Dynamic centrifuge model tests on embankment with different upstream conditions

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ABSTRACT

Dynamic analysis of earthen embankments is a crucial aspect in geotechnical engineering. It has been difficult to properly analyze the embankments, as it is difficult to obtain any experimental or field data. Centrifuge experiments on embankments would help us to properly understand the behavior of embankment, if we could simulate the conditions in centrifuge as close as to field. This study aims to experimentally simulate the response of an earthen embankment which is usually used for agricultural purposes, in centrifuge. Water level in the embankment is controlled and drawdown of the water was induced using a custom developed in-flight control of water path during centrifugal rotation. LVDT is used to measure the surface settlements. We have simulated the phenomenon which make the embankment weak in strength, steady state and rapid drawdown, and give shaking to the model to observe how these phenomenon would affect the strength of embankment. Time histories of acceleration and pore water pressure are shown in this paper. Even though both steady state and rapid drawdown are critical phenomenon of embankment, cracks and failure of upstream slope is seen only in rapid drawdown condition.

Keywords: reservoir, seepage, embankment, rapid drawdown, dynamic analysis, centrifuge model

1 INTRODUCTION

Earthen embankments, which act as a barrier to water in small reservoirs have numerous kind of uses for human kind, are distributed all over the world. These were mostly constructed in large numbers in the period when technology was not as advanced as now. These embankments are subjected to various kinds of conditions annually depending on the season and climatic conditions prevailing at the location of embankment. It is important to clearly understand the complete behaviour of embankments when subjected to different conditions which prevail in practical conditions. Observing and understanding the behaviour of embankment is necessary to make required preventive measures to embankments depending on the phenomenon it is subjected to.

Recent studies done by some researchers are either done on centrifuge tests on embankment on different foundations (Okamura & Matsuo 2002, Okamura & Tamamura 2011 and Okamura et. al. 2013) or road embankments with different moisture content (Thorel et. al. 2013, Hayashi et. al. 2002, Higo et. al. 2015). But, the centrifuge tests targeting the seepage and the dynamic analysis of the earthen embankment at different stages was not done in earlier studies.

Understanding the behaviour of embankment during seepage and shaking when it is subjected to the phenomenon which makes it unstable like steady state and rapid drawdown is important. So, centrifuge experiments are conducted on embankment, as obtaining results from the field is really complicated and impossible at certain type of locations when concerning particularly about earthen embankments. In this study we have made an embankment model and subject it to a centrifugal acceleration field of 50G. We have observed the dynamic accelerations at different points in embankment when it is in steady seepage state and rapid drawdown state. We have also observed the seepage in the embankment by using pore water pressure transducers.

2 TEST SET UP

2.1 Geotechnical centrifuge

In this study, to perform the centrifuge experiments on earthen embankment, the geotechnical centrifuge at the Disaster Prevention Research Institute (DPRI), Kyoto University was used. The effective rotation radius, defined as the length from the rotation axis of the
arm to the centre of the model, is 2.5±0.05m. The maximum centrifugal acceleration is 200G when we would not use the shaking table, if we use shaking table there is a limitation for the centrifugal acceleration. Table 1 and Table 2 give the specifications of centrifuge and shaking table respectively of the centrifuge facility in DPRI, Kyoto University.

2.2 Centrifuge set up

In this study to perform the centrifuge experiments on earthen embankment, we have used a box having dimensions 60×15×30 (L×B×H) (cm) of space available to work with the model. The centrifuge box has numerous parts with different functions which helps to control the movement of water in the model remotely from control room during which the model is rotated in centrifuge. Fig. 1 shows the different components of the centrifuge box which have different functions to perform the test in centrifugal acceleration.

| Effective rotation radius | 2.50 (m) |
|---------------------------|----------|
| Effective space for model installation (L×B×H) | 800×320×800 (mm) |
| Allowable Weight of model | 120 (kg) |
| Test capacity | 24 (g/t) |
| Maximum centrifugal acceleration | 200 (g) |

Table 2. Specifications of shaking table.

| Vibration control method | Hydraulic pressure control |
|--------------------------|---------------------------|
| Allowable centrifugal acceleration | 50 (g) |
| Displacement | ±5 (mm) |
| Maximum frequency | 200 (Hz) |
| Input wave form | Any type of wave |
| Allowable weight of model | 100 (kg) |

Fig. 1. Centrifuge box setup with different components. a) Front view of the centrifuge box, b) Top view of the centrifuge box (units in cm)
We fill the overhead tank with water completely, prepare the embankment model by compacting each layer of 2 cm, after completing the compaction of all the layers of the model, scrap the soil out to shape into the shape of embankment, as shown in fig.1. Proper care must be taken to maintain the density as constant as possible and placing sensors at the specified points and no damage to occur to the sensors while compacting. Required density is achieved by calculating the amount of soil to be placed in the specified volume.

After setting up the centrifuge box on the machine and reaching 50g acceleration field, the reservoir valve is switched “ON” by a remote to let the water flow from overhead tank to the intermediate compartment (IC). Water then enters IC and the level of water in the IC is maintained automatically by electrodes. Water enters into the model compartment from IC through the supply valve which is operated manually, so supply valve is set before setting up the centrifuge box for rotation. Once the water level has reached to the required level, we can know the level of water by observing the sensors from the control room, we switch “OFF” the reservoir valve remotely. We can maintain the upstream level remotely by switching ON and OFF the reservoir valve.

Drainage valves are used to control the flow of water from the model compartment to drainage tank. Drainage valve on the upstream side of embankment is controlled in experiment when we want drain the water from the upstream of embankment by using remote control by switching “ON” and “OFF”. Drainage valve is connected to model compartment by slits for drainage. Slits for drainage on downstream is directly connected to drainage tank without any remote control so that whatever the water comes from seepage is flown directly into the drainage tank.

2.3 Material for embankment

We have used Masado as the material for the embankment as it is the most found material in Japan which is used for construction of earthen embankments. Fig.2 shows the grain size distribution of the Masado soil which we have used in the experiments.

![Fig. 2. Grain size distribution curve for Masado soil](image)

For finding the maximum dry density and optimum moisture content for the Masado soil we have used 2kg rammer for compaction test. Fig. 3 shows the compaction curve and we have tried to maintain a uniform 95% density of the maximum dry density. Properties of the soil are shown in table. 3.

![Fig. 3. Compaction curve for Masado soil.](image)

| Material property                              | Value   |
|-----------------------------------------------|---------|
| Sand (%)                                      | 90.23   |
| Silt (%)                                      | 9.77    |
| Maximum particle diameter (mm)                | 4.75    |
| Average particle diameter (mm)                | 0.38    |
| Solid particle density $\rho_s$ (gm/cc)       | 2.6     |
| Void ratio at maximum density $e$             | 0.465   |
| Optimum moisture content $w_{opt}$ (%)        | 14.3    |
| Maximum dry density $\rho_{dmax}$ (gm/cc)     | 1.72    |
| Permeability of soil at 95% DOC $k$ (cm/sec)  | $1.6\times10^{-5}$ |

2.4 Preparation of model

For preparing the embankment in the box we have calculated the amount of soil required to compact to achieve the target density of 95% of 2kg rammer compaction test (1.65 gm/cc) and compact in layers of 2cm of height each as shown in fig. 4a. Sensors are placed in first layer and third layer before compaction at the locations which we want to place them. After completing compaction, model is scraped using a tool to form a symmetrical embankment with a 1V:2H slope.

![Fig. 4. Model set up a) Schematic view of the model before scraping in bold line. b) Typical model and placement of sensors used in this study.](image)
Typical form of embankment and placement of sensors in the model compartment of centrifuge box is shown in fig. 4b. The foundation of the embankment is a cement foundation of 4 cm height. Cement is used as a foundation material, which acts as impermeable and rigid material, so that embankment would not be affected during seepage and shaking from foundation.

2.5 Centrifuge tests

We have performed a total of three centrifuge tests, of which first two are done with steady seepage flow and third one is subjected to rapid drawdown (which is explained in later sections). In each experiment we have given two shakings consecutively. Table 4 shows the details of the experiments conducted in this study.

Table 4. Detail plan of experiments conducted in this study.

| 1st experiment | 2nd experiment | 3rd experiment |
|----------------|----------------|----------------|
| Seepage        | Two consecutive shakings | Rapid drawdown |

3 SEEPAGE

Real field is imitated in the centrifuge box by using centrifuge box and its components with different functions (as explained in section 2) and embankment model. After the test equipment is set up we start the machine to accelerate till the centrifugal acceleration is achieved till 50g. After that we switch ON the reservoir outlet valve to let water enter from overhead tank into the IC and then into the model compartment where water then fills up the upstream side of embankment. After filling the upstream side until the required height we switch OFF the reservoir outlet valve.

3.1 Steady state flow

Steady flow in embankment is the state in which the outlet flow is equal to inlet flow. This is achieved in centrifuge experiment by allowing the flow in embankment through seepage and wait till the readings in PWP sensors would become constant.

As shown in fig. 5, in which P1 is placed at downstream toe of embankment, P1 would be the last one to become constant. Where fig.6a and fig.6b shows the values of pore water pressure in prototype scale for first experiment and second experiment respectively. We could observe in fig.6b that as we increase upstream water level (represented by P7), the values of P2, P5 and P1(red, blue and black respectively) had changed as the time has passed. In fig.6b, we could also observe that, at different points of time, which have the same value of P3, have different values of P1 and P5. This may be because of decrease in the suction pressure around that point because of wetting and drying cycles of unsaturated soils and the water level has increased slowly within the embankment.

3.2 Rapid drawdown

Rapid drawdown is one of the state in which embankment is at its least strength. So, we have tried to replicate this phenomenon in centrifuge. This phenomenon is replicated by draining out the upstream water by switching "ON" the drainage valve remotely which is connected to the slits on the upstream side of embankment and drainage tank. Once the steady state flow is achieved in the embankment, we would drain the upstream water as shown in fig.7. As shown in fig. 8 after the steady state is achieved, upstream water is drained out.
4 RESULTS OF SHAKING TEST

4.1 Steady state flow

In this study we have given two input motions to the model after we have achieved a steady state in the embankment. First motion is given after we have achieved steady state and the second motion is given after a 5 minutes’ interval in model scale. We have performed two tests giving almost the same conditions. Acceleration and Pore water pressures are measured in this experiment at different points of the embankment. Notations for PWP’s are shown in fig.5 and for accelerometers is shown in fig.9.

From fig.10 also we could say that the behavior of embankment isn’t altered by first shaking. This could also be well observed from the second centrifugal experiment, of which, results are shown in fig.11. Pore water pressures of transducers P4 and P5 in second experiment are shown in fig.12. We could observe that there is a very little reduction of P5 during first shaking but it is not altered because of second shaking.

Time histories of different points of embankment from first centrifuge experiment are shown in fig.13. We could observe that the behavior of embankment is unchanged by comparing both time histories of shakings as shown in fig.13. The variation of acceleration of A5 in fig.13 is because the sensor at that point is not properly fixed at top of embankment.

From the results of second experiment which is shown in fig.14 we can say that the behavior of embankment is well represented in both the experiments and behavior of embankment is not altered because of first shaking in both cases even though the first shaking is given with an higher amplitude than in second experiment. In second experiment sensor A5 is well placed and the time history of acceleration shows amplification at that point. Settlement of embankment is measured using LVDT at top and middle section of embankment. From fig.15 we could observe that there isn’t any major settlement in embankment because of shaking in the model.
Fig. 12. Time histories of Pore water pressure transducers P4 and P5 in the embankment for second experiment.

Fig. 13. Acceleration time histories of different points in embankment of different shakings given one after other in first experiment.
Fig. 14. Acceleration time histories of different points in embankment of different shakings given one after other in second experiment.

Fig. 15. Time history of Laser vertical displacement transducer (LVDT) reading in prototype scale of second experiment.
4.2 Rapid drawdown

In this study we have given two input motions to the model after we have drained the water in upstream side of embankment.

In fig. 16 we could observe that shaking has no kind of influence on pore water pressure values in the embankment except at the point where P6 is installed. In fig.17 we could observe the time histories of the pore water transducers placed at elevation of 2m from the base of embankment, but at different positions in embankment. But, we could observe the increase in pore water pressure only in the pore water transducer placed at upstream side of embankment.

There was damage observe on upstream side of embankment after rapid drawdown phenomenon which is shown in fig.18. We could say that the damage occurred at the upstream slope of embankment is because of the observed increase in pore water pressure in P6 as shown in fig.17.

Fig.19 shows the acceleration time histories at different points of embankment. We can observe from the results that point of amplification in rapid drawdown is not the same as in steady state condition which had amplification at A5. Although at different points it shows almost similar values for both shakings, acceleration at point A4 after rapid drawdown as shown in fig.19 is different in both shakings. Amplification of A4 is high in shaking 2 than shaking 1, this could also be explained by observing the difference in pore water pressure (P6) at the upstream slope. In fig.20 we could observe the time history of settlement of the top part of embankment, which is very less even though there is a failure occurred at the upstream slope side. From these we could say that there isn’t any settlement or major deformations in embankment only if embankment.

**Fig. 16.** Pore water pressure time histories during two shakings given after rapid drawdown phenomenon.

**Fig. 17.** Time histories of Pore water pressure transducers P4, P5 and P6 in the embankment after rapid drawdown during shaking.

**Fig. 18.** Damage in the model after shaking the embankment after rapid drawdown phenomenon. a) top view b) isometric view
Fig. 19. Acceleration time histories of different points in embankment of different shakings given after rapid drawdown phenomenon.

Fig. 20. Time history of Laser vertical displacement transducer (LVDT) reading in prototype scale after rapid drawdown phenomenon.
5 CONCLUSIONS

Dynamic centrifugal model tests were conducted on earthen embankment model which was subjected to different seepage conditions. Embankment was made at density of 95% of maximum density achieved from 2kg rammer test. Efforts were made to achieve steady state condition in embankment without any seepage flow in foundation. Rapid drawdown phenomenon which makes the embankment susceptible to failure was also achieved in this study to observe the behaviour of embankment.

Consequent shakings are given to the model to observe the strength of the embankment. Of all the tests, embankment was damaged only when it was subjected to shaking after inducing rapid drawdown phenomenon in the model. So, we can conclude from this study that

- If, the embankment was properly compacted so that there is no piping, it has good resistance to an earthquake in normal conditions.
- Rapid drawdown phenomenon for an embankment is a critical state for upstream slope of embankment.
- Major settlement or failure is not observed in embankment.

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