Final Technical Report

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Introduction

The objective of this grant was to install 100-meter deep borehole and wellhead seismometers, and four free-field seismometers within 100 m of the Factor building on the UCLA campus. The purpose of collecting the borehole waveform data is to understand the relationship between free-field incident waves and the building response to strong ground shaking. The soil amplification effects can be separated out of the near-surface ground motion. This in turn allows the input ground motion to be separated from the building response. The funds were used to research the optimal borehole and free-field sites, drill the borehole and conduct soil analysis testing, purchase the equipment, set up the data loggers and communications to record real-time data from all sites, and to integrate them with the building data.

The Factor building, a 17-story steel, moment-frame structure with an embedded 72-channel accelerometer array, was instrumented after the 1994 Northridge earthquake. The accelerometer array is composed of four horizontal channels per floor and an additional two vertical channels on the two bottom floors. The horizontal sensors are oriented north-south and east-west along the mid-sections of each floor. In the building's machine room in the attic, nine Quanterra 4128 recorders serve as data loggers with A/D converters. There are four GPS antennas installed on the roof. The data are being continuously streamed from all parts of the building along its entire height profile for real-time monitoring at our laboratory on campus. The Factor array serves as a full-scale, soil-structure interaction experiment representing an important class of urban structures: mid-rise moment-frame steel buildings. It is one of only a handful of buildings in the U.S. permanently instrumented on every floor, providing us with information about how the response may change as the building is damaged.

The Factor building consists of two stories below grade. Excavation during building construction found that the natural soils beneath the building consist of silty sand, silt, clayey sand, clay, and sand. The natural soils are firm throughout. Existing fill soils, 1/3 to 3 m in thickness, consist of silt, sand, clay, and silty sand with some debris. Deeper and/or poorer quality fill probably occurs between locations. There is backfill adjacent to the existing buildings. Comparison of building shaking with earthquake source models requires estimating nonlinear effects in the soil which are thought to be greatest near the surface. The borehole plus free-field array monitors the input signal on and below ground in order to characterize the building response function to incident seismic waves.

Borehole seismometers and soil testing

The main benefits of installing a borehole seismometer that extends to 100 m are greatly reduced noise levels, and better constraints on the near-surface effect for ground motion modeling and ground shaking prediction validation. Deconvolving an input signal from the response generated by the building using only seismometers located in the building is not always feasible because significant soil-structure interactions may not be accounted for. Use of a single, distant, free-field seismometer, as is presently done, is also inadequate because signals from a single instrument are rarely representative of the incident radiation.

The project began with a search of the UCLA archives for appropriate information on siting the optimal borehole location such as reports on soil types, seismic velocities, and depth to basement for possible sites within several tens of meters of the Factor Building. We took advantage of ongoing construction near the Factor building for gaining permission to drill the borehole and to gain access to computer networks within the nearest appropriate building for data transfer. These tasks involved interaction with UCLA Facilities Management and UCLA Capital Programs directors.

The vast majority of the budget funds were used to purchase the equipment. The 100-m deep borehole seismometer was installed approx. 25 m east of the Factor building in the UCLA Botanical Gardens. Instrumentation consisted of a three-component shallow borehole Kinemetrics Hyposensor at the bottom of the hole with cabling, a pressure transducer, a three-component Episensor at the wellhead, and a Quanterra 4128 digitizer located in a garden toolshed a few meters from the borehole. Ground motions are being recorded on the digitizer that is connected to the UCLA intranet. The data are being stored as part of the building array database and can be viewed via the Factor array real-time waveform viewer. A

professional drilling company, Gregg Drilling and Testing, Inc., was contracted to drill the borehole, completed in July, 2004 (Fig. 1).

Figure. 1. Professional drilling company, Gregg Drilling and Testing, Inc., drilling borehole in the UCLA Botanical Gardens in July, 2004.

While the borehole was being drilled, the soil was sampled and geophysically logged next to the target structure to provide *in situ* measurements of subsurface material properties before installation of surface and downhole seismometers (Fig. 2). The geotechnical logging of the well involved bagging the samples for testing, taking notes on the material cuttings, and collecting undisturbed samples for dynamic lab testing. Five *in situ* soil samples at different depths were collected to be tested for strain amplitude-dependent modulus and attenuation changes. The samples were retrieved from the borehole during the drilling process in standard 3-inch diameter Shelby tubes. Each tube was sealed with wax at the top and bottom, and capped by plastic caps which were secured around the tube by tape.

Figure. 2. Retrieval of soil samples at various depths at UCLA borehole site.

Just after the drilling was completed, the uncased boring hole was sampled on July 15, 2004 for suspension P-wave and S-wave velocities by GEOVision Geophysical Services. The purpose of this study was to supplement stratigraphic information obtained during UCLA's soil sampling program and to acquire velocities as a function of depth which, in turn, can be used to characterize ground response to earthquake motion. The OYO Model 170 Suspension Logging Recorder and Suspension Logging Probe were used to obtain *in situ* horizontal shear and compressional wave velocity measurements at 1.64 ft intervals. The acquired data was analyzed and a profile of velocity versus depth was produced for both compressional and horizontally polarized shear waves. The suspension logging system directly determined the average velocity of a 3.28 ft high segment of the soil column surrounding the boring of interest by measuring the elapsed time between arrivals of a wave propagating upward through the soil column.

GEOVision wrote up the results in a report available on the Factor array web site (GEOVision Geophysical Services Report, 2004). A graphical display of the results are shown in Fig. 3 (left). A log of the borehole deviation from true vertical was made by Pacific Surveys in June, 2005 (Fig. 3, right). Note the large deviation at the bottom of the hole.

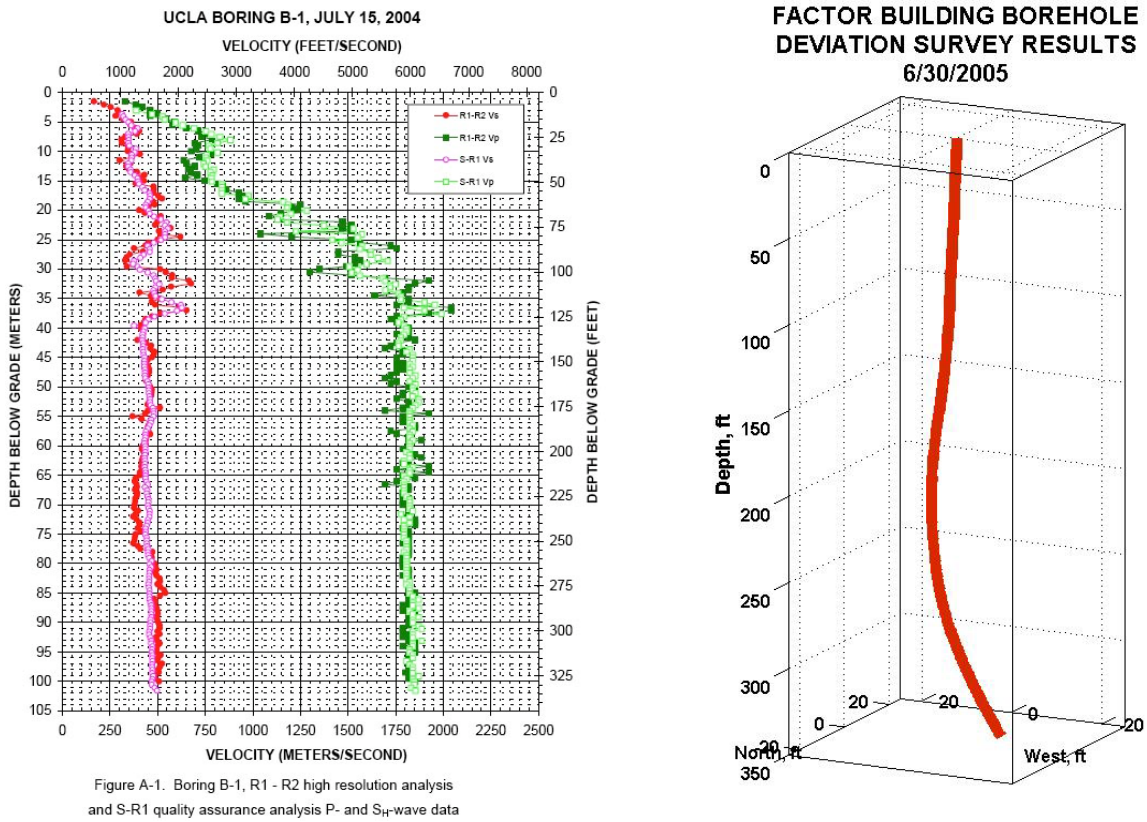

Fig. 3. Left: Suspension P- and SH-wave velocities as a function of depth down the borehole. Right: Borehole deviation from true vertical.

We used supplementary funds to carry out dynamic testing of soil samples that were collected when the borehole was drilled. UCLA Engineering Professor M. Vucetic was contracted to obtain laboratory estimates of soil non-linearity and attenuation as a function of amplitude at the confining pressures corresponding to the various depths. The soil samples were tested in his lab for cyclic stress-strain response using the UCLA Dual-Specimen Simple-Shear system (Vucetic, 1994). The estimates draw on previous results from dynamic soil testing and the geotechnical characterization of the site. The results of the testing done at the UCLA borehole will be used in future computations for the dynamic soil response and its relationship with Factor building motions during strong earthquakes.

Prof. Vucetic's lab performed the following tests and derived the following data: two direct simple shear tests on intact specimens from 162 and 151 feet; nine classification tests on samples throughout the boring which included wet sieve analyses on all nine sols and Atterberg limits tests on three cohesive soil; evaluation of the modulus reduction (G_s/G_{max}-log γ_c) curves for nine soils from nine depths based on the classification tests results (presented in the form of data bands); and evaluation of the equivalent viscous damping ratio (γ-log γ_c) curves for nine soils from nine depths based on the classification tests results (presented in the form of data bands) (e.g., Fig 4). These results were written up in a report (Vucetic, 2006).

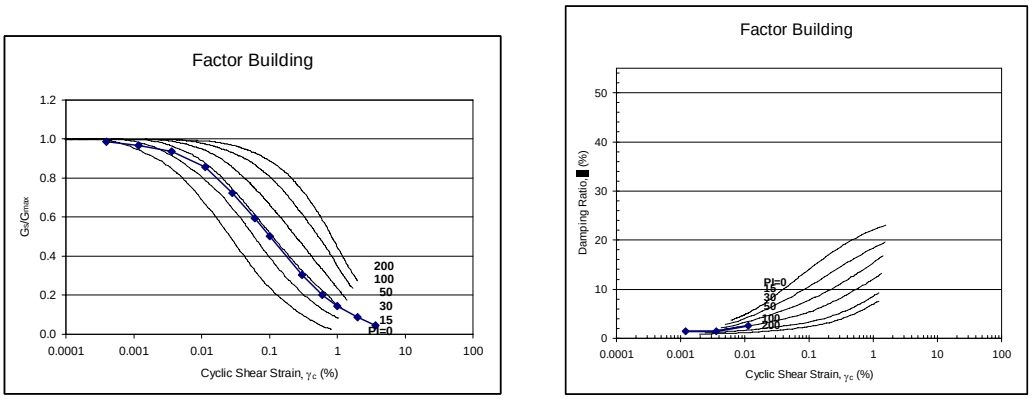

Figure 4. Geotechnical laboratory tests on one of the soil samples from the UCLA Factory array borehole showing modulus reduction data (left) and viscous damping data (right), both as a function of cyclical shear strain.

Free-field seismic array

Four free-field seismometers were installed using supplementary funds to augment the existing UCLA Factor building seismic array in the Factor structural health monitoring project. As part of the vibration monitoring of the Factor building done to date, a large quantity of ambient vibration data as well as earthquake data showed that measurable softening effects were occurring (Kohler et al., 2005; Kohler et al., 2006). If softening of the building is occurring during earthquakes, it may be due to the effects of nonstructural components such as walls and partitions that separate from the main system during larger amplitudes. However the possibility that the soil weakens for large strain is another possibility that needed to be tested. Nearby soil surface movements were needed to determine the relationship with resonant vibrations in the building. The objective of the free-field installation was to measure surface ground motions for soil response waveform data. Nonlinear effects in the soil can reduce the amount of shaking at the surface relative to bedrock and can modify frequency content.

The free-field seismometers consist of Kinemetrics Episensors (±2*g* scale range, 200 sps, GPS) with Q330 dataloggers. The real-time monitoring software package *Antelope* (Boulder Real Time Technologies, Inc.) has been used to monitor Factor building data flow for the past five years. The *Antelope* software is being used to continuously monitor the building-borehole-free-field array. The array is being used to record weak and strong motions from local earthquakes. Backup storage and internet connectivity are being provided by the Center for Embedded Networked Sensors (CENS) data communication controllers (CDCC). The CDCC houses an Xscale Stargate computer and has a backup memory of 1 Gbyte on a flash card. The Stargate runs Antelope and connects to the Internet through the ethernet port. It has the flexibility to be either hard-wired or have wireless connectivity.

North station

The north free-field UCLA campus site is located on a cement floor on the second floor of the Geology building on the side that is level with the ground. Power is obtained through a nearby lab on the second floor and GPS signal is obtained by receiver placed outside a vent window.

South station

The south site is an exterior location in soil inside the UCLA Botanical Gardens along the western boundary next to Tiverton Ave (Fig. 5). Power is obtained from a nearby light pole using an industrial transformer in the base of the light pole to down step the power from 480 V to 24 V. A battery charger further down steps power from 24 V to 12 V. Telecommunications consists of an 802.11 radio link at 2.4 GHz with 15dB using a Yagi antenna pointing to the Factor building roof. The system is controlled by the CENS Data Communications Controller, an Intel-Stargate X-scale computer in a mil-spec case.

Figure 5. Photos of UCLA campus free-field South site seismometer.

East station

The east site is an exterior soil location next to a large greenhouse (the UCLA Plant Growth Center) on the eastern side of the UCLA Botanical Gardens. Power is obtained from the greenhouse. Telecommunications consists of an 802.11 radio link at 2.4 GHz with 15dB using a Yagi antenna pointing at the Factor building roof. The system is controlled by the CENS Data Communications Controller, an Intel-Stargate X-scale computer in a mil-spec case.

West station

The west site is located in the basement of the Life Sciences building in a machine shop. GPS signals are received via the receiver placement next to a south-facing window. Power and internet data transfer are obtained through outlets/ports inside the machine shop.

Access to data

The IRIS DMC has made archival and subsequent retrieval of the data for general engineering research convenient. The continuous, 100 sps data are being archived at the IRIS DMC in miniSEED format and are immediately available for request. The DMC also has the metadata for use in generating the miniSEED files, and for conversion to other data formats. An information web page describes how to download and use IRIS software to request the waveform data. Details on array instrumentation, soil conditions, accessing data, real-time waveform viewer, and known problems and corrections to recorded data can be found in links on the Factory array web site: http://factor.gps.caltech.edu.

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