Soil Dynamics and Earthquake Engineering 71 (2015) 13–26

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Shake table lateral earth pressure testing with dense c-ϕ backfill

Patrick Wilson [a], Ahmed Elgamal [b,*]

[a] Earth Mechanics, Inc., 17800 Newhope Street, Suite B, Fountain Valley, CA 92708, USA
[b] Department of Structural Engineering, University of California, La Jolla, San Diego, CA 92093-0085, USA

ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form
12 December 2014
Accepted 20 December 2014
Available online 29 January 2015

Keywords:
Retaining wall
Dynamic earth pressure
Seismic
Earthquake
Mononobe–Okabe

ABSTRACT

Dynamic lateral earth pressure is recorded during ten shake table testing events. In these tests, peak input acceleration at the base of the retaining wall varied in the wide range of 0.13–1.20 g in order to include scenarios of relevance to recently observed strong earthquake excitations. The results shed light on the influence of soil cohesion and the effect of small wall movements on the magnitude and distribution of earth pressure. In accordance with field practice, a commonly encountered dense sand backfill with a small percentage of fines (SP-SM) is used. Inside a large soil container, earth pressure is measured against a rigid wall (backfill height $H=1.7$ m) that is allowed to undergo limited translation/rotation due to the imparted dynamic excitation (up to 10 mm or 0.006H at 1.2 g base acceleration). In this particular series of experiments, favorably low dynamic pressures were recorded at backfill accelerations of up to about 0.7 g in light of: (i) the relatively high soil strength (including cohesion) that precluded a limit equilibrium type failure in the backfill, and (ii) the high soil stiffness coupled with the small value of observed wall translation/rotation (as much as 3 mm or 0.0018H at ground surface). In tests with instants of very high acceleration (in the range of 1 g), the corresponding dynamic earth pressure is found to be of much significance for practical applications. Lateral thrusts recorded during these instants of strong shaking compare well with limit equilibrium predictions that include the soil cohesion intercept. Exclusion of the cohesion intercept results in substantial over-prediction of the measured lateral forces.

1. Introduction and background

Dynamic earth pressure has been an area of active research for over 80 years due to the abundance and importance of earth retaining structures and the complexity of their dynamic response. Recent studies suggest that analytical methods currently used to assess seismic loads on retaining structures (e.g., [24,20,43]) may oversimplify the problem or incorrectly estimate the loads [16,12,5,3,18,13,36,34]. At this time, additional insights into dynamic pressures and the involved mechanisms may advance our understanding and help lead to further progress towards safer and/or more economic seismic designs.

Over the past several decades, the Mononobe–Okabe equations [24,20] have been used extensively for evaluating the magnitude of dynamic earth pressure. Those equations were developed based on limit equilibrium for cohesionless soil. In practice, soils consisting of predominately sand with a moderate silt or clay fraction meet code requirements (e.g., [8]), and are commonly used as backfill [10,5]. Such soils often exhibit small to fairly significant cohesion intercept values in laboratory strength test results [11]. A cohesion intercept can also exist for cemented or partially saturated sand [5,7,18]. During the short-term loading of an earthquake, such cohesion in sandy soils could significantly reduce the level of dynamic earth pressure that a wall may experience [28,5,15].

Dynamic earth pressure with c-ϕ soil backfill has been investigated in analytical studies (e.g., [32,28,5,35,38]). In these analytical studies, a dimensionless cohesion term (normalized by unit weight and height of the supported soil) is employed. Lower dynamic earth pressure is predicted for higher values of this parameter. However, Vahedifard et al. [38] caution that cohesion should be used in design only when its value can be reliably assessed.

In addition to overall magnitude, the distribution of dynamic pressure along the wall height can have a substantial impact on performance. Simplified dynamic earth pressure distributions are often assumed in practice, such as a triangular or inverted triangular distribution along the wall height [21,33,3]. However, numerical model studies have demonstrated that the backfill stiffness and retaining wall flexibility/movement can substantially impact the distribution of dynamic earth pressure, leading to lower overall dynamic thrusts and moments [4,39,29,12,26,14,13].

* Corresponding author.
E-mail addresses: p.wilson@earthmech.com (P. Wilson), elgamal@ucsd.edu (A. Elgamal).

http://dx.doi.org/10.1016/j.soildyn.2014.12.009
0267-7261/

Previously conducted experimental studies have primarily been performed in the centrifuge (e.g., [25,6,37,44,9,22,3]) using cohesionless sand for the backfill. Based on recent experiments conducted using medium-dense cohesionless backfill, Al Atik and Sitar [2,3] found the earth pressures to be generally lower than those predicted using the Mononobe–Okabe [24,20] equations. Al Atik and Sitar [2,3] also concluded that further decreases in seismic earth pressure may result for scenarios of denser, moderately cemented and cohesive backfills, and for walls that may experience rocking and/or translation at the base.

In order to provide additional insights and expand on those gained from prior studies, this paper presents an experimental program in which full scale shake table testing is conducted, using a relatively short (1.7 m) wall section supporting a c-ϕ dense sand with silt backfill (with a low but significant cohesion intercept). In the employed test configuration, the model wall can undergo low levels of rotation and translation which mimic possible displacement characteristics (Fig. 1) of actual retaining walls [12].

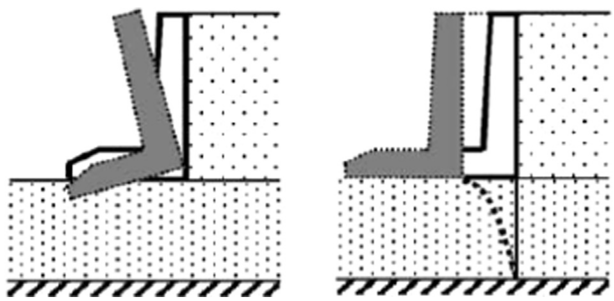

Fig. 1. Schematic of rotation and translation of an L-shaped wall (after [12]).

As such, the primary goal of this study is to shed light on three main issues which are relevant to a wide range of dynamic earth pressure scenarios: (i) influence of the shear stiffness and strength (including the peak and residual states) of typical compacted sand backfills which include a moderate fines content, with contributions from both friction as well as cohesion; (ii) system response under moderate as well as high levels of seismic excitation reaching and exceeding 1 g in peak input acceleration, and (iii) potential influence of wall movement on the resulting magnitude and distribution of earth pressure. In addition, it is of relevance to note that the dynamic testing studies reported herein complement an existing set of experimental data concerned with passive earth pressure load–displacement behavior [40,42]

In the following sections, details of the experimental setup are presented. Related results from earlier laboratory shear strength tests and full scale passive earth pressure load–displacement experiments conducted using the same backfill soil are briefly highlighted (all recorded data, static and dynamic, is available for public access and use at https://nees.org/warehouse/experiment/553/project/33). Salient data sets from the shake table earth pressure experiments are discussed in order to describe the system response characteristics, including: (i) movements of the test wall and backfill, (ii) associated pressure distributions, and (iii) overall dynamic forces. Limit equilibrium analysis is conducted to assess the recorded levels of earth pressure and role of cohesion and peak/residual soil strength states. Finally, the main observations are summarized and conclusions are drawn.

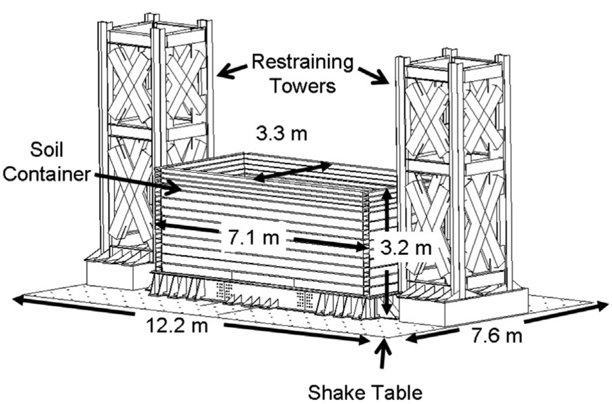

Fig. 2. Schematic view of soil container on shake table and stiff towers that restrain the container laminate relative displacement.

2. Testing facility

The Englekirk Structural Engineering Center (ESEC) of the University of California San Diego (UCSD) is home to the world's first outdoor, and currently the largest US shake table [19,27]. Testing for the presented study was performed on this 12.2 m (40 ft) by 7.6 m (25 ft) outdoor shake table (Figs. 2 and 3), which allows for imparting one dimensional lateral dynamic excitation (along the 12.2 m length direction).

3. Test configuration

Along with the dynamic earth pressure experiments presented below, the testing configuration and model dimensions were designed with the additional purpose of investigating passive earth pressure. Under this loading scenario, the corresponding force–displacement

Fig. 3. Restrained laminar soil container on outdoor shake table at UCSD.