Behaviour of Model Footing Near a Sloped Surface under Cyclic Loading

Thomas W. Close

University of New South Wales at the Australian Defence Force Academy

This investigation researches the behaviour of a strip footing adjacent to the crest of a sand slope. The strip footing will undergo cyclic normal and lateral loading on compacted layered sand within a large scale model testing tank with dimensions 1.1m x 0.5m x 0.5m. Details of the investigation and testing results are presented. The focus of this experiment is the influence of the amplitude of the lateral cyclic loading. All other influencing factors were controlled; number of cycles, amplitude of normal loading, distance from slope, gradient of slope and the frequency of the cycles. Many investigations have been conducted but do not focus only on the behaviour of deformation due to the amplitude of the lateral loading. This thesis summary report details the testing, results and justification of this investigation.

Contents

I. Introduction 2
II. Experimental Set Up 2
   A. Model/Dummy Tests 3
   B. Slope Preparation 3
III. Testing 4
   A. LVDTs 4
   B. Loading 4
III. Issues 5
   A. Moisture Content 5
   B. Compaction 5
   C. Time Constraints 5
   D. Testing System 5

1 Lieutenant, School of Engineering & Information Technology. ZEIT4500.
I. Introduction

Construction of foundations near sloped surfaces is common in today’s civil engineering industry. Analysis of footings located near sloped surfaces is important due to the effects on bearing capacity as well as permanent deformation. Foundations constructed near a sloped surface may be in a location where the soil’s strength and bearing capacity may not be ideal.

Many foundation footings are subjected to significant vertical monotonic loadings. In addition to its self-weight, a structure has to support live loads of different forms which can be cyclic. These include machine load, seismic load, traffic load, wave load, wind load etc. These dynamic forces can also create horizontal loading on the foundation footing; therefore significant analysis must be conducted to determine expected settlement and deformation.

Horizontal loading has been observed in previous studies to cause sufficient deformation to the footing and therefore must be carefully considered in the structural design of the footing. If vertical and horizontal deformation can be predicted this can be allowed for in the design to ensure longevity of the structure. Thus, further investigation into the effects of the amplitude of horizontal loading during vertical and horizontal cyclic loading on unreinforced soil near a sloped surface needs to be conducted.

II. Experimental Set Up

Significant preparation was conducted in order to have the setup ready for testing. This included cleaning the hydraulic hoses and removing all air bubbles from them, ensuring the containers were full of water, preparing LVDT clamping frame and plastic cover, cleaning the walls of the tank and redrawing the layer and slope lines, and running some calibration (dummy) tests.
A. Model/Dummy Tests

The dummy tests were conducted by building up support in an empty tank for a steel plank to operate the vertical loading whilst the horizontal cable was attached to a fixed steel span. This can be seen in Figure 1.

These tests were conducted to ensure that the experiment was functional and could run for the desired 1000 cycles (approximately 5 and half hours). The tests were also conducted to observe the consistency of the loading after a prolonged period of time and observing any changes in the magnitude of the applied loads. After approximately five hours of vertical cyclic loading, there was a drop of around 0.2 kN in the loading; this is insignificant and should not have noticeably affected the results on further tests.

As the loading is measured in voltage, it is difficult to immediately apply an exact load of your choosing, and thus these tests were used to determine some near values for our desired loads to ensure the loads immediately applied are close to our target load. For example, in order to apply a vertical cyclic load of 15 kN at the peak and 9 kN at the trough, an offset of voltage 4.36 and amplitude of 1.32 was applied. The exact loads applied were 15.01 and 8.99 for the peak and trough respectively. After several minutes of altering, these were as close to the target loads as the test would allow in an appropriate time frame. Near values were also obtained for horizontal loads for 10% and 20% of the vertical loading. However, these voltages are applied as a multiplying and adding factor to the vertical loads; causing more difficulties to the application of immediate and accurate loads.

B. Slope Preparation

At this stage, the experimental set up was ready to conduct the first test of vertical cyclic loading only (0% horizontal loading). The soil is prepared in 5 boxes (four of 21kg and 1 of 18.3kg) for each layer of soil; with an overall moisture content of around 5%. Overall, there are five layers of soil that were compacted in stages to fill the tank of dimensions 1100x500x500mm. The soil was tipped into the tank and mixed around and then
smoothed out before a mechanical flat bottomed dynamic compacter was used to compact the soil until it reached the required depth. This process was repeated another four times to fill the tank. A wooden footing was used to apply compaction over a rectangular area to achieve a true and smooth level for the top layer where the loading was applied.

On the same day that a test was conducted, the slope (gradient 2:1 horizontal to vertical) was cut away. This was achieved by following the drawn line on the walls of the tank and trimming the sand away carefully. The footing of width 130mm with a vertical load cell was placed near the slope, at a distance 130mm away from the slope. The surface of the base of the footing had a sand paper like roughness in order to create friction and reduce slip. The top of the vertical load cell is a roller, allowing lateral movement of the spread footing when horizontal loading is applied, as seen in figure 3.

III. Testing

A. LVDTs

The LVDTs were used to measure the vertical and lateral deformations of the footing. They were set up as seen in figure 2 numbered from 2 to 7. The collection of load and displacement data were carried out utilising a computerised data acquisition/control system in which a software program, LABVIEW was used for these purposes. The data was analysed using a MATLAB program by identifying the 10 recordings per second and how many recordings per cycle. The program selects the lowest and highest load in the cycle. The corresponding LVDT readings are also recorded at this time and this process continues for the whole test. Excel was used to graph and order the entire test’s data into a readable format.

B. Loading

The vertical cyclic loading was applied using multiple actuators which are activated through water pressure from an air-water interface (AWI) system. The pressure is converted to water pressure along the lines and is controlled by an electro-pneumatic regulator (EPR). The horizontal cyclic loading is applied using the same system with a cable bolted to the footing and loading is applied on the footing through the cable.

This study focused on the behaviour of deformation of a footing located near a surface and subject to vertical and horizontal cyclic loading. The vertical loading was kept constant with a trough of 9kN and peak of 15kN for
all tests. The horizontal loading was increased as a percentage of the vertical loading. Tests were conducted for 0% (vertical loading only), 5%, 10%, 10%, 15% and 20% each for 1000 cycles.

After each test the soil was removed and placed back in the sealed boxes. The moisture content was measured at three locations within the layers; near the surface, in the middle and near the bottom layer.

IV. Issues

A. Moisture Content

The moisture content needed constant monitoring of the sand to ensure that it was at a similar level for the entirety of this project. In order to maintain the moisture content a spray bottle was used. Before a sealed box was filled with soil, the box was sprayed with water. During compaction, water was sprayed on the soil as it was mixed around just before a layer of soil was compacted. After a layer of soil was compacted, the top of the layer was also sprayed with water. This procedure seemed to maintain the moisture content at around 4.9-5% for the whole project.

B. Compaction

Compaction for the top layer was difficult to create a consistent process and replicate this for all tests to ensure exact likeness. Before the layer is compacted, the soil was above the top of the tank’s edges thus sand was not fully contained in the tank during compaction causing some sand to spill on to the edges. The soil was continually placed back onto the layer and compaction continued. To ensure smoothness in the loading area, a wooden footing was placed under the compactor to smooth the top layer. However, there would have been small differences in each soil slope. To reduce this problem, many tests at each loading case would need to be conducted; however there was no further time to conduct multiple tests at each loading case.

C. Time constraints

Due to the scale of the test, significant time was spent preparing and conducting tests, meaning a limited amount of tests were conducted. This effort also made it difficult to redo tests that might have involved errors. Testing wasn’t started until July due to limited free area within the laboratory and previous academic commitments. Testing was continually conducted until no further time was available.

D. Testing System

The software program used to apply the loads is recorded in Volts while the loading is read back through the load cells in kN. However, it wasn’t as simple as calculating the number of Volts that correlates to a certain number of kN; every case was different. When applying the vertical cyclic loading; the Volts that were applied (offset and amplitude) were different in any case. This meant that once the loading was stepped up, it could take several minutes of adjusting the loads to get it near as possible to the target load.
Also, it was difficult to apply the horizontal load at the same time as the vertical load. The horizontal load also seemed to affect the vertical load values. Overall, it was difficult to apply the loads (both horizontal and vertical) for the project at consistent times; thus affecting the reliability of the results.

In addition to the difficulty in applying the loads, the loads also seemed to vary as the test continued over several hours. As seen in figures 4 and 5, the amplitude of the loading was increased whereby reducing the magnitude of the trough and increasing the magnitude of the peak in the cyclic loading process over 1000 cycles. This may affect the results and also the horizontal loading and is not exactly consistent for all tests.

The tests were identified by file name. VCS_1, LCS_1, LCS_2, LCS_3, LCS_4, LCS_5 were the 0%, 10%, 20%, 10%, 15% and 5% respectively and were conducted in that order. A 0% test was conducted prior to all these but was not included due to errors in the set up and loading.
V. Results and Discussion

A. Permanent Deformation

The variation of settlement of the footing is summarised figures 6 and 7. It must be noted that the horizontal loads of 15% and 20% lead to failure of the slope and can be seen in figures 8 and 9 respectively. It is evident that as horizontal loading increased, the permanent horizontal deformation increased. The tests for 0%, 5%, and 10% horizontal loading, the deformation increased for approximately 100 cycles before becoming almost a residual value, where the rate of increase of permanent deformation slowed. However, for the slopes that failed (15 and 20%) the permanent deformation continued to increase over time and the rate of increase accelerated when nearing failure. LCS_4 failed very near the end of 1000 cycles thus data is collected for the behaviour of the footing for 1000 cycles that eventually fails.
It should be noted that there is a significant increase in horizontal deformation for the second 10% test (LCS_3) compared to the other 10% test (LCS_1). It initially follows the path of LCS_1 before a significant increase after approximately 16 cycles of loading. The sudden increase is neither anticipated nor normal having observed the behaviour of LCS_1, LCS_5 and VCS_1 tests. This could be explained by a lack of consistency and structure of the compacted slope and error in the test. From observing figure 6, it is evident that the tests that do not lead to failure all have similar permanent vertical deformation values. However, LCS_1 shows less deformation than VCS_1; which could indicate that LCS_1’s deformation was less than likely anticipated. This could also explain the significant difference in deformation for the two 10% tests.

B. Resilient and Total Deformation

![Horizontal Permanent Deformation](image)

**Figure 9** Horizontal permanent deformation.

![Vertical Total Deformation](image)

**Figure 10** Vertical total deformation.
Figures 10 and 11 show there is little difference between resilient and total deformation. However, total deformation would be slightly greater than resilient deformation to cause permanent deformation to the footing. The greatest difference can be seen in the early cycles; this is where the most permanent deformation is caused. As seen in figure 12, the ratio of resilient to total deformation neared 100% after approximately 100 cycles, which is further evidence of the majority of permanent deformation occurring in the first 100 cycles. The ratio percentage began to drop just prior to failure for the tests that failed; showing that the rate of increase in deformation accelerated prior to failure of the sloped surface. The total and resilient values become much more equal as cycles progress; thus the rate of increase of permanent deformation reduces over time. It could be said that for load cases that will not cause failure, a stable, resilient response is observed once the majority of plastic strain has occurred and will not continue to deform much after this point. However, interestingly, the 5% load case shows that permanent deformation continues slowly even though the 0% and
10% tests obviously reduce the rate at which deformation occurs.

C. Tilt

Figure 13 shows the tilt behaviour of the footing. Tilt is calculated by determining the deformation of the slope end of the footing by observing LVDTs 4 and 7 and comparing this with the deformation of the rear of the footing (LVDTs 5 and 6). An angle is calculated for each cycle. The footing tilted towards the slope when no horizontal loading was applied. However, when horizontal loading was applied, the footing actually tilted away from the slope. The significant amount of deformation and tilt can be observed in Figure 9. Interestingly, the 5% horizontal test caused more tilt than the 10% tests; this is consistent with the behaviour for this test in figures 6, 10 and 11. The rate of tilting increased for both tests (15 and 20%) that failed.

Figure 13 Tilt of the footing.

VI. Justification of Research

These results are useful because they assist engineers in the understanding of the behaviour of a footing near a sloped surface when subject to vertical and horizontal cyclic loading. Footings can be located near sloped surfaces in structures such as retaining walls and bridge abutments. Engineers can allow for this deformation in their design and also monitor the deformation of the structure. Tilt in the footing will also cause added stress and force throughout the structure, and thus must be considered by the designer. Construction in bridges occurs in a way to accommodate for movement in the structure, which can be either permanent or residual deformation. Joints where movement is allowed for, a reduction in the forces transferred through occurs. Examples of elastomeric bearings supporting the structure can be built and designed to allow for

Figure 14 Elastomeric joints that allow of deformation.
the deformation that will occur to a footing when subject to cyclic loading. Steel rocker bearings can also be used; allowing for the tilt that will occur in the structure. In retaining walls, flexible retaining walls can be constructed to resist displacements and pressures with the retaining wall elastically restrained at the base.

If deformation is monitored throughout the life of the structure, failure due to increase in stresses can be predicted. If, the deformation follows the behaviour of a load case which is unlikely to fail, the engineer can assume that it is unlikely to fail in the near future. However, if the rate of permanent deformation begins to increase; or total deformation begins to increase, the engineer should re-evaluate the design and consider potential solutions to ensure that the structure or slope does not fail. The observation of deformation behaviour is a way of determining the current condition of the slope and footing.

VII. Recommendations

There are several recommendations that have resulted from this study. The first recommendation is to conduct experiments for the exact same conditions as this test focusing on two load cases just to determine the overall consistency of this testing method. For example, 0% and 10% load cases could be conducted five times each and an analysis of their consistencies could occur. This would then provide confirmation of previous tests that have been conducted using this testing method at UNSW@ADFA and for future tests.

The same experiment should be conducted but with the addition of soil reinforcement. Additional investigation into the effects of soil reinforcement when undergoing horizontal and vertical cyclic loading would be useful. These results could then be compared to the results of the same experiments without reinforcement.
References

AS1289.1.1, Methods of testing soils for engineering purposes - Sampling and preparation of soils - Preparation of disturbed soil samples for testing.

AS1289.5.1.1, Methods of testing soils for engineering purposes - Soil compaction and density tests - Determination of the dry density/moisture content relation of a soil using standard compactive effort.

AS1289.6.2.2, Methods of testing soils for engineering purposes - Soil strength and consolidation tests - Determination of shear strength of a soil - Direct shear test using a shear box.

Beer, R. Behaviour of footing near geocell reinforced slope under cyclic loading, UNSW@ADFA, 2012.


Heming, M. Behaviour of a shallow footing on a triaxial geogrid reinforced sand slope under cyclic loading, UNSW@ADFA, 2012.

