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Effective stress back-analysis of past earthquake ground motions at paleoliquefaction sites

Analyse des mouvements de sol résultant de séismes passés en utilisant une approche de contrainte effective aux sites de paleoliquéfaction

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ABSTRACT
A methodology that provides a ground motion time history at paleoliquefaction sites is presented. The methodology presented uses the Meramec site as an example paleoliquefaction feature, and modeling the dynamic soil behavior during liquefaction using an effective stress approach. This paper presents a research effort using a one dimensional non-linear site response analysis, with assessment of pore water pressure build up, in addition to site characterization of the liquefaction features. Thus site-specific conditions and the non-linear response of soils are both taken into account.

RÉSUMÉ
Une méthodologie qui donne un mouvement du sol dans le temps durant l'événement sismique aux sites de paleoliquéfaction est présentée. Cette méthodologie est présentée en utilisant le site de la rivière de Meramec (MR25W) comme exemple de formation de paleoliquéfaction. Le comportement dynamique des sols durant les secousses sismiques est modelé en adoptant une approche de contrainte effective. Cet article présente les résultats d'un effort de recherche utilisant une analyse unidimensionnelle, non linéaire avec l'évaluation de l'accumulation des pressions d'eau interstitielle, en plus de la caractérisation géotechnique des formations de liquéfaction. Par conséquent, les conditions spécifiques au site à l'étude, ainsi que le comportement non linéaire des sols sont pris en considération.

1 INTRODUCTION

Earthquake-induced liquefaction can occur without leaving behind tangible evidence. However, in certain field settings, liquefaction of cohesionless sediments can be indicated by clastic sand dikes and sills that intrude a low-permeability fine-grained host stratum, which overlies the liquefied source sediments (i.e. liquefaction features).

Geotechnical site characterization, in conjunction with analytical dynamic modeling of the soil column at designated paleoliquefaction sites are used to back-calculate earthquake parameters adopting an effective stress approach. The paleoliquefaction features considered by the authors were discovered along the banks of the Meramec River near St. Louis, Missouri (Tuttle et al., 1999), and in southeast Missouri along the banks of the Dudley Main Ditch, Clodfelter Ditch and Wilhelmina Cutoff (Vaughn, 1994). The largest features were reported at Site MR25W, located about 0.8 kilometers east of US Highway 61/67 Bridge over the Meramec River north bank. Site MR25W will be further discussed in this paper to present the methodology proposed.

1.1 *Available back-analysis methods*

There are four commonly used methods to back-calculate past earthquake seismic parameters (moment magnitude and peak ground acceleration) based on paleoliquefaction evidence. These methods however, do not provide a back-calculated ground motion time history, and some uncertainties are associated with each one of these methods (Jadi, 2003).

The Seed et al. (1983) cyclic stress method uses a generalized equation, not accounting for site-specific conditions. The magnitude bound method (Ambraseys, 1988), which utilizes relations between the earthquake magnitude and distance from the tectonic source requires a well-defined energy center and outer limits of liquefaction. The Ishihara (1985) method has been shown to be valid only for sites where liquefaction has been severe. Finally, the energy-based methods (Berill & Davis, 1985, Trifunac, 1995), which relate the seismic energy to the ability of the soil to resist liquefaction, use the empirical Gutenberg-Richter relation (1956), which calculates total energy as opposed to dissipated energy. Depending on the geological setting, distribution and mechanism of formation of the observed features, one or the other of the four methods may be preferred. A combination of these methods is preferred for back-analyses and a suggested methodology is presented herein.

2 METHODOLOGY

Geotechnical site characterization and dynamic modeling of the soil column using a one-directional non-linear site response analysis, with assessment of pore water pressure build up are used to back-calculate credible past earthquake ground motion time history and seismic parameters (M, PGA and R). The approach adopted herein is presented in the following, based on the Meramec River site (MR25W) case study.

2.1 *Input Synthetic Ground Motions*

A series of synthetic ground motion time histories developed for the city of St. Louis (Hermann, 1999) for 2% probability and 10% probability of exceedance in 50 years were used in the numerical analyses as input earthquake ground motion at the base of the soil column. Table 1 lists a sample of the synthetic ground motions utilized, associated earthquake magnitudes, distance from source, and peak acceleration values. Synthetic ground motions are developed using band-limited white-noise stochastic simulations and random vibrations theory (Hermann, 2003).

Table 1 - Sample synthetic rock motions used for MR25W Site for a 2% Probability of Exceedance based on Hermann, 1999.

Sample No.	M	Epicentral Distance (km)	Focal Depth (km)	Peak Acceleration (g)	Duration Considered (sec)
1	8.0	229.5	9.10	0.106	104.16
2	5.4	28.70	2.10	0.300	20.470
3	7.1	253.1	5.50	0.098	81.910
4	8.0	213.9	25.6	0.070	104.16
5	6.8	224.8	5.80	0.093	81.910
6	8.0	196.3	33.9	0.104	104.16
7	8.0	186.5	9.10	0.062	104.16
8	8.0	260.7	9.10	0.100	104.16
9	8.0	280.5	9.10	0.102	104.16
10	5.9	47.70	4.40	0.216	40.950

2.2 *Geotechnical Characterization*

A field investigation program was designed to characterize the soil column, identify the source materials of the clastic dikes, and determine both low strain and large strain soil parameters for use in liquefaction modeling. The geotechnical field investigation was undertaken by a team of geologists and engineers and reported in Jadi et al. (2004). Field techniques included bank cleaning and logging, advancing two boreholes at the crest of the riverbank, testing and sampling, and two seismic piezocone probing. The site characterization techniques provided shear wave velocity profiles, values of resistance to penetration via seismic CPT and SPT values via standard exploration methods. A laboratory testing program, included particle size distribution analyses, Atterberg limits (liquid limit and plastic limit), field moist density, minimum and maximum void ratios, and stroke-controlled cyclic triaxial testing on representative paleoliquefaction sand.

The soil column at site MR25W consisted of typical alluvial deposits that consisted of clay and silty clay soils, overlying sand, clayey silt, and gravely-sand to sandy gravel soils Bedrock was encountered at a depth of 25.5 metes. For modeling and analyses, a simplified soil profile consisting of 10 layers was developed as shown in Figure 1.

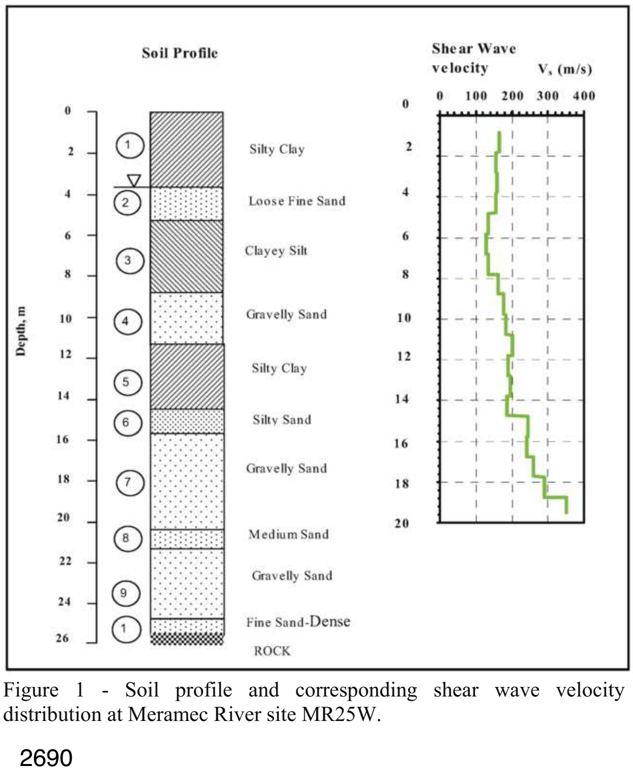

Figure 1 - Soil profile and corresponding shear wave velocity distribution at Meramec River site MR25W.

2.3 *Modeling and Analyses*

To model the soil column and the liquefaction behavior of the source sand beds, the one dimensional effective stress analysis site response computer program DESRA-MUSC (Qiu, 1998) was utilized. DESRA-MUSC was selected for its ability to model the non-linear response of soils using an effective stress approach in the time domain, as opposed to site response analysis programs, which assign equivalent linear soil properties to represent the non-linear hysteretic stress-strain behavior of soils due to cyclic loading. The state of stress, strains, pore water pressure build-up, and acceleration at each layer can be assessed at different times during the earthquake.

<u>*Identifying the Source Sand Layer*</u>*:* The source sand layer is the soil stratum, which liquefies under dynamic loading, and given the appropriate conditions, leads to the formation of liquefaction features. Factors considered for the identification of such layer(s), include comparing the gradation of samples collected from cohesionless strata, and samples collected from the exposed paleoliquefaction features, the depth range in which the source sand layer should lie, and the potential for the designated layer(s) to liquefy under a credible earthquake.

The main source sand layer at site MR25W was identified as layer 4 (gravelly sand). Layer 4 was found to have a near identical gradation to sand samples collected from the large paleoliquefaction dike. The designated source sand layer, which was encountered from the depth of 8.7 meters to a depth of 11 meters lies below the bottom of the exposed feature. Sand samples collected from smaller paleoliquefaction dikes, observed at higher elevations along the riverbank, were found to be of similar gradation to the fine sand layer (layer 2) encountered from about 3.6 to 5.2 meters of depth. As a result, layer 2 was also considered a potential paleoliquefaction source sand layer. It is likely that both layers liquefied under the past earthquake loading, and with the low permeability caps overlying each sand layer, the setting was favorable for the formation of the sand dikes observed.

<u>*Input Soil Properties*</u>**:** Table 2 presents the soil properties used in the analyses. These properties were determined based on the field and or laboratory testing conducted, or estimated using appropriate correlation.

Table 2 - Soil properties used in the analyses

Layer No	Unit Weight (pcf)	Cohesion (psf)	Friction Angle (deg)	Avg. PI	Shear Wave Velocity, ft/s	$(N_1)_{60}$
1	123	3000	N/A	20	525	9
2	120	N/A	30	N/A	492	3
3	121	750	N/A	15	394	1
4	126	N/A	38	N/A	590	16
5	131	3000	N/A	15	640	10
6	108	2000	24	N/A	656	17
7	128	N/A	38	N/A	656	31
8	115	N/A	35	N/A	984	57
9	128	N/A	38	N/A	984	57
10	115	N/A	35	N/A	984	N/A

The sites under study are located in infrequent earthquake zones such that long times (hundreds to thousands of years) separate earthquake events, allowing for significant aging of the soil deposits between events. Therefore, current penetration resistance values obtained at the paleoliquefaction sites via SPT and/or CPT tests were considered “representative” of the pre-earthquake values for back-analyses.

<u>*Shear Modulus Degradation and Damping*</u>*:* To account for soil non-linearity, normalized shear modulus-shear strain curves by Vucetic and Dobry (1991) were adopted in the analyses to represent the shear modulus degradation of fine-grained soils. Shear modulus degradation curves representing sand and gravelly sand layers, were adopted from Electric Power Research Institute (EPRI, 1993). The EPRI curves, which

account for the confining pressures and depth of soils were modified to include strains that are larger than 1% to obtain reasonable 'backbone' curves or normalized shear stress–shear strain curves (Qiu, 1998). The shear modulus degradation curve obtained from the laboratory cyclic triaxial testing on fine to medium paleoliquefaction sand was used to develop and compare the modulus degradation at strains higher than 1%. Hysteretic damping is generated in the program DESRA-MUSC with the mechanical Iwan Model (1967), thus no corresponding damping curves were needed for the input.

Liquefaction Analysis and Pore Pressure Parameters: To determine the values of pore pressure parameters the Byrne (1991) two-parameter model, which is a simplified version of the Martin et al, (1989) model, was utilized. Martin, et al. (1989) demonstrated a practical procedure of calibrating these parameters by back-fitting the given field liquefaction strength curves, and pore pressure build up function. First the field liquefaction curves are assessed for potentially liquefiable layers, based on SPT or CPT data. Then, based on available in-situ tests, shear modulus is determined as a function of shear strain amplitude and confining stress. The one-dimensional rebound modulus is determined after calibrating a set of laboratory tests or assumed curves to a reasonable set of constants k, m, and n. Finally, through a trial and error process the pore pressure constants in Byrne's model are determined by applying uniform cyclic loadings, such that the resulting shear stress ratio versus number of cycles curve matches the curve obtained from field liquefaction strength curve based on Seed, et al., (1983) method.

Existing Adjacent Fault Systems or Seismic Source Possible sources of seismic activity near St. Louis consist of four main fault systems. The New Madrid seismic fault zone is located at a distance of 260 km to 350 km south of St. Louis. The fault features on Shoal Creek near Germantown, Illinois are located some 65-km east of St. Louis and about 100 km east of the site. The Du Quoin-Centralia Monocline fault system situated at some 140 km east of St. Louis and, the Eureka House springs system at a distance less than 40 Km from St. Louis (Tuttle, et al. 1999).

3 RESULTS

The resulting acceleration time histories at the ground surface and at designated paleoliquefaction source sand layers (i.e layers 4, and 2) were obtained. The pore water pressure build up was determined by plotting the pore water pressure ratio (r_u) versus time. Plots of shear stress versus shear strain were also obtained at each designated source sand layer. Figure 2 shows a typical presentation of results, using synthetic ground motion sample 6 (M=8.0, R=196 km), which in this instance did induce liquefaction of layer 2. However, none of the synthetic ground motions considered did directly induce the liquefaction of layer 4 (i.e. the main paleoliquefaction source sand layer). Synthetic ground motion samples 6, 8 and 9 pertaining to the 2% probability of exceedance in 50 years group induced or nearly induced liquefaction of layer 2.

The 10% probability of exceedance in 50 years group of synthetic ground motions were eliminated as they did not cause liquefaction of neither source sand layer, with low pore water pressure build up in these layers. To induce liquefaction of layer 4, synthetic ground motion samples 6, 8, and 9 were scaled upward, in order to increase their input acceleration amplitudes at rock base. A systematic increment scaling multiplier was applied to the selected input synthetic ground motions, until the pore pressure ratio in the designated source sand layer reached a value of 1.0 (i.e. 100 % liquefaction). Table 3 shows, the resulting peak accelerations, and pore pressure ratio values obtained at layers 2 and 4 with the scaled input ground motions. Table 3 also depicts increased peak acceleration values at the base of the soil column, and at sand layers 2 and 4. Compared to the unscaled ground motion peak acceleration values presented in Table 1, the average peak acceleration associated with scaled ground motion sample 6 is 2.8 times higher than the value associated with the original motion. This increase resulted in an amplification of peak acceleration values and pore pressure ratio (r_u) at source sand layers 2 and 4. All three scaled synthetic ground motion samples 6, 8, and 9 were considered possible ground motion time histories of a past earthquake event in the area.

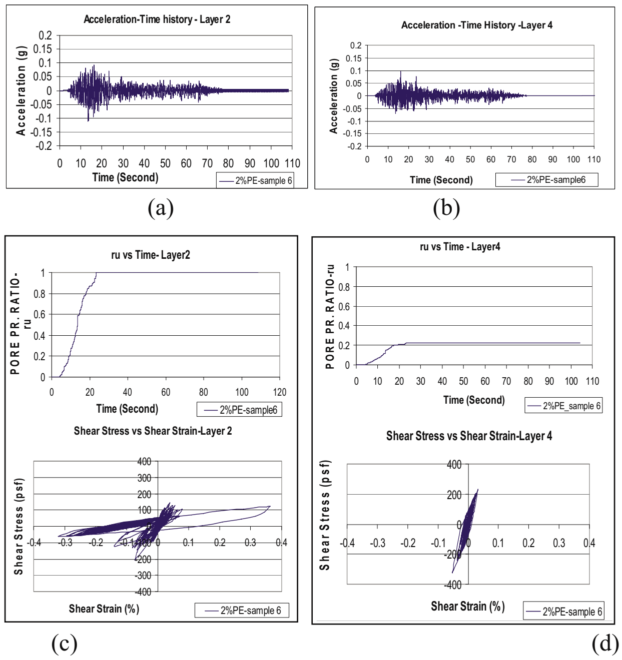

Figure 2 - Typical results of analysis (a) input synthetic motion at rock base: 2% probability of Exceedance-Sample 6, (b) resulting ground surface acceleration; (c) & (d) DESRA_MUSC effective stress solution at source sand layers 2, and 4, respectively.

The results also show that, the liquefaction of the main paleoliquefaction source sand layer (layer 4) required a minimum earthquake duration ranging from 23 to 30 seconds, with ground motions associated with a moment magnitude of at least M=8.0 and a minimum PGA of 0.18g. The peak ground accelerations (PGA) resulting from the input scaled ground motions samples 6, 8, and 9 at the site under study were 0.18g and 0.149 g and 0.207g, respectively. A distance from the paleoliquefaction site to a potential source of 196 km, associated with motion sample 6, can be attributed to the Du Quoin-Centralia fault system located at about 140 km east of St. Louis, Missouri and about 170 km east of the site. The distance from source of 260.7 km and 280.5 km associated with synthetic motion samples 8 and 9 can be attributed to the New Madrid fault system, where seismicity can originate from about 260 km to 350 km from the site.

Evaluation of Back-calculated Seismic Parameters: The synthetic ground motions described above were also evaluated using other existing methods. The moment magnitude M, and peak ground acceleration (PGA), were back-calculated using the Seed et al. (1983) cyclic stress method. The potential distance from source (R) was determined using the Energy-based methods [Davis & Berrill (1985) and Trifunac (1995)]. These values were then compared to corresponding seismic parameters associated with the synthetic ground motions obtained using the proposed effective stress method. The results, show that PGA obtained by scaled-synthetic ground motion 6 agrees best with the PGA back calculated using Seed's method. Using layer 2, PGA values were smaller than those obtained with the designated scaled synthetic ground motions. This was anticipated since source sand layer 2 liquefied prior to scaling the selected synthetic ground motions.

The back-calculated distance from source R using Davis and Berrill's energy-based method based on the strength characteristics of layers 2, and 4, respectively, were 280 km and 39 km for a M=8.0. Using Trifunac's method (1995), and considering layer 4, R was determined as 23 km for M=8.0. Trifunac's bound does not extend to soils with $(N_1)_{60}$ values less than 5, thus no value of R was estimated based on layer 2 with a $(N_1)_{60}$=3. It is evident there is a large discrepancy in the values of R obtained based on the two different source sand layers and using the two different methods. Much of the scatter is likely due to the fact that R is used as an epicentral distance by Trifunac and as a distance from the energy center by Davis and Berrill. Additionally, the seismic source mechanisms, directionality of strong motions, and local geologic settings are not accounted for in these models, which cause large differences in R–values obtained (Trifunac 1995). Scaled synthetic ground motion sample 6 associated with M=8.0, R=196 km and PGA=0.18g was therefore considered the optimal ground motion time history at this site.

Table 3 - Peak acceleration and pore pressure parameter (r_u) values obtained by effective stress solution for layers 2 and 4 with selected 2% probability of exceedance scaled ground motions.

Scaled Motion Sample No.	PA* (g)	Avg. PA** (g)	*Source Sand Layer 2*			*Source Sand Layer 4*			PGA (g)
			PA* (g)	Avg PA** (g)	r_u	PA* (g)	Avg. PA** (g)	r_u	
6	0.29	0.188	0.154	0.100	1.0	0.275	0.179	1.0	0.182
8	0.30	0.19	0.149	0.097	1.0	0.237	0.154	1.0	0.149
9	0.29	0.195	0.177	0.115	1.0	0.251	0.163	1.0	0.207

*PA = Peak Acceleration at base of soil column.
**Avg. PA= Average Peak Acc. (=0.65*Peak acc. value) at base of soil column.

4 CONCLUSIONS

The methodology presented herein has its limitations inherent on the assumptions made. Synthetic ground motion time histories, representing various earthquake scenarios need to be developed for the site under study, in order to back calculate the earthquake scenario(s) that will cause a ground failure condition similar to that observed at the paleoliquefaction site. The proximity to all potential seismic sources and the geological settings of the region should be considered when developing the synthetics. A detailed field and laboratory program needs to be carried with a sufficient level of detail and quality to match the modeling efforts. The most sensitive parameters in the analyses are resistance to penetration and shear wave velocity profiles used to estimate dynamic soil properties.

At the MR25W site, three ground motion time histories were found capable of inducing liquefaction of the source sand layers. The three ground motion time histories are associated with earthquakes of moment magnitude M=8.0, and distance from seismic source of 196.3 km, 260.7km, and 280.5 km, respectively. These distances indicate that the causative past earthquake(s) could have been centered closer to St. Louis, Missouri than the NMSZ. R-values of 260.7km, and 280.5km, show that even at such large distances from the seismic source, earthquake induced liquefaction can occur. Results of this study also show that the characterization of the soil column at paleoliquefaction sites using conventional field and laboratory tests results can be used to identify potential source sand beds within the soil column, and produce input parameters for a dynamic effective stress analysis in the time domain. The user can therefore input a variety of synthetic or real ground motion time histories at the base of the well-characterized soil column, and determine or back-calculate a ground motion that will simulate the effects of the causative paleo-earthquake.

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