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SYNOPSIS A series of dynamic centrifuge tests was carried out to simulate the seismic behaviours of an idealized model retaining wall and the liquefiable backfill supported by the wall. The wall is hinged at the base and is supported near the top by an anchor with finite strength. Eighteen tests with various peak accelerations were applied to six saturated sand models prepared at two relative densities and with two pore fluid viscosities. Permanent tilt in the wall as a result of temporary failure of the anchor occurred in some tests. Results from tests without anchor failures were used to form a model for estimating the amount of permanent tilt in the wall.

1. INTRODUCTION

Earthquake-induced problems with earth retaining structures and the backfill soil have been one of the major concerns with geotechnical engineers, especially when the backfill is liquefaction susceptible. Large displacements or excessive tilt of such structures are possible during strong earthquakes. A series of eighteen dynamic centrifuge model tests was performed to simulate some important aspects of the behavior of such soil-structure systems when shaken by earthquakes. Figure 1 shows the configuration of the testing model and instrumentation scheme. This model contains an idealized retaining wall, hinged at the base, with a simplified elasto-plastic tilting feature. The dimensions in this figure are prototype scale; actual dimensions are 50 times smaller.

For assuring the quality of the centrifuge models, Ting (1993) developed a low-pressure-saturation technique to produce highly saturated soil specimens for dynamic centrifuge tests. This technique ensures the saturation of both the soil skeleton and porous space within the soil. Ting and Whitman (1994) outlined the key features in designing and performing dynamic centrifuge tests of the model, including a summary for this saturation technique. Full results of these tests may be found in Ting (1993). Whitman and Ting (1993) presented some test results and offered a few general remarks for the entire set of tests. The authors also carried out a set of Class A numerical predictions for this test program (Ting, 1993). Bouckovalas et al. verified these numerical predictions (1993). This paper, describing the model and test procedures in brief, focuses upon cyclic thrusts acting on the retaining wall; estimation of permanent tilt in the wall due to temporary yielding during earthquakes; together with features of cyclic pore pressure fluctuations.

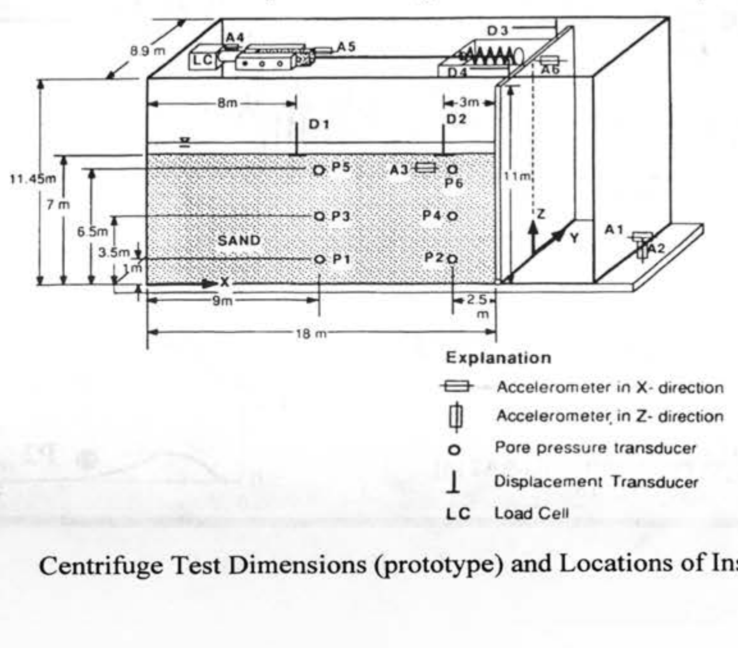

Figure 1 Centrifuge Test Dimensions (prototype) and Locations of Instruments

2. THE CENTRIFUGE MODEL

The centrifuge model involves a retaining wall and a saturated sand backfill. The wall, a 9.5mm thick alumina plate, is hinged at the base and supported by a tie-back system. The tie-back is connected at one end to the retaining wall and at the other to the end wall of the testing box via a load cell. A spring and a slider provide the tie-back with an elasto-plastic force-displacement relationship. This arrangement allows the wall to tilt about its toe during earthquakes. Slip at the slider may occur once the tie-back load exceeds the shear resistance of the slider due to dynamic earth pressures as a result of earthquake. The sliding will result in a plastic elongation of the tie-back and the permanent tilt in the retaining wall. It simulates the possible temporary anchor failure during earthquakes. This model resembles retaining walls in a very rough way but does contain important aspects of actual full-scale problems.

The backfill consists of a uniform bed of fine Nevada sand prepared through dry pluviation followed by an elaborate saturation procedure. The saturation technique, at an absolute pressure below 25 mTorr, guarantees the degree of saturation of the sand model as well as the fine porous stones of micro pore pressure transducers within the backfill (Ting, 1993).

Four types of data were collected: pore pressure, tilting of wall, force in the tie-back and acceleration at various locations of the system. The instrumentation scheme is shown in Figure 1. Table 1 lists the instrumentation information.

Table 1: Instrumentation Information

Instrumentation Type	Size	Manufacturer	Model Type
Pore Pressure Transducer	6.5mm(dia) x11.6mm	DRUCK	PDCR81
Accelerometer	7.3mm(dia) x11.5mm	PCB	303A03
Force (Load Cell)		Data Instrument	JP500
Displacement (DCDT)		HP	7DCDT

3. TESTING PROGRAM

Table 2 displays the testing program. The nominal centrifugal acceleration of these tests was 50g. Several horizontal earthquake shakings were applied to each model. The letters a, b etc. in Table 2 indicate the sequence of shakings applied to each model. Full dissipation of the excess pore pressure was reached prior to all subsequent tests on each testing model. In some tests, indicated by the bold-face test numbers, slip at the slider was identified. Actual liquefaction was observed in the underlined tests.

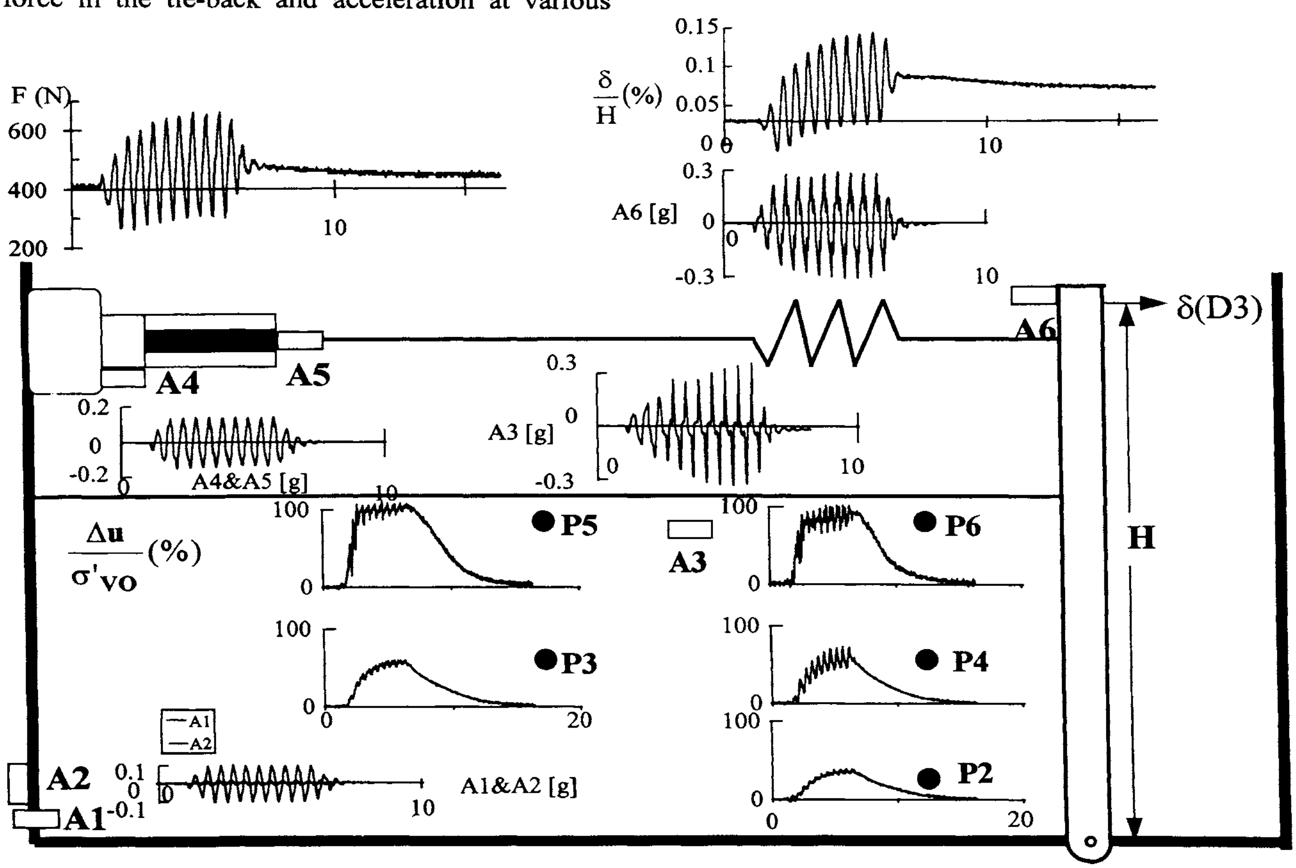

Figure 2 Results of Test 2b

Table 2: Testing program

Relative Density	Pore Fluid	Peak Input Acceleration 0.05g	0.10g	0.13g	0.25g	0.3g	0.35g
60%	Water	1a	***1b***		**1c**		
		4b	*4c*		**4a**		
75%	Water	2a	*2b*	*2c*	***2d***	*2e*	*2f*
			5b				**5a**
				6b	**6a**		
	55% Glycerol Solution		*3a*		**3b**		

The input motion for each test was ten cycles of more-or-less sinusoidal excitation at 100 Hz (2 Hz in prototype earthquake). The general form of the input base shaking was similar in all tests, with only the intensity of shaking varied. Five of the six models were prepared with water as the pore fluid; one model was prepared with a 55% glycerol solution as pore fluid, yielding a permeability equal to about one tenth that of the other models. The glycerol saturated model represents a more realistic soil model for dynamic centrifuge testing. Although the permeability is only reduced to one tenth that of water saturated models, results of this series of tests have demonstrated substantial differences from similar tests performed on water-saturated models.

4. TEST RESULTS

4.1 Typical results

Figures 2 through 4 present results in Tests 2b, 3a and 5a. Tests 2b and 3a are two similar tests with no slip at the slider; however, with pore fluid being water and glycerol solution, respectively. Test 5a is a test involving slip at the slider. All data are presented in prototype scales except for the load measurements (in model scale). The tilt in the retaining wall (δ/H in %) is obtained from the horizontal displacement measured near the top of the wall (D3 and D4). The pore pressure data are presented as excess pore pressure ratio ($\Delta u/\sigma'_{vo}$). In these figures, the horizontal axes are time scales. The time scales in pore pressure plots are two times smaller in Figure 2 and 4, and is three times smaller in Figure 3. Positive acceleration is towards the right. The data sets were not complete due to either channel shortage (e.g., P1) or unsuccessful recording during testing.

4.2 Pore pressure build-up

The permeability of the pore fluid plays an important role on the pore pressure build-up within the soil during

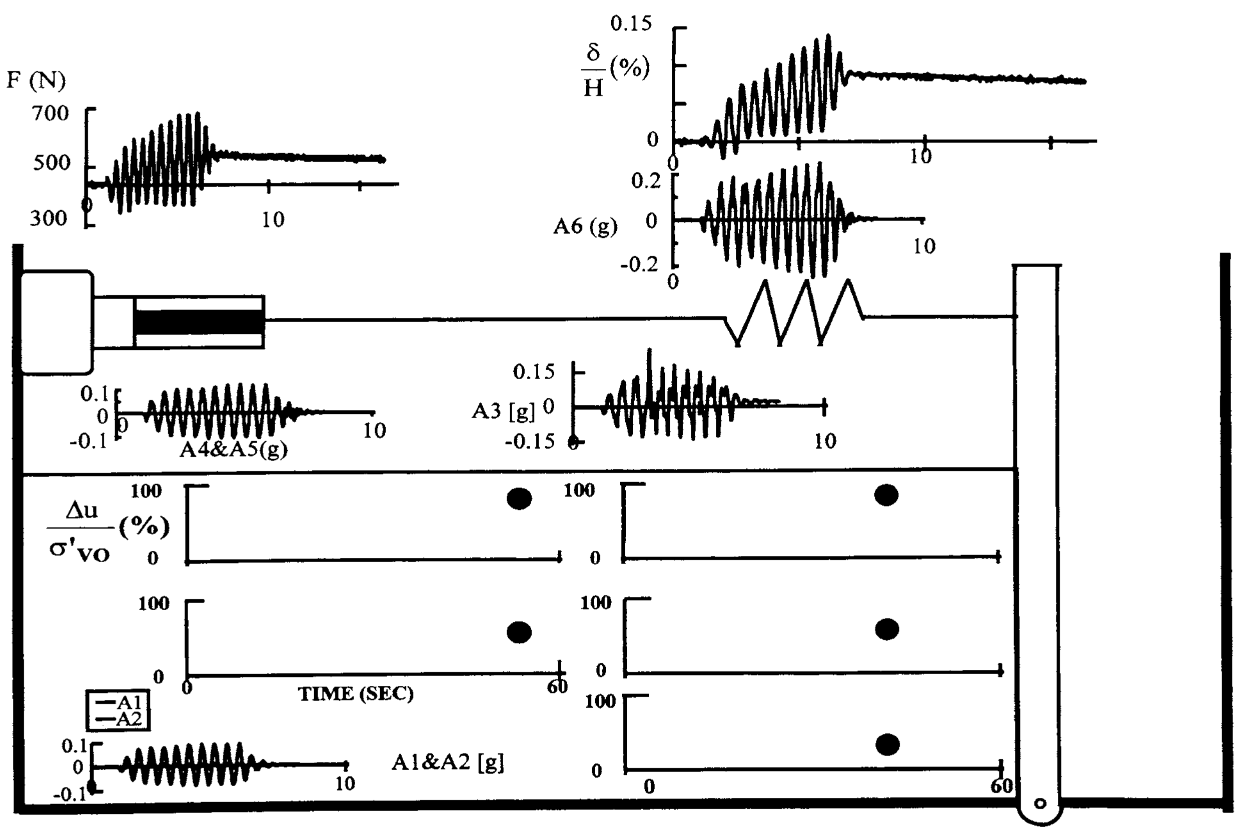

Figure 3 Results of Test 3a

cyclic shakings. The permeability ratio between model No. 3 and other models are first verified by comparing the rates of excess pore pressure dissipation after shaking. The dissipation time in Test 3a was about ten times that in 2b, which is consistent with the permeability ratio of these two models.

Comparison between results of Tests 2b and 3a shows that the permeability (or viscosity) difference does not have a significant influence upon the rate of excess pore pressure generation. However, it does affect the accumulation of excess pore pressure, and hence the overall pore pressure build-up, as a result of partial drainage during earthquakeshaking. The pore pressure plots in Figures 2 and 3 prove to be a clear demonstration. Comparing the pore pressure data P2, P3 and P4 among various tests show the above observation. The decrease in the rate of pore pressure accumulation is prominent during the shaking in Test 2b, while it is insignificant in Test 3a. This fact reveals that, in dynamic centrifuge tests, pore pressure dissipations *during earthquakes* have substantial influences on pore pressure build-up at deeper locations.

4.3 Cyclic pore pressure features

During the pore pressure build-up at initial load cycles, spikes of negative excess pore pressure appear in many pore pressure histories. The negative excess pore pressure is usually accompanied by double cycling of the excess pore pressure, the pore pressure cycles twice within one cycle of ground motion. The pore pressure plots in Figure 4 serve as proper illustrations for such pore pressure features. The double cycling of pore pressure manifests that the soil skeleton experienced a cycle of dilation-contraction-dilation-contraction during one load cycle. Such behavior can be explained with a cyclic stress path of sand (Ting, 1993). These features are thought to be results of intensive shearing of the soil skeleton.

4.4 Liquefaction

Liquefaction is indicated by both the pore pressure data and acceleration data. In Tests 2b and 3a, the excess pore pressure ratio reached about 100% near the surface (A5 and A6). However, A3 data indicate that the soil could still transmit ground accelerations. In Test 5a, the pore pressure ratio reached 100% in the upper soil, indicated by P3, P4, P5 and P6. A3 data show that the soil completely lost the capability of transmitting ground accelerations after the first load cycle. The soil, behaving as a fluid, was fully liquefied in Test 5a. Based upon such observations, Ting and Whitman (1993) used a term *quasi-liquefaction* to describe the soil conditions with pore pressure and acceleration features in Tests 2b and 3a.

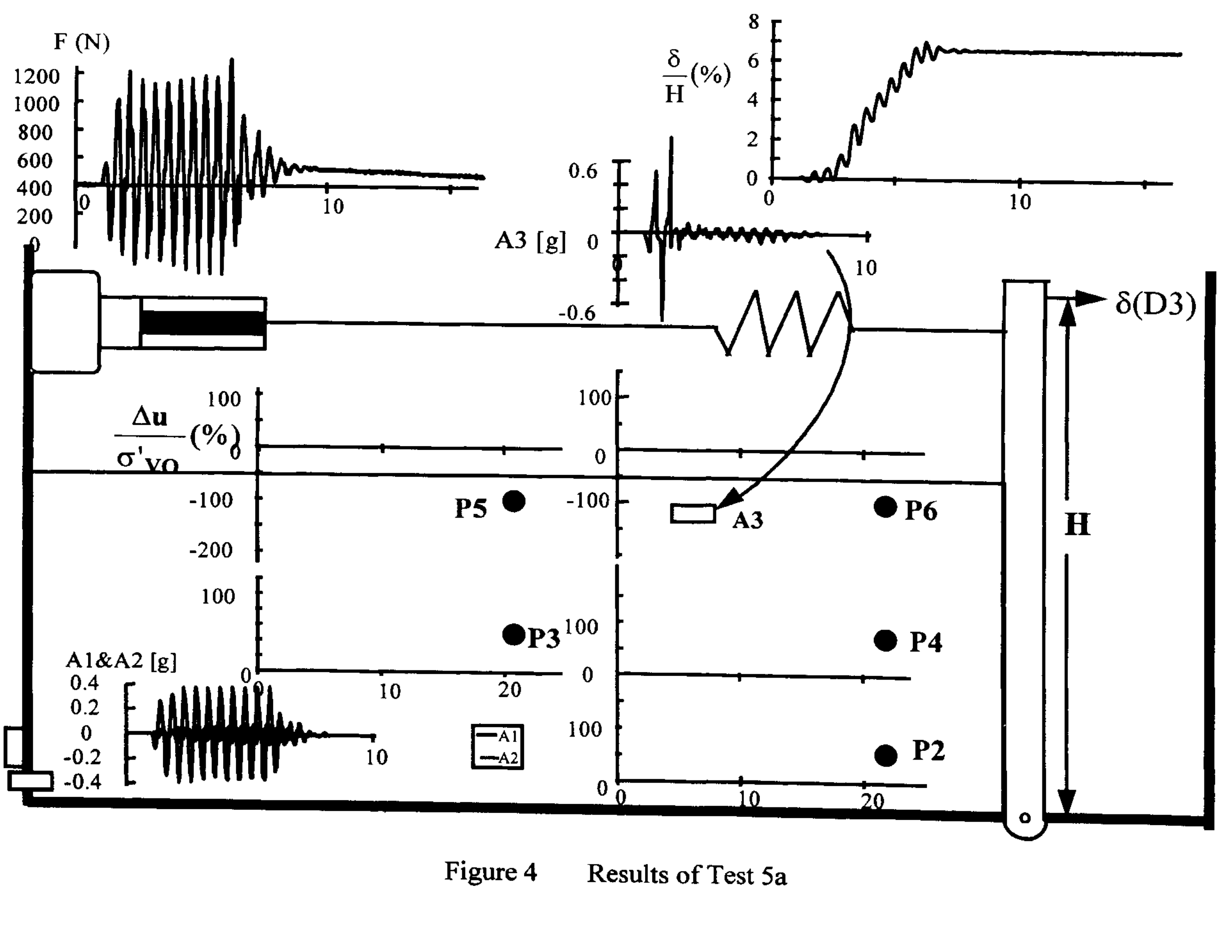

Figure 4 Results of Test 5a

4.5 Phase Relations

It is possible to interpret the dynamic earth thrust on the retaining wall. The saturated total earth thrust was obtained by separating the system inertia from the total force on the wall. Then subtracting the thrust corresponding to the pore pressure gives the soil skeleton thrusts. Figure 5 presentsfrom soil skeleton and excess pore pressure. The excess porepressure thrust in Figure 5 was obtained through a scheme integrating the pore pressure records of near the retaining wall. After reviewing plots such as Figure 5 and acceleration responses for all tests with no slip, phasing of cyclic thrusts was established. Figure 6 summarizes the results of phase lags of various components in this model. All phase lags are with respect to the input ground accelertion towards the backfill.

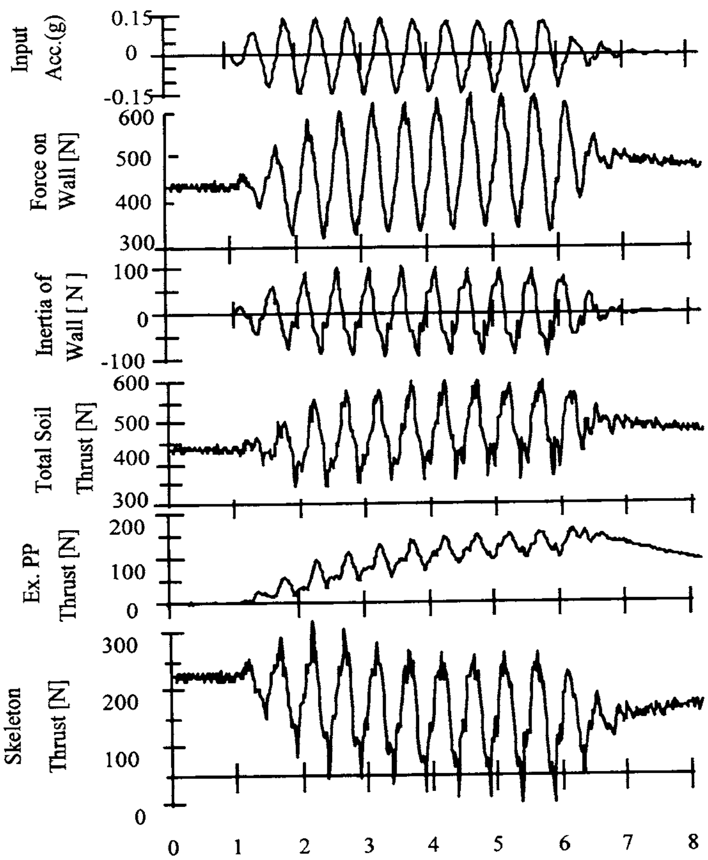

Figure 5 Cyclic earth and water thrusts acting on the retaining wall during Test 5b

5. ESTIMATIONS FOR SLIP AMOUNT

Slip occurred in most tests with input acceleration greater than 0.13g in this test program. A simple lumped-mass model was developed to estimate the amount of tilt in the retaining wall, taking into the slip at the slider into account. The amount of slip per load cycle was estimated using a modified Newmark's sliding block method.

Figure 7 presents the schematic diagram of the lumped-mass model for the actual centrifuge test model. The lumped mass "m_1" includes the masses of the retaining wall, partial mass of spring assembly, and the effective mass of soil that moves with the wall during cyclic rotation. The block "m_2" includes the sliding element of the slider and the part of the tie-back between the actual spring and the slider. The resistance of the soil backfill to the motion of the wall is represented by the spring constant k_1 and the damping coefficient c. The constant of the spring in the tie-back is k_2. The ground acceleration is marked by "$\ddot{S}$ ".

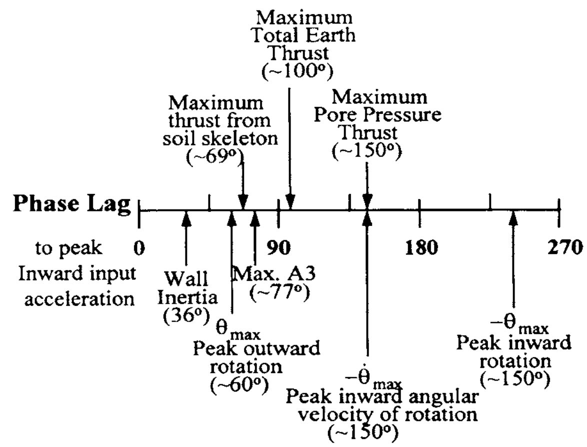

Figure 6 Phase relations amoung various components

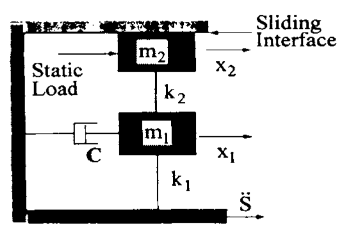

Figure 7: A lumped-mass model representing the soil-wall system

The sliding is represented by the relative movement between m_2 and the "ceiling", once the shear force exceeds the frictional resistance of the slider. The shear resistance was not certain until after the test results were obtained. The exact shear force at the slider was obtained from the force measured by the load cell minus the involved system inertia. Stick-slip behavior of the slider was observed in many of tests with slip occurred. The two upper plots in Figures 8 show the observed shear force at the sliding interface in Test 2d. The shear resistance in this test was about 750N, as indicated by the plateaus of the computed curves. The initial and final values of the computed curves was set equal to the observed values. The dynamic variations of the load was computed from the above lumped-mass model. As the true variation during cyclic loading of the "static load" applied to the slider is unknown, two assumptions was for the "static load" variation was made. Case I assumes that the total earthquake-induced incremental earth thrust happens intantly at the start of shaking. Case II assumes that the incremental load in the tie-back increases linearly with time during the shaking period. These two assumptions lead to upper bound and lower bound estimations for the amount of slip. Figure 8(c) presents the computed and observed curves of horizontal displacement at the level of tie-back. The total slip as well as the slip per cycle are within the two computed curves. As indicated in the two upper plots, the slider did not slip in the first few load cycles even though the load exceeded the shear resistance of the slider. Therefore, the residual displacement is closer to the Case II curve. In most slip tests, the observed slip per cycle was in between Case I and Case II estimations. The lumped-mass model together with modeified Newmark's sliding block method yielded effective estimates for the amount of slip per cycle.

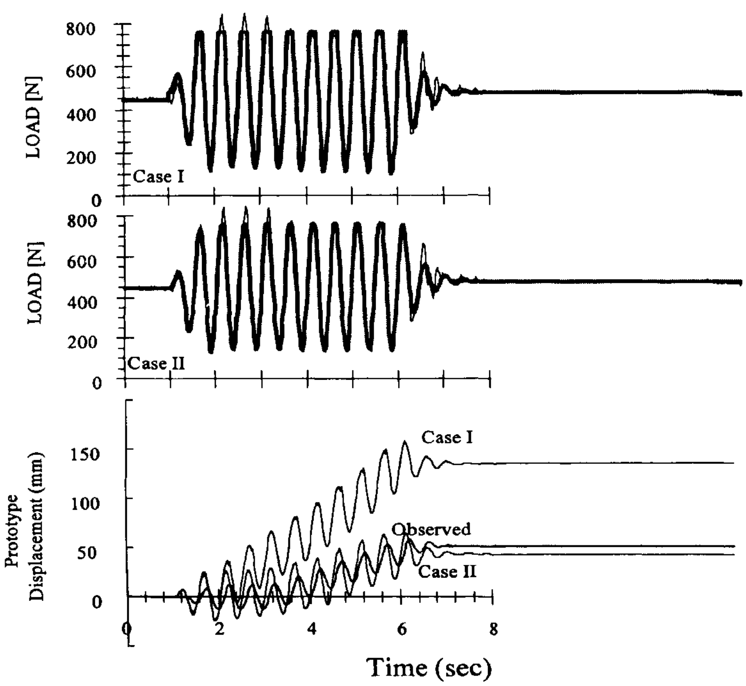

Figure 8: Observed and computed horizontal displacement of wall at the level of tie-back in test 2d

6. CONCLUSIONS

This paper is concerned with the results of the tests as well as the behavior of the centrifuge model during dynamic testing. Investigation of the test results helped the understanding of the behavior of a saturated backfill behind a retaining wall similar, at least conceptually, to the centrifuge model. It has also shown that

- the eaqrhquake-induced permanent tilt of the model retaining wall can be estimated with a lumped-mass model together with Newmark's sliding block theory; and
- the permeability of the pore fluid within the soil is a major concern in dynamic centrifuge testing.

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