This coherence function as mentioned above was used as the data quality control criterion.

A modal parameter estimation package (Modal 3.0 SE), developed by Structural Measuring Systems (SMS) was employed for extraction of modal parameters (linearity and reciprocity for the test structures is assumed). This package offers various options for curve fitting. Three different options were employed in this investigation and are discussed by Alampalli (1990) in detail. A different approach for testing and curve fitting was adopted when harmonic excitation (swept sine mode) was employed. It was found when performing such a test that a substantial amount of time was expended in trying to achieve a high accuracy variance convergence tolerance (in this case 1%) in the frequency bands away from a resonance. In these frequency bands, no significant amplification occurs and the signal amplitude approaches that of ambient noise. Attaining high convergence tolerances for such low amplitude signals was difficult and consumes significant time with minimal impact on overall quality of the measured FRF. In order to reduce the time required, while maintaining high data quality, the procedure described by Alampalli and Elgamal (1991) was adopted when testing with swept sine excitation.

Large Shaker Test

An eccentric-mass vibration generator (shaker) developed at RPI (Van Laak and Elgamal 1991) for resonance testing of full-scale structures based on the original Hudson (1964) design, was used for these tests. Eccentric mass shakers are particularly efficient in producing large dynamic forces at low frequencies. The RPI shaker was designed to provide up to 22 kN of horizontal force within the frequency range 0.5 to 30 Hz. Rotational speed of this shaker was verified to remain stable at any specified frequency within a 0.0625 Hz range. Operating speed was controlled by a calibrated precision potentiometer. A 1.8 m square (0.45 m thick) reinforced concrete pad was constructed flush with ground surface to provide a firm base for attachment of the shaker. Terra Tek (model SSA102) force balanced accelerometers were used to measure the horizontal wall and backfill accelerations. The HP3562A signal analyzer was used to digitize and record time histories; and to calculate transfer functions and coherence functions between the shaker input and response accelerometer signals (Elgamal, Alampalli, and Van Laak 1996). Testing was conducted over several nights in the absence of traffic induced vibrations.

Test Results

JEC Wall

Transfer functions of 85 measurement locations along the exposed side of the wall (Fig. 1) were measured (Elgamal et al. 1990, Alampalli 1990). The entire wall was tested three times, each time employing a different excitation technique (see Table 1). Natural frequencies and damping ratios obtained by curve-fitting the data (up to 100 Hz) of each test are shown in Table 2. Note that the small hammer even with multiple impacts (Tables 1 and 2) was unable to supply enough energy to excite the lowest frequency mode. While estimates of natural frequencies were in agreement, a noticeable difference in estimated damping may be observed (Table 2). The damping ratios shown in Table 2 were found to depend on the employed curve-fitting algorithm/procedure and consequently should be taken as rough estimates. Mode shapes obtained from all three tests appeared to agree well (first mode was not obtained from the small hammer test) with maximum variation of 8% in natural frequencies. Modes obtained by the swept sine shaker test (the third test) are shown in Fig. 4. Based on the above results, it may be concluded that the results obtained by sledge hammer impact and those obtained by harmonic shaker excitation are in good agreement.

It is noted that the modes shown in Fig. 4 were evaluated in the complex domain and were found to exhibit a gradual phase change (phase at resonance is not simply 0.0 or 180.0 degrees) as shown in Fig. 5. Such a phase relation between different points of the structure may be due to the presence of non-proportional damping mechanism (Ewins 1984), such as that due to radiation. It is also of interest to note that nonlinear dynamic response of the wall was detected when a particular transfer function was measured several times using a shaker force of varying amplitude (Fig. 6). The response is similar in character to that of a nonlinear yielding system (Jennings 1964, Nayfeh and Mook 1979), and should be a subject of further investigations.

CII Wall

High Frequency Tests: Initially, the same test setup as described for the JEC Wall was used. Transfer functions of 178 measurement locations along the exposed side of the wall were measured. Dynamic excitation was imparted using the large 12 lb sledge hammer (Table 1). During the curve-fitting phase, it became evident that extremely high modal coupling existed due to close resonances. In addition, the presence of significant damping smoothed off most peaks in the measured transfer functions. This complicated the curve-fitting process and no reliable resonant properties can be obtained in the low frequency range. At higher frequencies, the natural frequencies and associated mode shapes are given in Figure 7. A rough estimate of damping ratios suggested a value of about 8% for most of these modes.

Low Frequency Tests: The new large RPI shaker was employed in this case (Elgamal et al. 1996). A plan view of the shaker and measurement locations on the wall and backfill are shown in Figure 8. The shaker horizontal force and all measurements were oriented in the direction perpendicular to the wall face. Data was recorded starting at 6 Hz (before the first resonance identified by analysis) and up to 17 Hz using a frequency increment of 0.125 Hz at points (Fig. 8) 2, 2A, 8, 8A, 8B, 11, 11A, and 0 (as

Table 1. Summary of user defined settings for various excitation mechanisms employed.

Testing Device	Excitation Employed (Note 1)	Frequency (Hz)		No. of Avgs. (Note 2)	Coherence Value (Note 3)	Curve-fit Procedure (Note 4)
		Range	Δf			
Small Hammer (3 lb weight)	Multiple Impact	20-180	0.2	10	0.9-1.0	@
Large Hammer (12 lb weight)	Single Impact	5-405	0.5	5-10	0.9-1.0	@,$,#
Electro Magnetic Shaker (with 8 lb force)	Swept Sine Constant Force	10-100	0.11	2 (Note 5)	0.98-1.0	*

Notes:

1. A force-exponential window was employed with the large hammer time domain data (Alampalli 1990).
2. Number of averaged signals for each measurement.
3. Value of the coherence function in the frequency range of interest.
4. Different curve fitting techniques were used, which are briefly explained in this paper. $ indicates Peak curve fitting method, @ indicates Rational fraction Polynomial curve fitter with auto fitting method, # indicates Global curve fitting techniques, and * indicates the use of the curve fitting algorithm developed by Alampalli and Elgamal (1991).
5. Integration at each frequency point is done until 1% variance limit on the value of frequency response function is met or until the maximum integration time (120 sec. in this case) is reached. This procedure is repeated for each average.

Table 2. Natural frequencies and damping ratios for JEC wall using three different input excitation mechanisms.

Mode No.	Natural Frequency (Hz)			Damping Ratio (%)		
	Hammer 3 lb	Hammer 12 lb	Shaker 18 lb	Hammer 3 lb	Hammer 12 lb	Shaker 18 lb
1	-----	22.65	23.03	-----	5.86	2.60
2	39.25	38.09	37.05	9.97	5.90	4.90
3	56.36	54.65	52.16	3.85	5.66	3.86
4	71.69	71.96	67.96	3.44	5.31	2.97
5	98.07	97.35	94.42	0.56	1.08	3.00

Table 3. Resonant frequencies of CII System

Mode	Resonant Frequencies (Hz)	
	Shaker Test (excitation to Soil)	FEM (Elgamal et al. 1996)
1	6.7	6.67
2	8.2	7.75
3	9.5-9.7	8.86
4	10.4	10.27
5	11.3	11.75

Table 4. Observed viscous damping by half-power bandwidth method.

Mode	Frequency (Hz)	Damping (%)
1	6.7	8.7
2	8.2	15.9
3	9.5-9.7	12.2
4	10.4	8.7
5	11.3	6.6

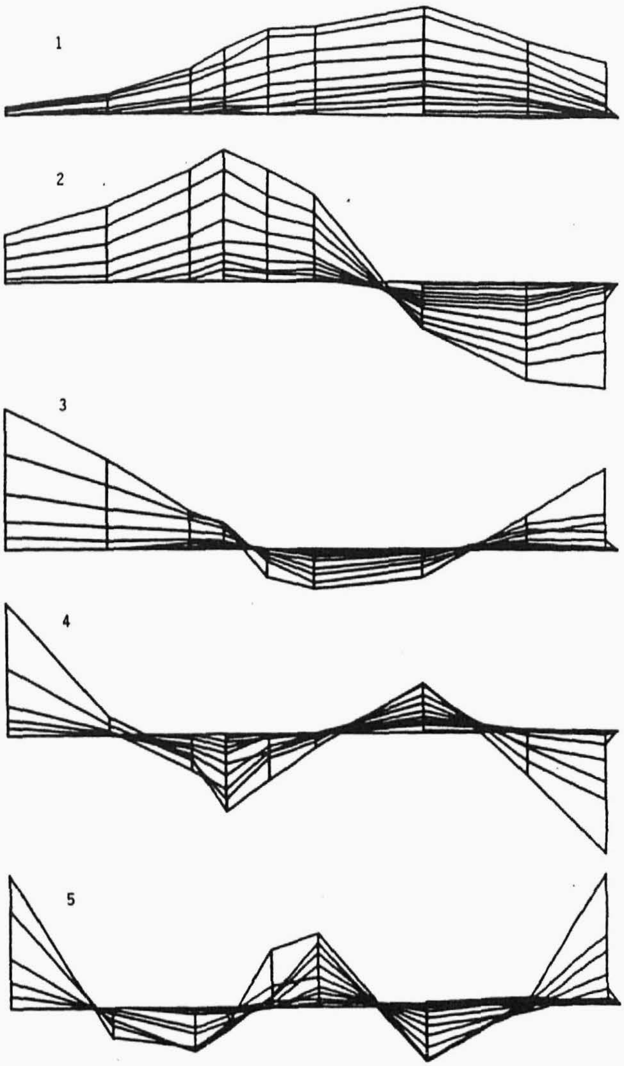

Figure 4. Mode Shapes of JEC Wall in Plan View

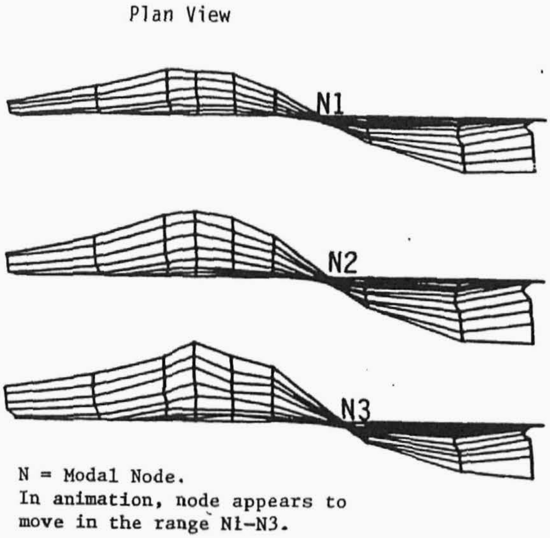

Figure 5. Various Still-Views During JEC Wall Mode 2 Animation

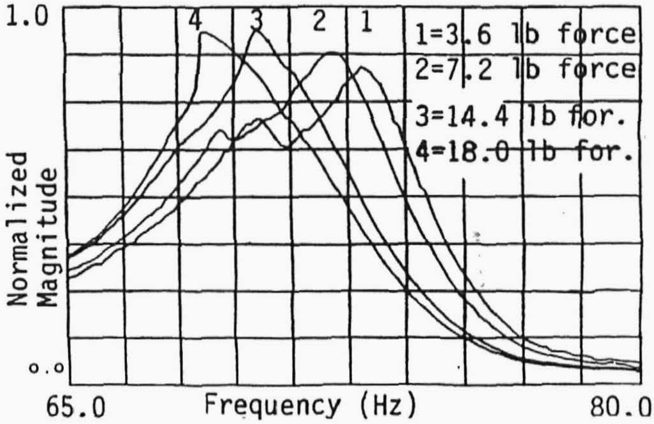

Figure 6. Transfer Functions Depicting Nonlinear Yielding Response

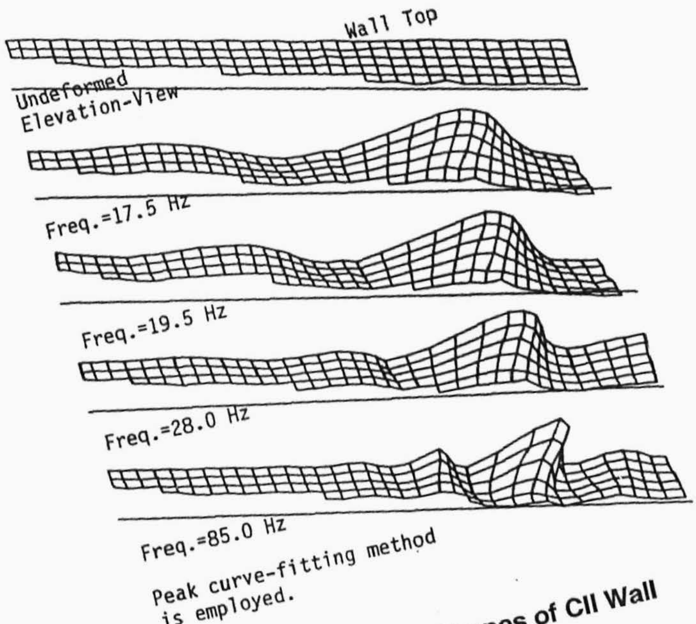

Figure 7. Typical Mode Shapes of CII Wall

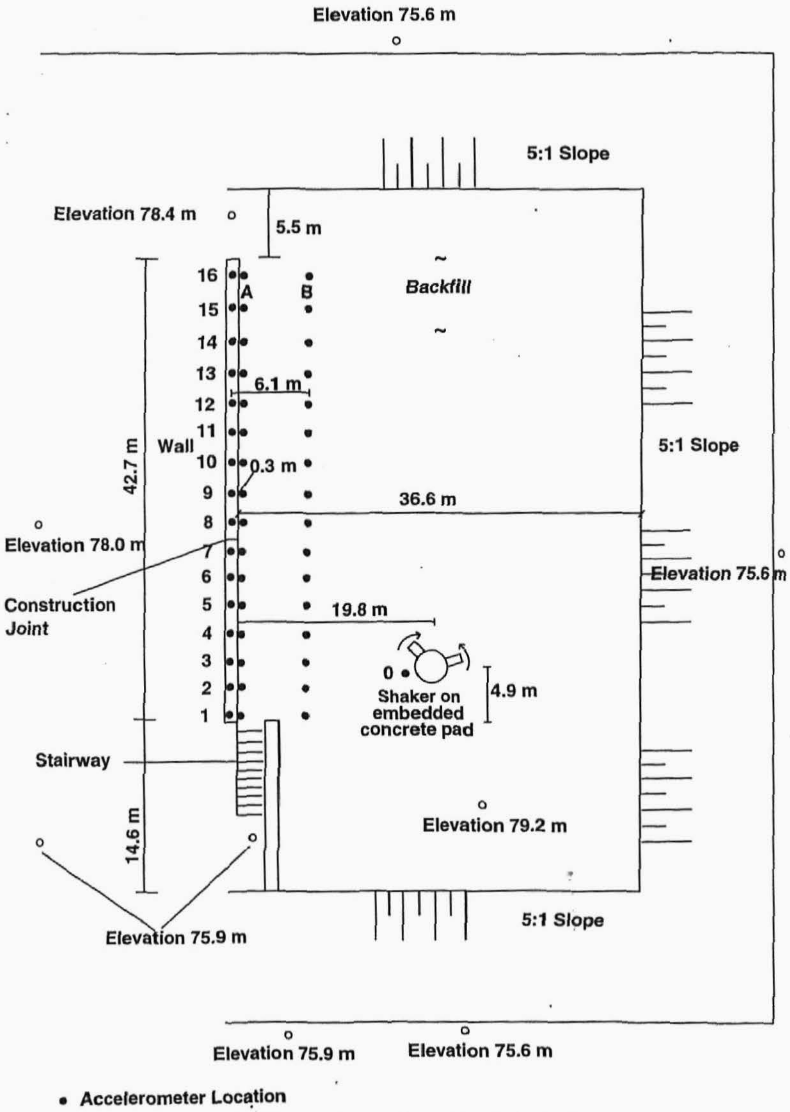

Figure 8. Schematic Plan-View of CII Wall-Soil System

a reference). The frequency sweep was performed at each measurement point to determine resonant frequencies at which significant amplification of motion at or near the wall occurred relative to ground motion near the shaker. Once these approximate frequencies were determined, a second series of measurements were performed in order to obtain more precise values of the system resonant frequencies. Finally, a high resolution frequency sweep (df = 0.0625 Hz) was performed around each resonance, as identified by the first set of tests. Peak amplitude response within each frequency band was taken to denote a system resonant frequency. Once, a resonant frequency was identified with required precision, the system was excited at this frequency and the corresponding amplitude ratios and phase relationships were measured at all measurement points in order to obtain the corresponding resonant configuration.

A typical transfer function is shown in Figure 9. The associated mode shapes are shown in Figure 10. Based on this test, the estimated resonant frequencies are shown in Table 3 along with those obtained using a calibrated 3 dimensional finite element model (Elgamal et al. 1996). The results indicated that the first wall-soil resonant frequency was 6.72 Hz. The associated resonant wall configuration mimicked that of a cantilever clamped plate, or a one-dimensional (1D) bending/shear beam model along the height. Along the length, the amplitude gradually increased with the increase in free cantilever wall height (Fig. 7). The higher resonant configurations were found to display variation in response along the wall length. Viscous damping, using the half-power method (Ewins 1984), was roughly estimated to be in the range of 6.60 to 15.90 percent (Table 4). All the obtained resonant configurations showed a gradual phase variation along the wall length (phase at resonance is not simply 0.0 or 180 degrees). Such a phase relation (Fig. 9) between different points (complex domain modes) may be partially due to the presence of non-proportional damping mechanisms (Ewins 1984), such as that due to radiation; and may also be influenced by the employed localized shaking mechanism.

Discussion and Conclusions

Two cantilever reinforced concrete retaining wall systems were studied employing forced vibration techniques. Modal parameters were evaluated in the complex domain. Within the scope of this work, good agreement was observed between the data obtained using impact hammer tests and harmonic shaker excitation tests (above 15 Hz or so). A harmonically forced transfer function repeatedly measured under an increasing force level, suggested the presence of non-linear yielding behavior. The impact hammer was unable to reliably excite the low frequency 6.7 Hz fundamental mode of the large CII wall. Hence, for massive heavily damped structure, an impact hammer may not be suitable.

The tested retaining walls were observed to display spatial variability in motion along the wall length as well as the wall height. Resonant configurations were found

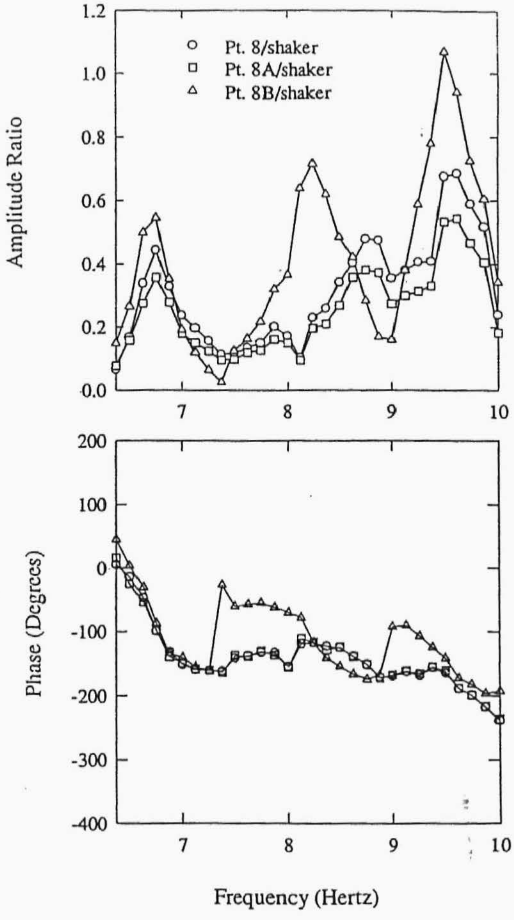

Figure 9. Typical Acceleration Transfer Function for Points 8, 8A, and 8B (0-10 Hz range)