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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. A series of four centrifuge experiments were performed to evaluate the influence of site response, structural stiffness, base fixity, and excitation frequency on the performance of relatively stiff reservoir structures buried in dry, medium-dense 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 magnitude 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 content of transient tilt, acceleration, dynamic thrust, and bending strain measured on the structure was strongly influenced by that of the base motion and site response, but was unaffected by the fundamental frequency of the buried structure ($f_{structure}$). 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.

1. Introduction

The seismic response of stiff-unyielding underground structures with minimum to no soil overburden is a fairly new topic at the interface between geotechnical and structural engineering. Buried structures can be classified as stiff-unyielding when they do not deform or rotate enough during seismic events to create active (yielding) conditions in the backfill soil due to the kinematic constraints at their roof or base, while they are not completely rigid and deform according to their stiffness. The majority of previous analytical, numerical, and physical model studies on the seismic response of buried structures focused on either yielding or rigid-unyielding underground structures (e.g., [1,5,6,16–19,22,23,25,27]). However, a number of important buried structures such as nuclear facilities, bunkers, culverts, and water reservoirs can be categorized as stiff-unyielding. The focus of this paper is on the seismic response of this type of structure (flexibility ratios ranging from approximately 0.1 to 2), particularly focusing on the buried water reservoirs being built by the Los Angeles Department of Water and Power (LADWP).

The seismic forces and deformations experienced by stiff-unyielding underground structures are not well understood. Soil-structure interaction near these structures is governed by the dynamic properties of the structure and backfill soil as well as the imposed kinematic constraints on the structure and the intensity, duration, and frequency content of the earthquake motion [2,11,12]. The available simplified procedures for buried structures introduced by Mononobe-Okabe [17,18], Seed-Whitman [22], or Wood [27] do not consider all of these effects. Although advanced numerical tools can take these effects into account, they may lead to complexities that require validation against the results from field observations or physical model studies.

Several of the previous experimental studies primarily focused on either yielding retaining structures [1,16,23] or flexible tunnels with large overburden (e.g., [3,24]). However, the seismic response of these structures is different from the stiff-unyielding structures

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with shallow or no overburden considered in this study. In response to this shortcoming, a series of dynamic centrifuge tests were recently conducted at the University of Colorado Boulder to evaluate the seismic performance of buried reservoirs with varying structural rigidity, soil cover, backfill soil type, backfill geometry, base fixity, and container boundary conditions. Hushmand et al. [11,12] summarized the insight obtained from these experiments regarding the influences of structural stiffness and the type and geometry of the backfill soil during earthquake loading. These experiments showed that stiff-unyielding buried structures could experience notable dynamic earth pressures. However, none of the available simplified procedures for buried structures was able to sufficiently capture the distribution and magnitude of seismic earth pressures or deformations experienced by the class of stiff-unyielding structures under the loading scenarios often used in their design. Further, the critical role of site response was displayed on the forces measured on the buried structures. Yet, the interacting influence of site response, structural stiffness, and base fixity on seismic forces and deformations was not investigated in detail, as is necessary in the validation of future numerical tools.

The dynamic behavior of underground structures fixed to a stiff rock foundation differs greatly from structures founded on soil, since the lateral base movement is prevented. Past analytical and numerical studies (e.g., [2,5,15,19–21,27]) 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, 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-unyielding structures, whether fixed at the base or free to translate, has not been evaluated experimentally.

This paper focuses on the combined effects of far-field site response, base fixity and stiffness of the structure, and the frequency content of the base motion on the dynamic behavior of stiff-unyielding 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, 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 base of the container in flight. The performance of buried structures was evaluated in terms of accelerations, rotational and lateral displacements, 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-unyielding buried reservoir structures to withstand earthquake loading.

2. Experimental method

Dynamic tests of model reservoir structures were performed at 60*g* 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. [9]. 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 Fig. 1a, but 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 Fig. 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 $D_r=60\%$ ($\gamma_{dry}=15.6$ kN/m^3). The soil deposit was pluviated in layers using a hopper at a calibrated height to achieve the target relative density (D_r). However, the D_r of and geostatic stresses in sand near the structure walls were likely affected by the presence of the structure and silo effects, influencing the recorded earth pressures and bending strains on the walls to some extent. These effects in smaller models that are commonly used in centrifuge need to be considered when evaluating the experimental results and comparing them with future numerical simulations.

The experimentally-measured small-strain, fundamental frequency of the far-field soil column (f_{so}) was estimated in an average sense prior to applying any dynamic motions using the

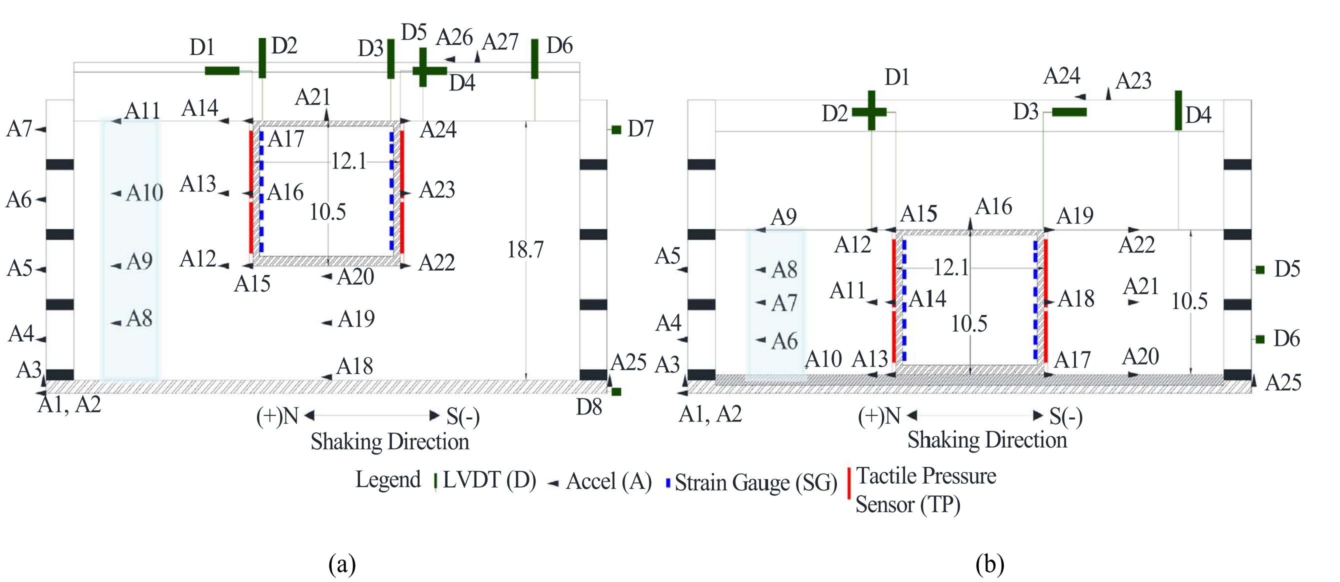

Fig. 1. Elevation views of centrifuge models in: (a) T-Flexible, T-BL, T-Stiff; and (b) T-Fixed. Notes: dimensions shown in prototype scale meters; highlighted region shows the far-field accelerometer array.