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Seismic Performance of Shallow Underground Structures Adjacent to Tall Buildings: A Centrifuge Experimental Study

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ABSTRACT

Shallow underground structures used for public transportation are a key component of sustainable cities. In dense urban environments, underground structures are often built near tall buildings. Although such buildings have the potential to alter ground motions in their vicinity and transmit significant forces to adjacent underground structures during earthquakes, these impacts are not well understood. This paper focuses on the experimental setup and results from centrifuge tests aimed to understand the seismic performance of a permanent box structure buried in medium dense, dry sand. The response of this underground structure is first studied in isolation, then, a highrise model building is added near the underground structure to evaluate its influence. Preliminary experimental results indicate that the presence of an adjacent highrise building slightly reduces racking displacements on the buried structure, but increases seismic lateral earth pressures on the building side of the tunnel.

Introduction

Underground structures have historically performed well during earthquakes. However, the collapse of the Daikai Subway station during the 1995 Kobe Earthquake serves as a reminder of the need to consider seismic loading in their design. Underground structures in dense, urban settings are often built near tall buildings. These buildings have the potential to transmit significant forces to the underlying soil and adjacent underground structures during earthquakes. The state of practice for the seismic design of cut-and-cover box structures currently relies on simplified procedures that do not consider an adjacent building, or numerical tools that have not been validated adequately against physical model studies.

The work presented in this paper is part of a larger research study that employs a combined experimental-numerical approach to evaluate seismic soil-structure-underground structure-interaction (SSUSI) in medium dense, dry sand. In a series of six centrifuge experiments (Figure 1), the seismic response of a permanent box structure and a temporary braced excavation was evaluated near mid to highrise buildings. T-No Bldg and E-No Bldg represent the baseline experiments that evaluated the individual response of permanent and temporary box structures, respectively, with no adjacent buildings present. In subsequent tests, mid and highrise buildings were placed in close proximity to underground structures and their influence was evaluated. Key experimental measurements included racking deformations of the underground structure, lateral

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earth pressures, and bending moments in the walls of the underground structures subjected to a series of earthquake ground motions. This paper presents a summary of preliminary experimental results from two centrifuge tests involving the permanent, underground box structure: T-No Bldg and T-Highrise.

The centrifuge experiments presented in this paper were performed using the 9 m-radius centrifuge at the University of California, Davis Center for Geotechnical Modeling (UCD-CGM). A Flexible Shear Beam (FSB) centrifuge container with model scale inner dimensions of 1650 mm (length) by 786 mm (width) by 588 mm (height) was used for testing. Displacement, acceleration, and strain measurements were obtained using the centrifuge fast data acquisition system (DAQ). Pressure recordings were obtained by tactile pressure sensors, which had a separate data acquisition system.

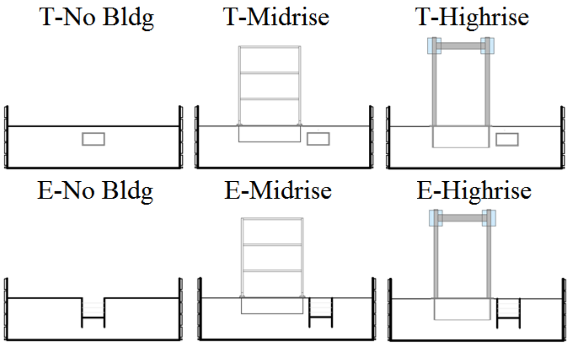

Figure 1. Schematic drawing of the centrifuge testing program (T: Tunnel; E: Excavation).

Centrifuge Testing Overview

Structure Properties

The size and stiffness of the permanent box structure were based on realistic subway tunnels with consideration for the limited size of the centrifuge container and the maximum centrifugal acceleration considered, in order to minimize boundary effects and maximize shaker performance. The racking displacement and stiffness of different box structure options were estimated and compared with those of the soil in free-field during each of the selected base motions based on the NCHRP 611 guideline. A target reinforced concrete box structure with prototype scale cross-sectional dimensions of 8 m (high) by 14 m (wide) was selected at 65 g of centrifugal acceleration, with design racking ratios ranging from approximately 0.9 to 1.6. A simplified box structure was then designed for centrifuge testing using aluminum with the same racking stiffness as the target, prototype reinforced concrete box structure. The model scale tunnel was then fabricated using four separate 6061 T6 Aluminum plates welded at the corners. In model scale, the tunnel dimensions measured 775 mm (length) by 215 mm (width) by 123 mm (height), shown in Fig 2. The tunnel was fabricated to be 10 mm shorter in length than the width of the container to allow for the placement of thin Teflon sheets at the tunnel-container interface to minimize side friction.

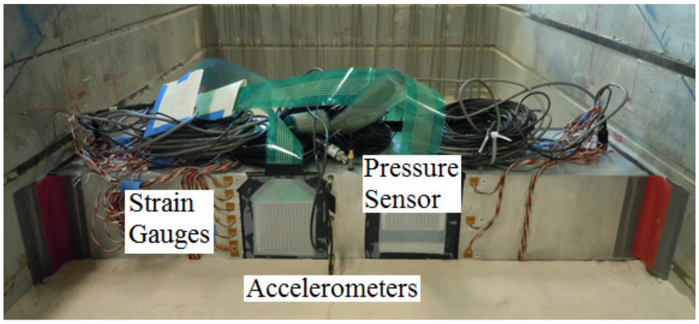

Figure 2. Model underground tunnel under construction in the centrifuge container in T-No Bldg.

A major challenge in this research was to design and construct a building model in centrifuge that represented the key dynamic properties of a realistic highrise building. The goal was to design a tall structure that had realistic dimensions and dynamic properties, conformed to the latest seismic design requirements in California, and simultaneously satisfied centrifuge container and overhead space limitations. No centrifuge experiment had been performed on a highrise model structure prior to T-Highrise by other researchers, to the best knowledge of the authors. Hence, its design process and considerations for centrifuge modeling is one of the intended contributions of this paper.

The Tall Building Initiative (TBI) Task 12 Final Report (Moehle et al. 2011) presented the results of dynamic time history analyses on selected tall buildings in San Francisco, CA. Concrete core SMRF building models in this report were selected as the target highrise buildings of interest. These models had 42 stories, 4 stories of basement, footprint dimensions of 69 m x 69m for the building and 33m x 33m for the core, a seismic weight of 453,719 kN, a fundamental period of approximately 4.3 to 4.9 s, and an average horizontal shear demand of 47,738 kN when subject to 7 motions matching the MCE target response spectra.

The target building footprint dimensions of 69m x 69m could not fit within the centrifuge container at the selected level of centrifugal acceleration (65g). Therefore, the target core footprint dimensions of 33m x 33m were selected instead. The overhead height available in centrifuge also did not allow a proper simulation of the building's center of gravity and hence, its seismic moments and rocking tendencies. However, the total seismic weight and fundamental period of the target building could be simulated, which were expected to strongly influence SSUSI and hence, the response of an adjacent underground structure.

A simplified single-degree-of-freedom (SDOF) system was designed to simulate only the fundamental period, weight, and shear capacity of the target highrise building. The structure was designed to have a prototype fundamental period of 4 s, which was confirmed through hammer impact tests after fabrication. Higher modes could not be simulated effectively in a scaled model and were therefore sacrificed. Beam and column fuses were not used in this model, because this structure was expected to remain elastic during all selected motions. Pushover analyses were performed in OpenSees and SAP2000 to ensure adequate factors of safety of beams and columns against axial, shear, and bending yield.

The basement of the building was designed as a box open at the bottom and filled with the test soil. The inclusion of a realistic, empty basement would significantly reduce the confining pressure under the building, particularly for the 4-story basement of the highrise structure. This would reduce the influence of the adjacent building on the seismic performance of a box structure and their interactions. Our goal in these fundamental experiments was to maximize the building's influence, in order to provide a more clear understanding of the underlying mechanisms of interaction. Figure 3 shows a diagram of the highrise and the adjacent tunnel.

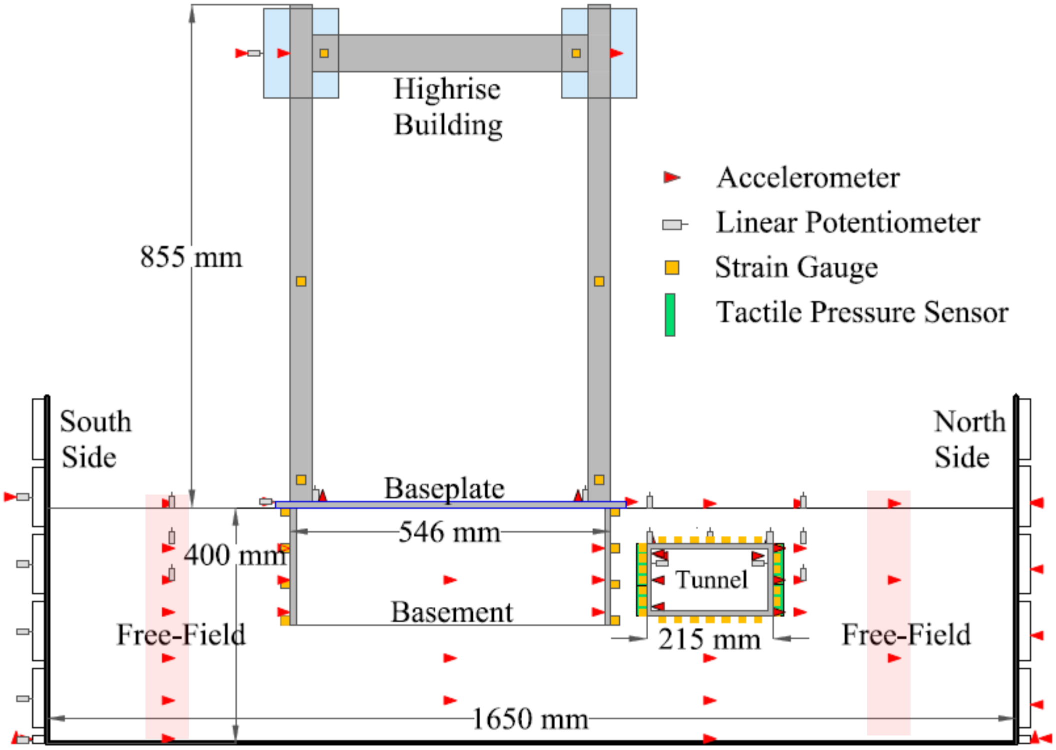

Figure 3. Instrumentation layout of T-Highrise (dimensions shown in model scale).

Soil Properties

Dry Nevada sand was used in all centrifuge experiments with a specific gravity (G_s) = 2.66, minimum dry unit weight ($\gamma_{d,min}$) = 13.7 kN/m^3, and maximum dry unit weight ($\gamma_{d,max}$) = 17.0 kN/m^3 (corresponding to e_{min} = 0.53 and e_{max} 0.90). Nevada sand was dry pluviated into the FSB container to achieve an initial relative density of approximately 55%.

Ground Motion Properties

Ground motions were selected with a range of characteristics in terms of intensity, frequency content, and duration to evaluate their effects on seismic SSUSI. Table 1 summarizes the properties of the ground motions as measured at the base of the container in a representative test (T-No Bldg), listed in the order they were applied.

Table 1. Properties of base motions as measured during T-No Bldg.

Record Source		Achieved Measures				
Event	Station	PGA (g)	PGV (cm/s)	PGD (cm)	I_a (m/s)	$D_{5\text{-}95}$ (s)
Northridge 1994	Newhall - WPC	0.46	49.4	12.1	1.00	6.2
Loma Prieta 1989	Santa Cruz - L. Obs.	0.1	10.5	0.6	0.10	11.3
Landers 1992	Joshua Tree	0.25	21.8	4.4	1.80	27.5
Chi Chi 1999	TCU078	0.34	26.9	5	2.50	26.8
Landers 1992	Lucerne	0.38	32.6	6.8	1.00	9.6
Kobe 1995	Takatori	0.45	52.8	16.2	3.40	11.6
Loma Prieta 1989	Los Gatos	0.04	9.2	3.1	0.01	8.0
Loma Prieta 1989	Los Gatos	0.07	18.0	6.3	0.14	8.1

Experimental Setup

Racking displacement of the tunnel and free-field soil during shaking were key measurements in addition to lateral earth pressures experienced on the tunnel walls. Other important measurements were accelerations at specific locations within the soil and structure and bending moment distributions on the walls of the underground structures. Four primary types of sensors were employed during testing: accelerometers, linear potentiometers (LPs), strain gauges, and tactile pressure sensors. The instrumentation layout for T-Highrise is presented in elevation view in Fig. 3. Transient racking displacements of the tunnel and free-field were obtained indirectly by double integrating accelerometer readings from the top and bottom of the tunnel and at the same elevations in the free-field. Tactile pressure sensors (manufactured by Tekscan Inc.) were used to measure the static and dynamic lateral earth pressures on the tunnel walls. These sensors were conditioned, equilibrated, and statically and dynamically calibrated, as detailed by Gillis et al. (submitted for review), before being used in the centrifuge.

Special considerations during model construction were needed to accommodate the highrise building due to its size and weight (190 kg). The highrise superstructure was installed on the model after it had been loaded onto the centrifuge shake table to prevent damage to the model during transportation. Safety straps were attached to each corner of highrise building’s top floor to catch or restrain the structure if tipping or component failure occurred during testing.

Experimental Results

Tunnel Racking Displacements

Racking displacement of a box structure is a critical design parameter, as it affects bending strains and stresses imposed on the tunnel and hence, its performance (Hashash et al. 2010). Racking was computed as the relative lateral displacement between the roof and floor of the box structure. Figure 4 compares the racking displacement time histories measured on the tunnel in both experiments during one representative motion: Joshua Tree. The tunnel experienced less racking in T-Highrise compared to T-No Bldg. This pattern was consistent during all motions.

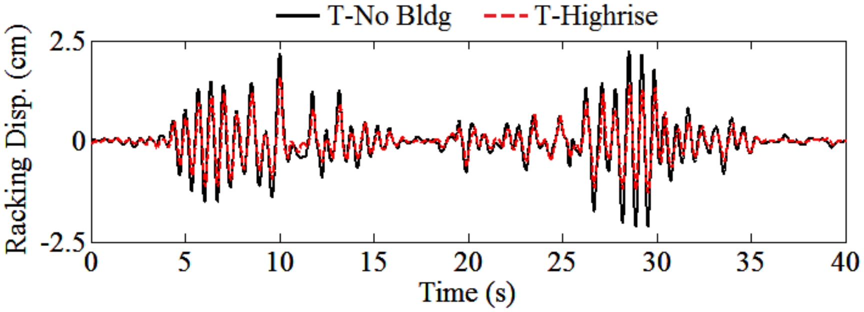

Figure 4. Racking displacement time history of the tunnel in T-No Bldg and T-Highrise during the Joshua Tree motion.

A primary factor that influences the racking deformation of a box structure is the relative shear stiffness of the buried structure compared to the surrounding soil (Hashash et al. 2010; Anderson et al. 2008). This measure of relative stiffness is referred to as the Flexibility Ratio (F), defined as $(G_m.B)/(K_s.H)$, where G_m is the strain-compatible shear modulus of the soil in the free-field, B is the width of the structure, K_S is the racking stiffness of the structure, and H is the height of the underground structure. To estimate G_m, the equivalent shear strain (γ_{eq}) was needed in the free-field. The maximum free-field soil shear strain (γ_{max}) was estimated during each motion by dividing the corresponding maximum racking displacement by the structure height. The small-strain, maximum soil shear modulus (G_{max}) was estimated at the depth corresponding to the mid-height of the tunnel using the empirical relations proposed by Seed and Idriss (1970), Bardet (1993), Jamiolkowski et al. (1991), Menq (2003), and Hardin and Drnevich (1972). The median and median +/- one standard deviation modulus reduction curves proposed by Darendeli (2001) at that depth were adopted and corrected for the implied shear strength of soil, as detailed by Romero et al. (submitted for review). The equivalent, free-field, shear strain ($\gamma_{eq} = 0.65\gamma_{max}$) was subsequently estimated during each motion, which was used together with the range of estimated empirical G_{max} values and the corrected median and median +/- one standard deviation modulus reduction curves to obtain a range of possible G_m values.

To calculate the racking stiffness of the structure, a lateral force was applied to the structure's roof (when fixed from movement at its base), and the resulting lateral deflection was measured. In this way, the racking stiffness, K_S, was experimentally obtained as the force applied divided by the lateral displacement observed at the roof. Subsequently, a range of Flexibility Ratios (F) could be estimated for each motion, and its median and standard deviation calculated. The racking ratio (R) was estimated as the ratio of the maximum racking of the underground structure to that of the free-field soil. The racking displacement can be calculated from double integrated accelerometer recordings on the box structure and in the free-field. Free-field racking displacements were obtained from T-No Bldg, which had the most representative free-field condition with more separation between the buried structure and container boundaries.

The relationship between R and F according to the NCHRP 611 guideline (Anderson et al. 2008), which is based on the results of dynamic finite element analyses, is presented in Figure 5. This figure also shows the range of R versus F values obtained experimentally during the tunnel tests and different motions, including the uncertainty in G_m values. Experimental values of R versus F followed the NCHRP 611 guideline closely during T-No Bldg. Figure 5shows an overall reduction in R at different F values when the highrise building was added adjacent to the box structure during all motions.

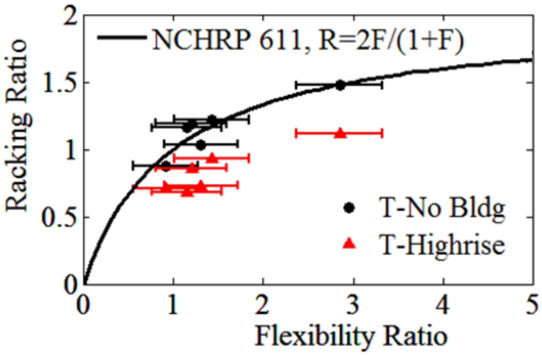

Figure 5. Racking versus Flexibility Ratios (R versus F) obtained experimentally compared to the NCHRP 611 guidelines. Free-field racking obtained from T-No Bldg.

Lateral Earth Pressures

Dynamic lateral earth pressures were recorded on both tunnel walls in all tests and compared during different motions, to evaluate the influence of an adjacent building. The dynamic increment of pressure was integrated over the wall height at each time to obtain the dynamic thrust time history. Figure 6 shows the dynamic thrust time history on the south or building side of the tunnel in both experiments. This comparison indicated an increase in dynamic thrust on the building side of the tunnel in T-Highrise compared to T-No Bldg.

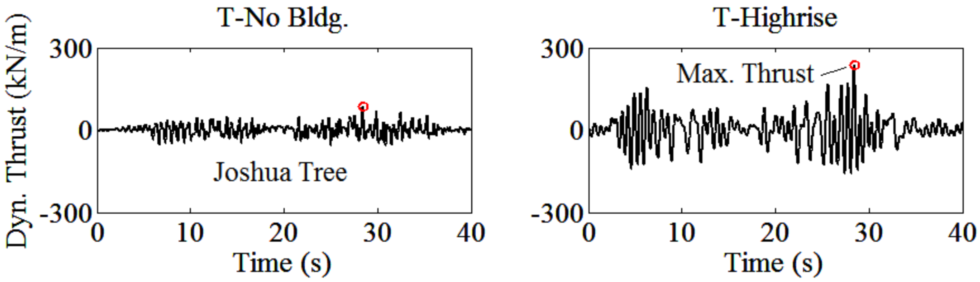

Figure 6. Dynamic thrust time history recorded on the south or building side of the tunnel during the Joshua Tree ground motion.

Concluding Remarks

Centrifuge tests were conducted to investigate the seismic response of a shallow permanent box structures when in isolation and when adjacent to a highrise building. The response of the box structure was compared among two tests in terms of racking displacements and dynamic lateral earth pressures. Tunnel racking displacements were reduced when the adjacent highrise building was present during all motions. However, larger lateral earth pressures were recorded on the building side of the tunnel with an adjacent building, particularly at shallow depths. The test results are currently being further analyzed and compared with parallel numerical simulations, before providing recommendations for practice.

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