U.S. DEPARTMENT OF THE INTERIOR
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Effects of Sinkholes on Earth Embankments

DSO-99-02

Civil, Environmental, and Architectural Engineering
University of Colorado, Boulder, CO

August 1999

DSO
DAM SAFETY OFFICE

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave Blank)***	**2. REPORT DATE** August 1999	**3. REPORT TYPE AND DATES COVERED** Final

4. TITLE AND SUBTITLE Effects of Sinkholes on Earth Embankments	**5. FUNDING NUMBERS**
6. AUTHOR(S) Mandar M. Dewoolkar, Kitidech Santichaianant, Ton Goddery, Hon-Yim Ko	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Civil, Environmental and Architectural Engineering University of Colorado Boulder, CO 80309-0428	**8. PERFORMING ORGANIZATION REPORT NUMBER** DSO-99-02
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Bureau of Reclamation Dam Safety Office Denver, Colorado	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT Unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT ***(Maximum 200 words)***

See Page 1

14. SUBJECT TERMS	**15. NUMBER OF PAGES**
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UL	**18. SECURITY CLASSIFICATION OF THIS PAGE** UL	**19. SECURITY CLASSIFICATION OF ABSTRACT** UL	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

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by
Mandar M. Dewoolkar
Kitidech Santichaianant
Ton Goddery
Hon-Yim Ko

U.S. Department of Interior
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Dam Safety Office
Denver, Colorado

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Mandar M. Dewoolkar, Research Associate
Kitidech Santichaianant, Graduate Student
Ton Goddery, Professional Research Assistant
Hon-Yim Ko, Professor

Civil, Environmental and Architectural Engineering
University of Colorado, Boulder, CO 80309-0428

August 13, 1999

Submitted to:
The United States Bureau of Reclamation
Denver, Colorado

Abstract

Centrifuge experiments were conducted on small models of earth embankments to study the effects of sinkhole formations on the stability of dams. A special container and various trap door assemblies were designed to simulate formation of sinkholes in a displacement controlled fashion. Significant efforts were invested in the initial design and subsequent modifications of the trap door assemblies in order to measure correct soil loads in its undisturbed state, i.e. before the trap door is lowered. Calibration tests on level ground sand and compacted Bonnie silt models were conducted to investigate this aspect of the experimental developments. The results from level ground model tests were found to be repeatable, reliable, and consistent. Finite element simulations of these experiments using `PLAXIS` compared well with the experimental results.

Centrifuge tests conducted on embankment models revealed mechanisms involved in the cavity formation inside embankments, as a result of sinkhole development. The two models of compacted Bonnie silt were very similar except the presence of water reservoir in the second model. In the test with no water reservoir, the surface of the embankment did not suffer major deformations; although a large cavity was formed above the sinkhole. In the test with water reservoir, the cavity reached the dam surface which created a 12 ft (3.6 m) deep and 35 ft (11 m) diameter depression in the dam surface in terms of prototype scale.

Results from centrifuge tests on level ground and embankment model tests as well as numerical simulations of the level ground tests are presented in this report. Possibilities for continuing research are also discussed.

Contents

List of Figures

This document reports the progress made in the research project investigating the effects of sinkholes on earth dams. Readers are referred to “Progress Report: Effects of sinkholes on earth embankments” submitted on March 17, 1999. A copy of that document is provided in Appendix A.

1 Introduction

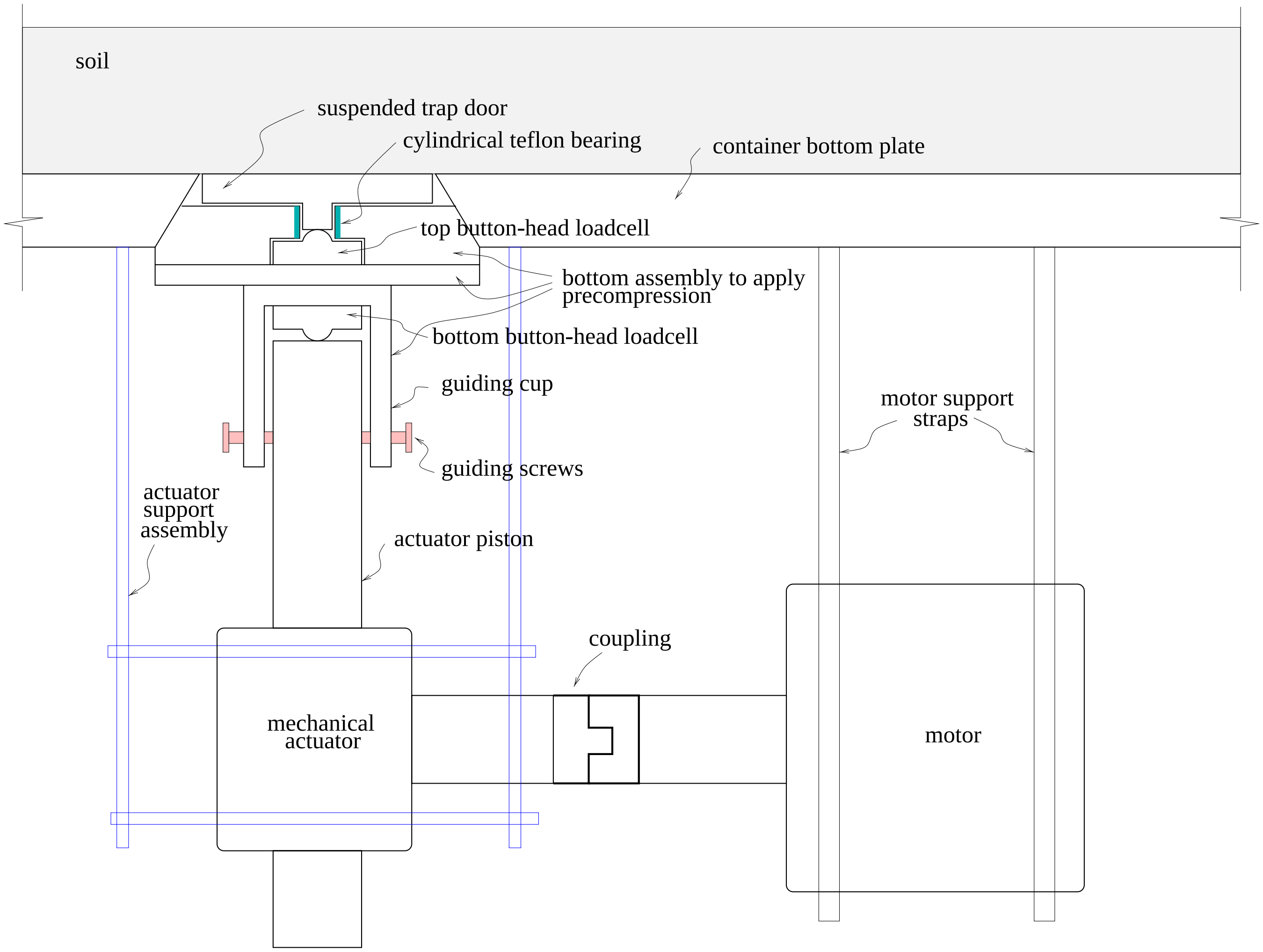
In the first report, the development of the centrifuge model test container was discussed. This container with a soil model could be placed in a bigger container. Two trap door locations were available. At each location, two trap door sizes were available. It was observed that the trap doors separated from the container bottom prematurely. This resulted in premature arching effects in the soil before reaching the desired g-level. Thus, correct loads from soil (in undisturbed state) on the trap door could not be measured. In order to keep the trap doors in contact with the container floor, a process of applying a precompression load was investigated. Preliminary test results indicated that correct soil loads could be measured prior to the lowering of trap doors by preventing the separation of trap doors prematurely. However, this system did not function well in a consistent manner. It was difficult to precisely locate the point at which the trap door separates from the container bottom.

Therefore, the trap door assembly was modified. In the new system, the trap door was isolated from the precompression assembly in such a way that it would support only the soil on top. Calibration tests were performed on level ground sand and compacted silt models to verify that the new system was successful in measuring the correct load from the undisturbed soil above the trap door. After establishing confidence in the new technique, two tests on embankment models were conducted.

2 The new trap door system

The new trap door system is shown in Figures 1 and 2. The system was modified for the 3.0” (7.62 cm) diameter door size. The loadcell from the other location was also employed in this system. The new assembly includes the following modifications:

> The *suspended trap door* is completely separated from rest of the components. It is resting only on the *top loadcell.*
>
> The *top loadcell* is attached to the *bottom precompression assembly* which is used to apply a precompression between the assembly and the *container bottom plate* to prevent premature separation. The bottom assembly includes two discs and the *guiding cup* that are attached together with bolts and, therefore, acts as a single unit.
>
> The *bottom loadcell* is attached to the *bottom precompression assembly* and rests on the *actuator piston.* The *guiding screws* help in preventing the assembly from tilting.



Not to scale.

Figure 1: Trap door assembly

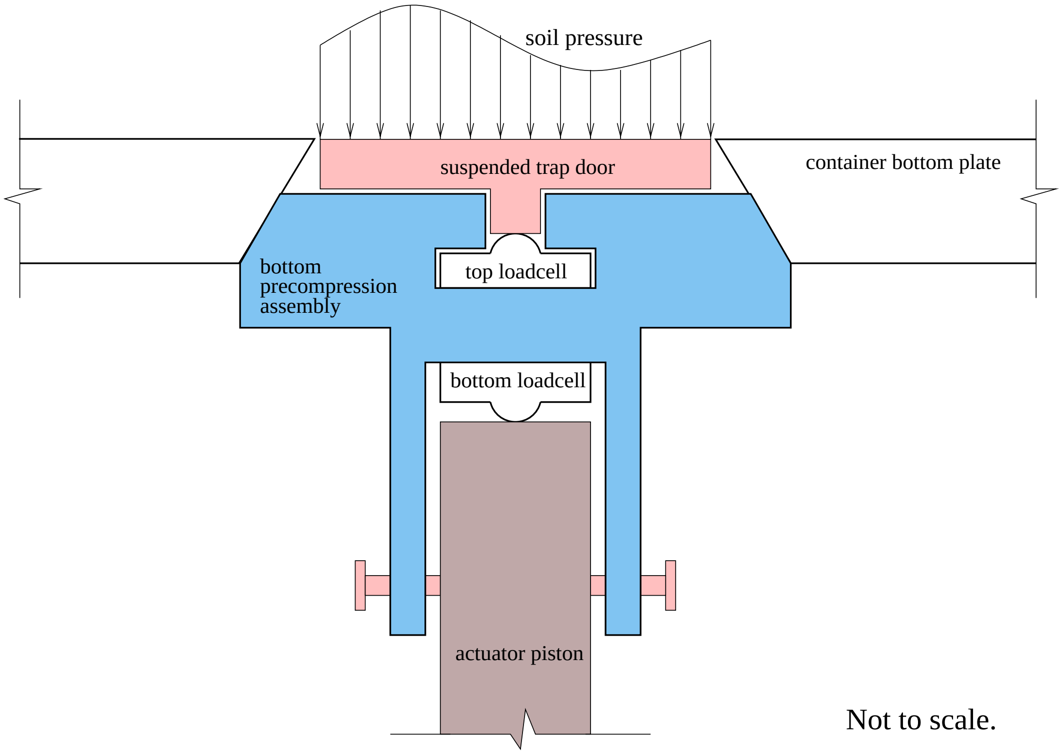


Figure 2: Trap door arrangement

By raising the *actuator piston*, a desired amount of precompression can be applied to prevent premature separation of the assembly from the *container bottom plate*. This load is measured by the *bottom loadcell*.

The measurement of the *top loadcell* is unaffected by the precompression. It measures only the load from the soil and the weight of the *suspended trap door*.

Possible tilting of the *suspended trap door* is prevented by the tight fit between the door and the *bottom precompression assembly*. In order to minimize the friction between the two, a *cylindrical teflon bearing* is introduced. This system was tested by conducting two tests. In the first test, a known weight (2 lb) was placed on the trap door at the center. The centrifuge was spun to 150g. This load was correctly measured by the top loadcell throughout the spin-up of the centrifuge. In the second test, the same weight was placed at an eccentricity of 0.25" from the center. Again, the centrifuge was spun to 150g. The top loadcell measured the same load which indicated that a small eccentricity in the load application did not affect the measurement. Therefore, if the pressure from the soil is not uniform, the loadcell would still measure the load from the soil correctly. These tests also indicated that the friction between the *trap door* and the *teflon bearing* was insignificant.

3 Measurement techniques

Figure 3 shows various forces that contribute to the loadcell measurements. As shown in the free body diagram (1), the top loadcell measures the soil force (W_s) plus the weight of the trap door (W_d). The bottom loadcell measures the weights of all the components plus the soil force. If the assembly is precompressed, the contact force (F_c) between the *bottom precompression assembly* and the *container bottom plate* must be added to the equation, as shown in Free body diagram (2).

All the tests were conducted at 150g measured at the bottom of the outer container. The radial distances to the center of gravity of the various components are different. Therefore, to calculate weights of these components at various g-levels, the masses of these components would have to be multiplied with g-levels at their respective center of gravity. Although these calculations can be performed relatively easily, to avoid unnecessary confusion, a simple experiment was conducted.

In this experiment ("no soil" test), the system was spun to 150g without anything on top of the trap door (hence, $W_s = 0$) and zero precompression ($F_c = 0$). In that case, W_d would be equal to L_t (the top loadcell measurement). Thus, if the soil is present on top of the door, the soil force (W_s) can be determined by Equation (1) in Figure 3. Similarly, the quantity $W_d + W_{tl} + W_{ba} + W_{bl}$ was determined from the bottom loadcell measurement of the abovementioned experiment. The quantities W_d, $W_{tl}+W_{ba}+W_{bl}$, and $W_d + W_{tl} + W_{ba} + W_{bl}$ were determined to be 41.4 lb, 210.1 lb, and 251.5 lb, respectively at 150g. These values will be used in the interpretation of subsequent test results.

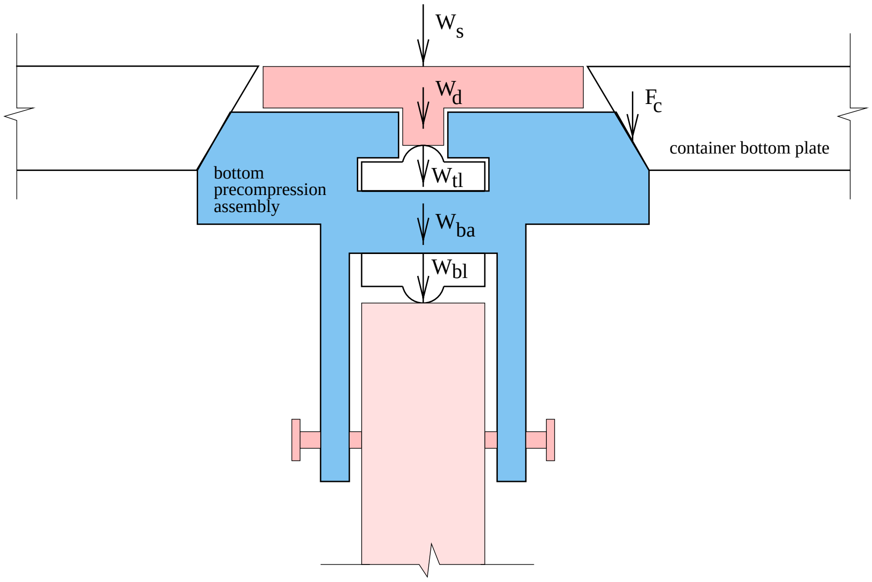
4 Results from centrifuge level ground model tests

Some preliminary tests on level ground sand models indicated that excessive amount of precompression (of about 800 lb) affects the performance of the trap door assembly. Therefore, instead of applying this relatively large precompression starting from 1g, a minimum amount of contact force (F_c) of about 100 lb between the precompression assembly and the container floor was maintained throughout the centrifuge spin-up. This prevented the separation of the trap door from the container bottom prematurely and also did not create excessive deflections of different parts of the system.

4.1 Test LevelSand1

The configuration of this test is depicted in Figure 4. An open-ended cylindrical container of 15" (38.1 cm) diameter was placed concentrically around the trap door. Nevada No. 100 sand was pluviated from a hopper to achieve a relative density of approximately 60%.

At 1g, before spinning the centrifuge, a precompression of about 120 lb was applied by turning the motor to move the door upwards. The test package was spun to 150g at the platform level. The g-level at the level of the trap door was calculated to be 143g. The measurements from the two loadcells are shown by solid curves in Figure 5. The dotted line "W_d" is the top loadcell measurement from the "no soil test" described earlier in which the

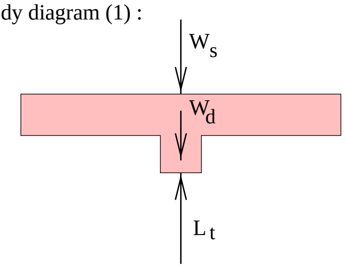


Known and experimentally verified forces:

W_d = weight of the trap door
W_{tl} = weight of the top loadcell
W_{ba} = weight of the bottom assembly
W_{bl} = weight of the bottom loadcell

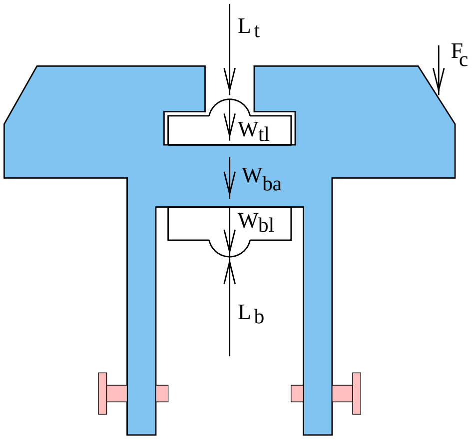
Measurements: top loadcell measurement = L_t
bottom loadcell measurement = L_b

Free body diagram (1) :



Equation (1) : soil force = $W_s = L_t - W_d$

Free body diagram (2) :



Equation (2) : $L_b = L_t + (W_{tl} + W_{ba} + W_{bl}) + F_c$

$L_b = W_s + (W_d + W_{tl} + W_{ba} + W_{bl}) + F_c$

where, Fc = contact force if precompression is applied

Figure 3: Trap door equations

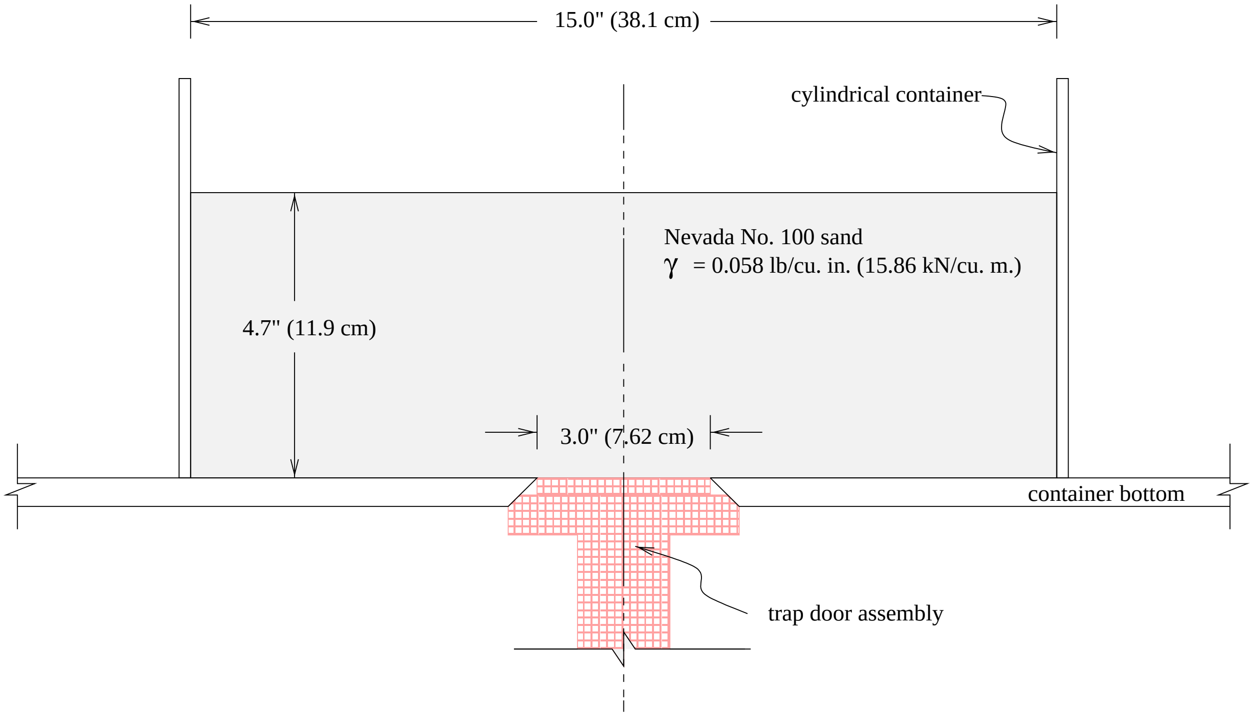


Figure 4: Configuration of test LevelSand1

assembly was spun to 150g without any soil. The second dotted line is obtained by adding the difference between the bottom and top loadcell measurements from the "no-soil" test to the top loadcell measurement from the test LevelSand1. The difference between this dotted line and the solid plot indicated by "L_b (the bottom loadcell measurement)" is the contact force that was generated by applying precompression throughout the centrifuge spin-up at every 10g or so. This was done in order to prevent the separation between the door and the container bottom.

In the second phase of the test, the motor was started in order to lower the trap door. First few revolutions are used to overcome the contact force between the trap door assembly and the container floor. Eventually, the contact force F_c becomes zero. At this point, the assembly separates from the container floor and then moves downward at the specified rate. In the tests reported in this report, the door was lowered at a rate of 0.0236 in/min (0.06 cm/min). Theoretically, the trap door is still flush with the container floor as long as there exists some contact force. Therefore, the top loadcell measurement should measure the undisturbed soil force. Once the door separates, this force would decrease due to positive or active arching and this decrease would be reflected in both loadcell measurements. However, as seen in Figure 6, the top loadcell starts showing the decrease before the contact force becomes zero which is supposed to be the point where the top two curves in Figure 6 merge. However, this discrepancy is insignificant. The difference between the bottom two curves is the soil force, which is shown in the top plot of Figure 7. The data in the top plot is normalized with respect to the undisturbed soil force (i.e. when the door displacement is zero) and presented as a percentile in the bottom plot of Figure 7.

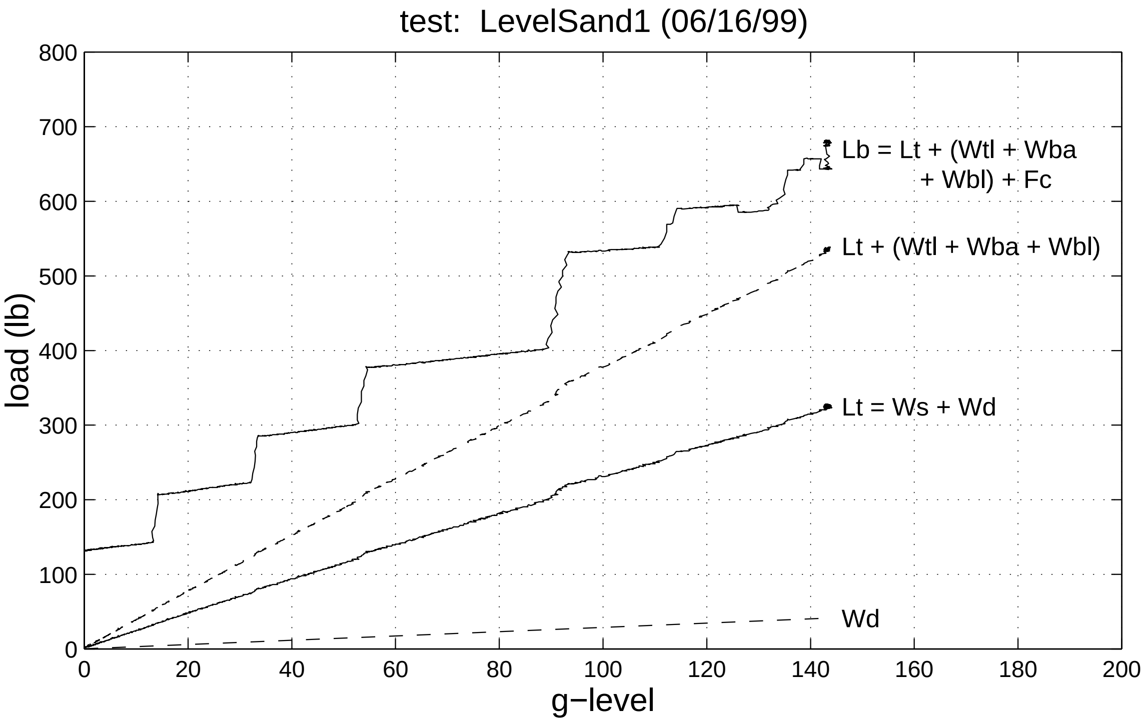


Figure 5: Loadcell measurements during centrifuge spin-up in test LevelSand1

The weight of the sand column above the trap door was calculated to be 1.921 lb at 1g. The g-level at the mid-height of the sand layer was calculated to be 141.3g corresponding to 150g at the bottom of the outer container. Therefore, the undisturbed soil force was expected to be 271.4 lb. As seen in Figure 7, the measured undisturbed soil force was 284 lb. In the door movement of about 0.04” (1 mm), the soil load decreased to about 17% of its undisturbed value.

4.2 Test LevelSand2

The configuration of test LevelSand2 was similar to test LevelSand1 shown in Figure 4. In this test, the open-ended cylindrical container was 6” (15.24 cm) in diameter. Nevada No. 100 sand was pluviated from a hopper to achieve a relative density of approximately 60%.

Similar to test LevelSand1, contact force of about 100 lb was maintained during the centrifuge spin-up portion of the test. The soil force as the trap door was lowered is plotted in Figure 8. The measured undisturbed soil force was 271 lb which once again compared well with the calculated value of 271.4 lb. Again, in the door movement of about 0.04” (1 mm), the soil load decreased to about 19% of its undisturbed value.

In general, the results from tests LevelSand1 and LevelSand2 were very repeatable. The undisturbed soil force was measured correctly.

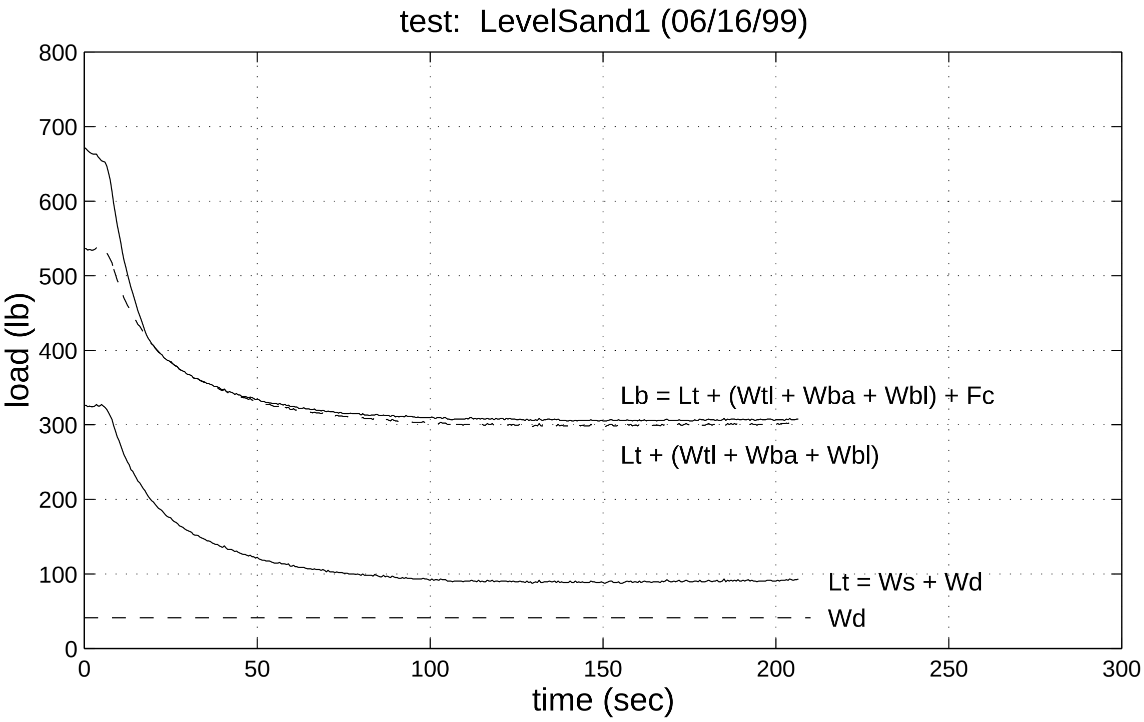


Figure 6: Loadcell measurements during lowering of the trap door in test LevelSand1

4.3 Test LevelSilt1

The results from the level ground sand model tests were consistent and repeatable. Therefore, it was concluded that the new design of the trap door assembly was successful in measuring soil forces correctly. The next test was conducted on level ground model of compacted Bonnie silt. Properties of Bonnie silts were reported in the first progress report, herein reproduced in Appendix A.

The model configuration of test LevelSilt1 was very similar to that of test LevelSand1 (Figure 4). The silt layer was 4.9” (12.45 cm) thick and the density was about 98.7% of the maximum standard Proctor density.

The test procedure was same as before. The soil load is plotted in Figure 9. The measured undisturbed soil force was 331 lb as opposed to the calculated value of 347 lb. The load reduced to about 43% upon lowering of the trap door.

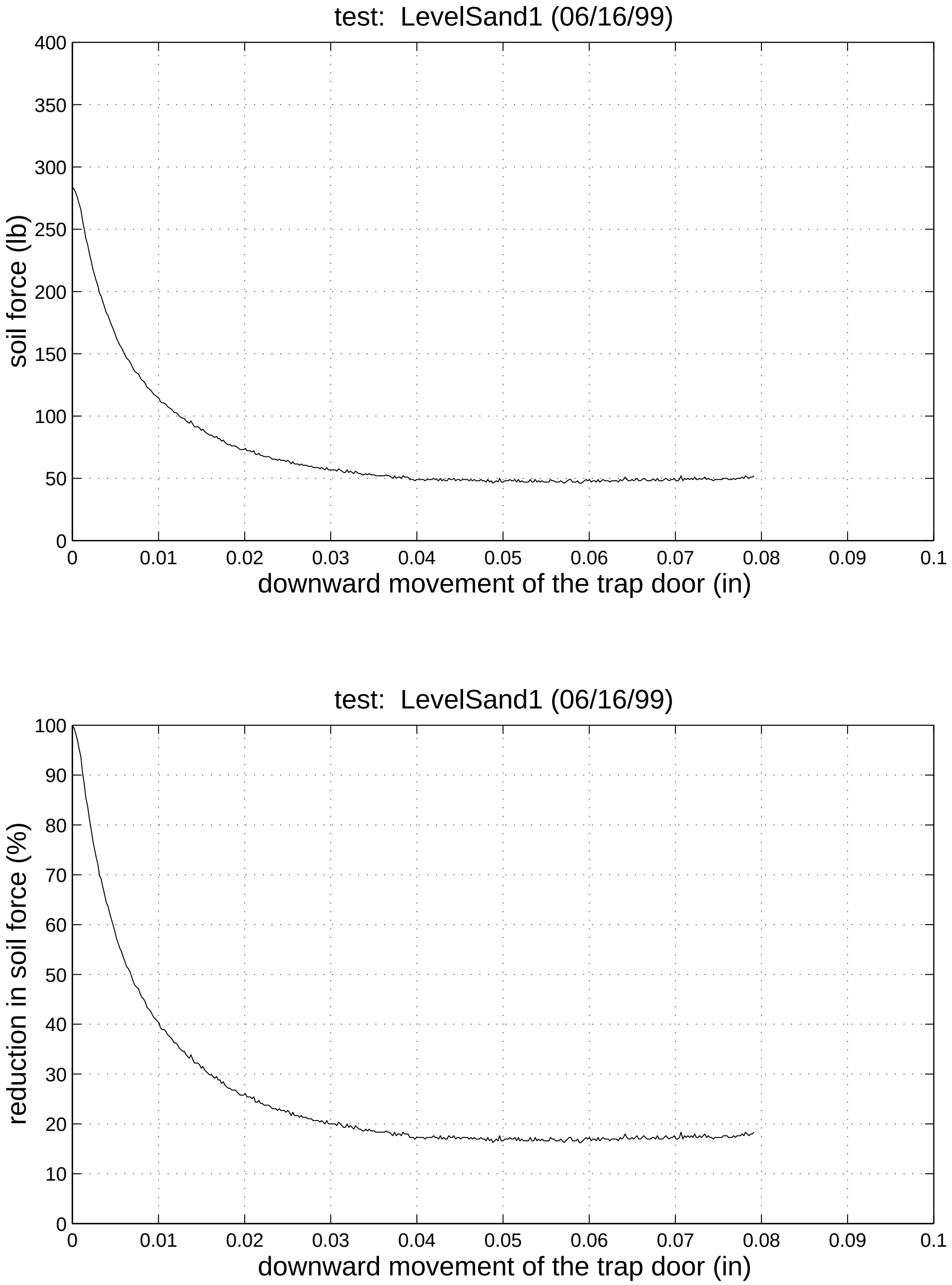


Figure 7: Reduction in the soil force during lowering of the trap door in test LevelSand1

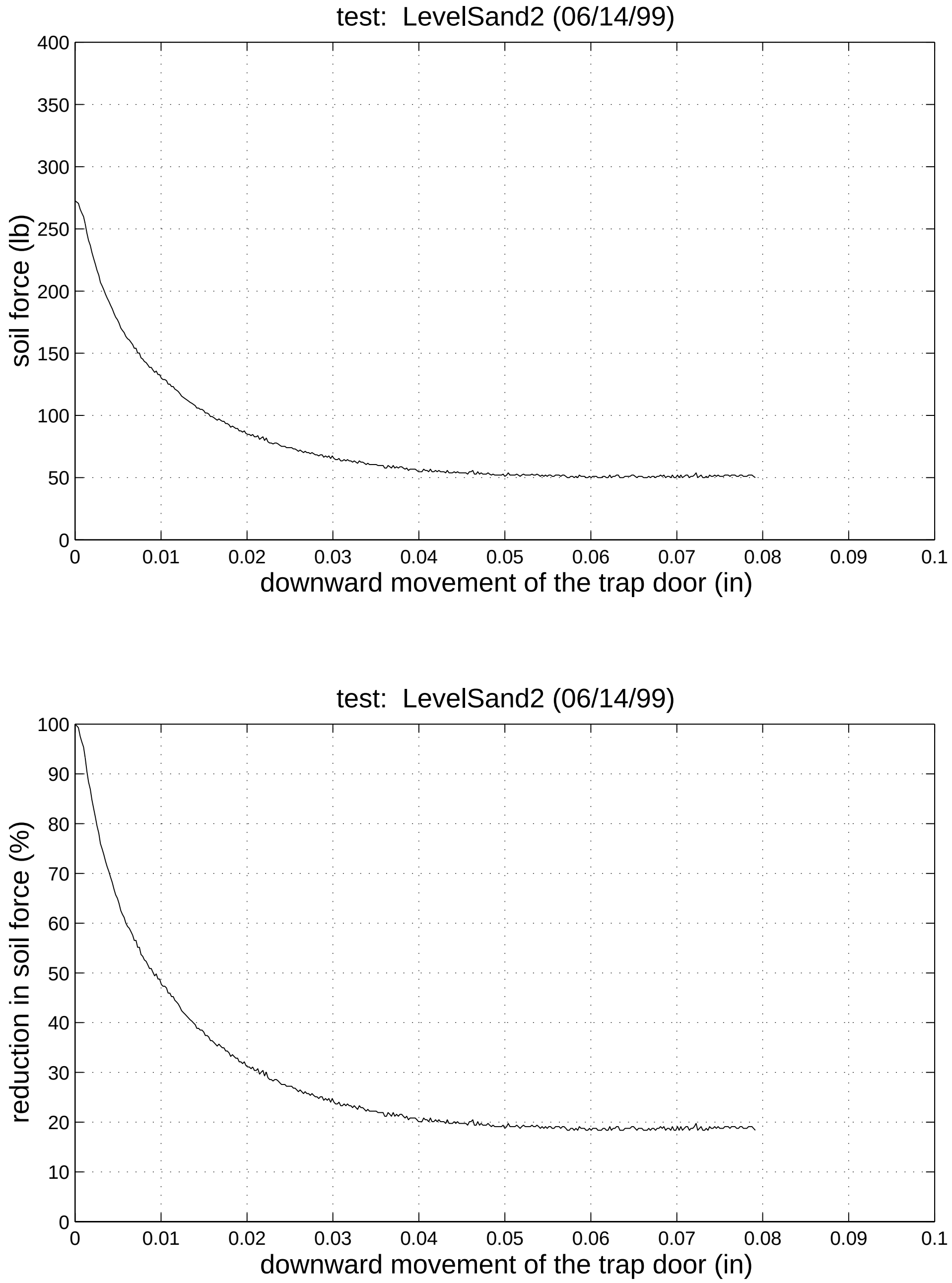


Figure 8: Reduction in the soil force during lowering of the trap door in test LevelSand2

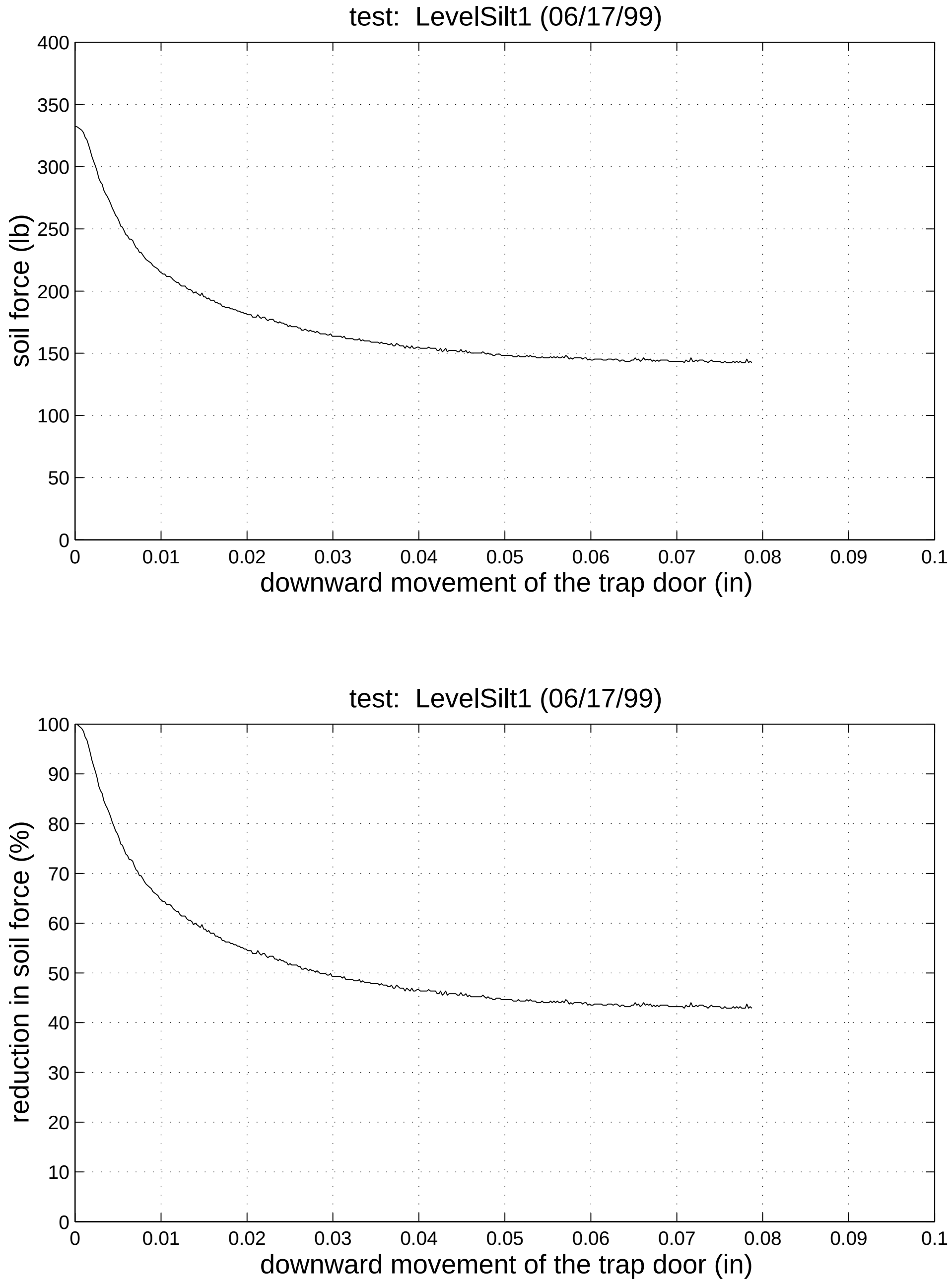


Figure 9: Reduction in the soil force during lowering of the trap door in test LevelSilt1

5 Centrifuge tests on embankment models

Two tests on embankment dam models of compacted Bonnie silt, namely damNW1 and damWW1, were performed.

5.1 Embankment model test damNW1

Model configuration of test damNW1 is depicted in Figure 10. The model preparation procedure is shown in Figure 11. A special wooden mould was prepared. As seen in the top photograph, the side support of the mould had metal grooves in which ten wooden plates could be inserted for both slopes of the model. This arrangement facilitated the construction of an embankment model in ten 1" (2.54 cm) thick layers. The total embankment height was 10" (25.4 cm). Volume compaction technique was adopted. For each lift of the model, the final volume of the compacted soil was calculated. A known weight of moist Bonnie silt was compacted in this volume to achieve a density of 90% of maximum standard Proctor density. After each layer, a very thin (about 1 mm) layer of white powder was introduced only in the location above the trap door. The diameter of this layer was 15" (38.1 cm). This was done to help determine the failure plane in the post-test investigation. The finished embankment model is shown in the bottom photograph of Figure 11.

The weights of the container before and after building the model were noted. The final value of density was calculated from this measured weight of the model and its known volume. The density was calculated to be 89% of the maximum standard Proctor density.

The test procedure was the same as that in the level ground tests. In the level ground tests, the trap door was lowered by only about 0.08" (2 mm). In the tests on embankment models, the door was lowered by 1". The soil force and LVDT measurements from test damNW1 for up to a displacement of 0.1" are shown in Figure 12. These quantities for a displacement of up to 1.0" are shown in Figure 13.

Unlike in the case of level ground, the stress distribution on top of the trap door is not known because of the inclined geometry of the model. As an approximation, the weight of the soil column on top of the trap door was estimated to be 322 lb. The measured undisturbed soil force was 358.5 lb. As seen in Figures 12 and 13, the soil force dropped to 22.5 lb which is only 6.3% of the undisturbed value. The displacement of the door at this point was only about 0.04" (1 mm). As the door continued to displace downward, more soil separated from the embankment creating a bigger cavity. As a result, the soil force increased. The surface displacements of the embankment were very small.

The post-test investigation revealed a failure pattern as shown in the photographs in Figure 14. The top photograph shows the view along section A1-B (Figure 10). The bottom photograph shows the view along section A1-A2. As indicated by white powdered layers that are visible in the photographs, above the cavity, the dam was intact even after the door displaced by 1". It is speculated that in the beginning, when the door displaced by about 0.04" (1 mm) and when the soil force was at its minimum, the cavity was small. As the door continued to move downward, the cavity continued to grow. The sudden increase in the soil force at the door displacements of about 0.51" and 0.75" in Figure 13 could be due to the presence of white powder layers (second and third from the bottom) which had smaller

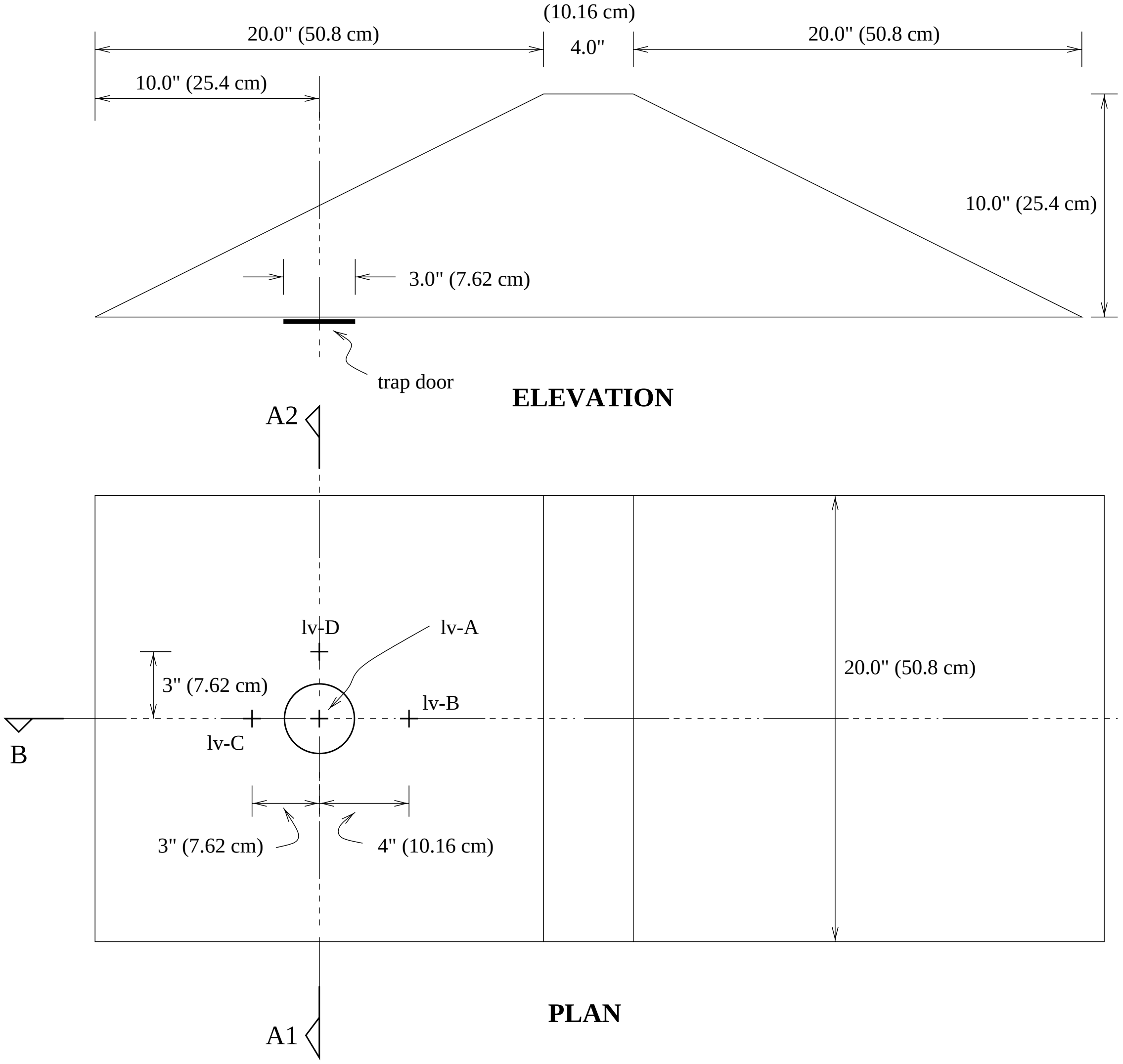


Figure 10: Model configuration of test damNW1

Figure 11: Photographs of embankment model preparation

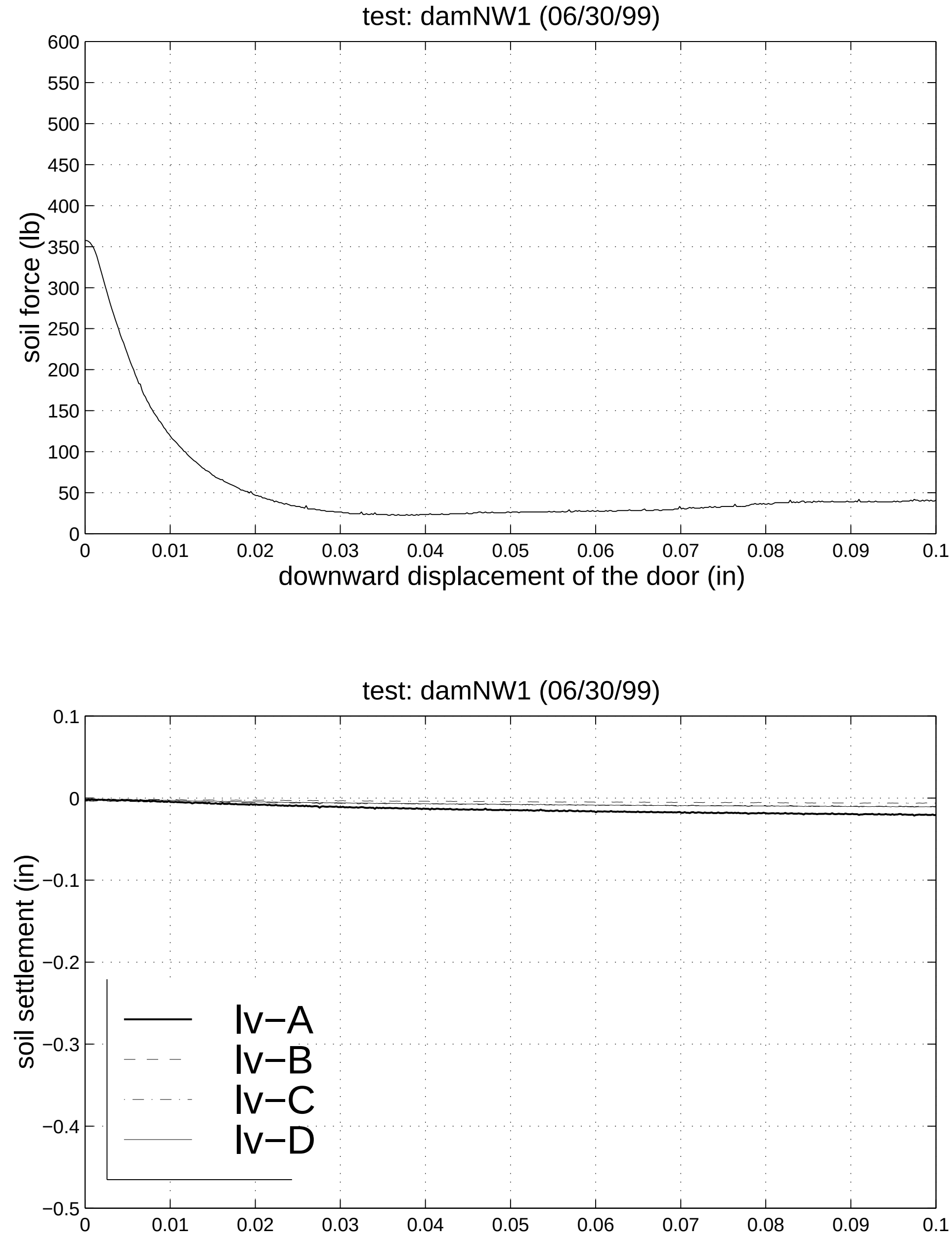


Figure 12: Measurements up to 0.1" movement of the trap door in test damNW1

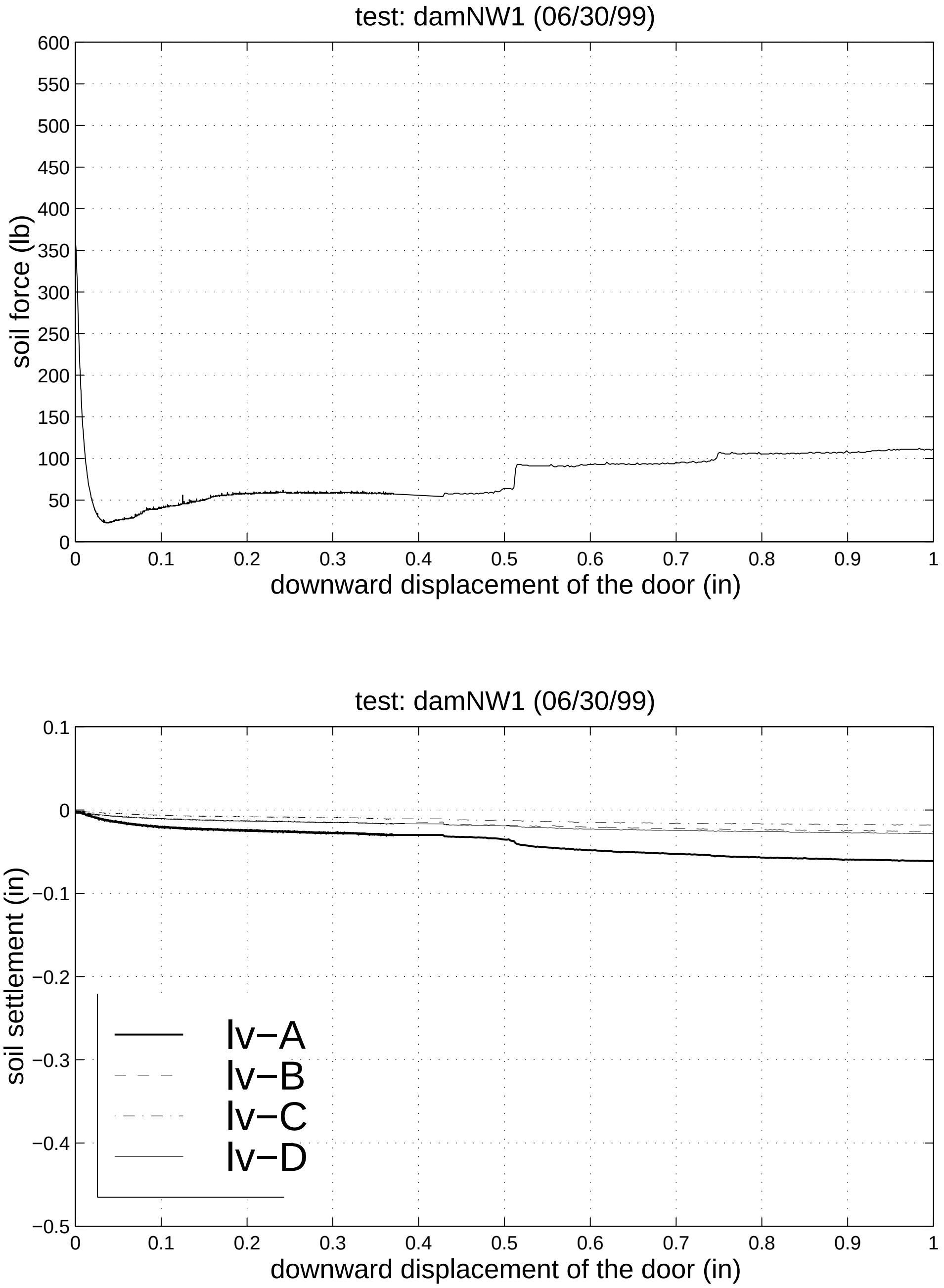


Figure 13: Measurements up to 1.0" movement of the trap door in test damNW1

strength than the compacted silt. As the cavity reached these powder layers, greater amount of soil separated from the embankment. The diameter of the cavity was about the same as the trap door diameter. The rest of the embankment was almost intact.

At the end, when the total trap door displacement was 1", the soil force was 110 lb, i.e. 30.7% of its undisturbed value. The weight of the soil on top of the door was estimated to be about 190 lb at 150g. The difference of about 80 lb was speculated to be balanced by the friction along the bottom half portion of the cavity.

5.2 Embankment model test damWW1

Configuration of test damWW1 is shown in Figure 15. The model dimensions are the same as in test damNW1. The only difference in the two tests was the water reservoir present in test damWW1. The water reservoir was contained in an impermeable latex membrane. Thus, seepage forces were not present in the model. The photograph of the model with the LVDT arrangement is shown in Figure 16. The density of the compacted silt was calculated to be 88% of the maximum standard Proctor density.

The test procedure was the same as that in test damNW1. The soil force and LVDT measurements from the test for up to a displacement of 0.1" are shown in Figure 17. These quantities for a displacement of up to 1.0" are shown in Figure 18.

Because of the presence of water reservoir, the undisturbed soil force was 458 lb, about 100 lb higher than that in test damNW1. As seen in Figure 17, the soil force dropped to 28 lb which is only 6% of the undisturbed value. The displacement of the door at this point was only about 0.05" (1.3 mm). The displacement of the embankment surface was very small. This reduction in soil force, the required door displacement to cause the reduction, and the surface settlements compared very well with those in test damWW1. This indicates that although a water reservoir existed on top of the embankment, the same volume of cavity was formed on top of the trap door.

However, as the trap door continued to move downward, the behavior of the embankment changed drastically from that in test damNW1. The top view of the dam after the test is shown in the top photograph of Figure 19. With the additional door movement, the cavity continued to grow and reached the surface of the dam. On the other hand, in test damNW1, without the additional load of water, the cavity did not reach the surface of the dam. The bottom photograph in Figure 19 shows the view along section A-A of Figure 15. As seen, the failure surface is cylindrical with the diameter equal to the trap door diameter. The displacement measured by lv-A in Figure 18 reached 0.42" (1.1 cm) after which the transducer went out of range. The total displacement measured during the post test investigation was about 1.0" (2.5 cm). The rest of the LVDTs were outside the failure zone and hence measured relatively small displacements.

At the end, when the total trap door displacement was 1", the soil force was 148 lb, i.e. 32% of its undisturbed value. The weight of the soil and water on top of the door was estimated to be about 477 lb at 150g. The difference of about 329 lb was speculated to be balanced by the friction along the failure surface.

Figure 14: Photographs of post-test investigation in test damNW1

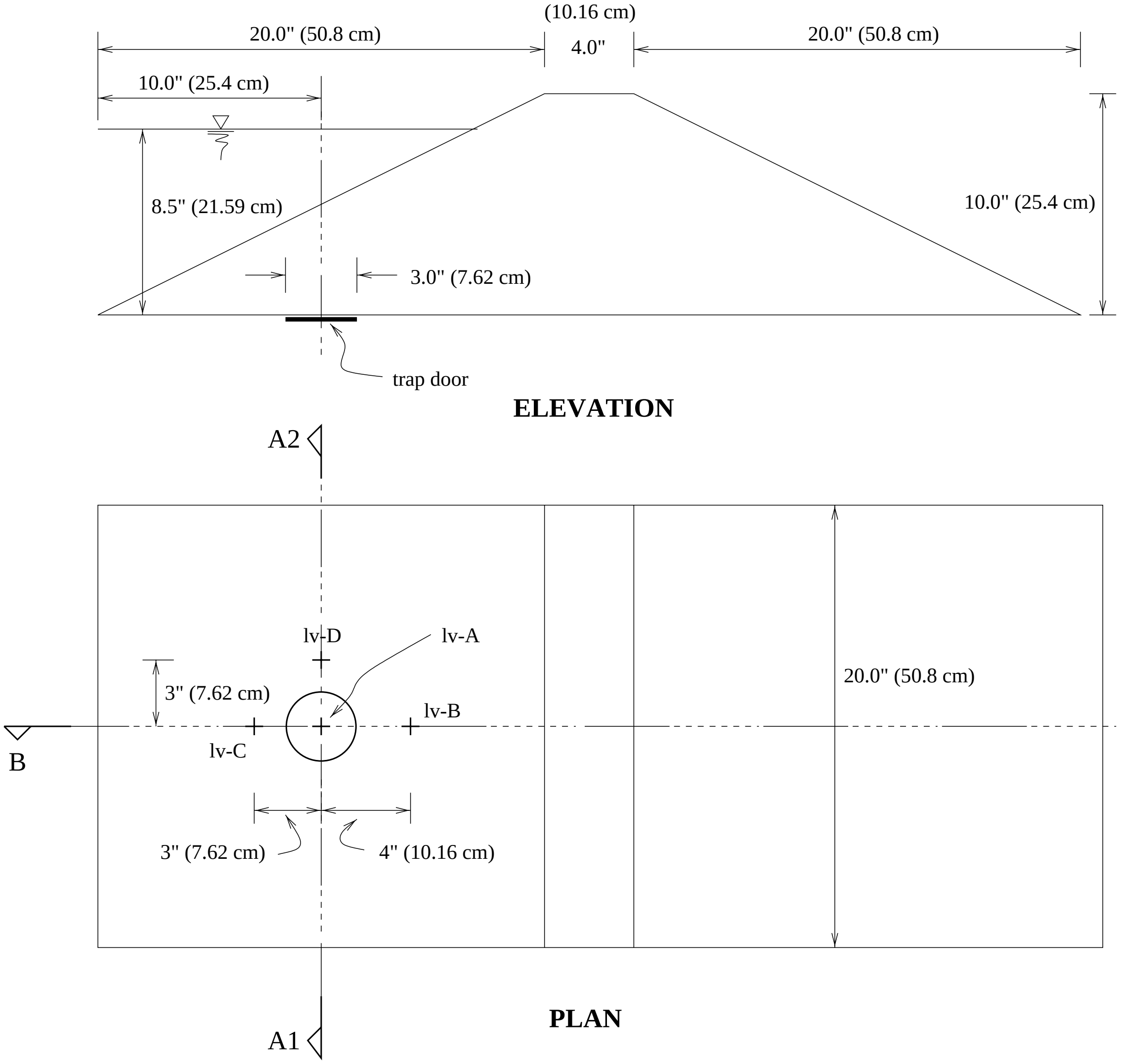


Figure 15: Model configuration of test damWW1

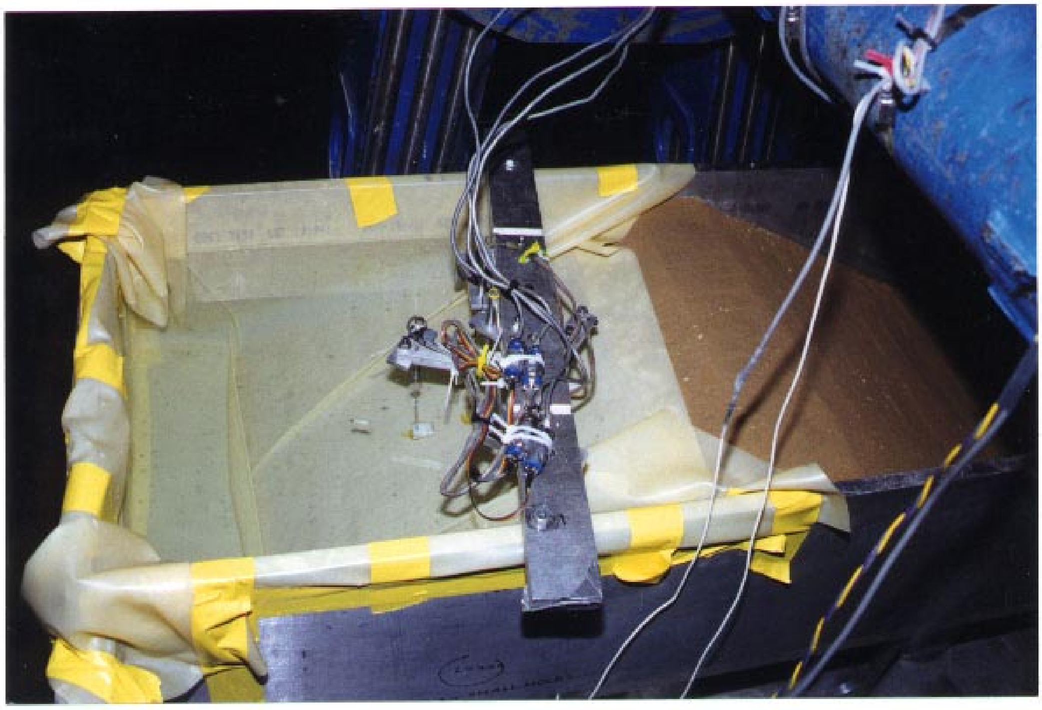


Figure 16: Photographs of the embankment model in test damWW1

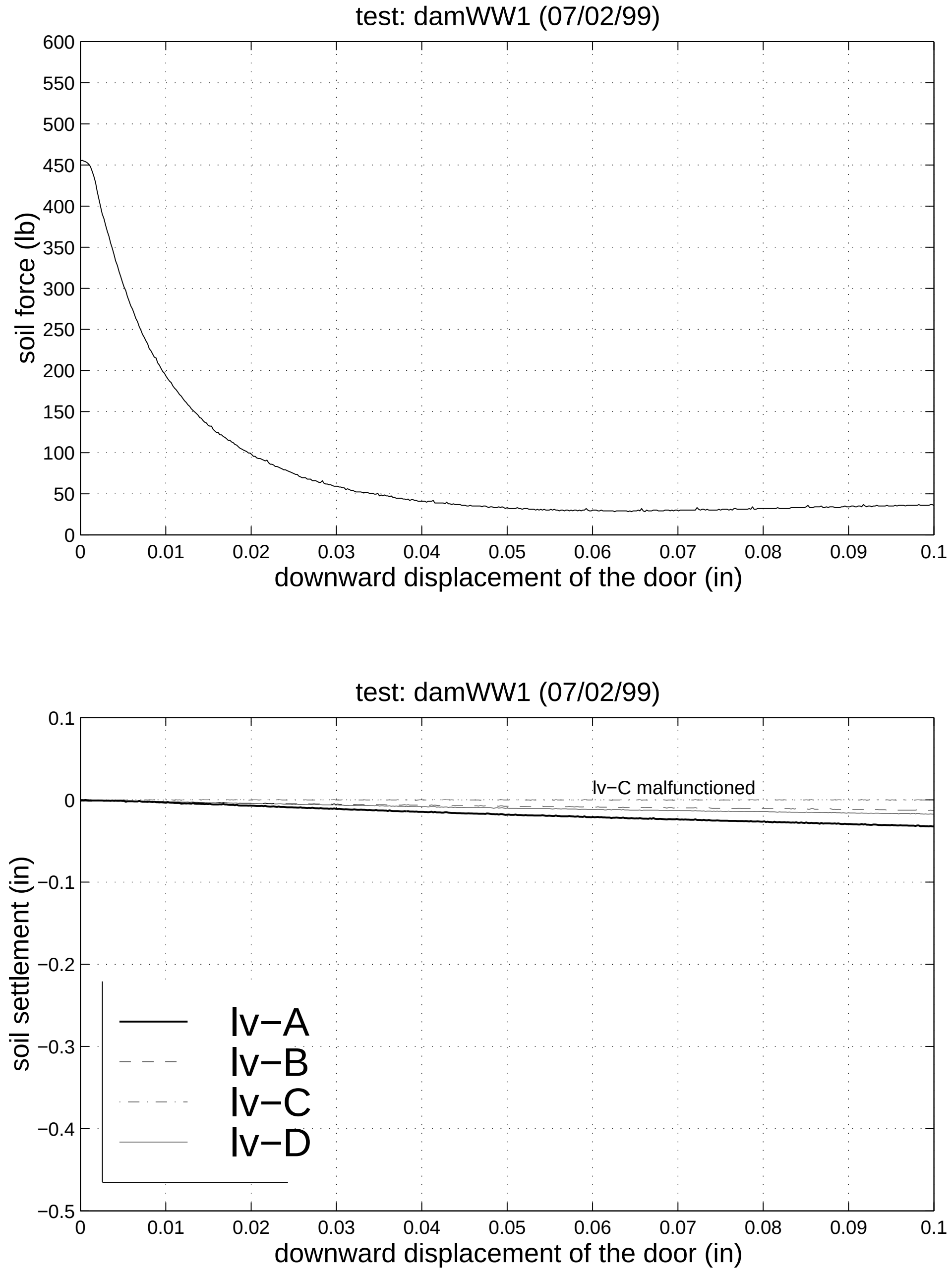


Figure 17: Measurements up to 0.1” movement of the trap door in test damWW1

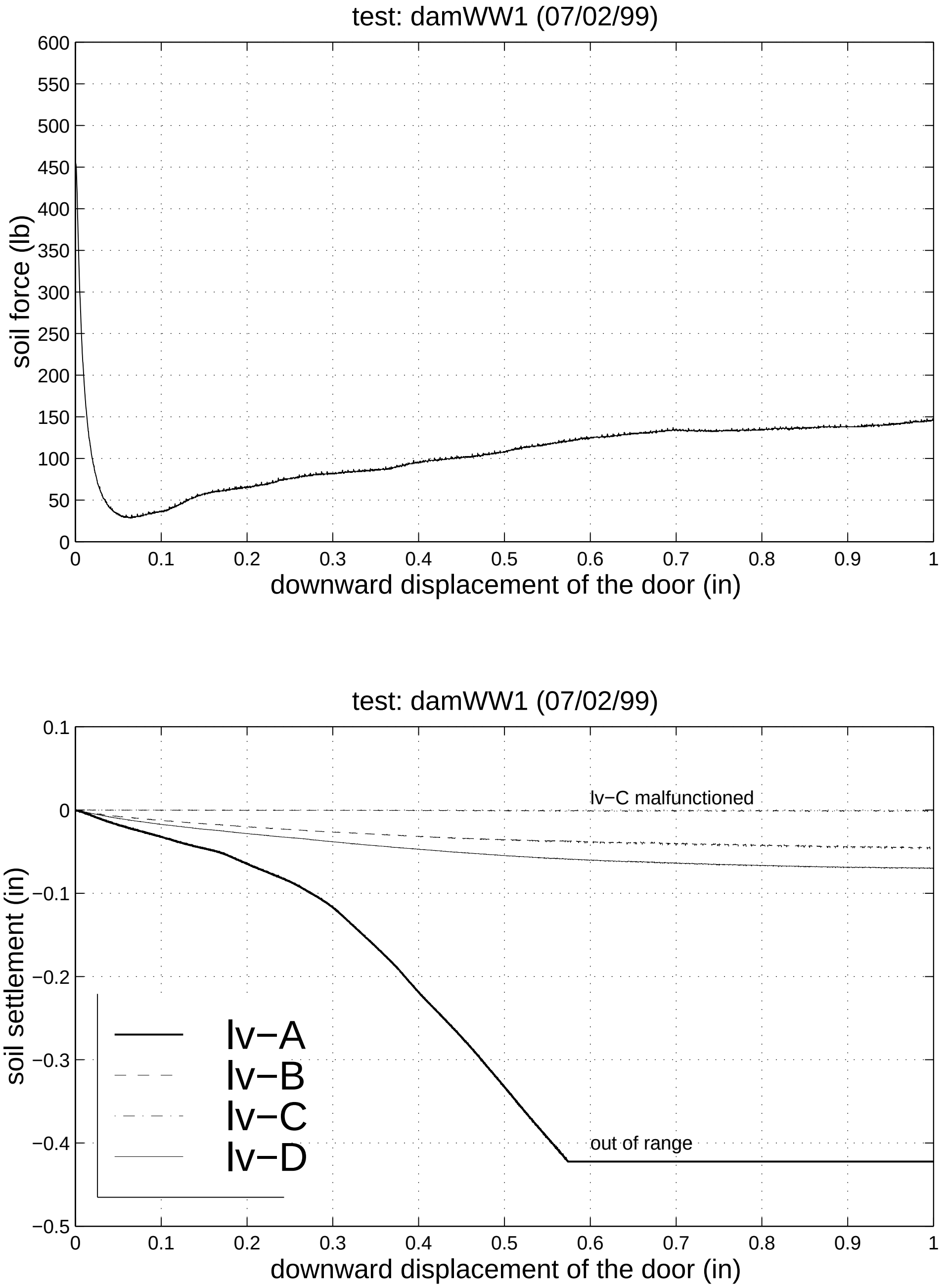


Figure 18: Measurements up to 1.0” movement of the trap door in test damWW1

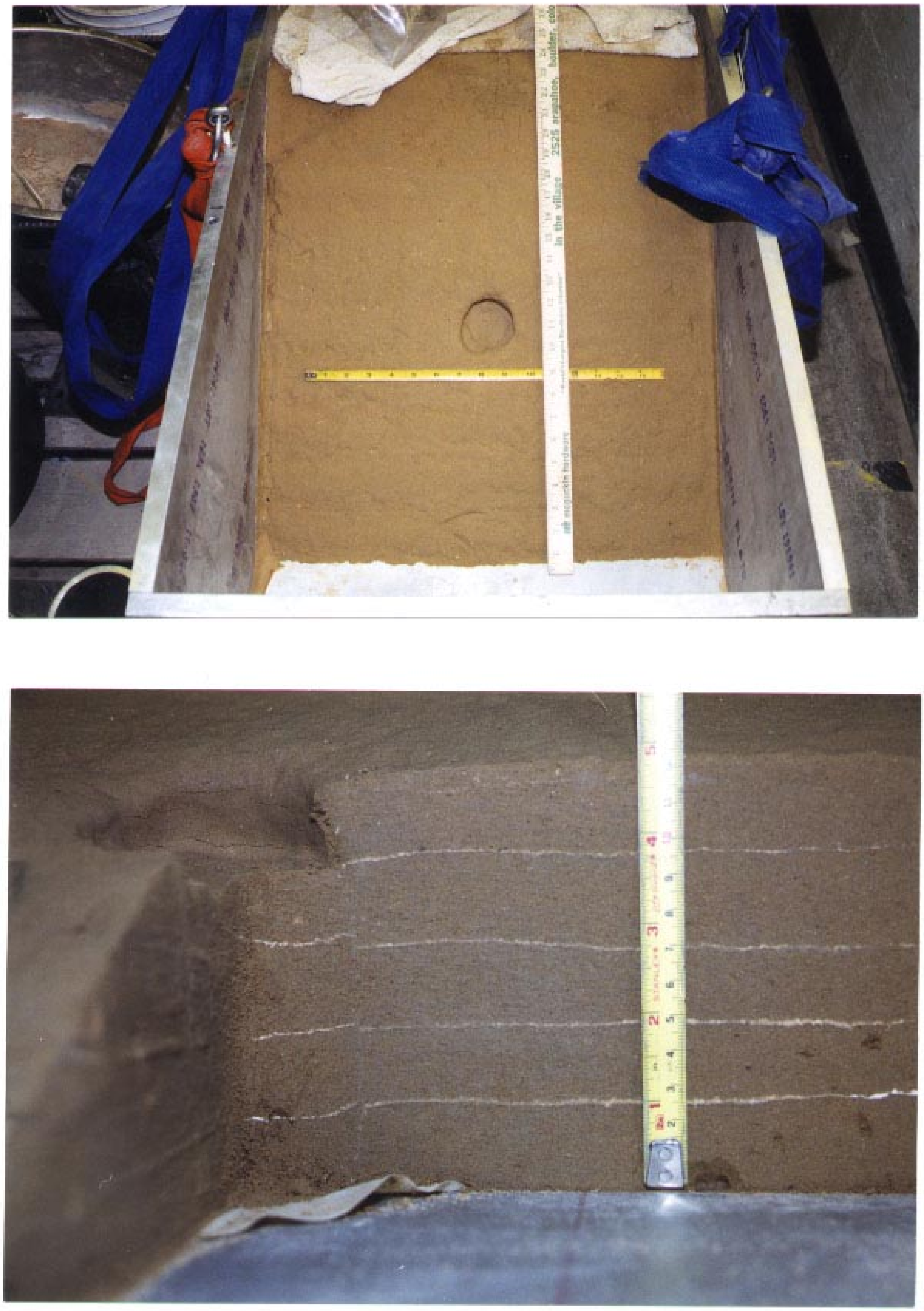
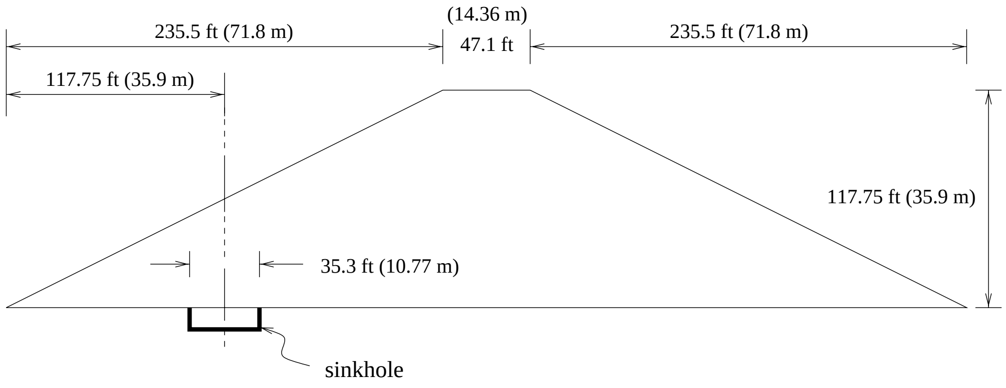


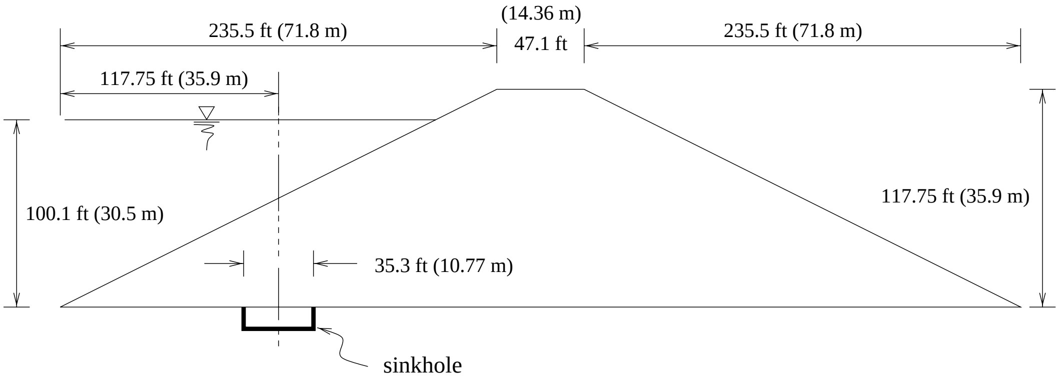
Figure 19: Photographs of post-test investigation in test damWW1

5.3 Prototype behavior

The embankment centrifuge models tested in experiments damNW1 and damWW1 represented prototypes shown in Figure 20. The prototype embankment is about 118 ft (36 m) tall. The results from test damNW1 indicated that if the water reservoir is absent, the formation of a 35 ft (11 m) diameter sinkhole would create a cavity inside the embankment; however, the surface of the dam would not suffer significant deformations. However, if the water reservoir is present, as in test damWW1, the formation of the same size sinkhole will eventually force the failure surfaces to reach the surface of the embankment. The depression in the embankment would be about 12 ft (3.6 m) deep and 35 ft (11 m) in diameter.



test damNW1



test damWW1

Figure 20: Prototype dimensions of the models in tests damNW1 and damWW1

6 Finite element simulation of test LevelSand1

The finite element program `PLAXIS` was used to conduct preliminary analysis of tests LevelSand1 and LevelSand2. The finite element mesh shown in Figure 21 was used. 15-noded triangular elements were used. In order to generate a sharp transition between the prescribed displacements of the trap door and the adjacent fixed boundary, an interface is introduced. As a result, the size of the transition zone between the two displacements is zero. Axi-symmetric calculations were performed on the mesh that simulated only half the configuration shown in Figure 4.

The results from the finite element analysis are shown in Figure 22. Numerical computations compare fairly well with the experimental measurements of tests LevelSand1 and LevelSand2.

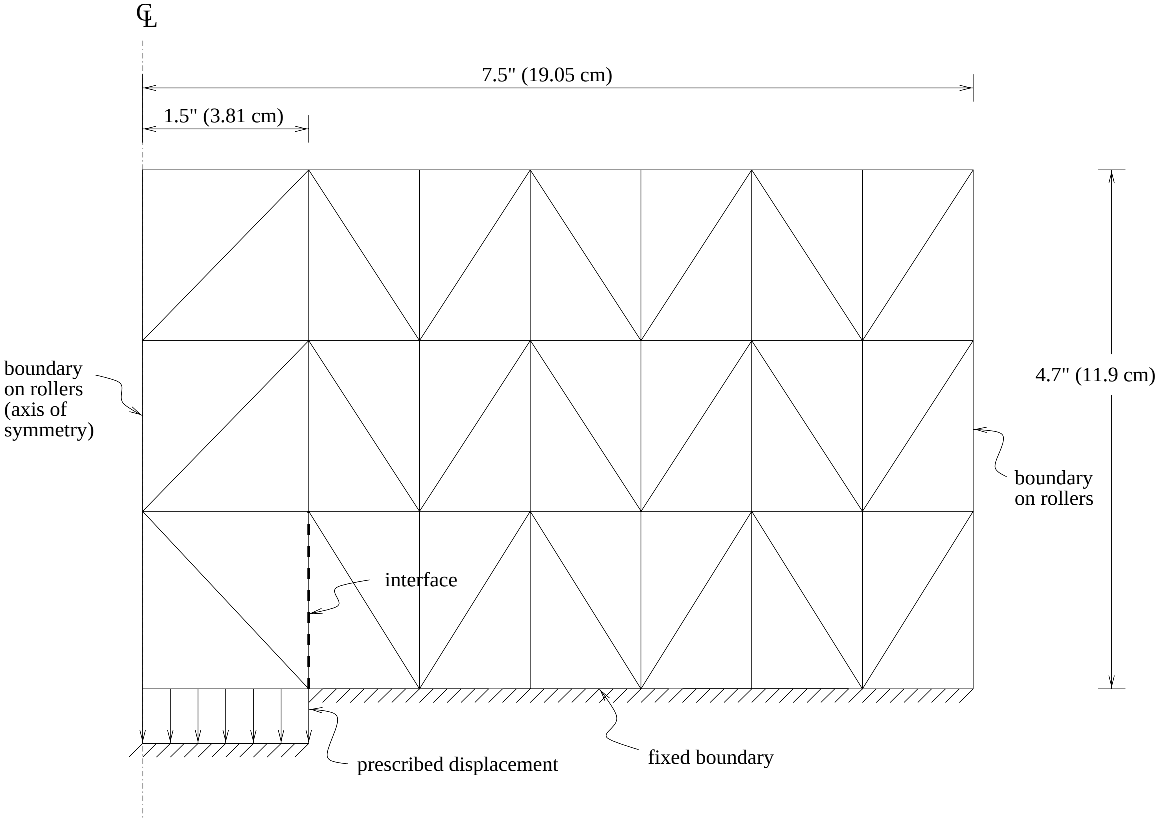
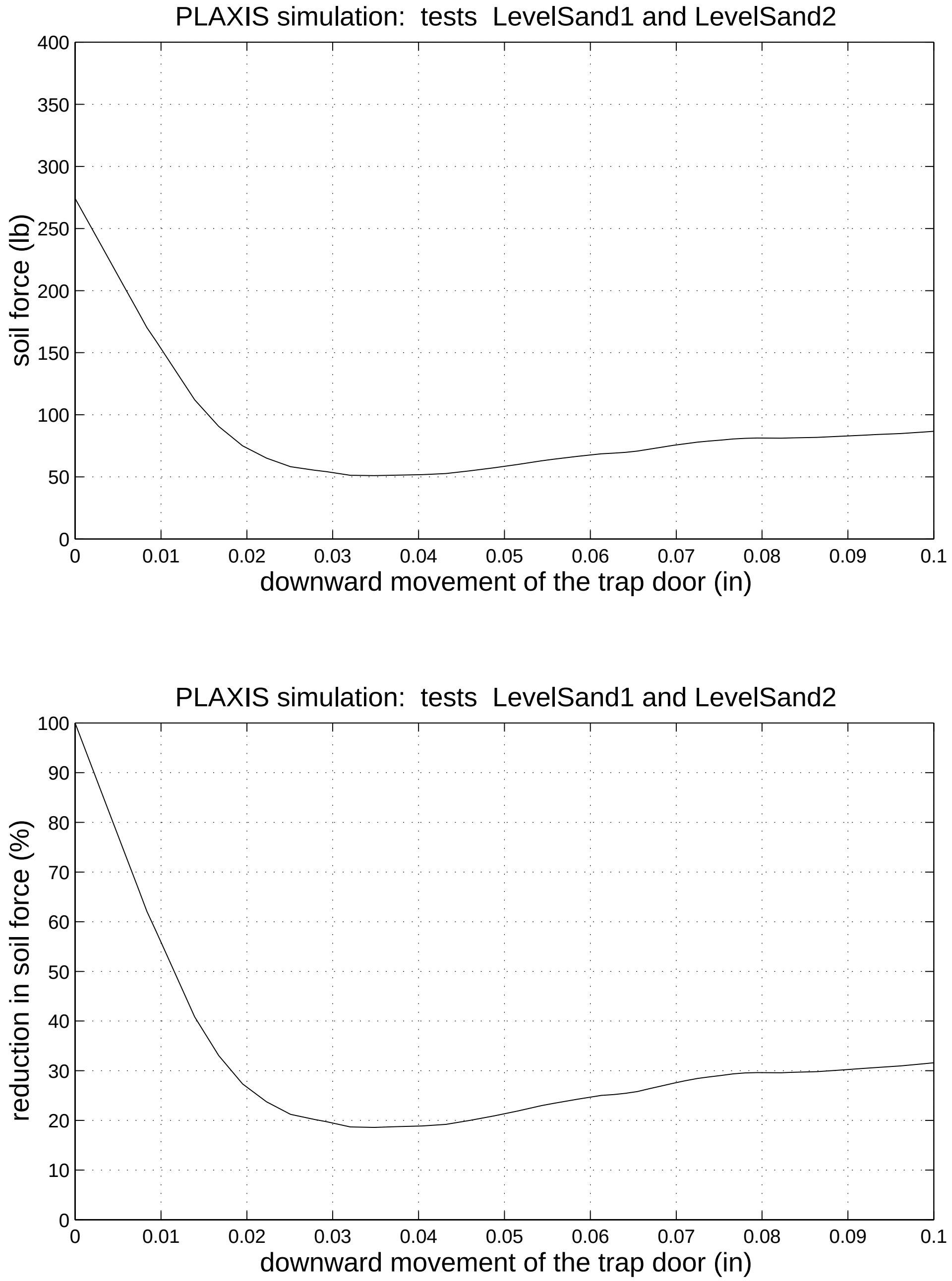


Figure 21: Finite element mesh simulating tests LevelSand1 and LevelSand2



PLAXIS simulation: tests LevelSand1 and LevelSand2

PLAXIS simulation: tests LevelSand1 and LevelSand2

Figure 22: Numerical simulation of tests LevelSand1 and LevelSand2 using `PLAXIS`

7 Conclusions

With the improved trap door assembly, correct soil loads prior to the lowering of trap door could be measured. Repeatable, reliable, and internally consistent measurements were obtained from centrifuge experiments conducted on level ground and embankment models. Therefore, the techniques used in the existing trap door assembly can now be used confidently to study effects of sinkhole formations in dam foundations and the classical problem of soil arching.

Finite element simulations of level ground sand experiments compared well with the measurements.

Centrifuge tests conducted on embankment models revealed mechanisms involved in the cavity formation inside embankments as a result of sinkhole development in the embankment foundations. The behavior of the models in the two tests were very similar for a small value of trap door deformation. In the test with no water reservoir, the surface of the embankment did not suffer major deformations, although a large cavity was formed above the trap door. In the test with water reservoir, with greater trap door displacements, the cavity eventually reached the dam surface which created a big depression in the dam surface. It would be interesting to examine what would have happened if the door was displaced further. The soil that was supported by the door would have lost its support creating a bigger depression. In a real situation, when water is not contained in an impermeable bag, it could flow through this cavity into the sinkhole.

In retrospect, the trap door should have been lowered to a greater depth also in the tests on level ground models. This could be done in the future.

7.1 Continuing Research

The effects of sinkholes on dams can now be studied systematically with the new trap door system. In addition, the classical problem of trap door or active arching can be studied by conducting experiments on level ground models. The following possibilities for continuing research are envisioned.

Improvements in hardware:

At this moment, only one trap door is being successfully used. The original plan was to have two trap door sizes available at two locations. It would still be very useful to reproduce the current system for the other three trap door sizes. A motor-gear box-actuator system already exists for the other trap door location. Some modification to the trap door discs and two additional loadcells would be required. The software and electronics hardware that operate the trap door assembly would have to be modified in order to operate two trap door systems simultaneously or consecutively without stopping the centrifuge.

With these improvements, instead of one test, two tests can be conducted on each model, increasing the productivity by a factor of two.

Centrifuge tests on embankment configurations:

- The embankment tests presented in this report, if repeated, would establish repeatability of sample preparation procedures and measurement techniques.
- If different door sizes are available, "modeling of models" can be conducted to verify the scaling relations involved. For example, a 10" high embankment model on 3" trap door can be tested at 75g. If the measurements from this test compare well with a 5" high embankment model on 1.5" trap door at 150g, the assumed scaling relations would be correct.
- Effects of sinkhole size can be studied if different door sizes are available.
- The speed at which the trap door is lowered can be changed to study the effects due to slow or rapid formations of sinkholes.
- Effect of the location of sinkholes can be studied by shifting the dam location along the longitudinal axis of the container.
- Some experiments can be conducted with geosynthetics to study this soil improvement technique to bridge over cavities.
- It would be very useful to model these experiments numerically. Formation of a circular cavity in the dam foundation is a three dimensional phenomenon. Therefore, a 3-D finite element program would have to be used. In the simulation of the trap door experiments on level ground sand models, the 2-D finite element program `PLAXIS` was used. The comparison between the experimental and numerical results was fairly good. A 3-D version of `PLAXIS` is almost ready to be released. The intention is to use this program to simulate the centrifuge tests on embankment models. In order to conduct finite element analysis, constitutive parameters of the compacted silt need to be determined.

  Determination of constitutive parameters: Conventional triaxial tests could be conducted; however, it would be difficult to follow the same soil compaction technique as in centrifuge models to prepare small cylindrical specimens of compacted silt. An electronically controlled, 7" cubical cell apparatus has recently been developed at the University of Colorado at Boulder. A cubical soil specimen can be prepared and tested virtually under any stress path in three-dimensional principal stress space. The sample preparation procedure used in building embankment models can easily be followed in the preparation of a specimen in a 7" cubical mould. Several tests can be conducted at different confining pressures to determine cohesion, friction angle, and other relevant properties of Bonnie silt compacted to 90% of the maximum Proctor density.

Centrifuge tests on level ground configurations:

In addition, the fundamental problem of trap door or active arching in soils can be studied by conducting trap door experiments on level ground sand and compacted silt models. These models can be prepared significantly faster than the embankment models. Effects of trap door sizes, speed of trap door movement, modeling of models, etc. can also be investigated on the level ground configuration.

Appendix A

Progress Report : Effects of sinkholes on earth embankments

M. M. Dewoolkar, K. Santichaianant, T. Goddery and H. Y. Ko

March 17, 1999

This document reports the progress made in the centrifuge investigation of the effects of sinkholes on earth dams. The centrifuge model studies are conducted at the University of Colorado at Boulder.

1 Introduction

The appearance of sinkholes in embankment dams is a frequent occurrence that can result from internal erosion, or in Karst terrain, from foundation subsidence. They can also occur as a result of soil collapse on wetting. Formation of these sinkholes can adversely affect the stability of dams and their foundations. Questions such as how and when localized loss of foundation support can cause a sinkhole to "stope" to the surface, need to be answered.

This and similar phenomena will be studied using the 400 g-ton geotechnical centrifuge at the University of Colorado at Boulder. The principle behind centrifuge modeling is to create a stress field in a small scale model, identical to that in a real or hypothetical prototype, which is being simulated in the geometrically similar model. This can be accomplished by increasing acceleration levels in the model placed in a centrifuge rotating at ω rad/sec, which produces at a radius R an acceleration N times earth's gravity g, where $N = R\omega^2/g$. The stress-strain relationships at all the equivalent points in the two systems will be the same if prototype soil is used in the model.

The research plan includes building models of earth dams in a specially designed container with trap doors in the container bottom. The models will be spun to desired g-levels and trap doors of different sizes will be lowered to simulate formation of sinkholes. In the next sections, container fabrication, trap door design, soil testing, and the results of preliminary experiments are discussed.

2 Container and trap door assembly

The conceptual design of the container and the trap door assembly is shown in Figure 1. The container holding an embankment model was specially designed and fabricated. This container has internal dimensions of 21" x 20.5". The height of the model could be up to 10". This container is housed in a larger container (51" x 40.5" internal dimensions and 20" deep) that was available in the centrifuge laboratory. The inside container is supported by six tubes. The space between the containers is used to accommodate trap door assemblies as shown in Figure 1. Detailed dimensions of the inside container are shown in Figure 2.

As shown in Figure 2, two trap door locations are available. At each location, two trap door sizes are available. The inner trap door is a disc. The outer trap door is a ring which rests on the inner disc. Both of these have inclined edges as shown in Figure 3. At location-1, the outer trap door diameter (ϕ) is 3” and the inner trap door diameter is 1.5”. At location-2, the available sizes are 4” and 2.25”. When only the inner trap door is to be lowered, the outer disc is locked in place by using support strips as shown in Figure 2. The doors are referred as a1, a2, b1, and b2.

location 1 :

trap door “a1” : $\phi = 1.5$”
trap door “a2” : $\phi = 3.0$””

location 2 :

trap door “b1” : $\phi = 2.25$”
trap door “b2” : $\phi = 4.0$””

As shown in Figure 3, the inner trap door is attached to a guiding cup. A loadcell is attached to the inside of the guiding cup. This assembly rests on the actuator piston. The actuator is operated to displace the door at a specified rate by operating the motor. A similar assembly exists for the other set of trap doors. The motor and actuator are attached to the bottom of the inner container. This particular design was adopted so as to avoid any relative movement between the container floor and trap doors. It was envisioned that if the container floor is to deflect with increasing g-level, the trap door will deflect with it.

At a given moment, the loadcell would measure the weight of the trap door assembly (i.e. the trap door, bolts, guiding cup, and part of the loadcell) and the soil on top of the trap door.

3 Preliminary test results

It was necessary to calibrate the system for being able to correctly measure the load from the soil above the trap door. For this purpose, several tests on door only (without anything on top of the door), water reservoir, and level ground sand tests were performed. All the tests were conducted at 150g; however, at the center of gravity of the test package, the g-level was estimated to be 140.5g.

The following symbols are used:

Wd : weight of a trap door

Ww : weight of water above the trap door

Ws : weight of soil above the trap door

The first series of test included experiments on just the doors barely in contact with the container floor without any soil on top. Figure 4 shows plots of door weight versus g-level for doors a1 ($\phi = 1.5$”) and a2 ($\phi = 3.0$”). As expected, the load measured by the loadcell increases linearly with the g-level. The measurements were very close to the calculated values.

In Figure 5, results from a water-reservoir test on door b2 ($\phi = 4.0$") are shown. The height of the water column on top of the trap door was 10". The trap door was just in contact with the container floor at 1g. The loadcell under door b2 measured the weight of the trap door assembly plus the weight of water. The measured values compared very well with the calculated values.

The next series of tests was conducted on horizontal layer of sand. The particular test discussed here involved a 5.0" thick layer of dry Nevada No. 100 sand at 60% relative density on door b2 ($\phi = 4.0$"). The trap door was just in contact with the container floor at 1g. The load versus g-level is plotted in Figure 6. The measured load was not in a good agreement with the calculated load. That suggested that there indeed was a relative movement between the container floor and the trap doors. Due to this movement, the load on the door was lower than the expected value as a result of some arching effects. In case of water (Figure 5), the relative movement between the floor and the door did not make any difference since the stresses in water are unaffected by arching effects. Hence, correct hydrostatic pressures were measured.

3.1 Alternative test plan

Several different approaches were tried to restrict the movement of trap doors with respect to the floor. The process of applying some precompression on trap doors seems to be working.

In this approach, certain amount of precompression (as measured by the loadcell) is applied to ensure that the trap door will stay in contact with the floor. This precompression is applied by turning the motor to move the door upwards. The top plot of Figure 7 shows the measurement of the loadcell versus g-level for a set of two tests, one without soil and one with soil for trap door a2 ($\phi = 3.0$"). The precompression loads were 797 lb and 625 lb at 1g. As the g-level increased, the precompression values decreased differently in the two tests. Based on several different test results it was concluded that this drop is inconsistent and not repeatable, even in cases when the starting precompressions are the same. After reaching the desired g-level (140.5g), the motor was operated to adjust the precompression to the same value (590 lb) in both tests. The trap door was lowered at a rate of 0.00625 mm/sec. The results are plotted in the bottom plot of Figure 7. As seen, the initial portion of the two curves are very similar. At around 470 lb, the two curves separate. The value of 470 lb is very close to the theoretically calculated value of 464 lb (183 lb of the door assembly + 281 lb of soil weight). This concept is explained in Figure 8.

In Figure 8, the abovementioned tests are explained conceptually. The weight of the door assembly at 1g was 1.3 lb. In the test with soil, the depth of the dry sand layer was 5.0". At 1g, the weight of the cylinder of soil on top of the door was calculated to be 2.0 lb. The precompression value at 1g was adjusted to 615 lb. Thus, the contact force (Fc) would be 611.7 lb. As the g-level is increased to 140.5g, the weight of the door and the soil above it would be 183 lb and 281 lb, respectively. Because of some unidentified reasons (probably due to some slack in the actuator-motor assembly) the precompression dropped to 590 lb. The precompression load decreased also in the test without soil. It was adjusted to be 590 lb at 140.5g. The contact force now became 126 lb. On the other hand, when the soil was absent, this contact force was 407 lb. When the motor was started to lower the door, it consumed greater revolutions to overcome the contact force of 407 lb (without soil) as opposed to 126 lb (with soil). As seen from the bottom plot of Figure 7, the slopes of the curves were the same until the contact force of 126 lb was overcome. At this point, the door was just separated from the floor. The further reduction in the load was a result of the actual phenomenon of positive arching which is intended to be studied. On the other hand, in the test without soil, the same slope of the curve was continued until the contact force of 407 lb was overcome. After this contact force was overcome, the door was separated from the floor and the loadcell measured just the weight of the door assembly at 140.5g.

Thus, using the concept of the application of precompression load, correct soil load of approximately 280 lb could be measured. In the top plot of Figure 9, the reduction in the load as the door was displaced is plotted. In the bottom plot, percent reduction (with respect to the initial soil load of 280 lb, therefore the starting point is 100%) in the soil load is plotted against normalized displacement (with respect to the trap door diameter). The load was reduced by 80%.

Several such experiments are currently being conducted to establish confidence in the approach of applying precompression load. The next phase of testing will involve experiments on models of earth embankments.

4 Future experiments

A box of Bonnie silt was supplied by the Bureau. The properties of the soil were not known. Therefore, sieve and hydrometer analysis, Atterberg's limit, and Standard and Modified Proctor tests were performed.

The grain size distribution curve for the silt is shown in Figure 9. The results from Standard and Modified Proctor tests are shown in Figure 10. Other properties were determined to be:

specific gravity = 2.65

liquid limit = 28.5%

plastic limit = 20.3%

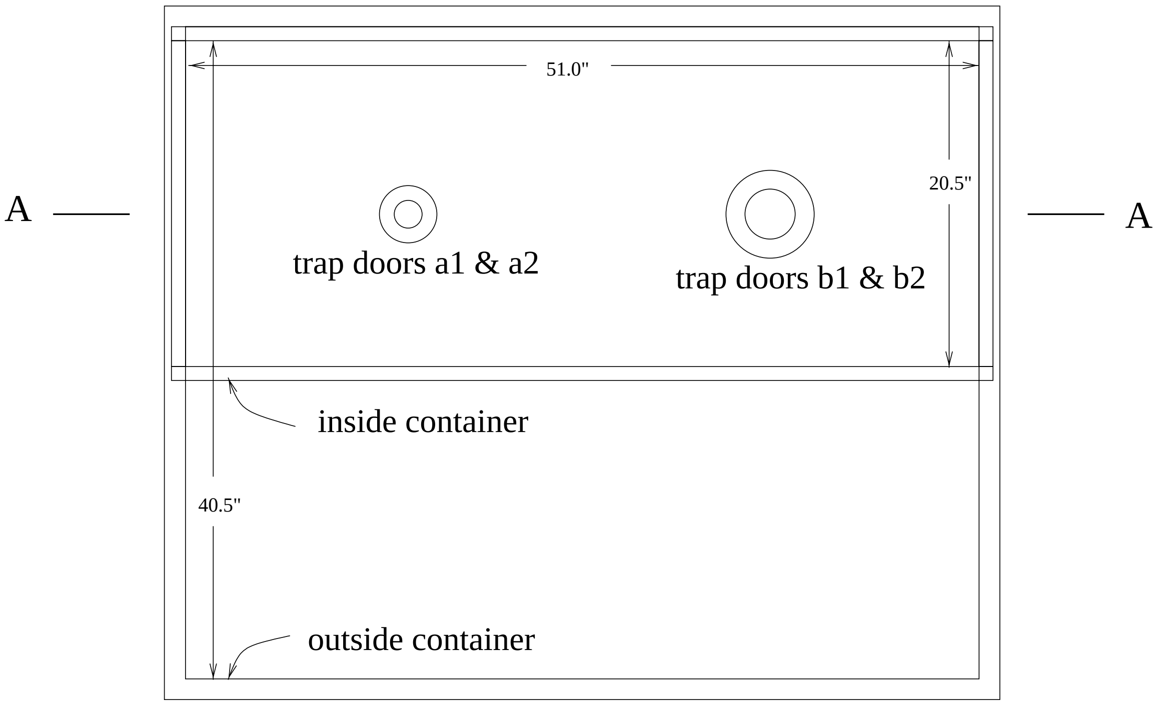
plasticity index = 8.2

It is envisioned that the embankment models will be prepared by compacting Bonnie silt at 90% Standard Proctor density. The model embankments would be 9” tall with 1V:2H sloping faces. Water reservoir would be present on one of the faces as shown in Figure 1. In addition to the loadcell measurements, settlements of embankment profile will be measured using LVDTs (Linear Variable Differential Transformers). Specific test plan will be developed after preliminary embankment model test results are evaluated.

5 Conclusions

A special container and trap door assemblies were designed to simulate formation of sinkholes. At present, calibration check tests have been performed on models of water reservoirs and horizontal soil layers. It was found that by applying some precompression load, trap doors can be prevented from separating from the container floor prematurely. Correct soil loads could be measured prior to the lowering of trap doors. In the next phase, models of Bonnie silt embankments will be tested.

Any comments or suggestions for possible improvements in the testing plan from the Bureau of Reclamation are welcome.



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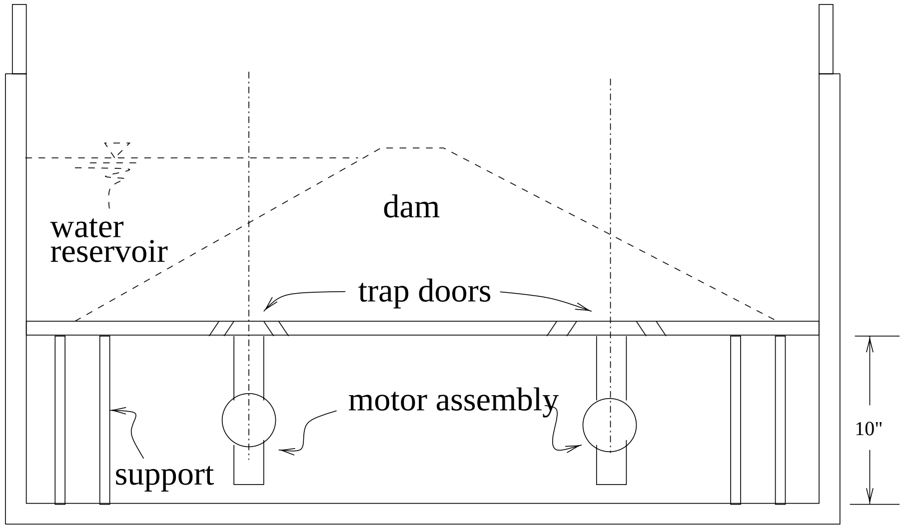


SECTION A-A

Not to scale.

Figure 1: Test configuration, container, embankment model

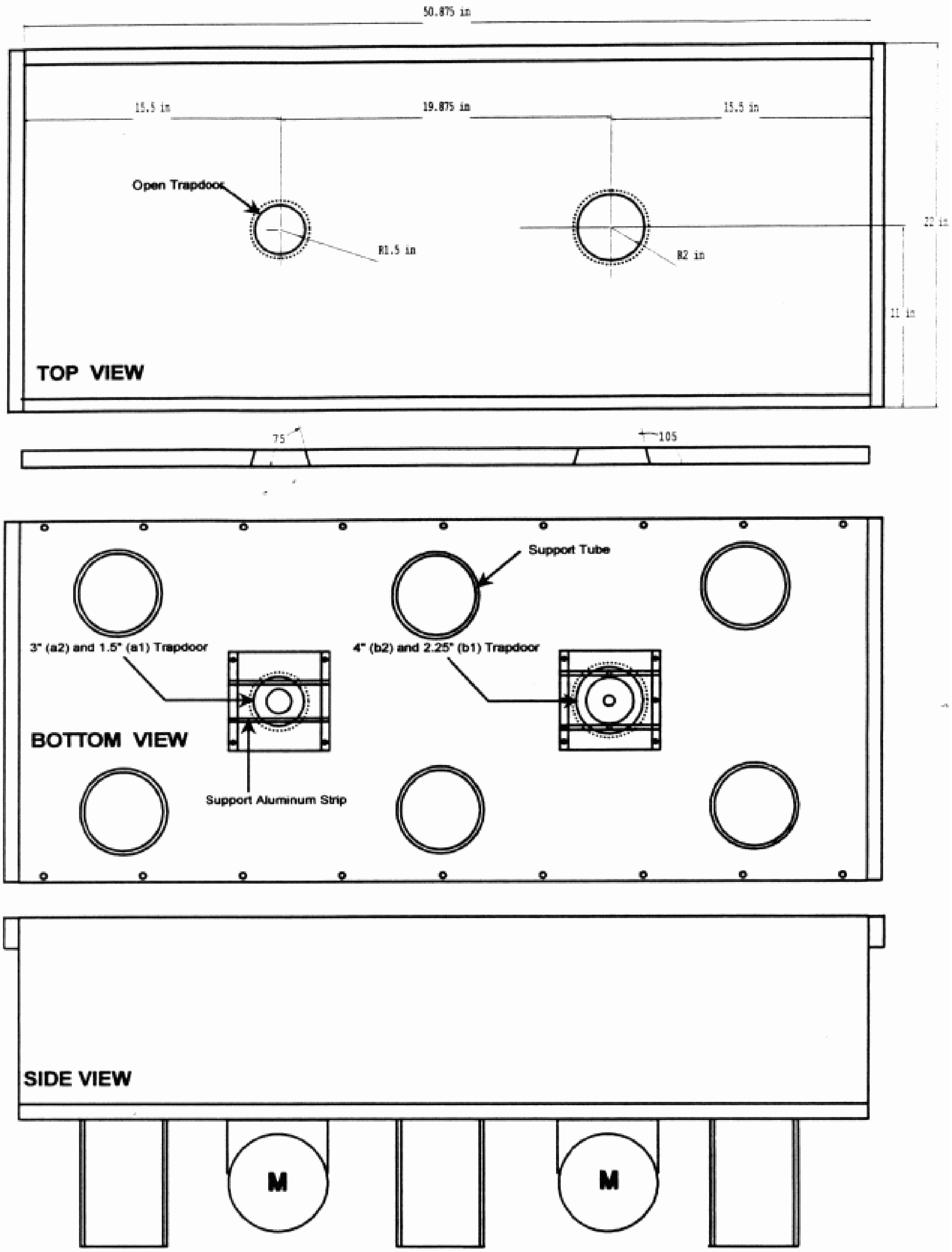


Figure 2: Container dimensions

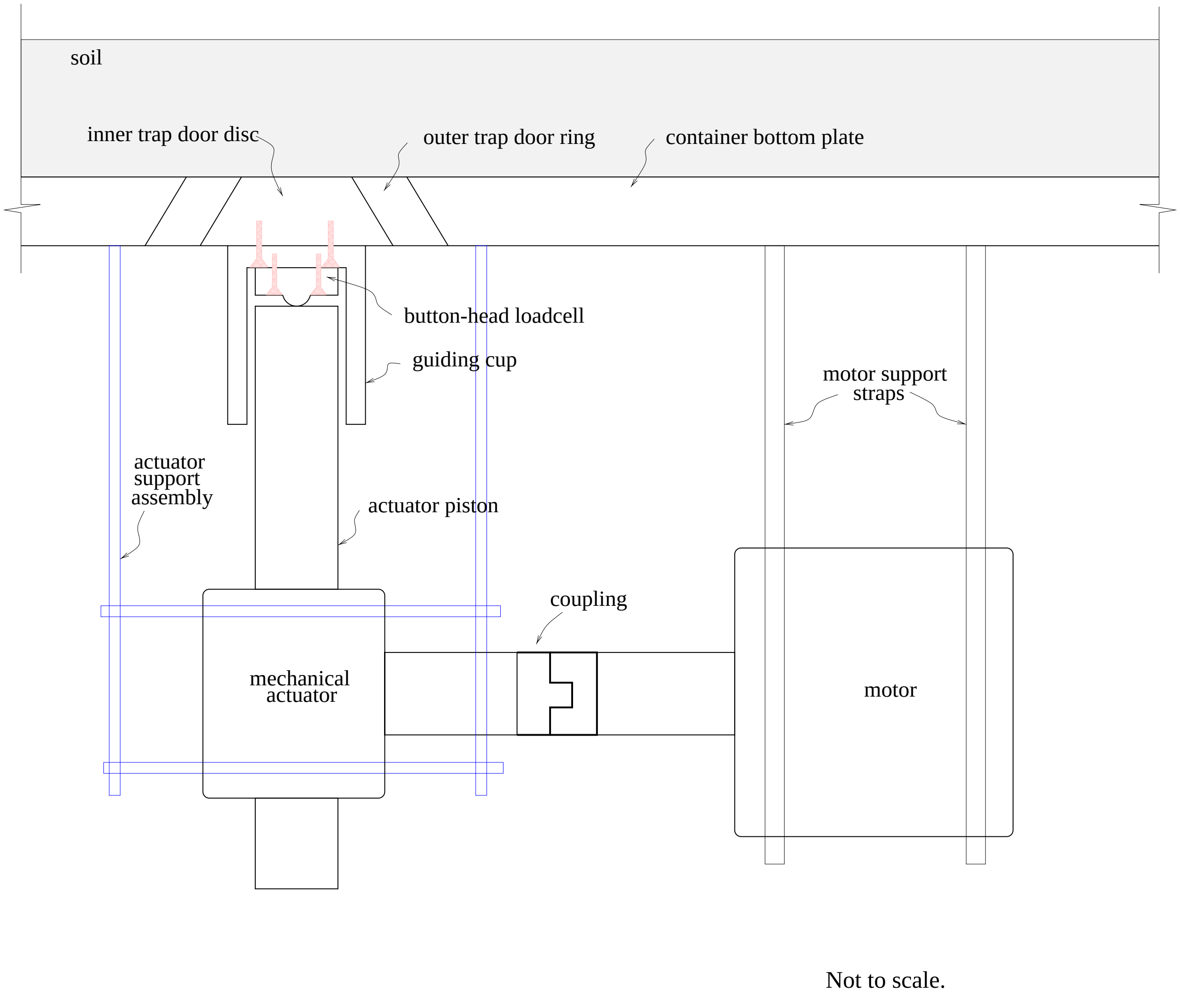
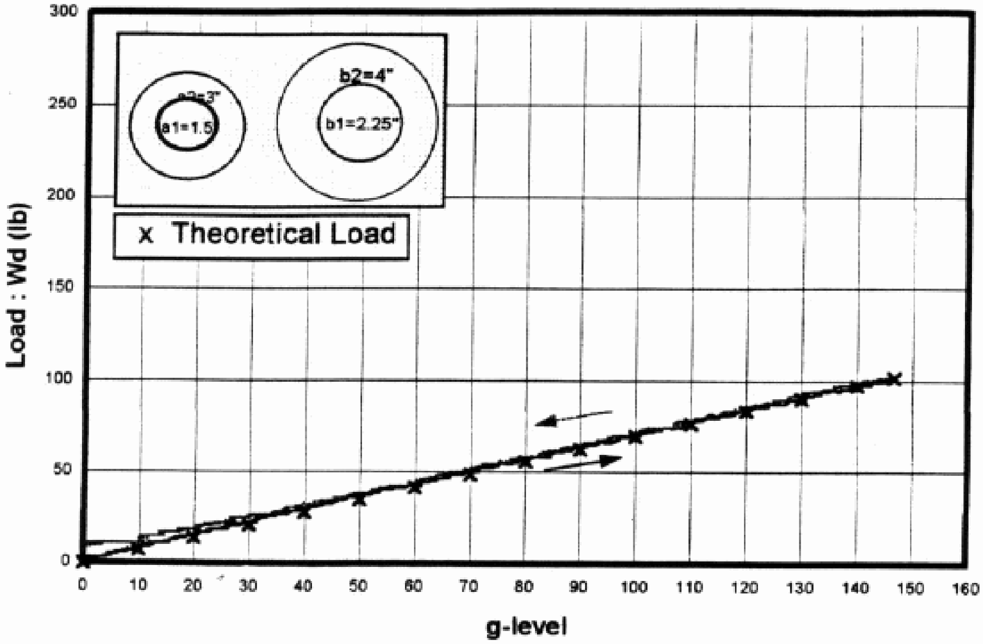
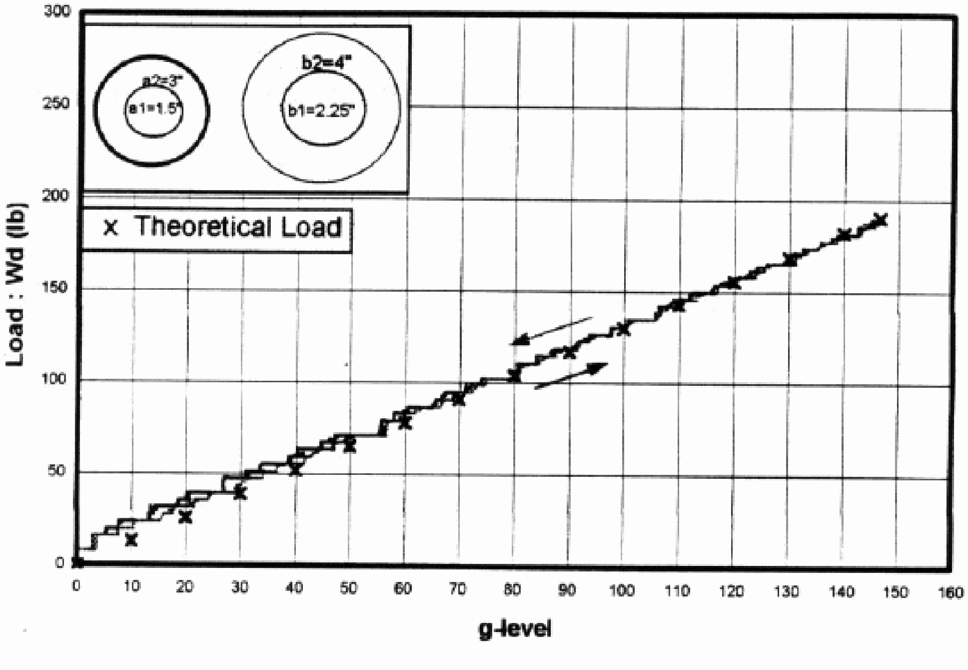


Figure 3: Trap door assembly

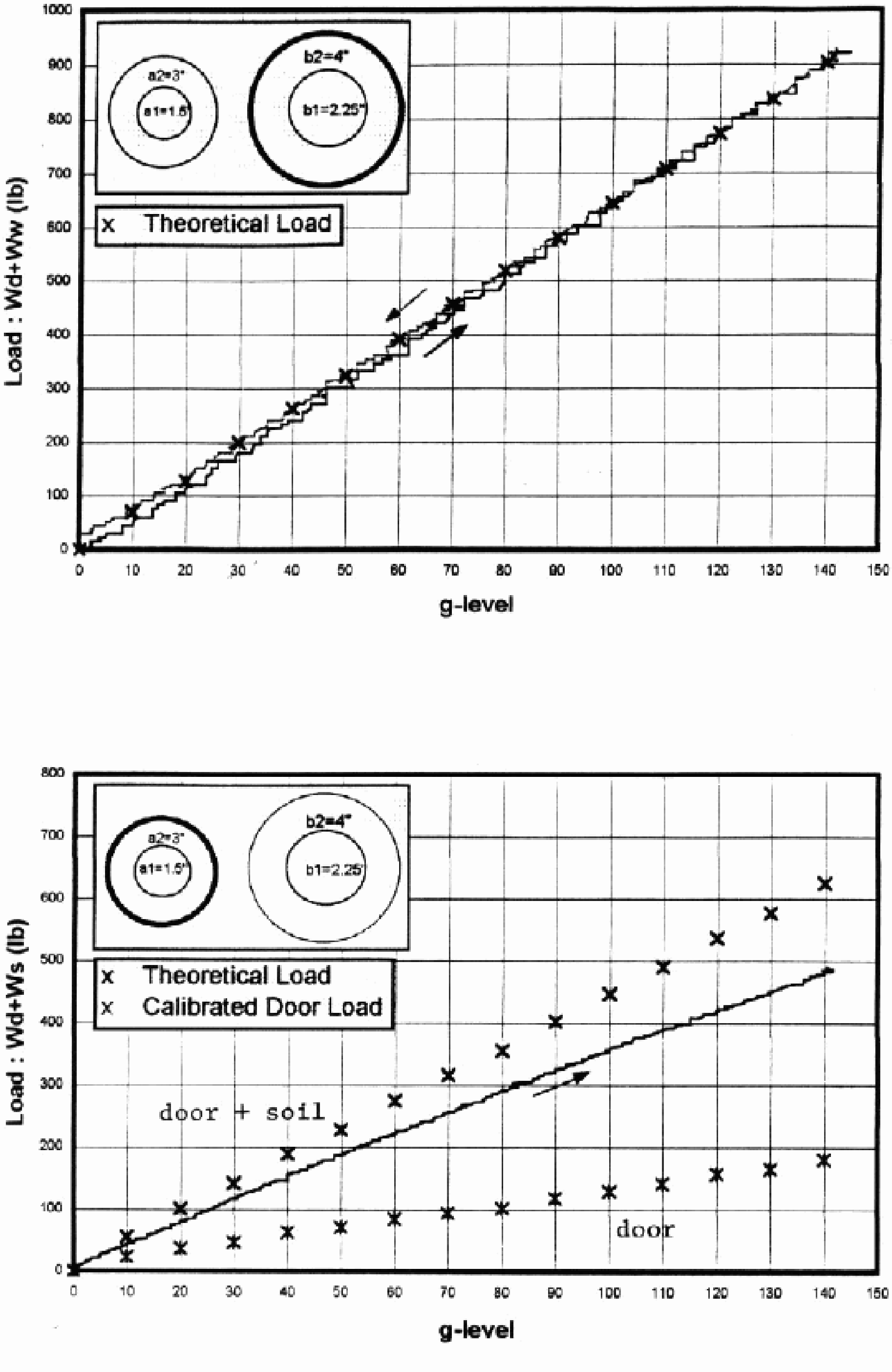


door a1



door a2

Figure 4: Centrifuge tests on empty doors a1 and a2



water reservoir

soil layer

Figure 5: Centrifuge tests on water reservoir and horizontal dry sand layer

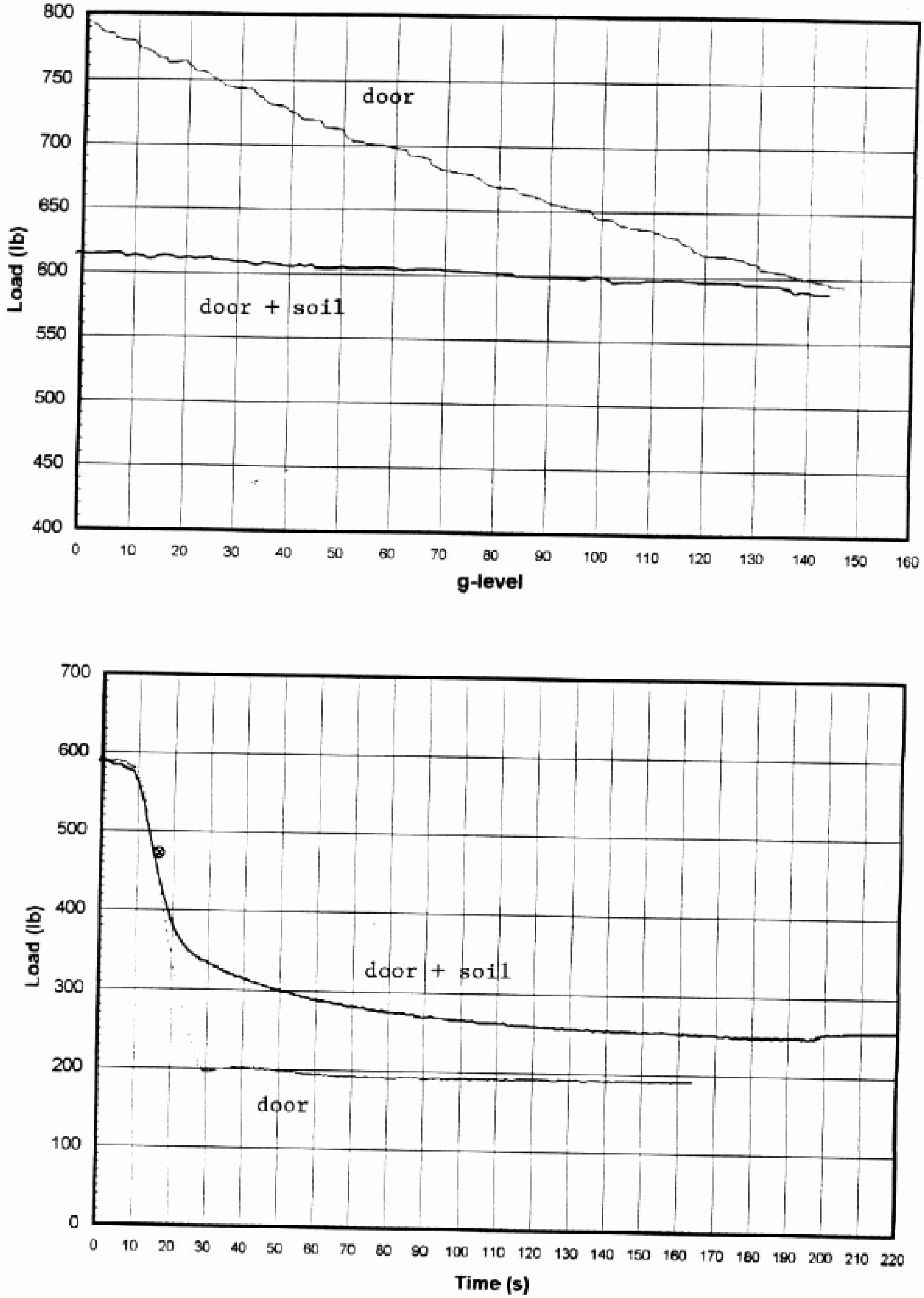


Figure 6: Centrifuge test on empty door and horizontal layer of dry sand with precompression load

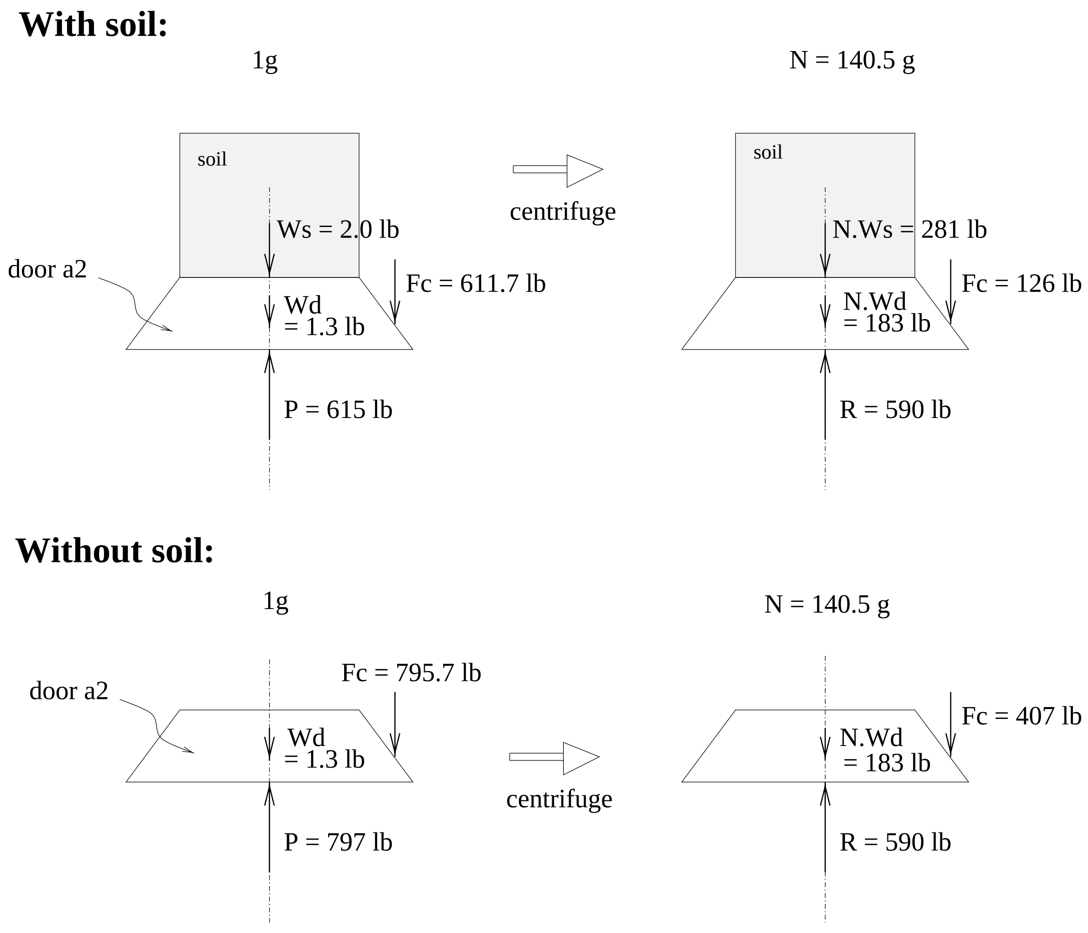


Figure 7: The concept of the application of precompression load

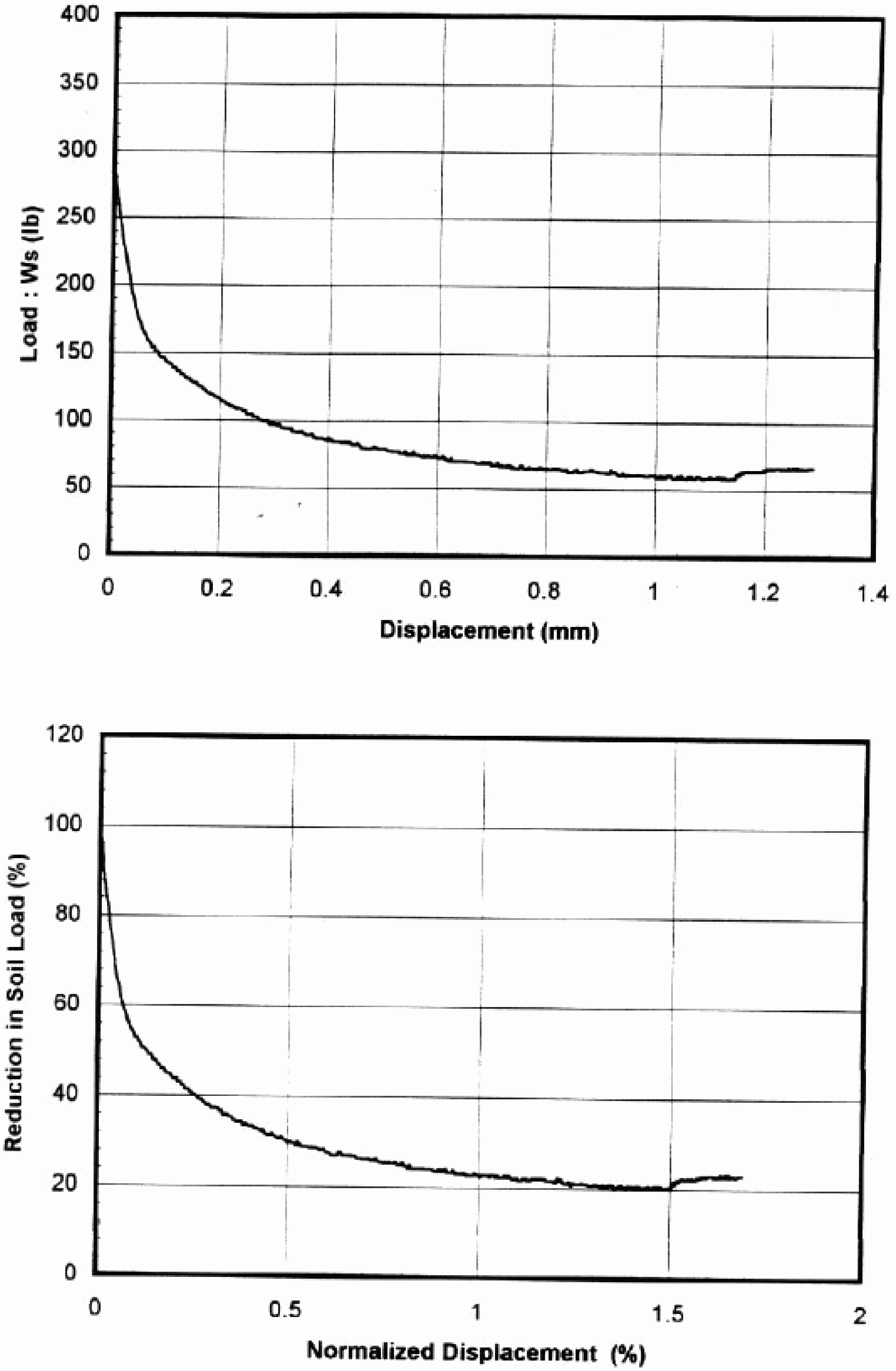


Figure 8: Reduction in soil load as the trap door displaced

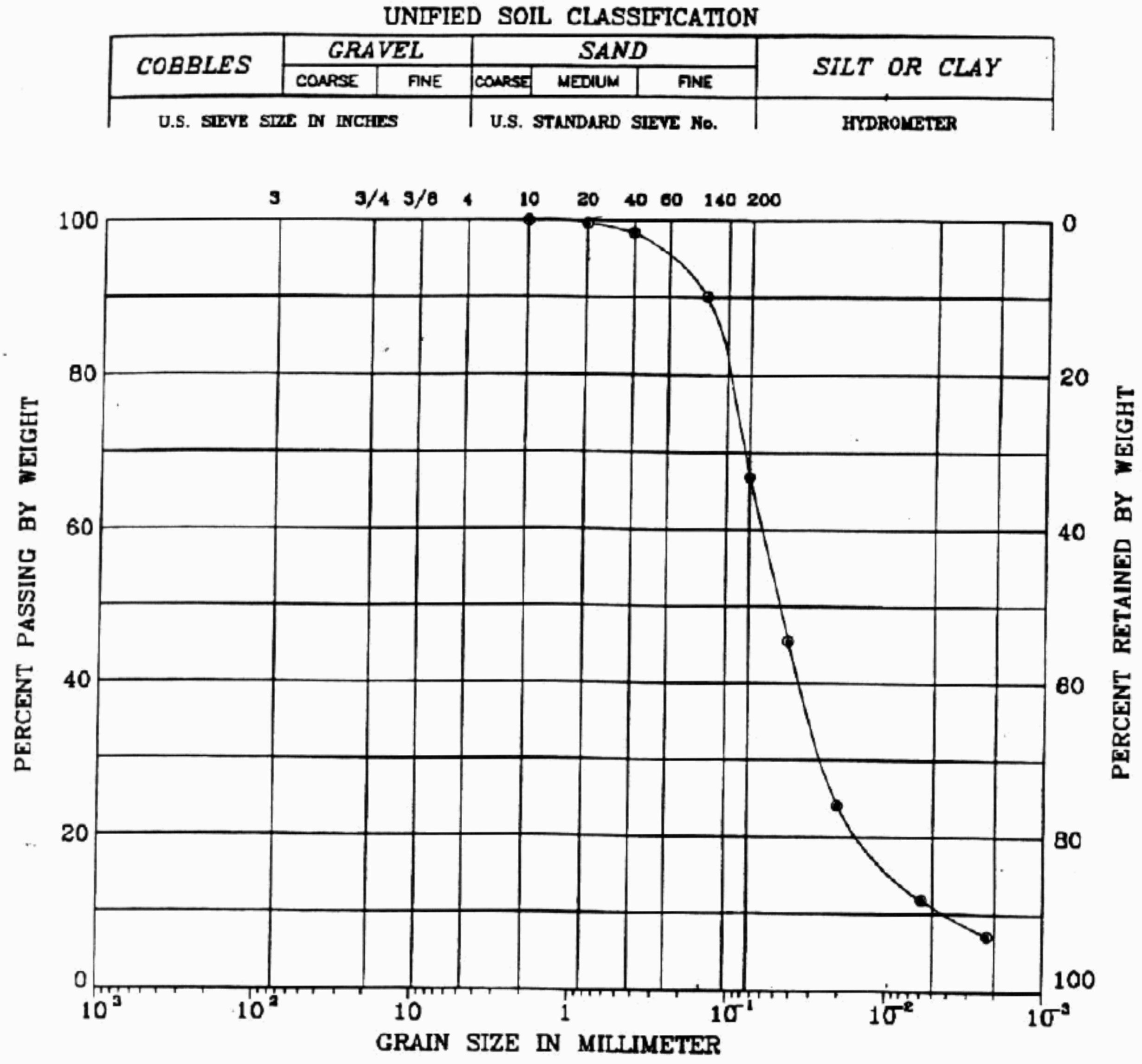
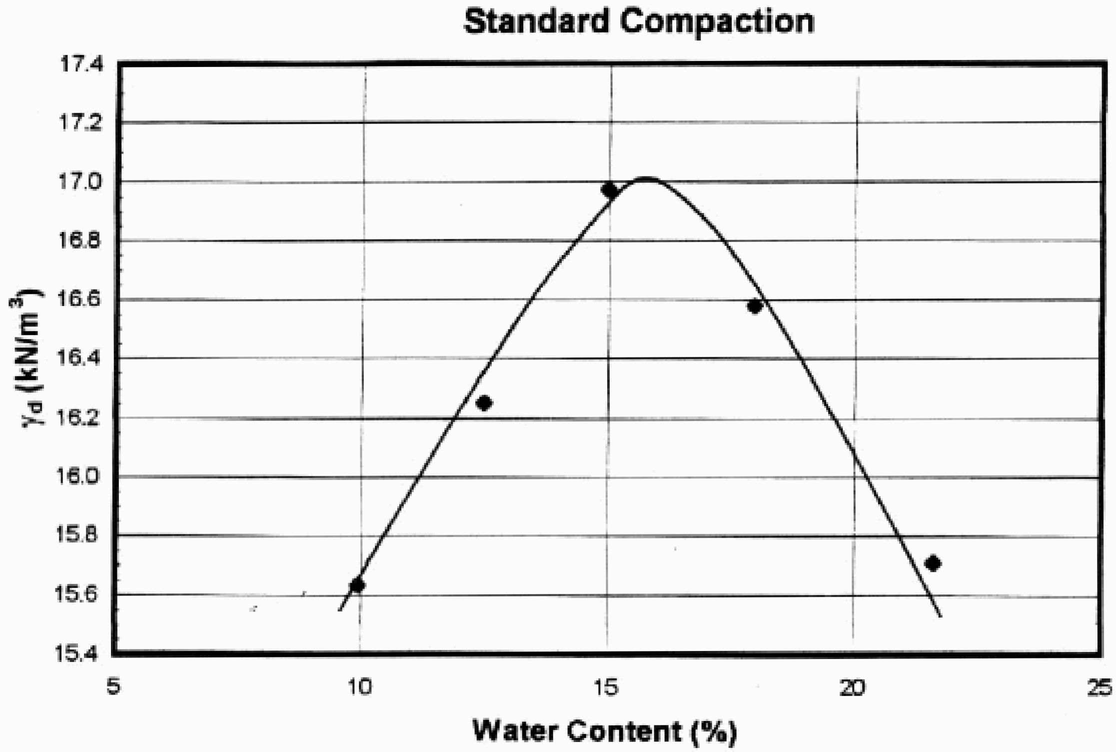


Figure 9: Grain size distribution curve for Bonnie silt



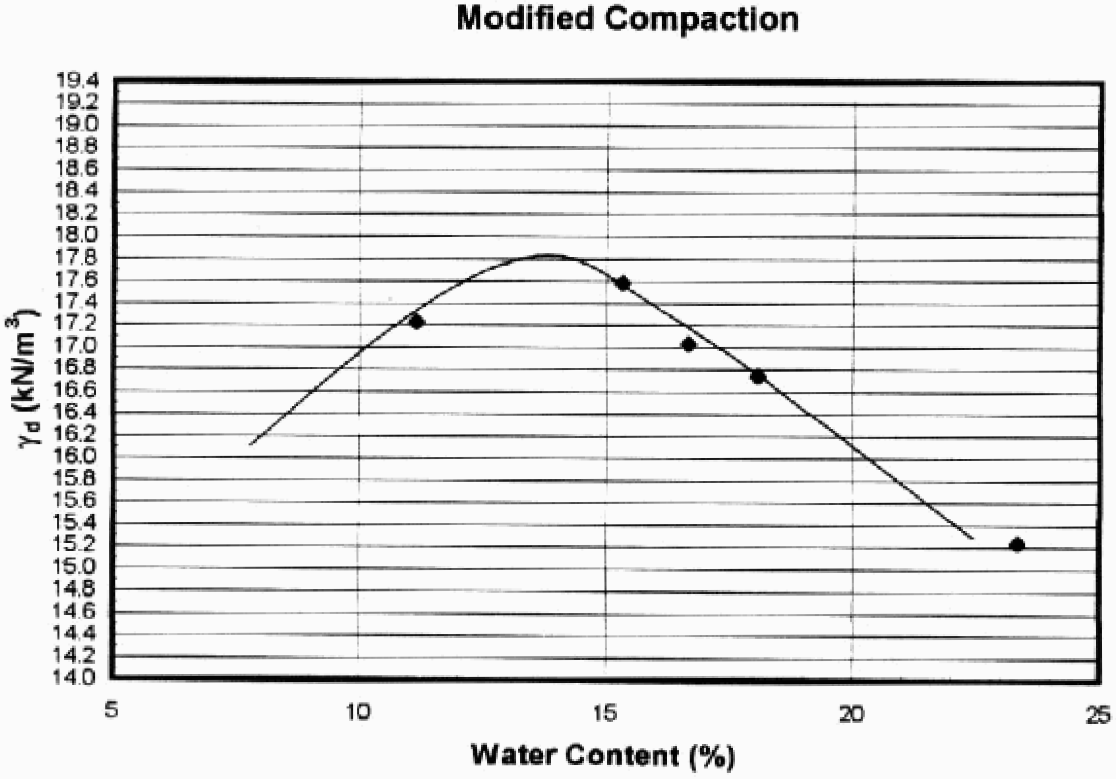


Figure 10: Standard and modified compaction test results on Bonnie silt