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A Centrifuge Study of the Influence of Site Response, Relative Stiffness, and Kinematic Constraints on the Seismic Performance of Buried Reservoir Structures

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ABSTRACT: The seismic performance of underground reservoir structures depends on the properties of the structure, soil, and ground motion as well as the kinematic constraints imposed on the structure. This paper seeks to understand the influences of site response, structural stiffness, base fixity, and excitation frequency on the performance of buried structures through the evaluation of results from four dynamic centrifuge experiments on relatively stiff and unyielding reservoir structures buried in dry, medium-dense clean sand. The magnitude of seismic thrust increased and the distribution of seismic earth pressures changed from approximately triangular to parabolic with increasing structural stiffness. Heavier and stiffer structures also experienced increased rocking and reduced flexural deflection. Fixing the base of the structure amplified the magnitudes of acceleration, seismic earth pressure, and bending strain compared to tests where the structure was free to translate laterally, settle, or rotate atop a soil layer. The frequency contents of transient tilt, acceleration, dynamic thrust, and bending strain measured on the structure was strongly influenced by the frequency content of the base motion and site response, while it was unaffected by the fundamental frequency of the structure ($f_{\text{structure}}$). None of the available simplified procedures could capture the distribution and magnitude of seismic earth pressures experienced by this class of underground structures. The insight from this experimental study is aimed to help validate analytical and numerical methods used in the seismic design of reservoir structures worldwide.

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1 INTRODUCTION

2 The seismic response of stiff-unyielding underground structures with minimum to no soil
3 overburden is a fairly new topic at the interface between geotechnical and structural engineering.
4 Buried structures can be classified as stiff-unyielding structures when they do not deform or
5 rotate enough during seismic events to create active (yielding) conditions in the backfill soil due
6 to the kinematic constraints at their roof or base, while they are not completely rigid and deform
7 according to their stiffness. The majority of previous analytical, numerical, and physical model
8 studies on the seismic response of buried structures focused on either yielding or rigid-
9 unyielding underground structures (e.g., Okabe 1926; Mononobe and Matsuo 1929; Seed and
10 Whitman 1970; Wood 1973; Veletsos and Younan 1994; Davis 2003; Ostadan 2005; Stadler
11 1996; Dewoolkar et al. 2001; Al Atik and Sitar 2010; Mikola 2012). However, a number of
12 important buried structures such as nuclear facilities, bunkers, culverts, and water reservoirs can
13 be categorized as stiff-unyielding. The focus of this paper is on the seismic response of this type
14 of structures, particularly focusing on the buried water reservoirs being built by the Los Angeles
15 Department of Water and Power.

16 The seismic forces and deformations experienced by stiff-unyielding underground structures
17 are not well understood. Soil-structure interaction near these structures is governed by the
18 dynamic properties of the structure and backfill soil as well as the imposed kinematic constraints
19 on the structure and the intensity, duration, and frequency content of the earthquake motion
20 (Hushmand et al. 2016; Brandenberg et al. 2015). The available simplified procedures for buried
21 structures introduced by Mononobe-Okabe (Okabe 1926; Mononobe and Matsuo 1929), Seed-
22 Whitman (Seed and Whitman 1970), or Wood (1973) do not consider all of these effects.
23 Although advanced numerical tools can take these effects into account, they may lead to

1 complexities that require validation against the results from field observations or physical model
2 studies.

3 Several of the previous experimental studies primarily focused on either yielding retaining
4 structures (Stadler 1996; Al Atik 2010; Mikola 2012) or flexible tunnels with large overburden
5 (e.g., Cilinger and Madhabhushi 2011; Tsinidis et al. 2015). However, the seismic response of
6 these structures is different from the stiff-unchanging structures with shallow or no overburden
7 considered in this study. In response to this shortcoming, a series of dynamic centrifuge tests
8 were recently conducted at the University of Colorado Boulder to evaluate the seismic
9 performance of buried reservoirs with varying structural rigidity, soil cover, backfill soil type,
10 backfill geometry, base fixity, and container boundary conditions. Hushmand et al. (2016 and
11 forthcoming) summarized the insight obtained from these experiments regarding the influences
12 of structural stiffness and the type and geometry of the backfill soil during earthquake loading.
13 These experiments showed that stiff-unchanging buried structures could experience notable
14 dynamic earth pressures. However, none of the available simplified procedures for buried
15 structures was able to sufficiently capture the distribution and magnitude of seismic earth
16 pressures or deformations experienced by the class of stiff-unchanging structures under the
17 loading scenarios often used in their design. Further, the critical role of site response was
18 displayed on the forces measured on the buried structures. Yet, the interacting influence of site
19 response, structural stiffness, and base fixity on seismic forces and deformations has not yet been
20 investigated in detail experimentally, as is necessary in the validation of future numerical tools.

21 The dynamic behavior of underground structures fixed to a stiff rock foundation differs
22 greatly from structures founded on soil, since the lateral base movement is prevented. Past
23 analytical and numerical studies (e.g., Wood 1973; Li 1999; Richards et al. 1999; Davis 2003;

Psarrapolous et al. 2005; Ostadan 2005; Brandenberg et al. 2015) showed that underground structures with a fixed base experience larger dynamic earth pressures compared to structures that can translate laterally. In addition to the magnitude of thrust, the distribution of earth pressures along the wall height can have a great influence on seismic performance. However, there is no consensus among past studies on what shape the pressure profile takes for structures with a fixed base condition, as well as those that can translate laterally. Further, the influence of the frequency content of the base motion on the forces and deformations experienced by stiff-uniyielding structures, whether fixed at the base or free to translate, has not been evaluated experimentally.

This paper focuses on the effects of far-field site response, the base fixity and stiffness of the structure, and the frequency content of the base motion in relation to the fundamental frequencies of the structure and backfill soil on the dynamic behavior of stiff-uniyielding underground structures. Experimental data was obtained from four dynamic centrifuge tests conducted on small-scale model structures in dry, medium dense Nevada sand with different structure stiffness, structure base fixity, and applied base motions. The model structures represented prototype reinforced concrete reservoirs having 11 to 12 m-high walls that are restrained against rotational movement at their roof and floor levels. A sequence of earthquake and sinusoidal motions with different frequencies was applied to the buried model structures in flight, and the performance of the buried structure was evaluated in terms of accelerations, seismic lateral earth pressures, and bending strains. The application of sinusoidal motions in particular allowed for a comprehensive study of the influence of loading frequency in relation to the fundamental frequency of the site and structure. The insight from these experiments is intended to guide the future modeling and

design of an entire class of stiff-uniyielding buried reservoir structures to withstand earthquake loading.

EXPERIMENTAL METHOD

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 four different centrifuge tests considered in this study are referred to as T-Flexible, T-BL (baseline), T-Stiff, and T-Fixed. T-Flexible, T-BL, and T-Stiff had the same test configuration shown in Figure 1a, but have different flexural rigidities of the structures, as detailed in Table 1. In T-Fixed, the same baseline structure as T-BL was used, which was bolted to the base of the FSB container to emulate a fixed-base condition, as shown in Figure 1b.

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 placed in the FSB container at a target relative density of $D_r=60\%$ ($\gamma_{\text{dry}}=15.6$ kN/m³). The soil deposit was 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 estimated prior to applying any dynamic motions using the Transfer Function (TF) of accelerations recorded at the soil surface to those at the container base under centrifuge ambient vibrations (prior to any shaking). The estimated f_{so} corresponding to the peak TF ranged from approximately 2.1 to 2.4 Hz in experiments T-Flexible, T-BL, and T-Stiff, and was approximately 4 Hz in T-Fixed, as shown in Figure 2. The corresponding small-strain, average shear wave velocity of soil, $\bar{V}_s = 4 \cdot f_{\text{so}} \cdot H_{\text{site}}$, in the far-field ranged from approximately 157 to 180 m/s in T-Flexible, T-BL, and T-Stiff, and was approximately 166 m/s in T-Fixed.

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/m³; Young's modulus = 2×10⁸ kPa). The dimensions and natural frequencies of the structures used in different tests are summarized in Table 1. Teflon sheets were placed on both ends of the open tubular structure to prevent the backfill sand from entering the structure, and were also placed on the sidewalls of the container to facilitate relative sliding and minimize friction and simulate plane strain conditions.

Figure 1 shows the large number of sensors, including accelerometers, linearly-variable differential transformers (LVDTs), strain gauges, and tactile pressure transducers that were used to measure the seismic response of the soil-structure system. Miniature piezoelectric accelerometers were used to measure accelerations in the soil, on the structure, and on the FSB container. The settlement of soil and structures and the lateral displacement of the structure, container frames, and container base were measured using LVDTs. Eight strain gauges were mounted along each wall of the structures in a half bridge configuration to measure bending strains. Two tactile pressure sensors were installed along the height of each wall of the structures perpendicular to the direction of shaking to measure static and seismic lateral earth pressures. The tactile sensors were equilibrated, conditioned, and statically and dynamically calibrated prior to use in centrifuge, following the procedure recommended by Dashti et al. (2012), Gillis et al. (2015), and El Ganainy et al. (2014). The acceleration, displacement, and strain data were recorded at a sampling frequency of 3,000 samples per second (sps). The tactile sensors were attached to a different data acquisition system and had a sampling frequency of 4,000 sps per sensel.

The motions were applied to the container base in flight using the servo-controlled, electro-hydraulic shake table (Ketcham et al. 1991). The selected earthquake motions consisted of the following scaled horizontal records: Sylmar Converter Station of the 1994 Northridge Earthquake, the LGPC Station of the 1989 Loma Prieta Earthquake, and the Istanbul Station of the 1999 Izmit Earthquake in Turkey. The achieved base motions are referred to as Northridge-L (low intensity), Northridge-M (medium intensity), Northridge-H (high intensity), Izmit and Loma. Figure 3 presents the acceleration response spectra (5% damped) of the achieved (recorded) base motions in each of the four experiments and Table 2 includes a summary of the ground motion properties achieved in each test, in terms of peak ground acceleration (PGA), Arias Intensity (I_a), significant duration (D_{5-95}), and mean frequency (f_m). As expected, the largest difference in the properties of the achieved motions was observed during T-Fixed, in which the total weight of the model specimen was significantly different from the other tests.

The earthquake motions in each test were followed by a sequence of eight sinusoidal motions with similar amplitudes (primarily ranging from 0.3 to 0.5g) but different frequencies (0.33 Hz, 1 Hz, 2 Hz, 3 Hz, 4 Hz, 5 Hz, 6 Hz). Each sinusoidal motion had fifteen cycles. These motions enabled a comprehensive evaluation of the impact of the frequency of base motion on the response of the soil-structure system. As shown in Table 2, two of earthquake motions were repeated after the sinusoidal motions to evaluate the response of the system after soil densification, followed by one final intense motion (Loma) and the highest frequency sinusoidal motion (6.7 Hz).

EXPERIMENTAL RESULTS

Soil Densification after Subsequent Motions

1 The application of successive motions changes the soil characteristics through shearing and
2 densification, which consequently affects the accelerations, strains, and earth pressures
3 experienced by the soil-structure system during shaking. Notable cumulative soil and structure
4 settlements were observed after each successive ground motion in the centrifuge. Figure 4 shows
5 the cumulative settlement of the structure and soil in the near- and far-field during all the applied
6 ground motions in one representative test (T-Flexible). The relative density of the far-field soil
7 increased from approximately 60 to 73% during this test. The largest settlement occurred during
8 the first three ground motions when the soil was at its loosest state. During T-Flexible, the lighter
9 structure (as compared to the baseline and stiff structures) settled less than the adjacent soil and
10 far-field. The settlement of the buried structure increased as its weight increased, as expected.

11 The relative density of the granular backfill soil increased from 72 to 81% and from 60 to
12 75% in the centrifuge experiments conducted by Al Atik (2010) and Stadler (1996), respectively.
13 However, the influence of soil densification and seismic history could not be evaluated in these
14 experiments because the same motion was not repeated after multiple ground motions. The
15 Northridge-L and Izmit ground motions in the presented experiments were repeated towards the
16 end of the test (Table 2), which are referred to as Northridge-L2 and Izmit-2, in order to evaluate
17 the influence of repetitive soil densification and shearing on the response of the soil-structure
18 system.

19 The change in relative density (D_r) of the far-field soil was estimated to be ~12% between the
20 Northridge-L1 and Northridge-L2 motions and 3% between the Izmit-1 and Izmit-2 motions.
21 Figure 5 compares the transfer function (TF) of accelerations at the surface to base in the far-
22 field soil during Northridge-L1 or Izmit-1 with those during Northridge-L2 or Izmit-2, which
23 were applied after several motions. The effective, strain-dependent, fundamental frequency of

1 the far-field soil (f_{so}') corresponding to the peak TF increased only slightly from Northridge-L1
2 to Northridge-L2 due to soil settlement and densification. No change was observed in soil
3 fundamental frequency from Izmit-1 to Izmit-2 due to a smaller degree of settlement and
4 densification. In all the motions considered, f_{so}' of the far-field soil was estimated to range from
5 approximately 0.92 to 1.3 Hz, which corresponds to an average, effective shear wave velocity
6 ($\bar{V}_s'$) ranging from about 69 to 97 m/s.

7 Figure 6 compares the amplification in peak ground accelerations (PGAs) along the far-field
8 soil column from the base during the two sets of Northridge-L and Izmit motions. A de-
9 amplification of PGAs was prominent during the Northridge-L1 motion, with a looser soil
10 column. After soil densification and subsequent shaking, during Northridge-L2, amplification of
11 PGA was prominent. The change in PGA amplification patterns was minimum from Izmit-1 to
12 Izmit-2 motions, again because of minor soil densifications that occurred in between those two
13 motions.

14 The dynamic increment of lateral earth pressures recorded on each structure during the two
15 sets of Northridge-L and Izmit motions at the time corresponding to peak dynamic thrust is
16 compared in Figure 7. In general, the distribution and magnitude of seismic earth pressures were
17 consistent during the two sets of motions, increasing slightly during the second set primarily due
18 to densification. There was, however, one exception. As will be discussed in more detail in later
19 sections, the distribution of seismic earth pressures was generally observed to change from
20 linearly increasing with depth to a higher order polynomial as the structure's flexural stiffness
21 was increased (Hushmand et al. 2016). However, the flexible structure during T-Flexible,
22 Northridge-L1 did not show the linearly increasing trend that was expected based on trends
23 observed in the other tests and motions. This may be because of looser soil conditions near the

1 wall face in this particular test leading to less contact between the backfill soil and the wall (or
2 sensor) prior to the first motion. However, the distributions of earth pressures immediately
3 following the first motion were more linear during T-Flexible due to the densification effect
4 mentioned earlier. The influence of soil densification on the dynamic response of underground
5 structures can also be evaluated in terms of dynamic strain profiles at the time of maximum
6 moment (or strain), as shown in Figure 8. The dynamic increment of strain was consistently
7 slightly larger during the Northridge-L2 motion compared to L1. The change was negligible
8 during the Izmit motions, as expected, with little soil densification between the two shakes.

9 **Accelerations**

10 The transfer functions of far-field soil surface to container base accelerations as well as
11 structure roof to container base accelerations for the different structures and earthquake motions
12 are shown in Figure 9. The highlighted area shows the approximate range of effective, strain-
13 dependent, fundamental frequencies (f_{so}') of the far-field soil and the soil-structure system. The
14 f_{so}' ranged from approximately 0.9 to 1.6 Hz during T-BL, T-Stiff, and T-Flexible for both the
15 far-field soil column and the soil-structure system. The estimated f_{so}' in T-Fixed ranged from
16 approximately 2.2 to 3.5 Hz. The fundamental frequency of the buried structure-soil system was
17 primarily controlled by the response of the far-field soil rather than the fixed-base fundamental
18 frequency of the isolated structure.

19 The amplification or de-amplification of peak accelerations from the base of the container to
20 the soil surface in the far-field or to the structure roof in T-BL, T-Flexible, T-Stiff, and T-Fixed
21 during the different earthquake motions are shown in Figure 10. The base motion accelerations
22 were amplified at the lower levels of shaking ($PGA_{base} \sim 0.3g$) and started to de-amplify at higher
23 levels of shaking ($PGA_{base} > 0.6g$), as expected, due to additional soil nonlinearity and damping.

Larger accelerations were recorded on the structure in T-Fixed compared to the other experiments that allowed transient rocking, settlement, and damping of seismic energy.

The spectral ratios of acceleration at the top of the structure to those in the far-field soil in each test during different earthquake motions are compared in Figure 11. Overall, the acceleration response of the structure was amplified compared to the far-field in frequencies ranging from about 2 to 5 Hz for all motions and structures. Increasing the flexibility of the structure often slightly increased its acceleration amplification with respect to the far-field due to a greater deflection near the roof. The spectral ratio of the structure in T-Fixed was greater compared to the other three tests, because of the kinematic constraint imposed at the base of the structure, amplifying its acceleration more pronouncedly relative to the far-field soil.

Structural Tilt

The time histories and Fourier Amplitude Spectra of tilt measured on the three structures with a flexible base (i.e., T-Flexible, T-BL, and T-Stiff) during three representative shaking events (Northridge-L, Northridge-M, Northridge-H) are compared in Figure 12. The tilt of the structure was obtained by dividing the difference in the recordings of vertical LVDTs on the edges of the structure roof (D2 and D3) by the width of the structure. The degree of structural tilt or rocking was observed to amplify as the shaking intensity increased, as expected. Increasing the structural mass (i.e., from Flexible to BL to Stiff) consistently increased its transient and residual tilt during all shaking events, which was expected due to a greater inertia and seismic moment that would amplify the rocking response of the buried structure. The frequency content of the structural tilt was observed to be similar among the different tests, however. The primary frequency content of structural tilt was observed at approximately 1 Hz, which was near the mean frequency of the base motion (f_m) as well as the site's effective fundamental frequency

(f_{so}') during these experiments and motions, regardless of variations in the fundamental frequency of the isolated structure. The rocking response of the structure was expected to influence the distribution and amplitude of lateral earth pressures, which is discussed in more detail in the following section.

Seismic Earth Pressures

The dynamic increment of pressure ($\Delta\sigma_E$) was obtained directly from tactile pressure sensors by subtracting the pre-shake static pressure from the total value at a given depth. Dynamic thrust acting on each structure during a given motion was estimated by numerically integrating the dynamic distribution of earth pressures at each instance of time. The values of $\Delta\sigma_E$ at the time of maximum dynamic thrust in four tests (T-BL, T-Stiff, T-Flexible, T-Fixed) during different earthquake motions are compared in Figure 13. A few of the most common analytical methods used to calculate dynamic earth pressures on retaining structures are also plotted for comparison: Mononobe-Okabe (M-O) and Seed-Whitman (S-W) assuming yielding (or active) conditions, and Wood, assuming rigid-unyielding conditions.

To obtain analytical solutions of seismic earth pressures during each motion, 100% of the PGA recorded in the far-field soil surface (i.e., using sensor A9 in T-Fixed and A11 in the other tests) was employed. The M-O method provided indeterminate values of earth pressure at PGA values greater than 0.7g for a soil friction angle of 35°. Therefore, the M-O solution is not presented in Figure 13 during the Northridge-H and Loma motions. The S-W procedure uses an inverted triangle dynamic earth pressure profile, as shown in Figure 13. Wood's simplified procedure was computed based on an L/H ratio of 1.5 corresponding to the centrifuge tests, but was also computed based on a larger L/H of 10 to provide an upper bound for comparison, where L is the lateral extent of the backfill soil and H the wall height. Wood's procedure does not take

1 into account the increase in soil shear modulus with depth and therefore predicted large $\Delta\sigma_E$
2 values near the top of the wall compared to those observed.

3 The distribution of $\Delta\sigma_E$ in experiments T-BL, T-Stiff, and T-Flexible depended greatly on the
4 flexural rigidity of the structure, as also confirmed by other studies (Veletsos and Younan 1997;
5 Gazetas et al. 2004; Psarropoulos et al. 2005; Jung and Bobet 2008). Increasing the flexibility of
6 the structure (e.g., T-Flexible compared to T-BL and T-Stiff) tended in general to change the
7 distribution of $\Delta\sigma_E$ from a parabola to an approximately triangular distribution mainly increasing
8 with depth. Fixing the base of the structure in T-Fixed, on the other hand, increased $\Delta\sigma_E$ near the
9 base of the BL structure compared to T-BL, likely because of the greater inertial demand applied
10 to the base of the structure without the ability to settle or rock with respect to the surrounding
11 soil. This observation is consistent with the numerical results presented by Psaropoullos (2005).
12 Importantly, none of analytical solutions could sufficiently capture the distribution and
13 magnitude of seismic earth pressures experienced on this class of underground structures in a
14 consistent manner.

15 Time histories of the dynamic increment of lateral earth pressure at the top, middle, and
16 bottom of the structures during four representative earthquake and sinusoidal motions (e.g.,
17 Northridge-L, Northridge-H, Sine 1 Hz, Sine 2 Hz) in each test are compared in Figure 14, with
18 the time corresponding to maximum thrust marked. In general, the $\Delta\sigma_E$ time histories were
19 observed to be in phase along the height of the wall for the stiffer structures (T-BL, T-Stiff, and
20 T-Fixed). The more flexible structure in T-Flexible, however, experienced $\Delta\sigma_E$ time histories that
21 were slightly out of phase. The pressures peaked near the bottom before the middle and top. This
22 was due to larger wall deflections increasing from the base to roof of the flexible structure as

1 shown in Figure 8, which contributed to the overall reduction of dynamic earth pressures and
2 forces as compared to the other cases.

3 **Error! Reference source not found.**The short-time Fourier transform of accelerations
4 recorded on the container base and mid-depth of the structure wall are compared to those of
5 dynamic thrust during the Northridge-L motion in each of the four tests in Figure 15. The base
6 acceleration contained a significant content near 1 Hz in all experiments during Northridge-L,
7 particularly in the early part of the record. Similarly, the accelerations recorded at the mid-depth
8 of the structure and the dynamic thrust in T-Flexible, BL, and Stiff showed maximum content
9 near 1 to 1.5 Hz, which coincided with the effective natural frequency of the site (f_{so}') in those
10 tests.

11 In T-Fixed, the f_{so}' of the shallower soil deposit ranged from approximately 2.2 to 3.5 Hz
12 during different motions, corresponding to the peak of the surface to base transfer functions in
13 the far-field. An important frequency content was observed in the structure's acceleration and
14 dynamic thrust near 2 to 3 Hz in this test, but this frequency range was not dominant. The base of
15 the fixed structure experienced the same motion as the base of the container, with no influence
16 from site response. However, along the height of the wall, the structure's acceleration was
17 influenced slightly by site response, as also shown previously in Figures 9 and 11. Hence, the
18 Fourier amplitude of accelerations at the mid-depth of the wall showed amplification compared
19 to the base near f_{so}' of approximately 2 to 3 Hz in T-Fixed. The dynamic thrust during this test
20 also showed some content near 2 to 3 Hz corresponding to f_{so}' , but the primary content was
21 observed near 1 Hz over an extend period of time, corresponding to the mean frequency (f_m) of
22 the base motion. The sinusoidal motions (with a narrow frequency content) allowed an easier
23 evaluation of the impact of f_{so}' alone on the response of the structure.

The profiles of $\Delta\sigma_E$ at the time of maximum thrust are compared in Figure 16 for four tests (T-BL, T-Stiff, T-Flexible, T-Fixed) during sinusoidal motions with roughly similar amplitudes (mostly ranging from about 0.3 to 0.5g) but frequencies that varied between 0.33 Hz and 6.7 Hz. The shape of the $\Delta\sigma_E$ profile did not appear to have a significant dependence on the excitation frequency, and was primarily affected by the relative stiffness of the structure and base fixity, as observed previously during broadband earthquake motions. The largest dynamic pressures for all tests occurred when the base excitation frequency of the sinusoidal motion approached the far-field soil f_{so}' . In tests T-BL, T-Stiff, and T-Flexible the largest pressures were recorded at an excitation frequency of 1 Hz, near f_{so}' in those tests. The largest dynamic pressures in T-Fixed were recorded at an excitation frequency near 2 to 3 Hz, which was again near f_{so}' in that test. At higher frequencies, the dynamic increment of pressure reduced greatly compared to the resonance condition.

Dynamic Strains

Bending strains were measured with strain gages installed on the inside walls of the structures during and after each ground motion. The largest dynamic bending strains ($\Delta\epsilon_E$) were often recorded near the base of the structure. The dynamic bending strain ($\Delta\epsilon_E$) profiles are shown in Figures 17 and 18 at the times of maximum moment (or maximum strain) during different earthquake and sinusoidal motions, respectively. Tensile surface bending strain (i.e., outward wall curvature) is shown as positive in these figures. As expected, bending strains decreased when increasing the flexural stiffness of the structure. Additionally, fixing the base of the structure to the container in T-Fixed amplified dynamic strains (particularly at the base) compared to T-BL. Similar to dynamic earth pressures in Figure 16, dynamic strains in Figure 18 were observed to peak when the excitation frequency approached the effective fundamental

frequency of the site in the corresponding test (f_{so}' near 1 Hz in T-BL, T-Stiff, T-Flexible; and f_{so}' near 2 to 3 Hz in T-Fixed).

CONCLUDING REMARKS

A series of dynamic centrifuge tests were conducted to study 10.5 m-high box structures with varying flexural rigidities and fixity conditions, buried in medium-dense, dry sand undergoing one-dimensional shaking. All structures had their roofs at the ground surface. The base motions consisted of various earthquake motions with PGAs ranging from 0.26 to 1.39 g and sinusoidal motions with similar amplitudes (mostly ranging from about 0.3 to 0.5g), but frequencies ranging from 0.33 Hz to 6.7 Hz. The results of this experimental study indicate the following trends:

1. Soil densification (D_r increase from approximately 60% to 72%) and shearing after multiple motions resulted in greater PGA amplifications along the far-field soil column, greater static and seismic lateral earth pressures, and slightly greater dynamic bending strains along the height of the wall, but did not noticeably influence the effective fundamental frequency of the site (f_{so}').
2. The seismic response of the buried structure fixed at the base was noticeably different from the structures resting on soil with the ability to settle or rock. The structure to far-field acceleration spectral ratios and dynamic earth pressures were greater on the fixed structure compared to others.
3. The seismic performance of the buried structure in terms of tilt, acceleration, dynamic thrust, and dynamic bending strains was influenced greatly by the frequency content of the base motion as well as far-field site response. During the sinusoidal motions (with a narrower frequency band compared to earthquake motions), the dynamic earth pressures and bending strains always peaked when the excitation frequency approached f_{so}' ,

1 regardless of the fundamental frequency of the structure or base fixity. This observation
2 points to the critical importance of site response on the performance of buried reservoir
3 structures.

- 4 4. The magnitude of seismic thrust increased and the distribution of seismic earth pressures
5 changed from approximately triangular to parabolic with increasing structural stiffness.

6 The shape or distribution of dynamic earth pressures was shown as relatively independent
7 of the excitation frequency and mainly dependent on the structure's relative stiffness and
8 base fixity.

- 9 5. None of the analytical solutions could consistently capture the distribution and magnitude
10 of seismic earth pressures for the range of flexural stiffness, boundary conditions, and
11 ground motion intensities often used in the design of underground reservoir structures.

12 The analytical procedures commonly employed to evaluate the seismic response of
13 underground structures do not adequately consider the range of soil properties, flexural stiffness,
14 kinematic constraints, and ground motion characteristics for which critical underground reservoir
15 structures must be designed. Advanced numerical methods may also assume simplistic soil
16 properties, boundary conditions, or seismic loading that may not be applicable to realistic
17 conditions and may at times lead to misleading conclusions. The experimental results presented
18 in this paper are intended to help systematically evaluate the influence of soil densification,
19 flexural stiffness, base fixity, site response, and ground motion characteristics on the seismic
20 performance of stiff-uniyielding buried structures. Parallel nonlinear numerical simulations
21 validated using the centrifuge results but considering other variations than those permitted in the
22 experiments are necessary and underway. These simulations are needed before generalized
23 recommendations may be provided.

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Table 1. Dimensions and properties of model structures used in centrifuge (prototype scale).

Test	Structure	Outer Dimensions (m)	Thickness			Fundamental Frequency (Hz)
			Base (m)	Roof (m)	Walls (m)	
T-BL, T-Fixed	Baseline	H= 10.5 W=12.1	0.69	0.37	0.56	4.0
T-Flexible	Flexible		0.50	0.28	0.28	2.0
T-Stiff	Stiff		1.46	1.12	1.13	9.9

Table 2. Ground Motion Properties in T-BL, T-Fixed, T-Stiff, and T-Flexible

Shaking Event	Input motion parameters			
	PGA (g)	I _a (m/s)	D ₅₋₉₅ (s)	f _m (Hz)
Northridge-L1	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-1	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
Northridge-L2	0.31	1.8	18.4	1.3
Izmit-2	0.32	2.8	39.1	1.8
Loma	1.05	15.0	12.8	2.3
Sine 6.7	0.50	4.6	15.1	6.9

Figure 1. Elevation views of centrifuge models in: (a) T-Flexible, T-BL, T-Stiff; and (b) T-Fixed (dimensions shown in prototype scale meters).

Figure 2. Transfer Function (TF) of surface to base accelerations in the far-field under ambient vibrations, to obtain the small-strain fundamental frequency of far-field soil (f_{so}) in four tests (T-BL, T-Stiff, T-Flexible, T-Fixed).

Figure 3. Comparison of Northridge-L, Northridge-M, Northridge-H, Izmit, and Loma achieved base motion spectral accelerations (5%-damped) in four tests: T-BL, T-Stiff, T-Flexible, T-Fixed.

Figure 4. Cumulative settlement of far-field soil, adjacent to structure, and structure during T-Flexible subject to different earthquake and sinusoidal motions.

Figure 5. Transfer functions of surface to base accelerations in the far-field soil in T-Flexible during the two sets of Izmit and Northridge-L motions.

Figure 6. PGA ratios versus depth in T-Flexible during the two sets of Izmit and Northridge-L motions.

Figure 7. Dynamic increment of earth pressures ($\Delta\sigma_E$) at time of maximum thrust during the two sets of Northridge-L and Izmit motions in T-Flexible, T-BL, and T-Stiff.

Figure 8. The dynamic increment of bending strains ($\Delta\epsilon_E$) at the time of maximum moment during the two sets of Northridge-L and Izmit motions in T-Flexible, T-BL, and T-Stiff.

Figure 9. Transfer functions of far-field surface to container base as well as structure roof to container base accelerations during different experiments and earthquake motions. The highlighted area marks the range of effective, strain-dependent, fundamental frequencies (f_{so}') near the peak values of TF.

Figure 10. Base motion amplification/de-amplification of peak ground acceleration (PGA) in: (a) the far-field soil; and (b) on the four structures (BL, Stiff, Flexible, Fixed) during different earthquake motions.

Figure 11. Spectral ratio (5% damped) of structure to far-field accelerations at the elevation corresponding to the roof of the structure in four tests (T-BL, Flexible, Stiff, Fixed) during different earthquake motions.

Figure 12. Time histories and Fourier Amplitude Spectra of structural tilt in T-Flexible, T-BL, and T-Stiff during the Northridge motions.

Figure 12. Dynamic increment of earth pressure ($\Delta\sigma_E$) at the time of maximum thrust during four experiments (T-BL, T-Stiff, T-Flexible, T-Fixed) compared to the M-O, S-W, and Wood analytical methods.

Figure 13. Dynamic increment of pressure time histories along top, middle, and bottom of the structure during a few representative (Northridge-L, Northridge-H, Sine 1 Hz, Sine 2 Hz) ground motions. Vertical line identifies the time of maximum dynamic thrust.

Figure 14. Short-time Fourier transform of container base acceleration, mid-depth structural wall acceleration, and dynamic thrust recorded on the structure in T-Flexible, T-BL, T-Stiff, and T-Fixed during the Northridge-L motion.

Figure 15. Dynamic increment of pressure ($\Delta\sigma_E$) at time of maximum thrust during four tests and eight sinusoidal motions (0.3 Hz, 1 Hz, 2 Hz, 3 Hz, 4 Hz, 5 Hz, 6 Hz, and 6.7 Hz). Note: pressure recordings were not obtained in T-Stiff during Sine-6.7Hz.

Figure 16. Dynamic increment of bending strain ($\Delta\epsilon_E$) at the time of maximum moment during four experiments (T-BL, T-Stiff, T-Flexible, T-Fixed) and different earthquake motions.

Figure 18. The dynamic increment of bending strains ($\Delta\epsilon_E$) at the time of maximum moment during four tests (T-BL, T-Stiff, T-Flexible, T-Fixed) and eight sinusoidal motions with different frequencies.