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Seismic response of retaining walls with cohesive backfill: Centrifuge model studies

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ABSTRACT

Observations from recent earthquakes show that retaining structures with non-liquefiable backfills perform extremely well; in fact, damage or failures related to seismic earth pressures are rare. The seismic response of a 6-m-high braced basement and a 6-m free-standing cantilever wall retaining a compacted low plasticity clay was studied in a series of centrifuge tests. The models were built at a 1/36 scale and instrumented with accelerometers, strain gages and pressure sensors to monitor their response. The experimental data show that the seismic earth pressure on walls increases linearly with the free-field PGA and that the earth pressures increase approximately linearly with depth, where the resultant acts near 0.33 H above the footing as opposed to 0.5–0.6 H, which is suggested by most current design methods. The current data suggest that traditional limit equilibrium methods yield overly conservative earth pressures in areas with ground accelerations up to 0.4*g*.

1. Introduction

Despite being a broad simplification of what, in reality, is an extremely complex soil-structure interaction problem, the most commonly used approach to seismic analysis and design of retaining structures is the Mononobe-Okabe method (M-O). This method was developed by Okabe [1] and Mononobe and Matsuo [2] following the great Kanto earthquake of 1923 that devastated many retaining structures, particularly the quay walls in Yokohama Harbor. Their method, i.e., a Coulomb wedge limit equilibrium (LE) analysis, drew on the results of pioneering shaking-table experiments conducted by Mononobe and Matsuo [2]. Their model was a rigid box filled with dry loose sand subjected to harmonic motions. The total seismic load was measured using pressure gauges and resulted in excellent agreement with Okabe's general theory of earth pressure [1].

Since then, much research has been conducted on the seismic response of retaining walls, and generally, these studies suggest that the M-O theory is appropriate for low levels of ground accelerations. Other LE methods, e.g. [3–8], improved on Okabe's general theory to account features such as surface cracks, wall-to-soil adhesion, the backfill flexibility, inertial body forces, and log-spiral failure surfaces among others. Most of these solutions, however, lack of experimental data at large accelerations and the evaluation of the critical failure surface typically requires a numerical solution. Likewise, kinematic solutions [9] and methods based on the theory of elasticity have been developed [10–14], but their applicability is limited since a small wall deflection can induce a failure state in the soil. Finite elements or finite differences models have been used extensively to analyze retaining structures [15–20]. While these methods have been validated against real case histories and experimental data, their predictive capabilities is still debatable.

A number of experimental studies have been conducted to substantiate the magnitude of earth pressures on retaining walls, since the early work of Okabe [1] and Mononobe and Matsuo [2]. Recent experimental evidence [20–23] and the observed field performance [24–26] show that M-O theory yields very conservative designs in areas where the peak ground acceleration (PGA) exceeds 0.4g. Among other reasons, classic methods of analysis overestimate the seismic earth pressures on retaining walls because the cohesive strength of the soil is typically ignored and the models assume an infinitely rigid backfill [27].

In general, the experimental data fall into two categories: small-scale 1-*g* shaking-table experiments and geotechnical centrifuge experiments. The 1-*g* shaking-table experiments that were prevalent in the past, e.g., [28–32], produced seismic loads consistent with M-O theory; however, in general, these experiments

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suggested that the earth pressure resultant acts at a point higher than H/3. As a result, the line of action of the dynamic force was typically chosen to be between 0.6 and 0.67 H [e.g., 33]. However, an important limitation of scaled 1-*g* shaking-table experiments is that even with the most careful scaling, the soil response cannot be easily scaled to prototype dimensions because the strength and stiffness of the soil, which control the soil behavior, are nonlinear functions of the confining stress. In addition, shaking table models built in rigid boxes on a rigid base do not reproduce the boundary conditions encountered in field settings, and the models are typically limited to short walls, i.e., typically less than 2 m in height, founded on stiff rock and retaining a medium loose soil.

While not completely devoid of scaling problems, centrifuge tests allow for correct scaling of stresses and strains in the soil [34]. The earliest centrifuge model of the seismic response of retaining structures was reported by Ortiz et al. [35], who studied the response of flexible cantilever walls in medium-dense sand. The container was subjected to earthquake-like motions, which resulted in seismic pressures consistent with M-O theory, and a seismic resultant located at 1/3 H. Bolton and Steedman [36,37] studied the centrifuge response of micro concrete cantilever walls that retained a dry cohesionless backfill. The walls were fixed to the loading frame and were subjected to harmonic accelerations up to 0.22*g*. The results suggested that the wall inertial forces must be taken into account in addition to M-O earth pressures.

Later, Dewoolkar [38] modeled the centrifuge response of liquefiable backfills on fixed-base cantilever walls under harmonic accelerations and showed that excess pore pressure and inertial effects contributed significantly to the total seismic lateral pressure. Nakamura [39] modeled the centrifuge response of free-standing gravity walls retaining dense Toyura sand (Dr=88%). The author showed that a 'soil wedge' forms in the backfill and slides down plastically during the earthquake, i.e., plastic strain accumulate in the slip plane when the soil is loaded in both (active and passive) directions. In contrast, the response implied by M-O theory suggests that the soil wedge that follows the retaining structure moves down when loaded in the active direction and moves up when loaded in the passive direction. Additionally and contrary to M-O theory, the author observed that the earth pressure distribution is nonlinear, changes over time, and is a function of the type of ground motion used. Nakamura observed complex interaction patterns between the backfill and wall, and concluded that even in controlled environments, the underlying assumptions of M-O theory are generally not met.

More recently, Al Atik and Sitar [20] and Sitar et al. [21] modeled the seismic behavior of fixed-base U-shaped walls, basement walls and free-standing cantilever walls supported in medium-dense sand. The experiments used a flexible shear beam container that deforms horizontally with the soil. The authors concluded that the M-O method was conservative, particularly when PGA > 0.4*g*, providing further support to the Seed and Whitman's [33] observation that properly designed retaining walls should be capable of withstanding 0.3*g*. The authors also observed that seismic earth pressure increased approximately linearly with depth and that the Seed and Whitman [33] method with the resultant applied at 0.33 H is a reasonable upper bound to the total seismic load. However, while the past experimental work has been devoted almost exclusively to cohesionless backfills, many backfills are made of compacted soil or natural soil deposits that have a certain degree of cohesion that may significantly reduce the loading demands on the system [6,40,41]. Thus, this study was motivated by the lack of experimental data on the seismic response of retaining structures with cohesive backfills. The experimental program was conducted at the NEES Center for Geotechnical Modeling (CGM) and consisted of scaled centrifuge models of free-standing cantilever walls and basements walls with a level backfill. The numerical simulation of these centrifuge tests was performed in FLAC-2D and will be the subject of another article.

2. Centrifuge model

The primary advantage of centrifuge experiments over 1-*g* shaking-table experiments is the correct scaling of the stress-strain behavior in the soil, which enables the model to reproduce the behavior of full-scale prototypes. A thorough discussion of the centrifuge scaling principles can be found elsewhere [34]. Nevertheless, centrifuge models are not problem free: the gravitational field increases with depth; highly sensitive instruments are required to capture the frequency content of centrifuge earthquakes; and there are no stationary reference points because undesired vibrations develop in the loading frame as a result of the dynamic interaction with the soil model. The latter becomes an issue when there is mass asymmetry within the soil. The large centrifuge at CGM has a 9-m radius with a payload of 4.5 t at 75*g*'s of gravity (Fig. 1a). A 1-D shaking table mounted on the centrifuge arm reproduces earthquake-like ground motions and delivers a PGA between 20*g* and 30*g*, which is equivalent to 0.4*g* and 0.6*g* if a scaling factor of N=50 is used, respectively. In the present study, the models were built in a flexible shear beam (FSB) container (Fig. 1b), which deforms horizontally with the soil and helps simulate free-field conditions during earthquakes. Multiple sensors were used in the experiment; data were collected at a rate of 4096 Hz using a high-speed Data Acquisition system.

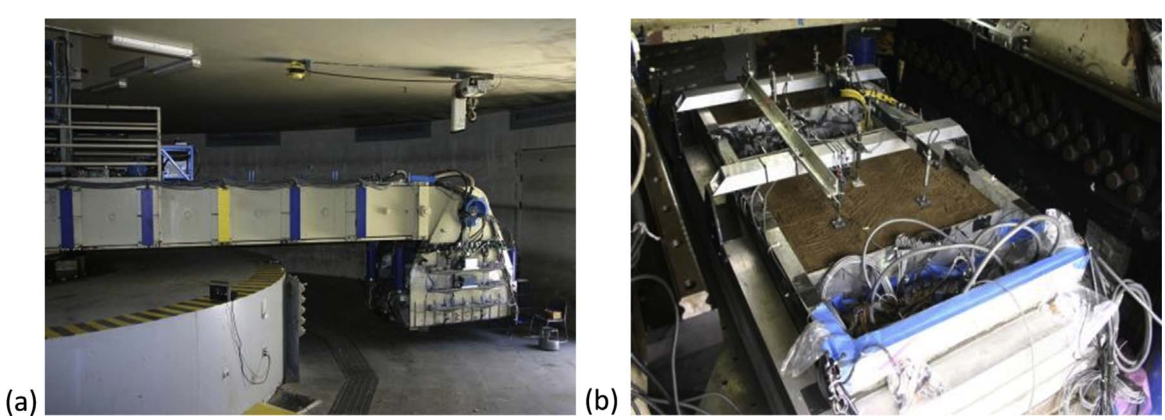

Fig. 1. (a) CGM's centrifuge at rest, and (b) centrifuge model in the arm.