FINAL TECHNICAL REPORT

A COMPREHENSIVE GEOTECHNICAL INVESTIGATION AND INSTALLATION OF A BOREHOLE ACCELEROMETER ARRAY IN THE NEW MADRID SEISMIC ZONE

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ABSTRACT

Estimating earthquake ground motions of earthquake engineering interest in the thick soil/sediment deposits in the upper Mississippi embayment is problematic. The problems can include: 1) site effects due to thick (>100 m) layers of low shear-wave velocity sediments, 2) non-linearity, 3) attenuation along propagation paths (lateral and vertical) between the seismic source and the surface, and 4) ground motion differences between lowland sites (i.e., floodplain) in northeastern Arkansas and southeastern Missouri and upland sites (i.e., loess bluffs) in western Tennessee (including Memphis) and Kentucky.

To address these issues, we have installed a 9-component vertical seismic array, VSAS, in the most active part of the New Madrid seismic zone (NMSZ). In addition to a surface accelerometer, a "deep" accelerometer was placed at the top of a very stiff horizon 260 m below ground surface (Paleocene-aged, Porter's Creek Formation?). An intermediate accelerometer was set at the bottom of an adjacent 30-m geotechnical hole. The site is located between existing University of Kentucky strong-motion stations VSAB and HIKY; data from the three sites will be incorporated to evaluate local site and path effects. Site characterization included surface compression- and shear-wave velocity measurements, as well as a downhole shear-wave velocity survey.

It is anticipated that we can evaluate the effect of deep soil conditions on earthquake ground motions in the NMSZ, characterize the dynamic soil properties (including nonlinear) of the post-Paleocene sediments in the NMSZ, and validate geotechnical techniques currently being used to characterize deep soil sites. We also expect to assess the NEHRP Recommended Provisions as they pertain to the upper Mississippi Embayment sediment, as well as, collect the pertinent data for a comparative study of site effects between the two predominant physiographic terranes (i.e., lowland floodplains and upland loess sites). All are important results. The validation of geotechnical techniques currently being used to characterize deep soil sites are applicable to sites throughout the upper Mississippi embayment, as well as, deep soil sites elsewhere (i.e., southern California). Quantifying and characterizing the path and site effects in the lowland and upland transition zone is necessary for realistic ground motion estimations in areas (i.e., western Tennessee and western Kentucky) that are not within the immediate boundaries of the NMSZ, but which are subject to the effects of earthquakes that occur in the seismic zone. The current NEHRP Recommended Provisions classify a soil site relative to the top 30 m, without regard to the damping effects and natural period of the overall sediment thickness. This methodology must be quantified and validated in order that local engineered structures are adequately constructed or retrofitted.

NONTECHNICAL SUMMARY

The thick Mississippi embayment soil/sediment deposits are expected to significantly alter the amplitude, duration, and frequency content of a significant earthquake. Estimating the ground motions of earthquake engineering interest in these thick deposits is problematic, however. To address these issues, we have installed a vertical seismic array consisting of three accelerometers in the most active part of the New Madrid seismic zone. It is anticipated that we can evaluate the effect of deep soil conditions on earthquake ground motions in the NMSZ, characterize the dynamic soil properties responsible for the effects, and validate geotechnical techniques currently being used to characterize deep soil sites. It is also anticipated that we can assess the NEHRP Recommended Provisions as they pertain to the upper Mississippi Embayment sediment. All are important results. The validation of geotechnical techniques currently being used to characterize deep soil sites are applicable to sites throughout the Mississippi embayment, as well as, deep soil sites elsewhere (i.e., southern California).

INTRODUCTION

The thick Mississippi embayment soil/sediment deposits are expected to produce significant earthquake site effects. Consequently, the primary objective of this ongoing study is to rigorously evaluate the soil transfer function of the post-Paleocene sediments at a site near the center of the New Madrid seismic zone (NMSZ) for the purpose of constraining existing and future site response models in the region (Fig. 1). The site of the new vertical accelerometer array is near the most active part of the NMSZ; therefore, it should provide the maximum amount of data in the shortest period of time. The location of the site is typical of what Toro et al. (1992) referred to as Embayment Lowlands (i.e., floodplains) that cover much of the northern embayment (Fig. 2). In addition, the site is midway between the existing strong-motion stations VSAB and RIDG (Street et al., 1995). The strong-motion station at VSAB is, on the average, triggered 1 to 2 times a month by an earthquake.

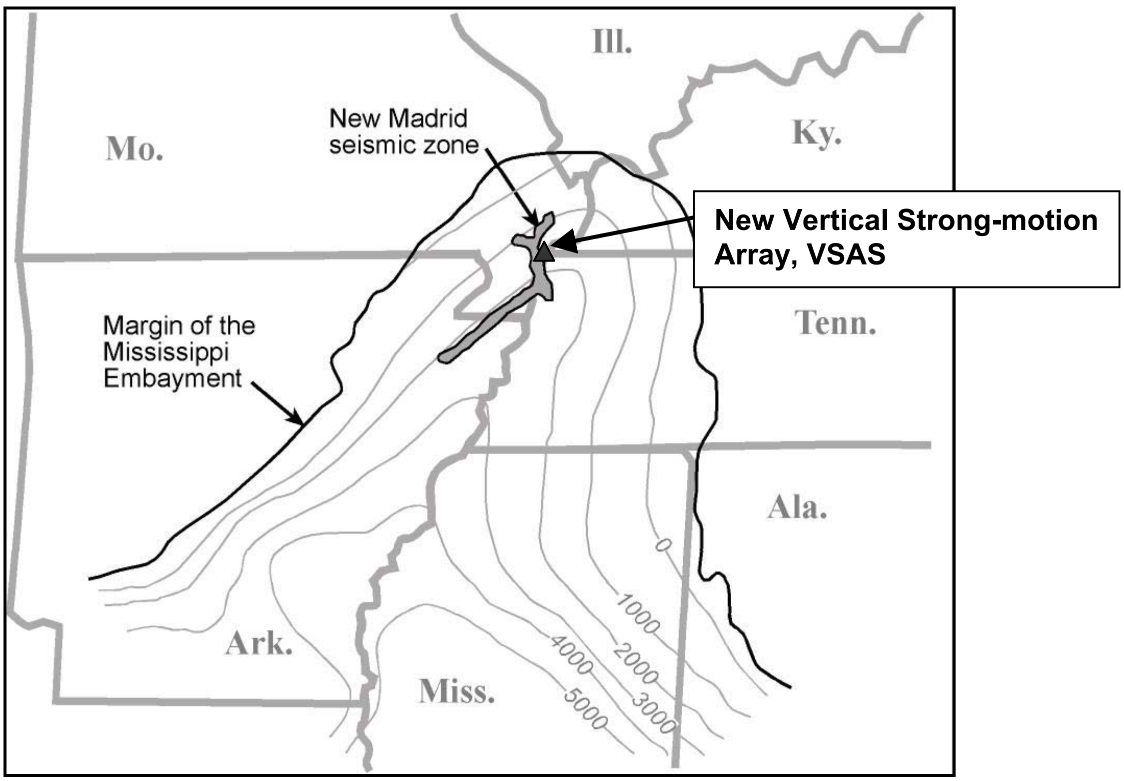


Figure 1. Location of the vertical strong-motion array, VSAS, in the central segment of the New Madrid seismic zone. The contours show sediment thickness in feet below mean sea level.

The upper Mississippi embayment is a south-plunging synclinal trough characterized by gently dipping post-Paleozoic sediments that thicken to the south. The depth to the Paleozoic bedrock at the site is approximately 595 m, and the depth to the very stiff Porters Creek Clay is 260 m. These depths are based on a proprietary seismic reflection line, the Ken-Ten Oil Exploration No. 1 Sanger hole (Schwalb, 1969), a walkaway sounding adjacent to the well site, and our experience in the area (Street et al., 1995; Woolery et al., 1999).

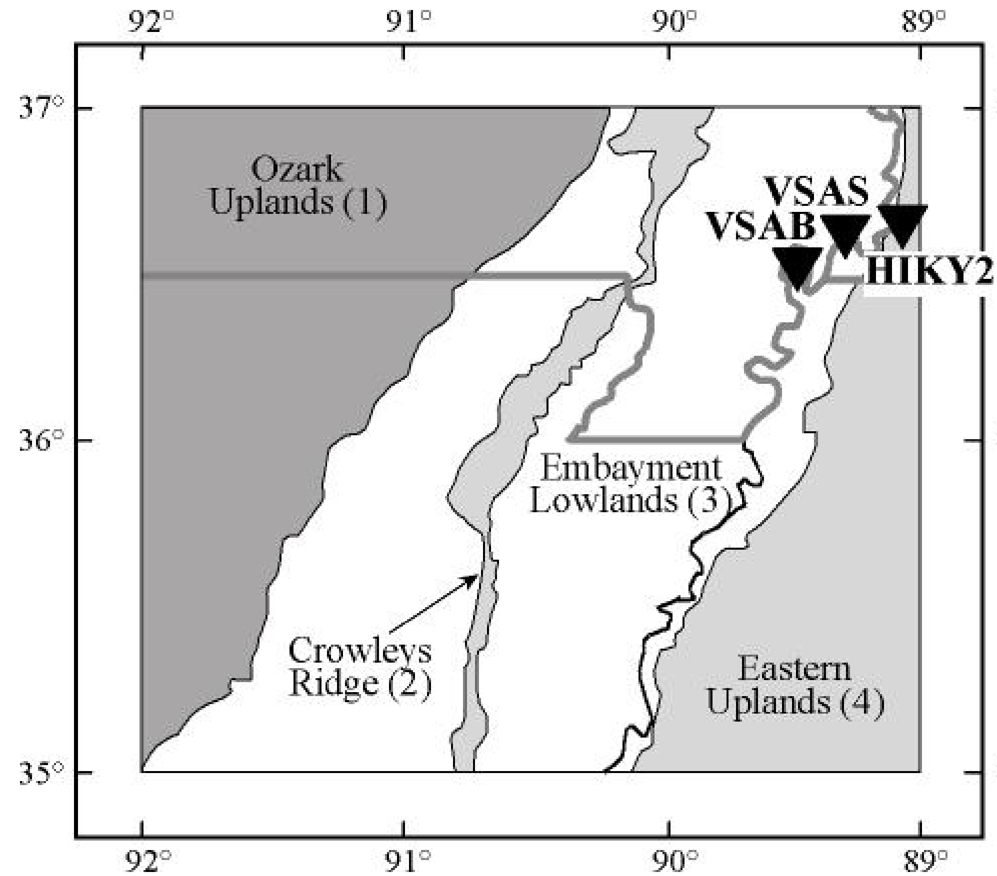


Figure 2. Four soil regions discussed by Toro et al. (1992). The proposed site for vertical accelerometer array (VSAS) is situated between existing strong-motion stations VSAB and HIKY2.

The vertical accelerometer array consists of three 3-component accelerometers, recorded on a 24-bit, 9-component accelerograph equipped with GPS timing (Fig. 3). The “deep” borehole accelerometer is placed in a hole drilled to the top of the Paleocene-aged Porters Creek Clay 260 m below the surface at the proposed site (Fig. 3). The Porters Creek Clay consists predominately of montmorillonitic clay, with minor amounts of interbedded sand and clay in the upper part of the formation (Olive, 1980). It appears as a distinct seismic impedance boundary on our sounding seismograms in the area. The second borehole accelerometer is placed at the bottom of a 30 m geotechnical hole. This corresponds to the critical depth used for the soil Site Classification as defined in the NEHRP Recommended Provisions. The borehole accelerometers will be installed in accordance with recognized procedures (Kinemetrics, 1999). The remaining accelerometer is a "free-field" installation placed in a surface vault between the two wells.

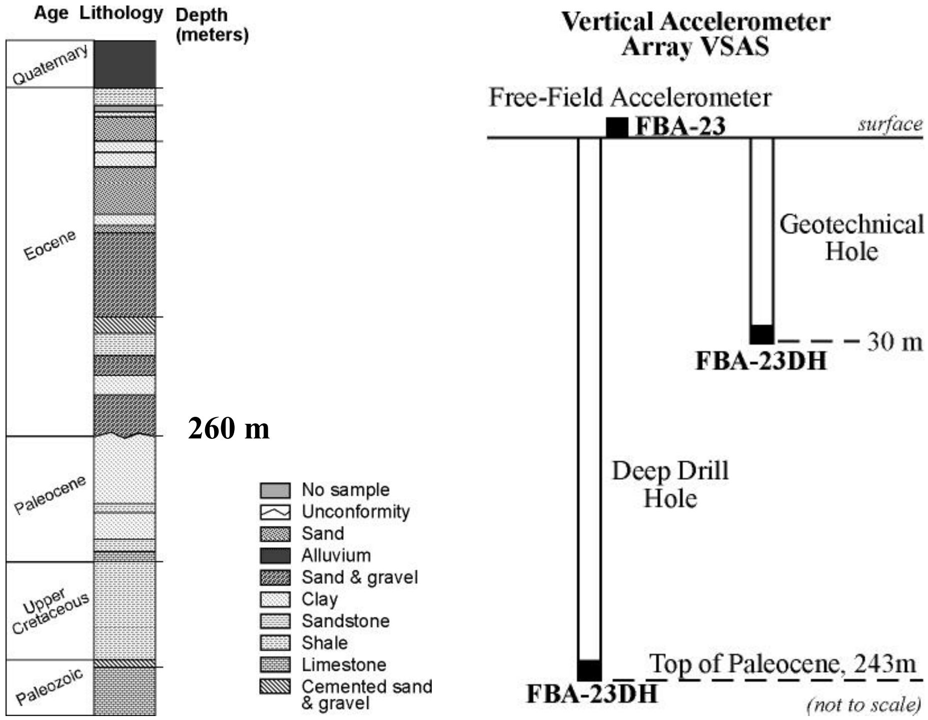


Figure 3. Stratigraphic setting and geometry of the vertical accelerometer array. Deep FBA 23 actually set at 260 meters.

LONG-TERM ARRAY OBJECTIVES AND CONTRIBUTIONS

Five significant contributions to the NEHRP program are expected from this vertical accelerometer array in the New Madrid seismic zone (NMSZ).

- Evaluation of the effect of deep soil conditions on earthquake ground motions in the NMSZ.
- Characterization of the dynamic soil properties of the post-Paleocene sediments in the central NMSZ.
- Validation of techniques currently being used to characterize deep soil sites.
- Evaluation of NEHRP Recommended Provisions, as they pertain to the NMSZ.
- Evaluation of path effects between stations VSAB, VSAS, and HIKY.

Local soil conditions have a profound influence on the characteristics of ground shaking experienced during an earthquake. Damage patterns in the 1989 Loma Prieta (M_w=6.9) and the 1994 Northridge (M_w=6.7) earthquakes generally correspond with areas underlain by deep and/or soft soil deposits, indicating that these soil deposits intensified ground motions and enhanced damage (Holzer T., 1994; Chang et al., 1996). These earthquakes highlight the importance of understanding how soil conditions affect ground motions. Exceptionally deep soil deposits, on the order of 100 to 1,000 meters deep, are found in the NMSZ; therefore, a major objective of the downhole array is to evaluate the effect of these deep soil deposits on earthquake ground motions. Because deep soil sites are found in other seismic regions of the country (e.g., southern California), data from this array will have significance throughout the United States.

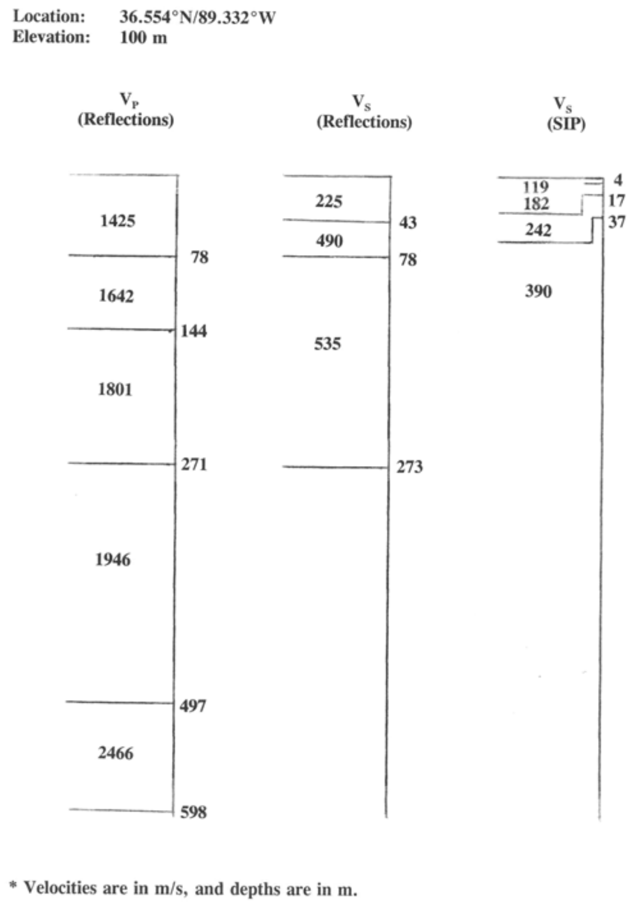
As previously mentioned, bedrock is concealed throughout the NMSZ by post-Paleozoic sediments that range between 100 and 1,000 m in thickness. The bedrock in the most active part of the NMSZ is overlain by nearly 600 m of sediments. These sediments consist of deltaic, shallow marine, and fluvial gravel, silt, and clay. The geometric configuration of these units is enigmatic due to the complicated structural and depositional geology. Consequently, surface recordings in the NMSZ consist of a complex mixture of source, path, and site effects (including anisotropy). Therefore, the only truly reliable means of separating source and path effects from site effects is to simultaneously record the earthquake at the base rock and ground surface. Although the VSAS does not have a sensor into rock, the ability to compare ground motions with records from the top of the first major stiff layer will provide significant improvement to the state-of-knowledge. Field et al. (1998) also noted the best source of information for characterizing the input motion at a site comes from a downhole array of accelerometers. They also state that downhole array recordings are essential to accurately resolving the source, path, and site effects (including nonlinearity). To gain the most from downhole array recordings, the dynamic soil properties must also be rigorously defined. As a result, a major task of the investigation has been the evaluation of the dynamic soil properties at the site. The in situ P- and S-wave seismic velocities for the underlying soil column was measured using surface refraction/reflection methods to top of rock. In addition, the downhole method was used to measure velocities to a depth of 30 m.

The deep borehole array provides a unique opportunity to investigate the seismic response of deep soil sites, and will allow current analytical models to be validated for deep (i.e., □100 m) soil sites. A downhole array is extremely useful in verifying analytical procedures because the input motion at the top of the very stiff Porters Creek Clay is known, and with reliable dynamic soil property data, the sole remaining uncertainty is the analytical procedure. Hence, the accuracy of current analytical procedures to predict surface motions can be assessed. Several analytical models are currently being used to predict the seismic response of deep soil sites; however, these analytical procedures have not been well validated for sites deeper than 100 m. The largest uncertainties in current analytical models are their use at sites deeper than 100 m and their treatment of soil nonlinearity. The most widely used program to analyze the seismic response of soil deposits is SHAKE (Schnabel et al., 1971; Idriss and Sun, 1992). SHAKE uses equivalent-linear soil properties to model soil nonlinearity. In an equivalent-linear analysis, the shear modulus and damping ratio of each soil layer are varied on the induced shear strain. Iterations are performed until the shear strains calculated by the program are compatible with those used to choose the soil properties. The equivalent-linear procedure is most accurate for smaller intensity ground motions where nonlinearity is less pronounced, and for stiff soil deposits where large strain is not induced even by large intensity motions. For larger intensity motions and/or softer soils, a fully nonlinear dynamic analysis is appropriate. A nonlinear analysis models the nonlinear shear stress–strain loops exhibited by soils in laboratory tests, changing the stiffness of the soil as earthquake shaking progresses. Consequently, nonlinear analysis captures more accurately the stress–strain response of the soil. Additionally, nonlinear analysis tends to capture the long-period response of deep soil sites more accurately than SHAKE. It is important to note that both equivalent-linear and nonlinear analyses can model parts of the soil deposit as linear and other parts as nonlinear. Comparisons between nonlinear and equivalent-linear computer programs indicate that both analytical procedures produce similar results for lower intensity motions where nonlinearity is less pronounced. At larger intensities, nonlinear analysis predicts smaller ground motions at the surface due to soil nonlinearity, in accordance with observations from recorded ground motions. Neither equivalent-linear nor nonlinear analyses have been adequately validated for soil depths greater than about 100 m. Recordings from the deep borehole array in the NMSZ will provide a unique opportunity to test both analytical procedures. Recorded motions at the top of the very stiff Porters Creek Clay will be used as input into dynamic analyses along with dynamic material properties evaluated as part of the site characterization parts of this study. Comparing the calculated surface response with the recorded surface response at the downhole array will provide significant insight into the analytical procedures used to predict earthquake ground motions at deep soil sites. Without a well-constrained analytical procedure engineers cannot have a high level of confidence in their predictions. The results will have implications not only in the NMSZ, but also in other parts of the United States, such as southern California, where soil deposits are often deeper than 100 m.

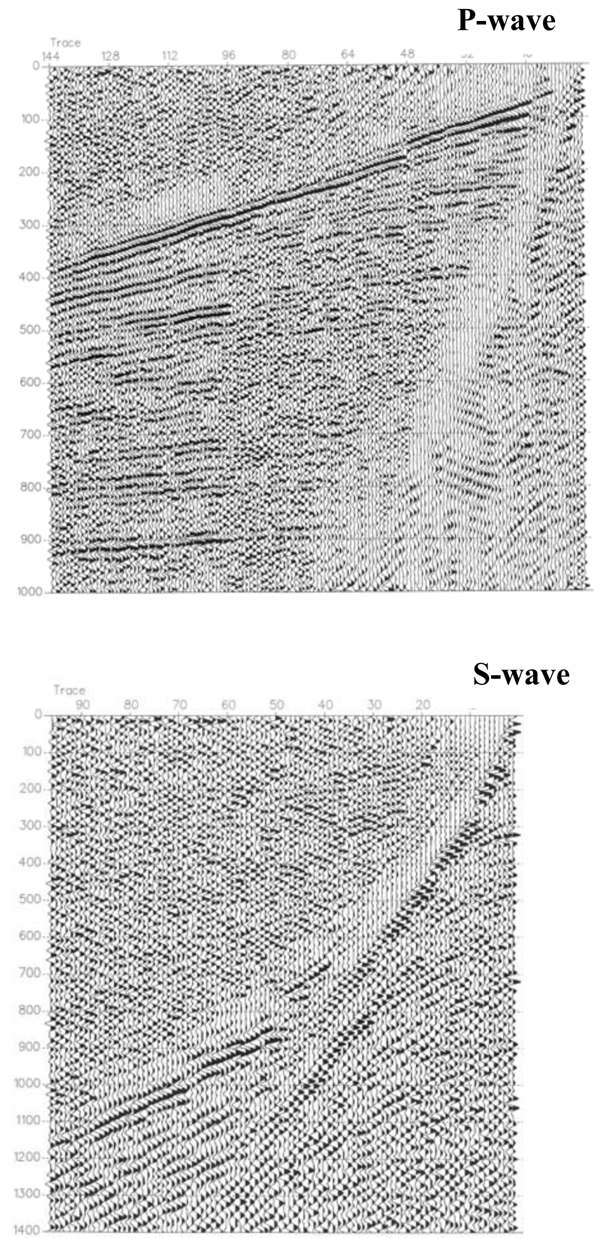
Seismic hazard maps for the United States have been developed by the USGS and NEHRP (National Hazard Reduction Program), and are included in the 2002 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. The current maps specify ground motions for soft rock sites with a specific probability of exceedance. A soft rock site is defined by an average shear-wave velocity in the top 30 m between 760 and 1,500 m/s, and is given the designation Site B. A simplified procedure that uses scaling factors attempts to adjust the ground motions for a particular site's soil conditions. The scaling factors are defined for five site classes, *A* through E (Site Class *F* requires a site-specific evaluation), and are a function of the intensity of input ground motions. However, site classes are established only on the properties of the top 30 m of soil. Specifically, site classes are based on time-averaged shear-wave velocity of the upper 30 m. This procedure assumes that only the top 30 m of soil significantly influences the ground motions at a site, which is a critical assumption, particularly when the soil is several hundred meters thick as in the NMSZ. Anderson et al. (1996) showed that damping properties of deeper soils (i.e., deeper than 30 m) are as critical to the resulting free-surface ground motions as the shear-wave velocities of the upper 30 m of soil. Bard and Chavez-Garcia (1993) showed that the deeper layers of surficial sediments in Mexico City have a significant effect on the ground motions at the surface. Further, using only time-averaged shear-wave velocities of the upper 30 m ignores the natural period(s) of the entire site, where the majority of amplification is expected to occur. Consequently, a primary objective of the ongoing research is to evaluate the applicability of the current NEHRP scaling factors and procedures to the NMSZ.

RESULTS

A Fulton County, Kentucky landowner (Mr. Austin Voorhees) granted the University of Kentucky a 5-year right-of-entry (with an option to extend) to a small parcel of land for the purpose of installation and operation of the central NMSZ vertical strong-motion seismic array, VSAS. Specifically, VSAS is sited in the community of Sassafras Ridge, Kentucky, at coordinates N 36º33.139', W 89º19.784'. Preliminary surface seismic refraction and reflection surveys at the site identified a significant shear-wave velocity increase at approximately 260 meters in depth (Fig. 4). This "stiff" boundary correlates well with the anticipated Eocene–Paleocene stratigraphic horizon shown in Figure 3. A mud-rotary drilling company was subsequently contracted, and a 102 mm cased borehole was competed to depth of 260 meters (Fig. 5). A contract for the 30 m geotechnical hole was negotiated with a second drilling firm, and a 102 mm PVC-cased hole completed. The topmost 40 meters of sediment at the site were found to consist of loose to dense sands (SW/SP) and gravels (GW/GP). Consequently, attempted "Shelby" sampling failed to recover sufficient material for laboratory testing. An in-situ downhole seismic velocity survey was performed, and the results shown in Figure 6.



(a)



(b)

Figure 4. a) P- and S-wave velocity/depth model (depth shown along the side of column; no elevation correction) for the unlithified sediment at the VSAS site. b) The soundings were derived from seismic refraction and reflection walkaway tests.

(a)

(b)

Figure 5. a) Mud-rotary drilling rig advancing the hole to 260 meters. (b) 102 mm ID casing and tri-cone drilling bit used in the installation and completion.

The Kentucky Geological Survey at the University of Kentucky has provided the downhole and surface accelerometers, as well as the recorder (Fig. 7). The three-component accelerometers are Kinemetrics FBA-23's. One downhole and the surface accelerometer are new, while the second downhole accelerometer was recently refurbished and calibrated at the factory. The recorder is a newly purchased, nine-component 24-bit Kinemetrics K-2 equipped with GPS timing and an internal dial-up modem. The KGS also contributed the required cable for the installation of the downhole accelerometer in the 30 m geotechnical hole. The completed station is shown in Figure 8. The recorded seismic data will be stored in standard format and available upon request. Requests for the information should be directed towards:

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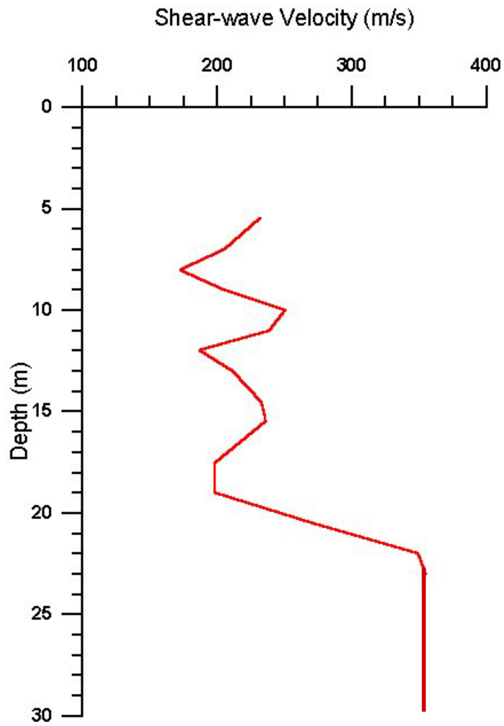


Figure 6. Downhole shear-wave seismic survey with a 3-pt smoothing function applied. Data were acquired with a 3-component, 14 Hz geophone.

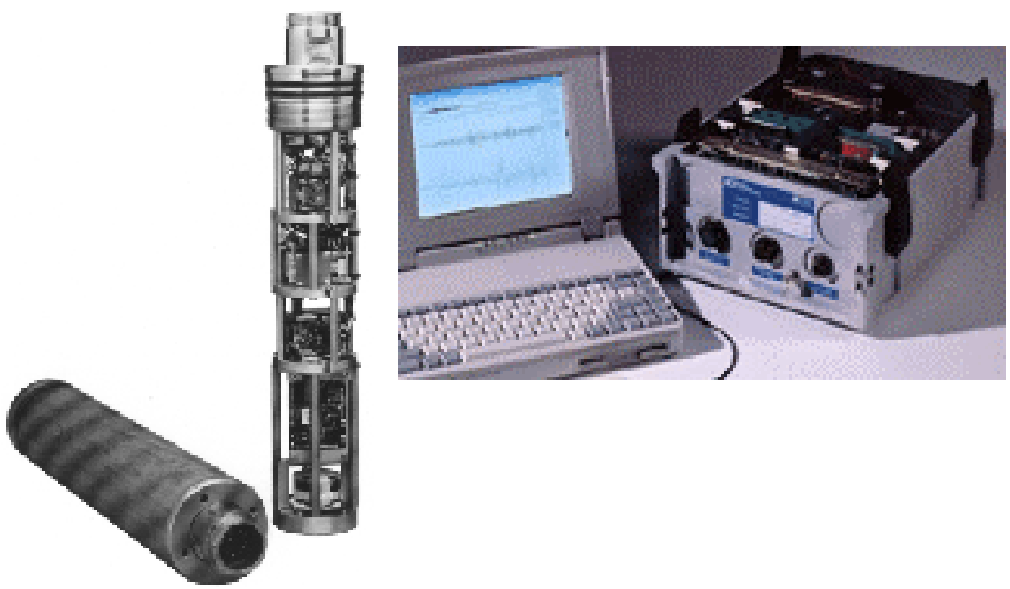
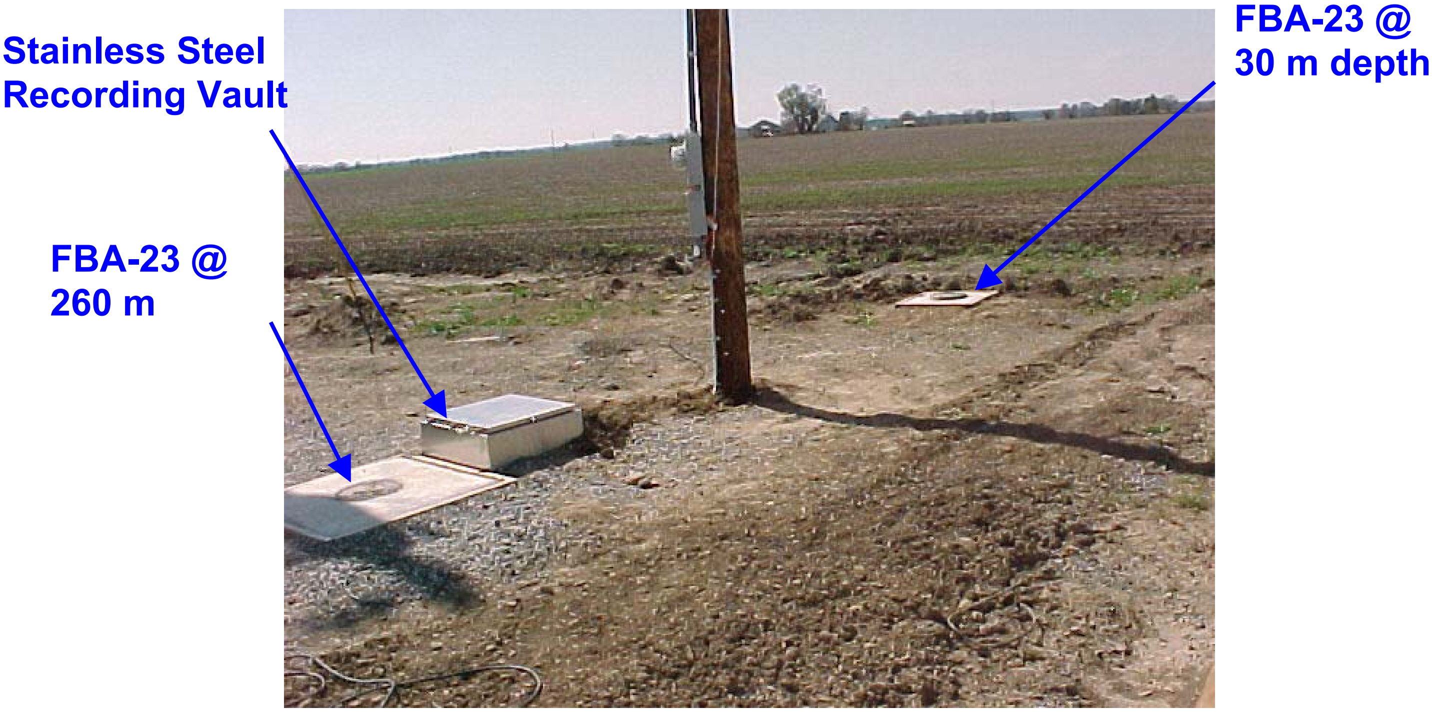


Figure 7. a) Kinemetrics FBA-23 downhole accelerometer used in the 260 and 30 m holes. b) Data are recorded at the site on a 9-channel Kinemetrics K-2 accelerograph (photos courtesy of Kinemetrics).



(a)

(b)

Figure 8. a) Surface view of VSAS installation. b) Stainless-steel recording vault containing K-2 accelerograph with onboard FBA-23 (surface) accelerometer, GPS clock, and internal modem.

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