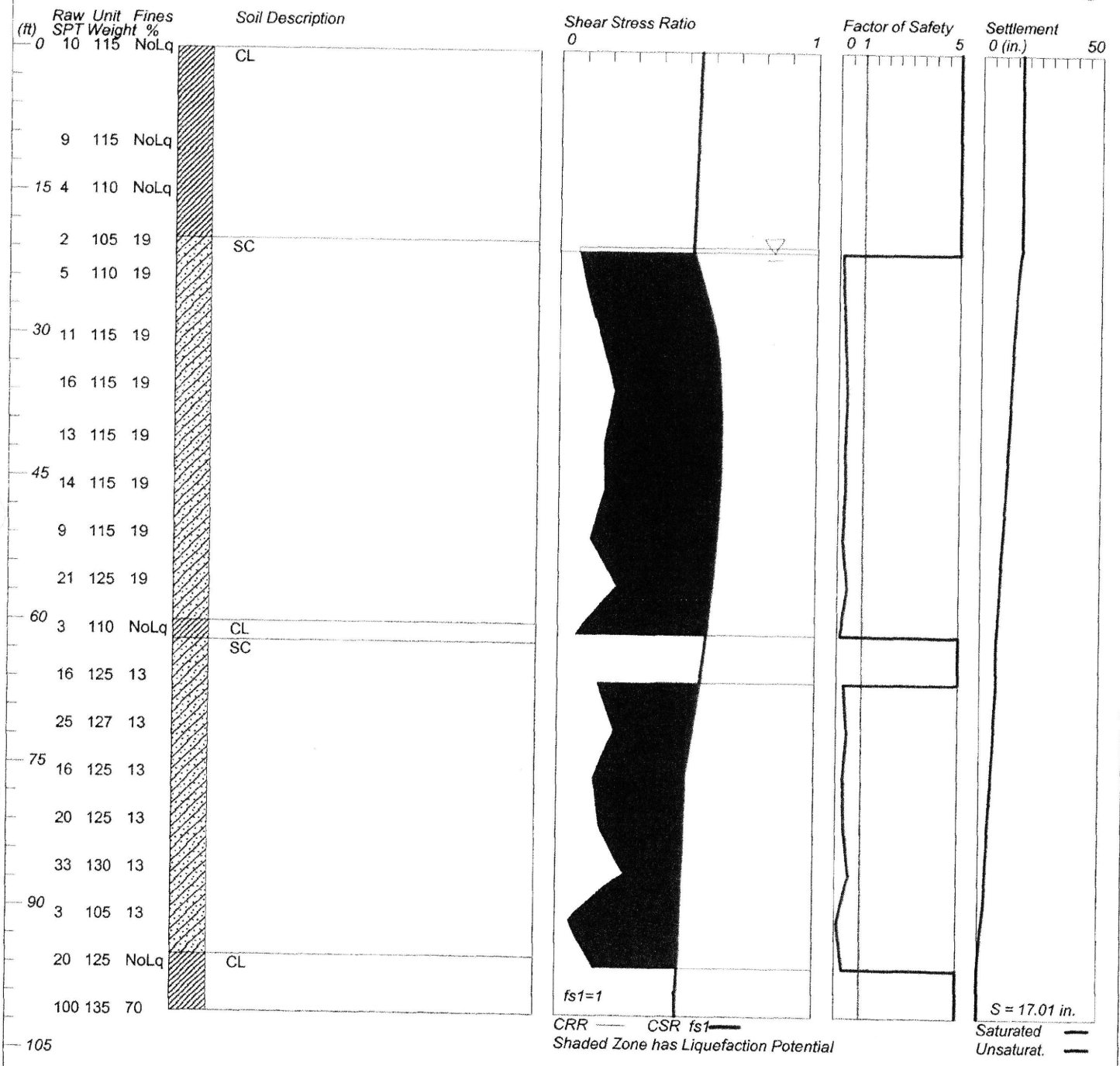
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110434

Hole No.=4 Water Depth=21.0 ft Surface Elev.=221.8

Magnitude=7.5
Acceleration=0.839g



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BN-4, Crittenden Country

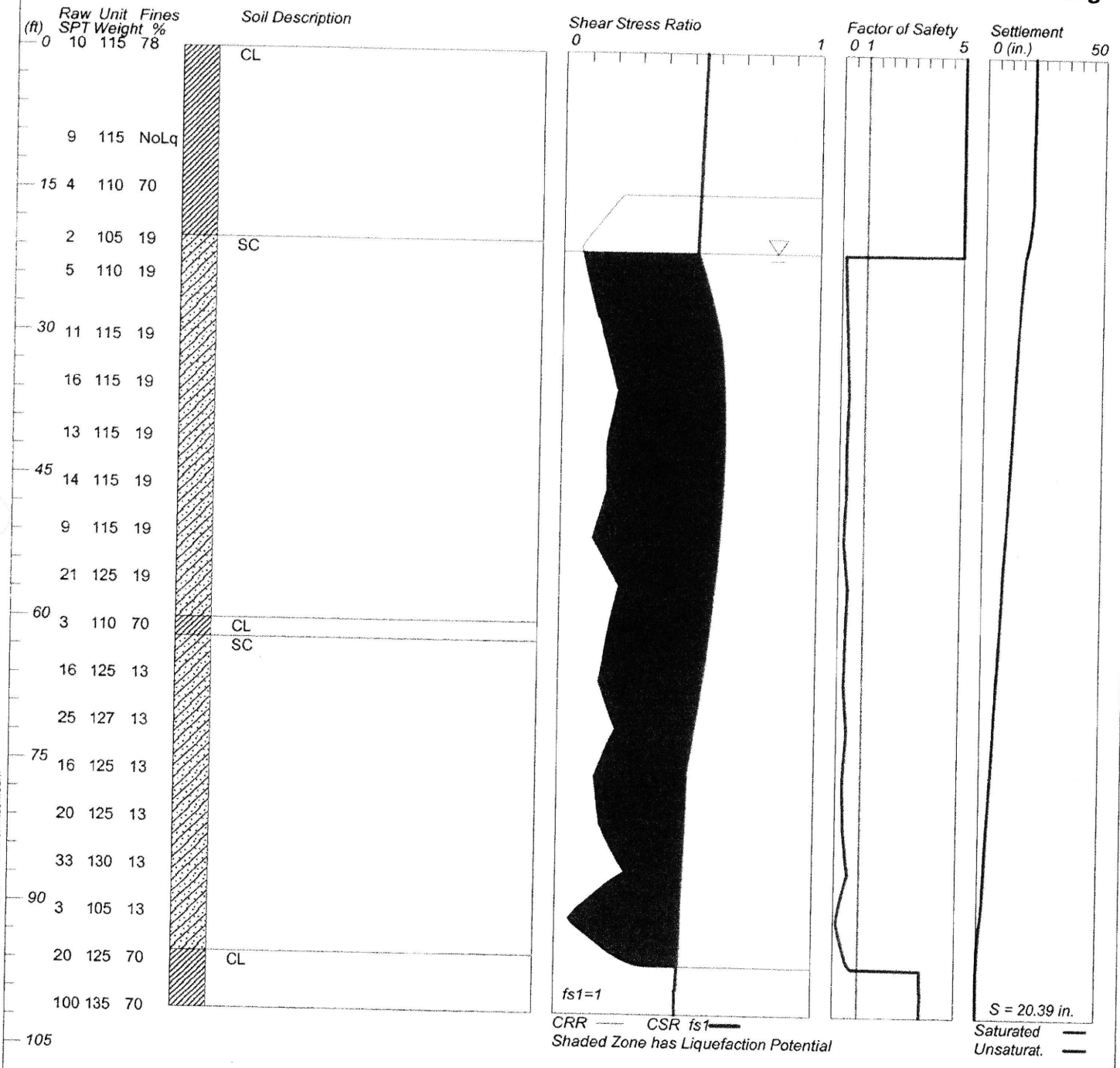
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110434

Hole No.=4 Water Depth=21.0 ft Surface Elev.=221.8

Magnitude=7.5
Acceleration=0.839g



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BN-4, Crittenden Country

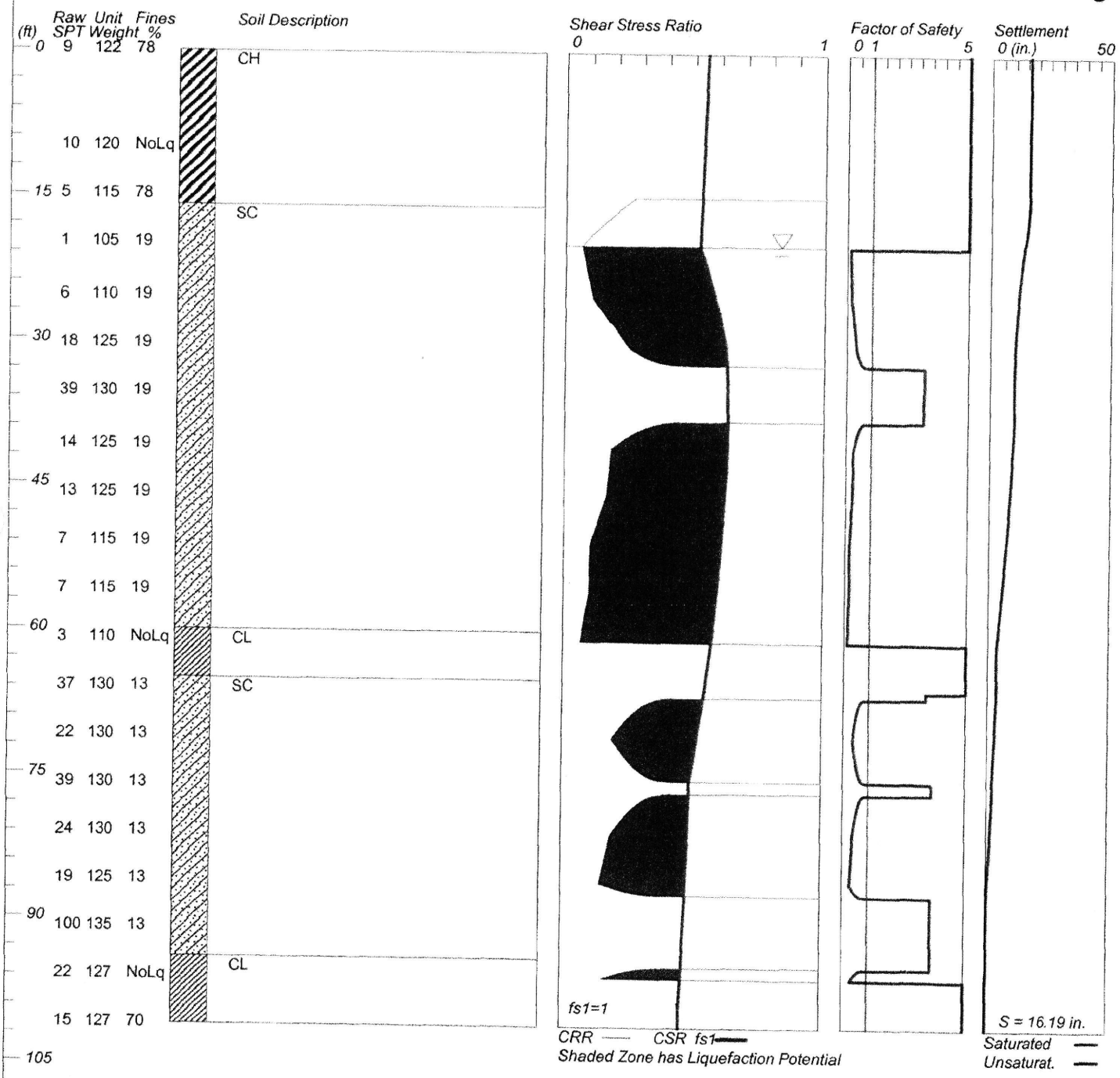
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110434

Hole No.=5 Water Depth=20.0 ft Surface Elev.=221

Magnitude=7.5
Acceleration=0.839g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-5, Crittenden County

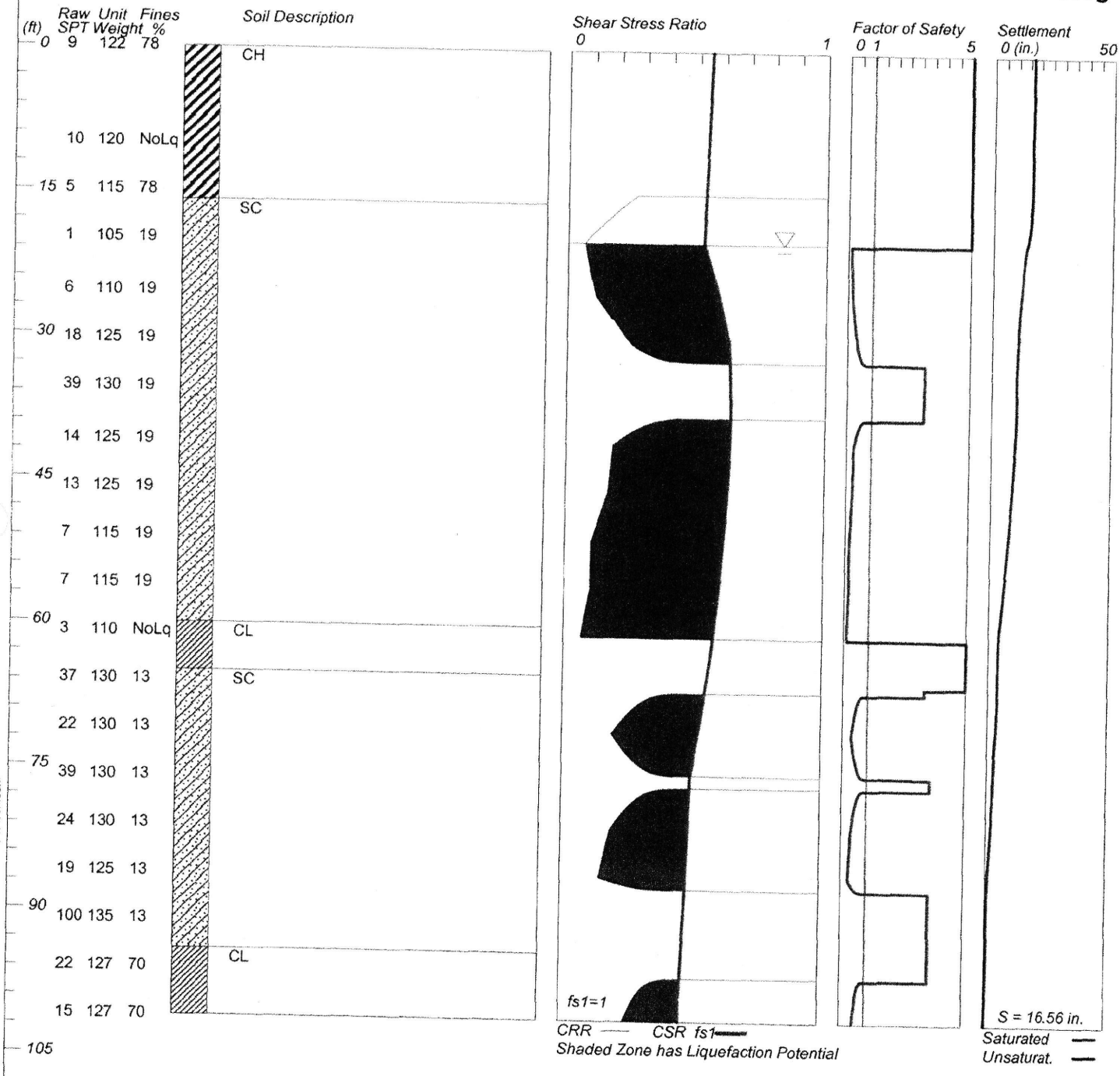
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110434

Hole No.=5 Water Depth=20.0 ft Surface Elev.=221

Magnitude=7.5
Acceleration=0.839g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-5, Crittenden County

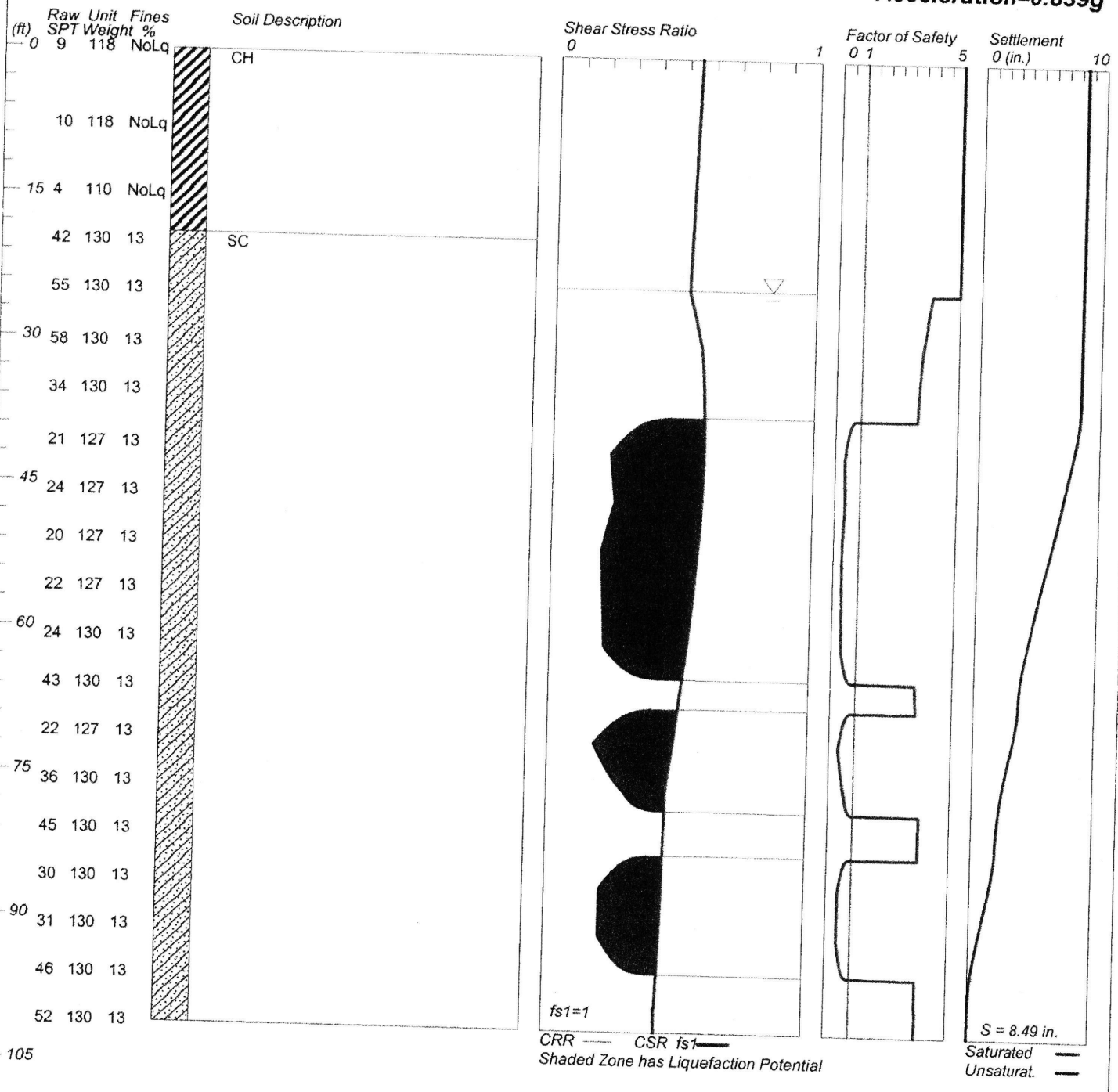
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110434

Hole No.=6 Water Depth=24 ft Surface Elev.=225.3

Magnitude=7.5
Acceleration=0.839g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-6, Crittenden County

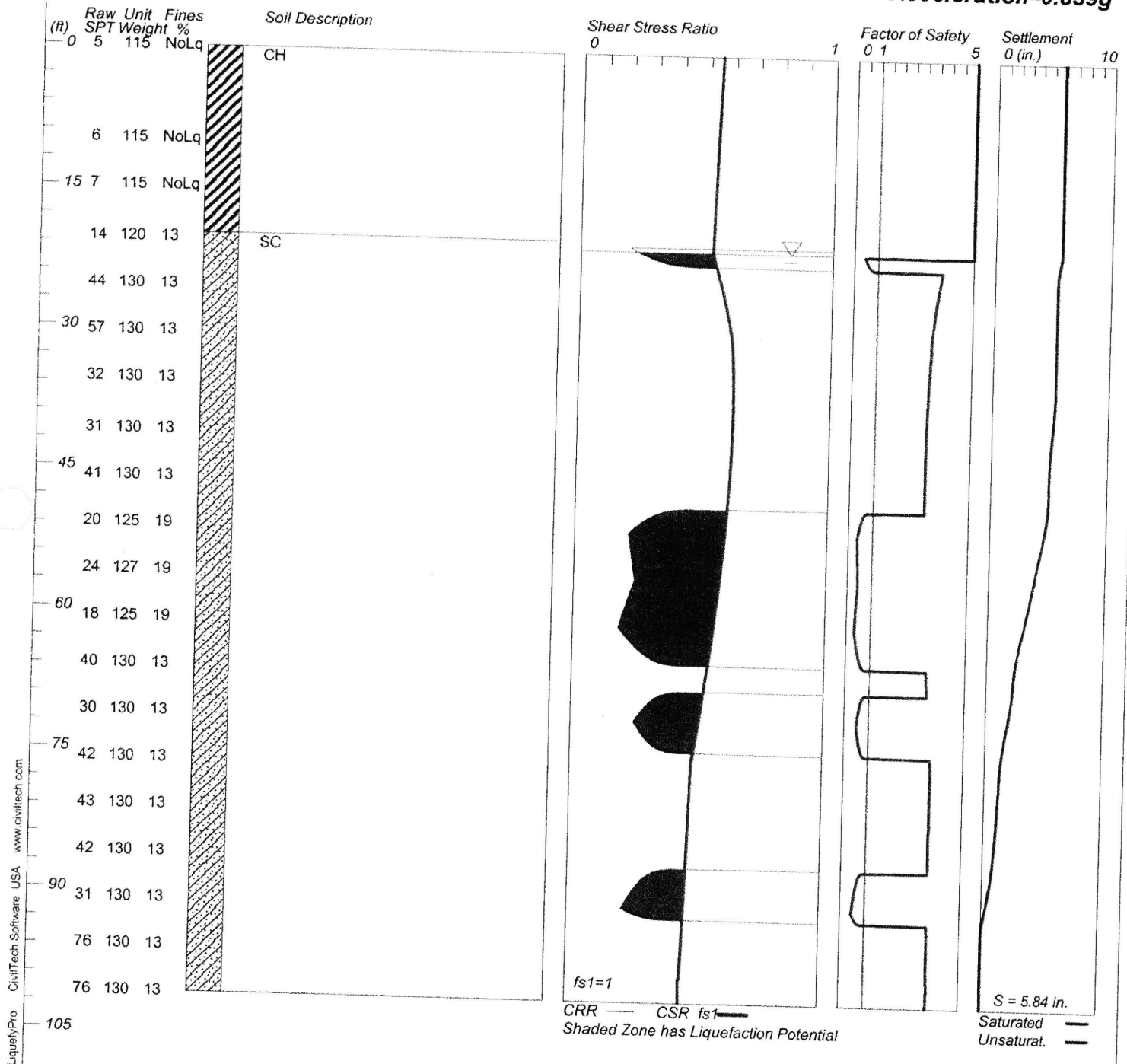
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110434

Hole No.=7 Water Depth=21 ft Surface Elev.=224.9

Magnitude=7.5
Acceleration=0.839g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-7, Crittenden County

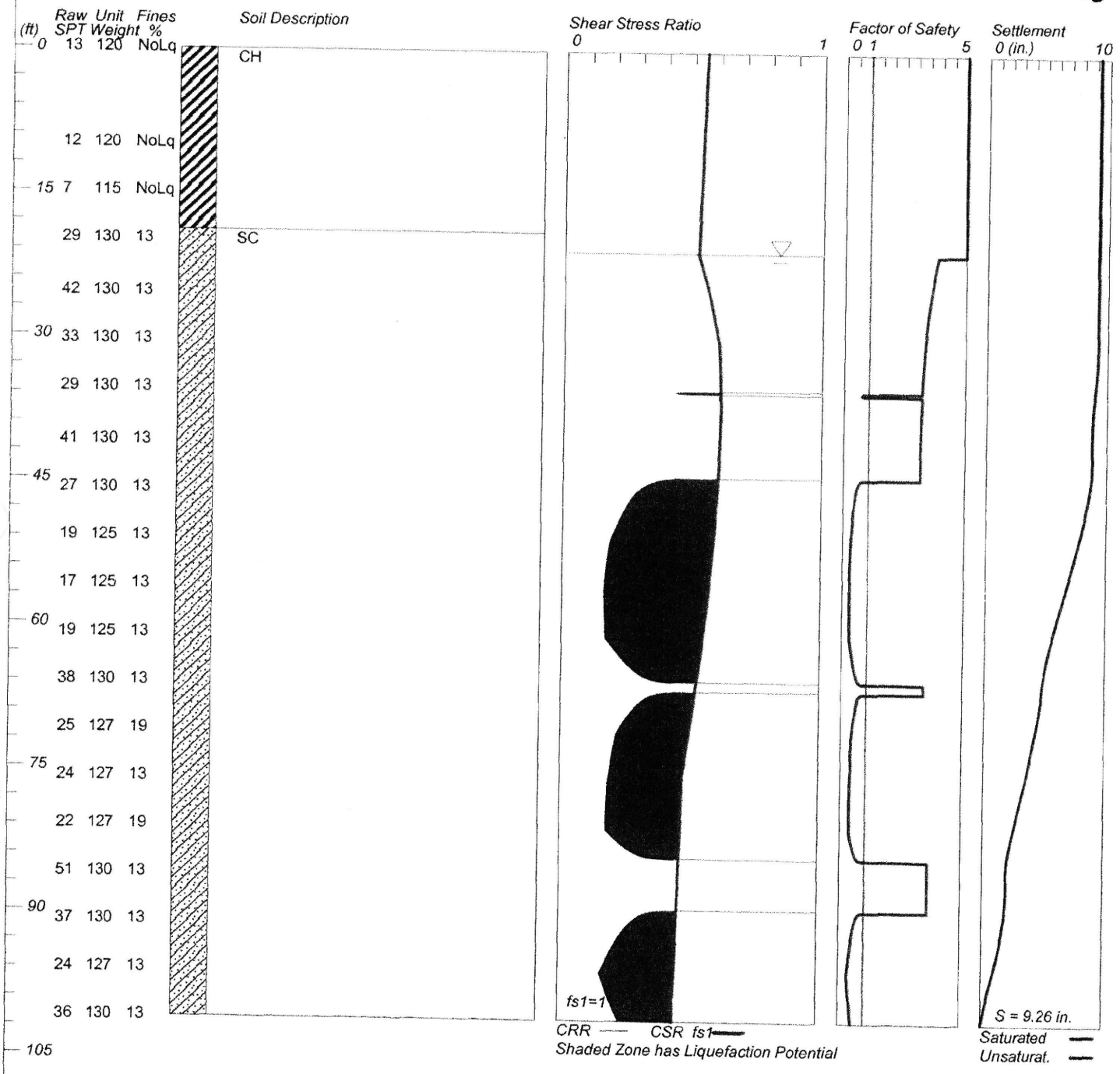
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110434

Hole No.=8 Water Depth=21 ft Surface Elev.=226

Magnitude=7.5
Acceleration=0.839g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-8, Crittenden County

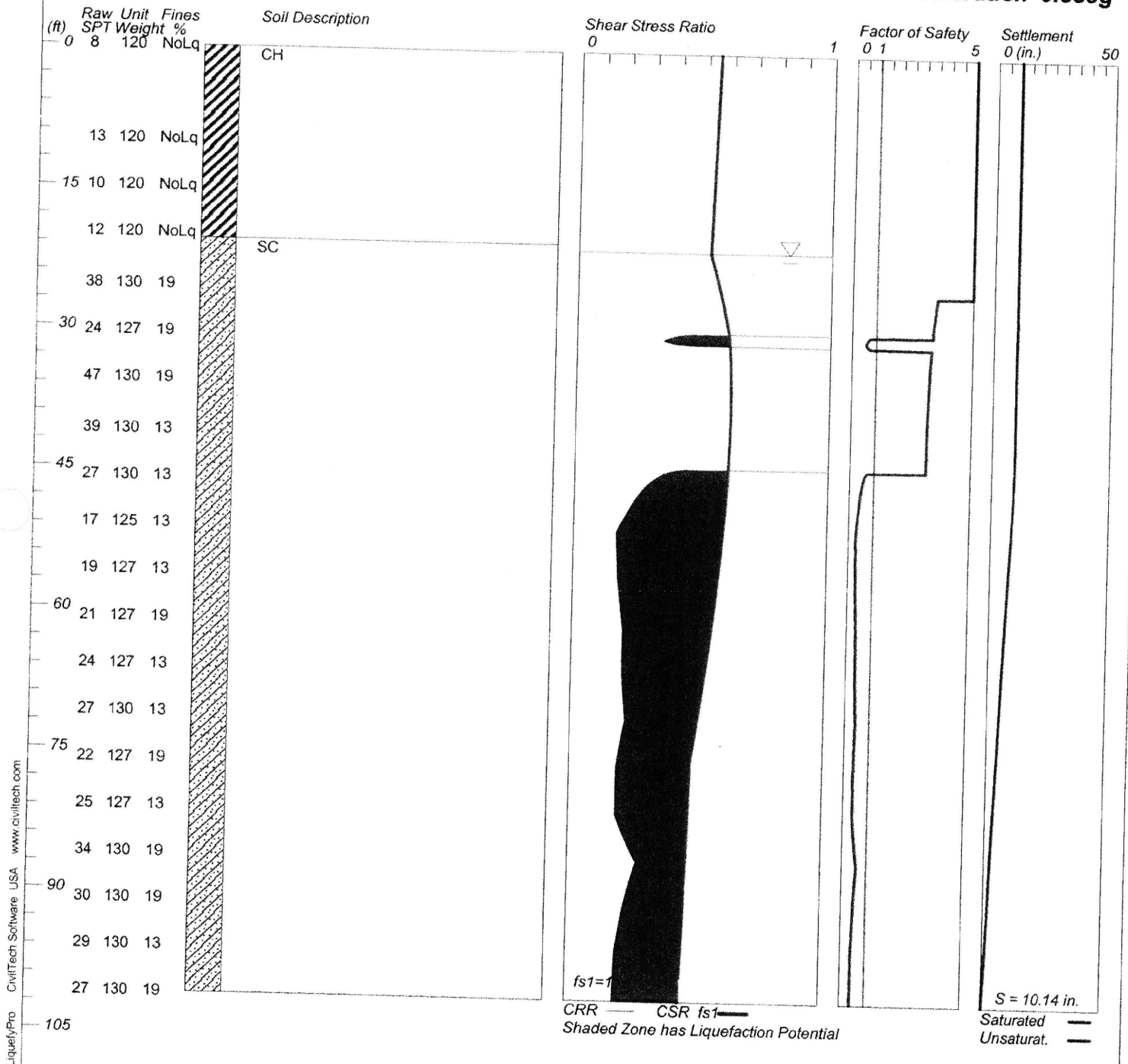
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110434

Hole No.=9 **Water Depth=21.2 ft** **Surface Elev.=226.8**

Magnitude=7.5
Acceleration=0.839g



BN-9, Crittenden County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-110434

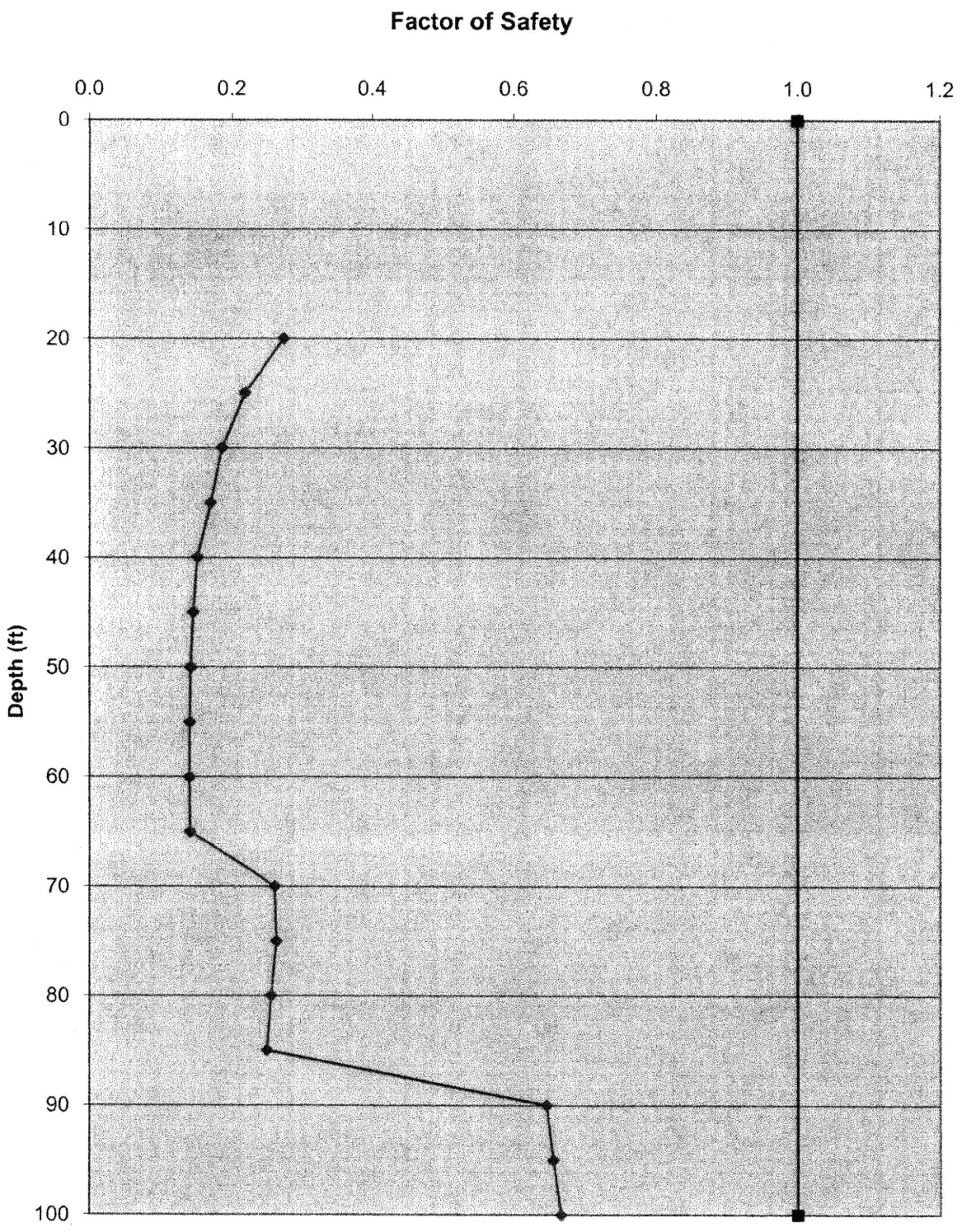
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5	depth to finish floor =	0 ft
PGA =	0.839 g	uniform floor load =	0 lb/ft^2
depth to groundwater during drilling =	20 ft	assumed depth to groundwater =	20 ft
estimated age of sand deposit =	2000 years		

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth (ft)	1=CL,ML,CH 2=SP,SM,SC	γ_s (lb/ft^3)	Field V_s (ft/sec)	Fines %	PI %	σ_{vo} (lb/ft^2)	σ'_{vo} (lb/ft^2)	σ'_{vo} (lb/ft^2)	r_d	CSR	V_{s1} (ft/sec)	$CRR_{7.5}$	MSF	K_σ	Corrected CRR	Factor of Safety
5	1	120	492	78	25	600	600	600	0.988	0.5390	665	NA	1.00	1.00	NA	NA
10	1	120	459	78	25	1200	1200	1200	0.977	0.5326	522	NA	1.00	1.00	NA	NA
15	1	120	394	92	0	1800	1800	1800	0.965	0.5263	405	NA	1.00	1.00	NA	NA
20	2	120	623	92	0	2400	2400	2400	0.953	0.5199	595	0.1432	1.00	1.00	0.14313	0.3
25	2	130	623	74	0	3050	2738	2738	0.942	0.5721	576	0.1251	1.00	1.00	0.125038	0.2
30	2	127	623	74	0	3685	3061	3061	0.930	0.6106	560	0.1139	1.00	1.00	0.113894	0.2
35	2	130	623	74	0	4335	3399	3399	0.889	0.6183	546	0.1054	1.00	1.00	0.105371	0.2
40	2	130	623	19	0	4985	3737	3737	0.848	0.6171	533	0.0939	1.00	1.00	0.093895	0.2
45	2	130	623	19	0	5635	4075	4075	0.808	0.6090	521	0.0893	1.00	1.00	0.089244	0.1
50	2	125	623	19	0	6260	4388	4388	0.767	0.5966	512	0.0855	1.00	1.00	0.085532	0.1
55	2	127	623	19	0	6895	4711	4711	0.726	0.5796	503	0.0822	1.00	1.00	0.08217	0.1
60	2	127	623	19	0	7530	5034	5034	0.685	0.5591	495	0.0792	1.00	1.00	0.079191	0.1
65	2	127	623	13	0	8165	5357	5357	0.645	0.5359	487	0.0765	1.00	1.00	0.076526	0.1
70	2	130	787	13	0	8815	5695	5695	0.604	0.5098	606	0.1338	1.00	1.00	0.133811	0.3
75	2	127	787	13	0	9450	6018	6018	0.563	0.4823	598	0.1278	1.00	1.00	0.12777	0.3
80	2	127	787	13	0	10085	6341	6341	0.549	0.4760	590	0.1227	1.00	1.00	0.122651	0.3
85	2	130	787	13	0	10735	6679	6679	0.537	0.4703	582	0.1180	1.00	1.00	0.118026	0.3
90	2	130	1050	13	0	11385	7017	7017	0.524	0.4640	767	0.3000	1.00	1.00	0.299946	0.6
95	2	130	1050	13	0	12035	7355	7355	0.512	0.4571	758	0.3000	1.00	1.00	0.299946	0.7
100	2	130	1050	13	0	12685	7693	7693	0.500	0.4496	750	0.3000	1.00	1.00	0.299946	0.7

Used Bore #9 for PI values & unit wt.

Vs Liquefaction Potential - Project 110434

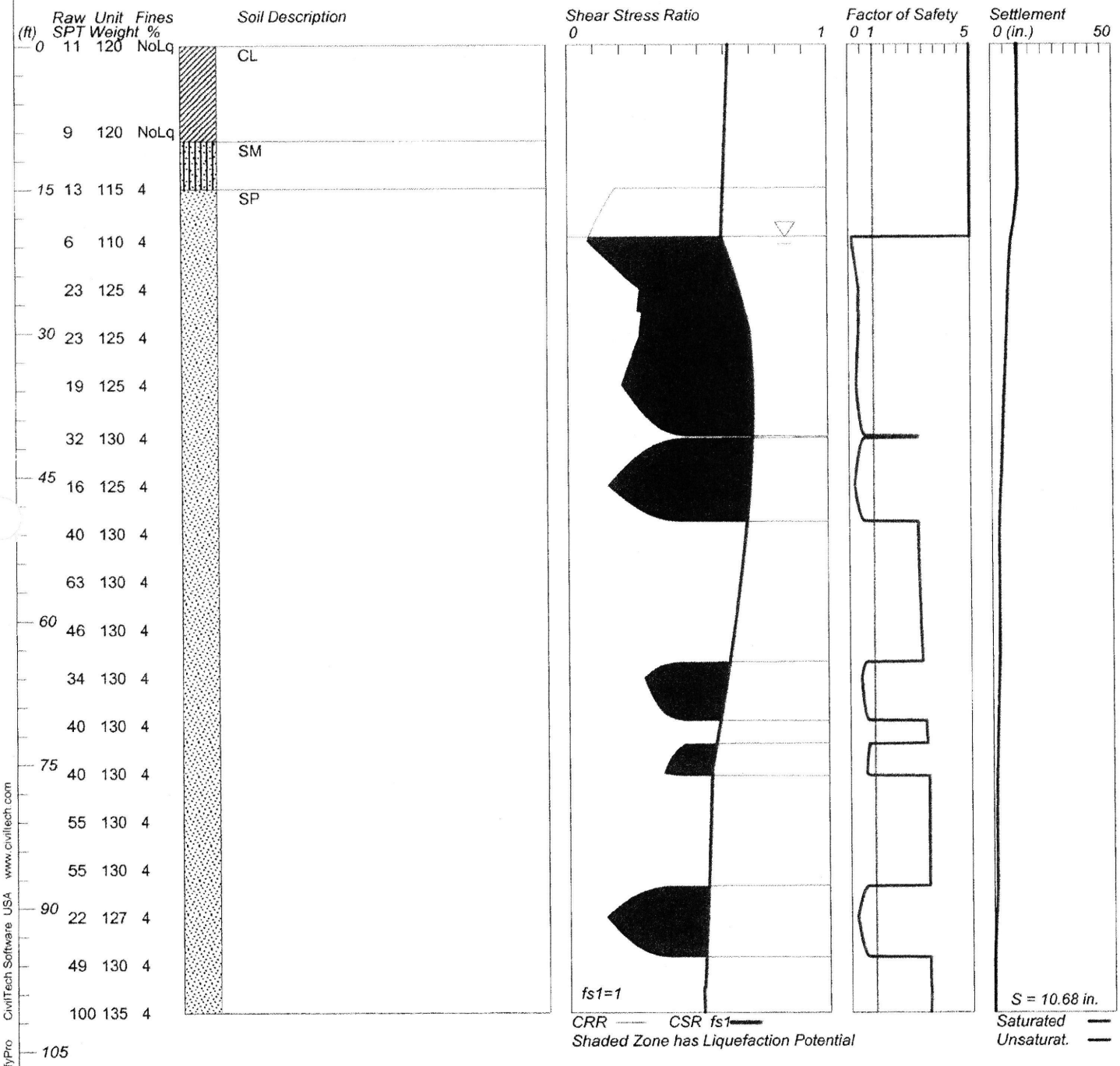


LIQUEFACTION ANALYSIS (ALT.A)

100547

Hole No.=1 Water Depth=20.1 ft Surface Elev.=213.5

Magnitude=7.5
Acceleration=0.951g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-1, Poinsett County

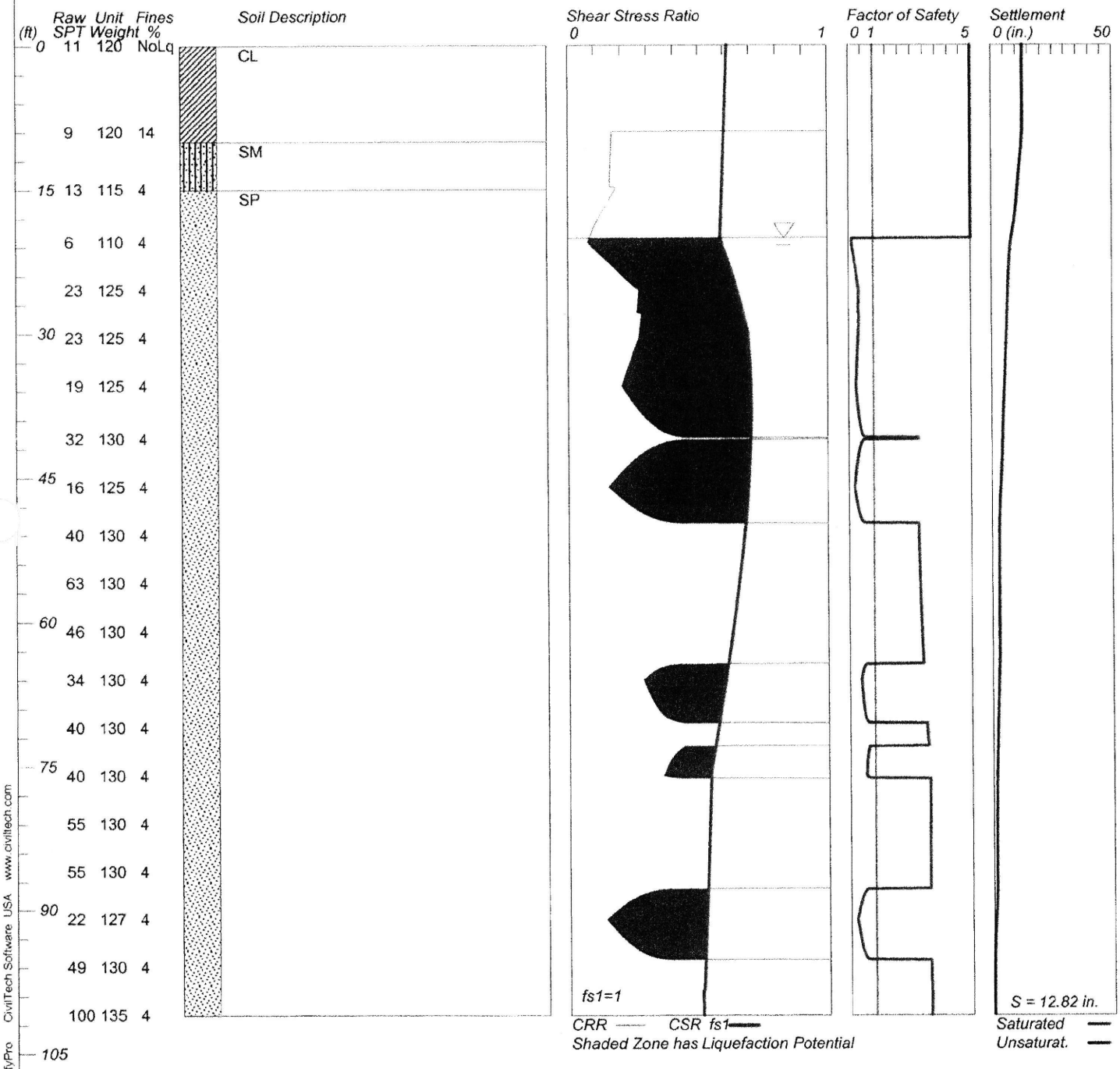
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100547

Hole No.=1 Water Depth=20.1 ft Surface Elev.=213.5

Magnitude=7.5
Acceleration=0.951g



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BN-1, Poinsett County

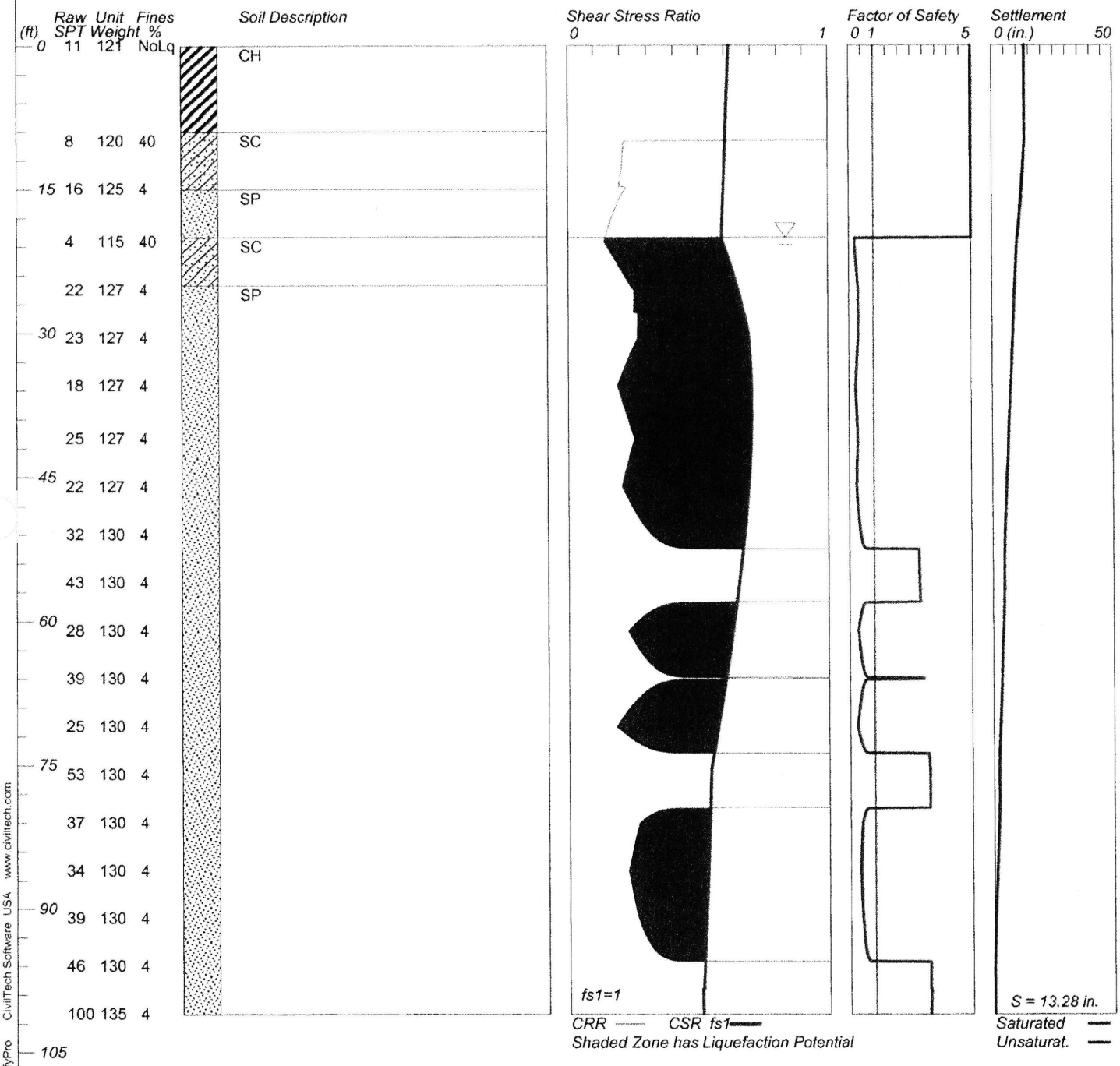
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100547

Hole No.=2 Water Depth=20.1 ft Surface Elev.=213.5

Magnitude=7.5
Acceleration=0.951g



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BN-2, Poinsett County

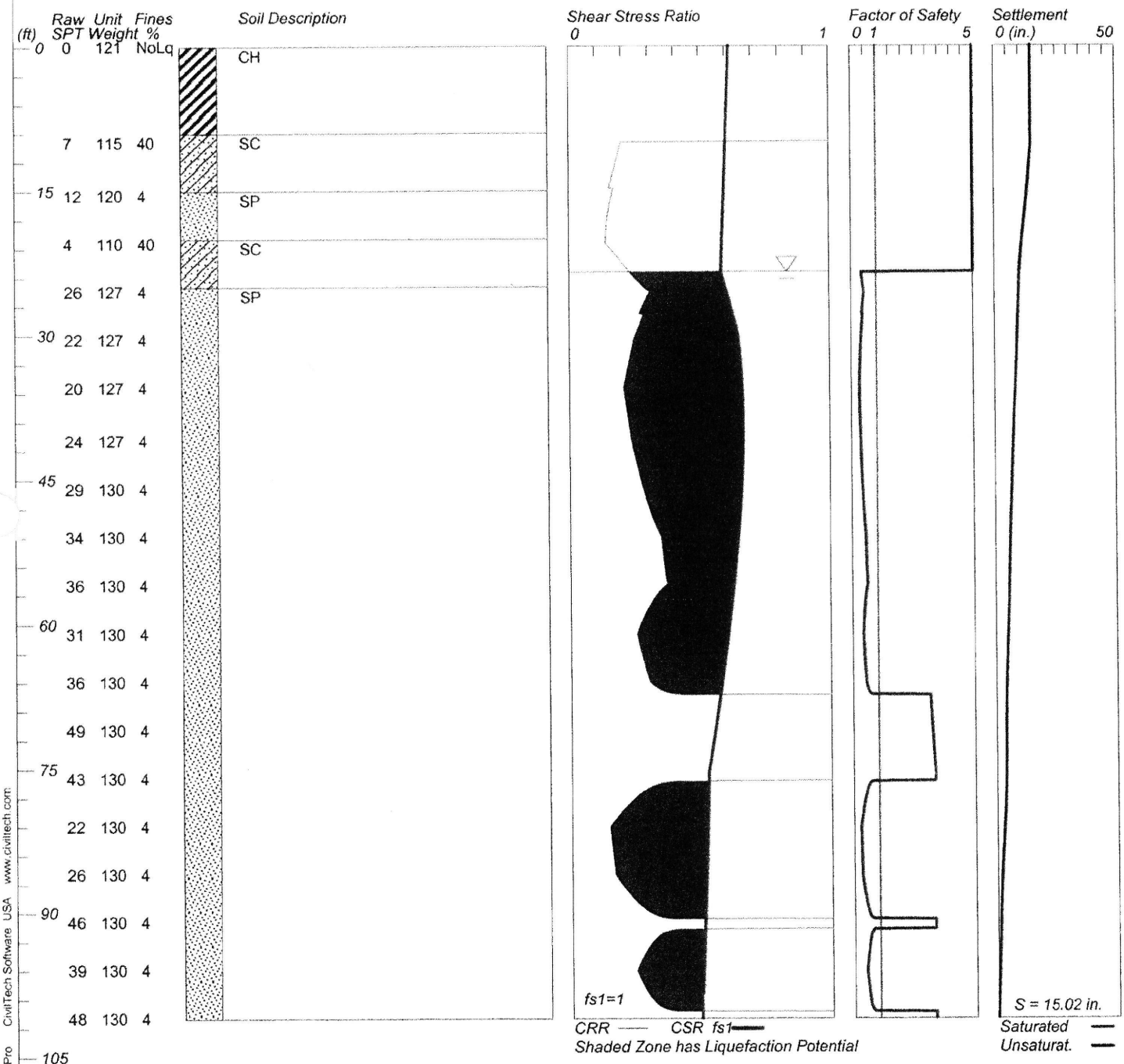
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100547

Hole No.=3 Water Depth=23.5 ft Surface Elev.=213.3

Magnitude=7.5
Acceleration=0.951g



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BN-3, Poinsett County

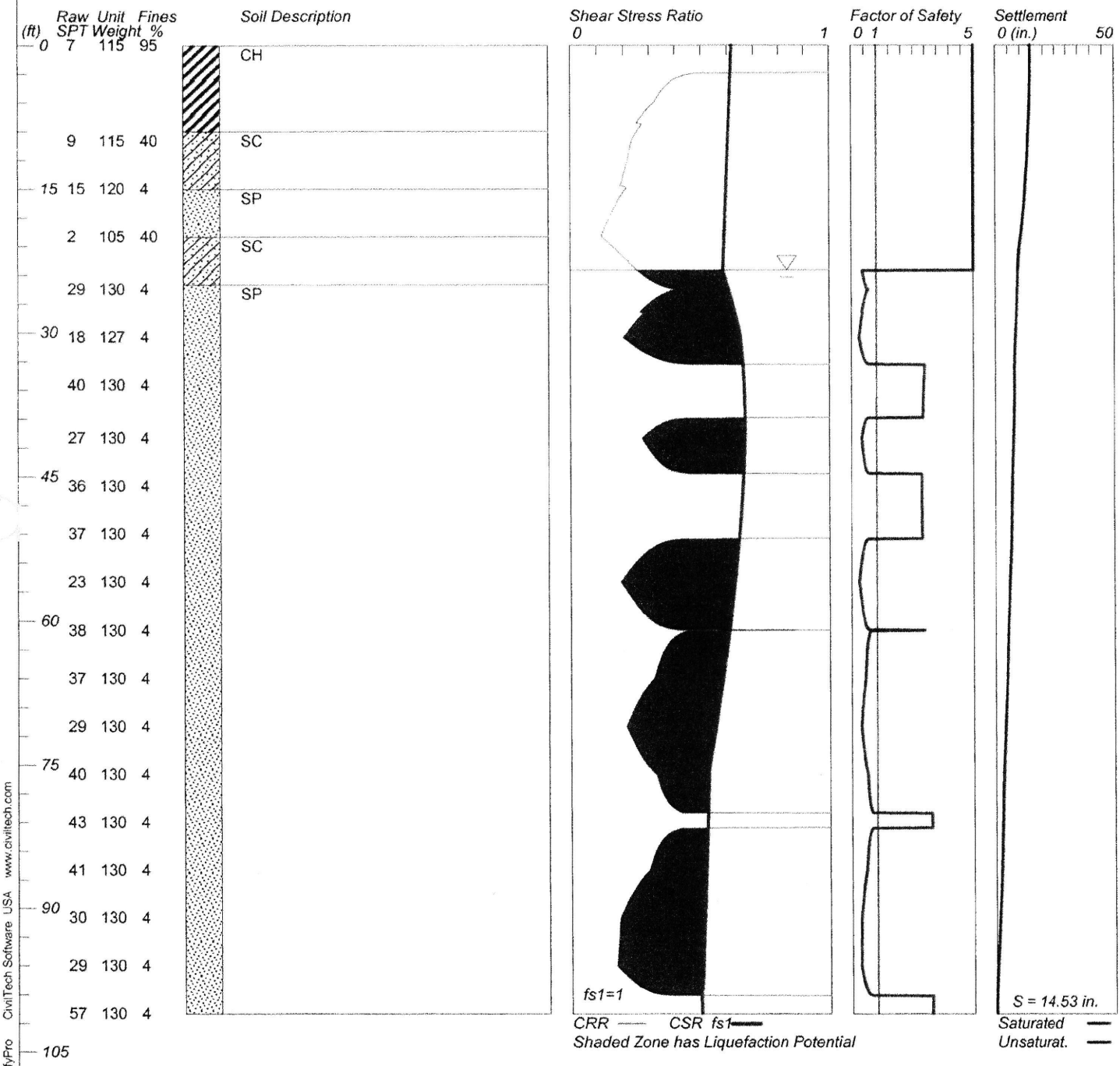
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100547

Hole No.=4 Water Depth=23.5 ft Surface Elev.=213.2

Magnitude=7.5
Acceleration=0.951g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-4, Poinsett County **Plate A-1**

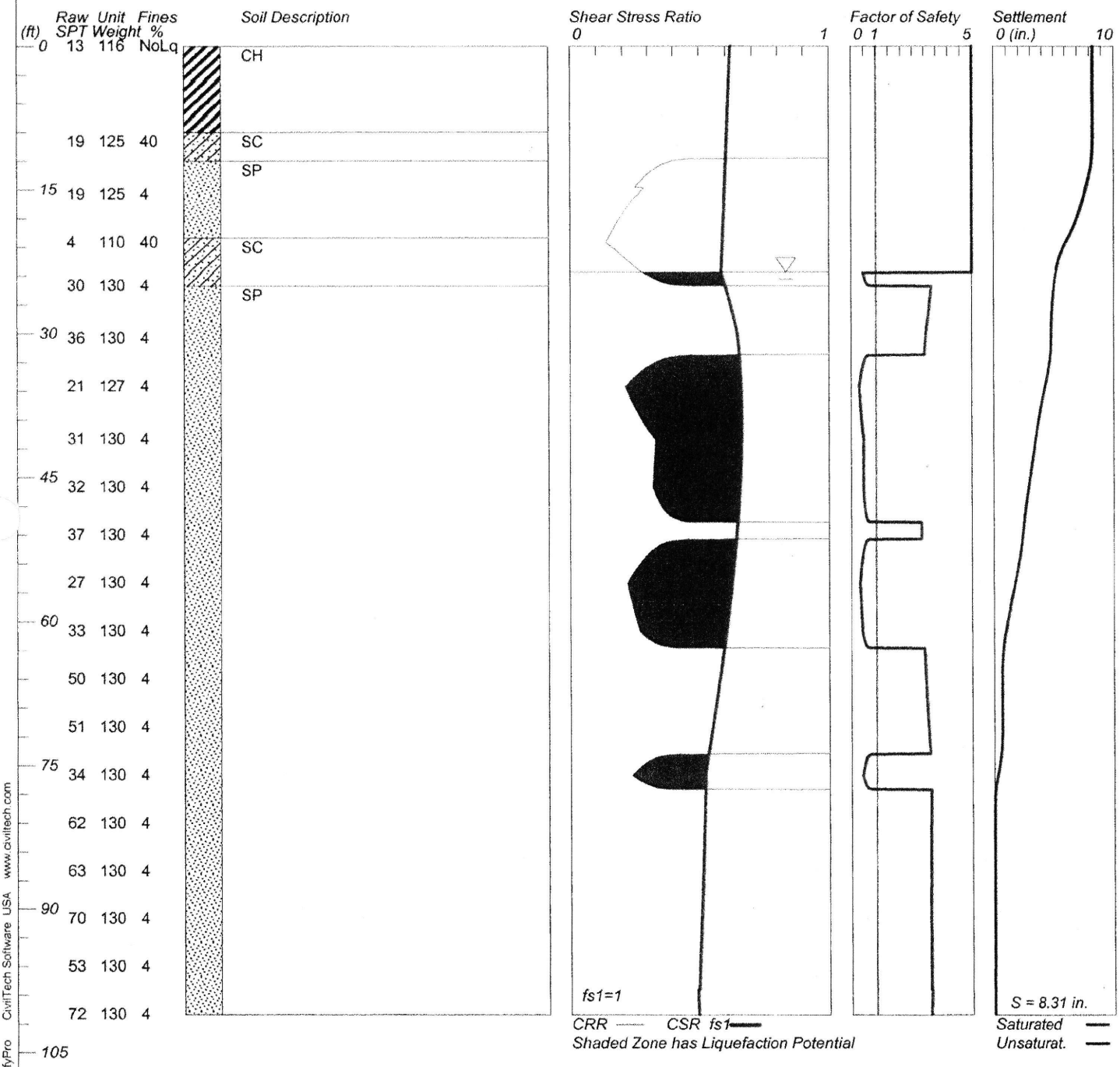
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

100547

Hole No.=5 Water Depth=23.6 ft Surface Elev.=213.4

Magnitude=7.5
Acceleration=0.951g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-5, Poinsett County

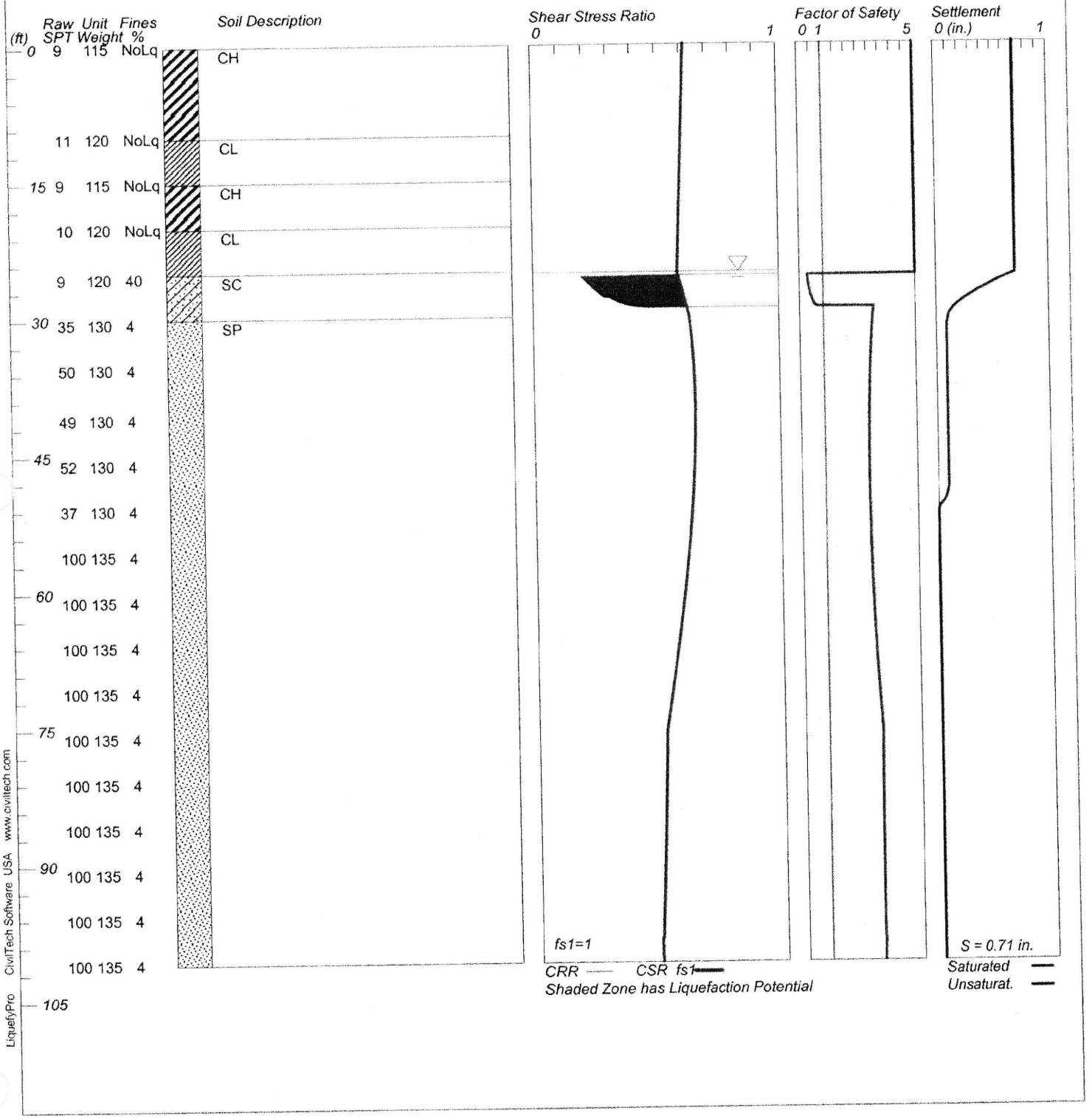
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100547

Hole No.=6 Water Depth=25.1 ft Surface Elev.=222.5

Magnitude=7.5
Acceleration=0.951g



BN-6, Poinsett County

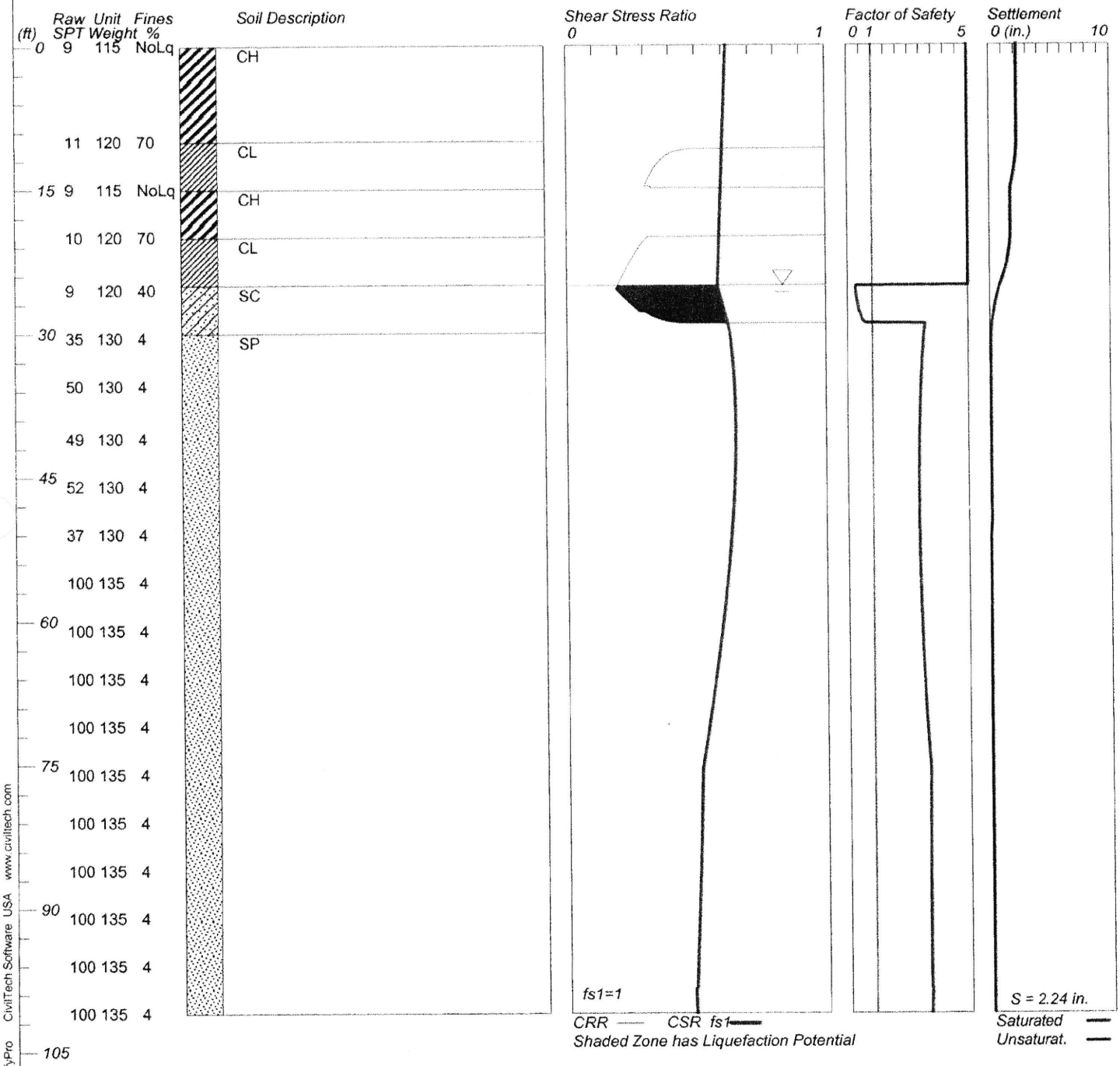
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100547

Hole No.=6 Water Depth=25.1 ft Surface Elev.=222.5

Magnitude=7.5
Acceleration=0.951g



Liquefy Pro CivilTech Software USA www.civiltech.com

BN-6, Poinsett County

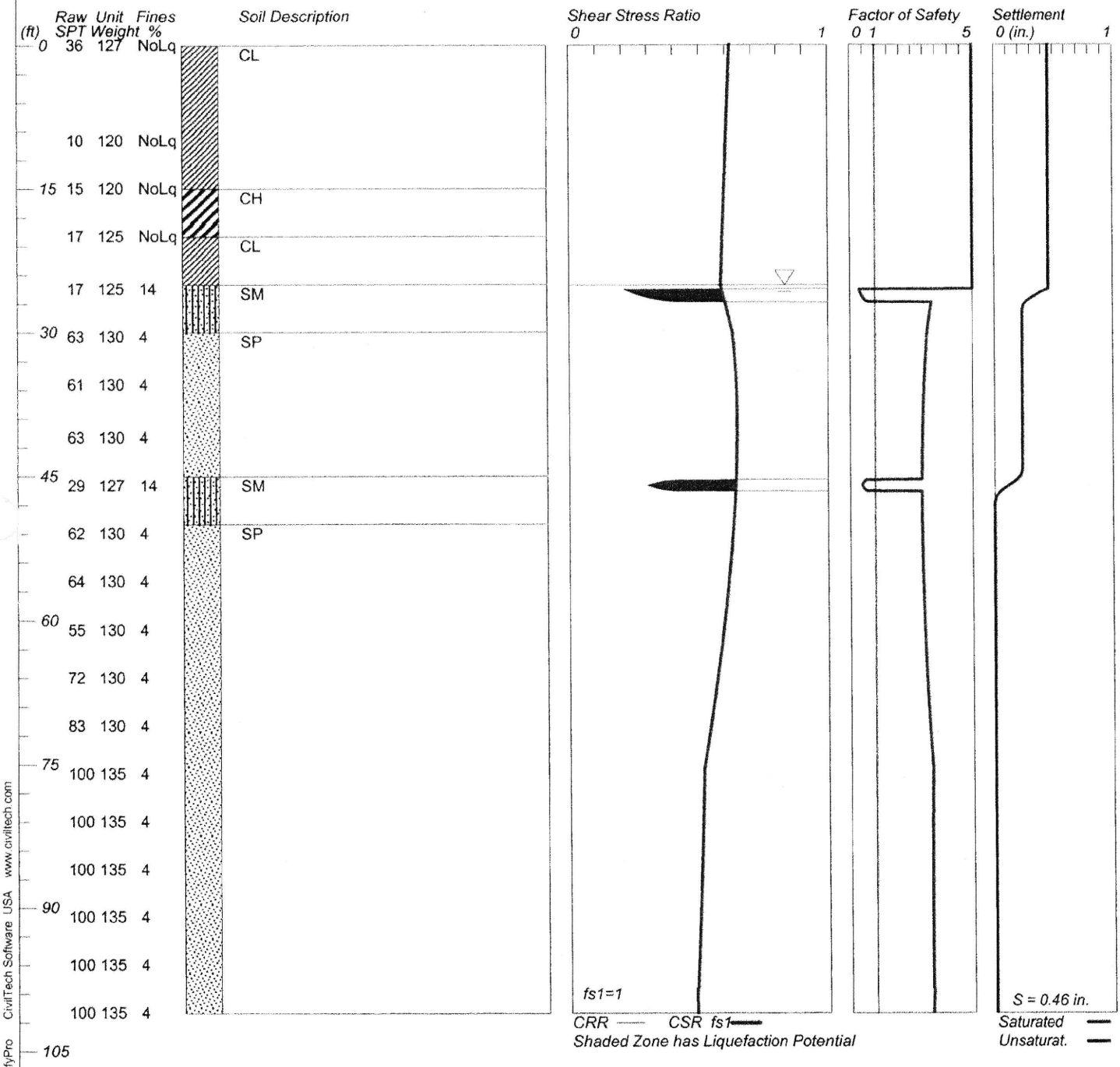
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

100547

Hole No.=7 Water Depth=25.1 ft Surface Elev.=223.1

Magnitude=7.5
Acceleration=0.951g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-7, Poinsett County

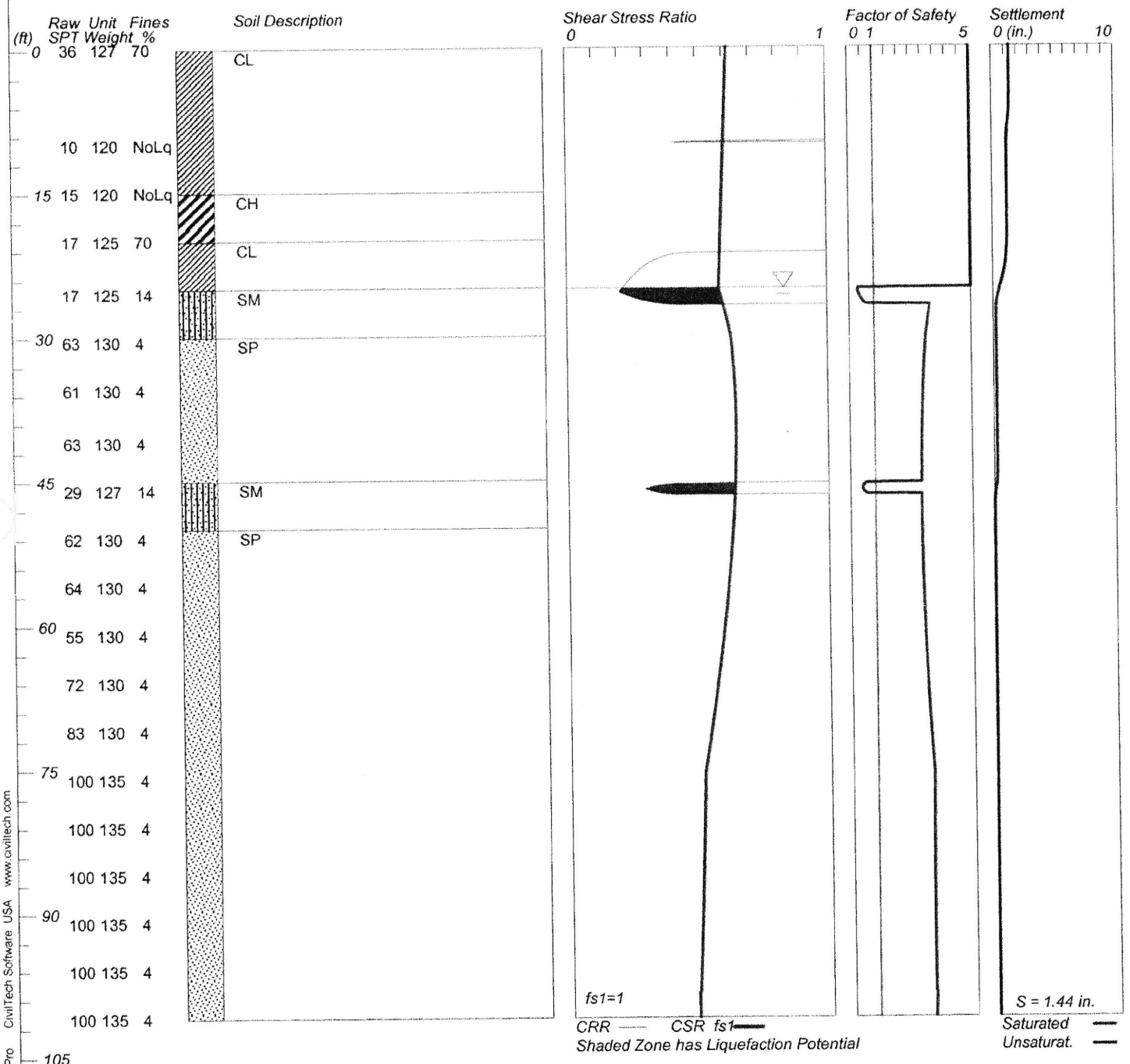
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

100547

Hole No.=7 Water Depth=25.1 ft Surface Elev.=223.1

Magnitude=7.5
Acceleration=0.951g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-7, Poinsett County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-100547

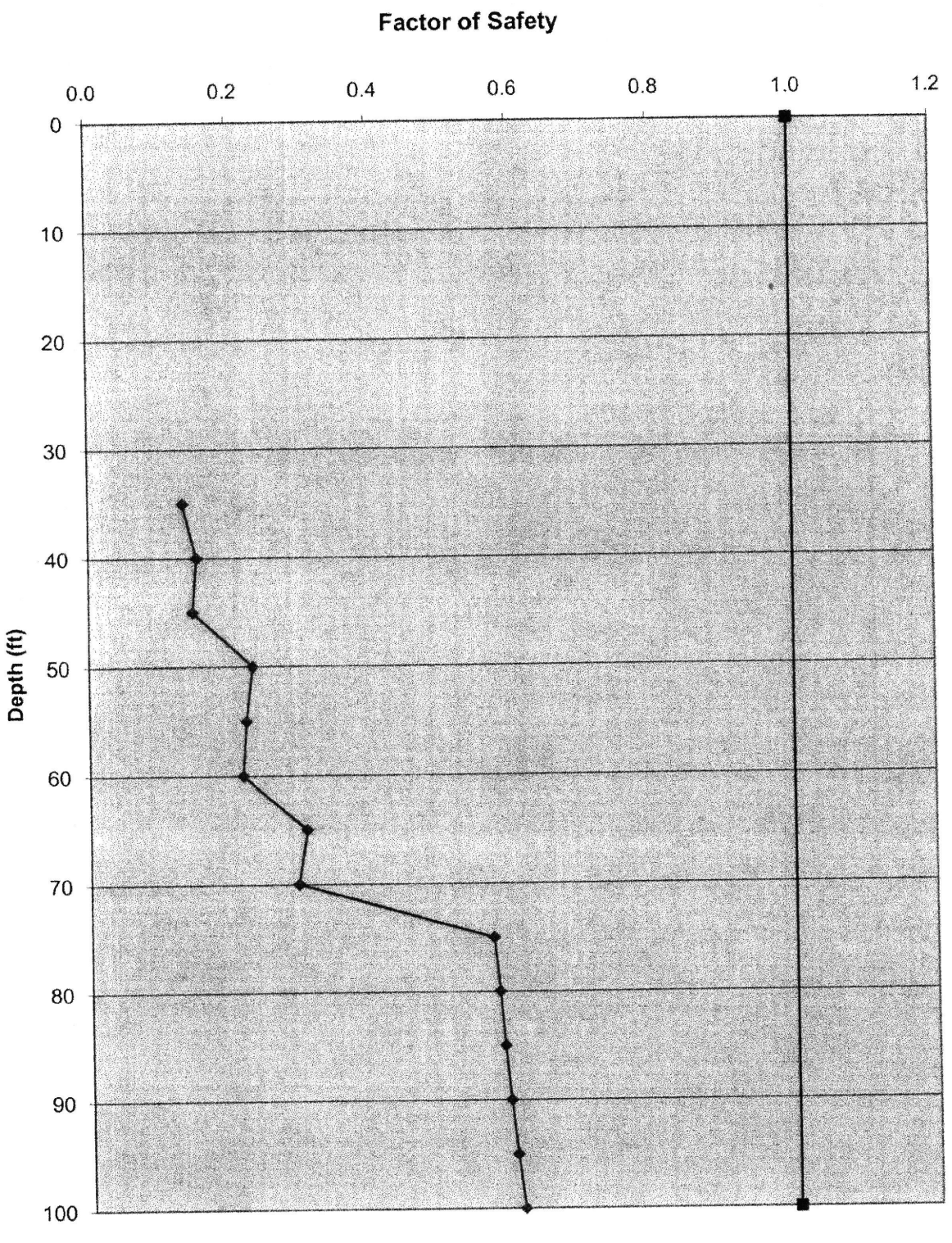
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	0.951	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	23	ft	assumed depth to groundwater =	23	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	127	344	70	14	635	635	635	0.988	0.6109	458	NA	1.00	1.00	NA	NA
10	1	120	492	70	14	1235	1235	1235	0.977	0.6037	555	NA	1.00	1.00	NA	NA
15	1	120	548	70	55	1835	1835	1835	0.965	0.5965	560	NA	1.00	1.00	NA	NA
20	1	125	591	70	14	2460	2460	2460	0.953	0.5893	561	NA	1.00	1.00	NA	NA
25	1	125	607	40	14	3085	2960	2960	0.942	0.6066	550	NA	1.00	1.00	NA	NA
30	1	130	607	14	0	3735	3298	3298	0.930	0.6510	536	NA	1.00	1.00	NA	NA
35	2	130	607	14	0	4385	3636	3636	0.889	0.6627	523	0.0898	1.00	1.00	0.089756	0.1
40	2	130	656	14	0	5035	3974	3974	0.848	0.6643	553	0.1026	1.00	1.00	0.102588	0.2
45	2	130	656	14	0	5685	4312	4312	0.808	0.6581	541	0.0976	1.00	1.00	0.097537	0.1
50	2	130	771	14	0	6335	4650	4650	0.767	0.6458	624	0.1505	1.00	1.00	0.15048	0.2
55	2	130	771	14	0	6985	4988	4988	0.726	0.6285	614	0.1401	1.00	1.00	0.140073	0.2
60	2	130	771	14	0	7635	5326	5326	0.685	0.6073	604	0.1321	1.00	1.00	0.13207	0.2
65	2	130	837	14	0	8285	5664	5664	0.645	0.5829	645	0.1800	1.00	1.00	0.179977	0.3
70	2	130	837	14	0	8935	6002	6002	0.604	0.5558	636	0.1647	1.00	1.00	0.164641	0.3
75	2	135	968	4	0	9610	6365	6365	0.563	0.5257	725	0.3000	1.00	1.00	0.299946	0.6
80	2	135	968	4	0	10285	6728	6728	0.549	0.5186	715	0.3000	1.00	1.00	0.299946	0.6
85	2	135	1050	4	0	10960	7091	7091	0.537	0.5127	765	0.3000	1.00	1.00	0.299946	0.6
90	2	135	1050	4	0	11635	7454	7454	0.524	0.5060	756	0.3000	1.00	1.00	0.299946	0.6
95	2	135	1050	4	0	12310	7817	7817	0.512	0.4986	747	0.3000	1.00	1.00	0.299946	0.6
100	2	135	1050	4	0	12985	8180	8180	0.500	0.4906	738	0.3000	1.00	1.00	0.299946	0.6

Used Bore #7 for PI values & unit wt.

Vs Liquefaction Potential - Project 100547

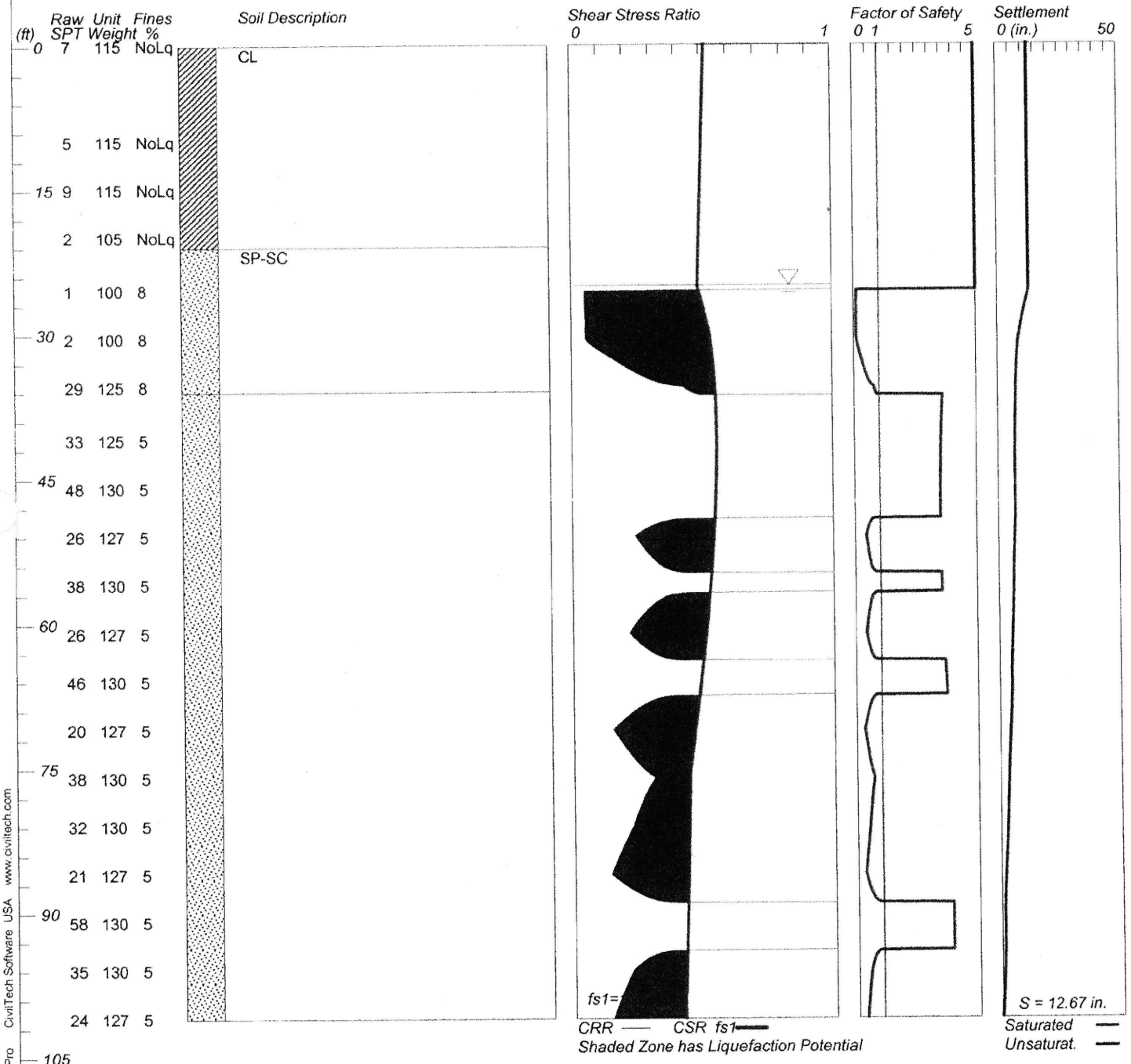


LIQUEFACTION ANALYSIS (ALT.A)

110401

Hole No.=1 Water Depth=25 ft Surface Elev.=223.6

Magnitude=7.5
Acceleration=0.800g



BN-R1, Crittenden County

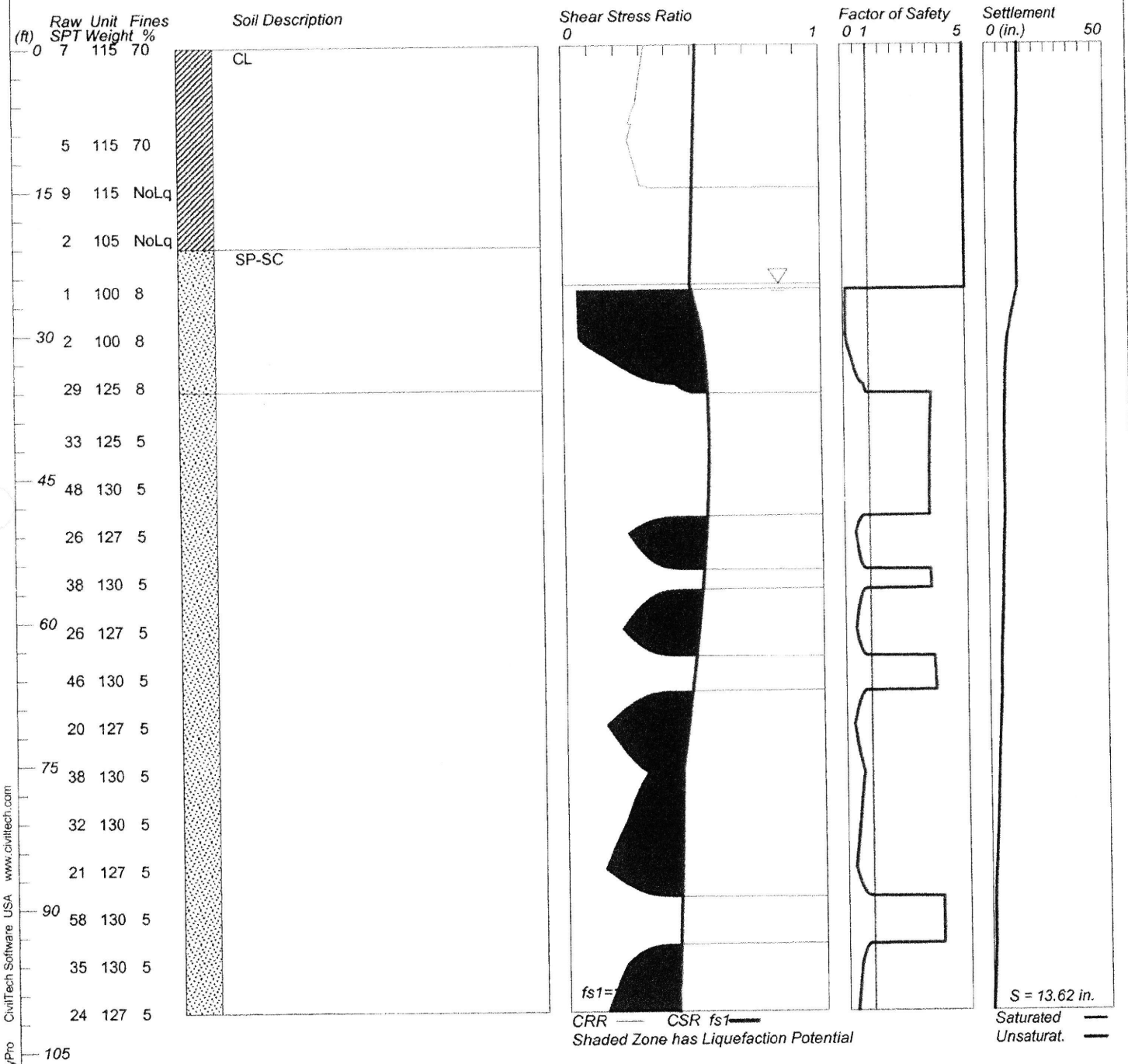
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110401

Hole No.=1 Water Depth=25 ft Surface Elev.=223.6

Magnitude=7.5
Acceleration=0.800g



BN-R1, Crittenden County

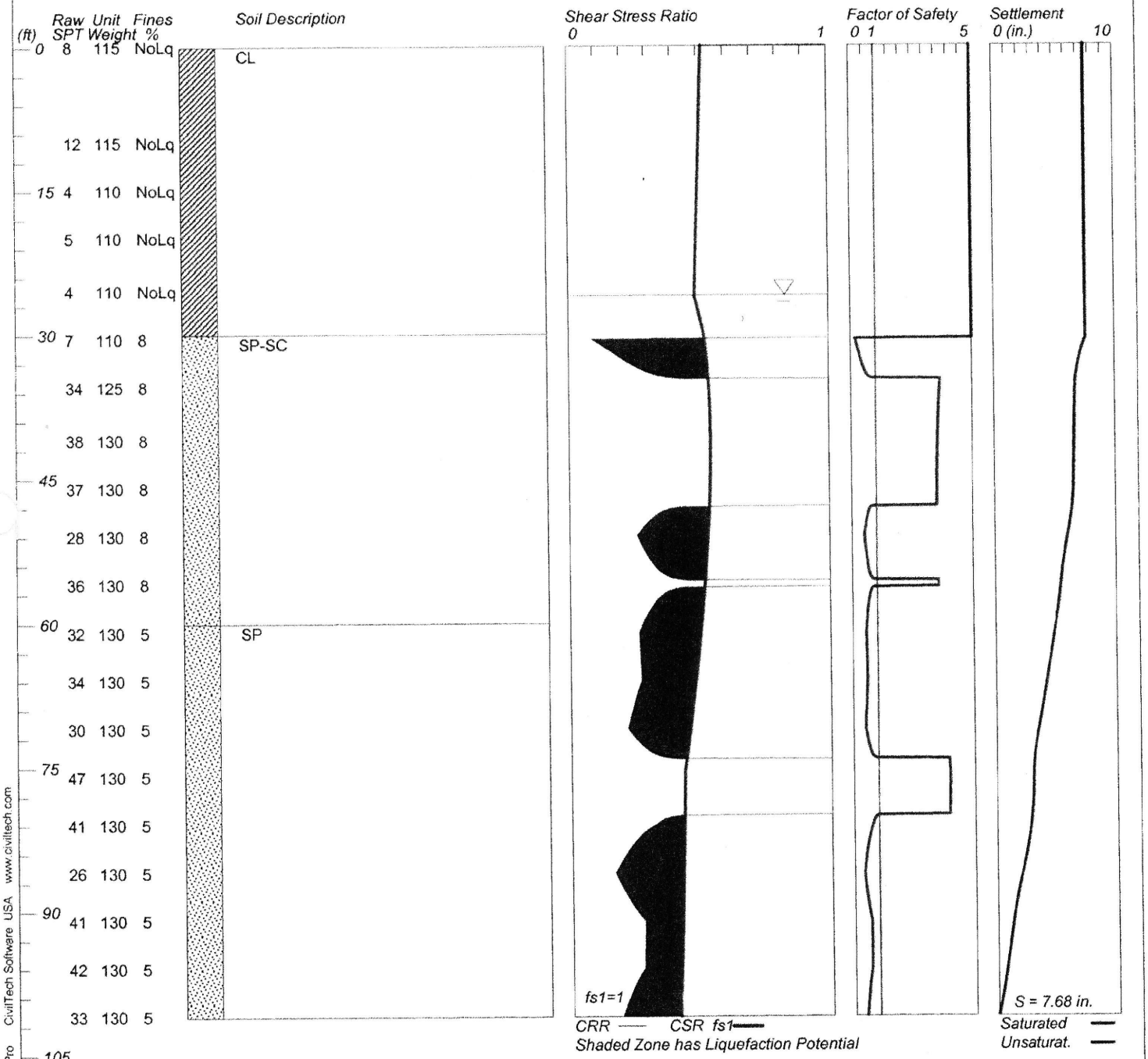
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110401

Hole No.=2 Water Depth=26 ft Surface Elev.=223.8

Magnitude=7.5
Acceleration=0.800g



BN-R2, Crittenden County

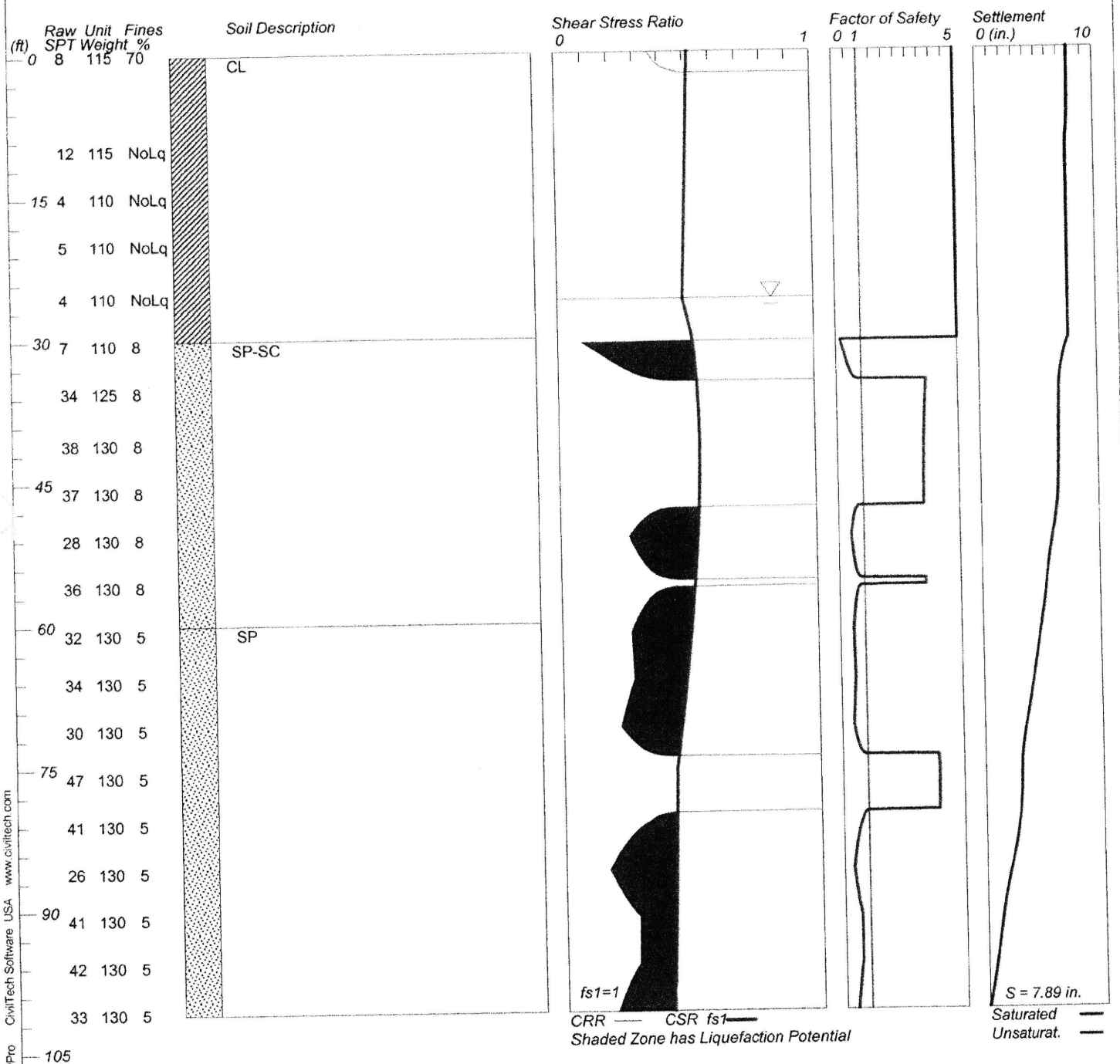
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110401

Hole No.=2 Water Depth=26 ft Surface Elev.=223.8

Magnitude=7.5
Acceleration=0.800g



BN-R2, Crittenden County

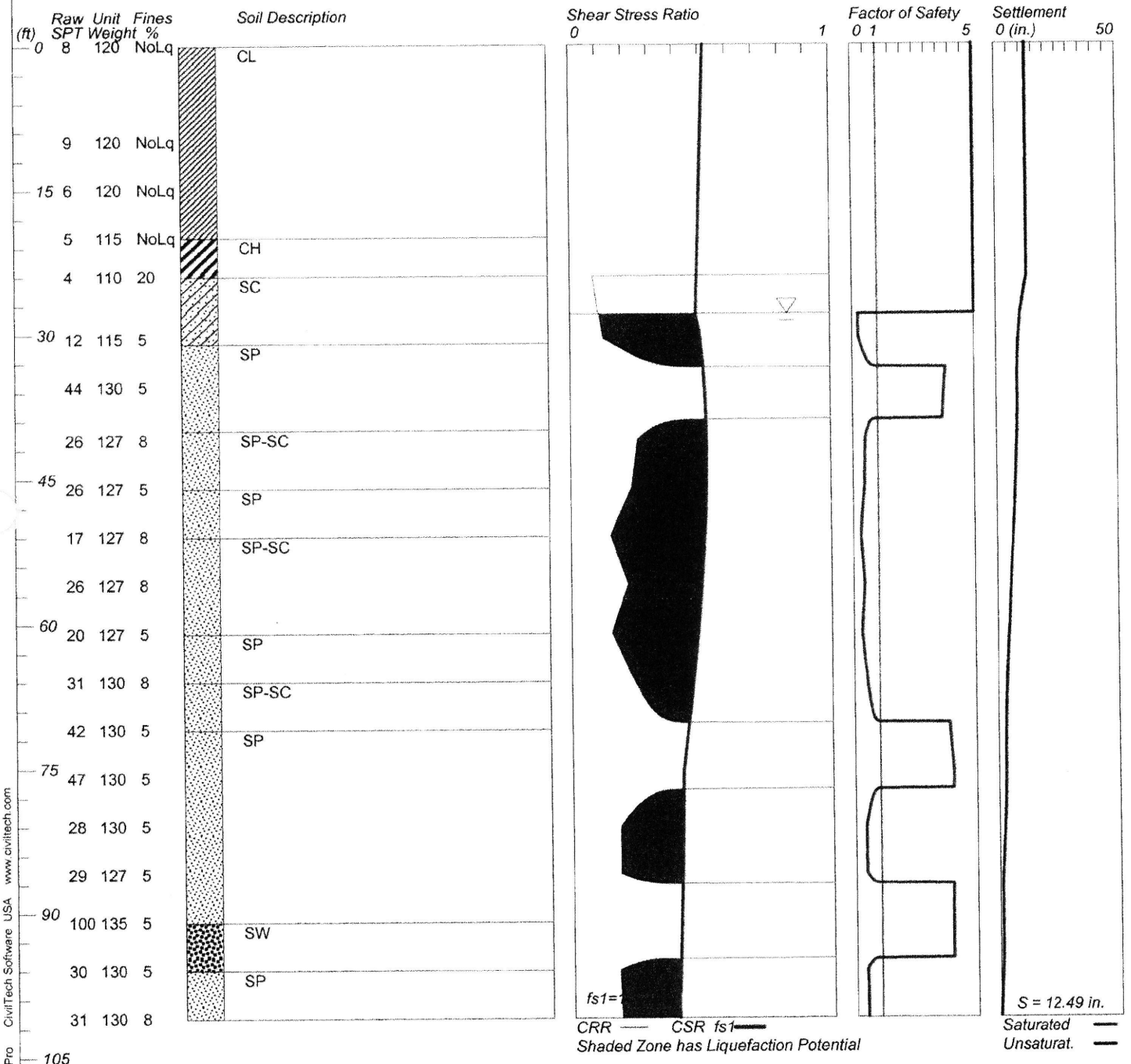
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110401

Hole No.=3 Water Depth=28 ft Surface Elev.=223.4

Magnitude=7.5
Acceleration=0.800g



BN-R3, Crittenden County

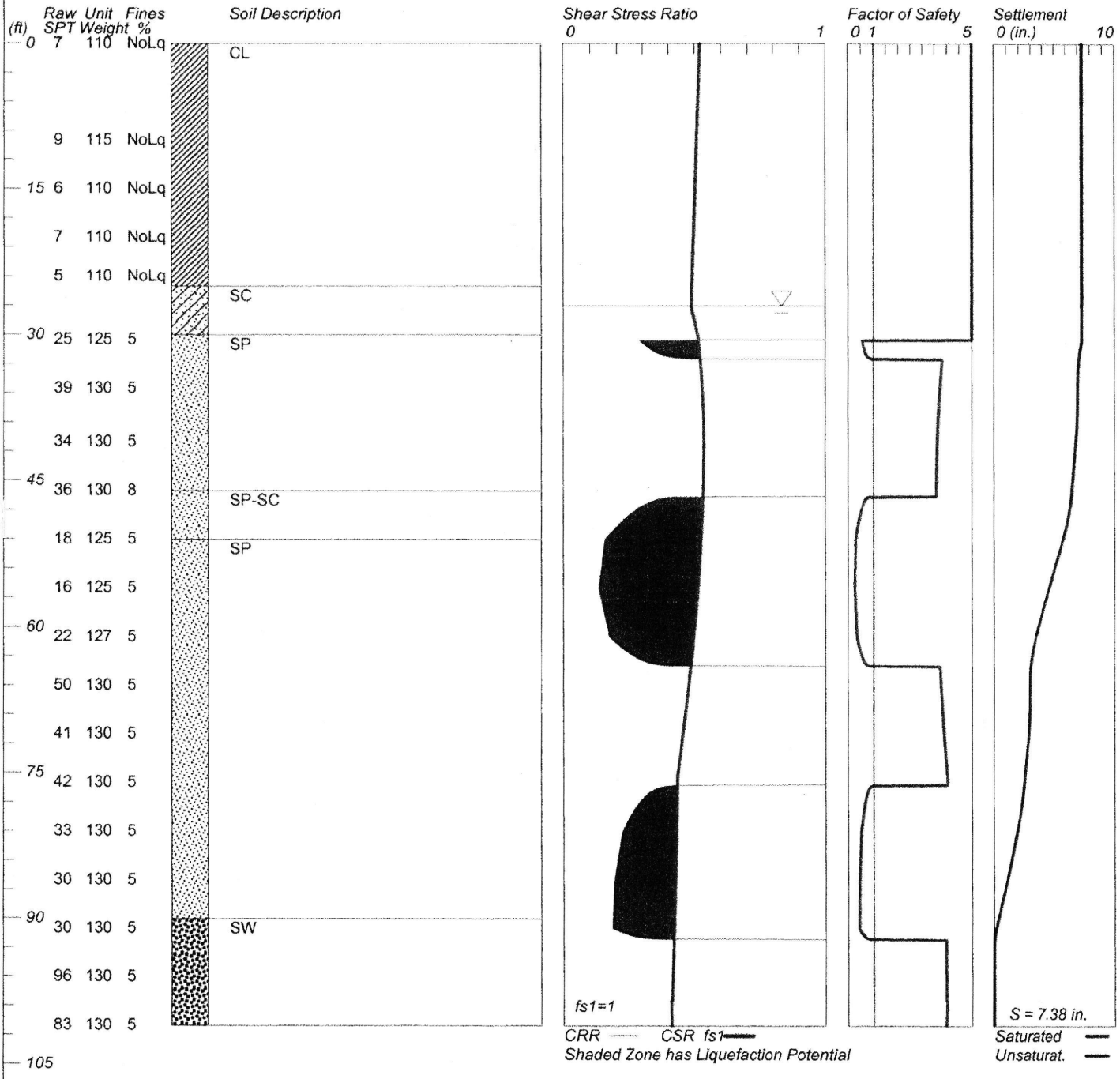
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110401

Hole No.=4 Water Depth=27 ft Surface Elev.=222.3

Magnitude=7.5
Acceleration=0.800g



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BN-R4, Crittenden County

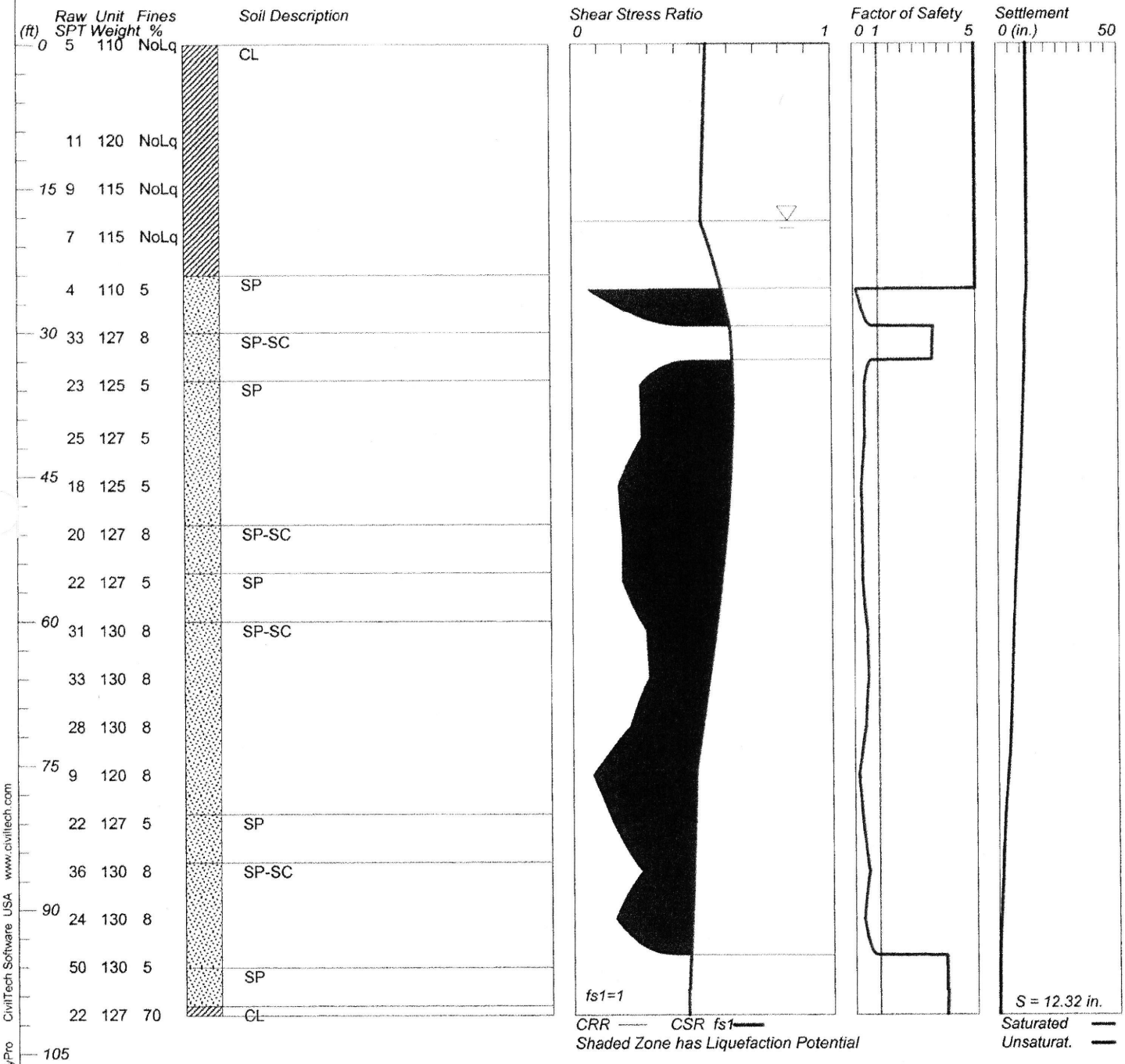
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110401

Hole No.=5 Water Depth=18.5 ft Surface Elev.=221.4

Magnitude=7.5
Acceleration=0.800g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-R5, Crittenden County

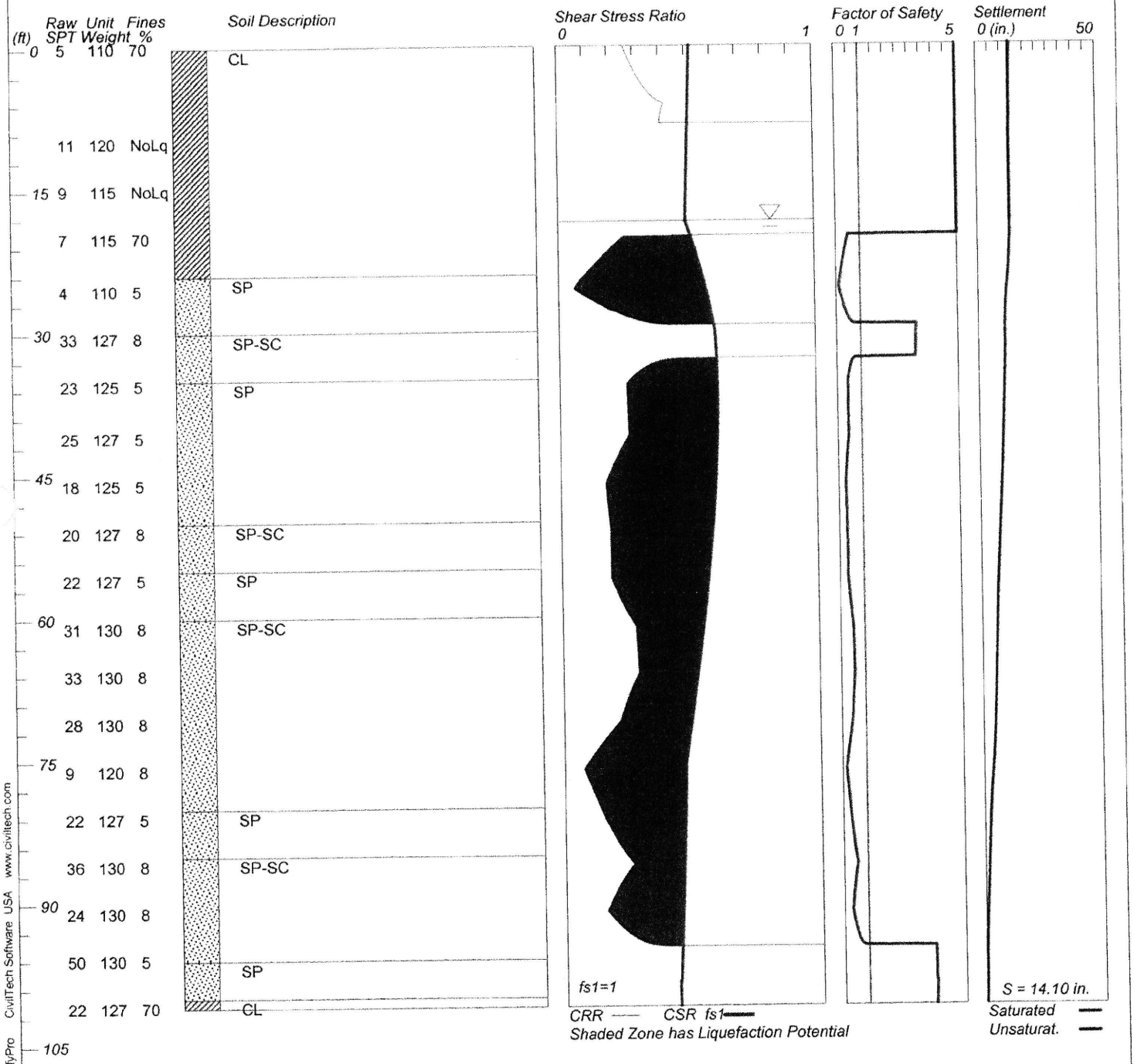
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110401

Hole No.=5 Water Depth=18.5 ft Surface Elev.=221.4

Magnitude=7.5
Acceleration=0.800g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-R5, Crittenden County

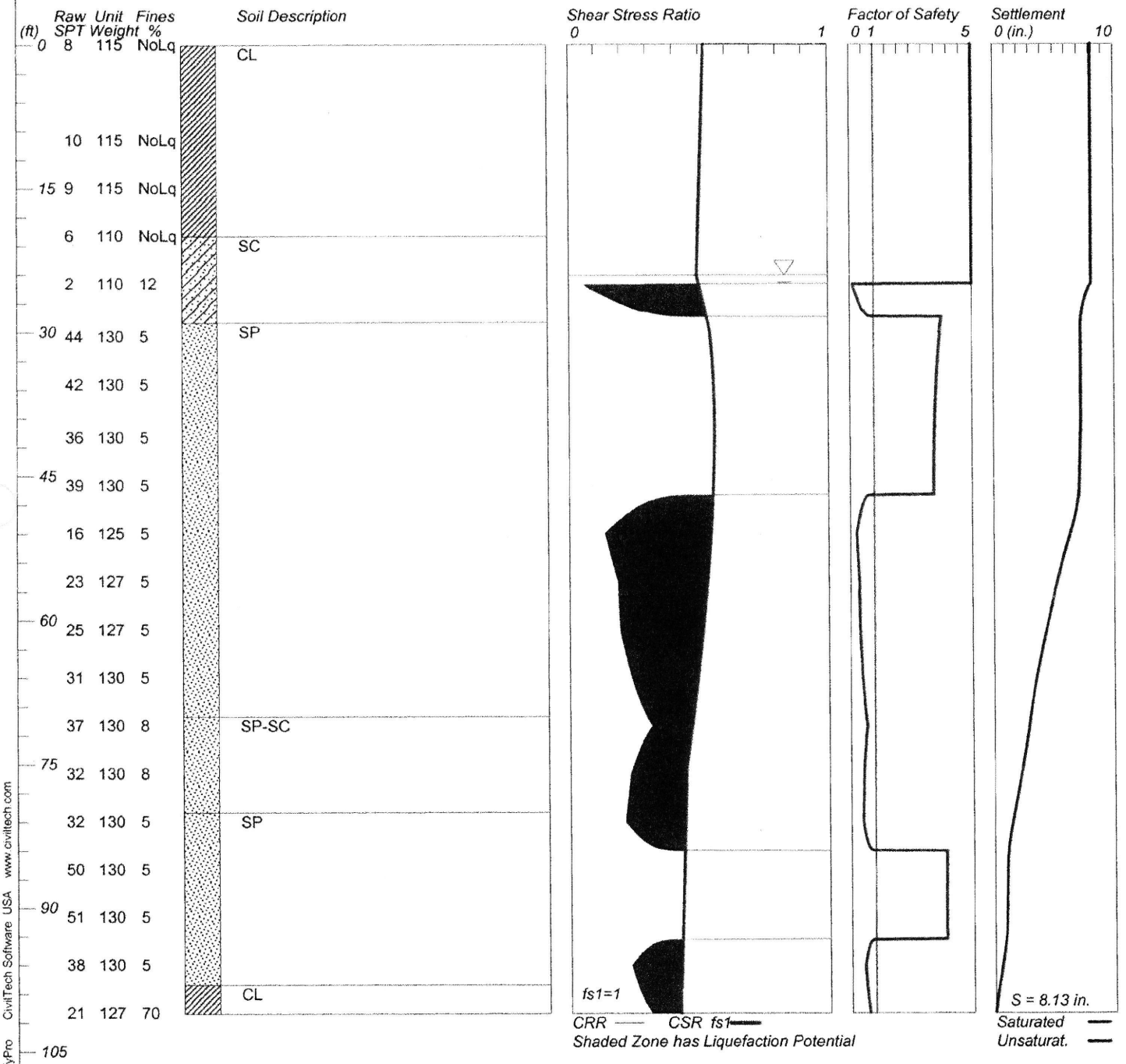
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110401

Hole No.=6 Water Depth=24.1 ft Surface Elev.=220.7

Magnitude=7.5
Acceleration=0.800g



BN-R6, Crittenden County

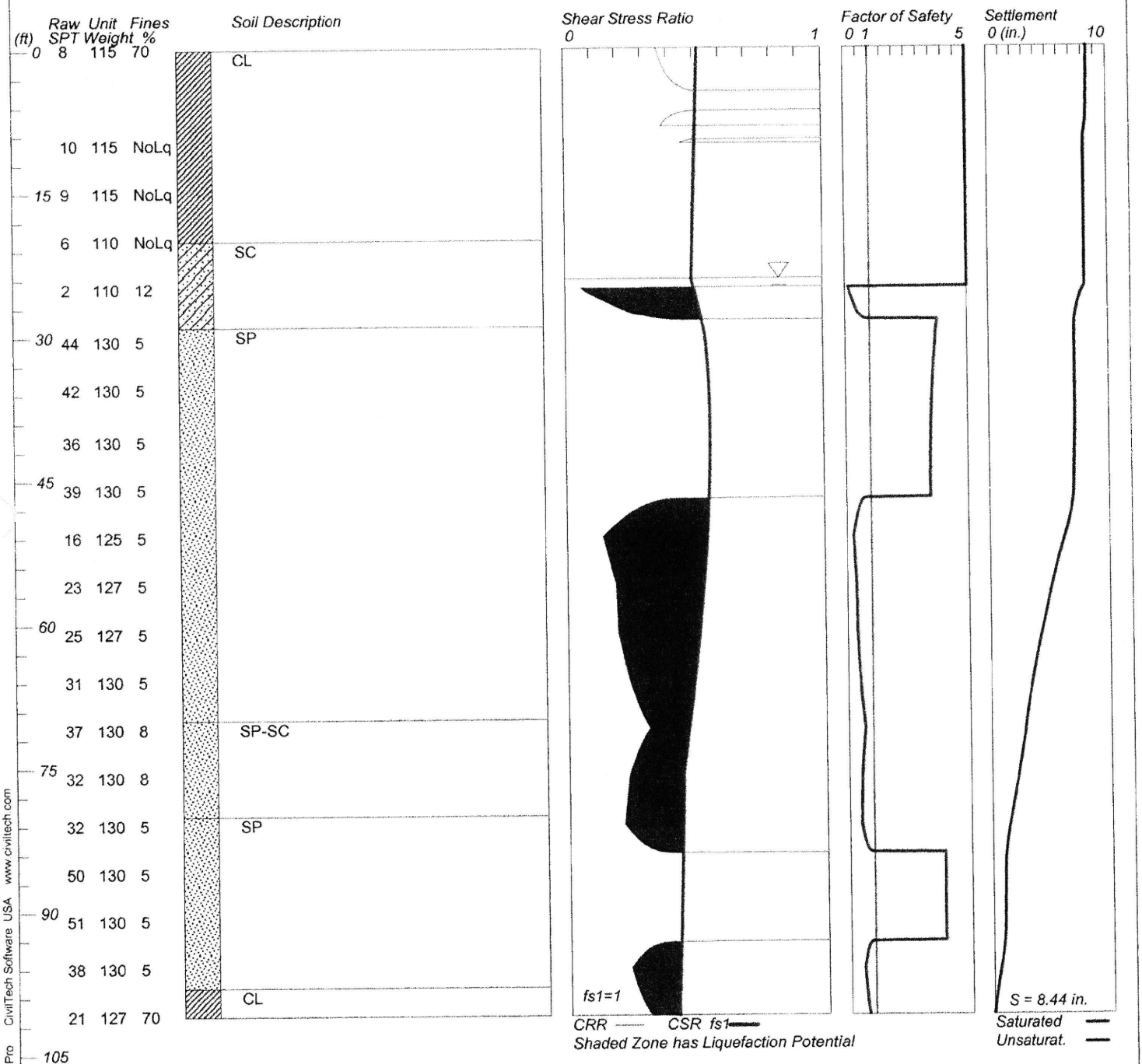
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110401

Hole No.=6 Water Depth=24.1 ft Surface Elev.=220.7

Magnitude=7.5
Acceleration=0.800g



BN-R6, Crittenden County

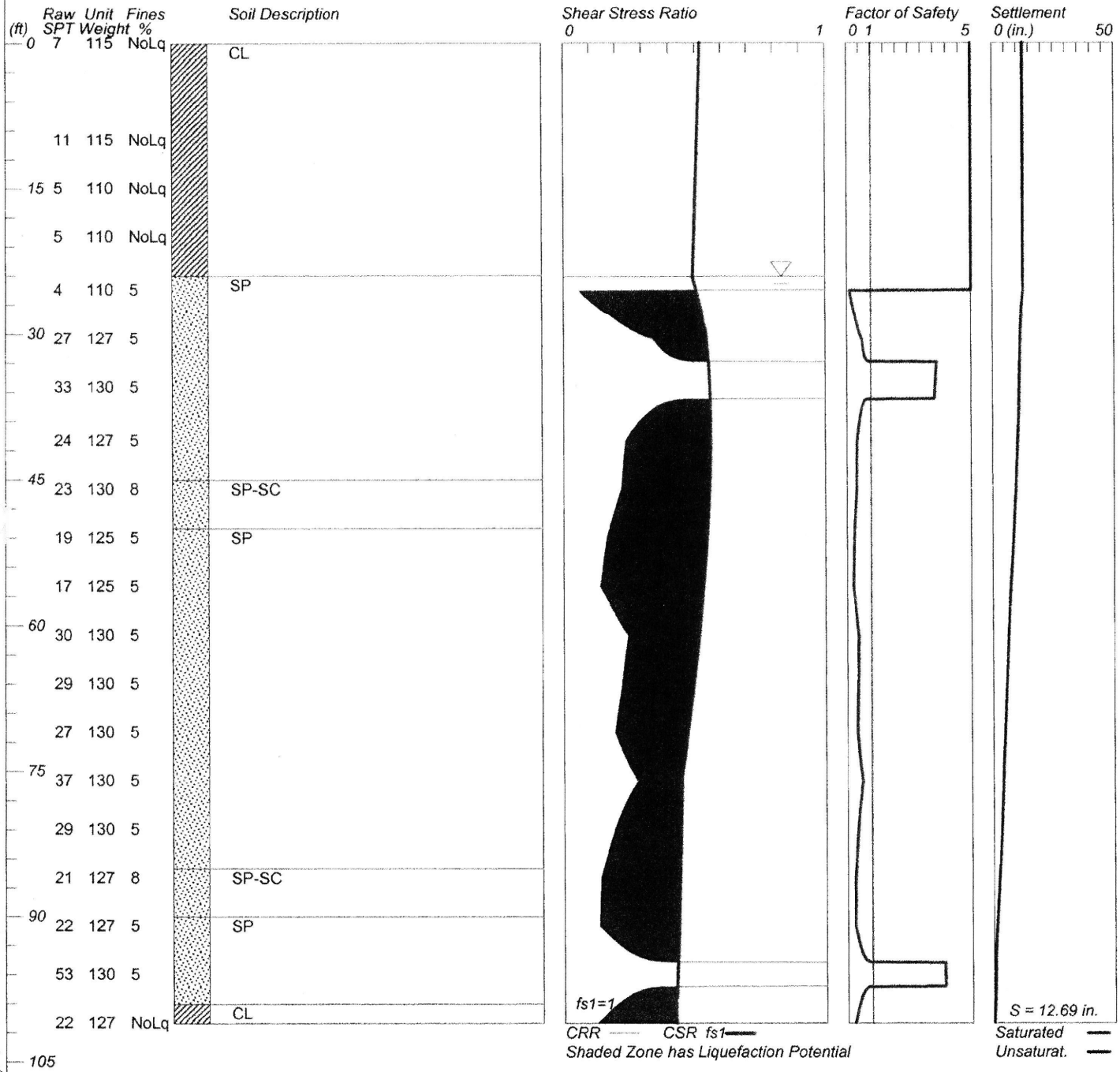
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110401

Hole No.=7 Water Depth=24.1 ft Surface Elev.=220.8

Magnitude=7.5
Acceleration=0.800g



BN-R7, Crittenden County

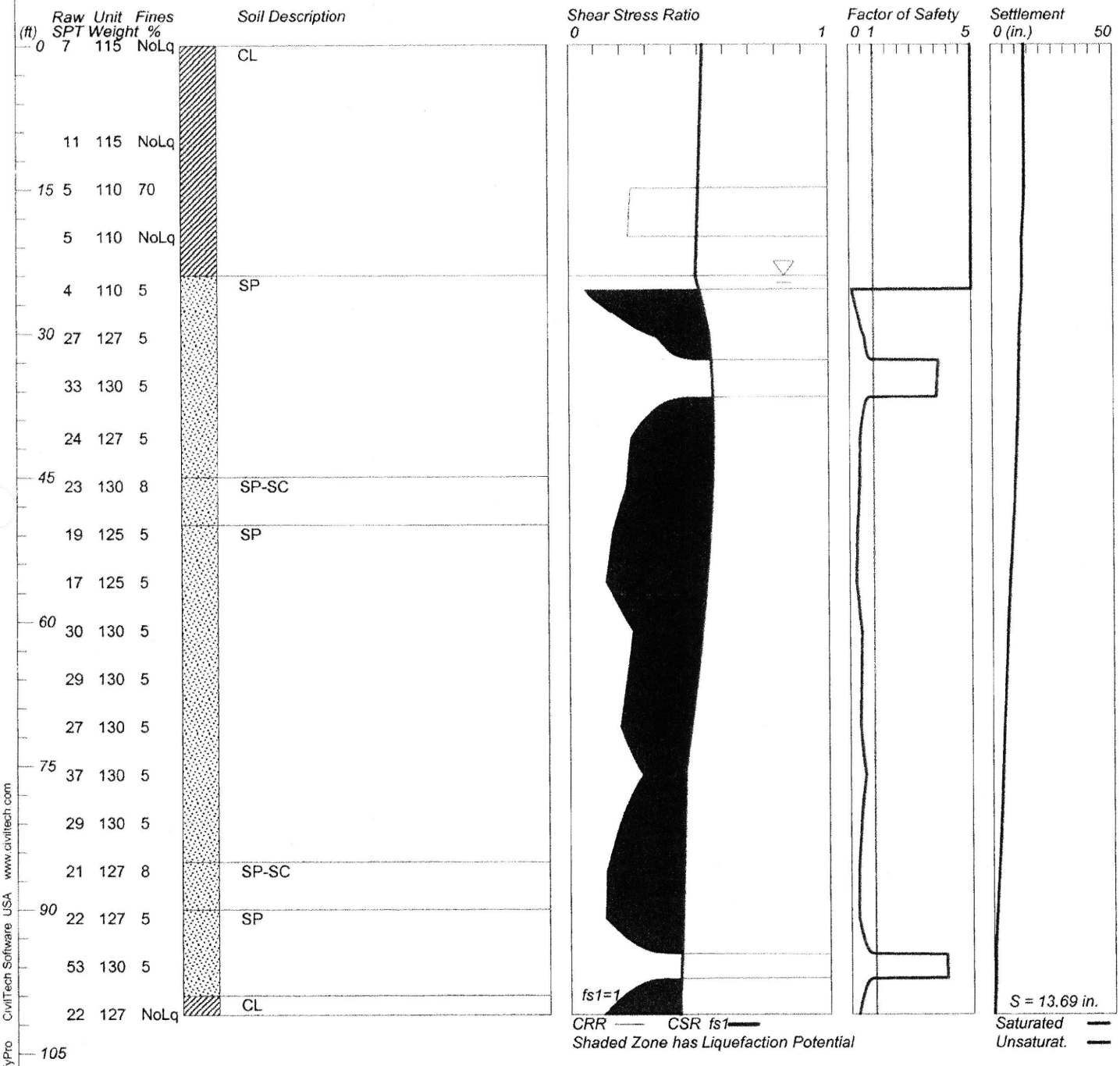
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110401

Hole No.=7 Water Depth=24.1 ft Surface Elev.=220.8

Magnitude=7.5
Acceleration=0.800g



BN-R7, Crittenden County

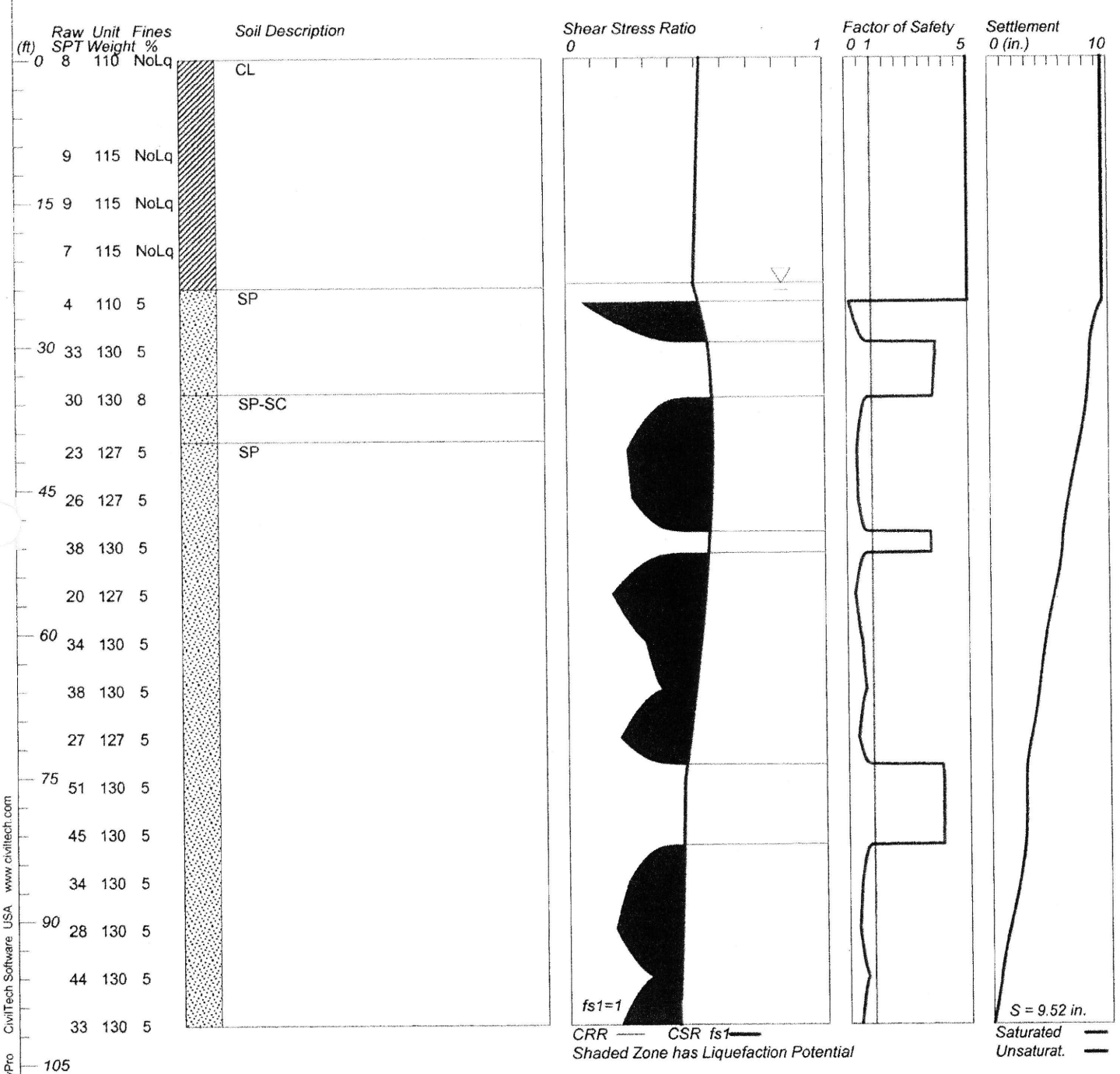
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110401

Hole No.=9 Water Depth=23.6 ft Surface Elev.=221.2

Magnitude=7.5
Acceleration=0.800g



BN-R9, Crittenden County

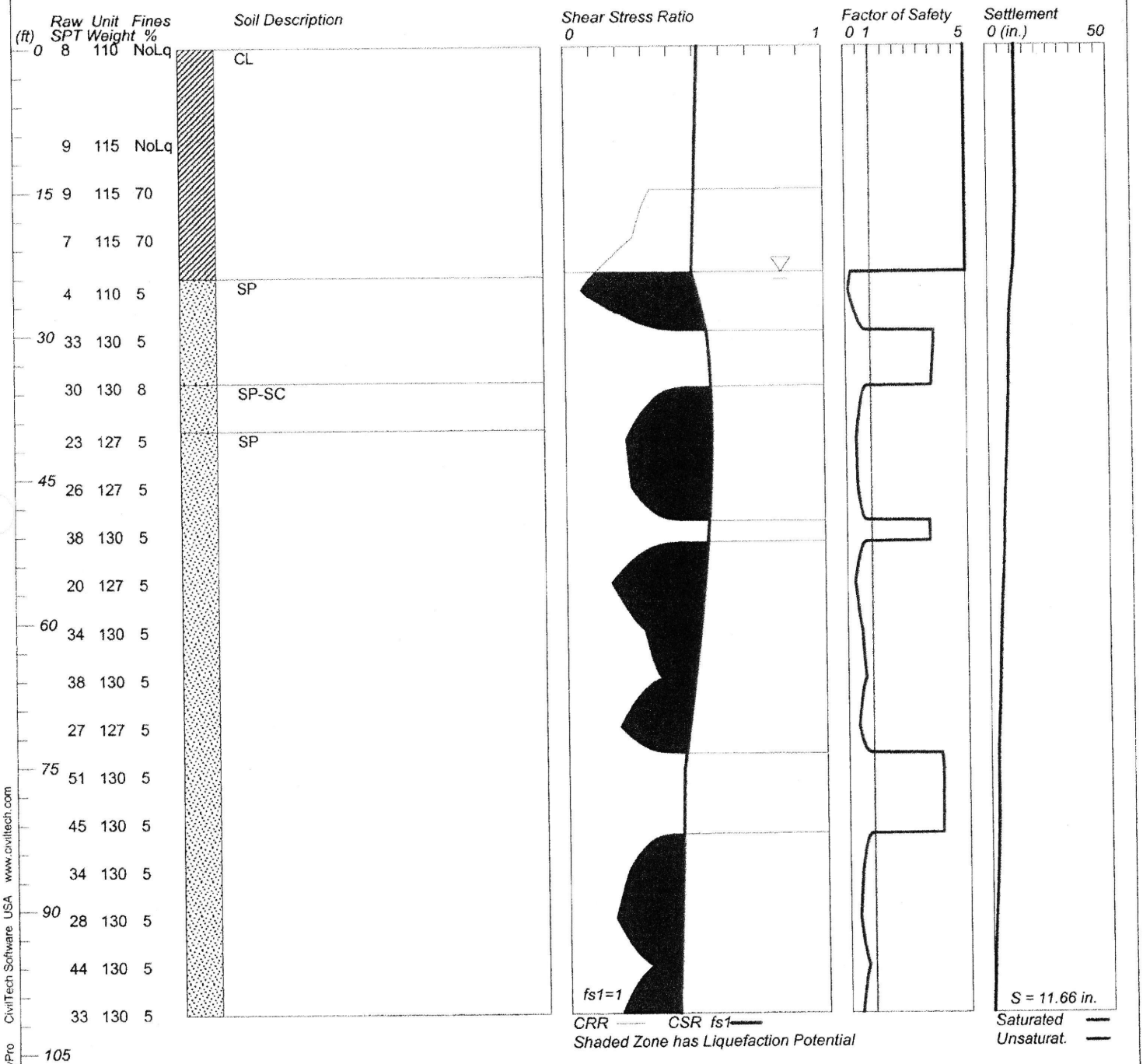
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110401

Hole No.=9 Water Depth=23.6 ft Surface Elev.=221.2

Magnitude=7.5
Acceleration=0.800g



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BN-R9, Crittenden County

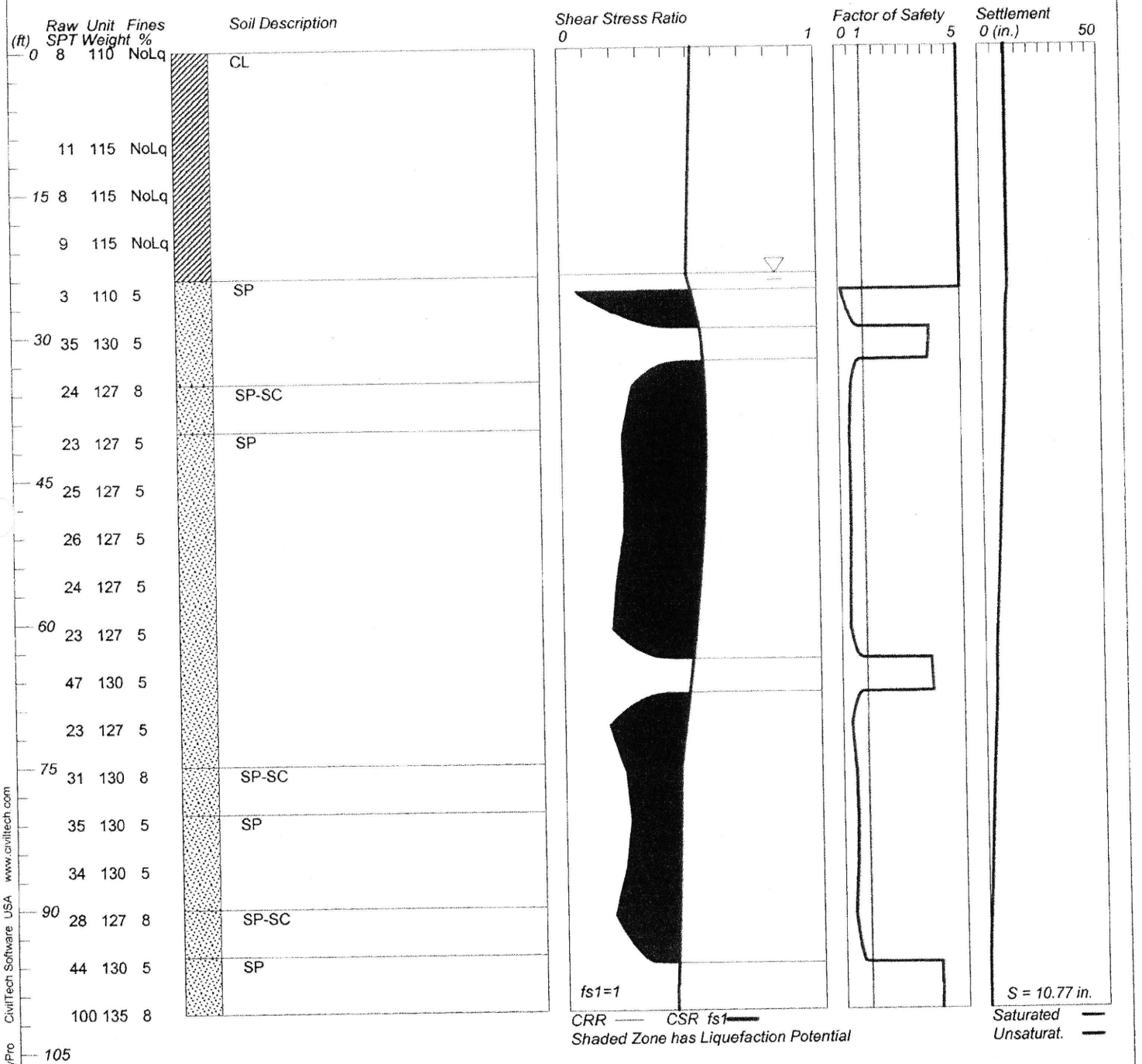
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110401

Hole No.=8 Water Depth=23.8 ft Surface Elev.=221.1

Magnitude=7.5
Acceleration=0.800g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-R8, Crittenden County

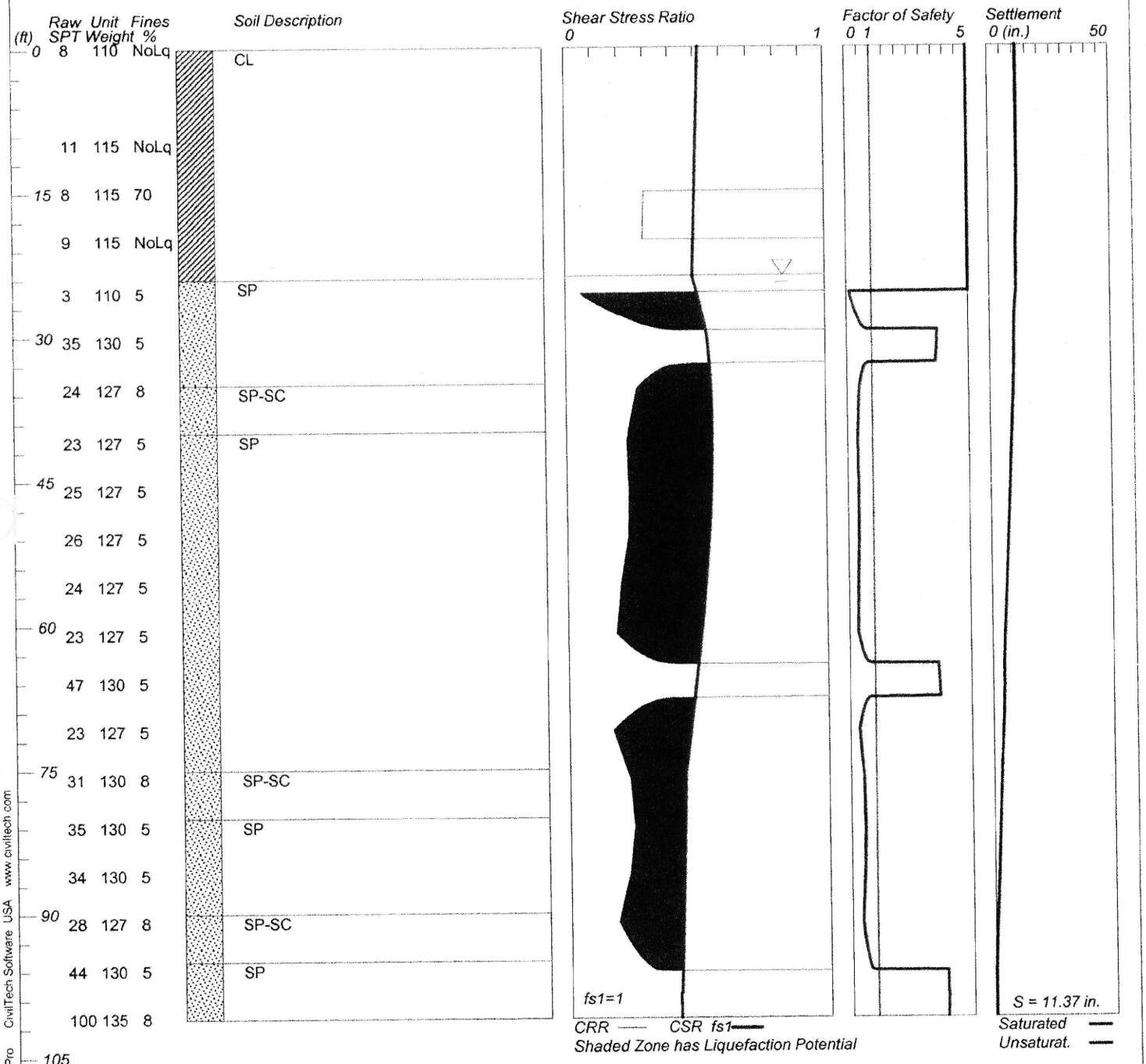
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110401

Hole No.=8 Water Depth=23.8 ft Surface Elev.=221.1

Magnitude=7.5
Acceleration=0.800g



BN-R8, Crittenden County

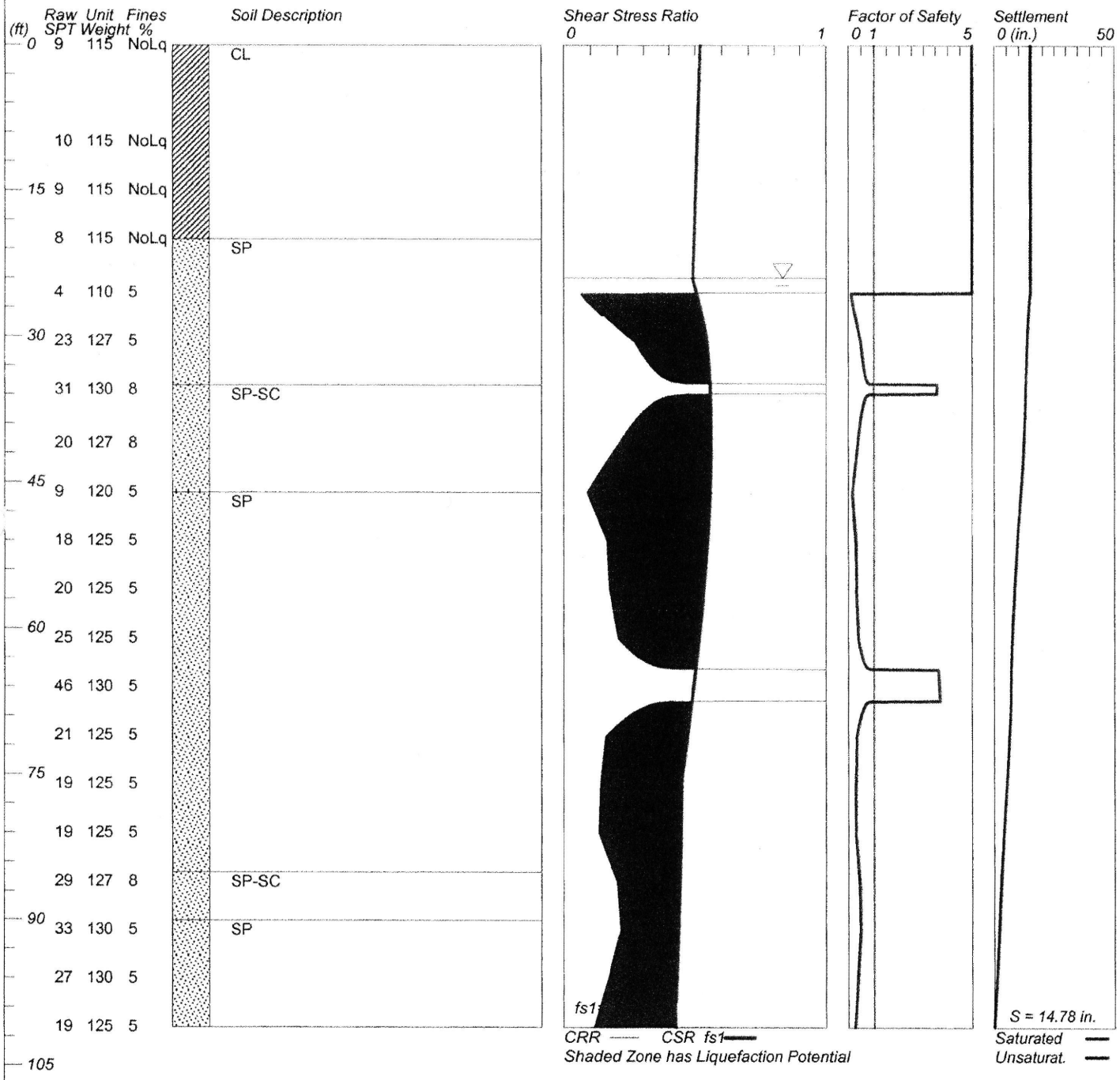
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110401

Hole No.=10 Water Depth=24.0 ft Surface Elev.=220.9

Magnitude=7.5
Acceleration=0.800g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-R10, Crittenden County

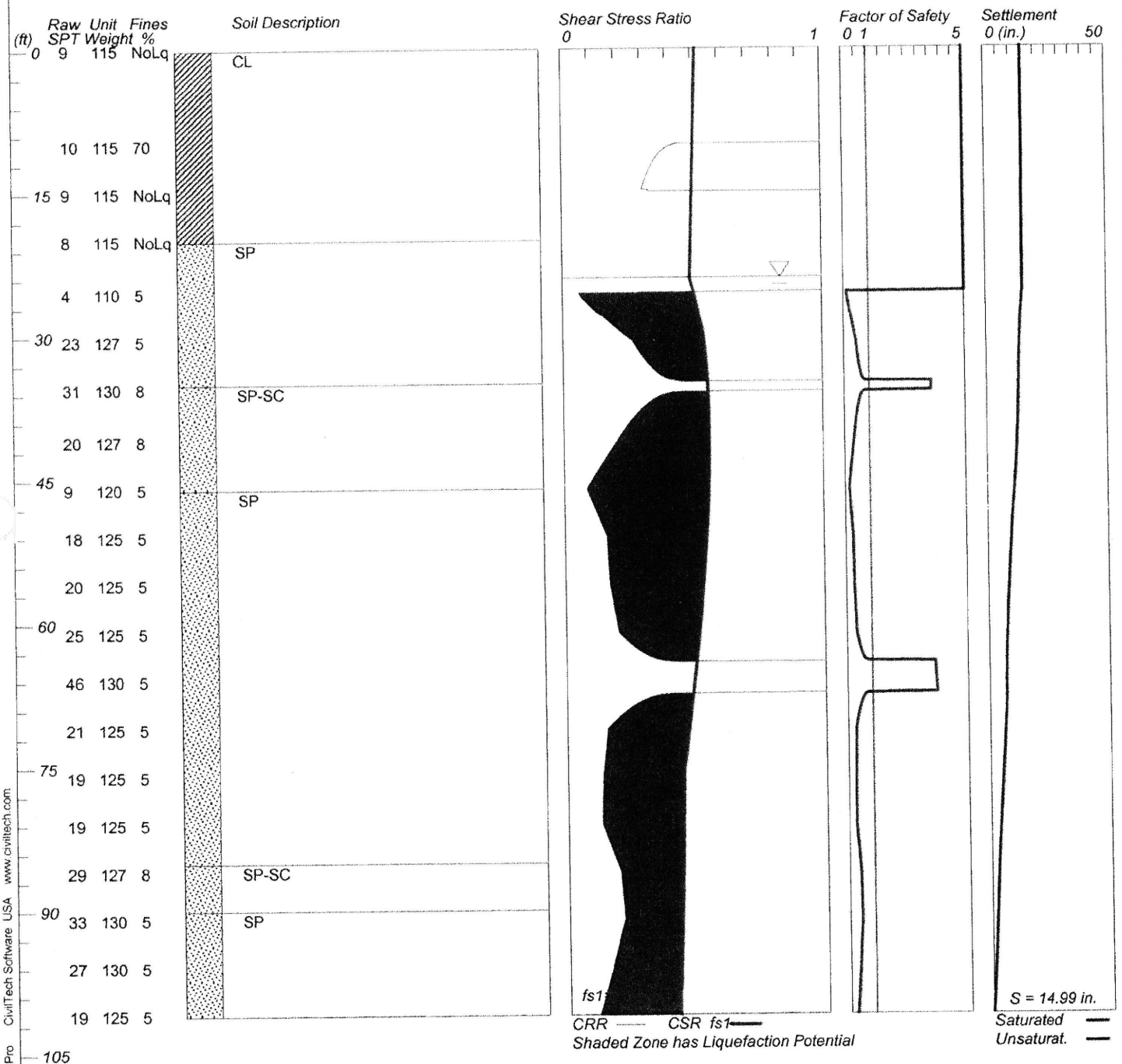
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110401

Hole No.=10 Water Depth=24.0 ft Surface Elev.=220.9

Magnitude=7.5
Acceleration=0.800g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-R10, Crittenden County

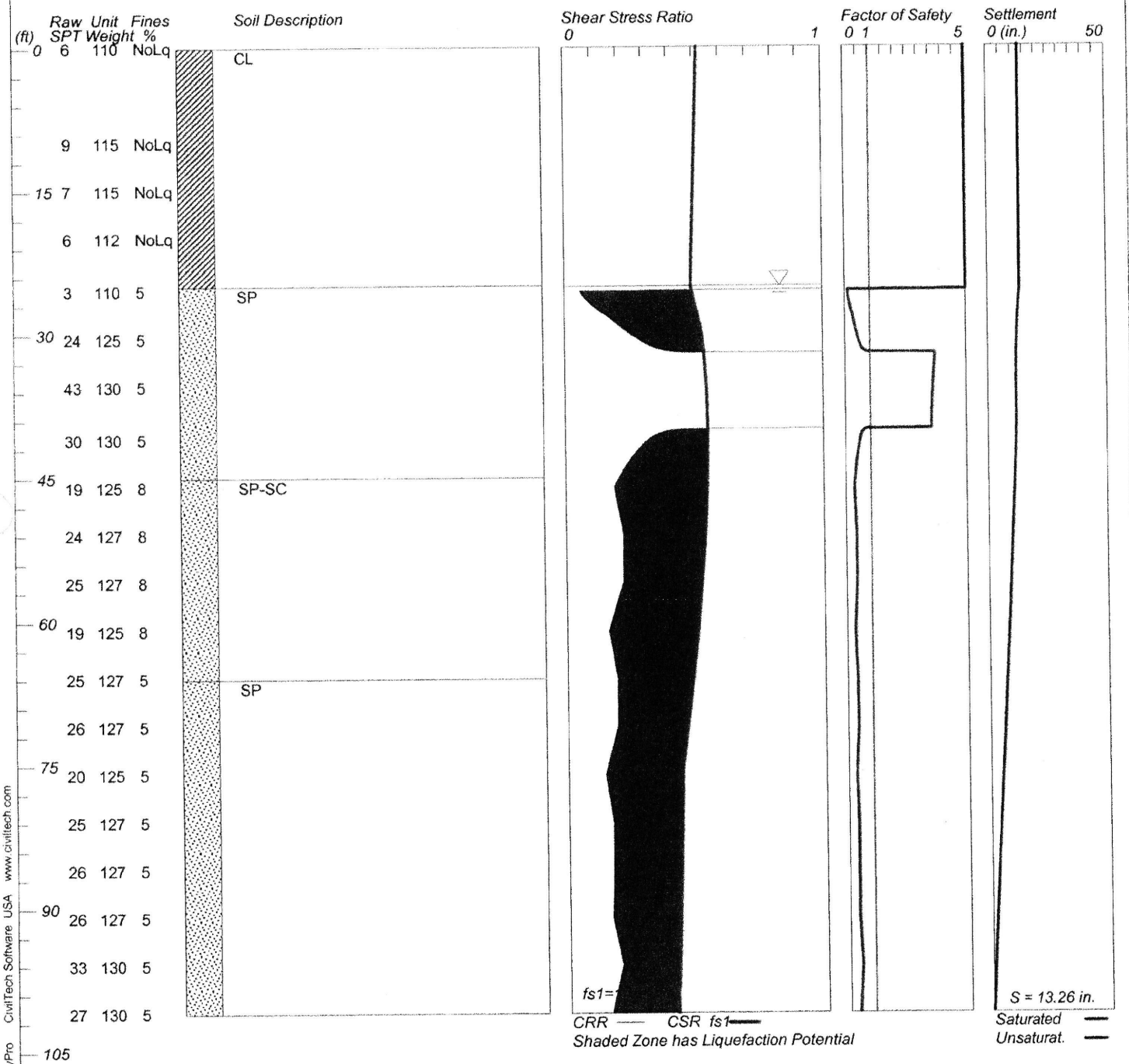
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110401

Hole No.=11 Water Depth=25.1 ft Surface Elev.=222.8

Magnitude=7.5
Acceleration=0.800g



BN-R11, Crittenden County

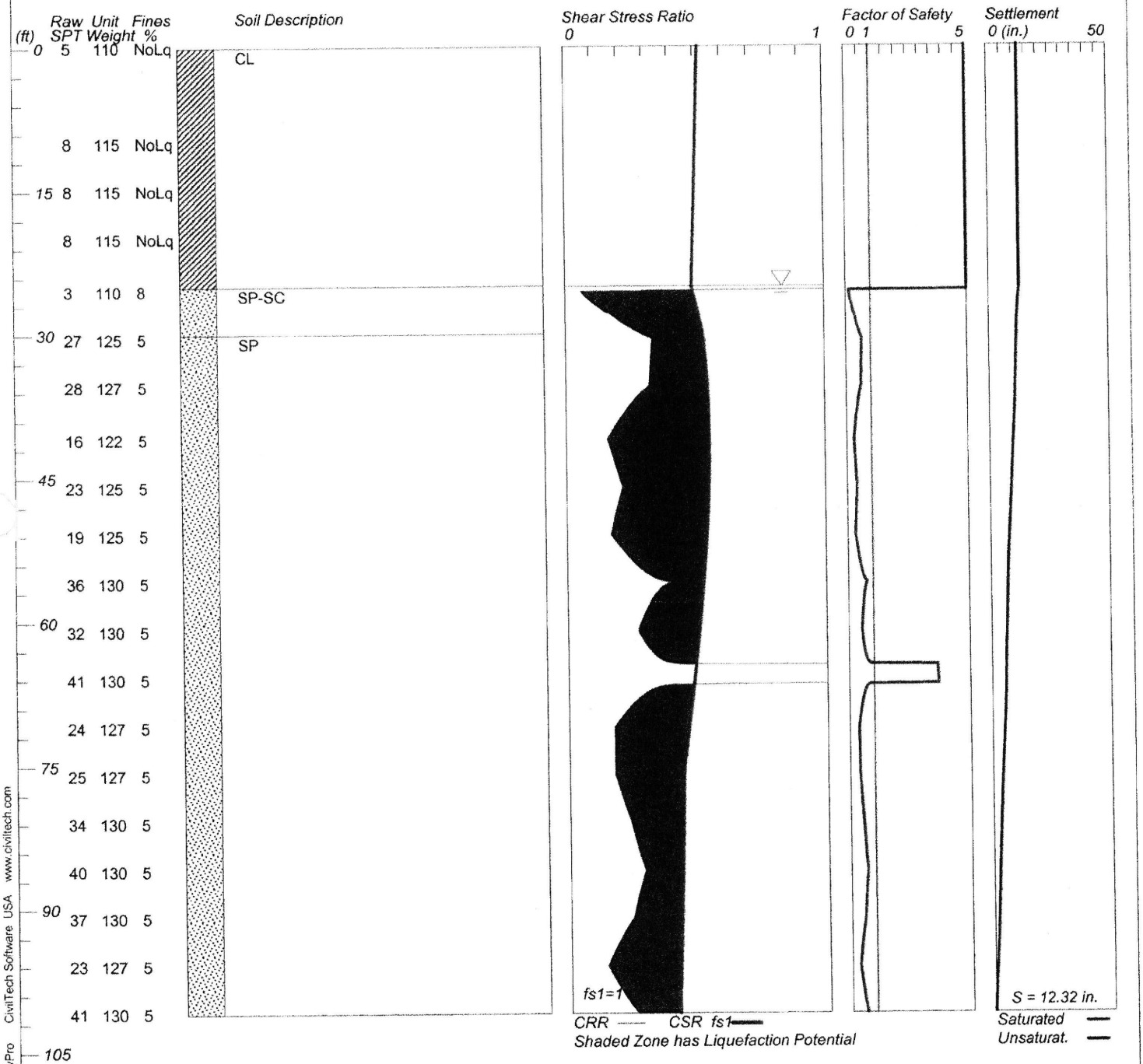
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110401

Hole No.=12 Water Depth=25.1 ft Surface Elev.=223.5

Magnitude=7.5
Acceleration=0.800g



BN-R12, Crittenden County

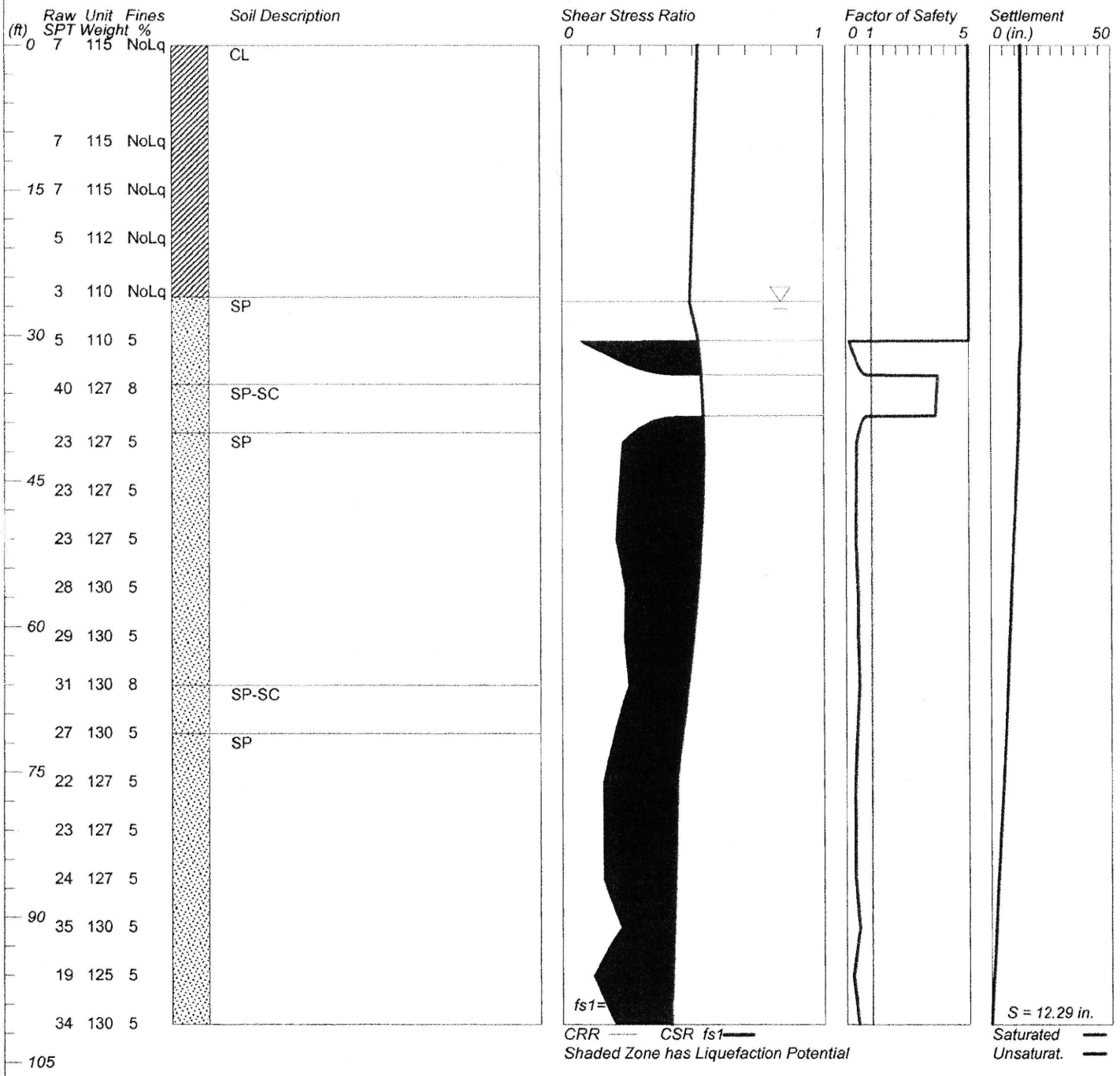
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110401

Hole No.=13 Water Depth=26.5 ft Surface Elev.=225.5

Magnitude=7.5
Acceleration=0.800g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-R13, Crittenden County

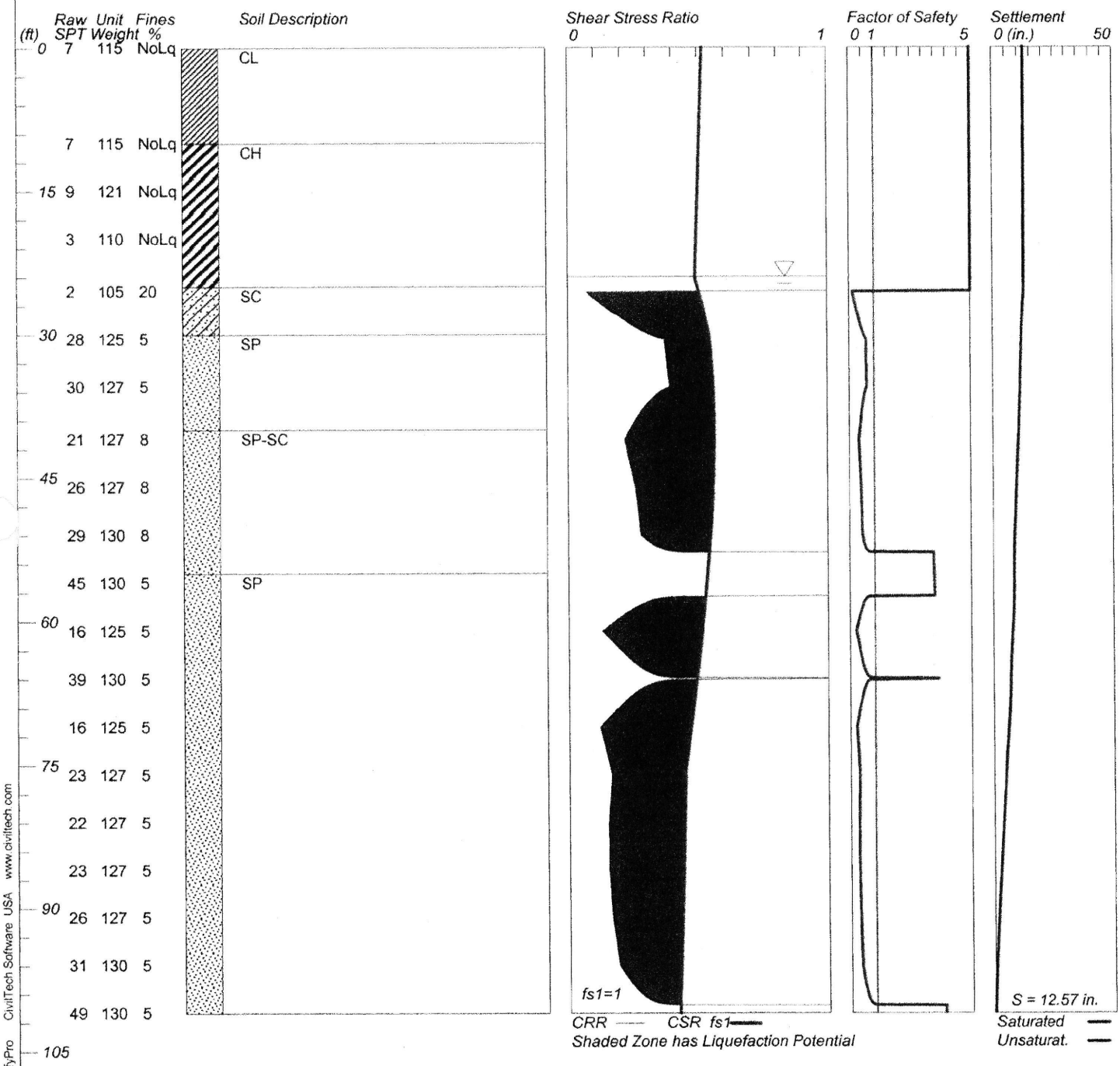
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110401

Hole No.=14 Water Depth=24.0 ft Surface Elev.=222.4

Magnitude=7.5
Acceleration=0.800g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-R14, Crittenden County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-110401

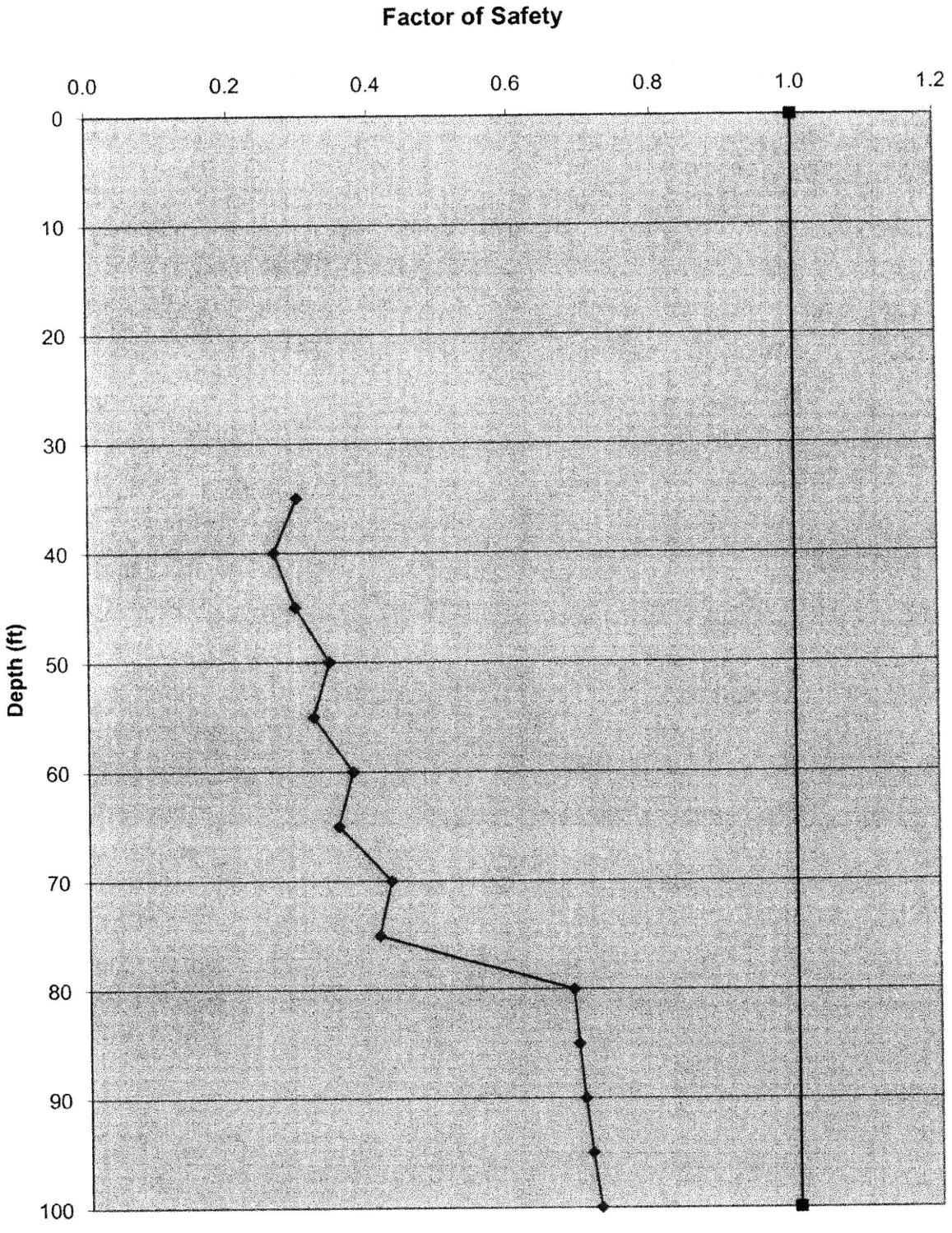
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		
PGA =	0.8	g	
depth to groundwater during drilling =	25	ft	
estimated age of sand deposit =	2000	years	
depth to finish floor =	0	ft	
uniform floor load =	0	lb/ft^2	
assumed depth to groundwater =	25	ft	

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	115	459	70	0	575	575	575	0.988	0.5139	627	NA	1.00	1.00	NA	NA
10	1	115	492	93	0	1150	1150	1150	0.977	0.5079	565	NA	1.00	1.00	NA	NA
15	1	110	427	93	26	1700	1700	1700	0.965	0.5018	445	NA	1.00	1.00	NA	NA
20	1	110	558	93	26	2250	2250	2250	0.953	0.4957	542	NA	1.00	1.00	NA	NA
25	1	110	656	93	26	2800	2800	2800	0.942	0.4897	603	NA	1.00	1.00	NA	NA
30	1	110	656	97	22	3350	3038	3038	0.930	0.5333	591	NA	1.00	1.00	NA	NA
35	2	125	722	8	0	3975	3351	3351	0.889	0.5483	635	0.1628	1.00	1.00	0.162796	0.3
40	2	130	722	8	0	4625	3689	3689	0.848	0.5530	620	0.1456	1.00	1.00	0.145578	0.3
45	2	130	755	8	0	5275	4027	4027	0.808	0.5501	634	0.1618	1.00	1.00	0.161725	0.3
50	2	130	787	8	0	5925	4365	4365	0.767	0.5413	647	0.1846	1.00	1.00	0.184602	0.3
55	2	130	820	5	0	6575	4703	4703	0.726	0.5279	662	0.1682	1.00	1.00	0.168154	0.3
60	2	130	853	5	0	7225	5041	5041	0.685	0.5108	677	0.1904	1.00	1.00	0.190342	0.4
65	2	130	853	5	0	7875	5379	5379	0.645	0.4908	666	0.1732	1.00	1.00	0.173129	0.4
70	2	130	886	5	0	8525	5717	5717	0.604	0.4683	681	0.1994	1.00	1.00	0.199373	0.4
75	2	130	886	5	0	9175	6055	6055	0.563	0.4438	672	0.1813	1.00	1.00	0.181237	0.4
80	2	130	1017	5	0	9825	6393	6393	0.549	0.4386	761	0.3000	1.00	1.00	0.299946	0.7
85	2	130	1017	5	0	10475	6731	6731	0.537	0.4342	751	0.3000	1.00	1.00	0.299946	0.7
90	2	130	1017	5	0	11125	7069	7069	0.524	0.4291	742	0.3000	1.00	1.00	0.299946	0.7
95	2	130	1017	5	0	11775	7407	7407	0.512	0.4234	733	0.3000	1.00	1.00	0.299946	0.7
100	2	135	1083	5	0	12450	7770	7770	0.500	0.4166	771	0.3000	1.00	1.00	0.299946	0.7

Used Bore #2 for PI values & unit wt.

Vs Liquefaction Potential - Project 110401

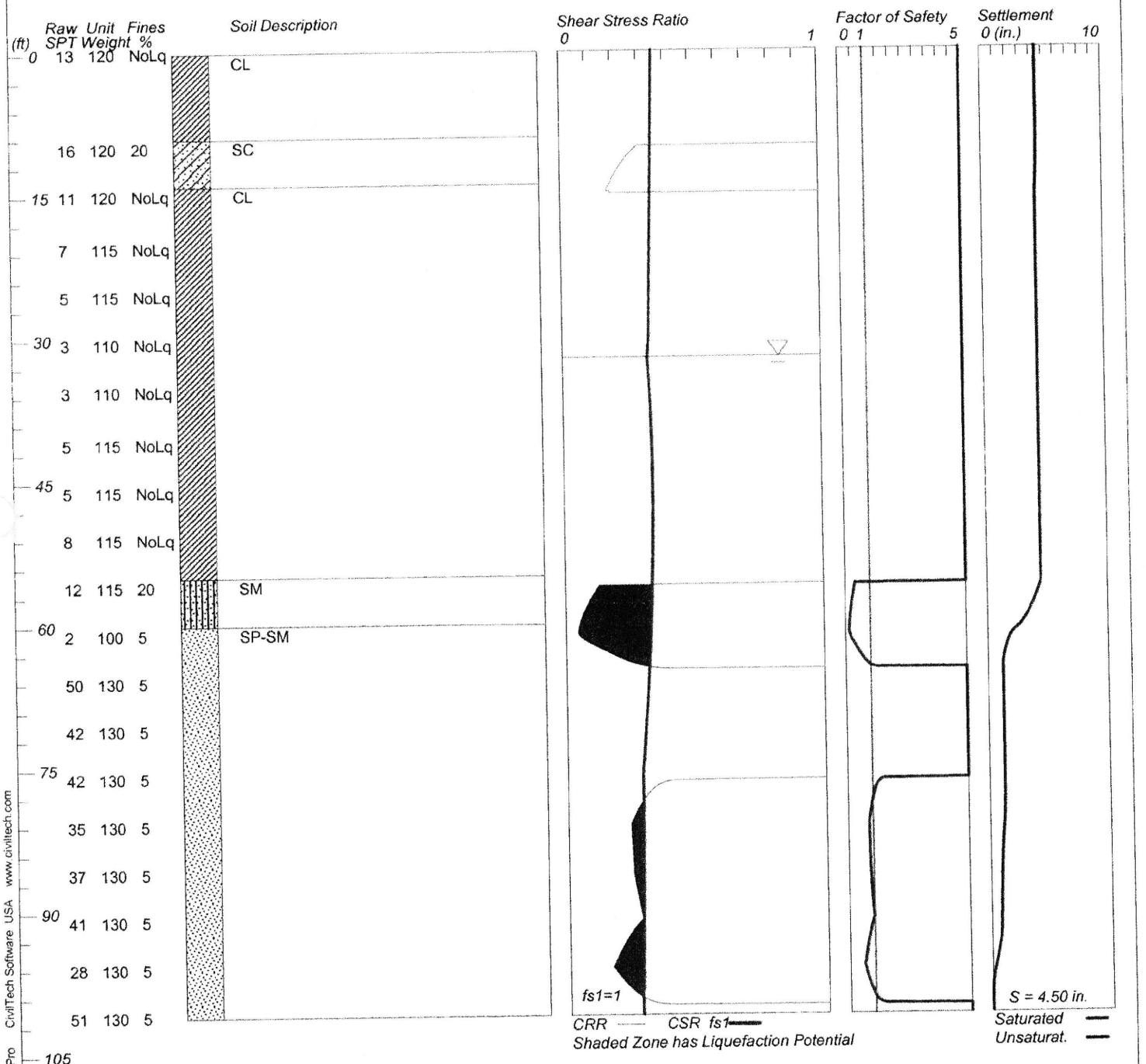


LIQUEFACTION ANALYSIS (ALT.A)

110358

Hole No.=1 Water Depth=32.2 ft Surface Elev.=231.5

Magnitude=7.5
Acceleration=0.552g



BN-1, Crittenden County

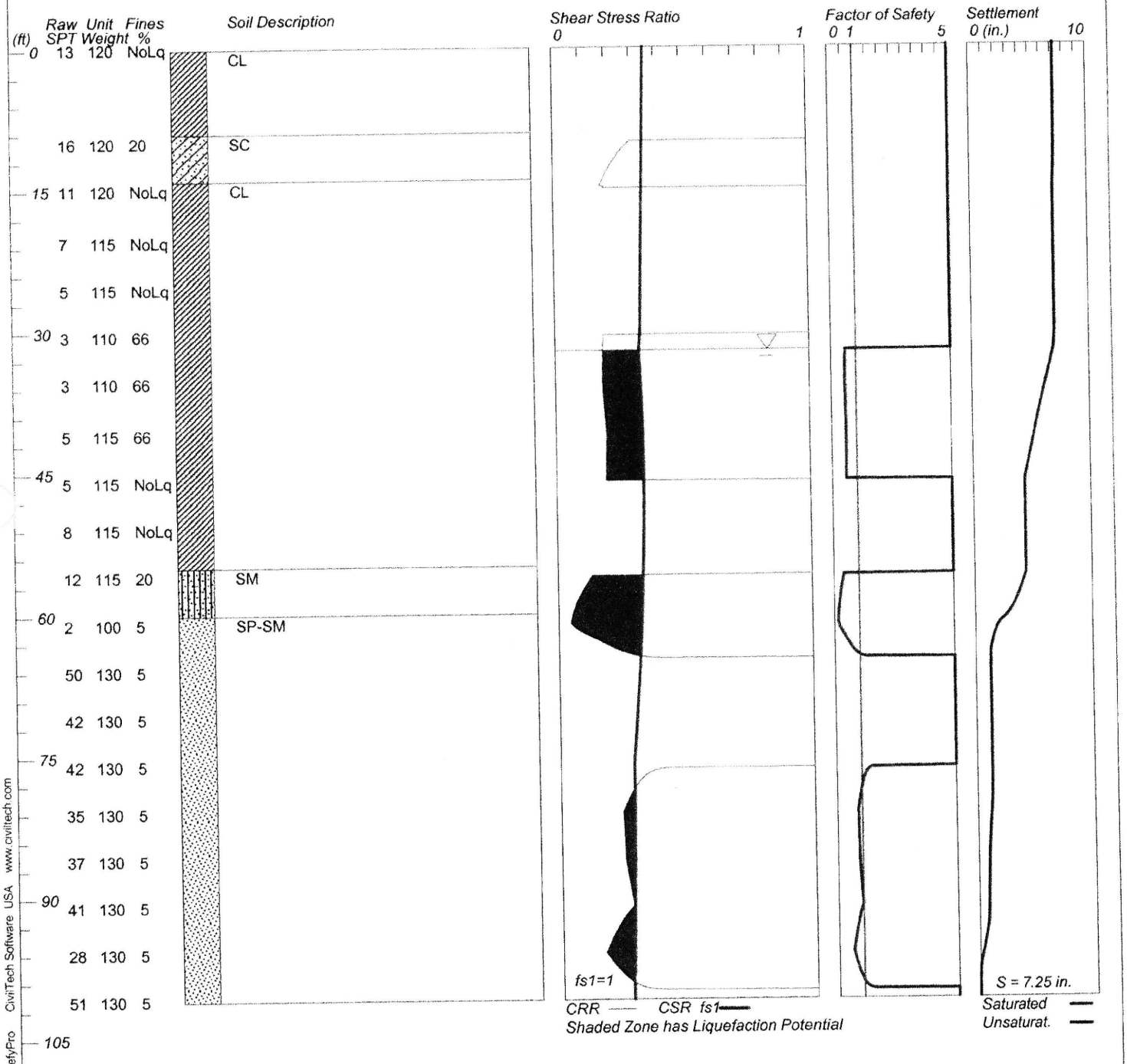
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110358

Hole No.=1 Water Depth=32.2 ft Surface Elev.=231.5

Magnitude=7.5
Acceleration=0.552g



BN-1, Crittenden County

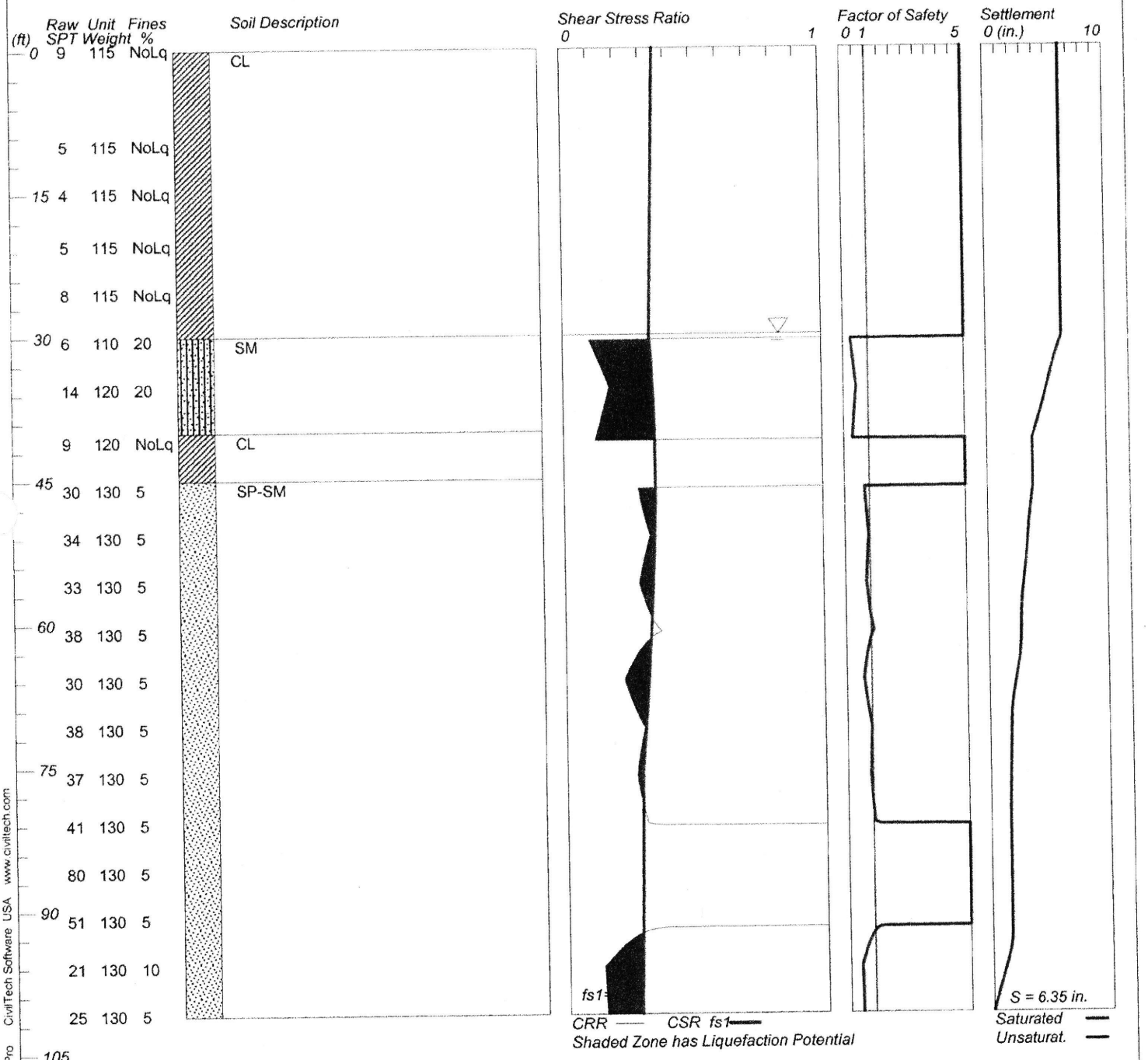
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110358

Hole No.=2 Water Depth=30.0 ft Surface Elev.=209.4

Magnitude=7.5
Acceleration=0.552g



BN-2, Crittenden County

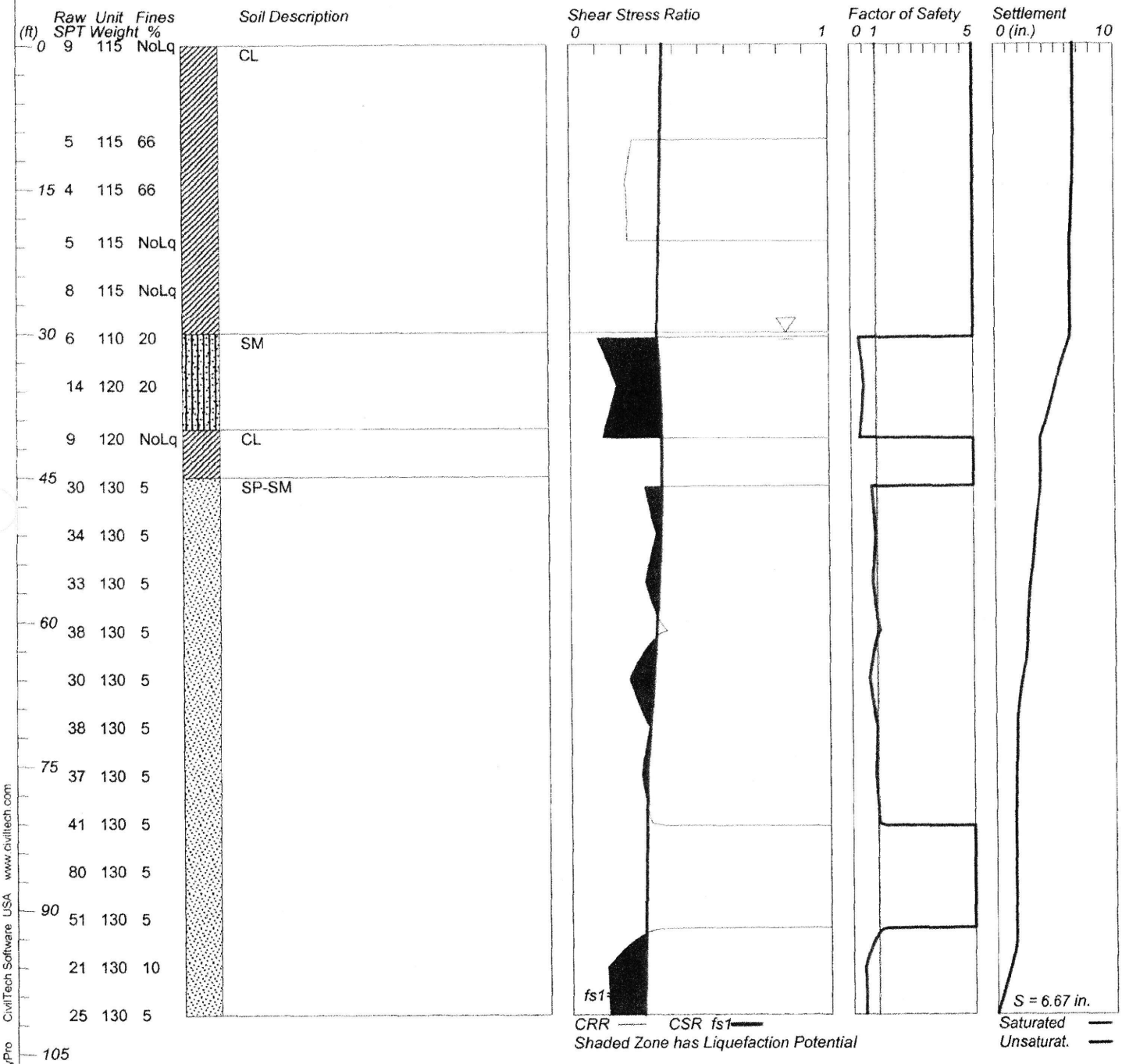
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110358

Hole No.=2 Water Depth=30.0 ft Surface Elev.=209.4

Magnitude=7.5
Acceleration=0.552g



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BN-2, Crittenden County

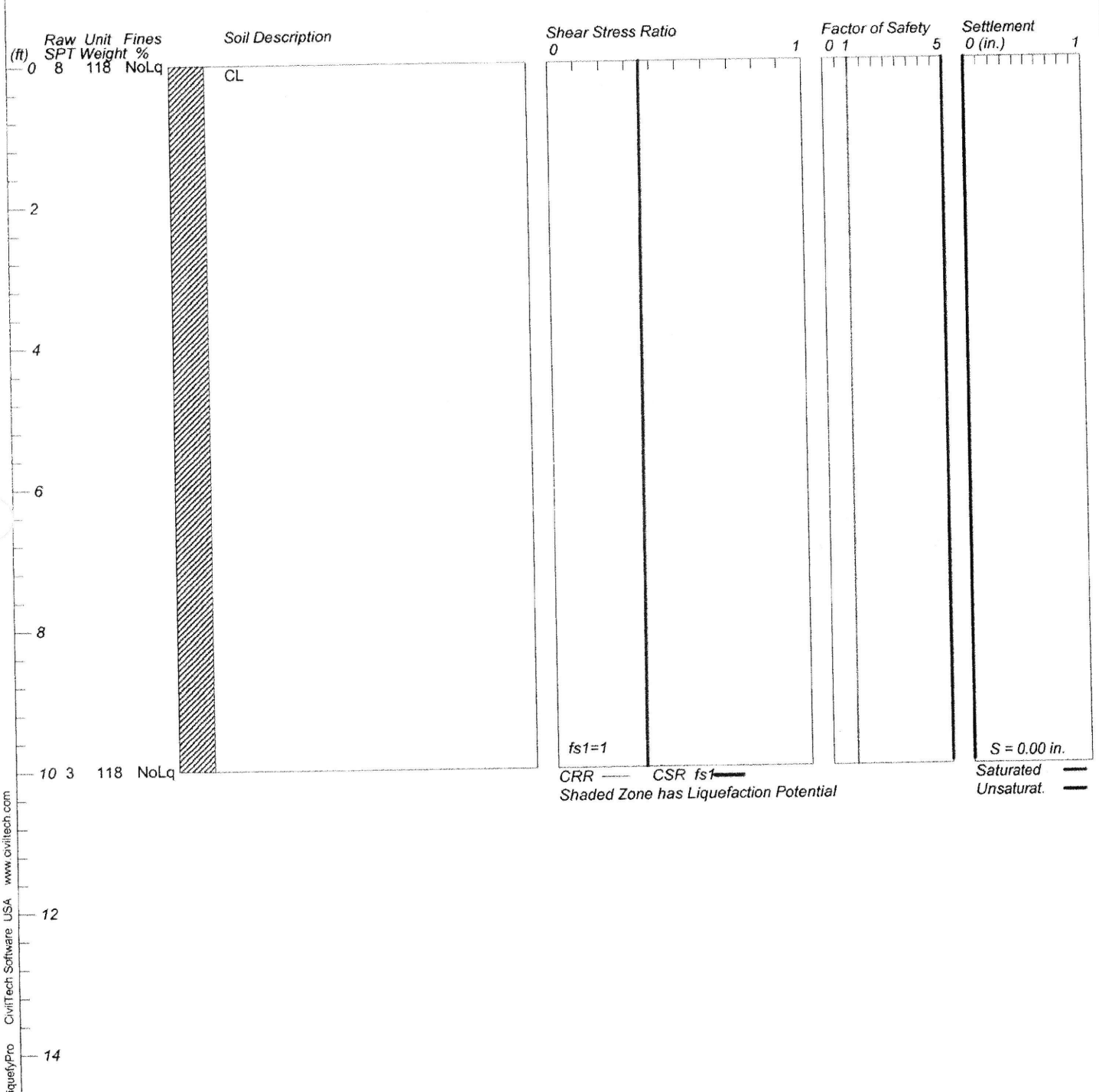
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110358

Hole No.=3 Water Depth=999 ft Surface Elev.=209.4

Magnitude=7.5
Acceleration=0.552g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-3, Crittenden County

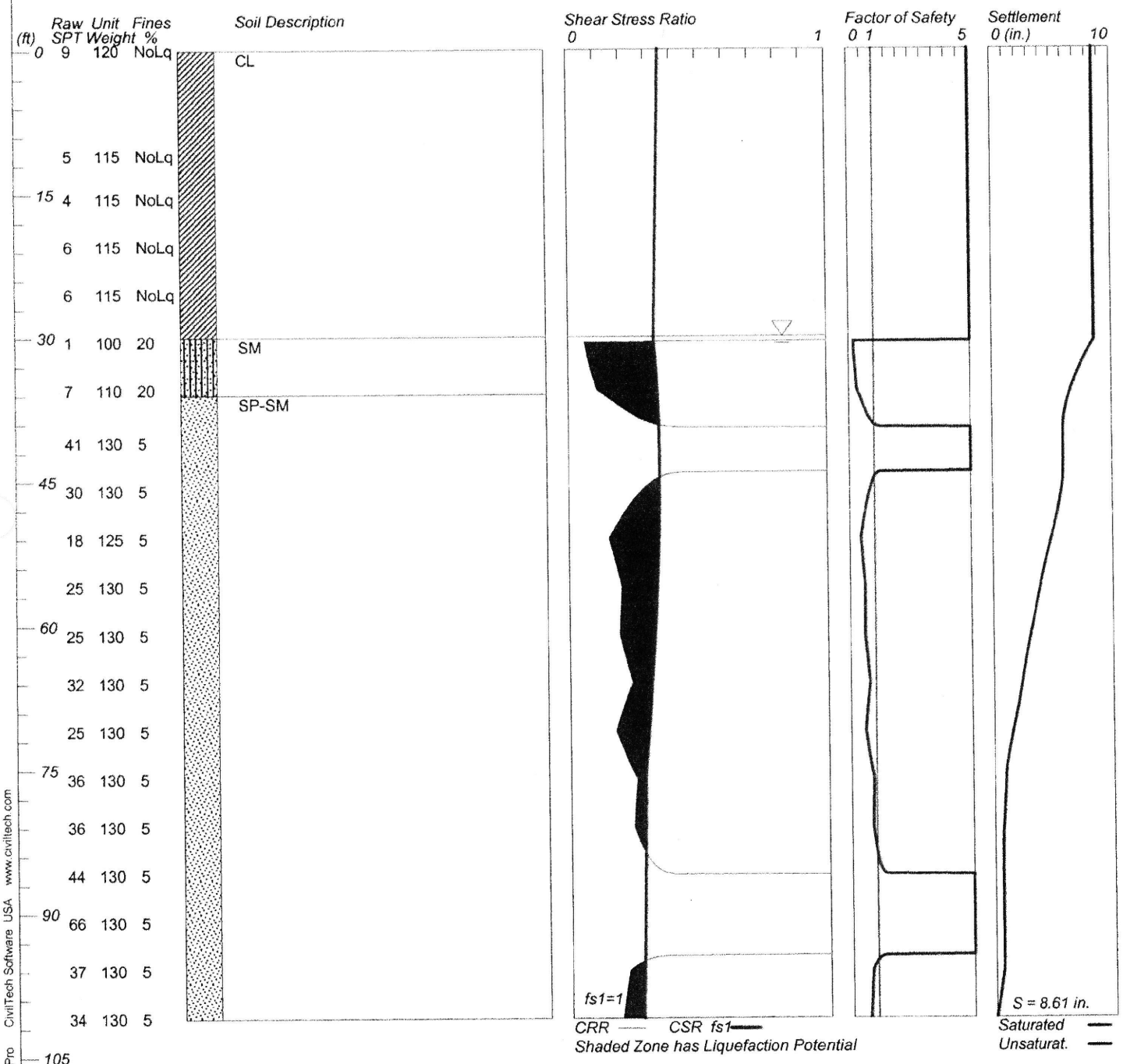
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110358

Hole No.=4 Water Depth=30 ft Surface Elev.=210.9

Magnitude=7.5
Acceleration=0.552g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-4, Crittenden County

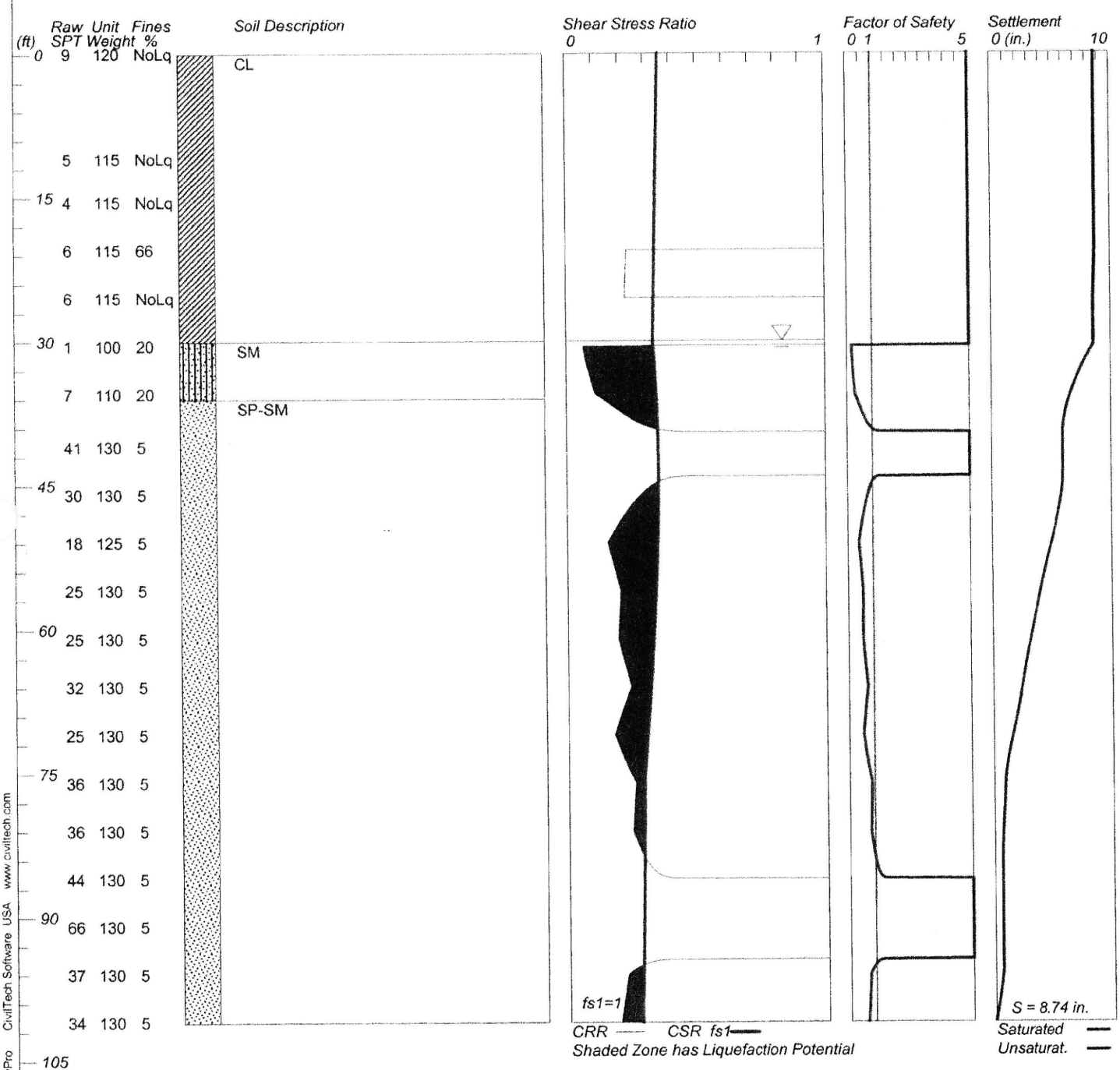
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110358

Hole No.=4 Water Depth=30 ft Surface Elev.=210.9

Magnitude=7.5
Acceleration=0.552g



BN-4, Crittenden County

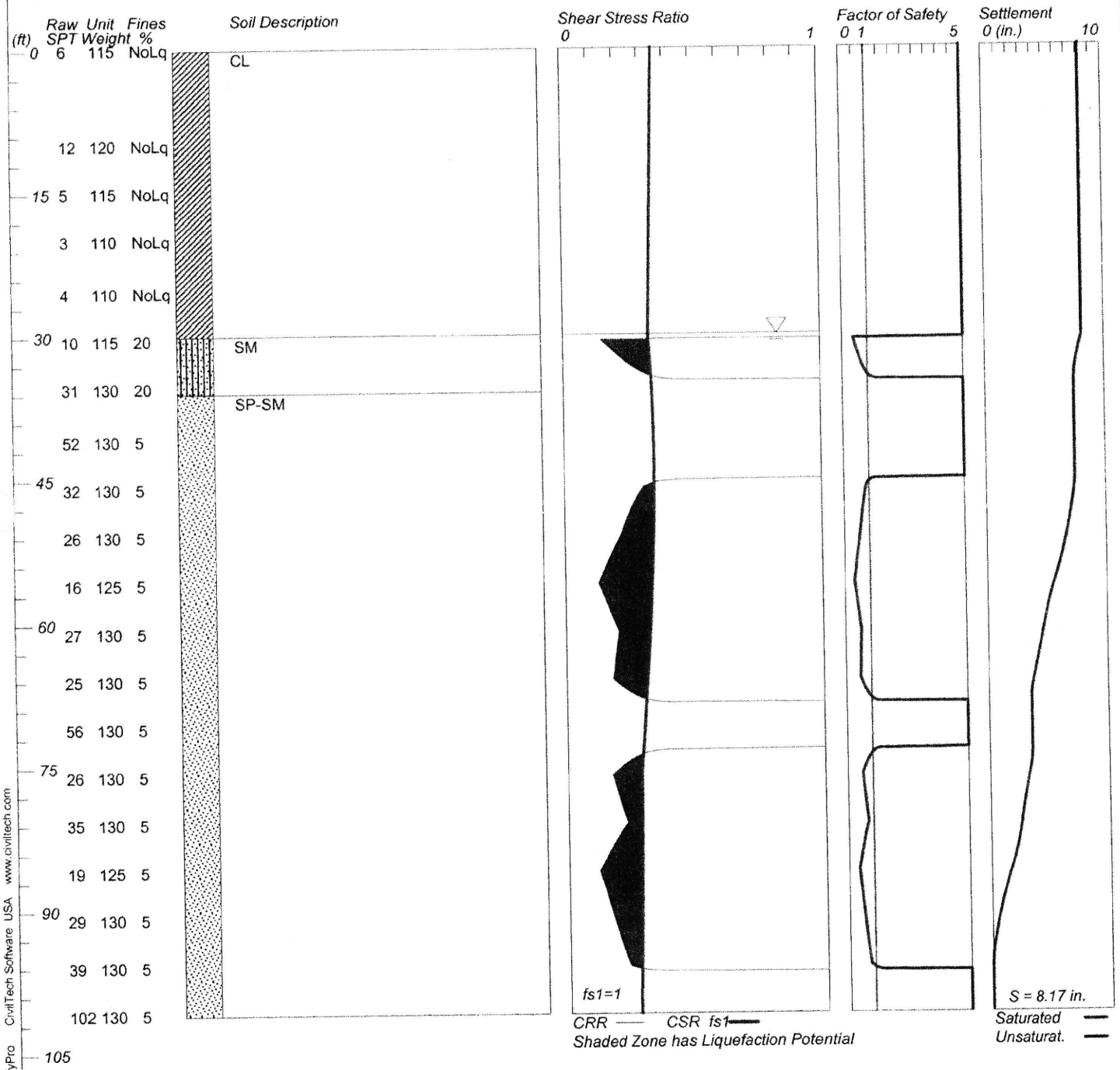
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110358

Hole No.=5 Water Depth=30 ft Surface Elev.=210.7

Magnitude=7.5
Acceleration=0.552g



BN-5, Crittenden County

Plate A-1

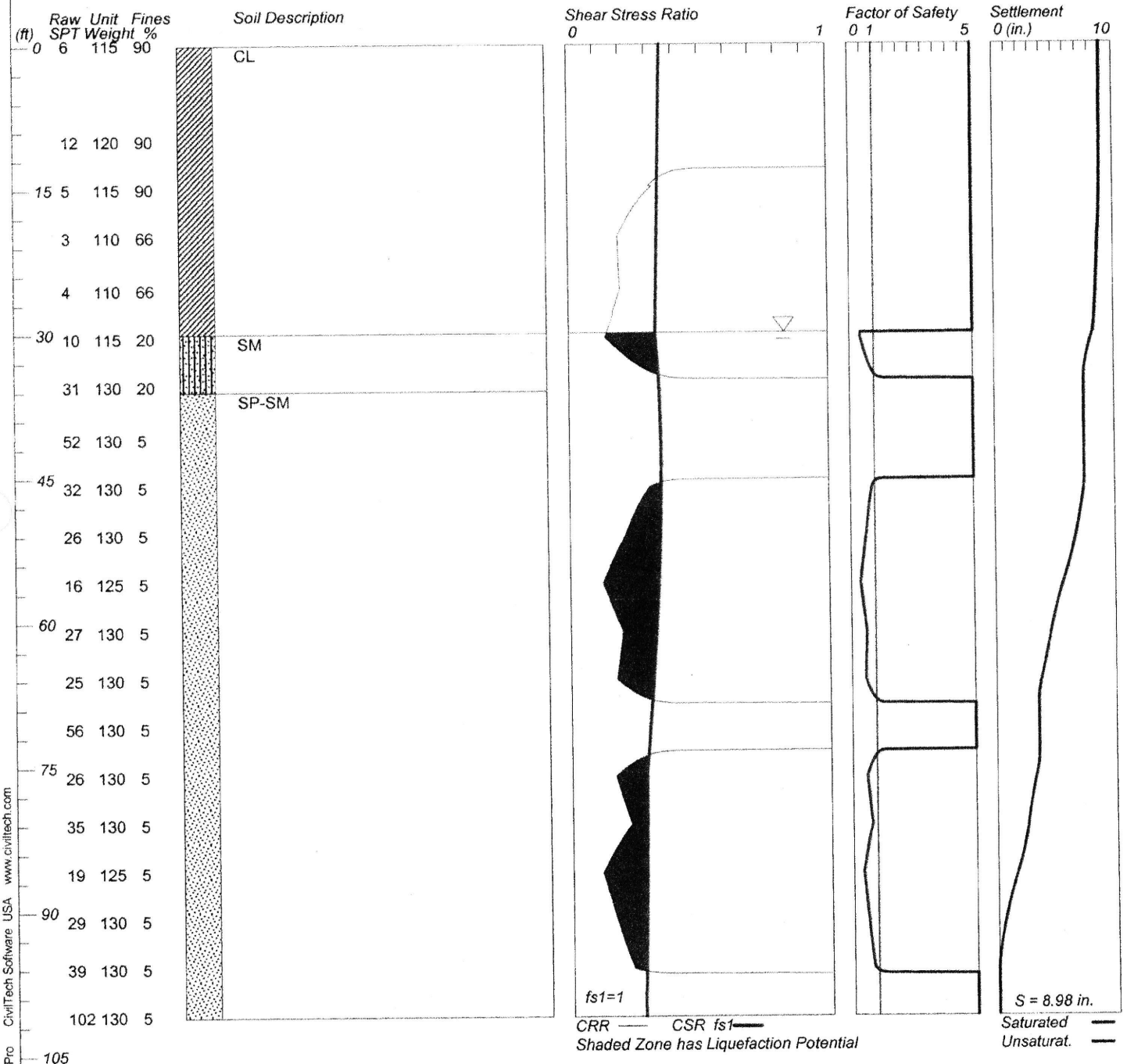
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110358

Hole No.=5 Water Depth=30 ft Surface Elev.=210.7

Magnitude=7.5
Acceleration=0.552g



BN-5, Crittenden County

Plate A-1

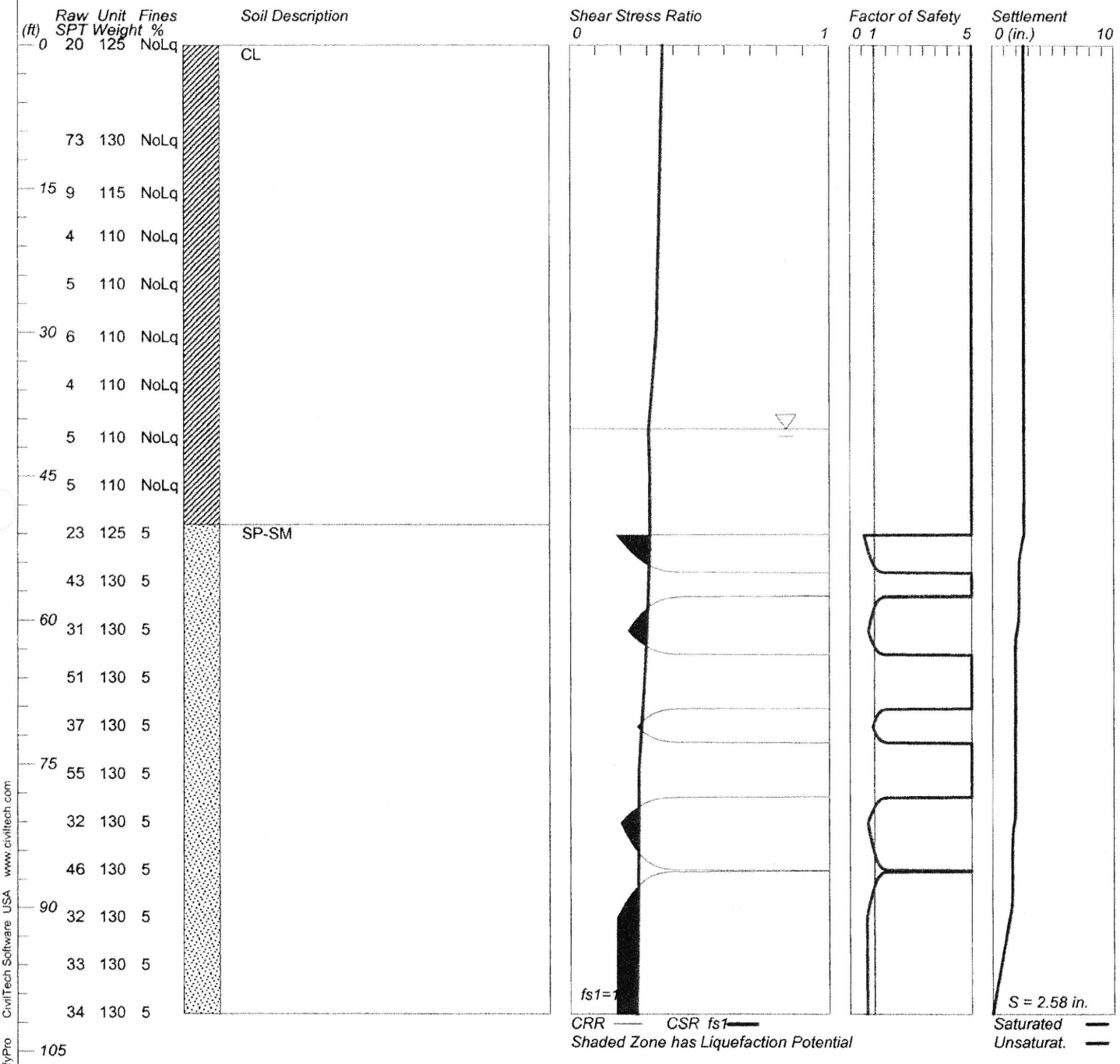
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110358

Hole No.=6 Water Depth=40 ft Surface Elev.=230.4

Magnitude=7.5
Acceleration=0.552g



BN-6, Crittenden County **Plate A-1**

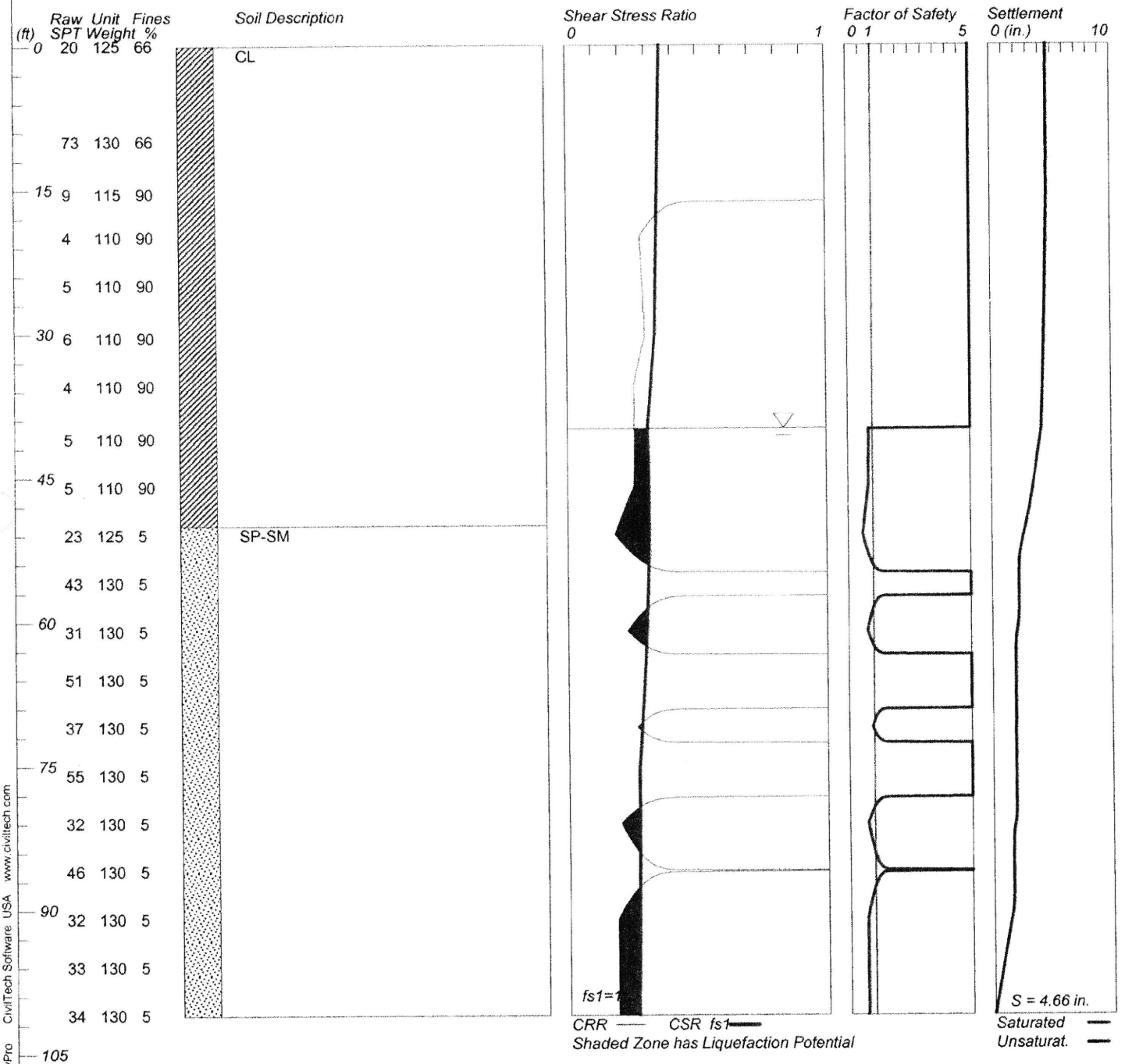
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110358

Hole No.=6 Water Depth=40 ft Surface Elev.=230.4

Magnitude=7.5
Acceleration=0.552g



BN-6, Crittenden County **Plate A-1**

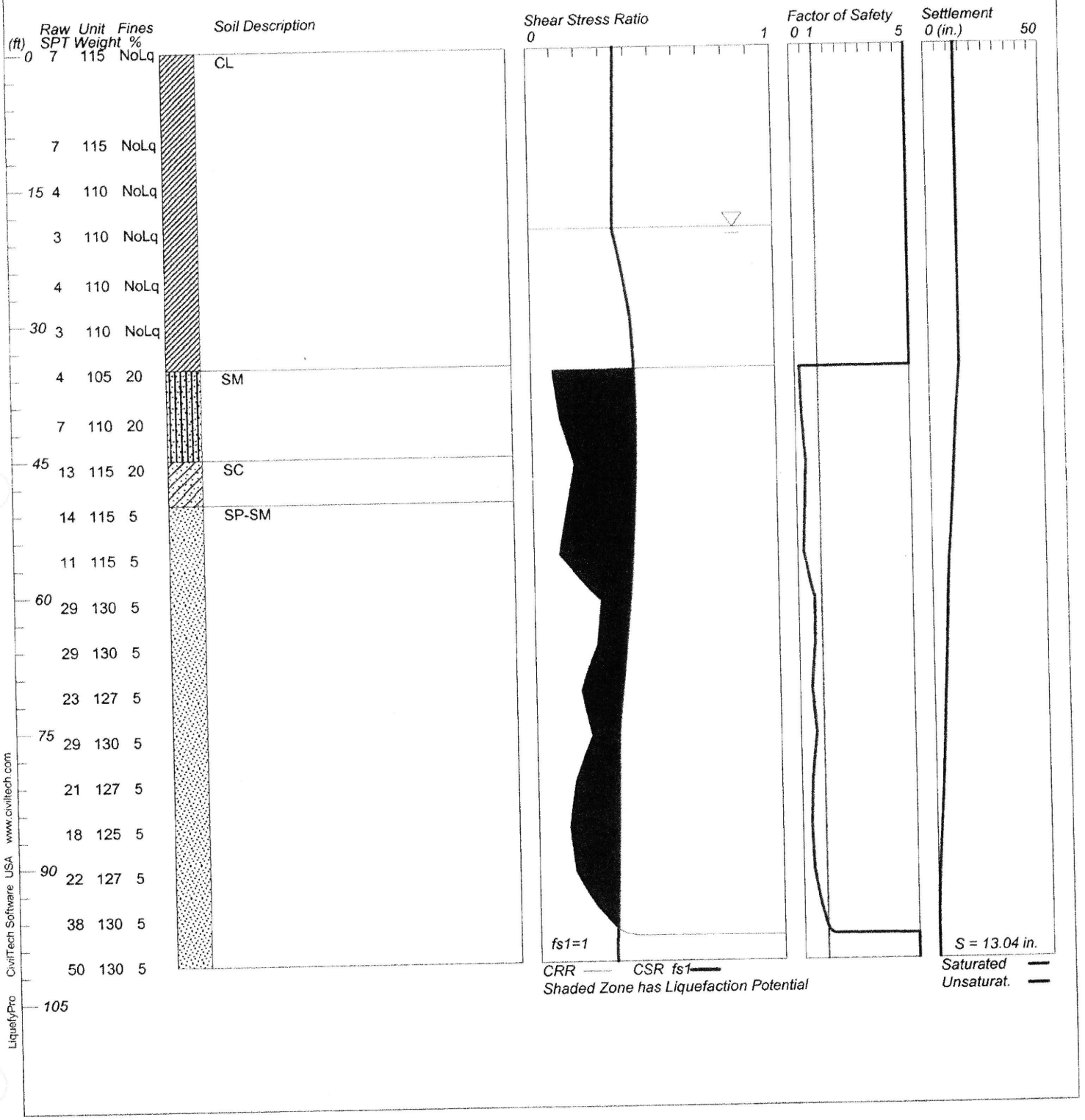
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110358

Hole No.=7 Water Depth=20 ft Surface Elev.=211.9

Magnitude=7.5
Acceleration=0.552g



BN-7, Crittenden County

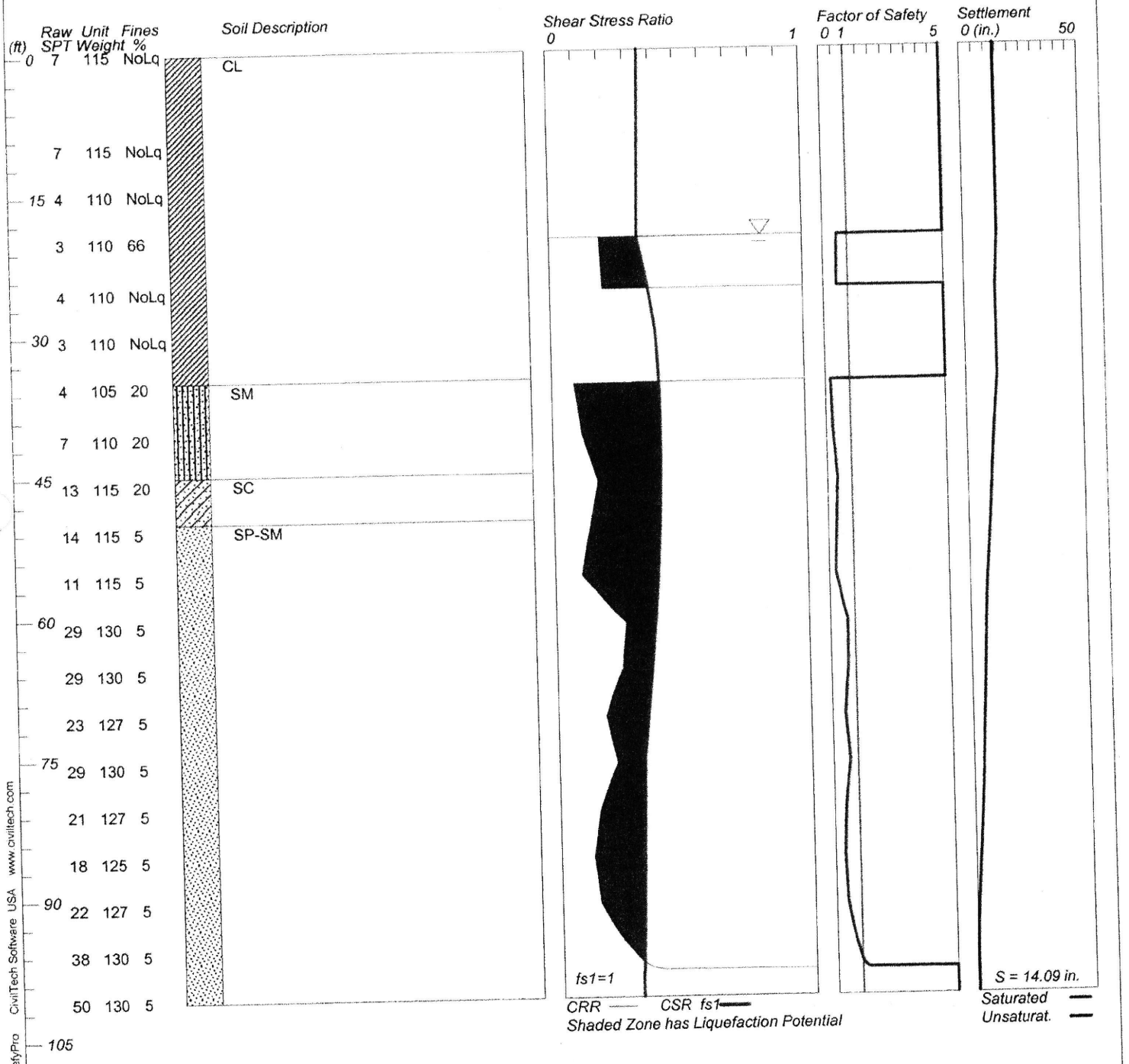
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110358

Hole No.=7 Water Depth=20 ft Surface Elev.=211.9

Magnitude=7.5
Acceleration=0.552g



BN-7, Crittenden County

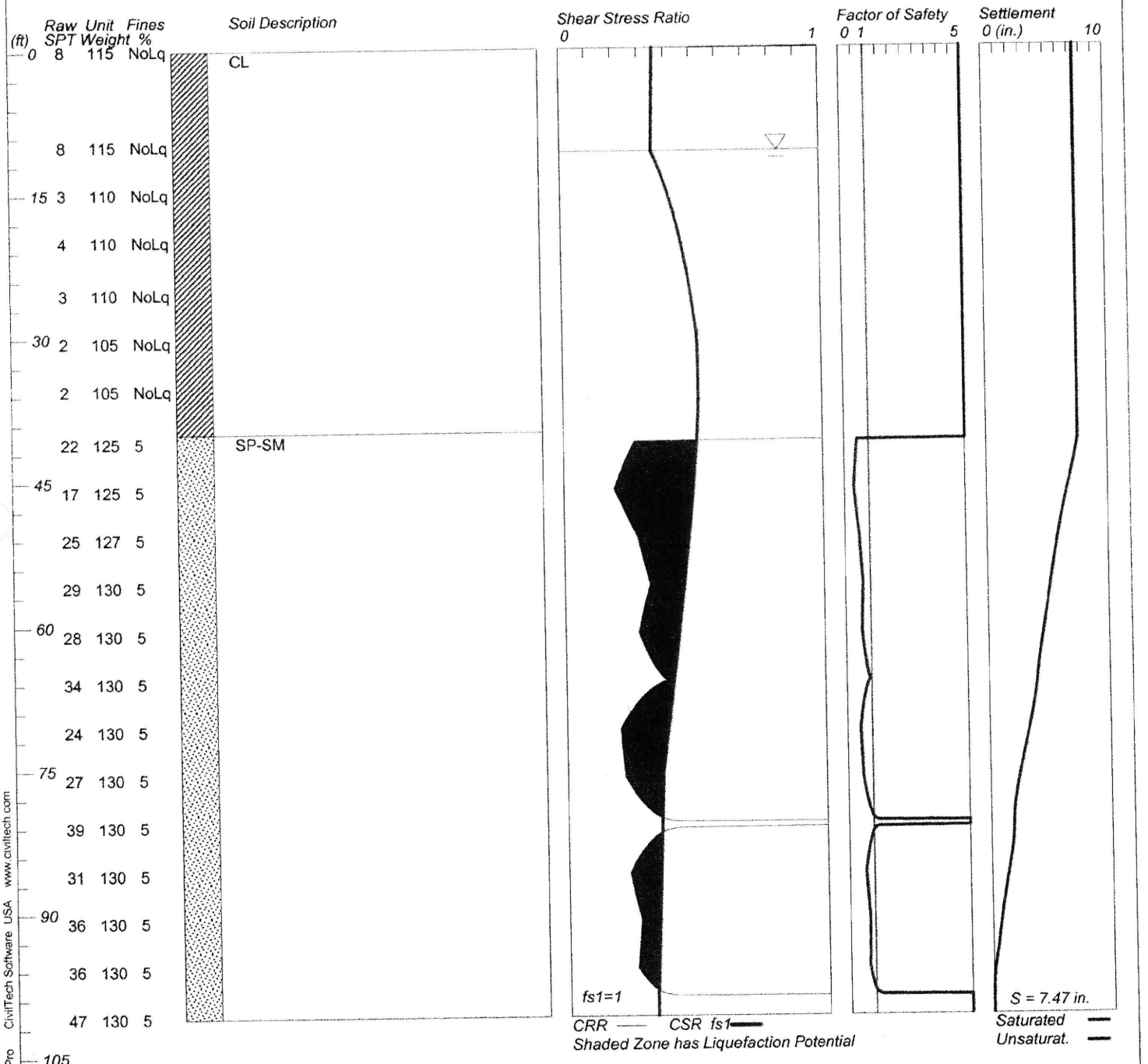
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110358

Hole No.=8 Water Depth=10.8 ft Surface Elev.=211.7

Magnitude=7.5
Acceleration=0.552g



BN-8, Crittenden County

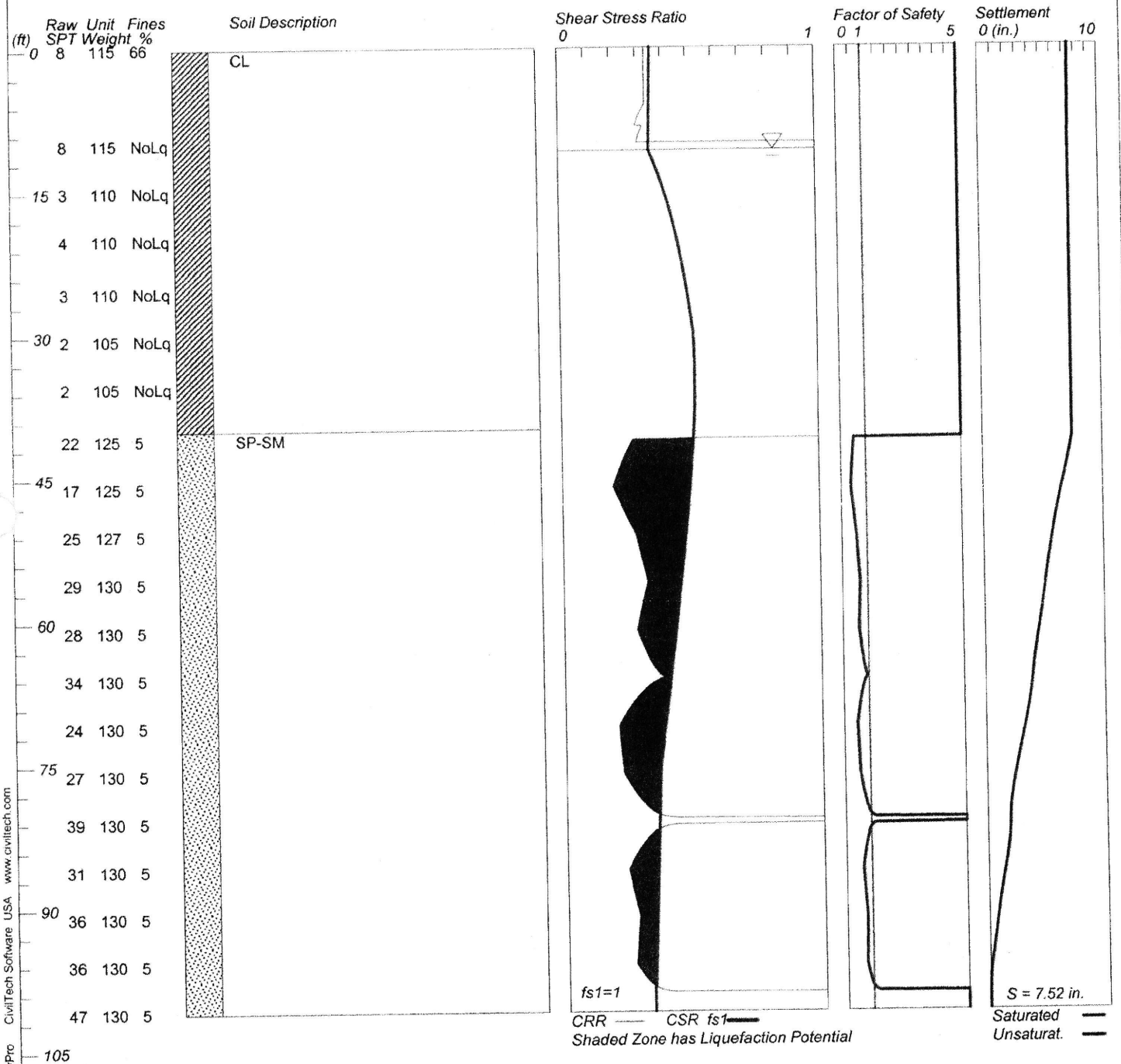
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110358

Hole No.=8 Water Depth=10.8 ft Surface Elev.=211.7

Magnitude=7.5
Acceleration=0.552g



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BN-8, Crittenden County

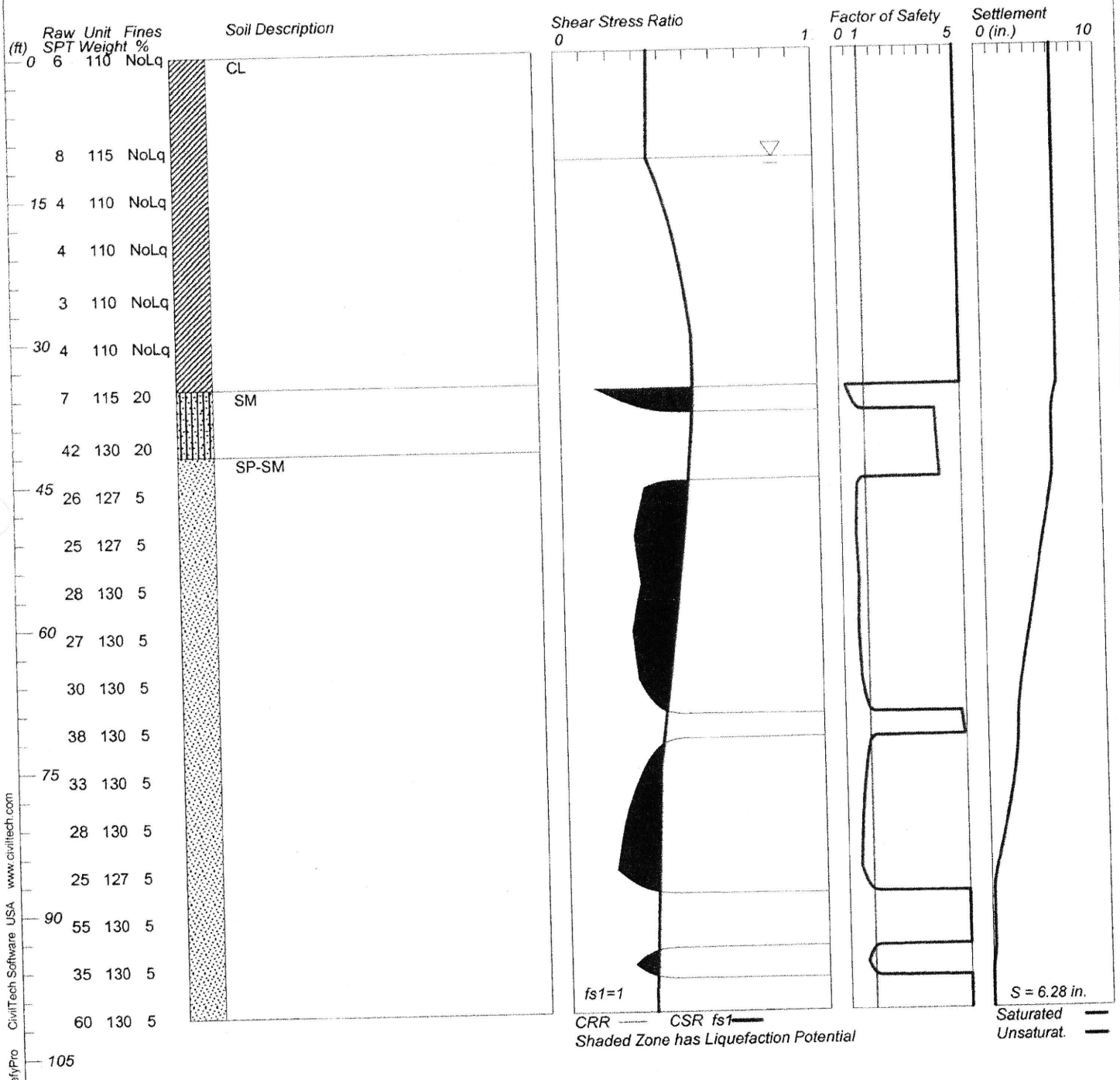
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110358

Hole No.=9 Water Depth=11.4 ft Surface Elev.=212.3

Magnitude=7.5
Acceleration=0.552g



BN-9, Crittenden County

Plate A-1

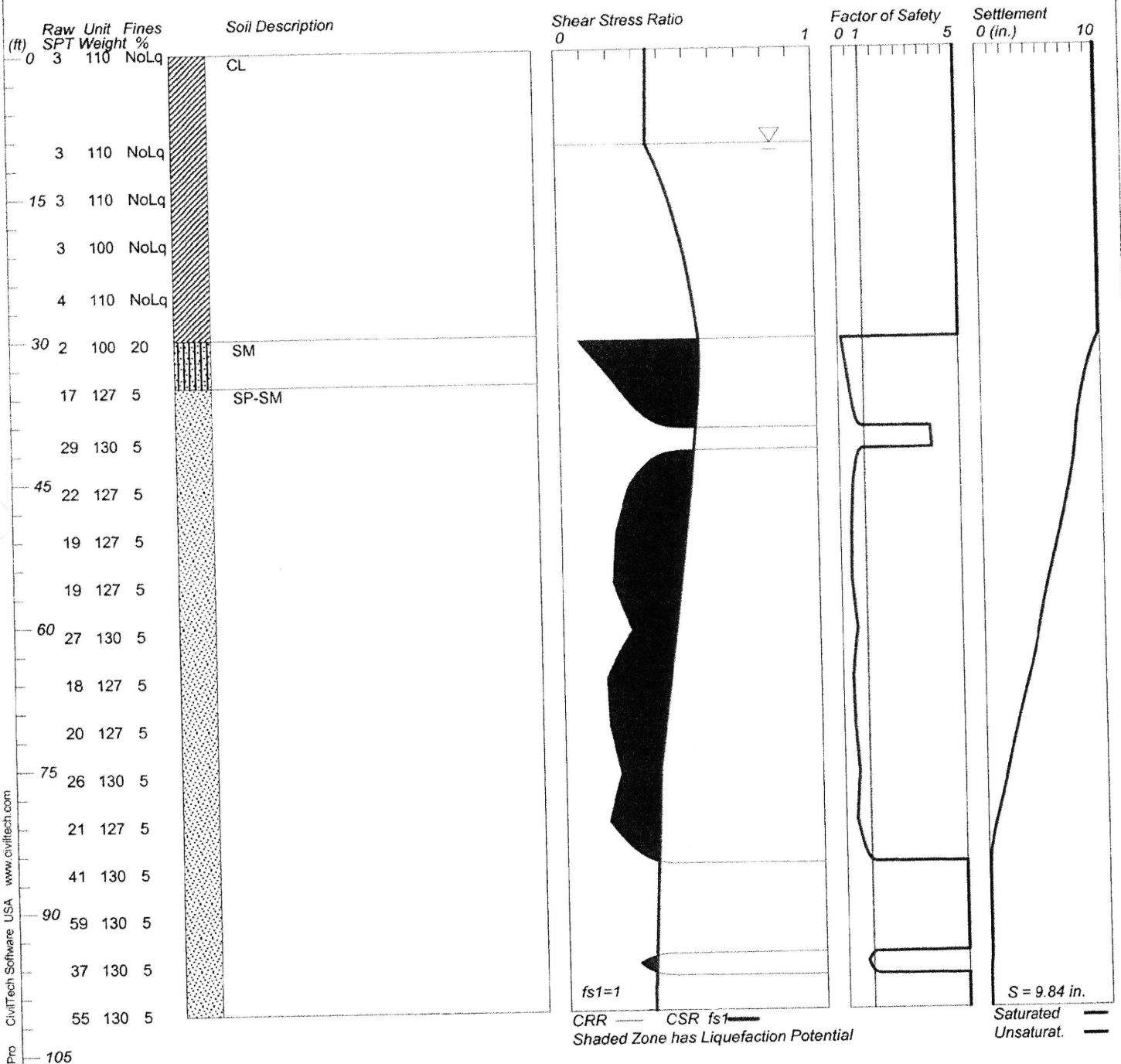
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110358

Hole No.=10 Water Depth=10.0 ft Surface Elev.=209.5

Magnitude=7.5
Acceleration=0.552g



BN-10, Crittenden County

Arkansas State University-College of Engineering

Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-110358

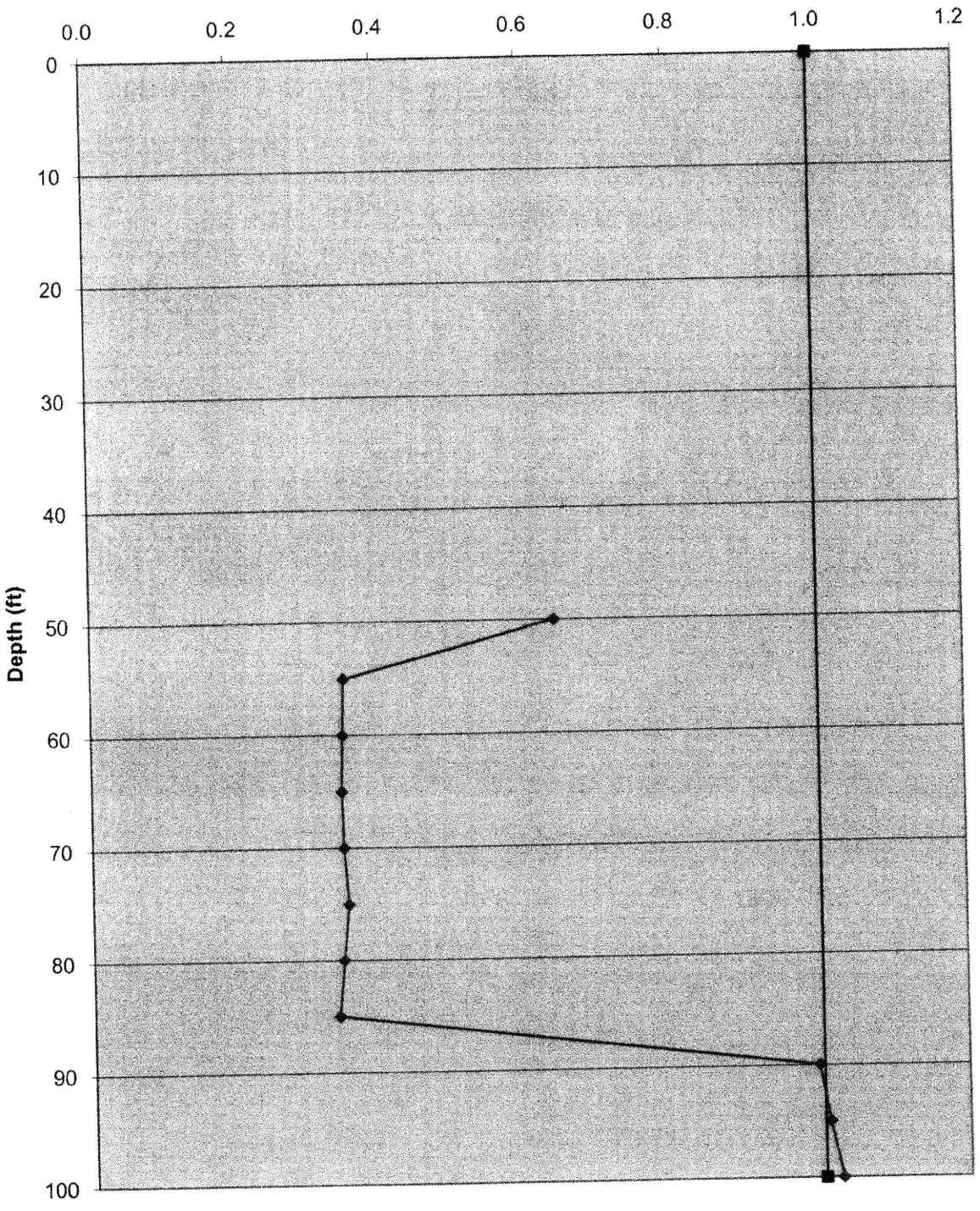
note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5		depth to finish floor =	0	ft
PGA =	0.552	g	uniform floor load =	0	lb/ft^2
depth to groundwater during drilling =	25	ft	assumed depth to groundwater =	25	ft
estimated age of sand deposit =	2000	years			

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	120	253	80	16	600	600	600	0.988	0.3546	342	NA	1.00	1.00	NA	NA
10	1	120	410	80	16	1200	1200	1200	0.977	0.3504	466	NA	1.00	1.00	NA	NA
15	1	120	410	80	16	1800	1800	1800	0.965	0.3462	421	NA	1.00	1.00	NA	NA
20	1	115	410	80	16	2375	2375	2375	0.953	0.3421	393	NA	1.00	1.00	NA	NA
25	1	115	689	66	16	2950	2950	2950	0.942	0.3379	625	NA	1.00	1.00	NA	NA
30	1	110	689	66	16	3500	3188	3188	0.930	0.3663	613	NA	1.00	1.00	NA	NA
35	1	110	837	66	16	4050	3426	3426	0.889	0.3771	732	NA	1.00	1.00	NA	NA
40	1	115	837	66	16	4625	3689	3689	0.848	0.3816	718	NA	1.00	1.00	NA	NA
45	1	115	837	66	16	5200	3952	3952	0.808	0.3812	706	NA	1.00	1.00	NA	NA
50	2	115	837	5	0	5775	4215	4215	0.767	0.3770	695	0.2414	1.00	1.00	0.241335	0.6
55	2	115	751	5	0	6350	4478	4478	0.726	0.3694	614	0.1286	1.00	1.00	0.128558	0.3
60	2	100	751	5	0	6850	4666	4666	0.685	0.3610	608	0.1249	1.00	1.00	0.124899	0.3
65	2	130	751	5	0	7500	5004	5004	0.645	0.3467	597	0.1192	1.00	1.00	0.119157	0.3
70	2	130	751	5	0	8150	5342	5342	0.604	0.3306	587	0.1143	1.00	1.00	0.114241	0.3
75	2	130	751	5	0	8800	5680	5680	0.563	0.3131	579	0.1100	1.00	1.00	0.109952	0.4
80	2	130	751	5	0	9450	6018	6018	0.549	0.3092	570	0.1062	1.00	1.00	0.106157	0.3
85	2	130	751	5	0	10100	6356	6356	0.537	0.3059	562	0.1028	1.00	1.00	0.10276	0.3
90	2	130	1453	5	0	10750	6694	6694	0.524	0.3022	1074	0.3000	1.00	1.00	0.299946	1.0
95	2	130	1453	5	0	11400	7032	7032	0.512	0.2979	1061	0.3000	1.00	1.00	0.299946	1.0
100	2	130	1453	5	0	12050	7370	7370	0.500	0.2933	1049	0.3000	1.00	1.00	0.299946	1.0

Used Bore #1 for PI values & unit wt.

Vs Liquefaction Potential - Project 110358

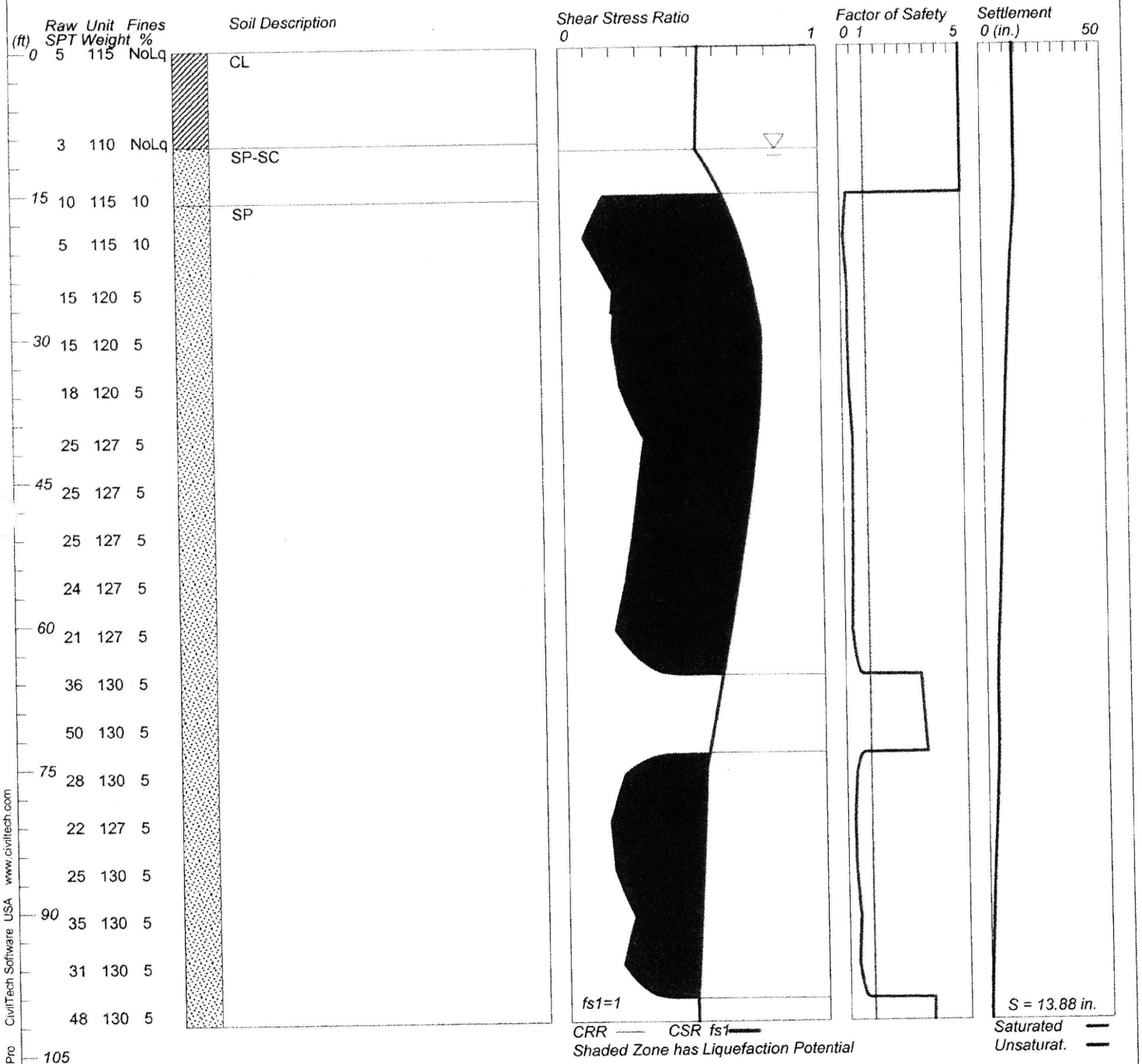


LIQUEFACTION ANALYSIS (ALT.A)

110288

Hole No.=B-1 Water Depth=10.8 ft Surface Elev.=196.2

Magnitude=7.5
Acceleration=0.833g



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BN-1, Cross County

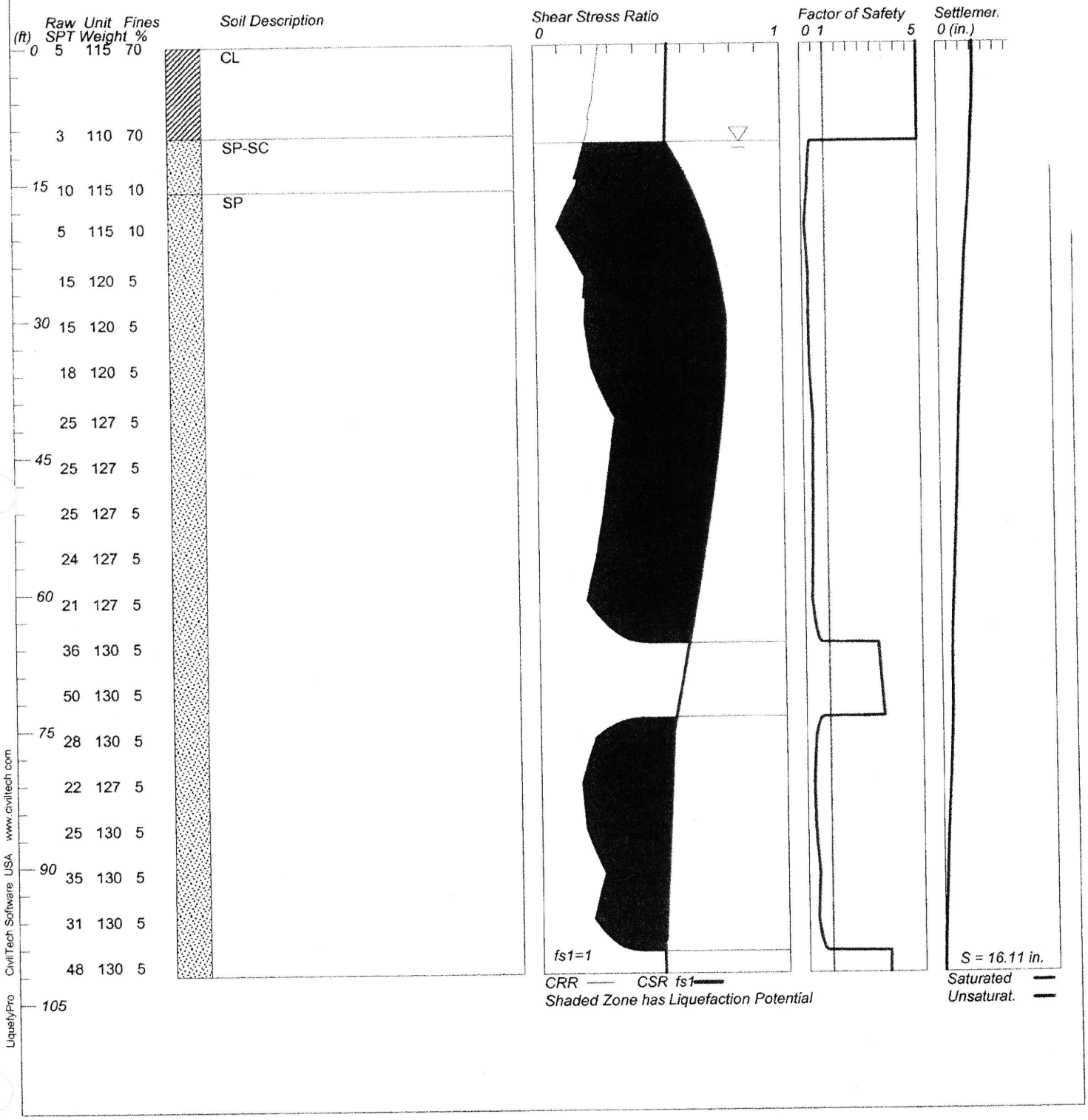
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110288

Hole No.=B-1 Water Depth=10.8 ft Surface Elev.=196.2

***Magnitu
Acceleration=0***



BN-1, Cross County

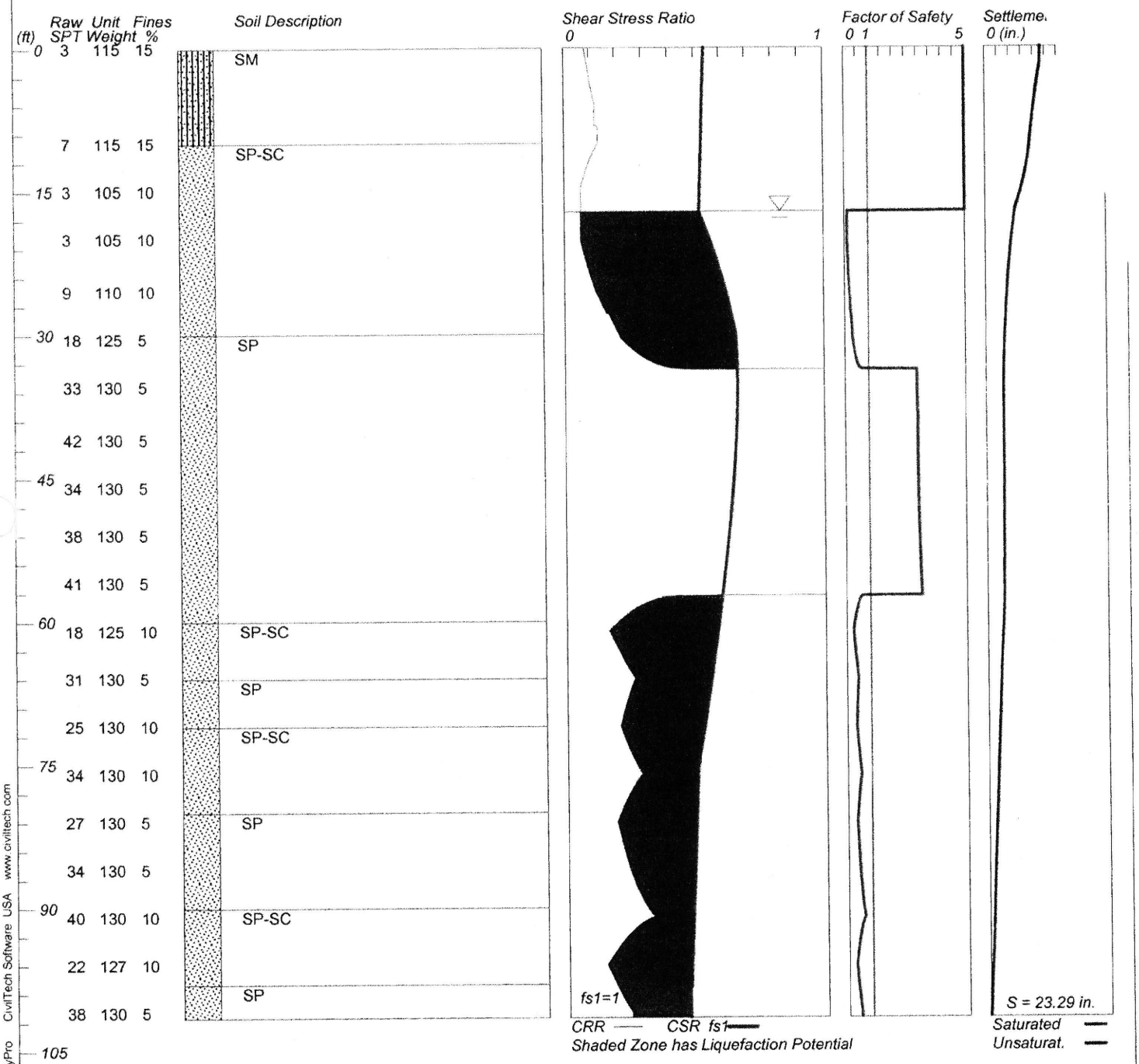
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS

110228

Hole No.=2 Water Depth=17.2 ft Surface Elev.=194

Magnitu
Acceleration=



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BN-2 CROSS COUNTY

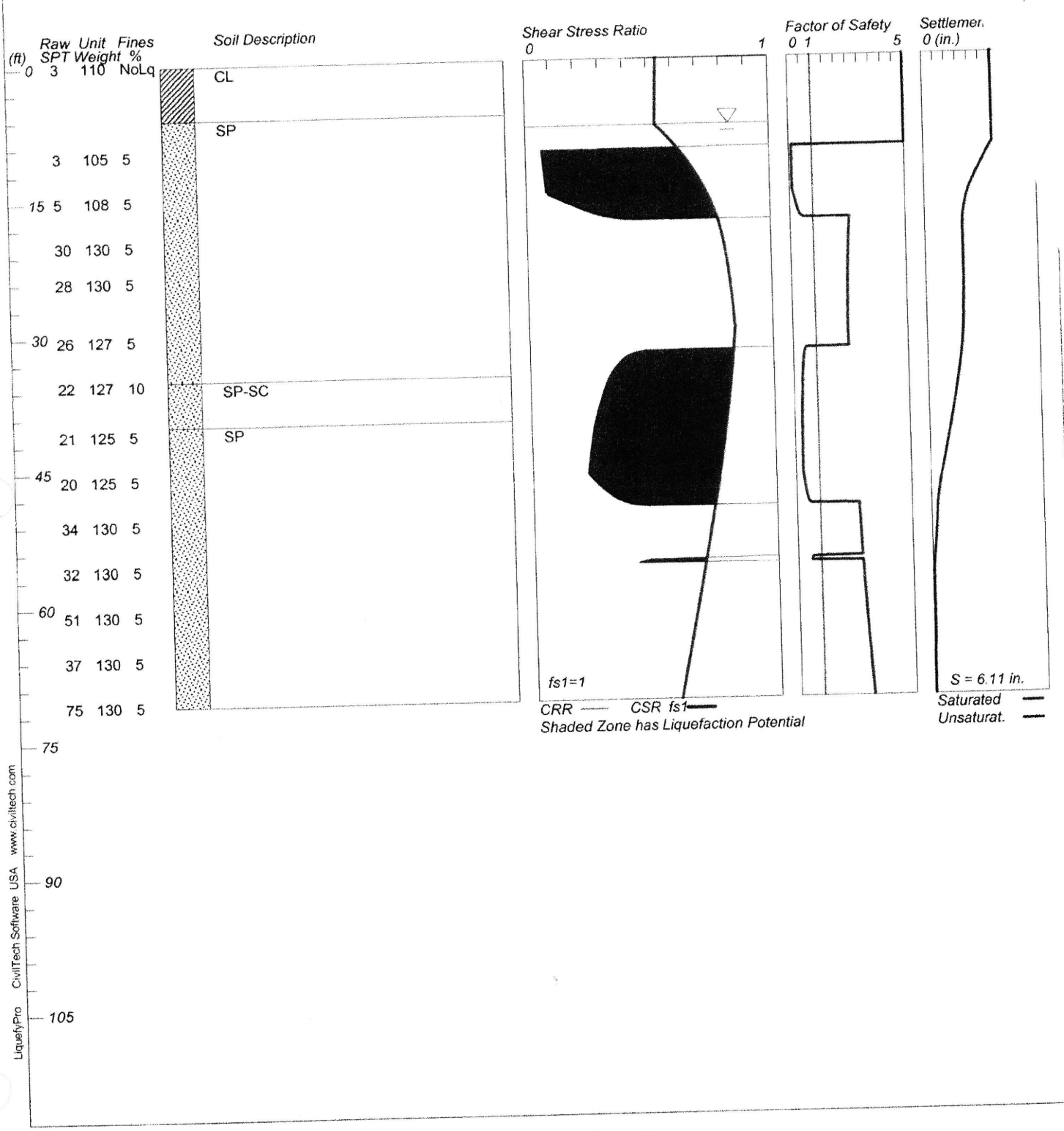
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110228

Hole No.=3 Water Depth=7.4 ft Surface Elev.=183

***Magnitu
Acceleration=0.***



LiquefyPro CivilTech Software USA www.civiltech.com

BN-3, Cross County

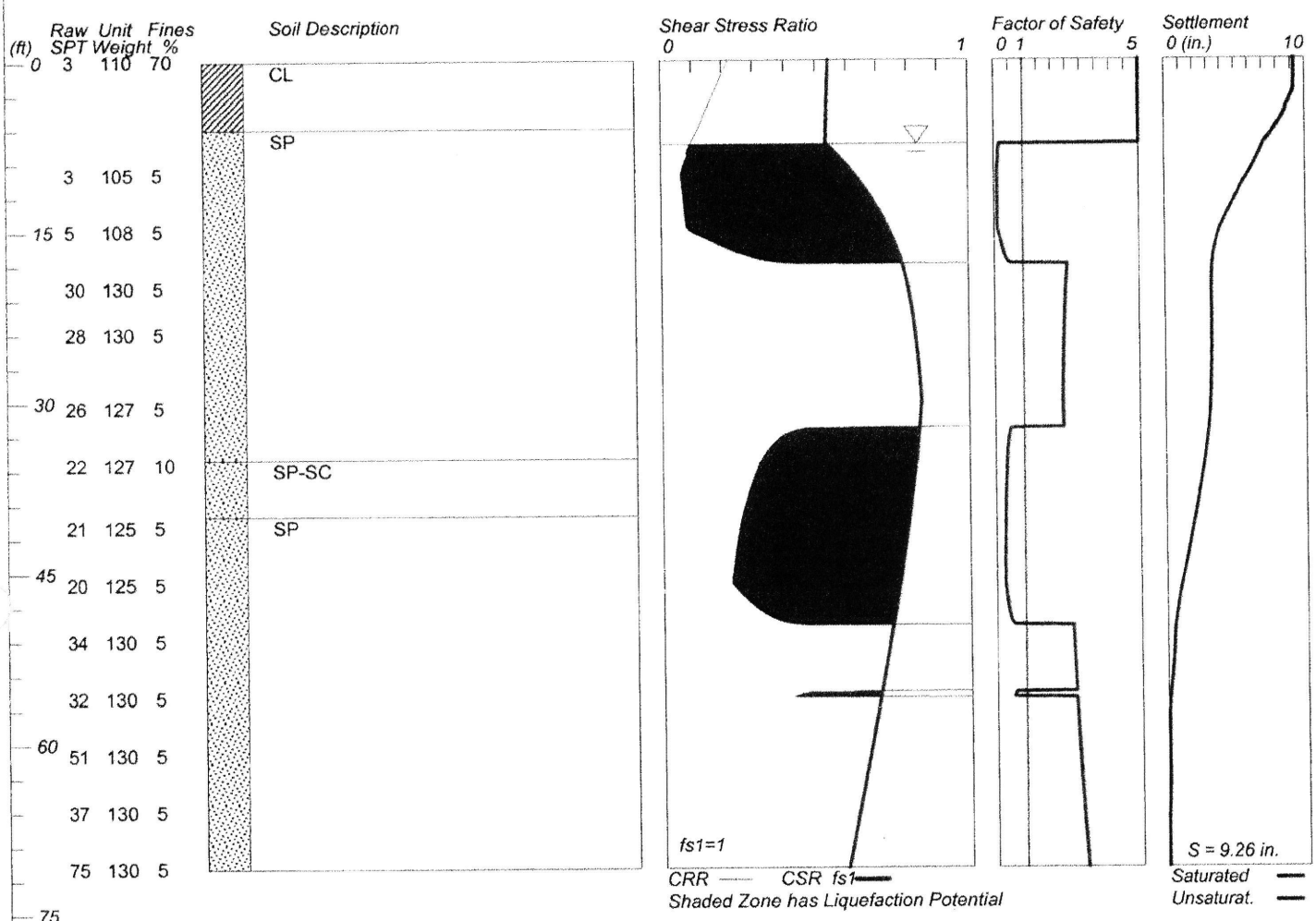
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110228

Hole No.=3 Water Depth=7.4 ft Surface Elev.=183

Magnitude=7.5
Acceleration=0.833g



LiquefyPro CivilTech Software USA www.civiltech.com

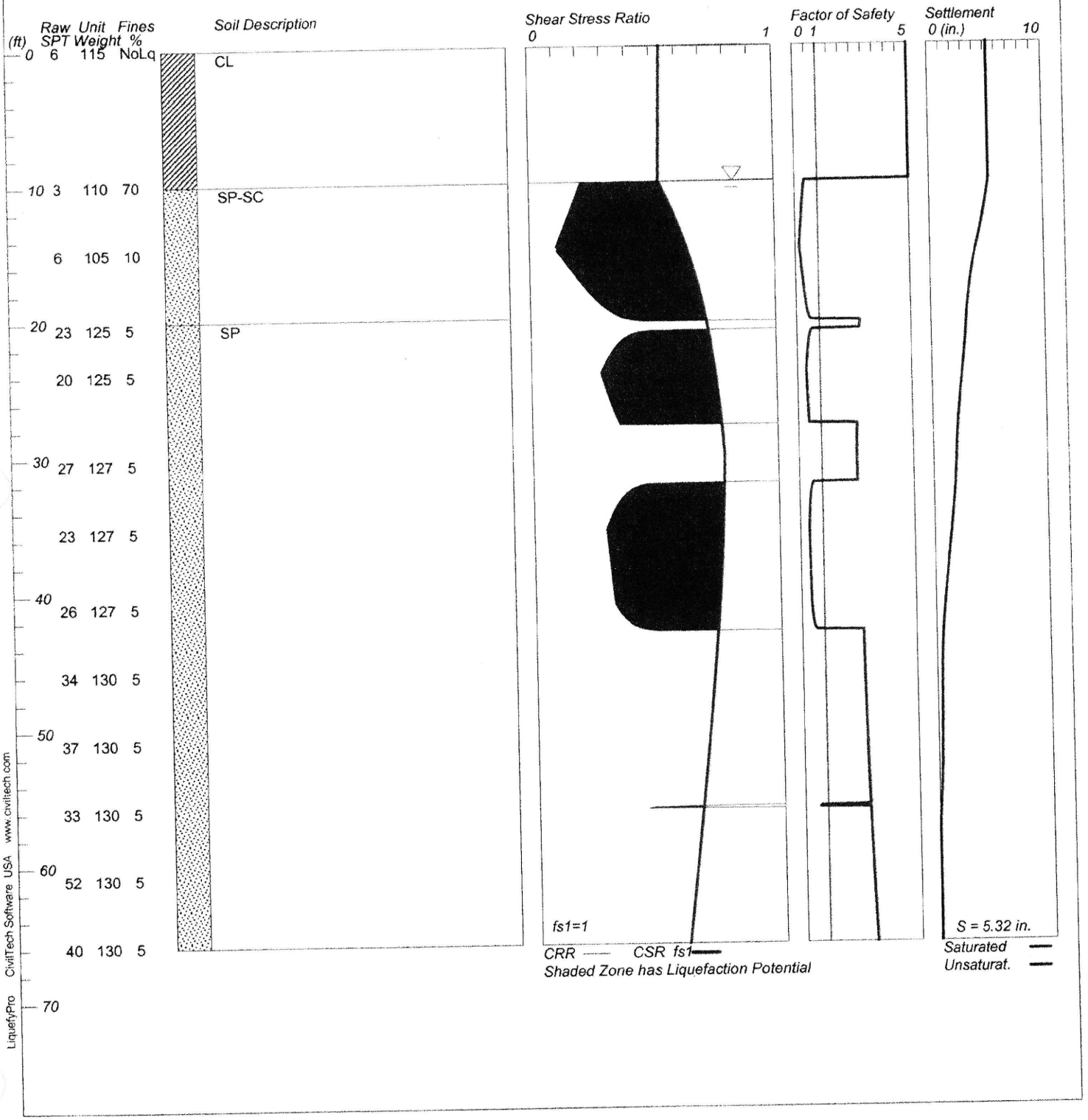
BN-3, Cross County

LIQUEFACTION ANALYSIS (ALT.A)

110288

Hole No.=4 Water Depth=10 ft Surface Elev.=185.6

Magnitude=7.5
Acceleration=0.833g



BN-4, Cross County

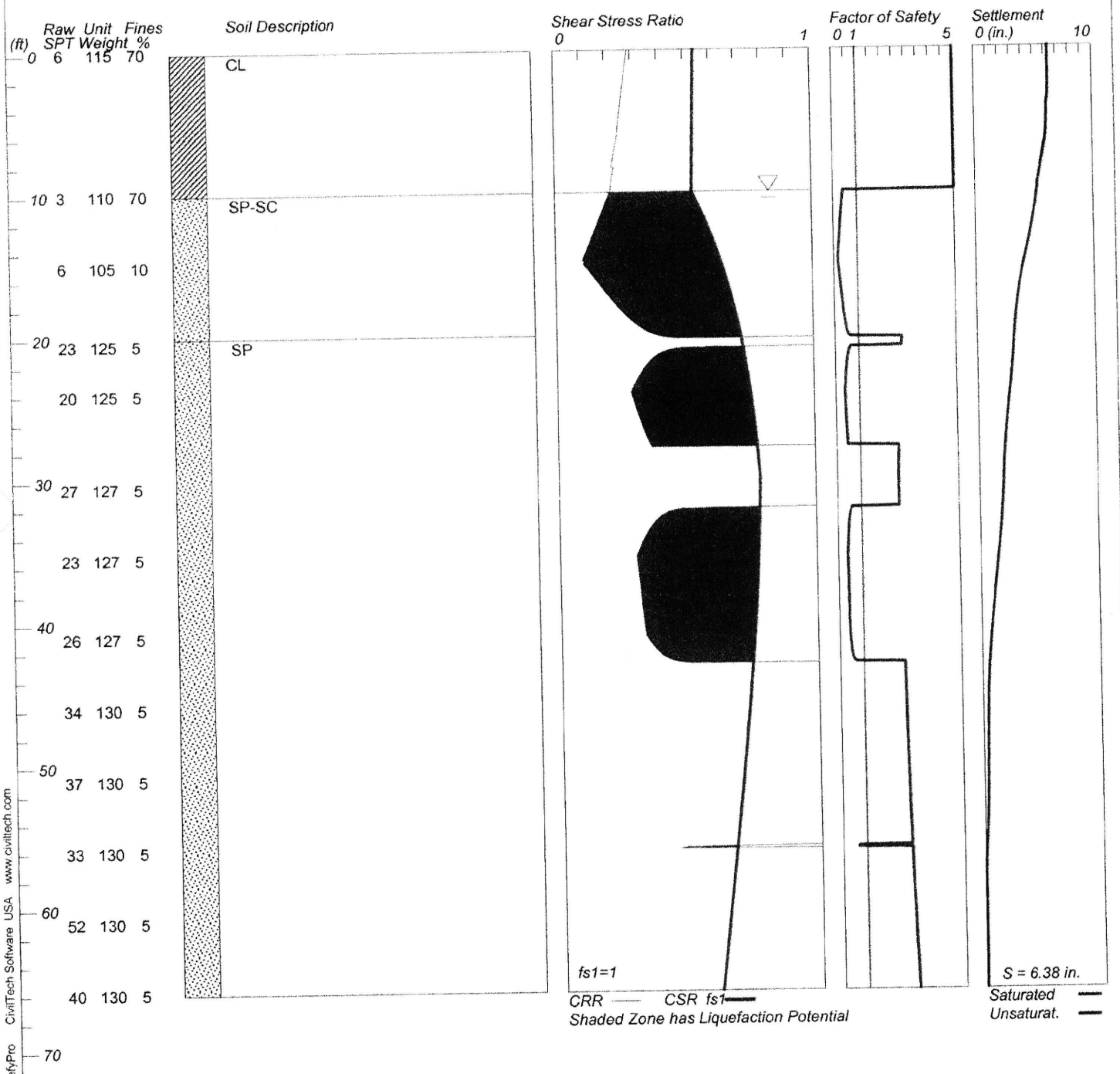
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110288

Hole No.=4 Water Depth=10 ft Surface Elev.=185.6

Magnitude=7.5
Acceleration=0.833g



BN-4, Cross County

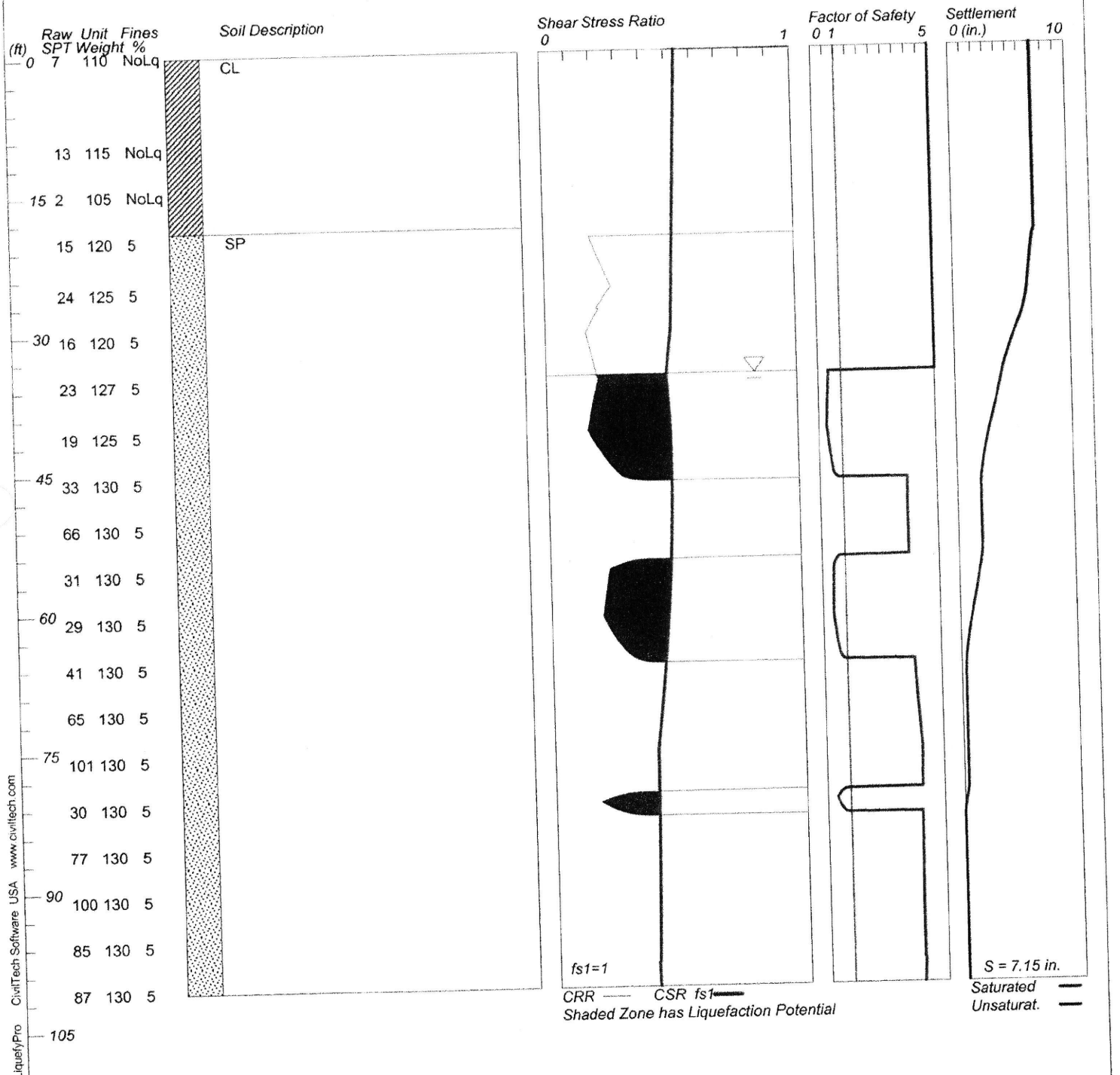
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.A)

110288

Hole No.=5 Water Depth=35.0 ft Surface Elev.=209.8

Magnitude=7.5
Acceleration=0.833g



BN-5, Cross County

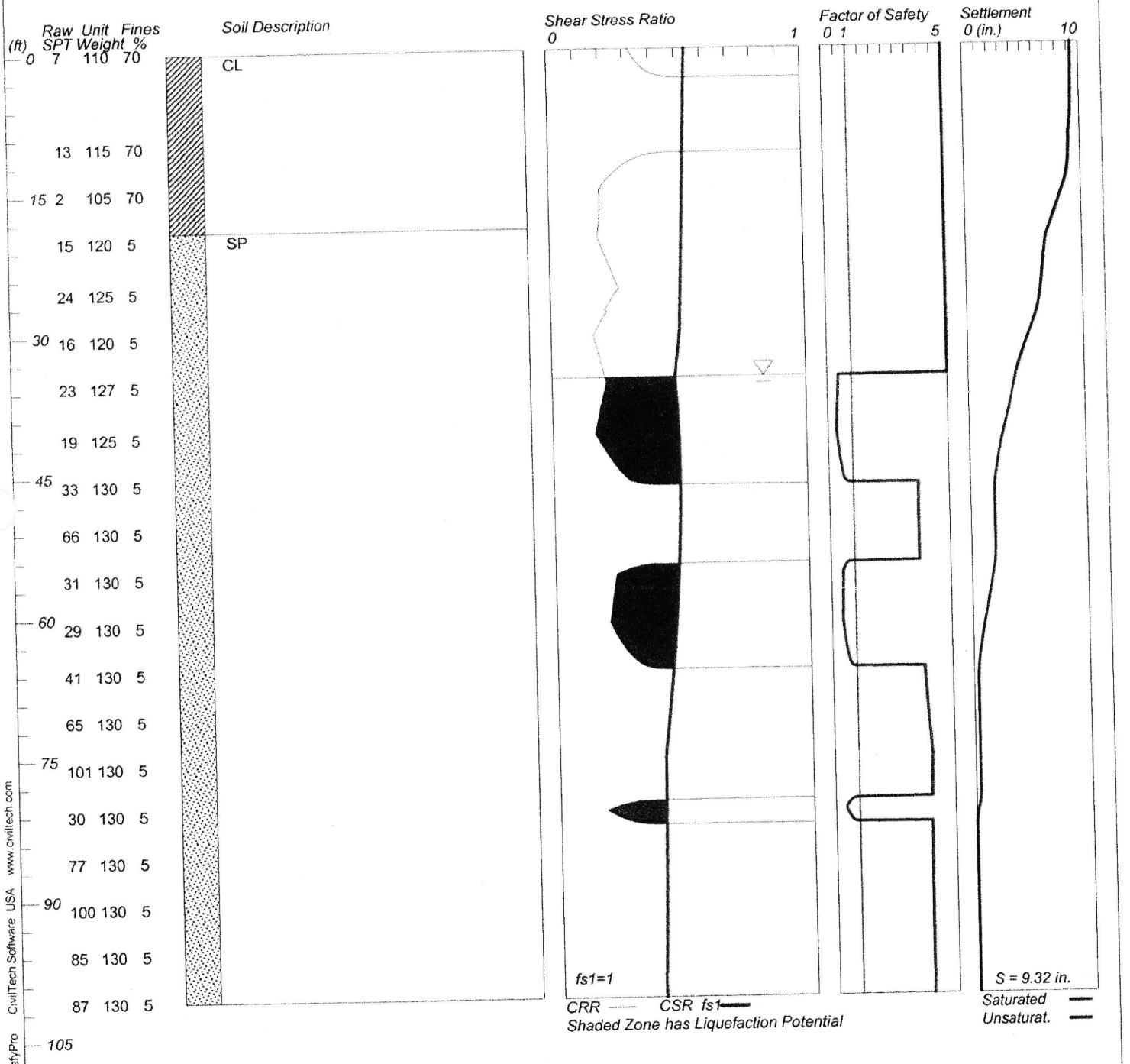
Arkansas State University-College of Engineering

LIQUEFACTION ANALYSIS (ALT.B)

110288

Hole No.=5 Water Depth=35.0 ft Surface Elev.=209.8

Magnitude=7.5
Acceleration=0.833g



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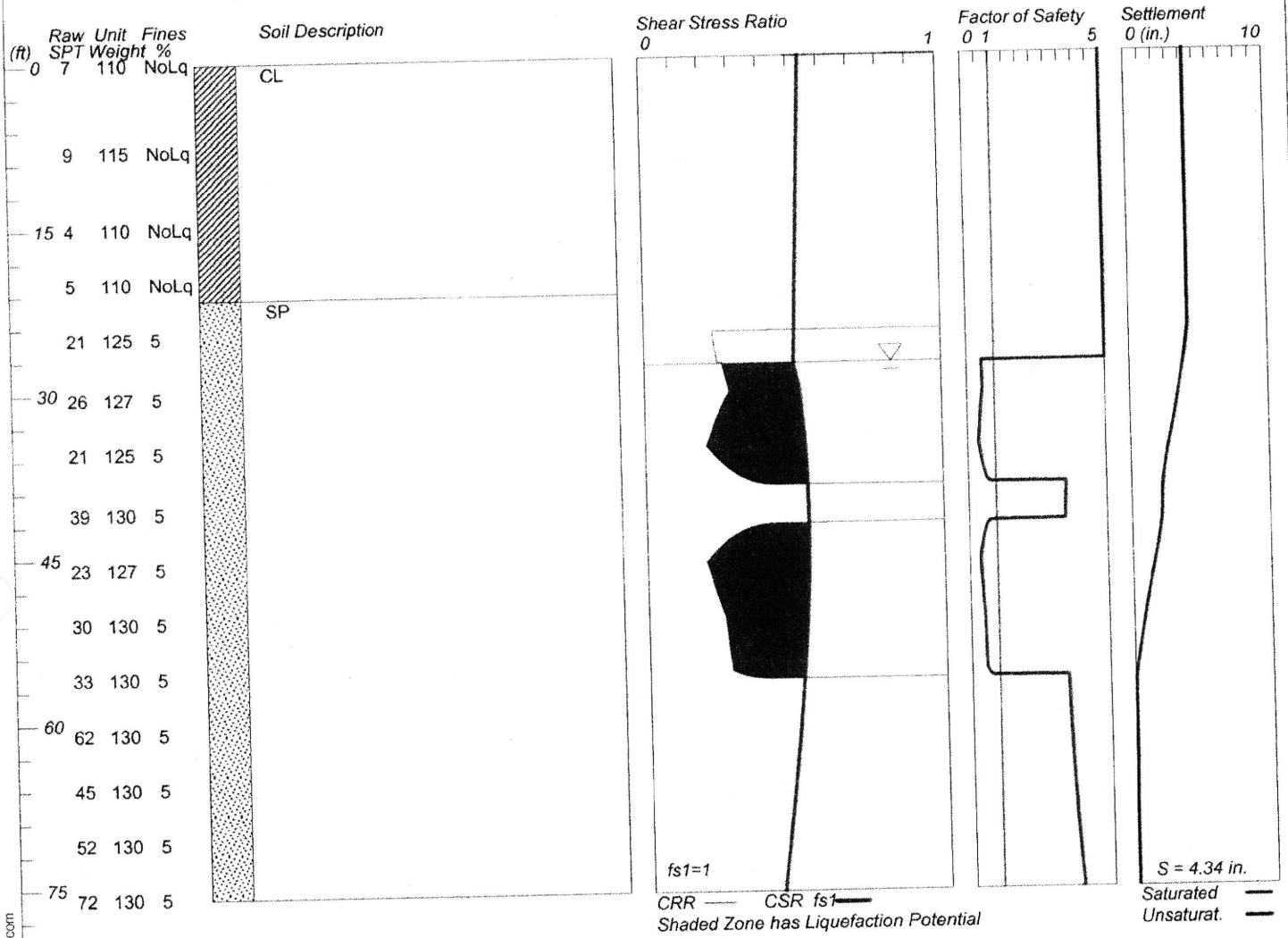
LIQUEFACTION ANALYSIS (ALT.A)

110288

Hole No.=6 Water Depth=28 ft Surface Elev.=211.3

Magnitude=7.5
Acceleration=0.833g



LiquefyPro CivilTech Software USA www.civiltech.com

BN-6, Cross County

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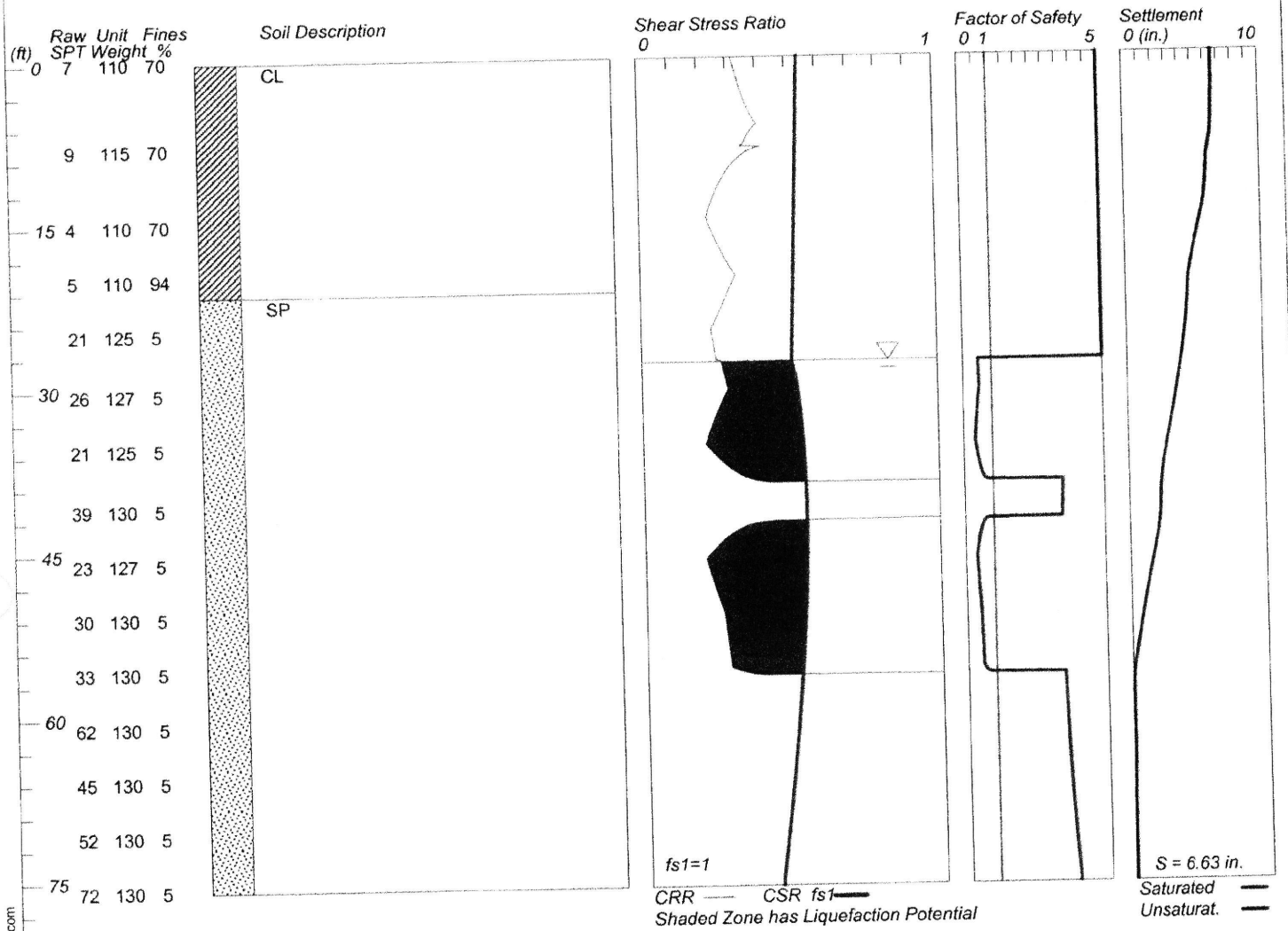
LIQUEFACTION ANALYSIS (ALT.B)

110288

Hole No.=6 Water Depth=28 ft Surface Elev.=211.3

Magnitude=7.5
Acceleration=0.833g



LiquefyPro CivilTech Software USA www.civiltech.com

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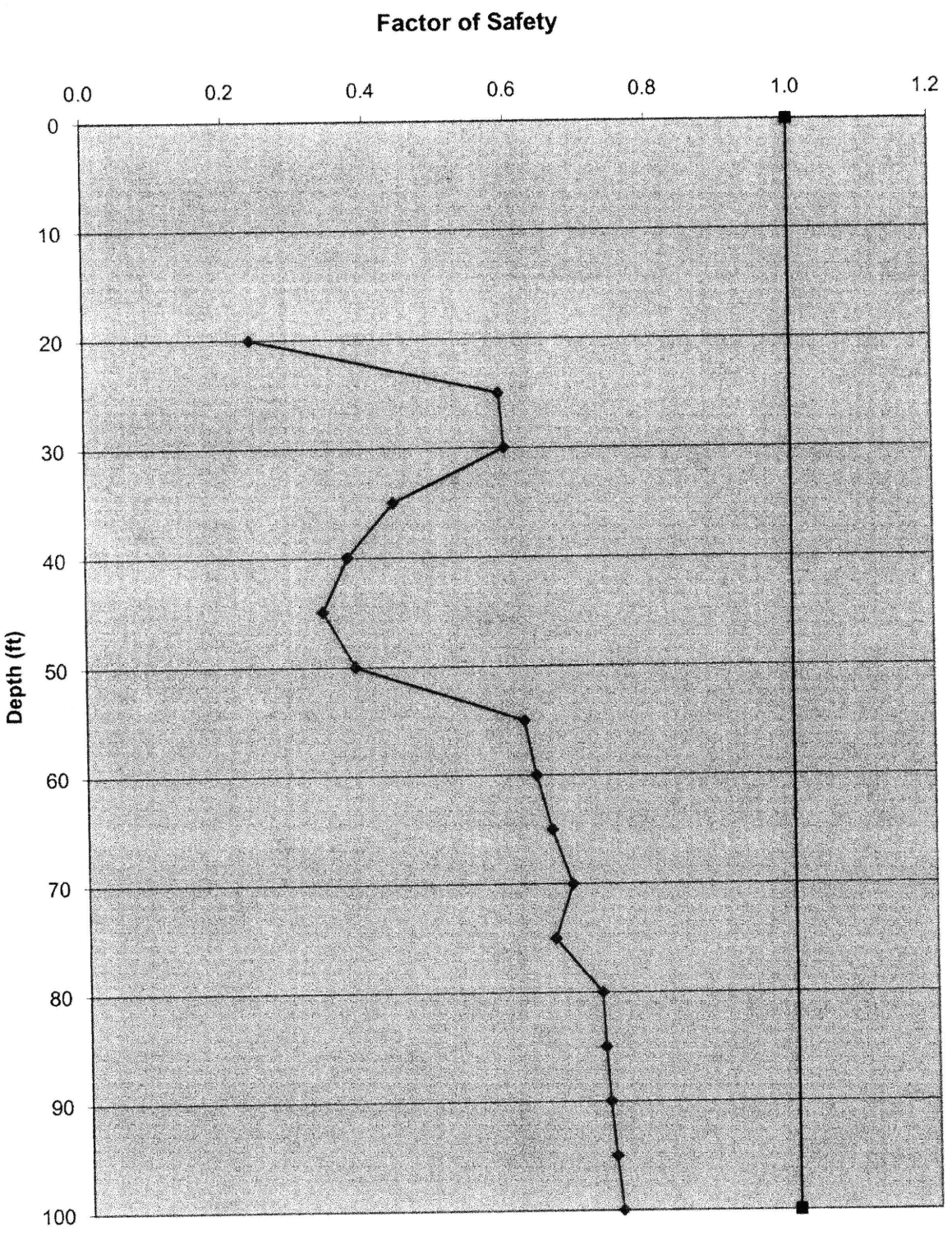
Liquefaction Spreadsheet - based on NCEER 1996 workshop
Simplified Procedure - Shear Wave Velocity Analysis
Project-110288

note applicible to sloping ground surfaces greater than about 6%

Moment Magnitude, M_w =	7.5	depth to finish floor =	0 ft
PGA =	0.833 g	uniform floor load =	0 lb/ft^2
depth to groundwater during drilling =	35 ft	assumed depth to groundwater =	35 ft
estimated age of sand deposit =	2000 years		

	Required Input Data					design		during drilling	Cyclic Stress Ratio		Analysis Based on Shear Wave Velocities					
depth	1=CL,ML,CH	γ_s	Field V_s	Fines	PI	σ_{vo}	σ'_{vo}	σ'_{vo}	r_d	CSR	V_{s1}	$CRR_{7.5}$	MSF	K_σ	Corrected	Factor of
(ft)	2=SP,SM,SC	(lb/ft^3)	(ft/sec)	%	%	(lb/ft^2)	(lb/ft^2)	(lb/ft^2)			(ft/sec)				CRR	Safety
5	1	110	787	94	15	550	550	550	0.988	0.5351	1087	NA	1.00	1.00	NA	NA
10	1	115	823	94	15	1125	1125	1125	0.977	0.5288	719	NA	1.00	1.00	NA	NA
15	1	105	607	10	15	1650	1650	1650	0.965	0.5225	637	NA	1.00	1.00	NA	NA
20	2	120	607	10	0	2250	2250	2250	0.953	0.5162	589	0.1224	1.00	1.00	0.122401	0.2
25	2	125	755	10	0	2875	2875	2875	0.942	0.5099	690	0.3000	1.00	1.00	0.299946	0.6
30	2	120	787	10	0	3475	3475	3475	0.930	0.5035	685	0.3000	1.00	1.00	0.299946	0.6
35	2	127	787	10	0	4110	4110	4110	0.889	0.4813	657	0.2108	1.00	1.00	0.210794	0.4
40	2	125	820	5	0	4735	4423	4423	0.848	0.4917	672	0.1825	1.00	1.00	0.182418	0.4
45	2	130	820	5	0	5385	4761	4761	0.808	0.4946	660	0.1658	1.00	1.00	0.165753	0.3
50	2	130	853	5	0	6035	5099	5099	0.767	0.4914	675	0.1869	1.00	1.00	0.186832	0.4
55	2	130	919	5	0	6685	5437	5437	0.726	0.4834	716	0.3000	1.00	1.00	0.299946	0.6
60	2	130	919	5	0	7335	5775	5775	0.685	0.4714	705	0.3000	1.00	1.00	0.299946	0.6
65	2	130	951	5	0	7985	6113	6113	0.645	0.4560	719	0.3000	1.00	1.00	0.299946	0.7
70	2	130	951	5	0	8635	6451	6451	0.604	0.4377	710	0.3000	1.00	1.00	0.299946	0.7
75	2	130	951	5	0	9285	6789	6789	0.563	0.4171	701	0.2756	1.00	1.00	0.275506	0.7
80	2	130	1017	5	0	9935	7127	7127	0.549	0.4142	740	0.3000	1.00	1.00	0.299946	0.7
85	2	130	1017	6	0	10585	7465	7465	0.537	0.4120	732	0.3000	1.00	1.00	0.299946	0.7
90	2	130	1181	6	0	11235	7803	7803	0.524	0.4088	840	0.3000	1.00	1.00	0.299946	0.7
95	2	130	1312	6	0	11885	8141	8141	0.512	0.4049	924	0.3000	1.00	1.00	0.299946	0.7
100	2	130	1312	6	0	12535	8479	8479	0.500	0.4002	914	0.3000	1.00	1.00	0.299946	0.7

Used Bore #9 for PI values & unit wt.

Vs Liquefaction Potential - Project 110288