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A COMPREHENSIVE GEOLOGICAL AND GEOTECHNICAL STUDY ON SITE RESPONSE AT SELECTED SITES IN THE NEW MADRID SEISMIC ZONE

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ABSTRACT

A comprehensive near-surface site investigation was conducted at two strong-motion stations, HIKY and RIDG, in the New Madrid seismic zone. A vertical strong-motion array was installed at both sites. Soil properties and subsurface geometries derived from these investigations were used, along with SHAKE91, for the numerical simulation of site response. The results from site HIKY show a maximum amplification factor of 8~36 between 19 m (down-hole) and the free surface with a predominant frequency of 3.8~4.3 Hz. Both amplification factor and predominant frequency depend on the input amplitude. The maximum amplification factor at site RIDG is approximately 4~44 between 34 m and the free surface, with a predominant frequency of 1.5~1.9 Hz.

KEYWORDS

Amplification factor; geological and geotechnical investigation; predominant frequency; site response.

INTRODUCTION

Site amplification is a well-documented phenomenon that results in great damages at some localities underlain by unconsolidated deposits. A large portion of the damage incurred in Mexico City during the 1985 Michoacan Earthquake was caused by the site amplification of unconsolidated lake deposits (Singh *et al.*, 1988). Stewart *et al.* (1995) also found that site effects contributed to significant concentrations of the structural damage during Northridge earthquake. Enhanced ground motions were also responsible for about 70% of the damage during Loma Prieta earthquake (Holzer, 1995).

The New Madrid seismic zone is located in the upper Mississippi Embayment where thick unconsolidated alluvium deposits overlie Paleozoic bedrock (Fig. 1). Consequently, the area is susceptible to extreme damage due to site effects. In order to study the site effects and strong-motion characteristics of this area, a network of strong-motion has been deployed by the NCEER (National Center for Earthquake Engineering Research) and University of Kentucky. The general site conditions down to the Paleozoic bedrock at strong-motion stations have been investigated using P- and SH-wave seismic refraction-reflection methods (Street *et al.*, 1995). Although these investigations provided useful information for site effect studies, the observations also indicated that more detail investigations, especially near-surface investigations, were necessary (Street *et al.*, 1995).

The detailed near-surface site investigations, using geotechnical and surface seismic techniques, were conducted at two strong-motion stations, HIKY in Hickman, Kentucky and RIDG in Ridgely, Tennessee (Fig. 1). A vertical seismic array, down-hole and free surface strong-motion recording system, was installed at both sites to collect the strong-motion data. The soil properties and subsurface geometries obtained from these investigations provide the essential data for site response studies. As a preliminary study, the site response at both sites was analyzed using 1-D nonlinear program SHAKE91(Idriss and Sun, 1992) in this paper.

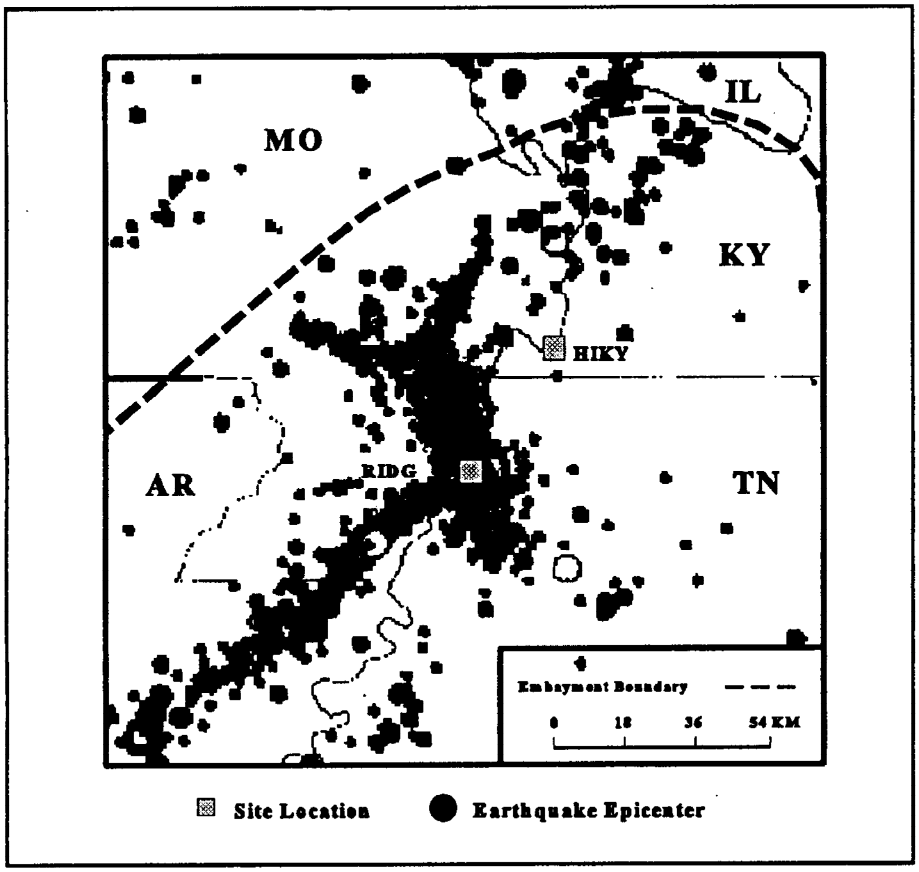

Fig. 1. Area of study and New Madrid Seismic Zone.

GEOLOGICAL AND GEOTECHNICAL INVESTIGATION

Geotechnical holes were drilled at sites HIKY and RIDG. The soil samples collected at both sites were tested in the Soil Laboratory in the Department of Civil Engineering, University of Kentucky. In-situ seismic tests, including surface refraction-reflection and down-hole methods, were also conducted at these sites. The test results are summarized as follow.

Site HIKY

A geotechnical hole was drilled at a state transportation garage in Hickman, Kentucky to a depth of 24 meters using rotary auger. The hole was subsequently cased with 10 cm diameter PVC for installation of FBA-23DH accelerometers. After settlement, the final depth of the hole is 19 m at which a FBA-23DH accelerometer was installed. The soils at this site consist of brown to gray, clayey silt with high water content. Split-spoon samples were collected at 3.05 m interval from the depth of 3.05 m to 21.3 m. Four Shelby tube samples were also obtained from the depth of 9.2 m to 18.2 m at 3.05 m interval. The soil properties for these samples were determined in the laboratory. The laboratory test results are summarized in Table 1.

Table 1. Summary of laboratory tests at site HIKY

Depth (m)	SPT (blows)	Specific Gravity (Gs)	Water Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plast. Index (PI)	USCS Class.	Perm. *k* (cm/s)
3.0-3.5	1-1-3	2.75	31.7	27	24	3	ML	
6.1-6.6	1-1-1	2.7	29.2	26	22	4	ML	
9.1-10.2	3-3-4	2.72	28.6	29	23	6	ML	1.4×10^{-7}
12.2-13.3	2-3-7	2.71	60.4	54	38	6	ML	1.0×10^{-8}
15.2-16.3	2-6-12	2.69	52.2	42	36	6	ML	3.5×10^{-5}
18.2-18.9	11-17-35	2.62	43.5	41	35	6	ML	
21.3-21.8	7-10-16	2.58	39.9	35	33	2	ML	

A SH-wave refraction profile was collected, using a 3.05 m group interval and a 3.05 m near offset. A short SH-wave CDP (Common Depth Profile) profile with a 1.5 m group interval and 6.1 m near offset was collected at site HIKY. A down-hole SH-wave seismic test was also carried out at this site. The results from these in-situ seismic tests are summarized in Fig. 2. A comparison between SPT values, water contents, and in-situ seismic test results is also included in Fig. 2. Laboratory tests show that the soils at site HIKY are made of clayey silt (Table 1), however, SPT values, water contents, and plasticity indexes suggest a jump at about 10 m deep. These soil properties' variations are coincident with the strong refractor and reflector recorded in seismic data.

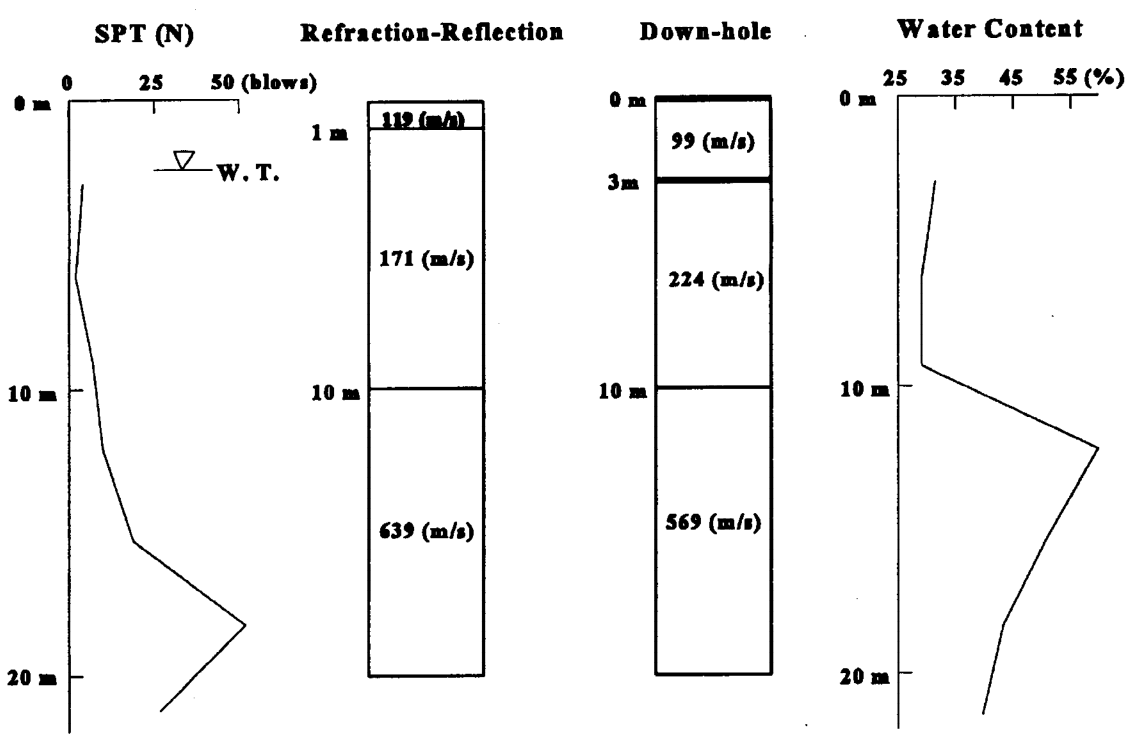

Fig. 2. Test results at site HIKY

Site RIDG

The geotechnical hole at strong-motion station RIDG in Ridgely, Tennessee was drilled down to the depth of 45.7 m. The water-table was encountered at depth of 5.8 m. Due to a very high water head in the silt and sand materials, a mud-rotary operation was used below 6.5 m to maintain the integrity of the boring. The hole was cased with 10 cm diameter PVC. After settlement, a FBA-23DH accelerometer was installed at the final depth of 35 m. The boring log below 6.5 m was based on samples retrieved from the drilling fluid. The most soils at this site consist of sand, except silt or silty clay near surface.

A short SH-wave refraction profile (1.52 m group interval, 6.10 m near offset) was collected across the geotechnical hole due to site limitation, and a SH-wave refraction-reflection profile was collected nearby. The down-hole SH-wave seismic test was also collected at this site. The soil column interpreted from refraction-reflection and down-hole seismic data are shown in Fig. 3.

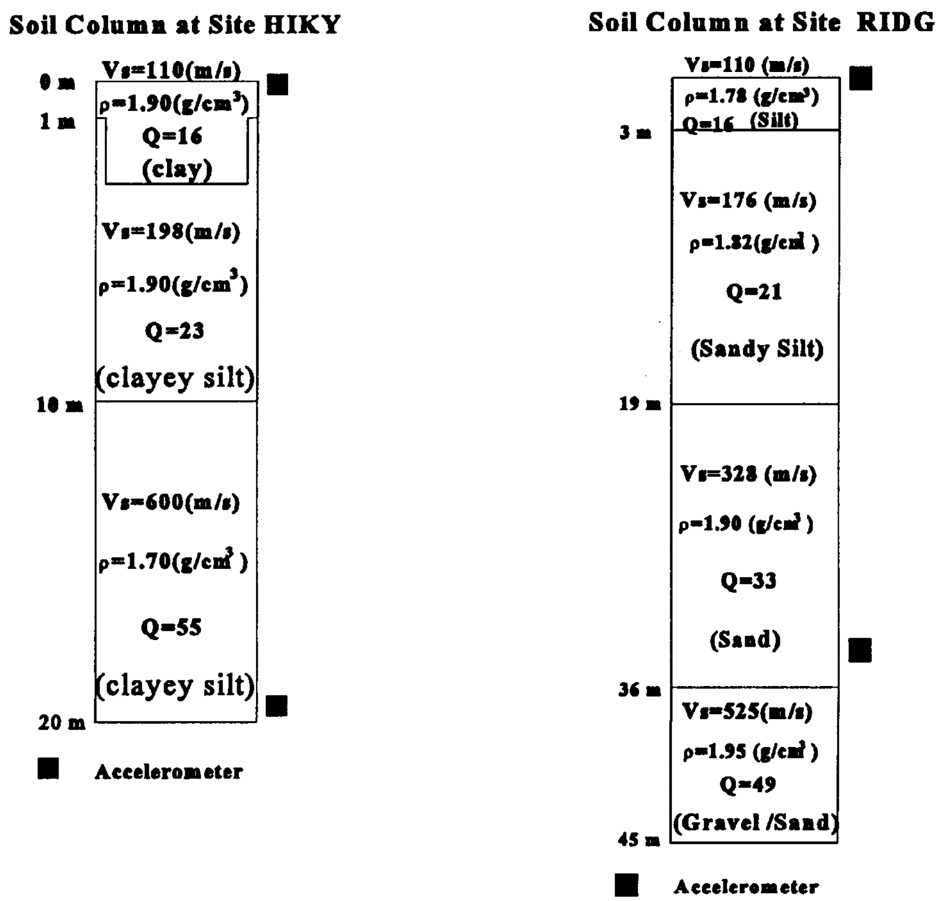

Fig. 3. Soil models at site HIKY and RIDG

SITE RESPONSE ANALYSIS

SHAKE91 (Idriss and Sun, 1992), a computer program for SH-wave propagation in 1-D and nonlinear multi-layer media, was used for site response analysis in this study. The input parameters for SHAKE91 are G_{max}, γ_{max}, densities (ρ), sublayer thickness, G-ε curves, and γ-ε curves. Here, G is shear module, γ is damping ratio, and ε is shear strain. G_{max}, densities (ρ), and sublayer thicknesses are derived from laboratory and in-situ tests. Damping ratio $\gamma_{max}=1/(2Q)$, and Q is shear wave quality factor which is estimated from shear wave velocity that was given by Wang *et al.* (1994) as

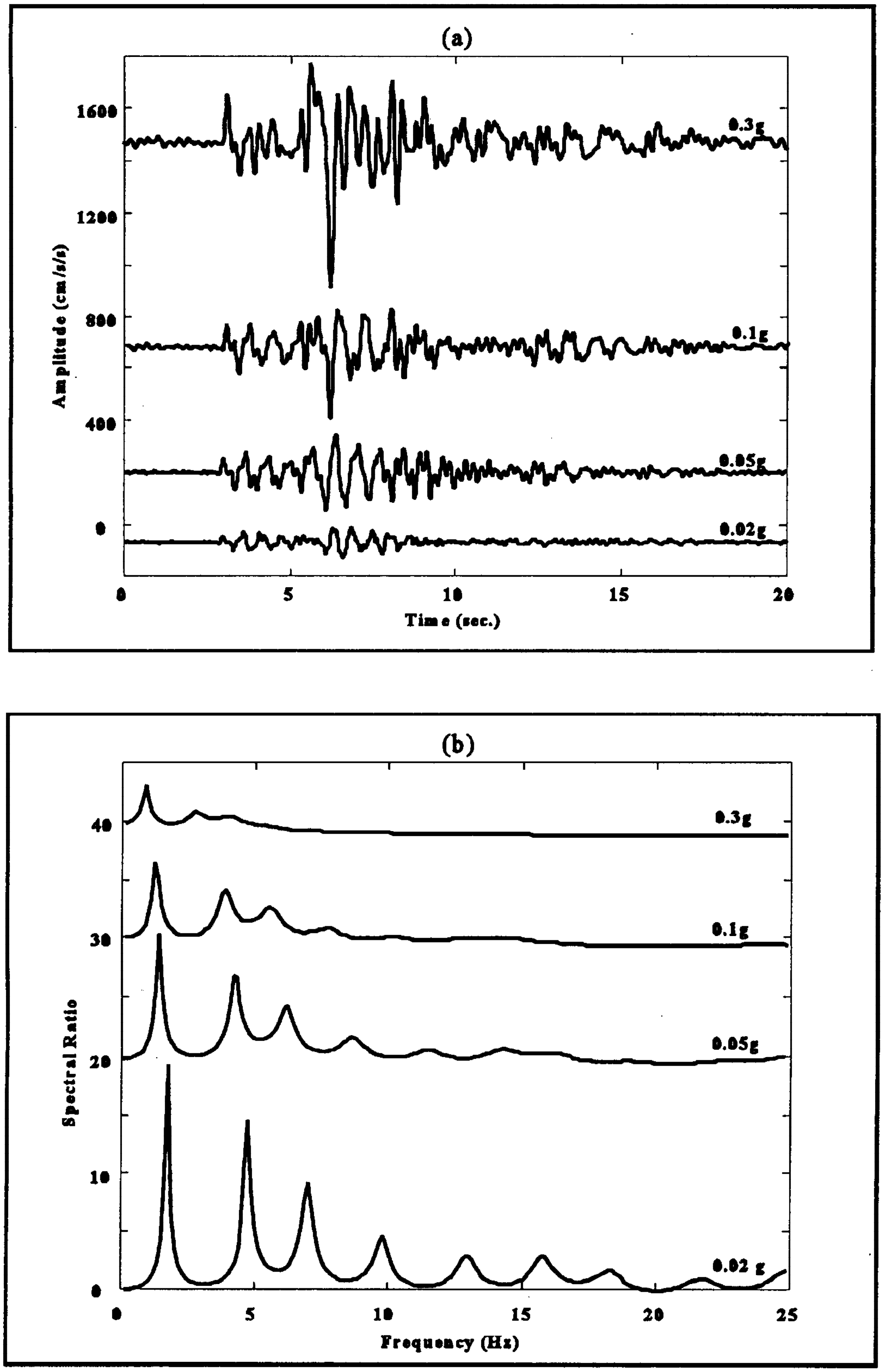

Fig. 4. Time histories and spectral ratios at site RIDG. (a) acceleration histories of surface corresponding to different maximum input amplitudes. (b) spectral ratios corresponding to different input maximum amplitudes.

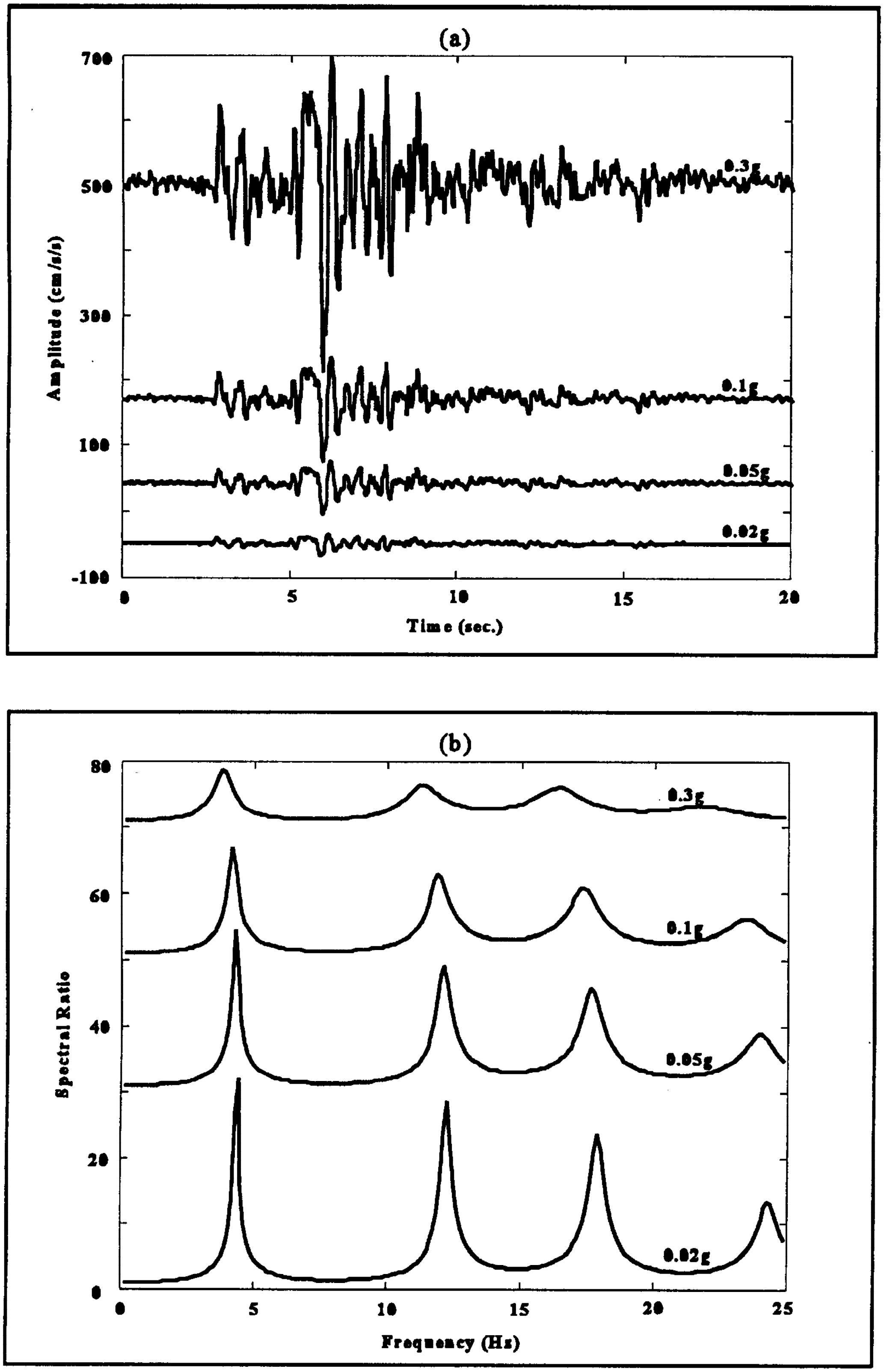

Fig. 5. Time histories and spectral ratios at site HIKY. (a) acceleration histories of surface corresponding to different maximum input amplitudes. (b) spectral ratios corresponding to different input maximum amplitudes.

$$Q = 0.08 V_s + 6.99 . \qquad (1)$$

The input parameters and geometries are shown in Fig. 3. The G-εcurves, and γ-ε curves for clay, silt, and sand used in this study are standard curves provided in SHAKE91 (Idriss and Sun, 1992) package.

Two strong motion records, Loma Prieta earthquake provided in SHAKE91 package that has duration about 5 seconds, and April 28, 1995 earthquake recorded at station LATN in the New Madrid Seismic Zone that has duration about 1 second, were used in this study. The input amplitudes of both earthquakes were also scaled to different levels in order to compare the site response corresponding to the input magnitude. The time histories corresponding to different input magnitude motions of Loma Prieta earthquake on free surface at site RIDG are shown in Fig. 4a, and the spectral ratios from 35 m (down-hole) to the free surface are shown in Fig. 4b. These results suggest that the amplification factor vary with the input magnitude, which is the higher input magnitude, the lower amplification. For Loma Prieta earthquake, the amplification factor at site RIDG varies from about 20 to 4 when the input changes from 0.02g to 0.3g maximum amplitude, and from 40 to 10 for April 28, 1995 earthquake. At site HIKY, the amplification factor varies from about 30 to 8 when the input changes from 0.02g to 0.3g maximum amplitude for Loma Prieta earthquake (Fig. 5), and from 40 to 10 for April 28, 1995 earthquake. The predominant frequency behaves in a similar characteristics that the predominant frequency declines as the input magnitude increase. The amplification factor also varies with the duration of input motion. For same scaled input amplitude, the amplification factor is lower for longer duration input motion.

CONCLUSION

Comprehensive geological and geotechnical site investigations provide the essential parameters for site response study. Along with 1-D and nonlinear program, SHAKE91(Idriss and Sun, 1992), site response at sites HIKY and RIDG was analyzed. The results show that amplification factor varies with the magnitude and duration of input motion (i. e. the higher amplitude, the lower amplification, and the longer duration, the lower amplification). The amplification factor from 19 m (down-hole) to free surface at site HIKY varies from 36 corresponding to maximum input amplitude of 0.02g to 8 corresponding to maximum input amplitude of 0.3g with the predominant frequency of 4.3~3.8 Hz. While at site RIDG, the amplification factor from 34 m (down-hole) to free surface varies from 44 to 4 with the predominant frequency of 1.9~1.5 Hz. The predominant frequency also depends on the input amplitude and duration.

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