RRW SYSTEM: SPECIFICATIONS, USAGE AND TRAINING EXAMPLE

MANUAL PREPARED BY:

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EXECUTIVE SUMMARY

The user’s manual of nees@berkeley describes the different procedures to perform an experiment using the UC-Berkeley NEES equipment site. The manual is organized around a specific experiment, referred to as the training experiment. This experiment aims at demonstrating the unique features of nees@berkeley. Special attention is given to the development of the test setup including installation of reaction wall units, attaching actuators to the reaction wall and the specimens and attaching the specimens themselves to the strong floor. Brief presentation of preliminary test procedure and results are also included as an example of how data can be collected and interpreted. The manual also contains a few appendices for important side issues related to the nees@berkeley experimental research facility.
Chapter 1: INTRODUCTION

1.1. Mission and Definition of nees@berkeley

The mission of nees@berkeley is to provide a leading equipment site specializing in earthquake response simulation of large-scale structural and non-structural systems through real-time integration of computer models and physical test specimens in a reaction wall facility.

The nees@berkeley is an integral part of George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) established by the US National Science Foundation. The role of nees@berkeley is to ensure the availability of the state-of-the-art technology in large-scale earthquake hybrid simulations involving computer modeling and physical testing and innovative application to the field of earthquake engineering.

The nees@berkeley equipment site supports large-scale simulation by:

- Leading the development of the hybrid simulation methods to enable:
  - High-speed testing
  - Advanced and robust computational tools
  - Hybrid substructures (i.e. computational and physical substructures)
  - Geographically distributed hybrid simulation
- Implementing data/metadata capabilities of NEES grid
- Simulating tests in a virtual mode prior to physical testing
- Allowing versatile capabilities for specimen and setup configurations
- Integrating a NEES Equipment Site to the number one rated Civil Engineering education program

The accessibility of nees@berkeley and its proximity to several major research universities, national research laboratories, and leading earthquake engineering professional community provide an excellent environment for efficient collaboration with other researchers. Moreover, nees@berkeley provides excellent ancillary research infrastructure, including office space, computational facilities, and the 100,000 volume Earthquake Engineering Library.
1.2. Objective
This user’s manual is aimed to familiarize the interested user with the facilities provided by nees@berkeley, and to guide the user throughout the operational stages to perform a general testing procedure. The organization of this manual is based on the chronological order of tasks necessary to run a test. This procedure starts with the basic idea for a test protocol and a test specimen, going through the design of the test setup configuration, its assembly, then running the test, and interpreting the results.

The main components of the nees@berkeley test facility discussed in the following chapters are:
1. Reaction wall units that can be configured in different layouts
2. Hydraulic actuators
3. Control systems: FlexTest and Hybrid Control.

1.3. Infrastructure of nees@berkeley
The nees@berkeley laboratory consists of the following:
- A 6 m × 18 m (20 ft × 60 ft) structural tie-down floor with 60 mm (2.5 in.) diameter tie-down holes located in an array at 910 mm (36 in.) on center to accommodate service load of 445 kN (100 kip) acting either up or down for each tie-down hole
- A 17.8 MN (4,000 kip) capacity Southwark-Emery Universal Testing machine
- An overhead 117 kN (12 US-ton) capacity bridge crane
- A 15.2 m × 30.5 m (50 ft × 100 ft) paved construction area
- Twenty four 3050 mm × 2740 mm × 760 mm (120 in. × 108 in. × 30 in.) hollow modular reinforced concrete wall units that may be post-tensioned to the floor using 12 threaded rods with a prestressing force of 445 kN (100 kip) per rod to build one or more reaction walls up to 13 m (42.5 ft) in height with the maximum shear force and bending moment of 1780 kN (400 kip) and 5420 m-kN (4000 ft-kip), respectively
- Two dynamic actuators with force capacity +/-667 kN (+/-150 kip) static, +/-556 kN (+/-125 kip)@510 mm/s (20 in./s); stroke capacity 510 mm (20 in.)
- Two dynamic actuators with force capacity +/-979 kN (+/-220 kip) static, +/-623 kN (+/-140 kip)@510 mm/s (20 in./s); stroke capacity 1020 mm (40 in.)
- Three static actuators with force capacity 1460 kN (328 kip) compression, 960 kN (216 kip) tension; stroke capacity 1830 mm (72 in.)
• A high performance MTS digital control system capable of operating up to 8 dynamic actuators simultaneously
• A fiber-optic network linking the MTS controller and a number of local personal computers enabling high-speed hybrid simulations
• A new MTS FlexTest system and an xPC digital control system, both capable of carrying out hybrid simulations
• A new 128+24 channel data acquisition system
• A wide variety of transducers
• Capabilities for telepresence, such as high-resolution still photography, NSTC and DV video cameras, and teleconferencing
• A personal robot avatar for off-site users to traverse the laboratory to view progress and talk to laboratory staff, students and others on site
• Capabilities to computationally simulate the seismic response of test specimens and develop computational models of substructures for hybrid simulations using the Open System for Earthquake Engineering Simulation, http://opensees.berkeley.edu/

In addition to the physical facility, nees@berkeley utilizes staff with extensive experience in earthquake engineering experimental research including previous experience in conducting research for off-site researchers.

1.4. Non-NEES Infrastructure Available for nees@berkeley

In addition to the nees@berkeley equipment mentioned above, the following equipment can also be made available to researchers using nees@berkeley:

• Two 300 kHz, 15 bit A/D converters with 144 channels of signal conditioning
• Three 100 kHz, 12 bit A/D converters with 48 channels of signal conditioning
• Five sets of 16 channels each, 12 bit resolution, ISA BUS data acquisition cards without signal conditioning
• 424 channels, 16 bit resolution, GPIB BUS with signal conditioning
• A total of 35 static actuators with the following specifications:
  • Two actuators with 6672 kN / 610 mm (1500 kip / 24 in.)
  • Two actuators with 4190 kN / 250 mm (942 kip / 10 in.)
  • Two actuators with 2046 kN / 510 mm (460 kip / 20 in.)
• Two actuators with 2046 kN / 250 mm (460 kip / 10 in.)
• One actuator with 1334 kN / 300 mm (300 kip / 12 in.)
• Four actuators with 667 kN / 910 mm (150 kip / 36 in.)
• Four actuators with 556 kN / 910 mm (125 kip / 36 in.)
• Two actuators with 556 kN / 610 mm (125 kip / 24 in.)
• One actuator with 543 kN / 510 mm (122 kip / 20 in.)
• One actuator with 351 kN / 300 mm (79 kip / 12 in.)
• One actuator with 338 kN / 300 mm (76 kip / 12 in.)
• Two actuators with 285 kN / 300 mm (64 kip / 12 in.)
• One actuator with 222 kN / 300 mm (50 kip / 12 in.)
• Two actuators with 156 kN / 2540 mm (35 kip / 100 in.)
• Four actuators with 129 kN / 100 mm (29 kip / 4 in.)
• Two actuators with 89 kN / 300 mm (20 kip / 12 in.)
• Two actuators with 53 kN / 300 mm (12 kip / 12 in.)
• Reciprocating dynamic shaker capable of developing 22 kN (5 kip) of inertia force up to 10 Hz

1.5. Location and Contact Information
nees@berkeley is located in Building 484 at the Richmond Field Station of the University of California, Berkeley.

Address: Richmond Field Station, Building 484
Mailing address: 1301 S. 46th Street, RFS 451, Richmond, CA 94804
Phone: +510 231-9527
Fax: +510 231-9471
Web site: http://nees.berkeley.edu/

1.6. Manual Layout
This user’s manual starts with an introduction in Chapter 1, followed by the design of a test configuration and setup of a selected structural system for the purpose of training, Chapter 2. The construction of the test setup is outlined in Chapter 3. Performing the experiment is discussed in Chapter 4, with an interpretation of the results briefly outlined in Chapter 5. Appendices A, B, and C provide information on the tools for the design, configuration and checks of the reaction
walls and available actuators. Appendices D, E, F, and G aim towards providing information about the validation tests conducted on the grout used between the wall units, the interface between the wall units, and the dynamic characterization of the reaction wall.
Chapter 2: DESIGN OF TEST CONFIGURATION AND SETUP

The development of the experimental protocol and test specimens are discussed in this chapter. A training experiment is chosen as an example to guide the user through the testing procedure. This training experiment consists of two specimens that may be tested independently or simultaneously, through a series of quasi-static and pseudo-dynamic tests.

2.1. Objectives of the Test Specimens

The training specimens are chosen to demonstrate the capabilities of the pseudo-dynamic testing methodology. Moreover, developing new algorithms are sought through the use of these training specimens. In pseudo-dynamic testing, experiments are conventionally conducted under displacement control. For stiff structures, it may be advantageous to conduct the test, during certain intervals, under force control. The main reason among many being that the target force can be applied more accurately in this case for such stiff systems.

The two specimens are presented in Figure 1. Specimen $C_1$ behaves linearly with constant stiffness $K_1$, while specimen $C_2$ is designed to behave bilinearly, starting with initial stiffness $K_1$ and stiffening to become $K_2$ as soon as the gap “g” is covered.

![Figure 1: Schematic illustration of the training specimens and their expected structural behavior](image)

The two training specimens represent the two physical substructures of the tested system, Figure 2. They are connected through a computational substructure represented by a spring with stiffness $k_s$. From symmetry, the response of specimen $C_1$ is assigned to the first and third degrees of freedom in the system, while specimen $C_2$ represents the second degree of freedom.
Note that, in Figure 2, $k_{c_1}$ represents the linear stiffness $K_1$ in Figure 1, while stiffness $k_{c_2}$ represents the bilinear behavior ($K_1-K_2$).

For specimen $C_2$, while the stiffness is relatively low, $K_1$, the test is run in displacement control. Once the stiffness increases to become $K_2$, the specimen is tested in force control mode.

For that purpose, a force control algorithm is developed and implemented using the hybrid control system, Mosqueda (2004). It is worth noting that the implementation of the force control algorithm for pseudo-dynamic testing, as well as the smooth transition between force and displacement control modes represent a major contribution to the pseudo-dynamic testing technique.

### 2.2. Design of Test Specimens

Two training specimens, Figure 1, consist of two vertical cantilever steel beams. Specimen $C_1$ consists of a simple cantilever with a fixed moment connection at the base. Specimen $C_2$ is the same as specimen $C_1$, except that a stiffener is attached to it by means of a pair of threaded bolts. The nuts on each bolt set a predetermined gap before the stiffener is engaged in the resistance of the load. This gap, characterized by the parameter $g$ in Figure 1, can be adjusted before testing. The expected behavior for both specimens is depicted by the force-displacement relationships shown in Figure 1. The specimens are designed so as to remain elastic during the tests allowing them to be reused for training purposes. Structural details of specimens $C_1$ and $C_2$ are illustrated in Figure 3 and Figure 4, respectively.
Figure 3: Details of Specimen $C_1$ of the training specimens [$1'=304.8$ mm and $1''=25.4$ mm]
2.3. Design of Setup Configuration

For each specimen, one reaction wall and one actuator are needed. Table 1 summarizes the main properties for the two specimens, based on which, the actuators are selected, and the reaction wall heights and locations on the strong floor are determined.
Table 1: Training specimen specifications

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C_1</th>
<th>C_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height at load application point</td>
<td>3150 mm (124 in.)</td>
<td>3150 mm (124 in.)</td>
</tr>
<tr>
<td>Expected maximum load</td>
<td>44.5 kN (10 kips)</td>
<td>97.9 kN (22 kips)</td>
</tr>
<tr>
<td>Expected maximum displacement</td>
<td>±508 mm (±2 in.)</td>
<td>±508 mm (±2 in.)</td>
</tr>
</tbody>
</table>

2.3.1. Step 1: Selection of reaction wall configuration

The reaction wall is constructed by assembling a number of prefabricated high strength reinforced concrete units of box-section type. The concrete geometry, for the wall unit, in plan and elevation are shown in Figure 5. Plan view of the reinforcement details of the wall unit is illustrated in Figure 6.

![Figure 5: Concrete geometry of the wall unit (total of 24 units) [1'=304.8 mm and 1"=25.4 mm]]
For the purpose of the training specimens, the required number of wall units is determined as \( n = \frac{124}{30} = 4.13 \) units. Therefore, five units are needed to construct each reaction wall. It is decided to use seven units for each wall to provide sufficient height for a diagonal chain to carry the self-weight of the actuator.

Figure 7: Diagonal chain to carry the self-weight of the actuator
The structural properties of the reaction wall are evaluated using the design spreadsheet discussed in Appendix A. The wall is checked for sliding, lateral displacement, shear, and tension limits. In case of dynamic loading, the modal frequencies of the assembled wall are also estimated. If any of the checks, including frequency estimates and their relationship to a dynamically tested specimen, are not met, the user may choose to change the height or the orientation of the weak and strong directions of the wall, or to stiffen it with another adjacent wall for possible different wall configurations.

2.3.2. Step 2: Selection of actuators

As mentioned in Chapter 1, seven actuators are available as nees@berkeley equipment in addition to other non-NEES equipment. These actuators are characterized by

1. Load capacity
2. Stroke
3. Type of loading (dynamic or static).

Based on these characteristics, the intended loading configuration, and the anticipated structural performance of the test specimen, the user should be able to select the most appropriate actuator(s) to be used in the experiment, refer to Figure 8.

Figure 8: A 979 kN (220 kip) actuator chosen for one of the training specimens
2.3.3. Step 3: Assembling the test setup

At this point, the user is able to use the provided AutoCAD file, discussed in Appendix C, which contains all the actuators, typical wall unit, strong floor, etc… as AutoCAD blocks, to perform the following:

1. Assemble the test setup
2. Determine the final location of the test on the strong floor
3. Perform any required modifications.

For the use of this AutoCAD file, the user should develop an AutoCAD drawing(s) of the desired specimen(s) and augment such drawing(s) with the provided AutoCAD blocks. The training specimens are used as an example to show this process where the AutoCAD file is used to assemble the setup, refer to Appendix C.

It is to be noted that the design of the test specimen and the setup configuration are interrelated in nees@berkeley test facility. For example, the test setup of the training specimens is located eccentrically with respect to the reaction wall to accommodate other test specimens, Figure 9, for another experimental project, shown by the shaded area. This arrangement required either modifications of the actuator base plate that connect it to the reaction wall, shown in detail B, or modifications to the base plates of the test specimens to accommodate eccentric locations of the anchors to the strong floor. For practical reasons, the latter choice was adopted. A few modifications had to be made to the base plate of the training specimens to resist the torsion due to the eccentricity of the load. This is shown in Figure 10 in case of specimen C_1. The same modifications were made in the case of specimen C_2.
Detail A: Load eccentricity of 7”

Elev. detail B-B: Alternative actuator base plate

Figure 9: Setup Configuration to accommodate another experiment project [1” = 25.4 mm]

Plan View
  a) Case of concentric loading
b) Case of eccentric loading

Figure 10: Modifications of the base plate of specimen C₁
Chapter 3: SETUP CONSTRUCTION

There are six components in a test setup within nees@berkeley facility. These are:

1. Reaction wall(s) and its assembly, Section 3.1.
2. Actuator(s) and its connection, Section 3.2.
3. Hydraulics and their connections and connection of the control system, Section 3.3.
4. Test specimen(s) and its installation, Section 3.4.
5. Instruments and their layout (channel list) and connection to the data acquisition system, Section 3.5.
6. Calibrating the installed instrumentation, Section 3.6.

The following sections elaborate on these six components.

3.1. Reaction Wall Assembly

3.1.1. Step 1: Moving the wall units to the strong floor

The wall units are stored outside the laboratory building on the paved construction area. As a first step, the units need to be brought within reach of the laboratory crane for their assembly. The wall units are examined before their use and any apparent irregularities in the prestressing ducts are marked and corrected. Each wall unit is given a number from 1 to 24. Once a reaction wall is assembled, the configuration is registered, for future reference. A record is therefore developed to facilitate reconfiguration of the reaction wall in the future. The required equipment and material for this step are:

1. Forklift (capacity: 53 kN (12 kips))
2. Lab bridge crane (capacity: 117 kN (26.7 kips))
3. Rigging equipment: straps, load chains with grab hooks, lifting cables
4. Steel wheels (capacity: 53 kN (12 kips) each)

The procedure to perform step 1 of the wall assembly is summarized in the following list and Figure 11.

1. Tie the upper face of a typical wall unit on one end to the forklift.
2. Lift the unit and place a wood block under the center of each side web.
3. Lower the wall unit from the fork lift end. The center wood blocks act as pivots, and the opposing extremity is lifted up. Wood blocks are placed under the lifted side.
4. At this point, the far end from the forklift is resting on wood blocks, the forklift is used to lift the near end up, and the steel wheels are placed at the center of each web.

5. The wood blocks are removed using the forklift, and the wall unit is tied to the forklift with lateral chains.

6. Using the forklift, the unit is driven inside the lab, where the crane is ready to pick it up.

Figure 11: Moving a wall unit to the strong floor
3.1.2. Step 2: Installing the lower wall unit

The first wall unit is a special unit as it is interfaced directly to the strong floor. The required equipment and material for this step are:

1. Foam sheets
2. Guide pins
3. Lab bridge crane (capacity: 117 kN (26.7 kips))
4. Rigging equipment: straps, load chains with grab hooks, lifting cables
5. Towels
6. Safety wood blocks
7. Grout equipment and material; refer to Appendix E for detailed description.

The procedure to perform step 2 of the wall assembly is summarized in the following list and Figure 12:

1. Fabricate 12 foam donuts per wall unit where the inner diameter of these donuts is the same as the diameter of the vertical wall unit ducts
2. The wall unit is laid on safety wood blocks in a different place from where it will be installed for cleaning purpose
3. Install donuts around strong floor tie-down holes to prevent grout from filling them
4. Wet floor with damped towels
5. Hang and secure the wall unit using the crane at a reasonable height clearance from the floor to allow enough room to work under the unit
6. Drive the guide pins in the prestressing ducts of the wall unit to ensure that the wall unit is in the right position, and rest it on safety wood blocks while it is still attached to the crane
7. Mix and place the grout; refer to Appendix E for detailed description.
8. Lower the wall unit in place and perform the final touches on the inner and outer edges of the wall unit to guarantee a good interface with the strong floor.
3.1.3. Step 3: Installing an upper wall unit

A typical wall unit is installed on top of another wall unit that was already in place. The required equipment and material for this step are:

1. Foam sheets
2. Guide pins
3. Lab bridge crane (capacity: 117 kN (26.7 kips))
4. Rigging equipment: straps, load chains with grab hooks, lifting cables
5. Towels
6. Safety wood blocks
7. Scaffold system consisting of an interior plate, refer to Figure 13, to be placed inside the wall interior box, and an exterior fence, refer to Figure 14, to be placed on top of the upper wall unit
8. Grout equipment and material; refer to Appendix E for detailed description.
The procedure to perform step 3 of the wall assembly is summarized in the following list and Figure 15:

1. Fabricate 12 foam donuts per wall unit where the inner diameter of these donuts is the same as the diameter of the vertical wall unit ducts. These donuts are glued to the upper face of the last laid wall unit around each duct where they prevent the grout from filling the lower wall unit prestressing ducts.

2. After the wall unit is cleaned, the rigs and crane equipment are hooked to it.

3. Install the scaffold where the interior plate is hooked to the first unit down from the wall unit to be installed, and the exterior fence is laid on the unit to be installed.

4. Place the wall unit at the exact position using guide pins, then lift the wall unit up and place it on the safety wood blocks, while keeping the guide pins in place.

5. Wet upper surface of the lower wall unit with damped towels.

6. Mix and place the grout; refer to Appendix E for detailed description.

7. Lower the wall unit in place and perform the final touches on the inner and outer edges of the wall unit to guarantee a good interface with the lower wall unit.

Figure 13: Interior working platform to the wall unit
Figure 14: Exterior safety fence to the wall unit
Step 3 is repeated for each additional wall unit until the desired height of the reaction wall is reached.

3.1.4. Step 4: Prestressing the reaction wall to the floor

There are 10 vertical ducts in each wall unit. Once the wall is built to the desired height, a steel rod (24.9 mm (1-3/8 in.) diameter) is placed in each duct through the height of the wall and the strong floor thickness. Each rod is designed for a prestressing force of 445 kN (100 kips). The required equipment and material for this step are:

1. Portable hydraulic jack
2. Gauged hydraulic pump
3. Steel washer plates and nuts
4. Lab bridge crane (capacity: 117 kN (26.7 kips))
5. Rigging equipment: straps, load chains with grab hooks, lifting cables
The procedure to perform step 4 of the wall assembly is summarized in the following list and Figure 16:

1. Lift the high strength prestressing rods one by one using the crane. The length of each of these rods should be long enough to have at least 460 mm (18 in.) of extra length for the post-tensioning process

2. Place each prestressing rod in the corresponding wall unit duct. Due to the imperfection in the wall unit manufacturing, while the guide pins ensure the alignment of any two adjacent wall units, imperfections accumulate over the height of the wall. Accordingly, the prestressing rods in some cases need to be wiggled manually while lowering them in the ducts. This is possible because of the over-size ducts in the wall units

3. A set of steel washer plate and nut secure each prestressing rod in place at each end, and to ensure perfect contact, the interface between the washer and the wall unit is grouted

4. After all the prestressing rods are positioned, they are prestressed one by one using a hydraulic jack and a gauged pump. It is preferred to prestress one rod on each side of the reaction wall first to secure the wall in place and then rotate over the remaining prestressing rods to reduce the eccentricity of the prestressing force.
3.2. Actuator Installation

3.2.1. Step 1: Attaching the actuator base plate to the reaction wall

The required equipment and material for this step are:

1. Lab bridge crane (capacity: 117 kN (26.7 kips))
2. Rigging equipment: straps, load chains with grab hooks, lifting cables
3. Lever chain hoist
4. Prestressing rods
5. Steel washer plates and nuts.

The procedure to perform step 1 of the actuator installation is summarized in the following list and Figure 17:

1. Place the prestressing rods horizontally in the ducts. For each set of four ducts on one horizontal level, the outer two rods run through the whole width of the wall unit, and the inner two rods run through one flange thickness
2. Hook up the base actuator plate to the crane
3. Lift the plate and place it in the exact spot using the lever hoist mounted on the chains connected to the straps of the crane
4. In the case where the base plate of the actuator extends over two wall units, and since the wall units are not perfectly aligned, some adjustments need to be performed to ensure full contact of the plate with the reaction wall face. Grout is applied on the depressed face of the two unit faces, in a stucco manner, and the plate is pressed against the adjusted wall face while the grout is still plastic.

Figure 16: Prestressing the reaction wall to the strong floor
5. Tie the nuts from both sides of each rod and prestress the rods using the same prestressing system adopted in prestressing the wall units to the strong floor, refer to Section 3.1.4.
3.2.2. Step 2: Mounting the actuator

The required equipment and material for this step are:

1. Lab bridge crane (capacity: 117 kN (26.7 kips))
2. Rigging equipment: straps, load chains with grab hooks, lifting cables
3. Lever chain hoist
4. Adapter plate
5. Steel washer plates, bolts and nuts.

The procedure to perform step 2 of the actuator installation is summarized in the following list and Figure 18:

1. An adapter plate is bolted to the actuator base plate. The slotted holes on the adapter plate allow the adjustment of the centerline of the actuator at the desired position in the horizontal direction, while the different sets of holes available on the actuator base plate allow the adjustment of the centerline of the actuator in the vertical direction
2. Provide support for the self-weight of the actuator. In the particular case of the training specimen, the actuator is chained to the higher wall units to carry the actuator self weight. This step can be replaced by a vertical support provided directly from the strong floor to minimize the wall height if necessary.
3. The actuator is transported using the crane to the desired location, and bolted to the adapter plate
4. The chains along with the lever chain hoist are used to adjust the position of the actuator in the horizontal and vertical direction if needed.
3.3. Connecting the Hydraulics and Controller

The required equipment and material for this step are:

1. Lab bridge crane (capacity: 117 kN (26.7 kips))
2. Rigging equipment: straps, load chains with grab hooks, lifting cables

The procedure to perform the hydraulics connection is summarized in the following list and Figure 19:

1. High pressure hoses are attached to the service manifolds
2. In the case where the length of one hose is not enough to reach the actuator, another hose is connected in series by means of a coupler.

3. The actuator is hooked to the crane at one end and lowered to the ground for ease of reach.

4. The lowered actuator end is secured to the ground for stability.

5. Two hydraulic hoses are attached to each actuator in addition to the pilot pressure hose.

6. Four electric cables are then attached to the actuator and connect it to the control system through an underground network of cables linked to the control room.

Figure 19: Connecting the hydraulics and the controller.
3.4. Specimen Installation

3.4.1. Step 1: Connecting the specimen to the strong floor

The required equipment and material for this step are:

1. Lab bridge crane (capacity: 117 kN (26.7 kips))
2. Rigging equipment: straps, load chains with grab hooks, lifting cables
3. Grout equipment and material; refer to Appendix E for detailed description
4. Portable hydraulic jack
5. Gauged hydraulic pump
6. Steel washer plates and nuts

The procedure to perform step 1 of the specimen installation is summarized in the following list and Figure 20:

1. The specimen is transported by means of the crane, and placed at the desired location.
2. The specimen is then slightly lifted and placed on shims that mark the depth of grout to be laid, and the verticality of the specimen is adjusted.
3. Grout is inserted under the specimen and complete contact throughout the base surface is ensured
4. Prestressing rods are inserted in the designated holes and prestressed to the design prestressing load.
3.4.2. Step 2: Connecting the actuator to the specimen

The required equipment and material for this step are:

1. Adapter plates
2. Prestressing rods
3. Lab bridge crane (capacity: 107 kN (24 kips))
4. Rigging equipment: straps, load chains with grab hooks, lifting cables
5. Lever chain hoist
6. Steel washer plates, bolts and nuts.

The procedure to perform step 2 of the specimen installation is summarized in the following list and Figure 21:

1. Adapter plates are attached to the specimen. The attachment method depends on the specimen shape, size and loading. In the case of the training specimen, one adapter plate is placed on each side of the steel cantilever, and rods are used to prestress the plates against the specimen at the desired height. This sub step precedes step 1, and is done while the specimen is laid horizontally on the floor for ease of handling and reach.

2. After the specimen is fixed to the strong floor, the actuator is hooked to the crane, and a lever hoist is used for accurate adjustment.

3. Once the actuator is brought to the desired elevation, it is bolted to the adapter plate on the specimen side. The connection to the crane may then be released.
3.5. Instrumenting the Specimen

The instrumentation procedure may vary according to the amount and type of instrumentation. In the case of the training specimen, a total of 22 strain gages were used. The location of the strain gages are as shown in Figure 22. For sections A through E, four strain gauges are installed as shown in the section detail. One 2-element Rosette is attached on the web to measure shear strain, and two single-element strain gages are attached to the two flanges to measure the normal strains induced by the applied moment. In addition, one longitudinal strain gage was attached to each of the two rods.
Novotechnik displacement transducers were used to measure the deflection at the top of the two cantilevers. For each of the specimens, one transducer measured the displacement in the out of plane direction, and two transducers measured the displacement in the in plane direction and were placed as shown in Figure 23, this allows to detect the torsional rotation that may be caused by any misalignment of the loading axis and the center line of the specimen.
The required equipment and material for this step are:

1. Strain gages
2. Novotechnik transducers
3. piano wires
4. Mechanical grinder
5. Instrumentation kit: Acid, neutralizer, alcohol, sand paper, prescribed glue, Teflon paper.

The procedure to attach the strain gages to the specimen is summarized in the following list and Figure 24:

1. The location of the strain gage is marked on the specimen
2. The steel surface is grinded using a mechanical grinder, and the grinded surface is degreased. Fine sand paper (grade 180 to 220) is used along with acid and then neutralizer to smoothen the surface of the specimen where the strain gage is to be placed. The exact spot is marked with a sharp pen, and erased with alcohol. The sharp trace of the pen defines the desired location of the strain gage
3. The strain gage is carefully glued to the surface and held for 60 seconds to ensure complete fixture
4. The strain gage cable is secured to the specimen
5. For each strain gage, the wire is connected to the corresponding cable through a special connector
6. The cable is then connected to the terminal box, which is linked to the data acquisition system.
The procedure to attach the displacement transducers to the specimen is summarized in the following list and Figure 25:

1. The location of the transducer is marked on the specimen and a plate is attached by means of epoxy.
2. The transducer is attached to a fixed reference point from the other end and connected to the plate by means of a piano wire.
3.6. Instrumentation Calibration

The installed instrumentation is calibrated using the software provided by Pacific Instruments, Inc. A channel is assigned to each instrumentation unit and the input parameters (e.g. input voltage, gain, etc…) are assigned, Figure 26.

Figure 26: Channel definition and parameter input
The calibration process may be divided into a number of steps as follows:

1. Voltage calibration
2. Bridge balance
3. Engineering unit calibration

The implementation of these steps may differ according to the instrumentation type (Pacific Instruments, 2004). Figure 27 shows the graphical interface through which the previous steps are executed.

![Calibration process through graphical interface](image)
Chapter 4: Running a Test

In this chapter, the two control systems (FlexTest and Hybrid Control) are introduced and described through their different functions and uses. The user should be able to choose the control system that best suits the objectives of the planned experiment.

4.1. Virtual Simulation of the Experiment

4.1.1. FlexTest simulation mode

This section is under construction

4.1.2. Hybrid control system simulation mode

This section is under construction

4.2. Preliminary Runs

4.2.1. Debugging the system

This section is under construction

4.2.2. Checking the channel readings

This section is under construction

4.3. Running the Test

4.3.1. Quasi-static test

This section is under construction

4.3.2. Pseudo-dynamic test

This section is under construction
Chapter 5: Interpretation of Results

In this chapter, only a few sample results from the training specimen tests are presented. Brief discussion of the implications of these results on other planned tests is also introduced.

5.1. Global Results

This section is under construction

5.2. Local Results

This section is under construction
REFERENCES


MTS (2003), *Model 793.00 System Software, User Information and Software reference*, MTS Systems Corporation


APPENDIX A: SPREADSHEET FOR REACTION WALL CONFIGURATIONS

A.1. Background

A spreadsheet is designed to estimate governing parameters of the reconfigurable wall. A fixed base condition is assumed throughout the spreadsheet calculations. The user provides a number of inputs to define the wall configuration and the conditions of its use. These inputs are:

1. Wall height (number of wall units)
2. Number of pretensioning rods used per wall (typically 10)
3. Pretensioning load applied per rod (typically 100 kips)
4. Loading direction with respect to the wall axis (weak or strong axis)

In the case where a second wall is used adjacent to the first wall for increased stiffness, the same four previous inputs are provided for the second wall, in addition to:

5. Position of the second wall with respect to the first wall (beside or behind)

The user also provides:

6. Deflection limit for the wall
7. Tension stress limit

Other parameters such as Young’s modulus of the pretensioning steel, coefficient of friction at the interface of the wall units, etc... are also considered as input variables, and may be modified by the user.

The output is in both tabular and graphical forms. Four governing limits are plotted as a function of the load amplitude and application height. These governing limits are:

1. Normal stress in tension
2. Shear stress
3. Deflection
4. Sliding

The vibration frequencies of the reconfigurable wall in all three directions -strong and weak axes, in addition to torsion- are estimated using Timoshenko beam theory (Weaver 1990), considering both shear and axial loads. Since the solution is an iterative one, the Euler beam solution is provided as a first guess for the fundamental frequency in each direction. Note that these results were calibrated during the wall vibration testing, refer to appendix G.
A.2. Example

The setup used during the wall vibration testing –eight unit high- is used as an example (Appendix G). The provided input is shown in Figure 28.

Figure 28: Design spreadsheet input
The output is shown in Figure 29. Notice that in this particular case, the tension limit governs the design.

![Actuator Load](image)

Figure 29: Design spreadsheet output

The vibration properties estimated by the spreadsheet are shown in Figure 30. The frequencies listed are calculated in the strong axis direction. The same is estimated in the weak axis direction, by changing the loading direction in the input sheet from “strong” to “weak”.

![Vibration Properties](image)
Figure 30: Vibration properties estimated by the design spreadsheet – strong direction
APPENDIX B: SAP2000 COMPUTATIONAL MODELS FOR DIFFERENT CONFIGURATIONS OF THE REACTION WALL

B.1. Background

A computational model for the reconfigurable wall system was developed using SAP2000. The different components modeled in the system are:

1. Reconfigurable reaction wall
2. Pretensioning rods
3. Strong floor
4. Underlying soil

The model provides the stress and displacement values according to the chosen configuration and case of loading. In addition, basic dynamic properties such as fundamental frequencies and corresponding modes are provided with better accuracy compared to the spreadsheet, refer to Appendix A and G. This is expected since in the case of the spreadsheet calculations, the connection at the base of the reaction wall is assumed to be completely fixed, while the flexibility of the strong floor and underlying soil is taken into account in the SAP2000 computational model.

B.2. Example

The setup used for the testing of the training specimen is used as an example, Figure 31.

Figure 31: Training specimen configuration - SAP2000 computational model
The input parameters are provided through the graphical interface of SAP2000 software. Different material and section properties are defined, Figure 32.
The structure is analyzed for the different load cases expected during testing, Figure 33. The stress and displacement values are checked for compliance with the design limits.

Figure 33: Analyses for different load cases - SAP2000 computational model

The dynamic properties represented by the vibration frequencies are displayed for different soil stiffness values, Table 2. Figure 34 shows the first mode of vibration for the considered configuration.

Table 2: Natural vibration frequencies

<table>
<thead>
<tr>
<th>K\text{\textsubscript{soil}} (kcf)</th>
<th>1\text{\textsuperscript{st}} mode frequency [Hz]</th>
<th>1\text{\textsuperscript{st}} mode frequency [Hz]</th>
<th>1\text{\textsuperscript{st}} mode frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>5.1</td>
<td>10.6</td>
<td>14.0</td>
</tr>
<tr>
<td>600</td>
<td>6.7</td>
<td>14.1</td>
<td>18.2</td>
</tr>
<tr>
<td>1200</td>
<td>8.4</td>
<td>17.5</td>
<td>18.7</td>
</tr>
<tr>
<td>fixed</td>
<td>17.6</td>
<td>22.8</td>
<td>24.1</td>
</tr>
</tbody>
</table>

Figure 34: 1\text{\textsuperscript{st}} Vibration mode – SAP2000 Computational model
APPENDIX C: AUTOCAD DESIGN DRAWINGS FOR nees@berkeley

C.1. Contents

As part of the test design process, the user has the ability to construct the test setup using the provided AutoCAD drawings, section 2.3.3. The items provided are listed below:

1. Strong floor
2. Reconfigurable wall units
3. Actuators
4. Actuator base plate
5. Adapter plate

These items, provided as blocks, in addition to the test specimen(s), are used to assemble the test setup virtually. The user can then make any adjustments if needed. Figure 35 shows the actuator drawings, provided as AutoCAD blocks. The three available types of actuators are provided, along with a brief description of the stroke and loading capacity.

![Actuators at mid height position](image)

Figure 35: Actuator AutoCAD drawings provided as blocks

C.2. Examples

As an example, the training specimens are drawn and added to the different components of the test setup, Figure 36.
Figure 36: Training specimen test setup, using provided AutoCAD drawings
APPENDIX D: GROUT TESTING

D.1. Specimens

Several specimens were fabricated to test different grout mixes and surface treatment of the wall units. Concrete blocks with similar surface texture to the wall units were selected for these tests. The specimen configuration consisted of six blocks arranged to test the grout joint in direct shear under constant axial stress. Four instrumented rods with two calibrated springs are used to apply the constant prestressing force normal to the grout joint, Figure 38 and Figure 39. By changing the value of the normal stress, $\sigma$, the peak, $\tau_p$, and residual, $\tau_r$, shear stresses are estimated and failure envelopes are developed as depicted in the schematic illustrations of Figure 42.

![Specimen for direct shear test of the grout](image1)

Figure 37: Direct shear test configuration of the grout

![Stresses applied to direct shear specimen](image2)

a) Specimen for direct shear test of the grout

b) Stresses applied to direct shear specimen

Figure 37: Expected results from the direct shear test of the interface (grouted or not grouted)

![Schematic shear stress-slip relationships](image3)

a) Schematic shear stress-slip relationships

b) Schematic failure envelopes of the interface

Figure 38: Expected results from the direct shear test of the interface (grouted or not grouted)
Several specimens were tested for three values of the normal stress and for the following different interface conditions:

1. Dry ungrouted interface, i.e. without any surface treatment or grout
2. Dry grouted interface, i.e. without any surface treatment but with grout
3. Treated ungrouted interface, i.e. with hardened surface, using commercially available hardener, treatment but without grout
4. Treated grouted interface, i.e. with hardened surface, using commercially available hardener, treatment and with grout

The applied normal stress ranged from 0.78 to 1.77 MPa (113 to 256 psi). This range was estimated to bound the design uniform compressive stress in the wall units when stressed with 5338 kN (1200 kips), namely 1.1 MPa (160 psi). Accordingly the test matrix of these specimens is as given in Figure 40 and Table 3.
Figure 40: Different specimens for the direct shear tests of the grout

Table 3: Test matrix of the grout test

<table>
<thead>
<tr>
<th>Test</th>
<th>σ [MPa (psi)]</th>
<th>Hardener</th>
<th>Grout</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>0.78 (113)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>1b</td>
<td>1.28 (185)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>1c</td>
<td>1.77 (256)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2a</td>
<td>0.78 (113)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>2b</td>
<td>1.28 (185)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>2c</td>
<td>1.77 (256)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
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</tr>
<tr>
<td>3b</td>
<td>1.28 (185)</td>
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<td>Yes</td>
</tr>
<tr>
<td>4c</td>
<td>1.77 (256)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

D.2. Observations

Typical results of the grout tests are discussed in this section. Figure 41 compares specimen 1c to specimen 4c, refer to Table 3, to demonstrate the combined effect of the hardener and the grout on the stress-stress/slip relationship. From these plots and ignoring the effect of cohesion, i.e. shear strength at zero normal stress, the coefficients of friction can be estimated for the peak, $\mu_p$, and residual, $\mu_r$, shear strengths using the applied constant normal stress as given in Table 4.
From the test results the following remarks can be made:

1. The results with grout but with and without hardener, e.g. specimens 4c and 2c, were comparable. Therefore, for simplicity, it was decided to use grout without hardening the surface in the actual wall units.

2. The expected coefficient of friction was not dependent on the applied normal stress within the selected range of normal stresses.

3. The minimum coefficient of friction when using grout was 0.8 which is 60% higher than that assumed in design, namely 0.5.

![Graph of load vs. displacement for specimens 1c and 4c](image-url)
Table 4: Estimation of the coefficients of friction from the grout tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\mu_p$</th>
<th>$\mu_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1c</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>4c</td>
<td>2.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>
APPENDIX E: GROUT MIXING AND PLACING

E.1. Equipment and Material

The following quantities, shown in Figure 42, of material and equipment are needed for one interface between two wall units:

a. Three 111.2 N (50 lb) bags of UltraCal 30, pre-chilled
b. Three table spoons of sodate retarder
c. Four plastic buckets
d. Chilled water containers
e. Grout handling tools
f. Electric mixer

![Figure 42: Grouting equipment and material](image)

E.2. Procedure

The grout is divided into three equal portions, each for one third of the surface area of the wall unit upper face. The procedure to perform the grout mixing and placing is summarized in the following list and Figure 43:

1. Working quickly, mix half a bag of grout with 0.44 liters (15 ounces) of water
2. Mix one table spoon of retarder with a small amount of water, shake thoroughly, and add to the mix
3. Add second half of grout bag and add 0.24 to 0.44 liters (8 to 15 ounces) of water to get good consistency of the mix
4. Working quickly, mix into a smooth batter
5. Place grout along center line of the wall unit side webs, and add more to corners as needed
6. Clean tools and buckets.

Figure 43: Mixing and placing grout
APPENDIX F: WALL INTERFACE TESTING

F.1. Specimen

Based on the discussions in Appendices D and E, sample assembly of the wall units was developed to test the selected mix design and process of mixing and placing the grout. This specimen consisted of two closely spaced stacks of three wall units where each stack was grouted and prestressed to the strong floor, refer to Figure 44. Several displacement transducers were used to monitor the sliding; one such transducer is marked by a circle in Figure 44, and opening; one such transducer is marked by a square in Figure 44, of all interfaces. Two synchronized jacks (capacity of 1379 kN (310 kips) each) were placed between the two stacks. The following three positions of the jacks were considered:

1. At the mid-height of the bottom units, Figure 45
2. At the mid-height of the middle units with similar arrangement as those in Figure 45
3. At the mid-height of the upper units with similar arrangement as those in Figure 45.

Figure 44: Wall interface assembly consisting of two stacks prestressed to the strong floor
F.2. Observations

Only sample results of the wall interface tests are given in this section. These results are given in Figure 46 for the applied load at the mid-height of the upper units. The load was increased gradually from zero to the maximum force of 2758 kN (620 kips) and then to zero again. The recorded maximum sliding and opening were less than under 0.0457 mm (0.0018 in.) as shown in Figure 46. These maximum values corresponding to more than 50% increase of the design level of the wall units, namely 1780 kN (400 kips), were viewed as small enough to indicate success of the chosen interface grouting and prestressing systems. It is to be noted that the resolutions of the used displacement transducers and data acquisition system are 0.0025 and 0.0051 mm (0.0001 and 0.0002 in.), respectively, which explain the jaggedness of the plots in Figure 46.
Figure 46: Results of the wall interface tests [1 kip = 4.45 kN and 1 in. = 25.4 mm]

a) Sliding of the interface with the floor (the plots correspond to measurements of the two webs)

a) Opening of the interface with the floor
APPENDIX G: WALL VIBRATION TESTING

G.1. Wall Configuration and Experimental Setup

A number of tests were carried out on the reconfigurable reaction wall for the purpose of characterizing the vibration properties of the wall, and validating the results obtained from the spreadsheet discussed in Appendix A and SAP2000 model discussed in Appendix B. The setup consisted of two reaction walls (Figure 47): the first wall was eight unit 6.10 m (20 ft) high, and the second wall, used as anchor in the pull-back test, was seven unit 5.33 m (17.5 ft) high, Figure 48(a). A cable was connected in series with a lever chain hoist, load cell, and a 6.4 mm (¼ inch) diameter rod. The whole system was stretched between the top units of the two reaction walls, Figure 47, during the pull-back test. In addition, a dynamic actuator was connected to the reaction wall at mid-height for forced vibration tests.

A total of thirteen accelerometers were used during testing. Accelerometers 1 through 10 were placed on the West side of the tested wall along its height, Figure 48(b), and measured the motion in the strong axis direction. Accelerometer 11 was placed on the North side at the top of the wall, Figure 48(c), and measured the motion in the weak axis direction. Accelerometers 12 and 13 were placed on the actuator head, and measured the motion in the weak and strong axes, respectively. In addition, one DCDT was installed to measure the displacement at the top of the wall in the strong axis direction, Figure 48(b). The sampling rate of the data acquisition system was 400 Hz. In the pull-back tests, the data were filtered at 80 Hz, while no filtering was used in the forced vibration tests.
Figure 47: Pulling cable connecting the two reaction walls

(a) Setups for pull-back and forced vibration tests
G.2. Observations

Four pull-back tests were executed. The results compared perfectly. Using the lever chain hoist, the load was increased gradually from zero to 1800 lbs, and the rod was cut. For accelerometers 1 through 10, the two accelerometers at every level were averaged to estimate the acceleration in the strong direction, and subtracted to estimate torsional vibration. Accelerometer 11 represented the acceleration in the weak axis direction at the top unit of the wall.

The damping ratio in mode of vibration along the strong axis direction was estimated to be 8% based on the damped free vibration plot in Figure 49 (Chopra, 2001). The frequency of the first modes of vibration in the direction of the strong and weak axes were evaluated, Figure 50 and Figure 51 respectively. Note that the peak observed at 60 Hz is due to the electric lines and does not represent any frequency of the reaction wall. The phase difference plot indicates practically no phase difference between the indicated accelerations at two different heights confirming the first mode response.

The stiffness of the wall was also estimated using the data obtained from the load cell and DCDT1, Figure 52. Since the force in this plot was measured in the cable direction, which makes
a 20° angle, with the strong axis, refer to Figure 48, the pull back force applied in the strong axis direction, $F_s$, is estimated as:

$$F_s = 1749 \times \cos(20) = 1643.5 \text{ lbs} \quad [7.31 \text{ kN}]$$

The stiffness of the 8 unit high reaction wall, $K_s$, is estimated as:

$$K_s = \frac{F_s}{D} = \frac{1643.5}{(2.95 \times 10^{-4})} = 5.57 \times 10^6 \text{ lbs/in} = 5570 \text{ k/lb/in} [975.5 \text{ kN/mm}]$$

These calculations were repeated for the four pull-back tests, and the average stiffness value was estimated to be 5489 k/in [961.3 kN/mm].

![Figure 49: Average acceleration – Strong axis – 8th block – Free vibration](image)
Figure 50: Frequency evaluation – Strong axis – Free vibration

Figure 51: Frequency evaluation – Weak axis – 8th block – Free vibration
To confirm the previous results and to estimate the higher frequencies, the wall was subjected to a random white noise excitation applied by means of a dynamic actuator and using the mass of the actuator head, estimated to weight 11.12 kN (2.5 kips), as the inertial mass. In the strong axis direction, the frequency of the first mode was confirmed to be 23.3 Hz and the frequency of the second mode was estimated to be 90.3 Hz, Figure 53. In the weak axis direction, the frequency of the first mode was found to be the same as in the pull-back test, i.e. 20.7 Hz. In addition, the frequency of the torsional mode was determined as shown in Figure 54 to be 71.9 Hz. The results of the reaction wall vibration tests are summarized in Table 5 and Table 6.
Figure 53: Frequency evaluation – Strong axis – White noise excitation
Figure 54: Frequency evaluation – Torsion – White noise excitation

Table 5: Structural and dynamic properties – Strong axis direction

<table>
<thead>
<tr>
<th></th>
<th>1&lt;sup&gt;st&lt;/sup&gt; mode frequency [Hz]</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; mode frequency [Hz]</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; mode damping ratio [%]</th>
<th>Stiffness [kN/mm (k/in)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>23.3</td>
<td>90.3</td>
<td>8</td>
<td>961.3 (5.49 x 10&lt;sup&gt;6&lt;/sup&gt;)</td>
</tr>
</tbody>
</table>

Table 6: Natural frequencies of 8 unit high reaction wall

<table>
<thead>
<tr>
<th></th>
<th>Direction</th>
<th>Weak axis</th>
<th>Strong axis</th>
<th>Torsion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [Hz]</td>
<td>20.7</td>
<td>23.3</td>
<td>71.9</td>
<td></td>
</tr>
</tbody>
</table>
G.3. Comparison with Spreadsheet and Sap2000 Computations

Comparison between the experimentally obtained results and the spreadsheet (Appendix A) and SAP2000 model (Appendix B) calculations is conducted in this section. Using the estimate of stiffness of the reaction wall as a cantilever, \( K = 3EI/L^3 = 12.23 \times 10^3 \) k/in. Accordingly, the ratio between the calculated and measured average stiffness is \( R_k = 12.23/5.49 = 2.23 \), which would make the ratio between the calculated and measured frequencies \( R_f = \sqrt{R_k} = \sqrt{2.23} = 1.49 \). Assuming this difference is due to uncertainties in material properties such as concrete Young’s modulus and unit weight or due to flexibility at the interface between the joints, one can apply this correction factor to obtain closer estimates of the frequencies to the measured ones, as summarized in Table 7.

<table>
<thead>
<tr>
<th>Method</th>
<th>Strong axis</th>
<th>Weak axis</th>
<th>Torsional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration test</td>
<td>23.3</td>
<td>20.7</td>
<td>71.9</td>
</tr>
<tr>
<td>Computational (SAP2000 - infinitely stiff soil condition)</td>
<td>24.1</td>
<td>17.6</td>
<td>N/A</td>
</tr>
<tr>
<td>Computational (Spreadsheet)</td>
<td>58.3</td>
<td>54.7</td>
<td>101.3</td>
</tr>
<tr>
<td>Corrected for material &amp; interfaces = Computed/1.49</td>
<td>39.1</td>
<td>36.6</td>
<td>67.9</td>
</tr>
<tr>
<td>Correction factor needed for base flexibility</td>
<td>0.596</td>
<td>0.566</td>
<td>1.059</td>
</tr>
<tr>
<td>Correction factor needed for spreadsheet calculations</td>
<td>0.40</td>
<td>0.38</td>
<td>0.71</td>
</tr>
</tbody>
</table>

In the last few tests, two accelerometers on the strong floor were added. One accelerometer was placed next to the wall and the other one was placed on the other end of the strong floor. This was conducted to determine if the fixed cantilever assumption is valid. From comparison of these two accelerometers, the floor flexibility was assessed.

The accelerometer next to the wall indicated considerable motion almost as much as the one on the second unit, 1.14 m (3.75 ft) high, which suggests that the strong floor is not perfectly rigid. On the other hand, the accelerometer on the other side of the strong floor indicated almost no motion, which suggests that the soil has a high stiffness, at least relative to the strong floor which deformed near the reaction wall when vibrated. Accordingly, it was concluded that the flexibility of the strong floor, in this case, may be the source of the difference in the frequency estimation between the computational results (using rigid base assumption) and the experimental results. It is worth mentioning that the corrected analytical torsional frequency is almost the same as the one estimated in the experiment, which supports the previous argument, since the flexibility of the strong floor, or the soil, would not affect the torsional stiffness. The reduction
factors listed in Table 7 are applicable to a reaction wall with the same properties as the tested one. The SAP2000 computational model, refer to Appendix B, was analyzed with the assumption of infinitely stiff underlying soil while accounting for the strong floor flexibility. The computed frequencies displayed in Table 7 compare well to the ones recorded during the vibration test.