

# CHAPTER 5 LIQUEFACTION ANALYSES OF AGGREGATE PIER FOUNDATION SYSTEM USING NUMERICAL MODELING

## 5.1 Parameters Used in Numerical Analyses

The models that were analyzed using FLAC version 4.0 (FLAC, 2000) are shown on Figure 5.1. The models have different soil types: loose silty sand with 20% fines content (Figures 5.1a and 5.1b), soft clay (Figure 5.1c), and silt (Figure 5.1d). Hence, the determination of the parameters is different for each model. The following sections discuss the determination of the parameters used in the analyses, with details are presented in Appendix A.

### 5.1.1 Soil Parameters

The following paragraphs illustrate the equations used in determining the parameters.

Since FLAC analyses were configured for groundwater (**CONFIGgw**), the dry density of the soil matrix should be used. FLAC will compute the saturated density of each element, using the known values of the density of water, the porosity, and the saturation. The dry unit weight of soil can be determined by the following equations:

$$G_s = \frac{\gamma_{sat}(1+e)}{\gamma_w} - e \quad (5.1)$$

$$\gamma_d = \frac{G_s \gamma_w}{(1+e)} \quad (5.2)$$

where:

$\gamma_{sat}$  = the saturated unit weight of soil

$\gamma_w$  = the unit weight of water

e = void ratio

$G_s$  = the specific gravity of soil

$\gamma_d$  = the dry unit weight of soil

The first three terms were selected based on typical values (for example, Das, 1994 and Coduto, 2001) and the last two were calculated using equations (5.1) and (5.2).

The void ratio of soil ( $e$ ) in the equations above can be determined using relationship with porosity ( $n$ ):

$$n = \frac{e}{1 + e} \quad (5.3)$$

The next step would be the determination of the soil bulk and shear moduli. But first, it is necessary to determine the values of the elastic modulus ( $E$ ) and Poisson's ratio ( $\nu$ ) using correlations (for example Das, 1994 and FLAC, 2000).

The values of  $E$  and  $\nu$  were then used to calculate the bulk modulus ( $K$ ) and the shear modulus ( $G$ ) using the following equations:

$$K = \frac{E}{3(1 - 2\nu)} \quad (5.4)$$

$$G = \frac{E}{2(1 + \nu)} \quad (5.5)$$

A similar procedure to the one outlined above was used to determine the parameters of the other two soil types: soft clay and silt.

The next step is to determine parameters used in the Finn model. The Finn model using equations proposed by Byrne (1991) was used for this research following the procedure in Section 4.3. By estimating the value of the corrected SPT blow count,  $(N_1)_{60}$ , for example as proposed by Peck, et al., (1974) and Das (1994), the values of constants  $C_1$  and  $C_2$  needed in the Finn model can be computed using equations (4.20) and (4.21).

### 5.1.2 Aggregate Pier Parameters

Fox and Cowell (1998) conducted in situ direct shear tests to find the values of the angle of friction ( $\phi$ ) of aggregate piers. They performed the tests on two materials: (a) open-graded AASHTO No. 57 stone and (b) well-graded AASHTO No. 21A base course stone and found the  $\phi$  values of  $48.8^\circ$  and  $52.2^\circ$ , respectively. Therefore, friction angle of  $50^\circ$  was selected for the aggregate pier.

Fox and Cowell (1998) also recommended the use of aggregate pier stiffness of 8 to 32 times stiffer than that of the surrounding soils. As a comparison, Wissmann, et al. (2001b) presented data from 31 modulus load tests carried out on aggregate piers constructed on residual Piedmont soils. They found that the elastic modulus of the aggregate piers varies from 115 MPa to 270 MPa (1,200 tsf to 2,800 tsf). These values correspond to stiffness ratio between the aggregate piers and the soil matrix varying from 5 to 60 for SPT blow counts ranging from 3 to 50 blows/foot. For this research, a conservative value of eight was selected.

The typical value of saturated unit weight of the aggregate pier ( $\gamma_{\text{sat}}$ ) is 147 pcf (or equal to FLAC saturated density ( $\rho_{\text{sat}}$ ) of  $4.57 \text{ slug/ft}^3$ ) and the dry unit weight ( $\gamma_{\text{d}}$ ) is 136 pcf (or equivalent of FLAC dry unit weight ( $\rho_{\text{d}}$ ) of  $4.23 \text{ slug/ft}^3$ ).

The permeability ( $k$ ) of  $10^{-1} \text{ cm/sec.}$  ( $3.28 \cdot 10^{-3} \text{ ft/sec.}$ ) was selected for the aggregate pier. This value corresponds to open-graded stone material.

Another parameter of the aggregate pier that has to be determined is the elastic modulus ( $E$ ). Figure 5.2 shows the basic model of aggregate pier that was used in FLAC analyses. The diameter of the aggregate pier is 3 feet. The width of the model is 8.4 feet while the depth is a variable as shown on Figure 5.1. Therefore, the area ratio of the model is  $3/8.4 = 0.36$ . On the other hand, the actual system has different area ratio. The area ratio of the actual system is the area of the aggregate pier normalized by the area of the cell.

The area of the aggregate pier is equal to  $\frac{1}{4} * \pi * 3^2 = 7.07 \text{ ft}^2$ .

The area of the cell is equal to  $8.4 \text{ ft} * 8.4 \text{ ft} = 70.56 \text{ ft}^2$ .

Therefore, the area ratio of the actual system is  $7.07/70.56 = 0.1$ . Since the area ratios are different, the stiffness of the aggregate pier should be reduced. The stiffness of the composite ( $E$ ) is calculated by using the following equation:

$$E = \frac{(E_g * A_g + E_s * A_s)}{A} \quad (5.6)$$

where:

$E_g$  = the stiffness of the aggregate pier = eight times the stiffness of the soil matrix

$A_g$  = the area of the aggregate pier = 7.07 ft<sup>2</sup>

$E_s$  = the stiffness of the soil matrix

$A$  = the area of the model = 3 \* 8.4 = 25.2 ft<sup>2</sup>

$A_s$  = the area of the soil model =  $A - A_g = 25.2 - 7.07 = 18.13$  ft<sup>2</sup>

It is apparent that the composite stiffness of the aggregate pier is affected by the stiffness of the surrounding soil matrix. Different values of elastic modulus of aggregate pier ( $E$ ) were computed depending on the type of the surrounding soil.

### 5.1.3 Water Parameters

As noted in Chapter 4, in FLAC the bulk modulus of water should be adjusted to reach equilibrium. For uncoupled flow-mechanical approach, the flow calculation can be set in flow-only mode (**SET flow on, SET mech off**), and then in mechanical-only mode (**SET flow off, SET mech on**). For the latter,  $K_w$  is set to zero, while for the former,  $K_w$  should be adjusted to  $K_w^a$  by using equation (4.29). The adjusted bulk modulus value ( $K_w^a$ ) is shown on Table 5.1. It can be seen that the values of  $K_w^a$  vary depends on the soil type.

For a coupled flow-mechanical problem (**SET flow on, SET mech on**), the value of  $K_w$  should be adjusted that the value of  $R_k$  is  $\leq 20$  by using equation (4.27). Hence,  $K_w$  of 3,995,730 psf was used.

Table 5.1 shows the summary of parameters that were used in FLAC analyses.

## 5.2 Numerical Modeling

The following sections explain how FLAC (2000) was used in the numerical modeling.

### **5.2.1 Grid Generation**

Figures 5.3 to 5.6 show the grid generation used in the numerical modeling analyses. The models are 8.4 feet wide with two different heights: 14.5 feet for Figures 5.3 and 5.4 and 26.5 feet for Figures 5.5 and 5.6. The smallest size of the grid is 0.5 feet by 0.5 feet and the largest size is 0.7 feet by 0.5 feet. The element size meets the requirement proposed by Kuhlemeyer and Lysmer (1973) as shown by equation (4.12).

In all figures, Points 1, 2, 3, 4, 5, 6, and 7 refer to the depths of 2.25 feet, 4.75 feet, 9.75 feet, 12.25 feet, 16.75 feet, 19.75 feet, and 24.25 feet, respectively. Point 1 is equivalent of grid (3,25), Point 2 is grid (3,20), Point 3 is grid (3,10), and Point 4 is grid (3,5) as shown on Figures 5.3 and 5.4. While for Figures 5.5 and 5.6, Point 1 is equivalent of grid (3,49), Point 2 is grid (3,44), Point 3 is grid (3,34), Point 4 is grid (3,29), Point 5 is grid (3,20), Point 6 is grid (3,14), and Point 7 is grid (3,5). The distance of all the above points is 1.25 feet to the left of the shaft of the aggregate pier. These points will be often referred to later in the discussion of the results.

### **5.2.2 Boundary Conditions**

The mesh generations used in FLAC analyses are shown on Figures 5.3 to 5.6. The nodes at both sides of the model were fixed in the horizontal (x) direction while the nodes at the base of the model were fixed in the vertical (y) direction. In addition to that, free field boundaries (Cundall, et al., 1980) were assigned at both sides of the model so that the outward waves propagating from inside the model can be properly absorbed by the boundaries. Silent boundary (Lysmer and Kuhlemeyer, 1969) was used at the base of the model for the same purpose as the free field boundaries, i.e., so that the outward propagating waves are not reflected back into the model by the boundaries.

### **5.2.3 Initial Conditions**

The initial conditions applied to the model are different for various types of soil used in the analyses. Figure 5.7 shows the initial conditions for the loose silty sand soil. The horizontal stress developed in the soil matrix adjacent to the aggregate pier is up to the passive capacity (White, et al., 2000), in this case up to 2500 psf.

The critical depth ( $z_{crit}$ ) can be calculated from:

$$(K_p \gamma_b) * z_{crit} = 2500 \text{ psf} \quad (5.7)$$

where:

$\gamma_b$  = the buoyant unit weight =  $(120 - 62.4)$  pcf = 57.6 pcf for silty sand

$K_p$  = the passive coefficient of earth pressure

$$= \tan^2 \left( 45^\circ + \frac{\phi}{2} \right) \quad (5.8)$$

= 3.0 for friction angle ( $\phi$ ) of  $30^\circ$

Therefore,  $z_{crit}$  of 14.5 feet was obtained. It means a triangular distribution of the soil pressure is appropriate for this case.

By using the same approach, the initial condition for silt soil was calculated as shown on Figure 5.8.

The groundwater level was assumed to be on the ground surface. Therefore, as an initial condition, the pore water pressure is set to the hydrostatic condition.

#### 5.2.4 Constitutive Model

It was decided that the soil was modeled with the Mohr-Coulomb plasticity model that incorporates the Finn model (Martin, et al., 1975). The aggregate pier was represented by elements in the FLAC grids that were assigned a Mohr Coulomb model without including the Finn model.

#### 5.2.5 Damping

For this research, Rayleigh damping was selected with both components: mass-proportional and stiffness-proportional were activated.

As noted previously in Chapter 4, the main idea is to obtain the center frequency ( $f_{min}$ ) of Rayleigh damping so it lies within the flat region, i.e. the range of predominant frequencies in the system. The center frequency ( $f_{min}$ ) is the frequency at which the mass-proportional and stiffness-proportional damping each contributes one-half of the total damping. To obtain this

value, FLAC was run for each model but no damping was assigned. The response of the system can be observed and the center frequency can be determined by plotting the frequency response of the undamped system.

### 5.3 Earthquake Motions

The following strong motions from two earthquakes were used in the numerical modeling:

1. The 17 October 1989 Loma Prieta earthquake as recorded at Corralitos station, California with magnitude ( $M_w$ ) of 7.1 and
2. The 25 November 1988 Saguenay earthquake as recorded at Chicoutimi-Nord, Quebec with magnitude ( $M_w$ ) of 6.0.

Both earthquakes records were filtered and baseline corrected following the procedures discussed in Section 4.2. By filtering the time histories and removing the high frequency components, a coarser mesh may be used without significantly affecting the results (Kuhlemeyer and Lysmer, 1973). Baseline correction was performed to force both the residual velocity and displacement to be zero. The purpose of this procedure is to prevent FLAC from exhibiting continuing velocity or residual displacements after the motion has finished. Both filtering and baseline correction were performed by using the software Bandpass (Olgun, 2001) written in MATLAB version 5.3 (1999).

The Loma Prieta earthquake records were scaled down to 0.45g from 0.64g. Figure 5.9 shows the scaled horizontal peak ground acceleration, velocity, and displacement time histories and Figure 5.10 shows the Fourier amplitude spectrum. For this earthquake record, the model was shaken for 16 seconds. The Saguenay earthquake, which has a peak ground acceleration of 0.05g, is shown on Figure 5.11. Figure 5.12 shows the Fourier amplitude spectrum. The model was shaken for 13 seconds for this earthquake record.

The Fourier amplitude spectrum expresses the frequency content very clearly. Both earthquake records show broad spectra. A broad spectrum corresponds to a jagged, irregular time history, which is the case observed. The Loma Prieta spectrum is strongest at low

frequency (high period) while the Saguenay spectrum is strongest at high frequency (low period).

In performing FLAC analyses using both earthquake records, the velocity record was used as input at the base of the model rather than using the acceleration record. This was suggested by FLAC (2000) and Cooke (2000) who found inaccuracies when using the acceleration record in dynamic analyses.



Table 5.1 Summary of parameters used in FLAC analyses

Parameters	Loose silty sand	Soft clay	Silt	Aggregate pier		Water
				Silty sand <sup>1)</sup>	Silt <sup>2)</sup>	
$\gamma_{sat}$ (lb/ft <sup>3</sup> )	120	110	115	147	147	62.4
$\rho_{sat}$ (slug/ft <sup>3</sup> )	3.73	3.42	3.57	4.57	4.57	1.94
$\gamma_d$ (lb/ft <sup>3</sup> )	94	77	85	136	136	N/A
$\rho_d$ (slug/ft <sup>3</sup> )	2.93	2.40	2.65	4.23	4.23	N/A
E (psf)	315,000	105,000	210,000	933,625	622,417	N/A
K (psf)	315,000	204,421	261,268	501,299	334,199	2.1*10 <sup>-6</sup>
G (psf)	118,125	37,118	76,865	392,412	261,608	N/A
c (psf)	0	210	63	0	0	N/A
$\phi$ (°)	30	17	25	50	50	N/A
$\psi$ (°)	0	0	0	0	0	N/A
(N <sub>1</sub> ) <sub>60</sub> (blows/ft)	10	4	8	N/A	N/A	N/A
C <sub>1</sub>	0.49	1.54	0.65	N/A	N/A	N/A
C <sub>2</sub>	0.82	0.26	0.62	N/A	N/A	N/A
e	0.7	1.1	0.9	0.25	0.25	N/A
n	0.412	0.524	0.474	0.2	0.2	N/A
FLAC permeability (ft <sup>3</sup> -sec/slug)	5.26*10 <sup>-8</sup>	5.26*10 <sup>-11</sup>	5.26*10 <sup>-10</sup>	5.26*10 <sup>-5</sup>	5.26*10 <sup>-5</sup>	N/A
K <sub>w</sub> (psf)	193,662	132,582	171,601	203,908	136,159	N/A

(Note: 1) Aggregate pier with silty sand as soil matrix  
 2) Aggregate pier with silt as soil matrix)

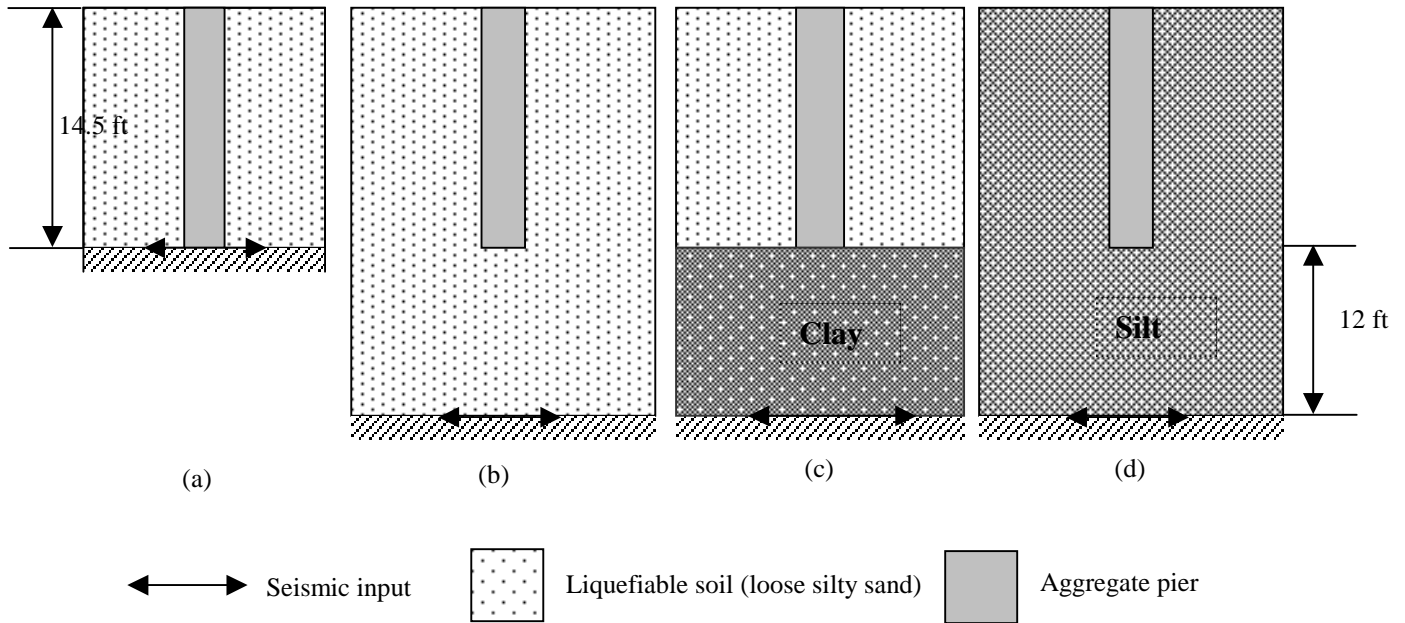


Figure 5.1 Models analyzed in FLAC analyses

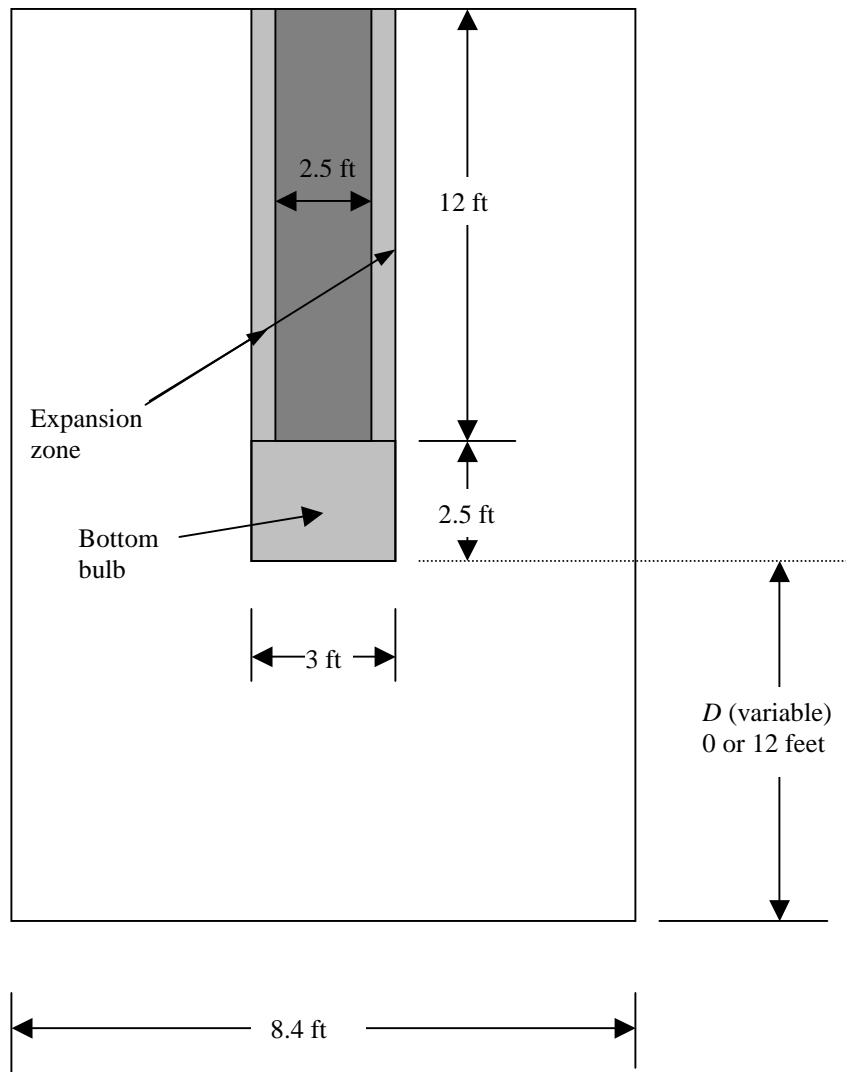


Figure 5.2 Single aggregate pier model

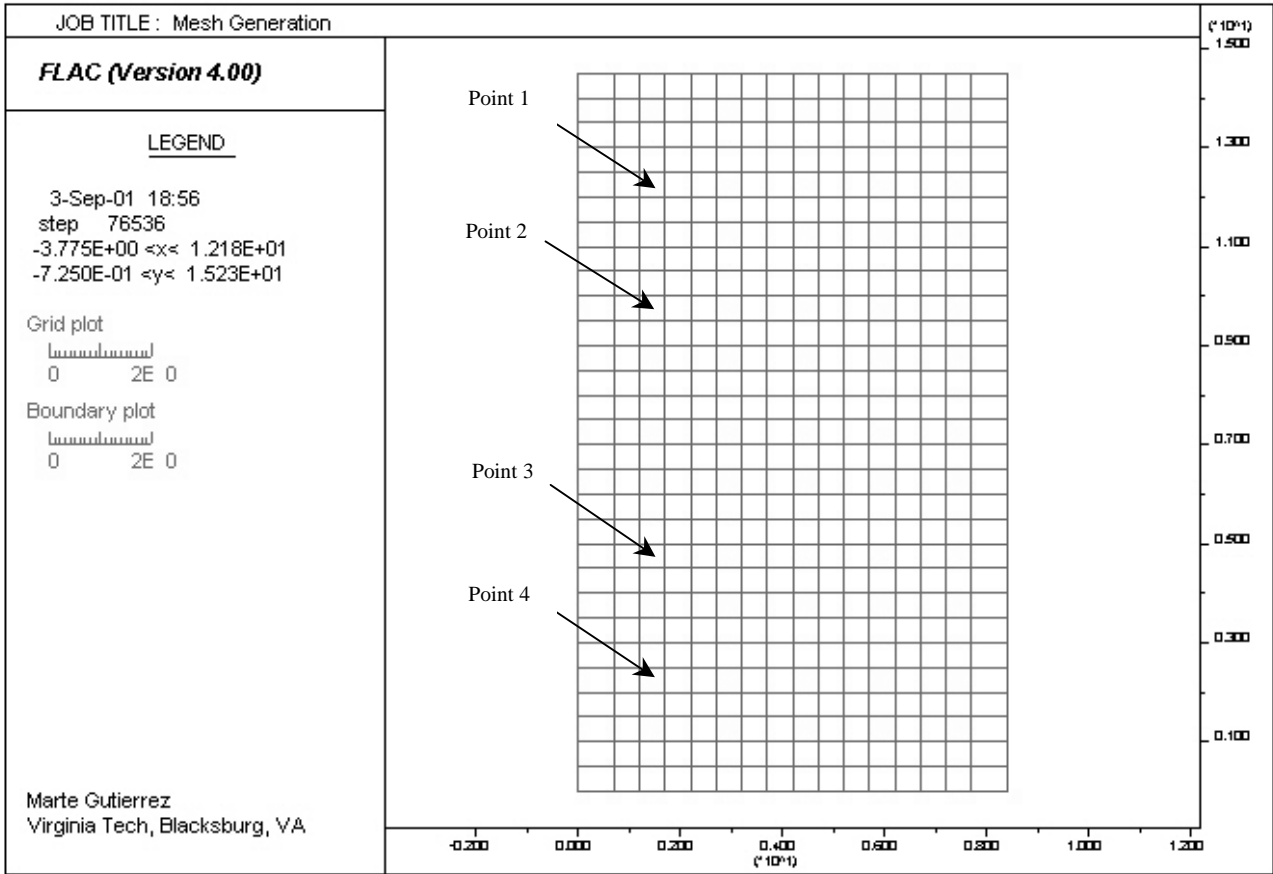


Figure 5.3 Grid generation 1

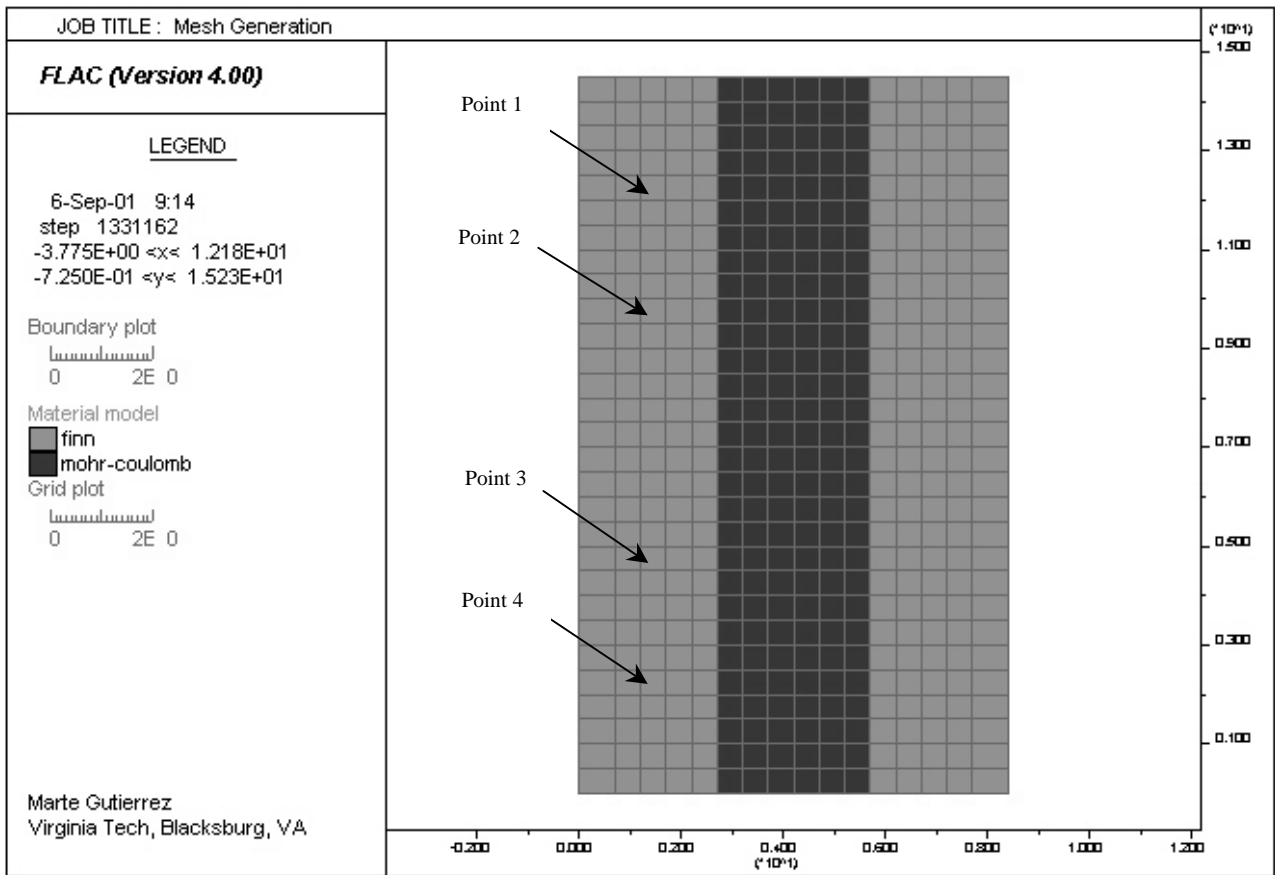


Figure 5.4 Grid generation 2

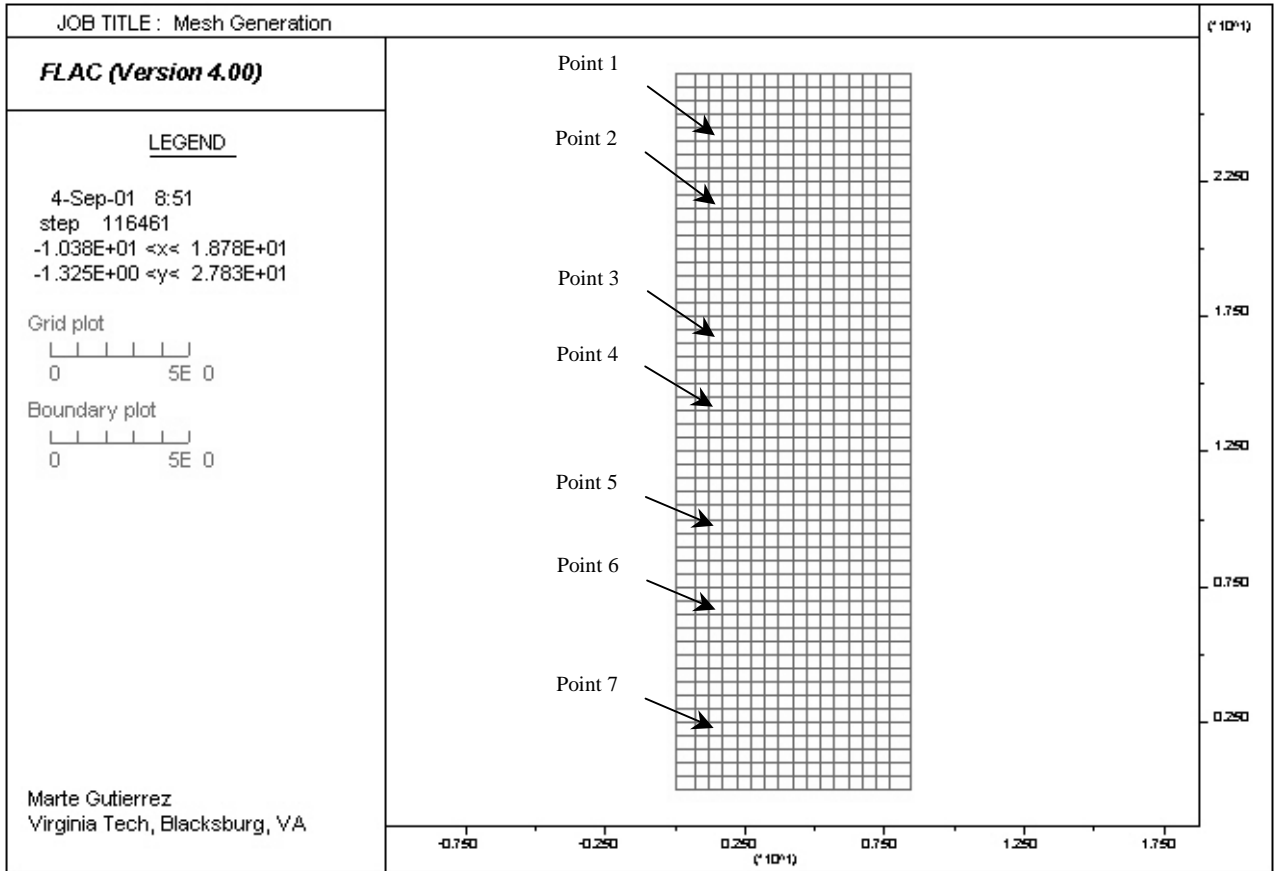


Figure 5.5 Grid generation 3

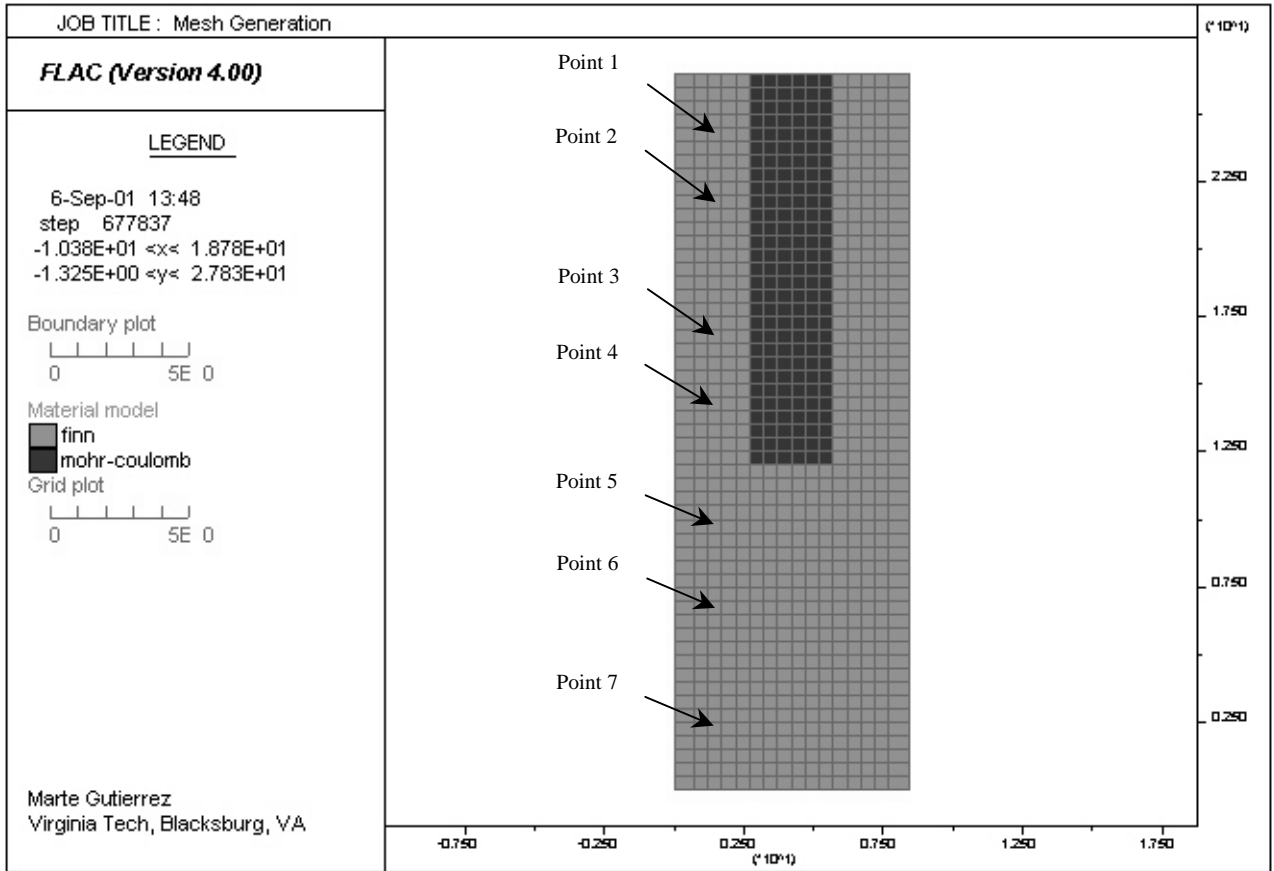


Figure 5.6 Grid generation 4

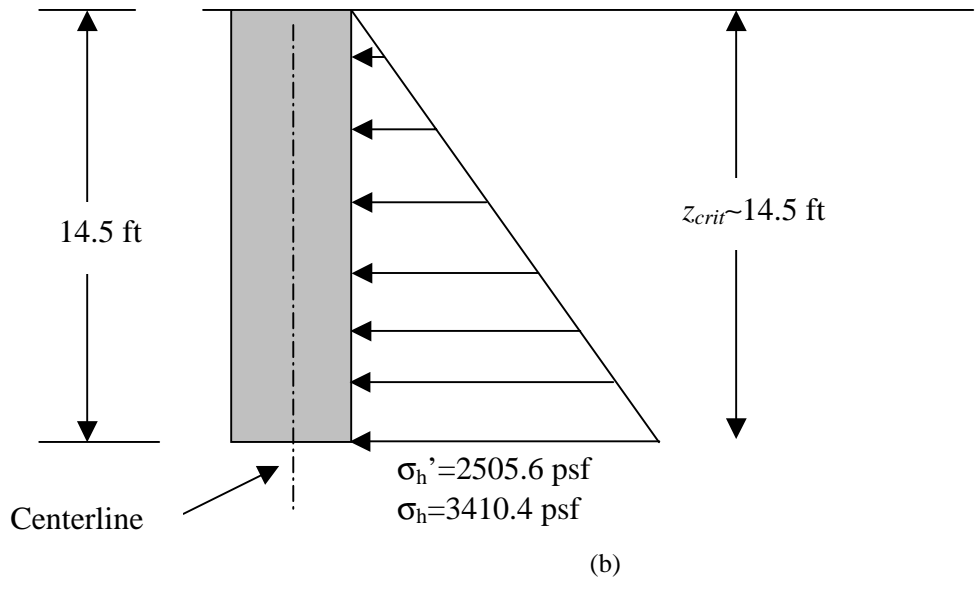
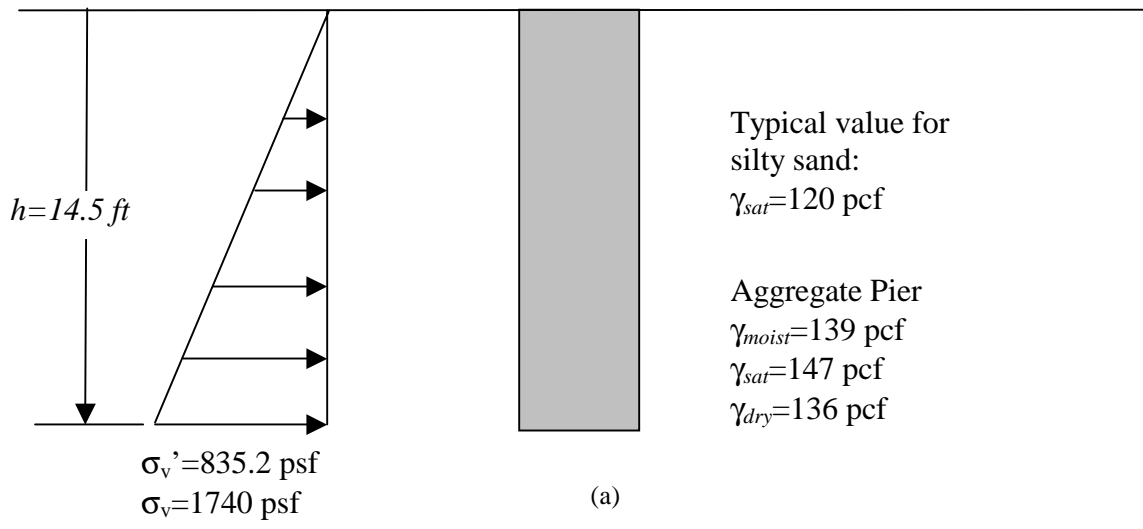


Figure 5.7 Initial in situ stresses for silty sand  
 (a) Vertical stress; (b) Horizontal stress



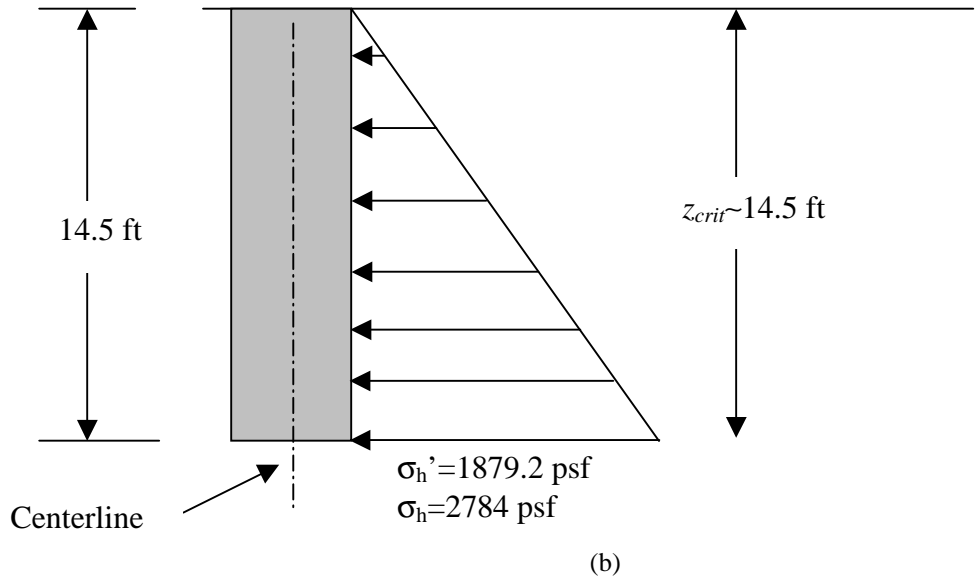
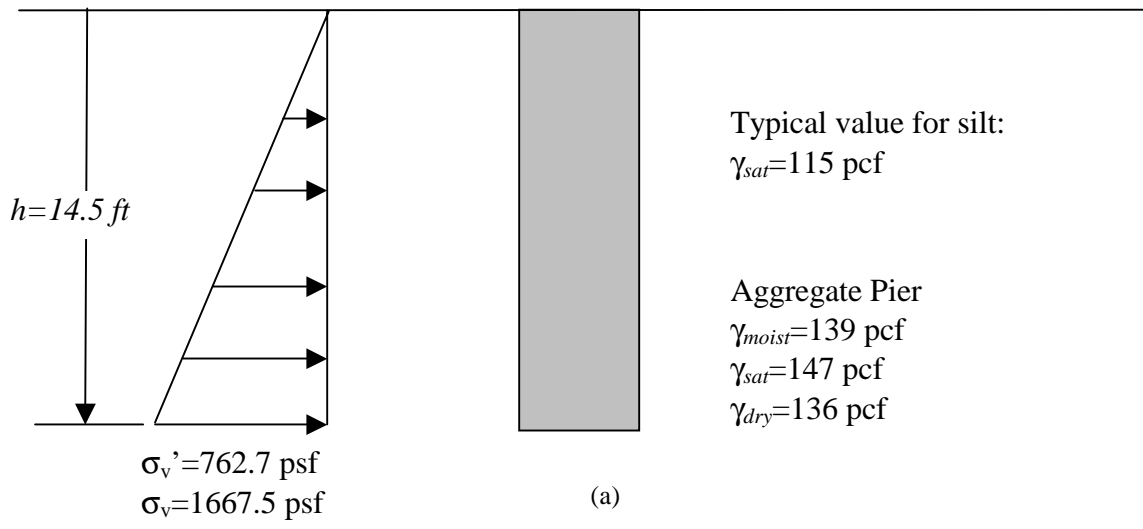


Figure 5.8 Initial in situ stresses for silt  
 (a) Vertical stress; (b) Horizontal stress

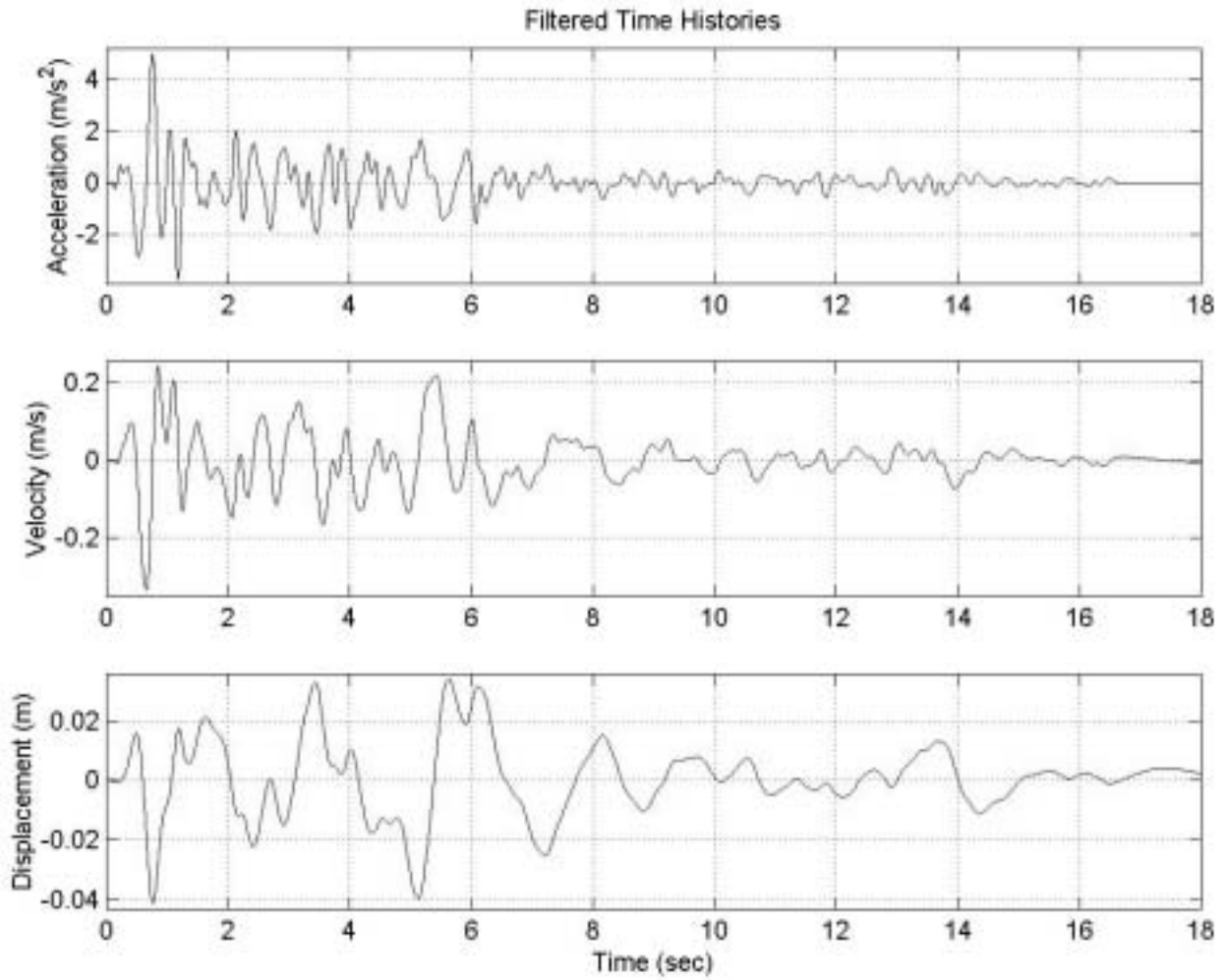


Figure 5.9 Loma Prieta earthquake time histories

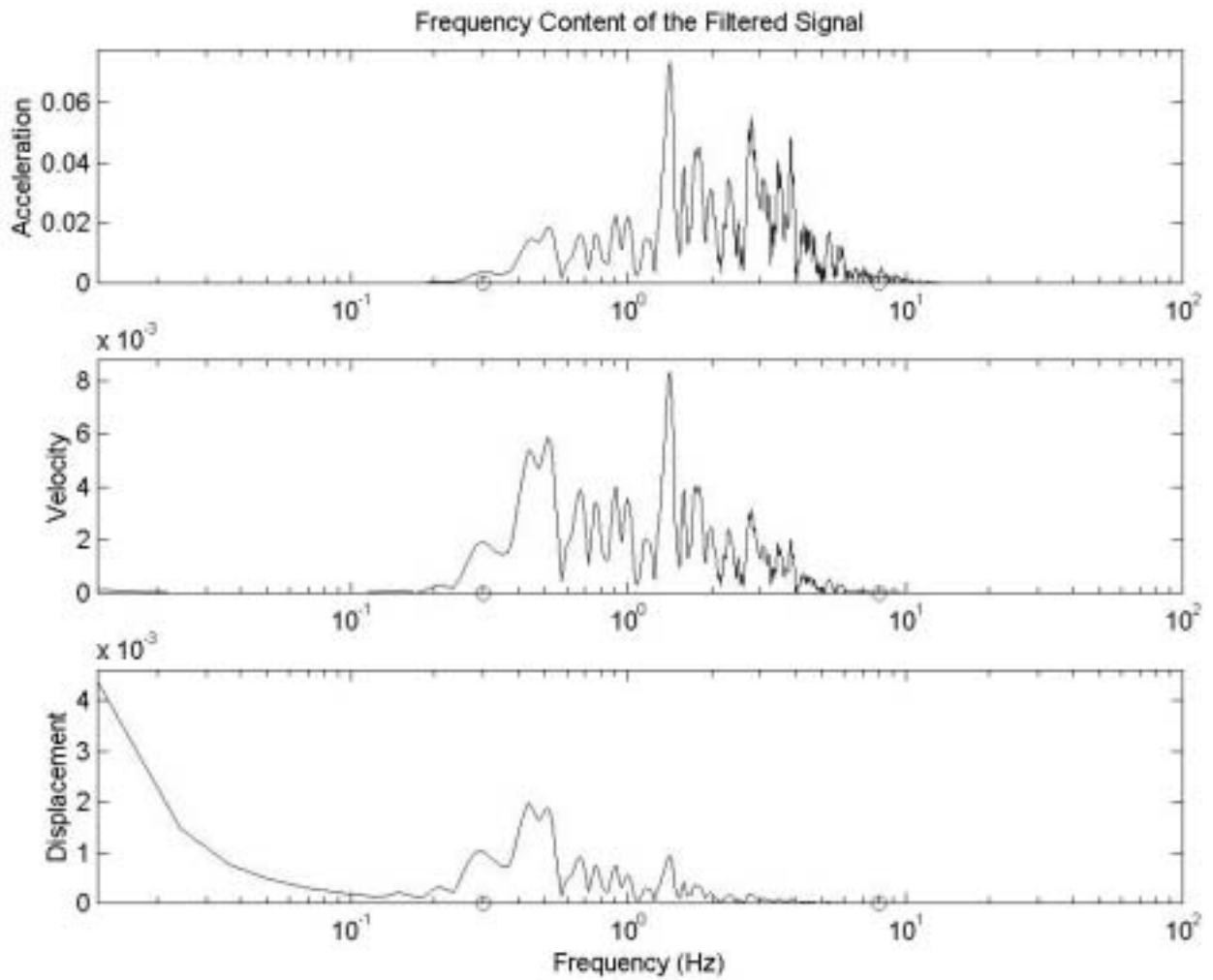


Figure 5.10 Fourier amplitude spectrum of Loma Prieta earthquake time histories

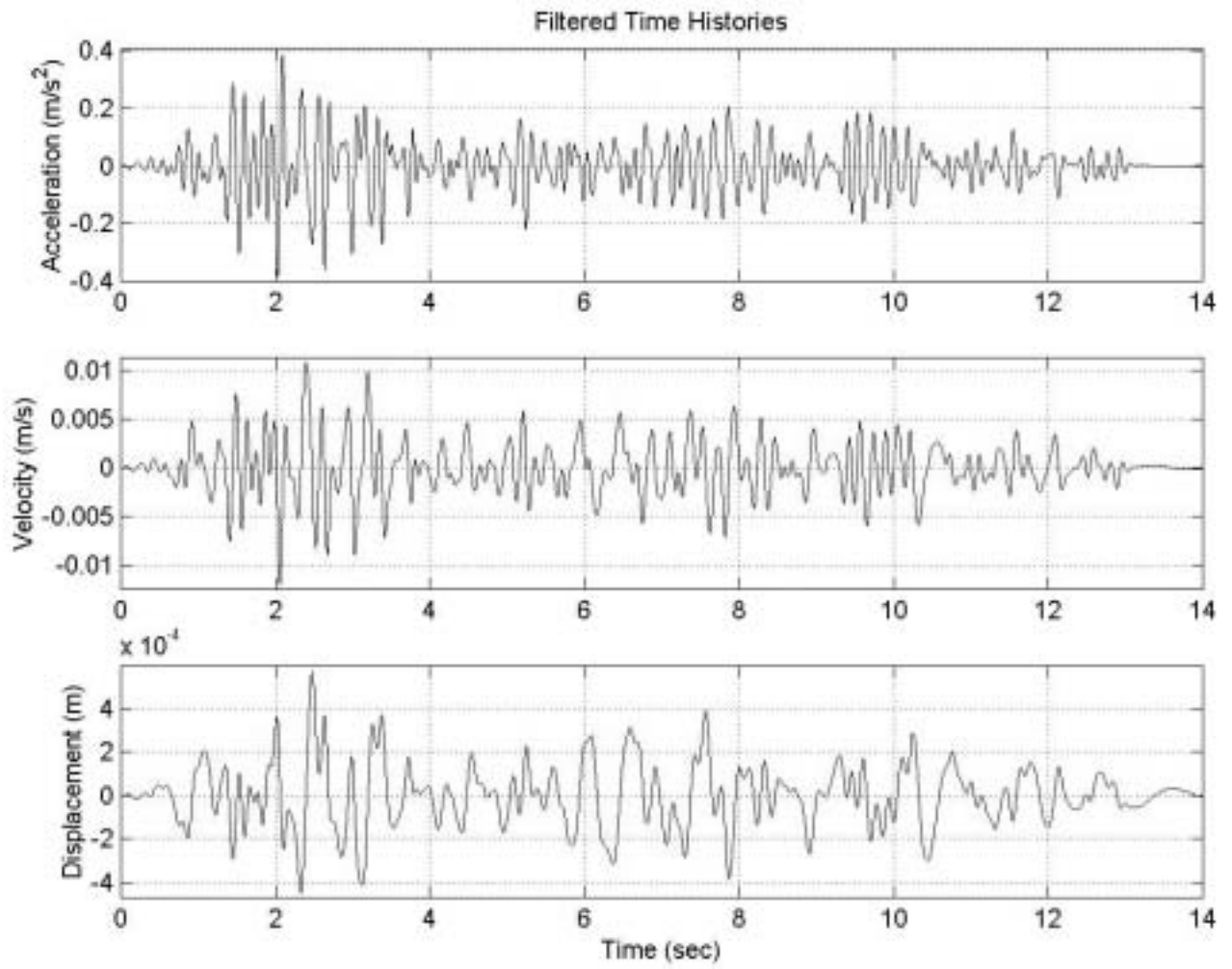


Figure 5.11 Saguenay earthquake time histories

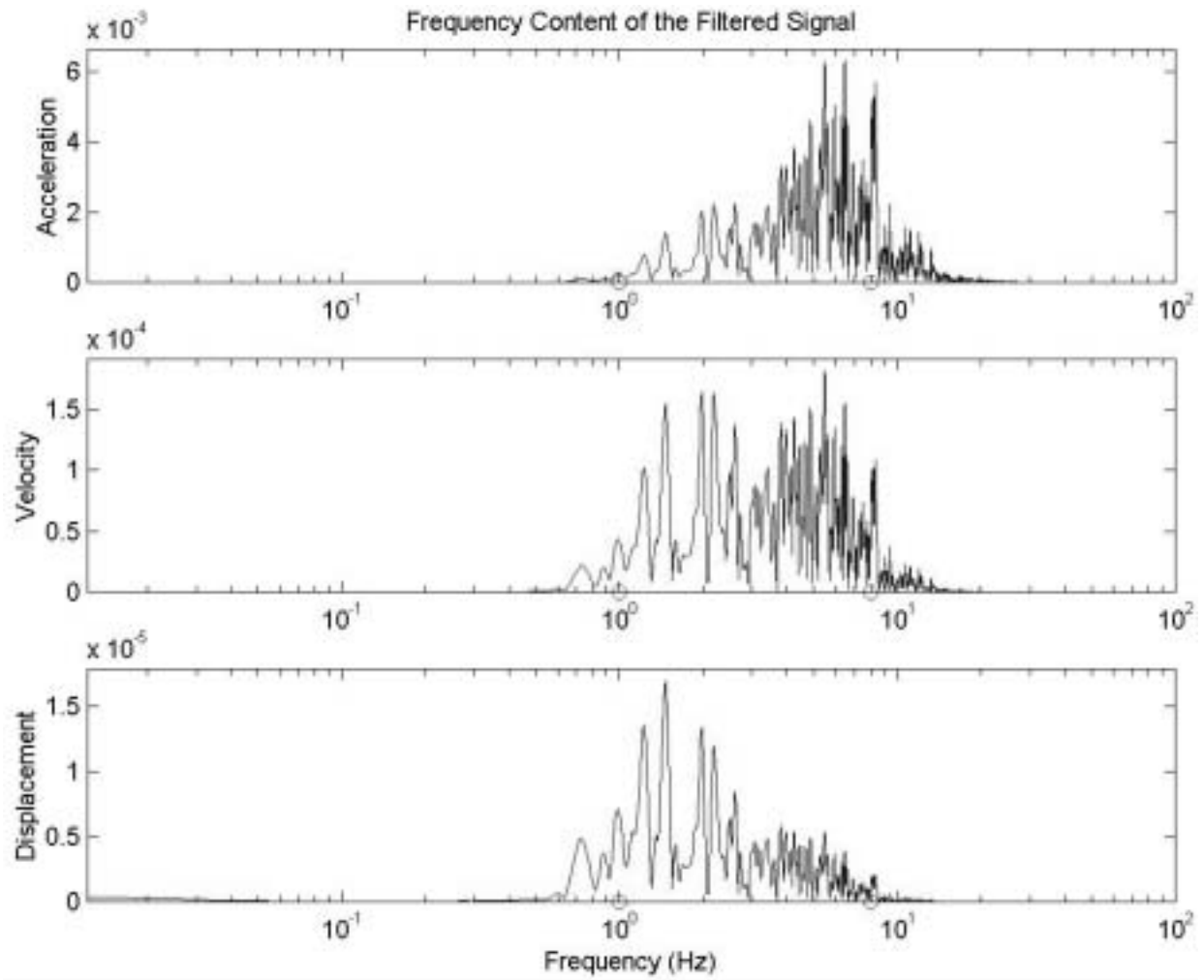


Figure 5.12 Fourier amplitude spectrum of Saguenay earthquake time histories