Shaking table tests of gravity retaining walls
E. Cascone, M. Maugeri
University of Catania, Catania, Italy

Abstract

The paper presents some preliminary results of an experimental program on the seismic behaviour of retaining walls, in progress at the University of Catania. Shaking table tests on small gravity walls retaining dry cohesionless soil subjected to simple armonic ground motion have been performed and the behaviour of the soil-wall system has been observed. Input acceleration, base and top wall acceleration and backfill soil acceleration have been recorded and displacement time histories have been obtained by numerical integration.

1 Introduction

Seismic design of retaining walls is traditionally based on the Mononobe-Okabe method of analysis. This method is an extension of the classical wedge theory in which both vertical and horizontal inertial forces are introduced in order to take into account the effect of earthquake shaking on the thrust acting on the wall.

Starting from the Newmark's model of the sliding block [7], Richards and Elms [9] proposed an alternative design procedure based on the concept of limited displacements. According to this method it is possible either to design walls for an assigned value of the maximum allowable displacement, or to evaluate the maximum permanent displacement that a wall would suffer under a given accelerogram.

In recent years a number of theoretical analyses using finite element (Nadim and Whitman [6], Siddharthan and Norris [11], Al-Homoud and Whitman [1]) or finite differences techniques (Siddharthan et al. [12], Cascone et al. [3], Rafnsson and Prakash [8]) have been presented to predict the seismic behaviour of gravity retaining walls. Although all these studies provided interesting results, there is the need of a against experimental evidence and documented real cases.
For a better understanding of the seismic behaviour of gravity retaining walls, experimental investigations have been carried out performing both centrifuge tests (Bolton and Steedman [2]) and shaking table tests (Sherif et al. [10], Lai and Berrill [5], Elms and Richards [4]). None of these approaches are free from experimental drawbacks: shaking table tests are usually not able to reproduce the stresses that occur in the field, while the impossibility of scaling the soil grain size and the inexact representation of the input acceleration records are some of the shortcomings of centrifuge testing.

In this paper some shaking table tests performed on two gravity retaining walls are described and the experimental results are presented with the aim to provide, though qualitatively, an insight into some aspects of the dynamic behaviour of rigid retaining structures resting on rigid foundation soil.

2 Experimental equipment and soil properties

All the investigations were conducted in the context of a research program on the dynamic behaviour of retaining walls in progress at the University of Catania using the shaking table schematically shown in Fig. 1. The available experimental equipment consists of four components: 1) shaking table and test box; 2) loading unit; 3) retaining walls and backfill soil; 4) data acquisition system.

The shaking table is made up of a rigid steel frame and a steel plate bolted on the frame. The table is 2 m long, 1 m wide and 80 mm thick and is supported by four wheels constrained to move each on a shaft so to restrict the motion to one direction. A test box 0.9 m long, 0.7 m wide and 0.4 m deep is fixed to the shaking table. The sides of the box are made of 10 mm thick transparent glass through which the behaviour of the soil can be observed. These glasses were carefully cleaned using a solution of acetone to limit the lateral

![Figure 1: Experimental set-up.](image-url)
friction effect. In order to provide adequate friction between the soil and the base of test box a sheet of abrasive paper was pinned onto the bottom of the box.

The loading unit consists in an electric engine equipped with a disk of adjustable eccentricity which provides an harmonic motion to the shaking table through a bearing mounted on one edge of the table. The contact between the disk and the bearing is maintained by a spring \((k=300 \text{ KN/m})\) fixed on a contrast beam. The simplicity of the loading system allows to control only the engine frequency thus it is impossible to vary input frequency and acceleration independently.

Several walls have been tested during the investigations in progress and a good agreement was found between the tests so far performed by Venora [14] and Tiberio [13]. The results reported herein are relative to a 25 cm high and to a 30 cm high microconcrete retaining walls designed using the Mononobe-Okabe method to resist a maximum earthquake acceleration \(a=0.1g\). The soil employed throughout the experimental program was a uniform \((D_{60}/D_{10}=1.72)\) beach sand presenting unit weight \(\gamma=15.5 \text{ KN/m}^3\) and peak friction angle \(\phi=36^\circ\). These parameters were determined trying to reproduce in the sample the same conditions of the sand in the test box.

The condition of a wall resting on a rigid foundation soil was achieved placing the wall on the bottom of the test box interposing only a very thin sand layer. Since the base friction was considered a crucial parameter for the interpretation of the experimental results, a simple test was carried out and allowed to determine \(\phi_b=24^\circ.75\). Accordingly the safety factors of both walls against sliding and tilting and the critical acceleration coefficient were found to be respectively \(F_S=1.12\), \(F_T=1.48\), \(N_{CR}=0.14\).

In each test the wall was instrumented with two accelerometers to record the accelerations at the top and at the base, one accelerometer was placed in the backfill behind the wall to measure the free-field motion as well. In order to store the remarkable amount of data generated during the dynamic tests a high speed acquisition system was used for data acquisition and processing. The analog signals from the accelerometers are taken with a sample time \(\Delta t=0.01\) s and are digitized by an A-D converter.

3 Shaking table tests

The experimental procedure consisted in a few steps. After having placed the wall, this was backfilled by pluvial deposition pouring dry sand from a constant height of 40 cm. in order to attain a reasonably dense state. When the model was complete and the accelerometers were ready at their locations all the electronic equipment was switched on and thermally stabilized. The system was then shaken for 80 seconds imposing to the table a maximum displacement of 2 mm and varying the frequency regularly from 1.5 Hz to 6.5 Hz in steps of approximately 1 Hz. During this phase neither wall displacements relative to the table or to the backfill, nor backfill settlements were ever observed and there is an almost perfect coincidence between the wall acceleration and the input
motion. The table, the wall and the backfill moved together like a rigid block. Afterwards the eccentric disk was adjusted so to provide a maximum displacement of 4 mm and again the system was shaken varying the frequency until a failure surface appeared in the backfill right behind the wall, shown by vertical or horizontal black sand markers. The displacements undergone by the wall were measured and then the system was shaken again until further permanent displacements of the wall occurred. Figures 2a and 2b show the soil-wall system after the development of a distinct failure surface for the two walls tested. It is evident that this surface can be well approximated by a plane that starts at the toe of the wall and grows towards the backfill surface.

Tests on walls resting on a 5 cm thick sand layer were also carried out showing a prevalent tilting behaviour (Fig. 3) but the results so far obtained still need to be studied and will not be discussed here.

The angles formed by the failure planes showed in Fig. 2 with the horizontal were $\alpha=51^\circ$ for the 25 cm high wall and $\alpha=47^\circ$ for the 30 cm high
wall. The comparison between the inclination of the failure surfaces experimentally measured and those predicted by Rankine and Mononobe-Okabe theories is presented in Fig. 4, where the good agreement between experimental and theoretical pseudostatic results is pointed out.

Figure 4: Comparison between observed and predicted failure surfaces.

Figure 5 shows the accelerograms recorded at the top of the 25 cm high wall and the input motion during failure. It is possible to observe that just before failure the wall and the table move together with the same acceleration. This is a steady situation in the sense that failure does not occur no matter how long the excitation lasts; but as soon as the excitation frequency is slightly increased a relative acceleration develops and the wall accumulates outward displacements.
The steady condition before failure is considered the critical condition for the soil-wall system and is defined in terms of input motion frequency and peak acceleration. For the two cases examined in this study (h=25 cm and h=30 cm) these parameters were found to be: f=5.7 Hz, a_max=0.24g and f=6 Hz, a_max=0.23g. It was also observed that the motion recorded in the free-field was substantially identical to the input motion not only before failure occurred in the soil but even during the accumulation of wall displacements.

The smaller wall suffered a translational displacement of 12.5 mm in 1.4 s (8 cycles); similarly the bigger wall experienced a displacement of 14 mm in 1 s (6 cycles). It was observed that sliding occurs in steps whose amplitude is approximately constant in each loading cycle. The base of the wall moved essentially outwards, conversely the top of the wall moved back and forth giving evidence of small rotations. Relative accelerograms of the wall with respect to the shaking table input motion have been numerically integrated in time domain and some typical results are shown in Fig. 6.

4 Discussion of results and conclusions

The specific aim of the tests reported in the present paper was to observe and qualitatively classify the behaviour of gravity retaining walls with dry cohesionless backfill, resting on rigid soil, subjected to simplified earthquakes of various intensities so to provide basic patterns for meaningful comparisons with theoretical predictions.

During the tests it was observed that the soil behaved like a rigid plastic body and did not show any appreciable deformation until failure occurred. This was probably due to the reduced dimensions of the model and do not necessarily
represent a real condition. The walls showed a sliding failure mode though overturning was not prevented and failure occurred when a critical threshold, expressed in terms of input motion frequency and peak acceleration, was overcome. It is worth to point out that the critical condition cannot be defined only in terms of input frequency or in terms of peak acceleration. In fact in the tests performed imposing to the table a maximum displacement of 2 mm, frequencies as high as those which produced the system failure, coupled with peak accelerations lower than those recorded at failure did not cause the wall to slide. Likewise, peak accelerations as high as those recorded at failure, coupled with high frequencies did not cause any displacement. This, however, cannot be considered a general result since the available loading system did not allow to uncouple the input frequency and acceleration.

A significant difference was found between the theoretical value of the critical acceleration \( a = N_{CR}g \) and the maximum acceleration recorded on the shaking table before failure \( a = 0.23-0.24g \). This difference is probably due to uncertainties in the values of the soil parameters at failure as well as to the unsuitability of the pseudostatic approach to derive the correct value of the dynamic cut-off acceleration. On the other hand the almost perfect coincidence between the critical frequencies and accelerations experimentally determined for the two walls seems to confirm that different walls with similar geometries, and thus with the same safety factors, show an identical dynamic behaviour.

Contrary to what is predicted by the sliding-block model and to some experimental results [4, 5] during sliding the absolute wall acceleration record did not present any flat plateau and showed peak values larger than those recorded for the input motion.
The results so far obtained point out that the Mononobe-Okabe method of analysis is moderately conservative for walls resting on rigid soil, however further evidence is needed to draw more general conclusions, especially for the case of walls resting on soft soil, in which severe wall rotations proved to be a major issue [13,14] to investigate.

References


