Seismically induced lateral earth pressures: a new approach

Pressions latérales de terre induites par des sismicité: Une nouvelle approche

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ABSTRACT

Methods for evaluating the seismically induced lateral earth pressures gradually evolved from the seminal Japanese work performed in the 1920's. The resulting design procedures suggest large dynamic loads during strong ground motion. However field evidence from recent major earthquakes fails to show any significant problems with the performance of retaining structures designed for static earth pressures only. Results of a series of centrifuge experiments performed by the authors indicate that seismically induced lateral earth pressures are significantly less than those estimated using the most current design methods based on the Mononobe-Okabe assumptions. Specifically, the data show that the earth pressure distribution remains roughly triangular, increasing with depth, and the maximum dynamic moments on the retaining structure are to a large extent caused by the moment of inertia of the structures themselves. Therefore, a new approach based on direct consideration of the inertial forces due to the mass of the structure and a limited contribution by dynamic earth pressures is being proposed.

RÉSUMÉ

Méthodes d'évaluation des pressions latérales de terre induites par la sismicité a progressivement évolué du travail séminal japonais effectué dans les années 1920. Les procédures de conception suggèrent de grandes charges dynamiques durant les movements de terre forts. Cependant, la prevue recénte de grands tremblements de terre ne présente pas de problèmes importants avec la performance du maintien de structures conçues pour des pressions statiques de terre seulement. Résultats d'une série d'expériences réalisées par centrifugation les auteurs indiquent que la sismicité induite par terre pressions latérales sont sensiblement inférieures à celles estimées en utilisant les plus récentes méthodes de conception fondées sur les hypothèses Mononobe-Okabe. Plus précisément, les données montrent que la répartition de la pression de la terre reste à peu près triangulaire, augmentant avec la profondeur et la dynamique maximum moment de torsion sur le maintien de la structure est en grande partie causée par le moment d'inertie des structures elles-mêmes. Par conséquent, une nouvelle approche basée sur l'examen direct des forces d'inertie due à la masse de la structure et d'une contribution limitée par la pression dynamique de la terre est proposée.

Keywords : seismic, earth pressure, earthquake, retaining structure

1 INTRODUCTION

Current methods for evaluation of seismically induced earth pressures principally rely on the pioneering analytical and experimental work of Okabe (1926) and Mononobe and Matsuo (1929), respectively. The basis of the so-called Mononobe-Okabe (M-O) method is an assumption that the Coulomb theory of static earth pressures on a retaining wall can be extended to include inertial forces due to horizontal and vertical acceleration in the backfill soil. The M-O method was developed for dry cohesionless backfill retained by a gravity walls and includes a number of important assumptions (Seed & Whitman 1970):

1. The wall yields sufficiently to produce minimum active pressure and the soil is assumed to satisfy the Mohr-Coulomb failure criterion;
2. When the minimum active pressure is attained, a soil wedge behind the wall is at the point of incipient failure, and the maximum shear strength is mobilized along the potential sliding surface; and
3. The soil wedge behaves as a rigid body, and accelerations are constant throughout the mass.

While many additional analytical and experimental studies have been conducted in the last eighty years, most of the basic assumptions inherent in the above approach have remained unchallenged until recently. However, recent advances in understanding of strong ground motion characteristics from recent major earthquakes, such as Loma Prieta, 1989, Northridge, 1994, Kobe 1995, Chi Chi, 1999, and Wenchuan 2008, suggest that new retaining and other structures should be designed for much stronger ground motions than has been the accepted practice in the past. Yet, observations of the actual performance of retaining structures in these earthquakes do not give any indication that well designed and constructed retaining structures experience problems even when not specifically designed for seismic loading.

In this paper we present a brief review of relevant existing studies of dynamic earth pressures We then present the results from dynamic centrifuge experiments performed by Al Atik (2008a) to elucidate the factors controlling the seismic performance of cantilever retaining structures and we suggest a new approach to evaluating the seismic earth pressure component in the design of retaining structures.

2 EXPERIMENTAL STUDIES

2.1 *Previous dynamic centrifuge studies*

The basic principle behind centrifuge testing in geotechnical engineering is to create a stress field in a model that simulates prototype conditions. The major advantage of dynamic centrifuge modeling is that scaling gives correct strength and stiffness in granular soils. Thus, in granular soils, for a reduced scale model with dimensions 1/N of the prototype and a

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gravitational acceleration during spinning that is N times the acceleration of gravity, the soil in the model will have same strength, stiffness, stress, and strain as the prototype (see e.g. Kutter 1995).

Dynamic centrifuge tests on model retaining walls with dry and saturated cohesionless backfills have been performed by Ortiz (1983), Bolton & Steedman (1985), Steedman & Zeng (1991), Stadler (1996), and Dewoolkar et al. (2001). In general, most of these researchers concluded that there was a general agreement between the maximum measured forces and the M-O predictions, although there was uncertainty about the point of application of the dynamic thrust. Stadler (1996) concluded that the incremental dynamic lateral earth pressure profile ranges between triangular and rectangular and suggested using a reduced acceleration coefficient of 20–70% of the original magnitude with the M-O method.

Most recently, however, Nakamura (2006) studied the seismic behavior of gravity retaining walls. His study presents invaluable insights into the seismic behavior of the gravity wall-backfill system. He concluded that the assumption inherent in the M-O method that the backfill soil can be represented by a rigid wedge moving in phase with the soil is not supported by experimental evidence and seismic earth pressures are out of phase with wall movements. As a result, large seismic earth pressures do not materialize. Most importantly, while Nakamura's experimental observations are in direct contrast to previous experimental studies, they are consistent with the actual observed performance of retaining structures in recent earthquakes.

2.2 *Centrifuge model configuration and testing*

Two centrifuge experiments were performed on the 400g-ton dynamic centrifuge at the Center for Geotechnical Modeling at the University of California, Davis. The centrifuge has a radius of 9.1m, a maximum payload of 4,500Kg, and an available bucket area of 4m^2. The shaking table has a maximum payload mass of 2,700Kg and a maximum centrifugal acceleration of 80g. (Kutter et al., 1994, Kutter, 1995).

The models used in the experiments were constructed in a rectangular flexible shear beam container with internal dimensions of 1.65m long, 0.79m wide and approximately 0.58m deep (Figure 1). The model container is designed such that its natural frequency is less than the initial natural frequency of the soil in order to minimize boundary effects. In prototype scale, the models represented two 6.5m high U-shaped reinforced concrete, cantilever retaining structures, one stiff and one flexible. The structures were fully embedded in dry sand backfill and the structures were underlain by approximately 12.5m of dry sand

The first centrifuge experiment was performed on a two-layer sand model with sand backfill and foundation having relative density of 61% and 73%, respectively. The second centrifuge experiment was performed on a uniform density sand model with relative density of 72%. Dry pluviation was used to place the sand in different layers underneath and behind the structures. The centrifugal acceleration used in the experiments was 36g and all test results are presented in terms of prototype units unless otherwise stated. The model structures were made from aluminum and lead was added to the structures order to match the mass of the prototype reinforced concrete structures. Figure 1 presents the configuration of the second centrifuge model and complete details can be found in Al-Atik and Sitar (2008b).

Multiple shaking events covering a wide range of predominant periods and peak ground accelerations were applied to each model in flight at a centrifugal acceleration of 36g. The shaking was applied parallel to the long sides of the container. The shaking events consisted of step waves and a number of ground motions recorded in recent earthquakes (Al Atik and Sitar 2008b).

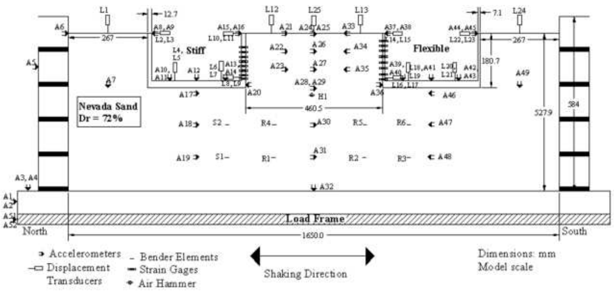

Figure 1. Section through the model showing the position of the model structures and the layout of instrumentation. Dimensions in model scale (mm).

2.3 *Instrumentation*

The centrifuge models were densely instrumented in order to collect accurate and reliable measurements of accelerations, displacements, shear wave velocities, strains, bending moments and earth pressures. Horizontal and vertical accelerations in the soil and on the structures were measured using miniature ICP and MEMS accelerometers. Soil settlement and the deformation and settlement of the structures were measured at different locations using a combination of spring loaded LVDTs and linear potentiometers. Shear wave velocities in the soil underneath and behind the structures were measured using piezo-ceramic bender elements and mini-shear air hammers. The locations of accelerometers, bender elements, air hammers, and displacement transducers for the second centrifuge experiment are shown in Figure 1.

Since accurate measurement of lateral earth pressure distribution was the major goal of this study three different sets of independent instruments were used in the experiments. The lateral earth pressures were measured directly using flexible tactile pressure Flexiforce sensors manufactured by Tekscan. Lateral earth pressures on one flexible and one stiff wall were also calculated by double differentiating bending moments measured by the strain gages (SG) mounted on the model walls. Finally, direct measurements of the total bending moments at the base of one stiff and one flexible wall were measured directly by using force-sensing bolts (LB) at the wall-foundation joints.

3 EXPERIMENT RESULTS

3.1 *Earth Pressure Distribution*

The distribution of seismically induced earth pressures with depth was directly measured with the tactile pressure sensors. Figure 2 is a plot of measured and computed seismically-induced earth pressures with depth for one of the shaking events. As can be seen from the plot the maximum dynamic earth pressure increases monotonically downward as is typical of static earth pressures. Also, in this case, the earth pressure magnitude and distribution on the flexible and stiff walls are essentially the same, suggesting that the wall stiffness has little influence in this particular case; although, in general, the earth pressures were higher on the stiff wall due to the relatively loose backfill in the experiments. The plot also shows a very good agreement between the magnitude of the earth pressure measured by the tactile sensors and those computed from the strain gauge data which provide an independent confirmation of the observed trends.

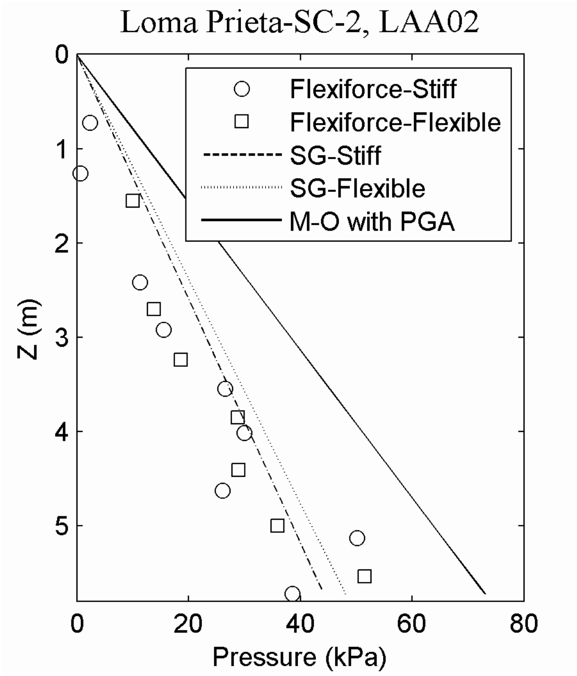

Figure 2. Maximum total earth pressure profiles measured with strain gauges (SG), tactile sensors, and estimated using the M-O method for Loma Prieta-SC-2 event (Sitar and Al Atik, 2009)

3.2 *Moment and earth pressure time history*

One of the assumptions in the current methods of estimating seismic earth pressures and corresponding wall moments is that the maximum moment and earth pressure occur simultaneously. In past experiments investigators were not able to make the distinction, since measured wall moments were typically used to back calculate estimated earth pressures. Because of the independent measurements of earth pressures and wall moments in our experiments, we can clearly distinguish between these different quantities. In contrast to the previous assumptions, our data show that the maximum moment and maximum earth pressure are in fact out of phase (Figure 3).

The above observation has a number of important implications for the evaluation of the seismic response of retaining structures. The most important being the conclusion that the maximum seismic moment in the retaining structures is due to the moment of inertia of the structures themselves.

3.3 *Seismic earth pressure coefficients.*

The traditional approach to the seismic design of retaining structures is to express the dynamic load increment in terms of a seismic earth pressure coefficient. Figure 4 shows the seismic coefficients computed from the dynamic earth pressures at maximum wall moments. As can be seen from data, there are no significant seismically induced earth pressures at the maximum moments experienced by a cantilever retaining wall until the peak ground acceleration exceeds 0.4g. Data presented in Figure 4 do not include any factors of safety typically incorporated in seismic designs. Such factors of safety would allow the retaining walls to resist moments due to seismically induced earth pressures at peak ground accelerations greater than 0.4g.

4 DESIGN CONSIDERATIONS AND CONCLUSIONS

The data obtained from the centrifuge experiments shows that much of the philosophy of seismic design of retaining structures that has been in use since the early part of the last century has to be reassessed. In particular, the past design philosophy has been based on shaking table experiments which were extended substantially beyond the range of their applicability. The data from carefully scaled dynamic centrifuge experiments show that the central assumption inherent in the M-O method that a complete Coulomb wedge is mobilized during shaking and that the maximum earth pressure and maximum wall inertial moment occur simultaneously is not appropriate.

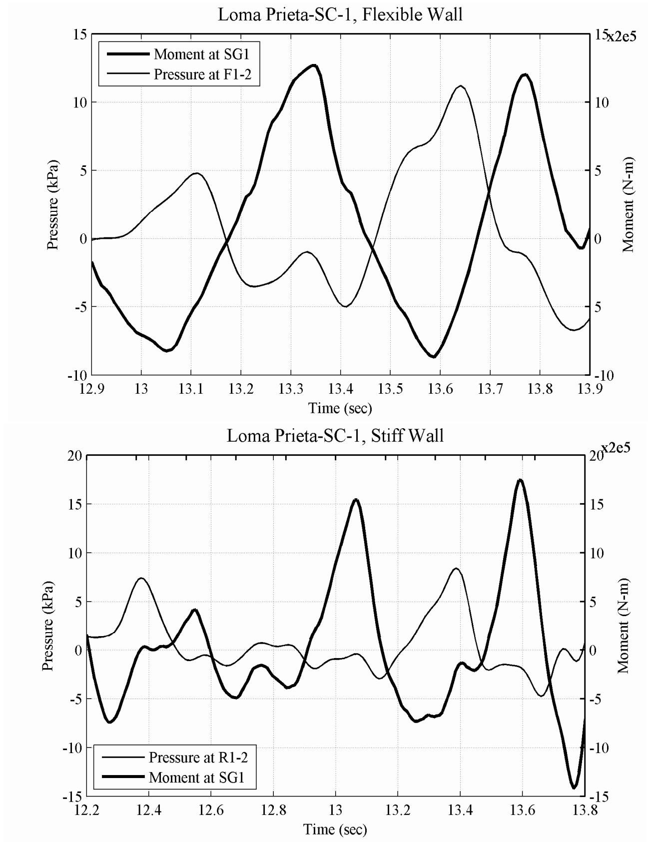

Figure 3. Comparison of dynamic wall moments and dynamic earth pressures on the south stiff and north flexible walls (Sitar and Al Atik 2009)

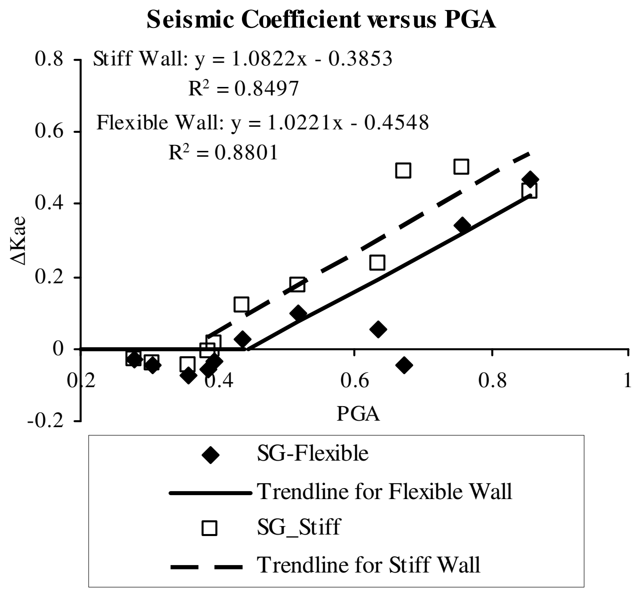

Figure 4. Seismic coefficients computed at maximum dynamic wall moments based on strain gauge (SG) data.

Similarly, the assumption put forth by Seed and Whitman (1970) that the seismic earth pressure acts at 0.6 to 0.7 H is not supported by the experimental data from the centrifuge experiments. In fact, the centrifuge experiments consistently demonstrate that the maximum dynamic earth pressures increase with depth and can be reasonably approximated by a triangular distribution analogous to that used to represent static earth pressures (Al Atik and Sitar, 2008b). The magnitude of seismic earth pressures depends on the magnitude and intensity of shaking, the density of the backfill soil, and the flexibility of the retaining walls. Similar results were independently obtained for gravity walls by Nakamura (2006).

In general, dynamic earth pressures are insignificant for low levels of shaking, on the order of 0.4g or less. In fact Seed and Whitman (1970) noted that a retaining structure designed for an adequate static factor of safety should perform adequately at peak ground accelerations up to 0.3g. However, the design forces quickly become excessive compared to experimental results at higher ground acceleration levels. As an example, Figure 2 shows a comparison between the computed M-O earth pressure distribution and the actual maximum dynamic earth pressures in one of the experiments. In this particular case the values computed using the M-O method exceed the actual measured values by factor of about two.

Given that moments are of the real concern for cantilever structures, the dynamic coefficient relationship at maximum wall moments seems to be the most suitable for use in design. In addition, the results from the centrifuge experiments presented here show that the contribution of the wall inertial moments to the overall dynamic wall moments is substantial and should be accounted for separately. Similar conclusion was reached by Richards & Elms (1979 and 1980) with respect to seismic design of gravity walls. Also, it should be noted that none of the data presented here consider any load factors or factors of safety. Thus, cantilever retaining structures designed with an adequate factor of safety should perform well at accelerations well in excess of 0.4g. This conclusion is supported by observed excellent performance of various types of retaining structures in recent earthquakes, which suggest that retaining structures under designed with respect to seismic forces perform well under seismic loading with peak acceleration in excess of 0.5g (see e.g. Clough and Fragaszy 1977).

Finally, it is important to note that the current results are strictly applicable only to flexible cantilever retaining walls in granular dry medium dense soils, level ground, and non-liquefiable backfill. In this sense the results are conservative, since even lower seismically induced earth pressures can be expected in denser soils and soils with cohesion (Al-Atik and Sitar 2008b). At this point, much more work is needed to address different soil conditions, different geometries, and different types of structures in order to further develop the necessary guidelines for seismic design of retaining structures in a variety of settings..

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