A Centrifuge Study: Influence of Site Response on the Seismic Performance of Buried Reservoir Structures

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ABSTRACT: The seismic performance of underground reservoir structures depends on the flexibility of the structure, soil properties, soil geometry, ground motion characteristics as well as the kinematic constraints imposed on the structure. This paper seeks to evaluate the influence of site response and excitation frequency on the performance of buried structures. A series of centrifuge experiments were conducted at the University of Colorado Boulder to evaluate seismic soil-structure-interaction, lateral earth pressures, bending strains, moments, and racking displacements of scaled model structures representing water reservoirs buried in medium dense, dry sand. The preliminary results indicate that the effective and fundamental frequency of the buried structure-soil system was primarily controlled by the response of the far-field soil rather than the fixed-base fundamental frequency of the isolated structure. It was found that the controlling frequency that determines the maximum seismic soil pressure, bending strain, and racking is that corresponding to the strain-dependent, effective natural frequency of the far-field soil.

INTRODUCTION

The majority of stiff-unyielding underground structures have performed well in recent earthquakes. The few cases of failure are mainly related to construction in poor ground conditions (e.g., soft fill, liquefiable soils, sloping ground) and inadequate or no seismic design. Currently there is disagreement among engineering professionals and design methodologies on seismic forces and deformations experienced by these structures, sometimes resulting in inaccurate design that maybe un-conservative or over-conservative. The current procedures (e.g., Okabe 1926; Mononobe and Matsua 1929; Seed and Whitman 1970; Wood 1973; Anderson et al. 2008) used to evaluate seismic loading and deformations of these structures rely on over-simplified analytical methods or advance numerical tools that have not been validated against physical model tests.

Previous analytical, numerical, and experimental studies have identified key factors such as structural flexibility, base fixity, and wavelength as being important in the seismic response of these structures. Increasing the flexibility of the structure results in a decrease in magnitude of thrust and pressure profile transitioning from parabolic to triangular (e.g., Veletsos and Younan 1997; Psarropoulos et al. 2005; Hushmand et al. 2016). Underground structures with a fixed base experience larger dynamic pressures compared to structures that can translate laterally (e.g., Li 1999; Davis 2003; Psarrapolous et al. 2005; Brandenberg et al. 2015). Pressures and deformations imposed on the structures are maximized when the frequency content of the base motion is similar to the natural frequency of the soil column (Scott 1973; Ostadan 2005;

Brandenberg et al. 2015). However, the commonly used simplified methods don't take into account these important factors.

Further, there is a lack of well-documented case studies and experimental research systematically evaluating the seismic response of stiff-unyielding buried structures that are restrained against excessive deformations at their base and roof. The majority of previous experimental studies were focused on either yielding retaining structures (Stadler 1996; Al Atik 2010; Mikola 2012) or flexible tunnels with a large overburden (e.g., Cilinger and Madhabhushi 2011; Tsinidis et al. 2015). Therefore, a centrifuge experimental study of the seismic response of these structures was performed by varying the key parameters and monitoring seismic lateral earth pressures, racking displacements, bending moments, and soil-structure interaction.

A series of centrifuge model experiments representing 11 to 12 m-high reinforced concrete underground reservoir structures were conducted at University of Colorado Boulder. The structure stiffness, backfill soil type and slope, embedment, container type (rigid versus flexible boundaries), fixity conditions, and ground motion characteristics were varied to evaluate their influence and relative importance on structural performance. The structures were buried in dry medium-dense sand at 60% relative density and compacted, site-specific silty sand with different backfill slopes. This paper presents the results of one centrifuge experiment with the baseline structure, focusing on the effects of site response and excitation frequency on accelerations, racking distortion, lateral earth pressures, and bending strains on the structure walls.

EXPERIMENTAL SETUP

Dynamic tests of model reservoir structures were performed at 60g of centrifugal acceleration using the 5.5 m-radius, 400 g-ton geotechnical centrifuge at the University of Colorado Boulder. The model specimens were prepared in a flexible shear beam (FSB) container developed by Ghayoomi et al. (2012; 2013).

The response of the system during testing was measured using 27 accelerometers, 8 LVDTs, 16 strain gauges (8 on each wall), 4 tactile pressure transducers (2 on each wall), and 16 earth pressure cells (8 on each wall). The location of the transducers is shown in Figure 1 and Figure 2. Each tactile sensor contains 14 rows and 14 columns of sensels (sensing points) amounting to 196 sensels, each 5.1 mm by 5.1 mm. Each of the 196 sensels recorded pressure data at a rate of 4,000 samples/sec during the dynamic centrifuge tests.

Dry Nevada sand No. 120 (G_s=2.65; e_{min}=0.56; e_{max}=0.84; D_{50}=0.13 mm; C_u=1.67) was pluviated in the FSB container at a target relative density of D_r=60% (γ_d=15.6 kN/m^3). The soil deposit was dry pluviated in layers using a hopper at a calibrated height to achieve the target D_r. The experimentally-measured small-strain, fundamental frequency of the far-field soil column (f_{so}) was approximately 2.2 Hz ($\overline{V}_s = 4 \cdot f_{so} \cdot H_{site} =$ 165 m/s) using the Transfer Function (TF) of accelerations recorded at the soil surface to those at the container base under centrifuge ambient vibrations that induced small strains.

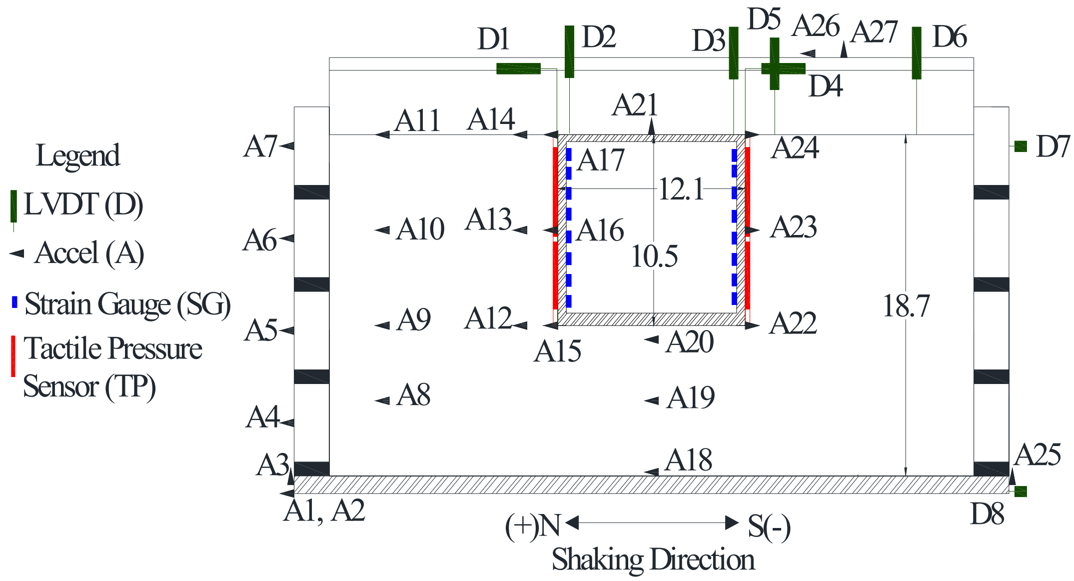

Figure 1. Instrumentation layout of a representative centrifuge test (dimensions shown in prototype scale meters).

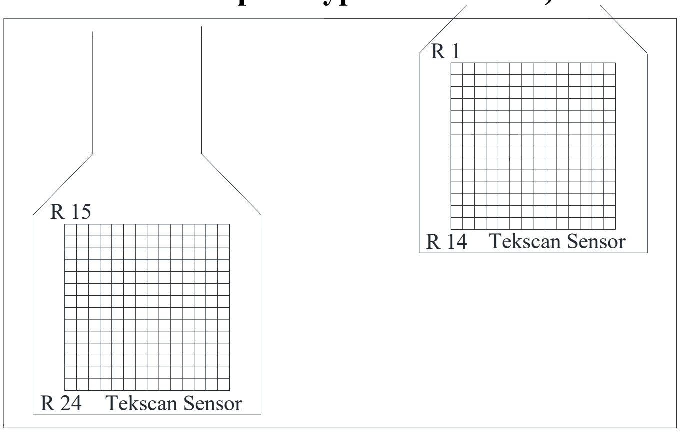

Figure 2. Layout of the pressure sensors on each wall of the buried structure.

The model structures were designed based on a simplified version of the prototype reservoir structures by maintaining a similar natural frequency and lateral stiffness (detailed by Hushmand et al. 2016). The model structures were constructed of four pieces of welded 1018 Carbon Steel (density = 7870 kg/m^3; Young's modulus = 2×10^8 kPa). The structure dimensions are: outer height = 10.5 m, outer width = 12.1 m, base thickness = 0.69m, roof thickness = 0.37m, and wall thickness of 0.56 m. The fundamental frequency was experimentally and numerically calculated around 4 Hz.

Ground motions were applied to the model specimens in flight using the servo-controlled, electro-hydraulic shake table (Ketcham et al. 1991) mounted on the basket at the end of the centrifuge arm. A series of five horizontal earthquake motions and eight sinusoidal motions (15 cycles) were applied to the base of the model specimen, as shown in Table 1. The amplitude of sinusoidal motions was kept approximately the same, while their frequencies were varied to evaluate the influence of excitation frequency on the response of the soil-structure system.

Table 1. Achieved base motion characteristics (prototype scale)

	Input motion parameters			
Shaking Event	PGA (g)	I_a (m/s)	$D_{5\text{-}95}$ (s)	f_m (Hz)
Northridge-L	0.26	1.3	21.6	0.9
Northridge-M	0.73	5.8	26.7	1.5
Northridge-H	1.26	12.9	26.7	1.7
Izmit	0.3	2.6	37.6	1.8
Sine 0.3	0.27	3.7	36.6	0.5
Sine 1	0.31	3.4	12.8	1.2
Sine 2	0.40	3.6	6.2	2.8
Sine 3	0.44	5.2	4.1	3.1
Sine 4	0.41	3.3	3.0	4.0
Sine 5	0.92	17.8	2.4	5.0
Sine 6	0.50	4.4	2.1	5.9
Loma	1.05	15.0	12.8	2.3
Sine 6.7	0.50	4.6	15.1	6.9

EXPERIMENTAL RESULTS

The transfer functions of far-field soil surface to container base accelerations as well as structure roof to container base accelerations during all the earthquake motions are presented in **Error! Reference source not found.**. The highlighted area shows the approximate range of effective, strain-dependent, fundamental frequencies (f_{so}') of the far-field soil and the soil-structure system. The f_{so}' ranged from approximately 0.92 to 1.3 Hz for both the far-field soil column and the soil-structure system during these motions. The fundamental frequency of the buried structure-soil system was primarily controlled by the response of the far-field soil rather than the fixed-base fundamental frequency of the isolated structure.

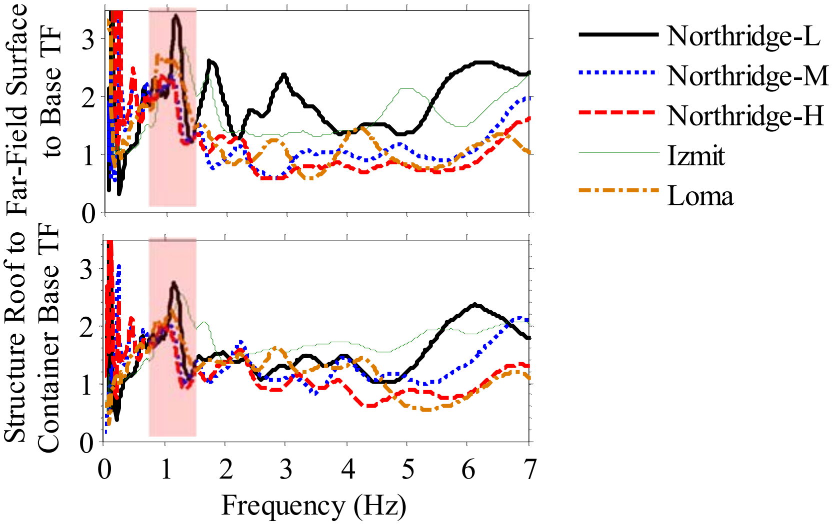

Figure 3. Transfer function (TF) of surface to base accelerations in the far-field and on the structure during different earthquake motions to obtain the effective fundamental frequency of the far-field soil column and the soil-structure system.

The short-time Fourier transform of accelerations recorded on the container base and mid-depth of the structure wall are compared to those of dynamic thrust during the Northridge-L motion in Figure 4. The base acceleration contained a significant content near 1 Hz in all experiments during Northridge-L, particularly in the early part of the record. Similarly, the accelerations recorded at the mid-depth of the structure and the dynamic thrust on the walls showed maximum content near 1 to 1.5 Hz, which coincided with the effective natural frequency of the site (f_{so}') in those tests. Although earthquake motions were insightful, the sinusoidal motions (with a narrow frequency content) allowed an easier evaluation of the impact of excitation frequency alone on the response of the buried structure.

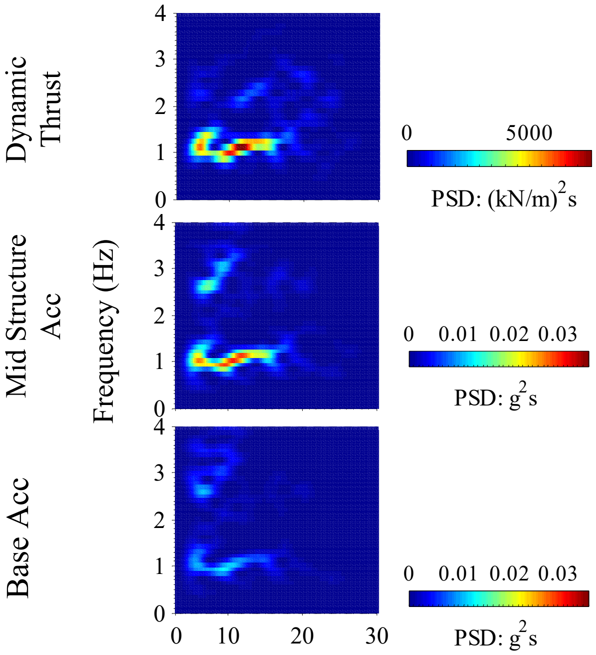

Figure 4. Short-time Fourier transform of container base acceleration, mid-depth structural wall acceleration, and dynamic thrust recorded on the structure during the Northridge-L motion.

The maximum racking displacement was plotted for each sinusoidal motion as shown in Figure 5. The racking was largest during the application of the 1 Hz sinusoidal base motion. The profiles of $\Delta\sigma_E$ at the time of maximum dynamic thrust are compared in Figure 6, as measured during the different sinusoidal motions. The shapes of the $\Delta\sigma_E$ profile did not appear to have a significant dependence on the excitation frequency. Maximum dynamic pressures, however, occurred when the base excitation frequency of the sinusoidal motion approached the far-field soil f_{so}' near 1 Hz. At higher or lower frequencies, the dynamic increment of pressure reduced greatly compared to the resonance condition. Similar to racking and dynamic earth pressures, dynamic strains in Figure 7 were observed to peak when the excitation frequency approached the effective fundamental frequency of the site. These observations were consistent regardless of the structural stiffness or base fixity.

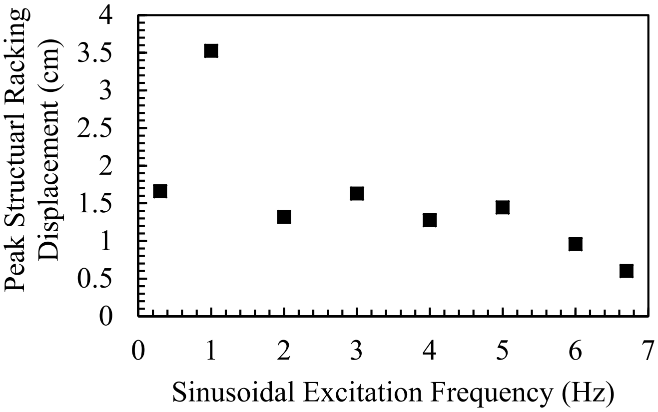

Figure 5. Maximum structural racking versus excitation frequency of the sinusoidal base motion.

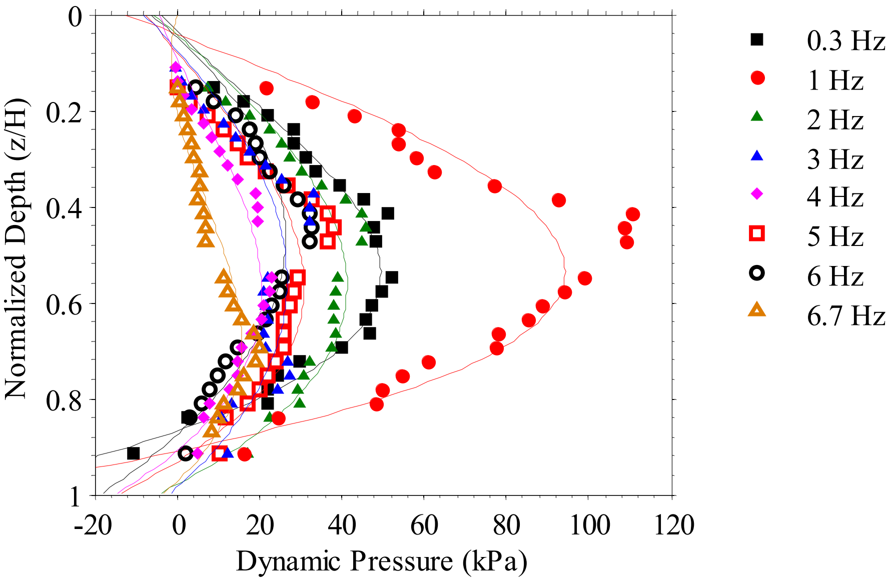

Figure 6. Dynamic increment of earth pressures ($\Delta\sigma_E$) at the time of maximum dynamic thrust during eight sinusoidal motions with similar amplitudes but different frequencies (0.3 Hz, 1 Hz, 2 Hz, 3 Hz, 4 Hz, 5 Hz, 6 Hz, and 6.7 Hz).

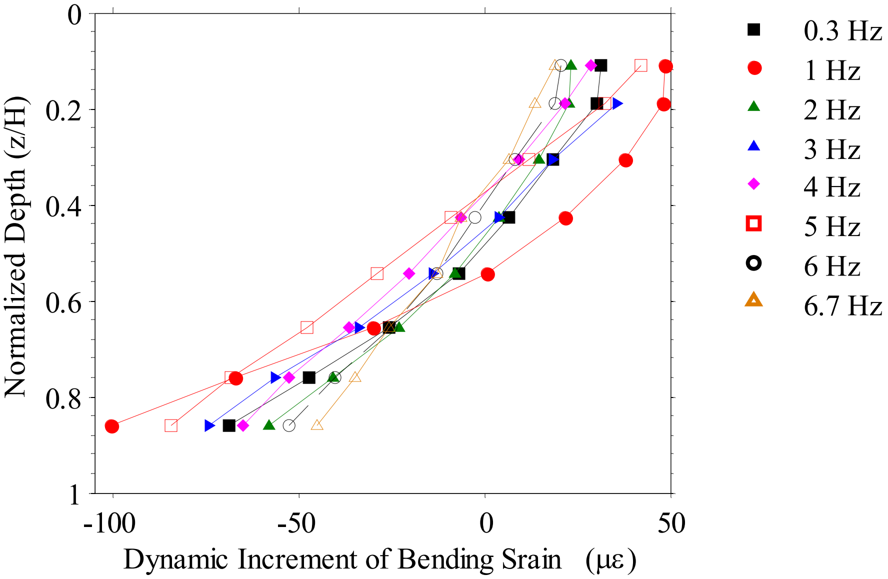

Figure 7. The dynamic increment of bending strains ($\Delta\varepsilon_E$) at the time of maximum moment during eight sinusoidal motions with different frequencies.

CONCLUSIONS

In this paper, the results of one centrifuge test are presented showing the influence of site response and the excitation frequency of the base motion on the response of stiff-unyielding buried reservoir structures in medium dense, dry sand. The preliminary results indicate that the effective and fundamental frequency of the buried structure-soil system was primarily controlled by the response of the far-field soil rather than the fixed-base fundamental frequency of the isolated structure. It was found that the controlling frequency that determines the maximum soil pressure, bending strain, and racking is that corresponding to the effective, strain-dependent, fundamental frequency of the far-field soil column.

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