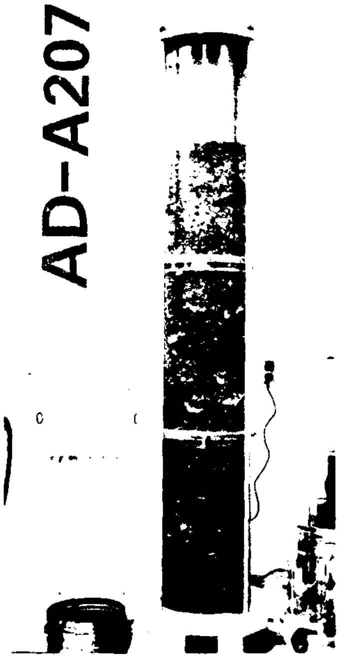
US Army Corps of Engineers

AD-A207 755



GEOTECHNICAL LABORATORY

MISCELLANEOUS PAPER GL-89-5

STUDY OF EMBANKMENT PERFORMANCE DURING OVERTOPPING AND THROUGHFLOW

Report 1

FEASIBILITY STUDY

by

Hon-Yim Ko, R. Jeffrey Dunn, Ebrahim Simantob

University of Colorado
Boulder, Colorado 80302

April 1989

Report 1 of a Series

Approved For Public Release. Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Contract No. DACW39-83-C-0011

89

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) Miscellaneous Paper GL-89-5
6a. NAME OF PERFORMING ORGANIZATION University of Colorado 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION USAEWES Geotechnical Laboratory
6c. ADDRESS (City, State, and ZIP Code) Boulder, CO 80302	7b. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39181-0631
8a. NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. DACW39-83-C-0011
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Study of Embankment Performance During Overtopping and Throughflow, Report 1, Feasibility Study

12. PERSONAL AUTHOR(S)
Ko, Hon-Yim, Dunn, R. Jeffrey, Simantob, Ebrahim

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Report 1 of a Series	FROM ______ TO ______	April 1989	81

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Centrifuge modeling Erosion Overtopping

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Overtopping of earth dams and embankments has resulted in great damages to property and facilities, and in some cases loss of life as well. Due to the large costs and possible consequences of full-scale overtopping studies and the limited accuracy of reduced scale model testing at natural gravity levels, testing of models in a centrifuge at increased gravity levels seems to be a suitable method for studying overtopping and erosion of earth embankments.

Tests on model earth and crushed rock embankments using the University of Colorado Geotechnical Centrifuge have indicated the feasibility of this method of testing. Failure modes in the models agreed well with those observed in actual overtopping events. In crushed rock embankments erosion began at the toe and progressed rapidly upstream, eventually leading to breaching failure of embankments. In clay embankments, erosion occurred over the entire downslope area below the spillway crest, with no breaching of the
(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

19. ABSTRACT (Continued).

crest occurring for the duration of overtopping flow utilized in the tests.

Embankment erosion in flight was recorded using a closed circuit video camera and video tape and a pair of 35mm SLR cameras, mounted to produce stereo pair photos of the embankment. Contour maps of the embankment surface were produced from the stereo pairs. Photographic records were verified by manual measurements of the eroded surface.

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

PREFACE

This study was conducted by the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado - Boulder under Department of the Army Contract No. DACW39-83-C-0011, "Study of Embankment Performance During Overtopping and Throughflow".

The investigation was conducted by Drs. Hon-Yim Ko and R. Jeffrey Dunn and Mr. Ebrahim Simantob during calender year 1983 under the general direction of Mr. S. Paul Miller (WES). Useful suggestions and comments by Mr. K.W. Cargill (WES) are appreciated. Mr. DeWayne Campbell of the U.S. Bureau of Reclamation was helpful in obtaining experimental soil materials. Mr. Milan Halek of the University of Colorado and Mr. Dario Carrera of Carrera and Associates, Denver, Colorado, provided valuable assistance with the stereo photography system. Mr. Carrera prepared contour maps of the eroded embankment from the stereo photographs. The report was written by Drs. Ko and Dunn and Mr. Simantob. Word processing was completed by Mrs. Patricia Wathen and Mrs. Kathy Van Veen.

Mr. Miller was the Contracting Officer's representative. The work was performed under the general supervision of Mr. C. L. McAnear, Chief, Soil Mechanics Division, Geotechnical Laboratory (GL), and Dr. W. F. Marcuson III, Chief, GL.

Acting Commander and Director of WES during publication of this report was LTC Jack R. Stephens, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENTS

U.S. Customary Units of Measurement Used in this Report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.400	millimetres
feet	0.3048	metres
cubic feet per second	0.0283	cubic metres per second
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	0.15709	kilonewtons per cubic metre

STUDY OF EMBANKMENT PERFORMANCE DURING OVERTOPPING AND THROUGHFLOW

PART I: INTRODUCTION

Use of Centrifuge to Study Overtopping

1. Embankment overtoppings in recent years have caused millions of dollars in damages to the embankments, their appurtenances, and downstream properties, while threatening downstream life. To arrive at better design methods of embankments resistant to erosion during overtopping, it is necessary to first obtain a better understanding of the overtopping phenomenon and the failure mechanisms that occur due to overtopping. As for other types of geotechnical structures, these observations could best be made on full scale prototypes, which can, however, be very costly. Since embankments are usually unique in their design, it is easy to recognize that many full scale tests will be required to collect sufficient data for a proper understanding of the influence of various parameters, such as soil type, compaction, construction techniques, flow rates, and embankment geometry.

2. The literature contains but a few recorded embankment overtopping events, confirming the scarcity of data and the difficulty encountered in the attempts to collect useful information. The governing factors that control overtopping and failure of an earth embankment are gravity-induced, suggesting that the centrifuge modeling technique is applicable to such situations.

3. Modeling embankment overtopping phenomena in the centrifuge is an attractive means of collecting data and performing parametric studies, since the centrifuge experiments can be readily conducted at low costs in comparison to measurements on full scale structures.

4. This report describes a feasibility study utilizing the centrifuge to model embankment performance during overtopping and throughflow. The work was carried out in the 10 g-ton geotechnical centrifuge at the University of Colorado at Boulder. Due to the relatively small capacity of this centrifuge, the study concentrated on developing techniques of simulating the overtopping, in particular, of transmitting and maintaining the large flow rate that was required for the experiment. In addition, techniques also were developed, during the study, to measure the depth of erosion of the embankment.

Outline of Report

5. In Part II of this report, the centrifuge system used for the study is described, with emphasis on the modifications that were made for the specific needs of this project. In Part III, the selection of the soil materials and the methods of model preparation of the test models are described. In Part IV, the procedure followed to conduct the overtopping experiments is described. Part V contains the experimental results, while Part VI contains the conclusions and recommendations regarding the feasibility of such overtopping experiments in the centrifuge.

PART II. DESCRIPTION OF CENTRIFUGE SYSTEM

The Centrifuge

6. The 10 g-ton geotechnical centrifuge which has been in operation at the University of Colorado at Boulder since 1978 is shown schematically in Figure II-1. This centrifuge is a Genisco Model 1230-5 G accelerator with a rebuilt symmetrical rotor to carry swinging baskets at the ends. The radius to hinges where the baskets are attached is 42 in. and that to the bottom of the baskets in the swing-up positions is 53.5 in. One basket carries the test payload, while the other carries the counterweights. The maximum payload size is 18 in. x 18 in. x 12 in. The rated capacity of the centrifuge is 10 g-ton, (typically 100 g on a 200 lb payload).

7. The centrifuge is equipped with 56 electrical slip rings and 2 hydraulic rotary joints which have 0.250 in. ID tubing inside the centrifuge. These rotary joints were judged inadequate in supplying the flow rates required for the overtopping experiments in this project. A new addition to the existing centrifuge system, made to satisfy this requirement, is described in a later section.

8. A closed-circuit television camera is carried on the centrifuge rotor for inflight test monitoring. A 35mm SLR camera with self-winder is also mounted on the centrifuge and operated by remote control for inflight still photography.

Sample Container

9. The embankment overtopping experiments were conducted in a

sample container specially built for the project. This container is shown schematically in Figure II-2. Due to limited space in the swinging basket, only the crest and downstream slope of the embankment were modeled in the centrifuge tests. This model embankment was placed on a floor supported 3.0 in. above the bottom of the container for the crushed rock embankments and 6.0 in. above the bottom in the clay embankment tests. The reservoir upstream of the test embankment received water from a water conveyance system, described later, through a pipe with a diffuser at its tip to ensure even flow along the embankment crest. Water from this reservoir was allowed to overtop the test embankment and to drain into the compartment below the support floor from which it was allowed to escape through ports on the sides of the container.

10. A similar container was placed on the counterweight basket to receive and conduct water in the same manner, so that balance of the centrifuge arm was maintained during the experiment.

Water Conveyance System

11. Using the formula for a broad crested weir, the required flow rate to overtop a 8 in. wide dam with a water depth of 0.6 in. under 100 g conditions was estimated to be around 0.2 cu. ft./sec. This exceeds the capacity of the two existing hydraulic rotary joints in the centrifuge. A new means of supplying this flow rate was therefore needed.

12. The water conveyance system adopted for the overtopping experiments is shown in Figure II-3 and consisted of a 4-in. ID alumi-

num tube bent into a 24 in radius toroid, mounted on the underside of the centrifuge arm. The inside of the toroid was slit all around, to receive water introduced through two stationary pipes coming up from the bottom of the centrifuge enclosure. Water caught in the rotating toroid is allowed to flow under the centrifuge force to the test container (as well as to the balancing end to maintain centrifuge balance), and after overtopping the test embankment, is allowed to escape through holes in the side walls of the test container. The water then drains through a hole in the bottom of the centrifuge enclosure into a tank below and is recirculated by a pump. A control valve in the line downstream of the pump is used to regulate the flow of water in the system.

Embankment Erosion Monitoring and Measurement

13. In this section, the water depth gauging system, the video system for inflight test monitoring, the twin camera system for stereo photography, and embankment erosion measurement techniques are described.

Water Depth Gauging System

14. The water depth in the compartment upstream of the test embankment and overtopping water depth above the embankment crest were monitored by a set of brass rods, 0.063 in. in diameter, which were mounted from a plexiglas plate fastened above the embankment crest. The tips of these rods were set over a range of heights above the embankment crest. The rods were wired individually to a common conductor which was mounted with its tip at the mid-depth of the back compartment. As water rose, making contact with the tip of one rod, a

corresponding light on a readout panel outside the centrifuge lit up. The gaps between tips of successive rods could be adjusted to provide a more precise measurement of the water depth. The rods were adjusted to provide for measurement of the water depth to the nearest 0.1 in. The configuration of this system is shown in Figure II-4.

15. Measurements of flow rate were not made in the experiments completed in this study. However, flow rates are being measured as part of the studies making up the contract extension.

Video System

16. A closed circuit television video camera, permanently mounted near the axis of the centrifuge, is pointed at the test package at all times. The transmitted picture is displayed on a television monitor and can be recorded on a 3/4 in. video cassette tape.

Twin Camera Stereophotography System

17. A second 35 mm SLR camera was added to the still photography system, so that stereo pairs could be taken. Different mounting positions were tried. The final configuration adopted is shown in Figure II-5. By putting the two cameras side by side, with one tilted slightly toward the other, nearly complete overlap of the photographs was obtained. Film was advanced by identical self winders, activated through the electrical slip rings, allowing successive photographs to be taken during centrifuge operation.

Embankment Erosion Measurement

18. The stereo pair photographs taken by the twin camera during the experiments were analyzed by routine aerial photogrammetry techniques, and contour maps of the eroded embankment plotted. From

these maps, the depth of erosion could be measured.

19. The accuracy of the calculations was confirmed by taking direct measurements of the erosion depths in both the clay and crushed rock embankments after completion of overtopping. Additional measurements were completed on the clay embankments by stopping the centrifuge during overtopping. These direct measurements were made at 8 points along two cross-sections on the embankment, which were located horizontally at 1.0 in. and 4.75 in. downstream of the crest, in the crushed rock embankments, as shown in Figure II-6, and at the crest and 4.75 in. downstream of the crest in the clay embankments as shown in Figure II-7.

20. Attempts were made to dye the crushed rock material using a variety of oil soluble dyes. The crushed rock materials did adsorb the dye; however, the intensity of color achieved did not increase the visualization of the erosion process sufficiently to warrant the use of colored layers of soils in the embankments.

21. Differently colored layers of the clay materials were not utilized due to the impact compaction method used, which tended to intermix materials between layers.

22. Instead of utilizing thin wire stakes buried in the soil, and thus subject to loss by erosion, four control points were marked on the experimental basket, adjacent to the embankment crest and toe. These points served as reference markers during analysis of the stereo photographs.

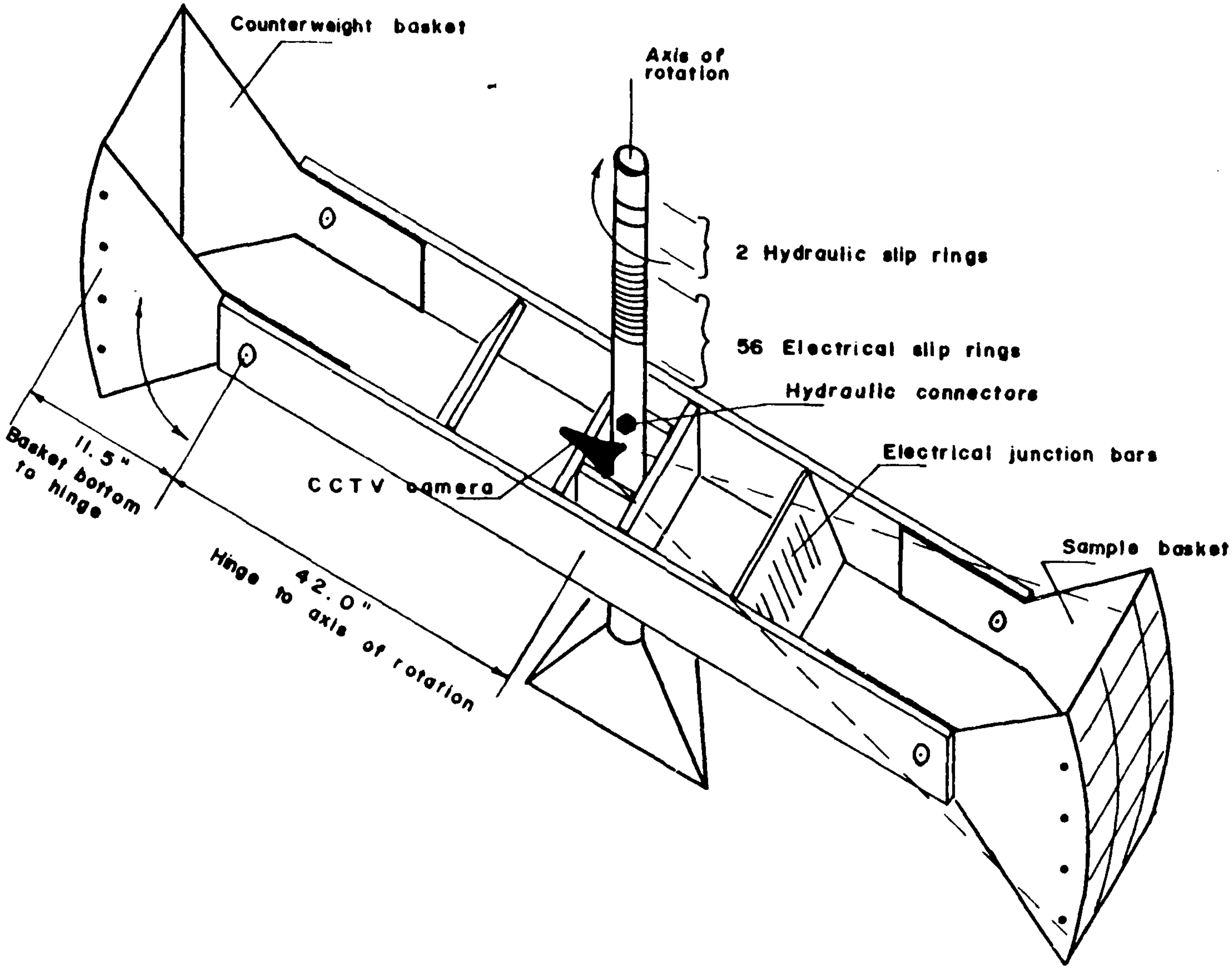


Fig. II.1 Schematic of 10 g-ton geotechnical centrifuge

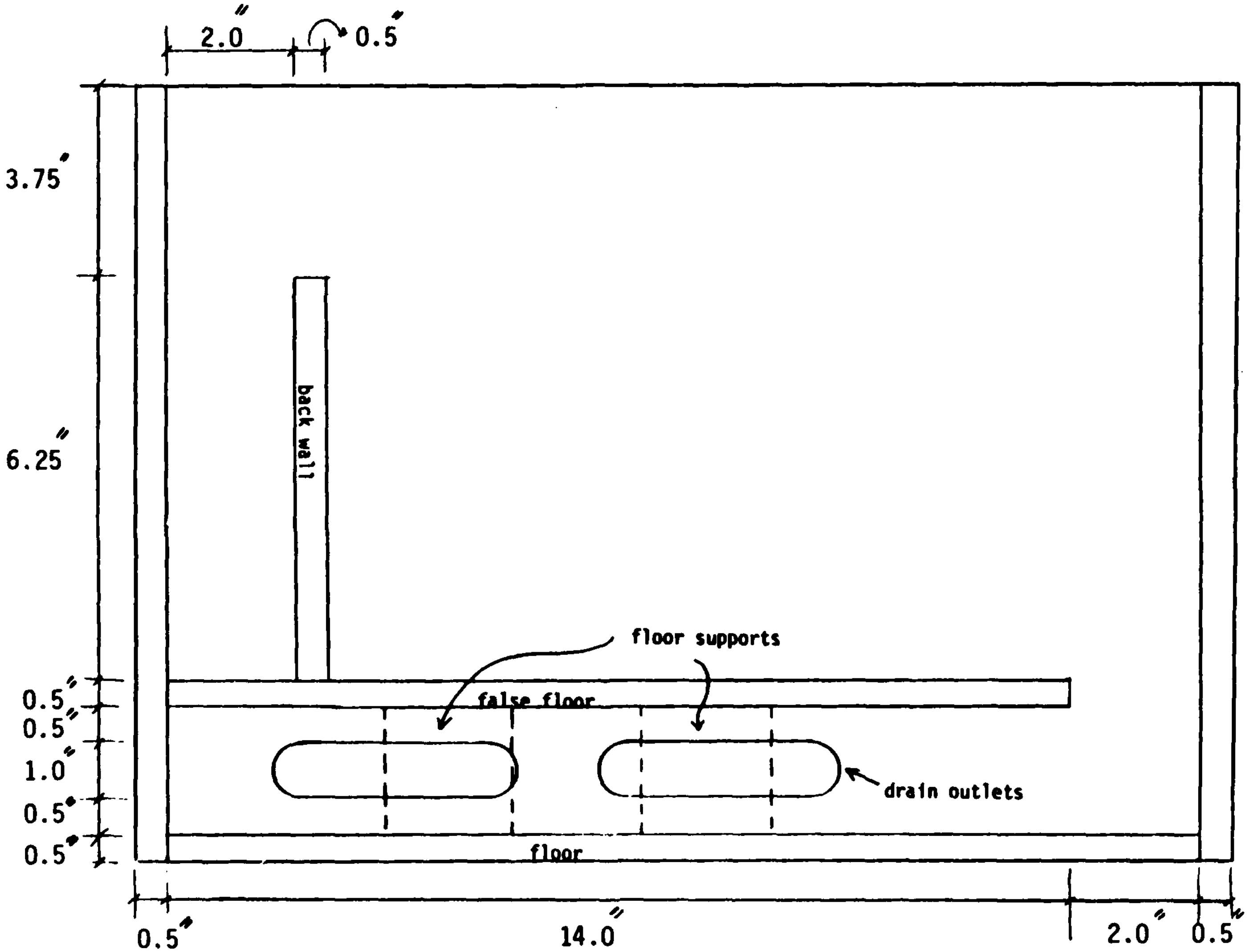


Fig.II.2 Sample container schematic

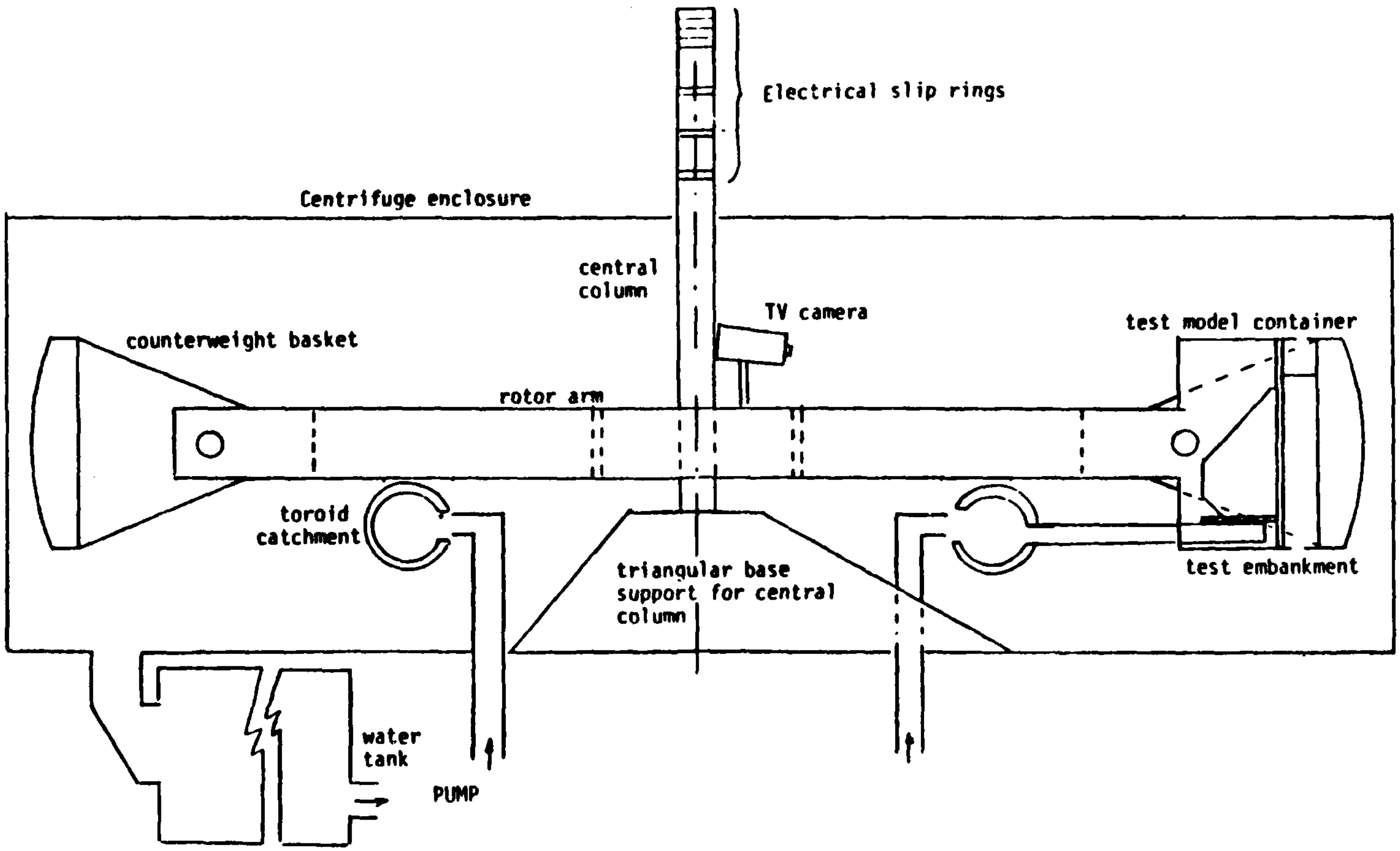


Fig.II.3 Schematic drawing of centrifuge and the toroid catchment system

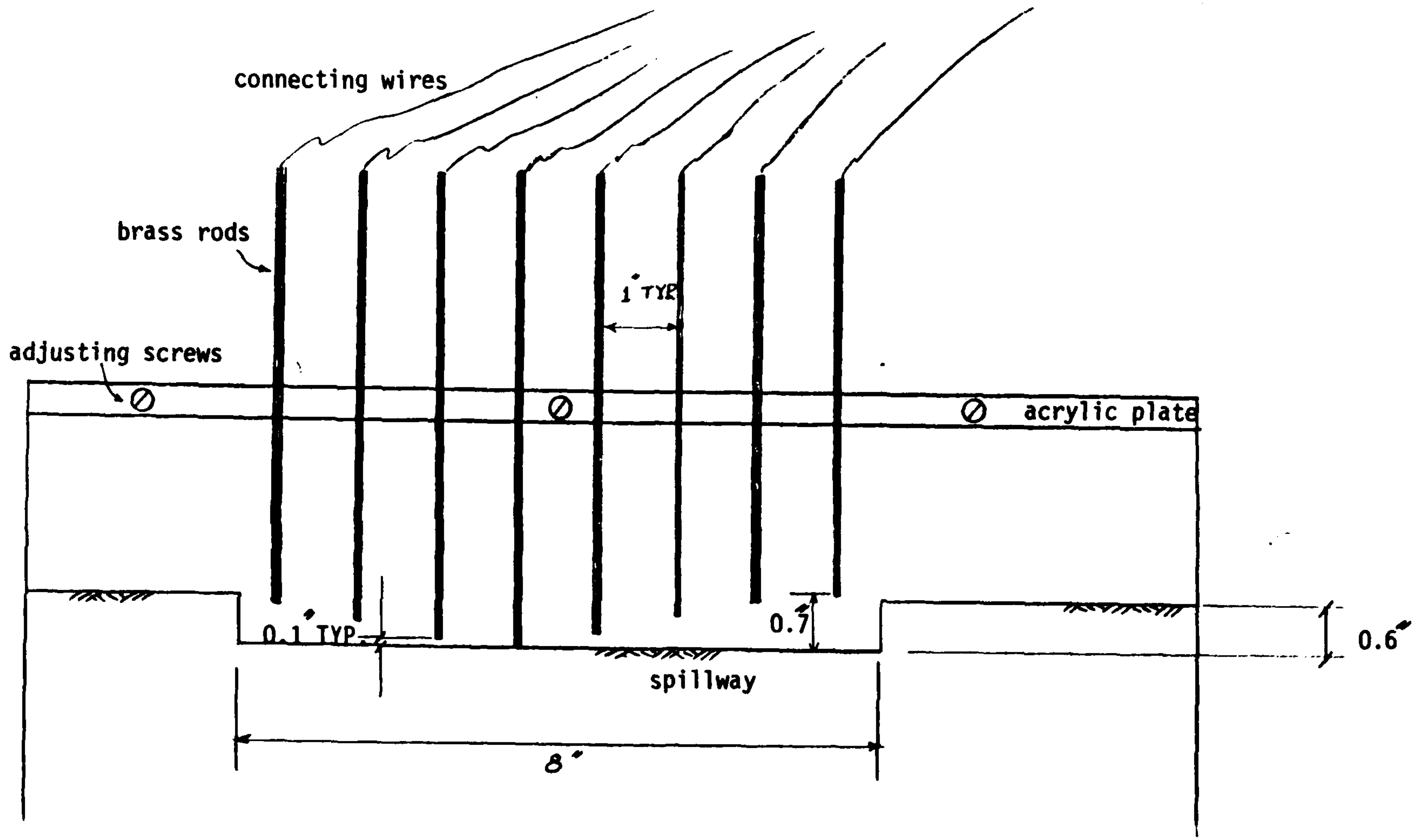
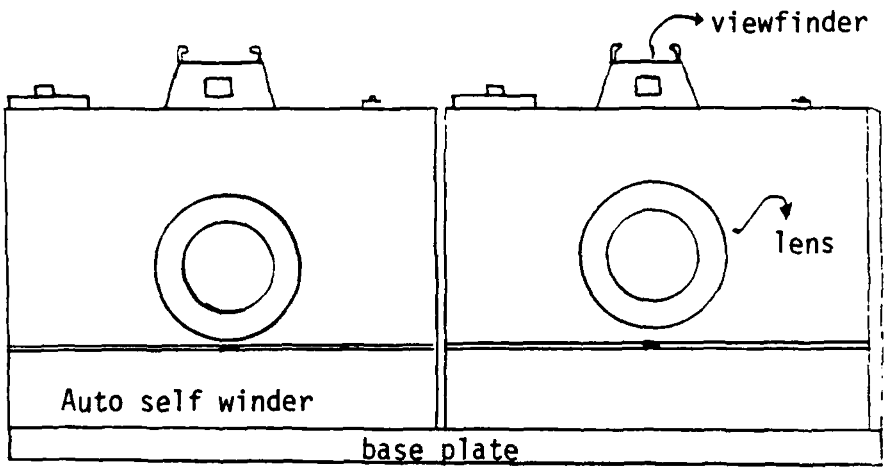


Fig. II.4 Water depth monitoring system located over the spillway



front view of the system

plan view of the system

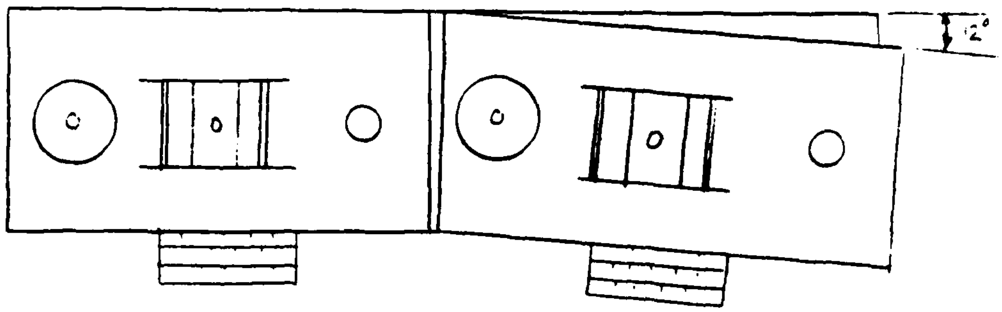
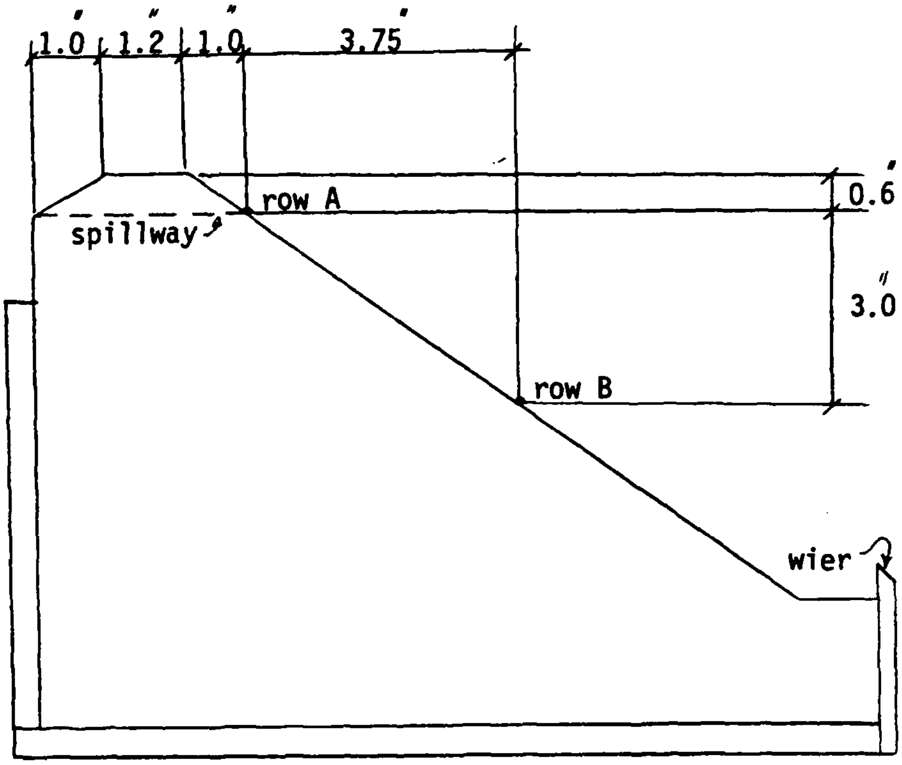
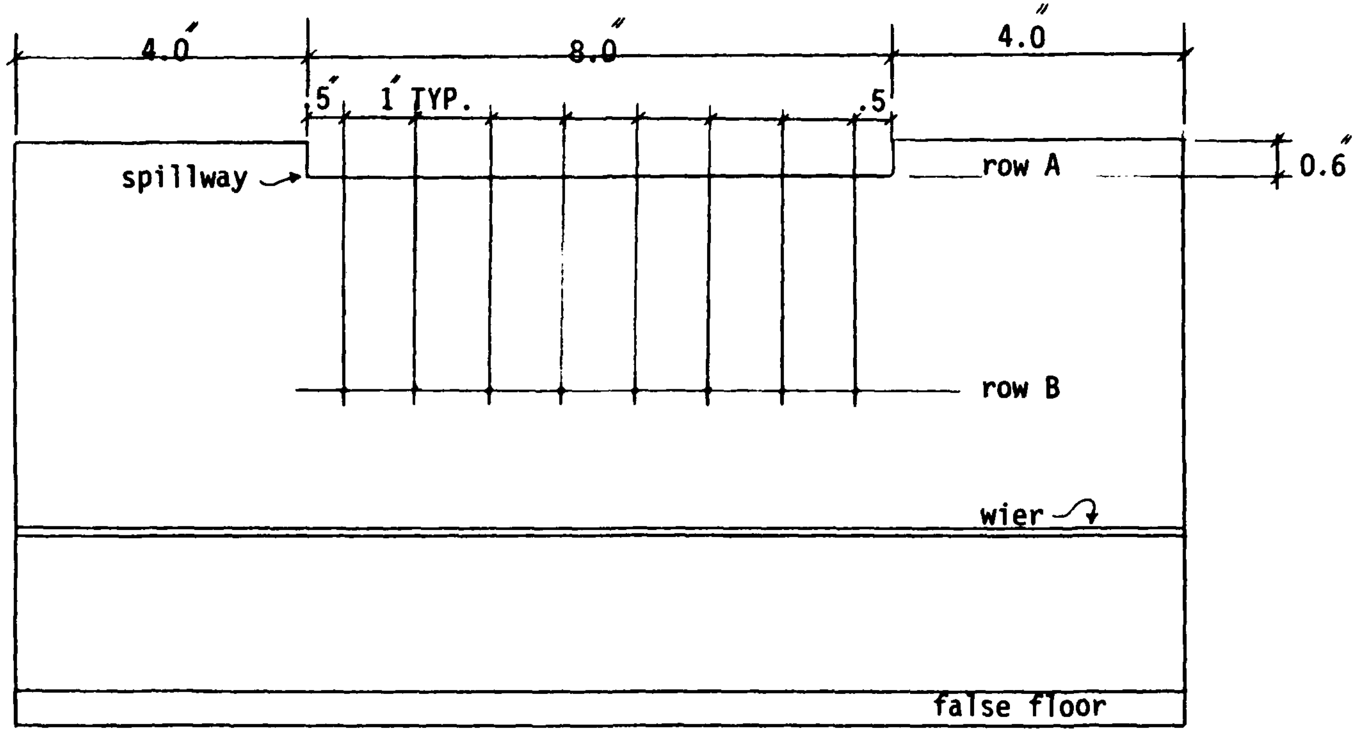


Fig.II.5 Camera system used for stereo photographic measurements



(a)

Fig.II.6 Manual measurement locations for crushed rock embankments, (a) Side view



(b)

Fig.II.6 Manual measurement locations for crushed rock embankments,
(b) Front view

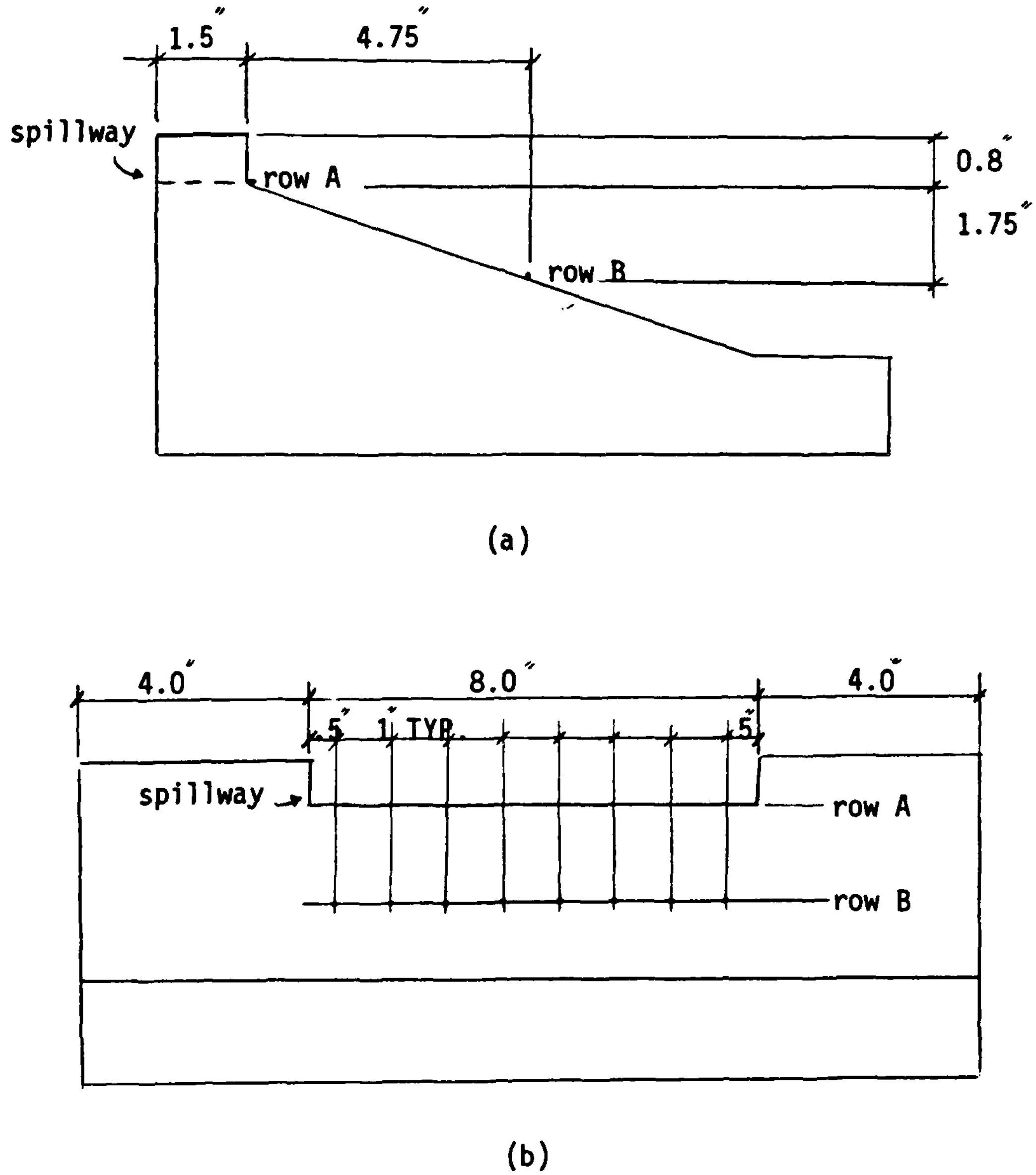


Fig. II.7 Manual measurement locations for clay embankments, (a) Side view , (b) Front view

PART III: TEST MATERIALS AND PREPARATION OF SAMPLES

Soil Materials

23. Two soils were used for embankment construction. Silty sand modeled a crushed rock material, while a silty clay soil represented fine-grained embankment materials.

Crushed Rock Material

24. The specified grain size distribution range for the prototype crushed rock material is shown in Figure III-1, along with the range for a 100th scale model. The grain size curve for the soil used to construct the crushed rock embankments is also shown in Figure III-1. The soil used consisted of a mixture of various sand sizes from the University of Colorado Civil Engineering Laboratories, and Bonny Loess Silt obtained from the U.S. Bureau of Reclamation (BUREC) Research Laboratory in Denver, Colorado. This silt is a low plasticity material with 90% by weight passing the #200 sieve. The test soil, Unified Soil Classification - SM, was batched by weighing appropriate weights of material retained on the #4, 8, 16, 30, 50, 100, and 140 sieves and adding 45 percent by weight of the Bonny Loess Silt. The segment of the grain size distribution curve for the experimental soil which is finer than the #200 sieve is based upon results of a hydrometer analysis completed on the silt soil. As shown in Figure III-1 the experimental soil was somewhat coarser than the range for the 100th scale model. However, it was felt that this variation would not measurably affect the results of the investigation.

25. The compaction characteristics of the silty sand were evaluated using Standard Proctor compaction, ASTM Test Method D698, and the results of this evaluation are shown in Figure III-2. The soil was found to have a maximum dry density of 121.0 pcf at an optimum moisture content of 11.8%.

Clay Material

26. The clay test material was obtained from the U.S. Bureau of Reclamation (BUREC) Research Laboratory in Denver, Colorado. Because of over 20 years of use in BUREC training the soil's engineering properties are well defined. As indicated by the grain size curve shown in Figure III-3, the soil is a sandy silty clay. It has a Liquid Limit (LL) of 28, a Plasticity Index (PI) of 15 and is classified as a CL material (Unified Soil Classification). Standard Procter Compaction data provided by BUREC is shown in Figure III-4. The maximum dry density is 120.0 pcf at an optimum water content of 12.0%.

Water for Overtopping Flow

27. Water used in the experiments was domestic supply obtained from the civil engineering laboratory outlets. The water became slightly turbid when placed in the centrifuge holding tank, and during the course of any centrifuge experiment was observed to be carrying some fine material in suspension. However, it is felt water with suspended solids, rather than clear water better simulated conditions of prototype overtopping.

28. Preliminary overtopping experiments, using the crushed rock material, indicated that erosion occurred very rapidly. Overtop-

ping flow apparently was much more important in generating erosion than throughflow. Therefore, measurements of the crushed rock material's permeability were not felt to be necessary and were not completed.

Preparation of Model Embankments

Crushed Rock Embankments

29. The silty sand used for the crushed rock embankment models was batched by thoroughly mixing appropriate air dry weights of individual sand size particles and the Bonny Loess silt. The soil was then mixed in two batches in an electric mixer with the appropriate quantity of water to attain the Standard Proctor optimum water content of 11.8%. The material was then compacted in eight thin layers directly in the sample basket to a dry density of 109 pcf ±2 pcf (90% Standard Proctor Maximum Dry Density). The top of each layer was scarified thoroughly to ensure good contact with the subsequent layer. Static compaction utilizing a hydraulic loading machine, and following undercompaction procedure discussed by Ladd (1978) was used to achieve a uniform density in each of the compaction layers. The compaction procedure developed a rectangular block o' soil 16 inches wide, 11.5 inches deep, and 10 inches high.

30. Embankment slopes and the spillway were then carefully trimmed to the configuration shown in Figure III-5 using soil spatulas and a small cement trowel. The 0.5 inch high, 16 inch long weir, used to develop a tailwater was installed at the downstream end of the

embankment, and the sample was then ready for installation in the centrifuge.

Clay Embankments

31. Sufficient silty sandy clay to construct one embankment was mixed in two batches with water to achieve Standard Proctor optimum water content of 12% using an electric mixer. Sufficient material for each compaction layer was then compacted in 1.0 inch thick layers directly in the sample basket. Due to the variation in embankment geometry from that of the crushed rock embankments, the clay embankment was constructed over a wood spacer block 2.25 in. high. Impact compaction using both ASTM D698 and ASTM D1557 type drop hammers was used to form the samples. A carpenter's hammer was used to compact material in the corners of the sample basket that were not accessible to the drop hammers. Layer heights were carefully monitored with a machinist's scale, and sufficient blows of the compaction hammers were used to achieve the proper layer thickness and thus a dry density of 114 pcf equal to 95% of Standard Proctor Maximum Dry Density. The resulting rectangular block of compacted clay was then carefully trimmed to test configuration shown in Figure III-6 using soil spatulas and a small cement trowel. Silicon caulking was applied between the clay and the aluminum wall immediately behind the dam crest to minimize the potential for leakage between the sample container and the embankment. The 0.5 inch high weirs used to develop a tailwater were installed and The sample was then ready for installation in the centrifuge.

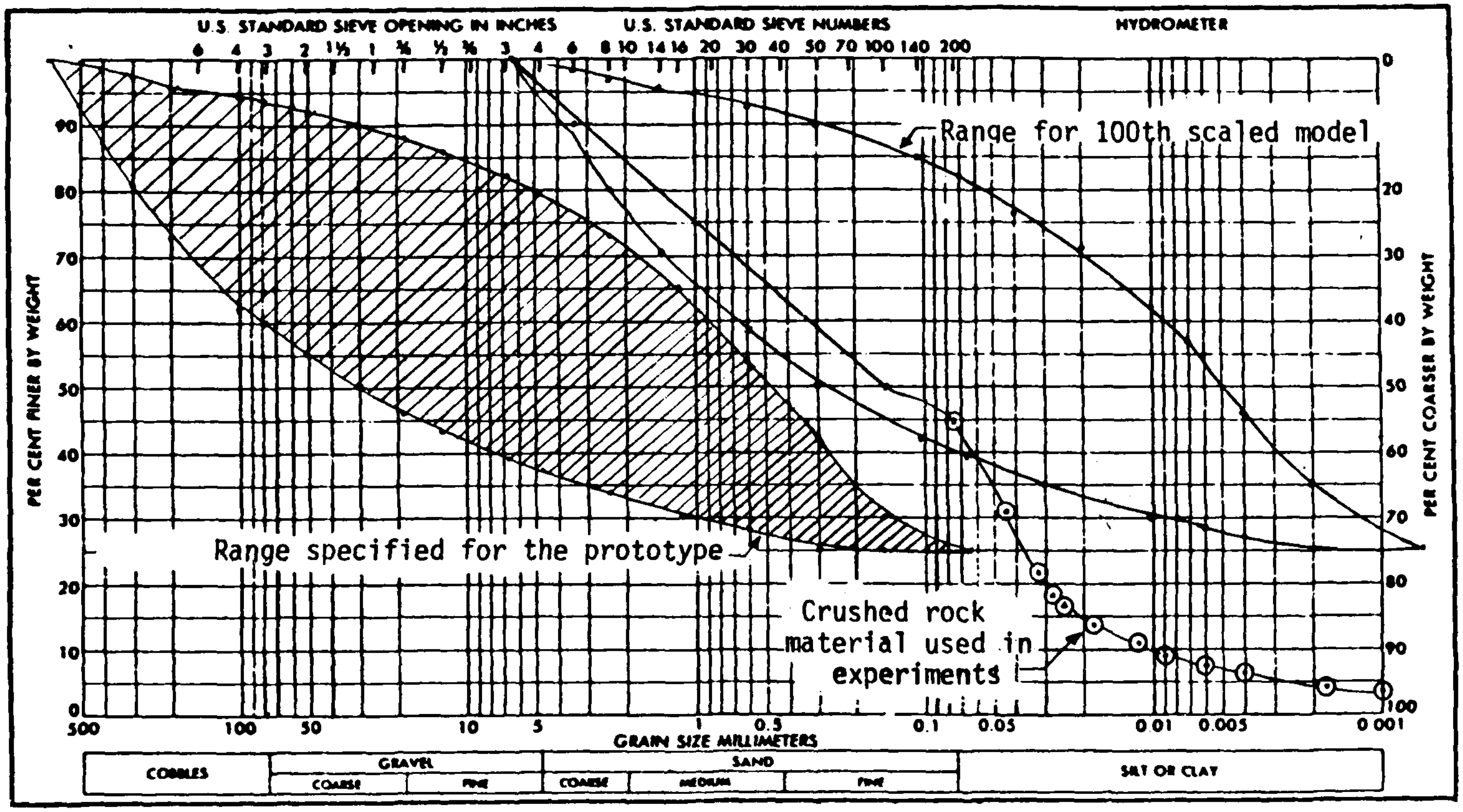


Fig.III.1 Crushed rock material grain size distribution curve

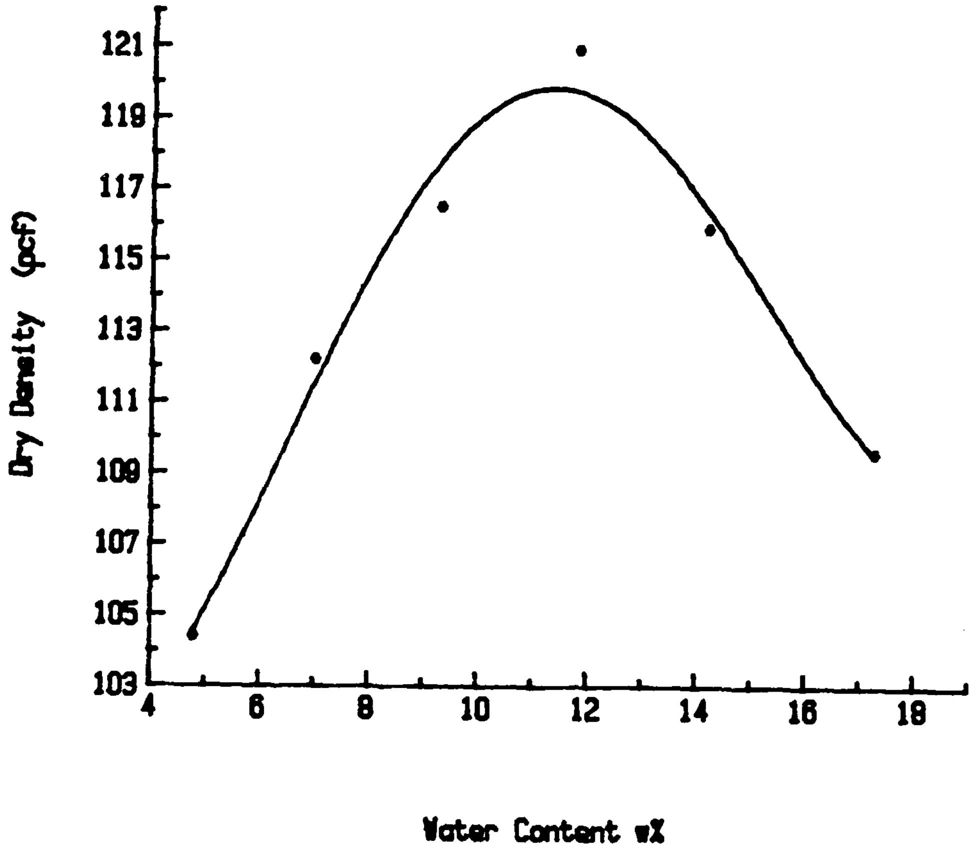


Fig.III.2 Compaction test results for crushed rock material (ASTM D 698)

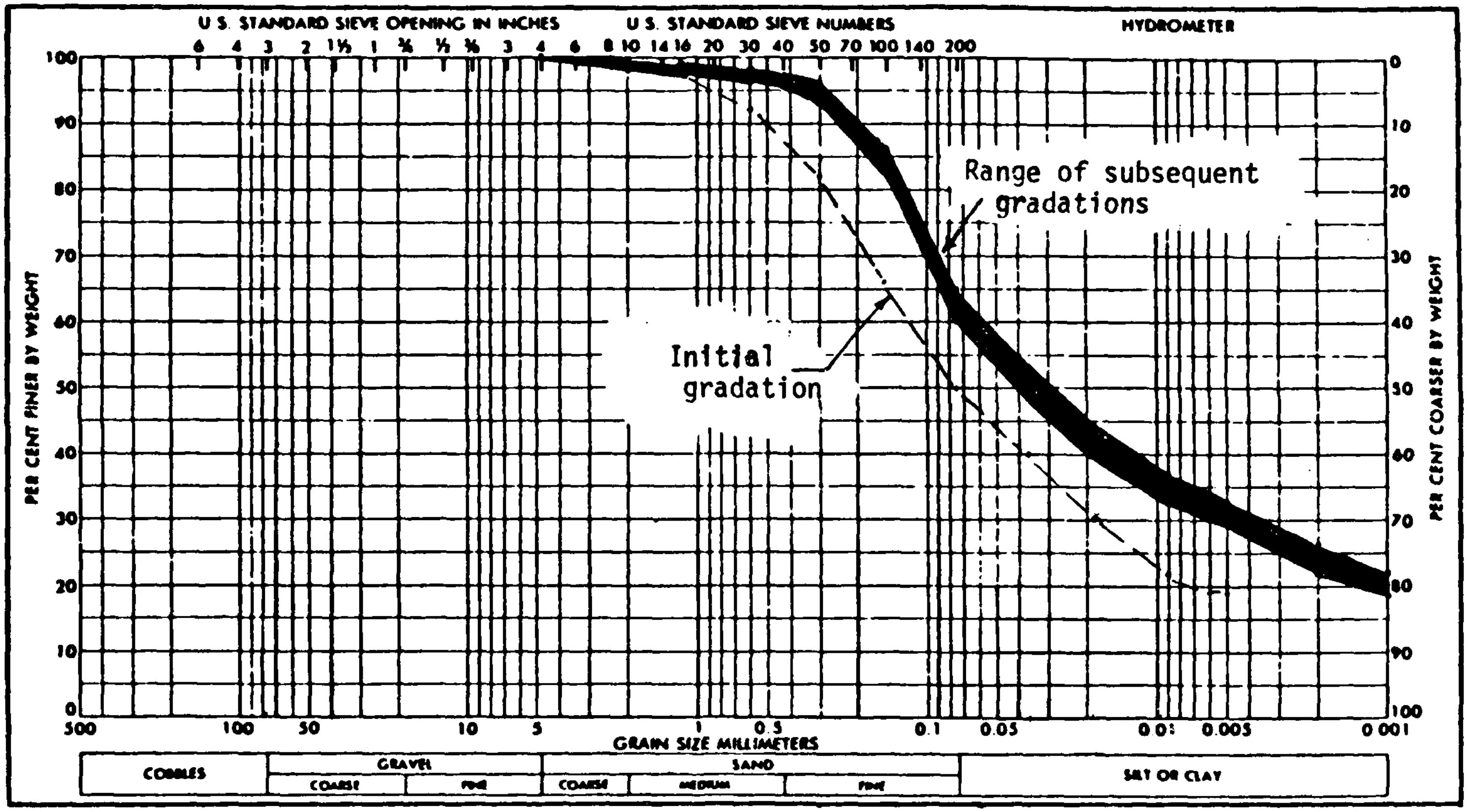


Fig.III.3 Clay material grain size distribution curve

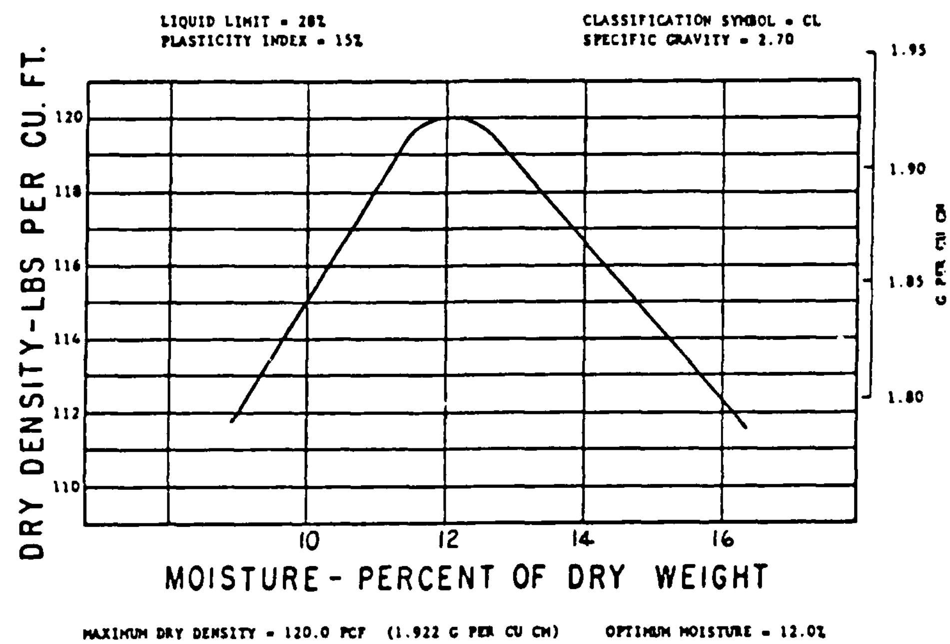
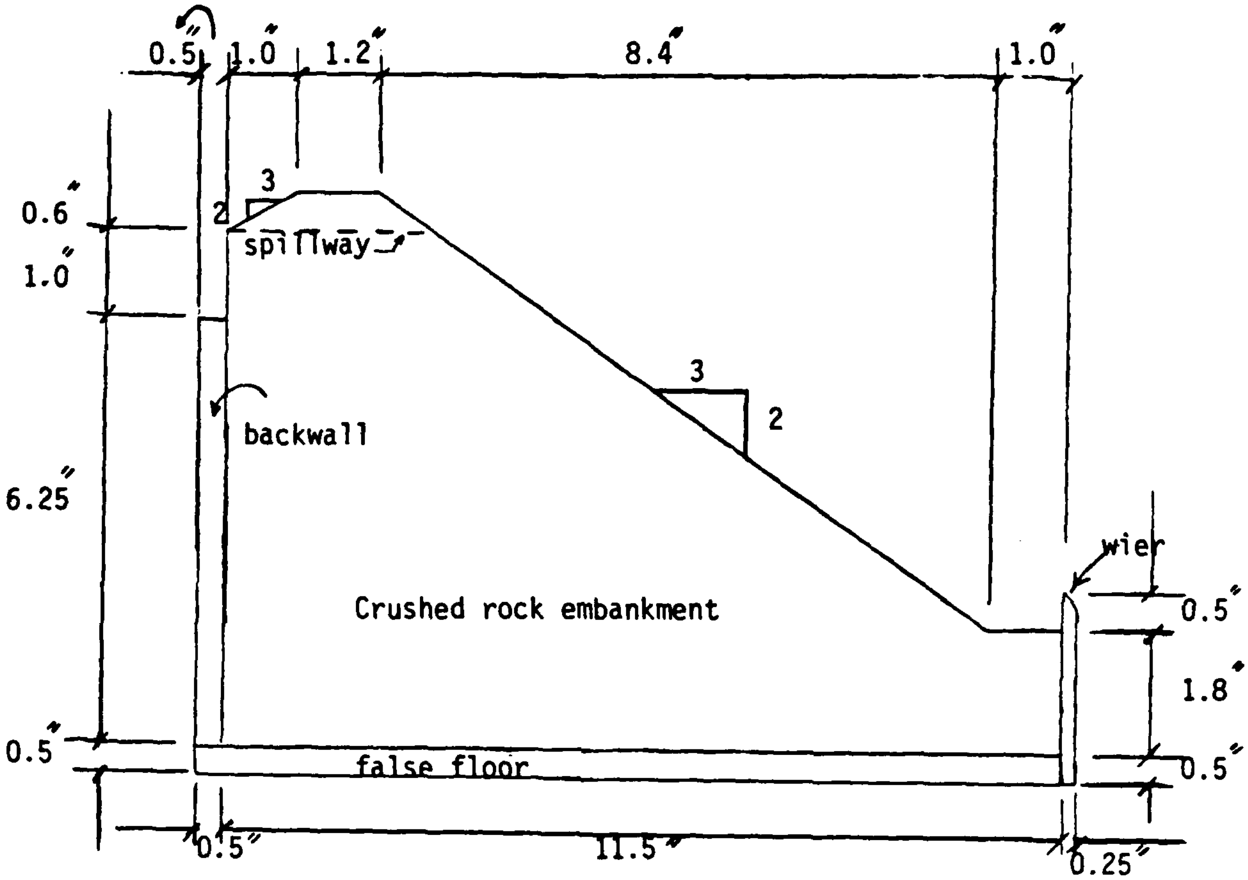
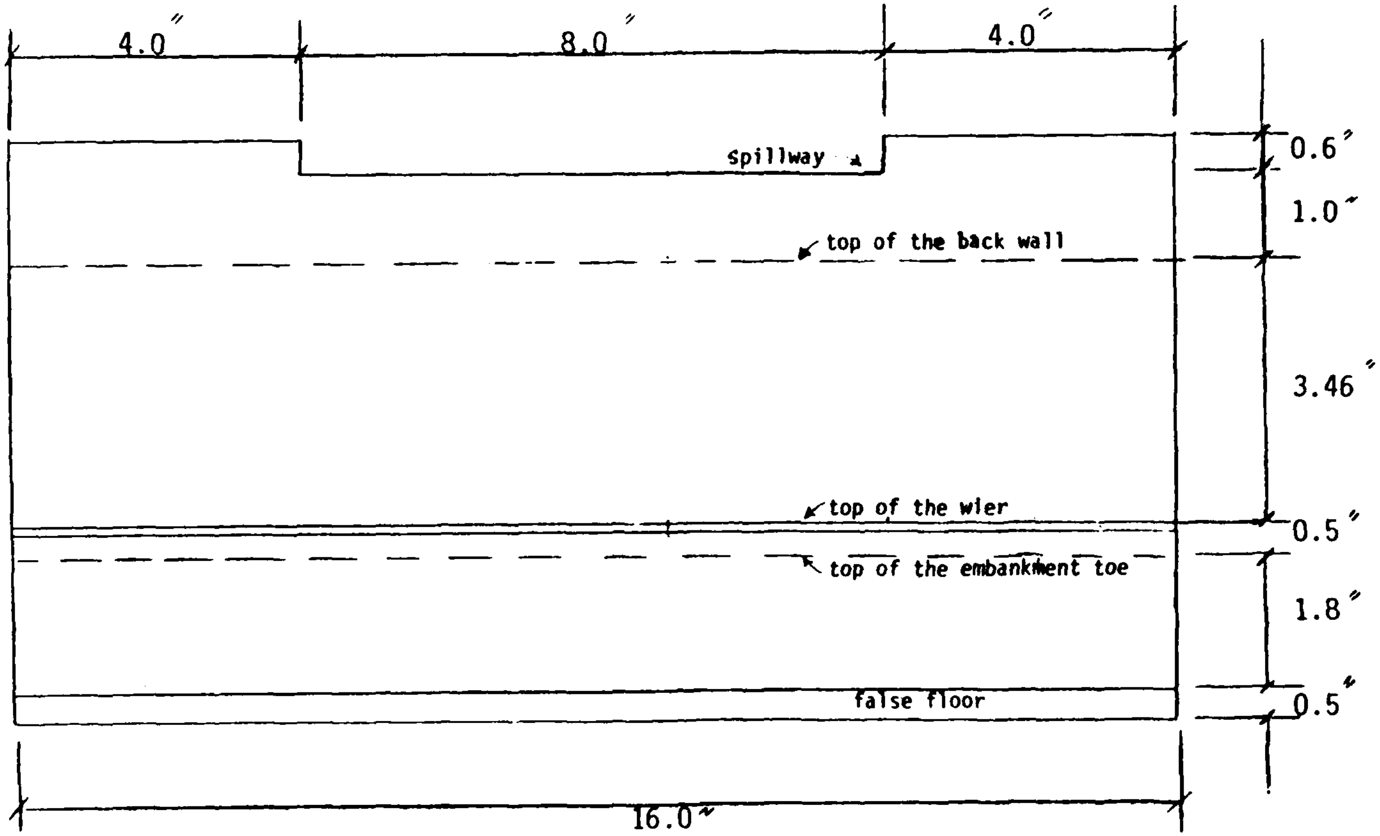


Fig.III.4 Compaction test results for clay material (ASTM D 698)



(a)

Fig. III.5 Crushed rock embankment configuration, (a) Side view



(b)

Fig. III.5 Crushed rock embankment configuration, (b) Front view

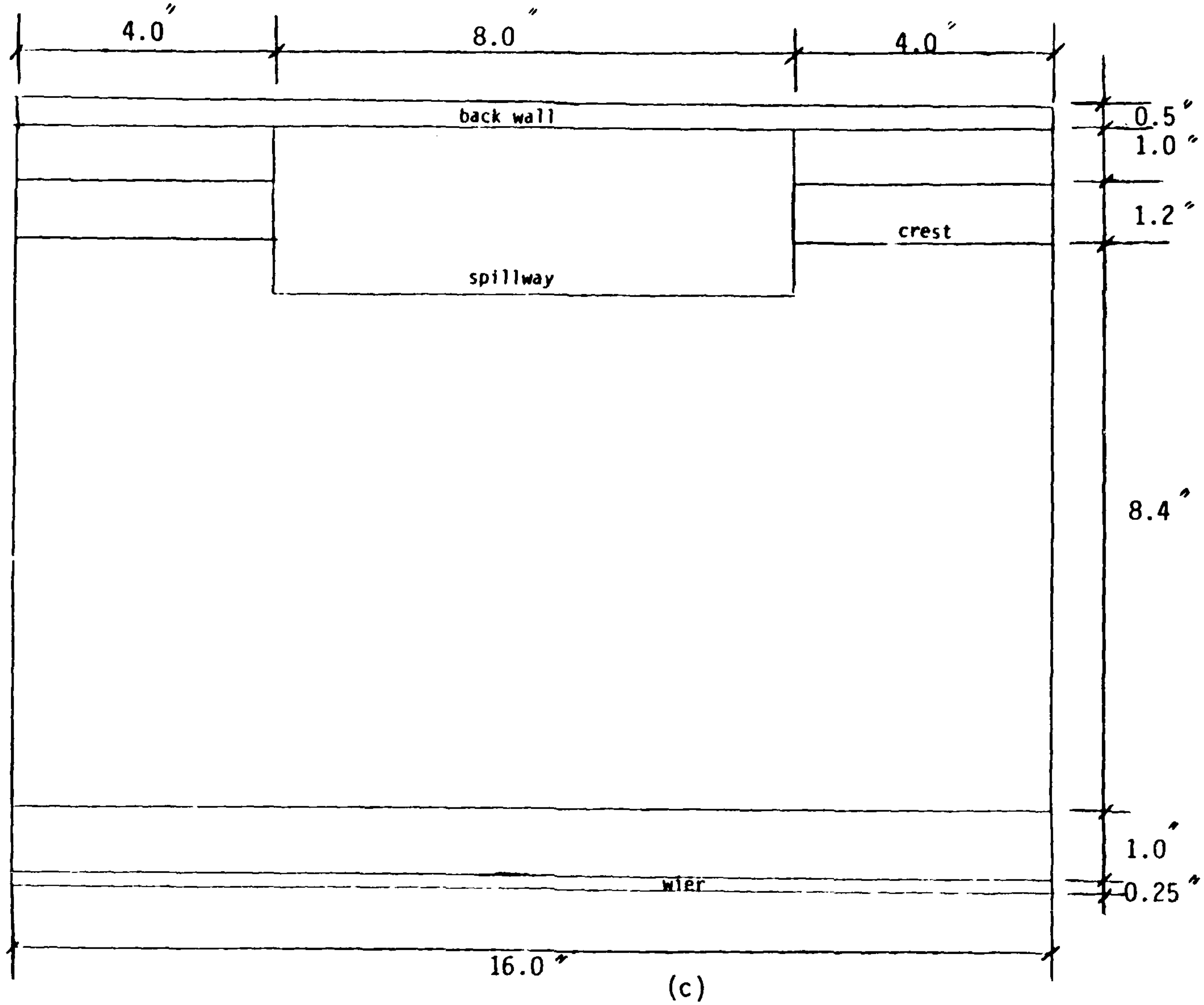
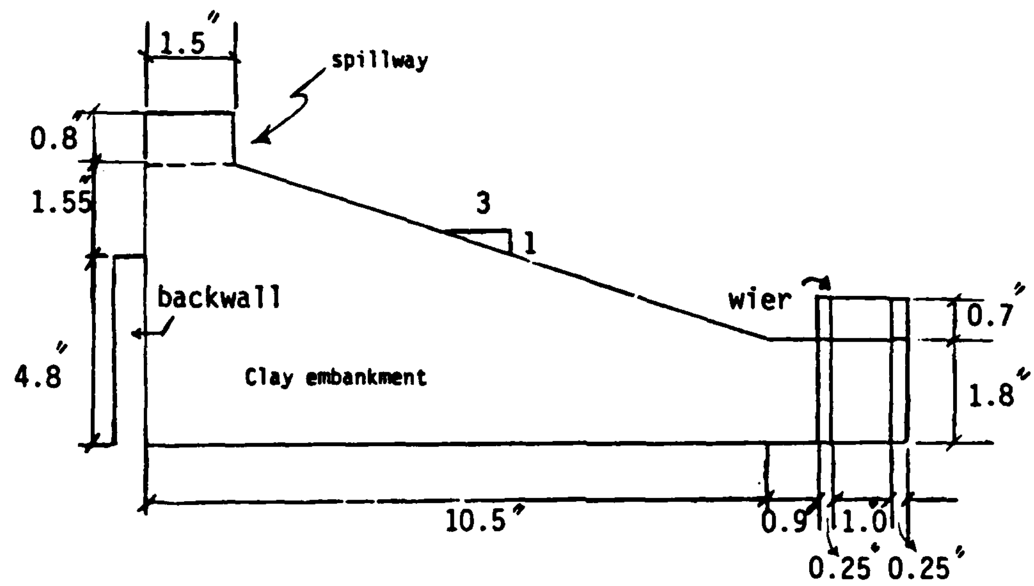
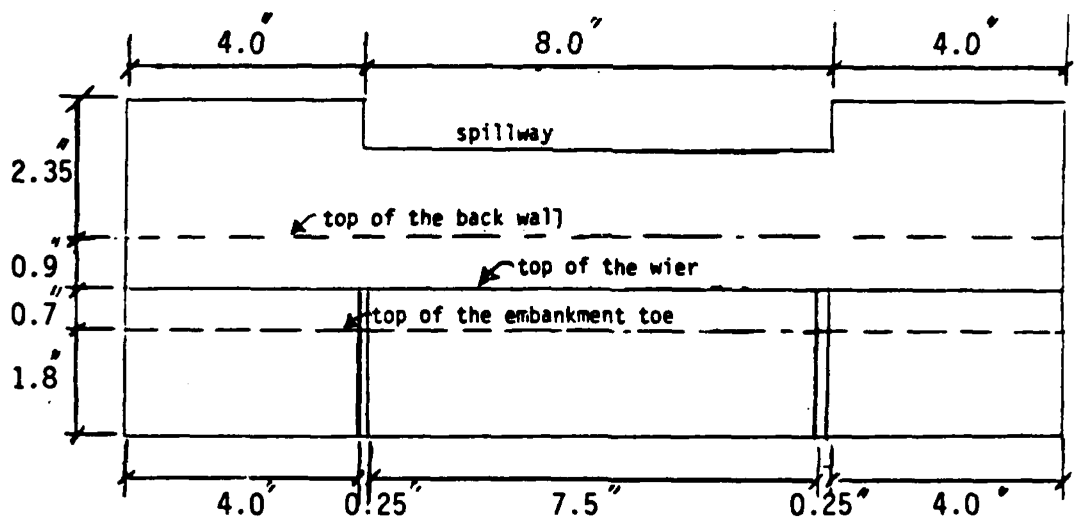


Fig.III.5 Crushed rock embankment configuration. (c) Plan view



(a)



(b)

Fig.III.6 Clay embankment configuration, (a) Side view, (b) Front view

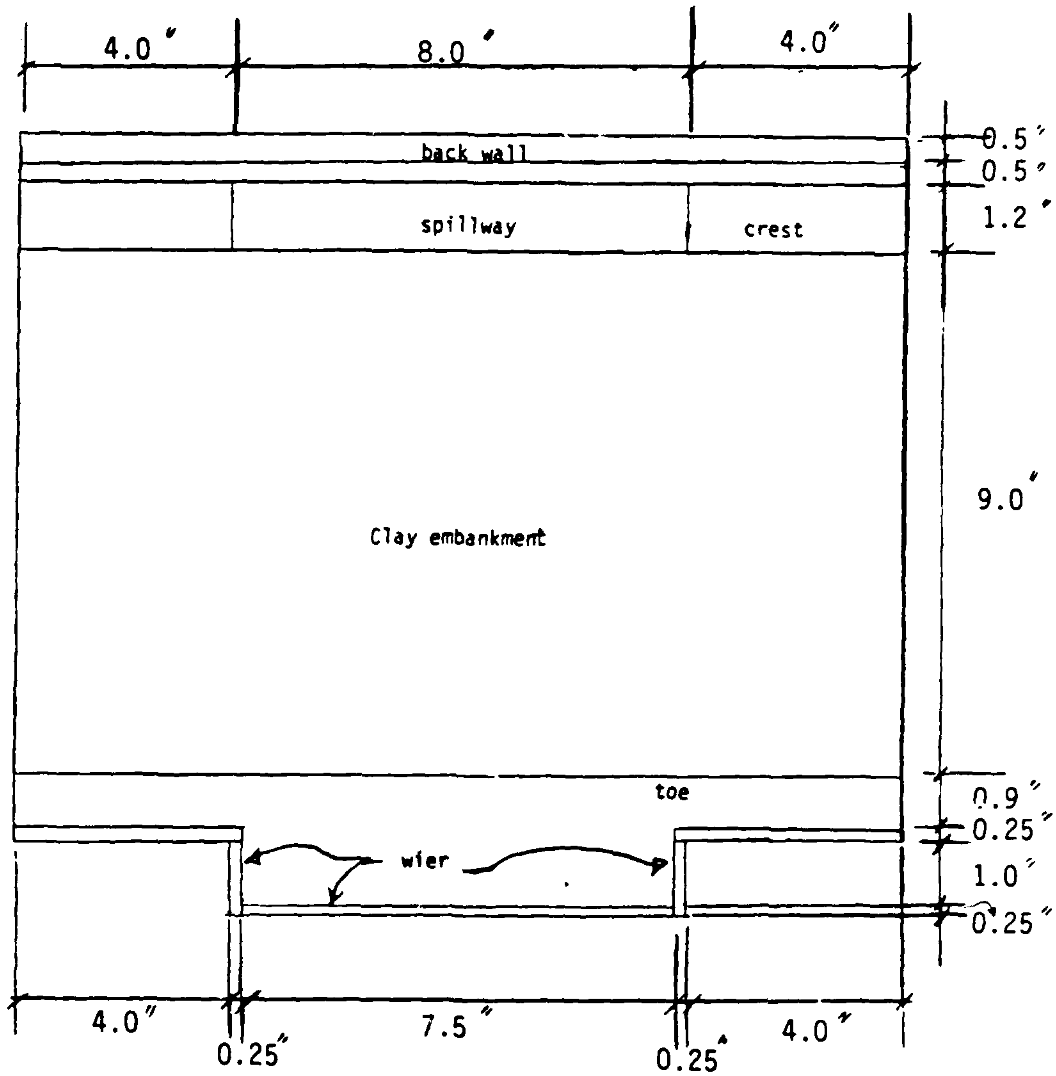


Fig.III.6 Clay embankment configuration, (c) Plan view

PART IV: TEST PROCEDURE

32. The experimental program included a total of six tests, three tests on crushed rock embankments and three on clay embankments. Additionally, approximately ten preliminary tests were completed on crushed rock and clay embankments for the following purposes:

- a. Verification of water conveyance system performance.
- b. Provide experience for research personnel with embankment preparation methods.
- c. Develop detailed test procedures for use in the experimental program, including method to monitor erosion.
- d. Allow preliminary evaluation of embankment erosion phenomena.

33. The embankments used in the preliminary tests had slight variations in dam crest geometry from those used in the final test sequences. Additionally, no wiers at the embankment toe were used in the preliminary tests. Erosion observed in these tests led to the decision to install the toe wiers and thus create a tailwater.

34. The following test procedure was used in each of six tests completed. Variations in procedure between crushed rock and clay during overtopping tests are discussed following the basic procedure.

- a. Make preliminary measurements of two surface cross-sections using a hand-held machinists scale at the locations shown in Figures II-6 or II-7.
- b. Photograph surface of embankment using twin 35mm SLR cameras to obtain preliminary, or before overtopping, view of embankment.
- c. Start video tape recorder to record test.

d. Accelerate centrifuge to approximately 270 R.P.M. or a 100g force on the embankment without allowing water into the system.

e. Start water pump and open control valve to a setting sufficient to develop an overtopping flow 0.2 inches deep over the dam crest. The resulting increase in payload due to the water caused the centrifuge speed to drop to approximately 230 R.P.M. or about a 70 g force on the embankment. This speed was maintained throughout the remainder of the test.

f. Maintain overtopping flow for appropriate period.

g. Slow centrifuge speed to about 200 R.P.M. and shut off water pump. Slowly bring centrifuge to a stop over a period of about one minute. Stop video recorder.

h. Photograph the embankment to record on stereo pairs the final eroded geometry of the embankment.

i. Make final measurements of two surface cross-sections using a hand-held machinist's scale at the locations shown in Figure II-6 or II-7.

Crushed Rock Embankments

35. Total duration of water overtopping in the three crushed rock embankment tests was for a period of 15 to 20 seconds. Stereo pair still photographs were taken approximately every two seconds throughout the period of overtopping. The centrifuge was then stopped, and final measurements and photographs taken as indicated in steps 7 through 9 of the basic procedure.

Clay Embankments

36. In each of the three tests completed using clay embankments, the total duration of overtopping was 16 minutes. At elapsed times of 4, 8 and 12 minutes, overtopping flow was stopped and the centrifuge brought to a stop. The embankment was then photographed with the stereo pair cameras, and two surface cross-sections at the locations shown in Figure II-7 were measured with the hand-held machinist's scale. The centrifuge was then restarted and overtopping flow resumed using the method outlined in steps 3 through 5 of the basic procedure. After a total of 16 minutes of overtopping the centrifuge was again stopped and final measurements and photographs taken as outlined in steps 7 through 9 of the basic procedure.

PART V: EXPERIMENTAL RESULTS

Crushed Rock Embankments

37. The crushed rock embankments eroded in 15 seconds, whereas the clay embankments exhibited moderate erosion after 16 minutes of overtopping flow. Figure V-1 presents some photographs of the crushed rock embankment S-2 taken in flight during overtopping. As can be seen in Figure V-1, erosion started at the toe of the sloped surface of the dam and quickly produced a vertical scarp, which then progressed upstream, eventualy leading to breaching failure of the embankment. Figure V-2 includes photos of the eroded sample. The steep gradient and the V-shaped cross-section of the breached area can be seen in these views. Some preliminary tests on crushed rock embankments were conducted in a 1g environment. In those tests, erosion failure was initiated at the crest of the embankment and progressed downward toward the toe. We believe this failure mechanism is not representative of prototype behavior as the self-weight forces induced are not properly simulated in the 1g environment. On the other hand, the failure mechanism observed under increased gravity is similar to those observed in case histories of dam overtopping failure compiled by Mr. Paul Miller of WES. Suga et al (1981) conducted large scale model tests of dam overtopping on silt and sand embankments, and reported a similar failure mechanism to that observed in the centrifuge tests.

38. Since the failure occurred rapidly, stereophotographs and manual measurements were only taken at the end of each test. Erosion

profiles obtained through the manual measurements are presented in Figure V-3. In Figure V-4 the erosion profiles at different locations, as determined by manual measurement, are presented for comparison. The configuration of the erosion in the three tests seems to agree well.

39. Based upon these results, we feel that the tests on the crushed rock embankments were reproducible and that the centrifuge is a feasible tool for modeling the overtopping phenomenon.

Clay Embankments

40. As indicated previously, the clay embankments did not fail after 16 minutes of overtopping flow. In Figure V-5 stereophotos of Sample C-1, taken at successive 4 minute intervals, are presented. The photos indicate that erosion occurred over the entire area below the spillway. The erosion profile was a wide U-shaped, moderately sloped channel, containing several ridges. This erosion profile agrees with the discussion of erosion gully shapes in different soil types presented by Winterkorn and Fang (1975). Photographs of the three clay embankments after completion of the tests are shown in Figure V-6 and show the similarity of the erosion profile between the tests.

41. The manually measured cross-sections of the erosion profile taken every 4 minutes are presented in Figure V-7. The cross-sections of the three tests are shown in Figure V-8 for comparison. A contour map of the embankment surface of test C-1 after 16 minutes of overtopping was produced from the stereo pair photographs

and is shown in Figure V-9. Cross-sections A and B in test C-1, as measured by both the manual method and in the contour map, are shown in Figure V-10. As indicated by the figure the results of the two methods are in good agreement, thus confirming the accuracy of the erosion contours prepared from the stereo pair photographs.

42. Based upon the observed erosion profile in the centrifuge tests, and comparison of erosion profiles presented in Figures V-8 and V-10, we conclude that tests on clay embankments are reproducible, and therefore the centrifuge is a feasible tool for modeling overtopping phenomena.

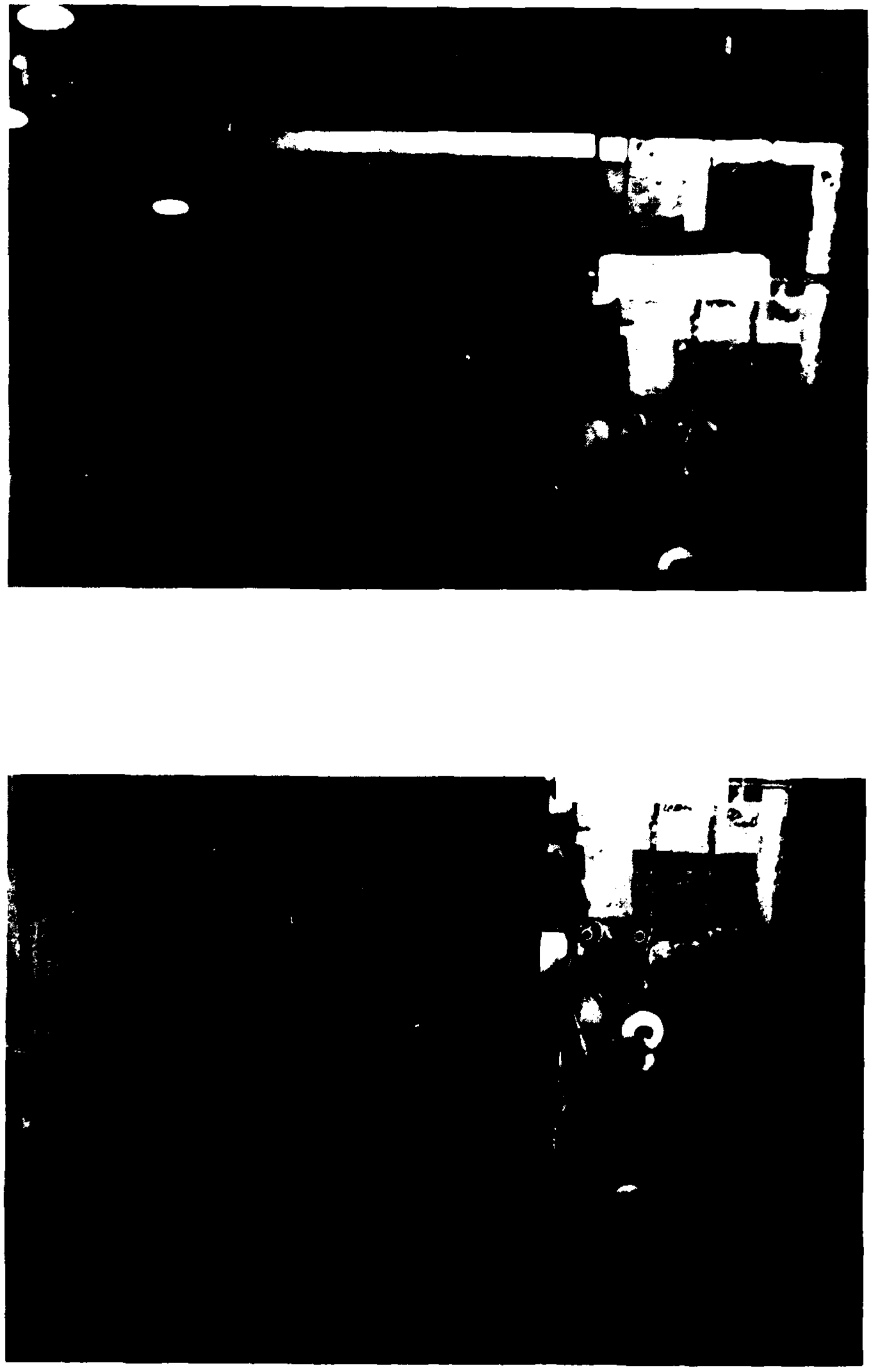


Fig. V.1 (a) Stereo photographs of crushed rock embankment S-2 prior to overtopping

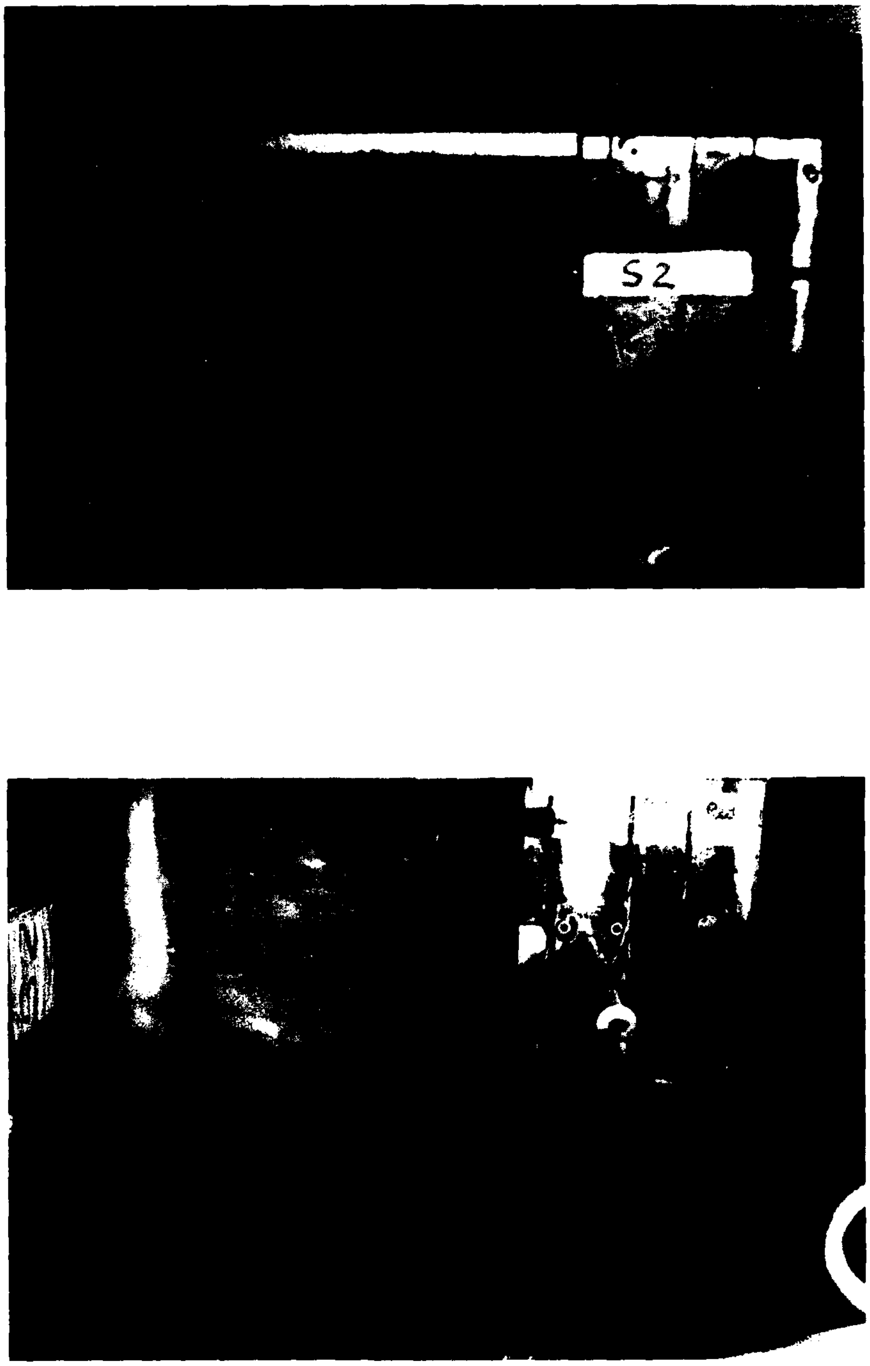


Fig. V.1 (b) Stereo photographs of crushed rock embankment S-2 after approximately 4 seconds of overtopping

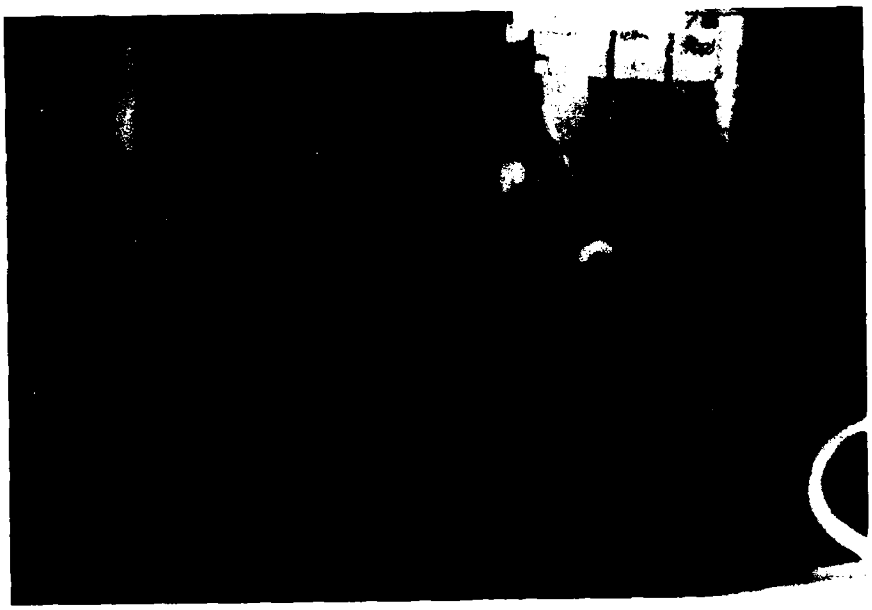


Fig. V.1 (c) Stereo photographs of crushed rock embankment S-2 after approximately 8 seconds of overtopping

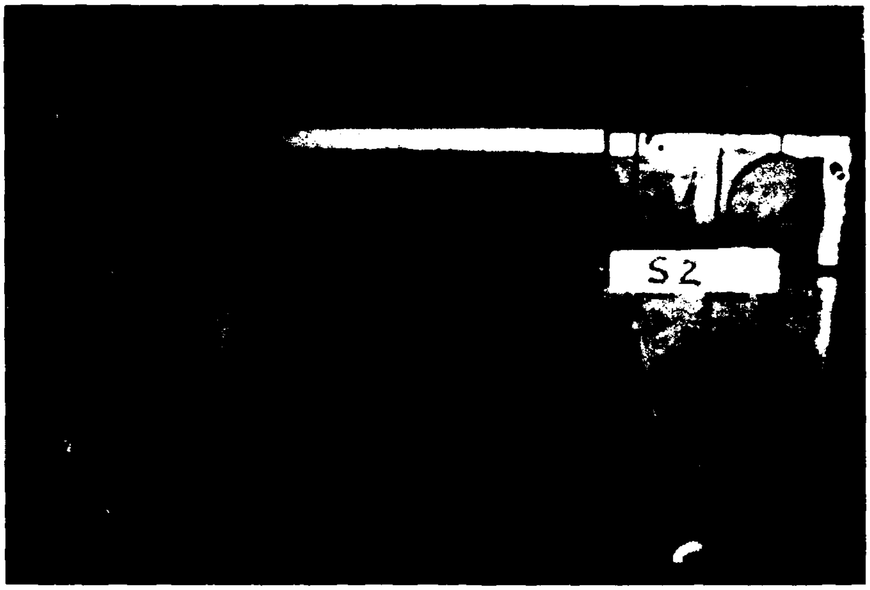


Fig. V.1 (d) Stereo photographs of crushed rock embankment S-2 after approximately 12 seconds of overtopping

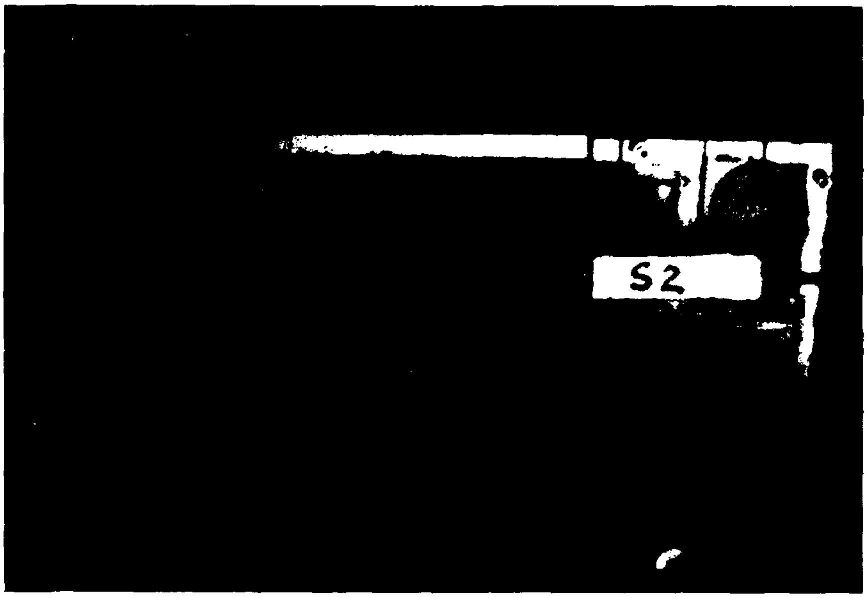


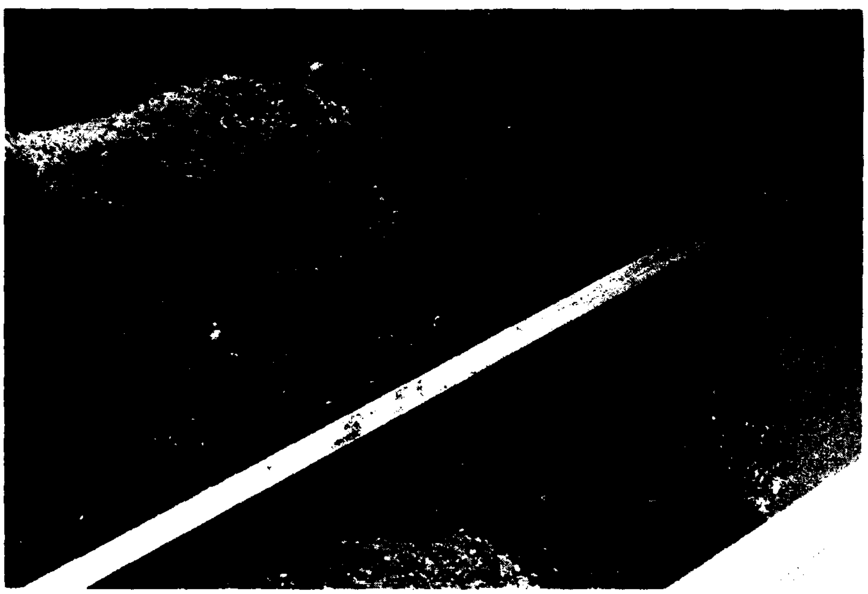
Fig. V.1 (e) Stereo photographs of crushed rock embankment S-2 after approximately 16 seconds of overtopping

(a)

(b)

Fig. V.2 Photographs of crushed rock embankment S-2 after completion of approximately 16 seconds of overtopping (a) Top view, (b) Front view

(c)



(d)

Fig. V.2 Photographs of crushed rock embankment S-2 after completion of approximately 16 seconds of overtopping, (c) and (d) Downstream slope

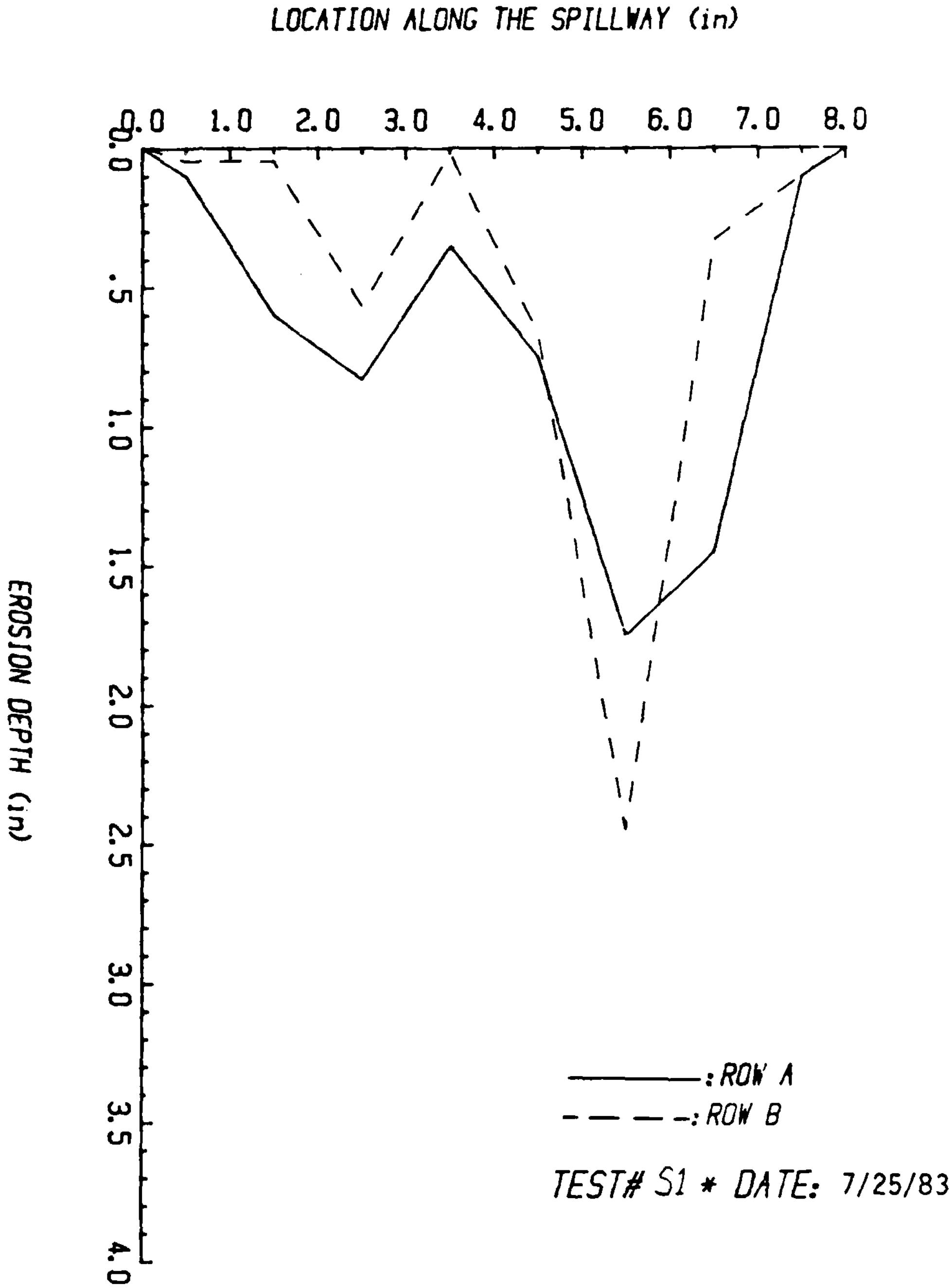


Fig. V.3 (a) Erosion profile cross sections of crushed rock embankment S-1 determined from manual measurements

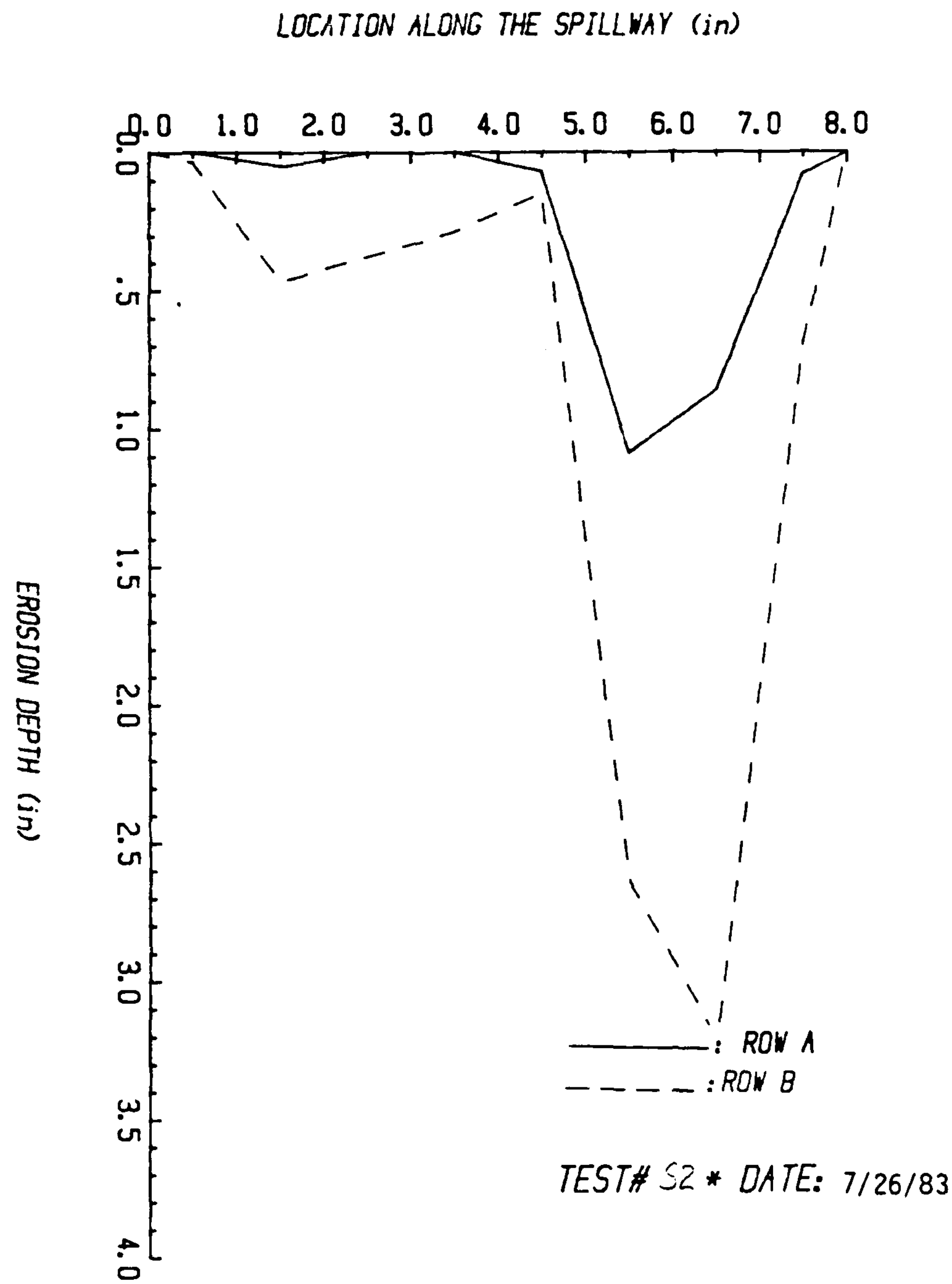


Fig. V.3 (b) Erosion profile cross sections of crushed rock embankment S-2 determined from manual measurements

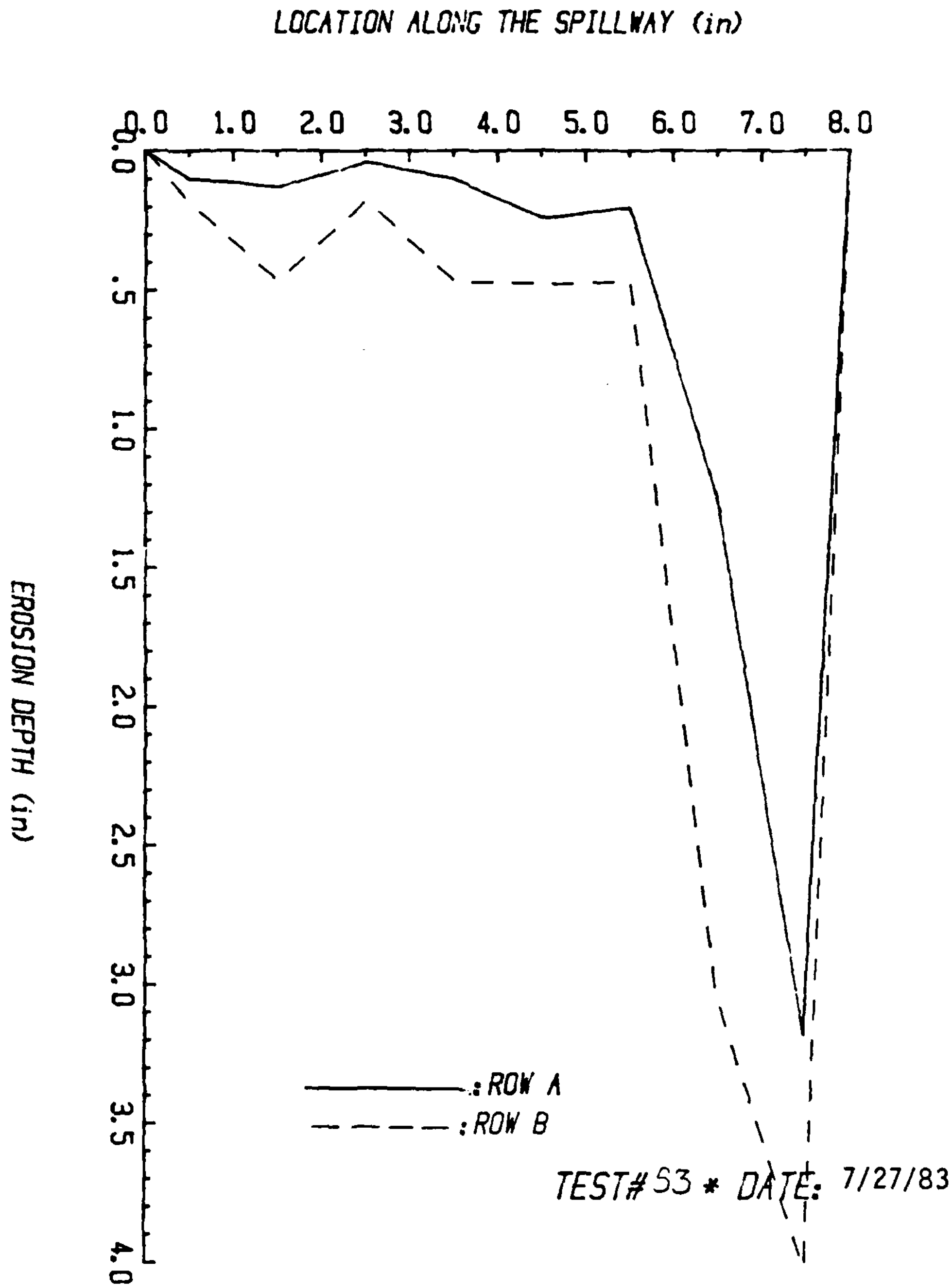


Fig. V.3 (c) Erosion profile cross sections of crushed rock embankment S-3 determined from manual measurements

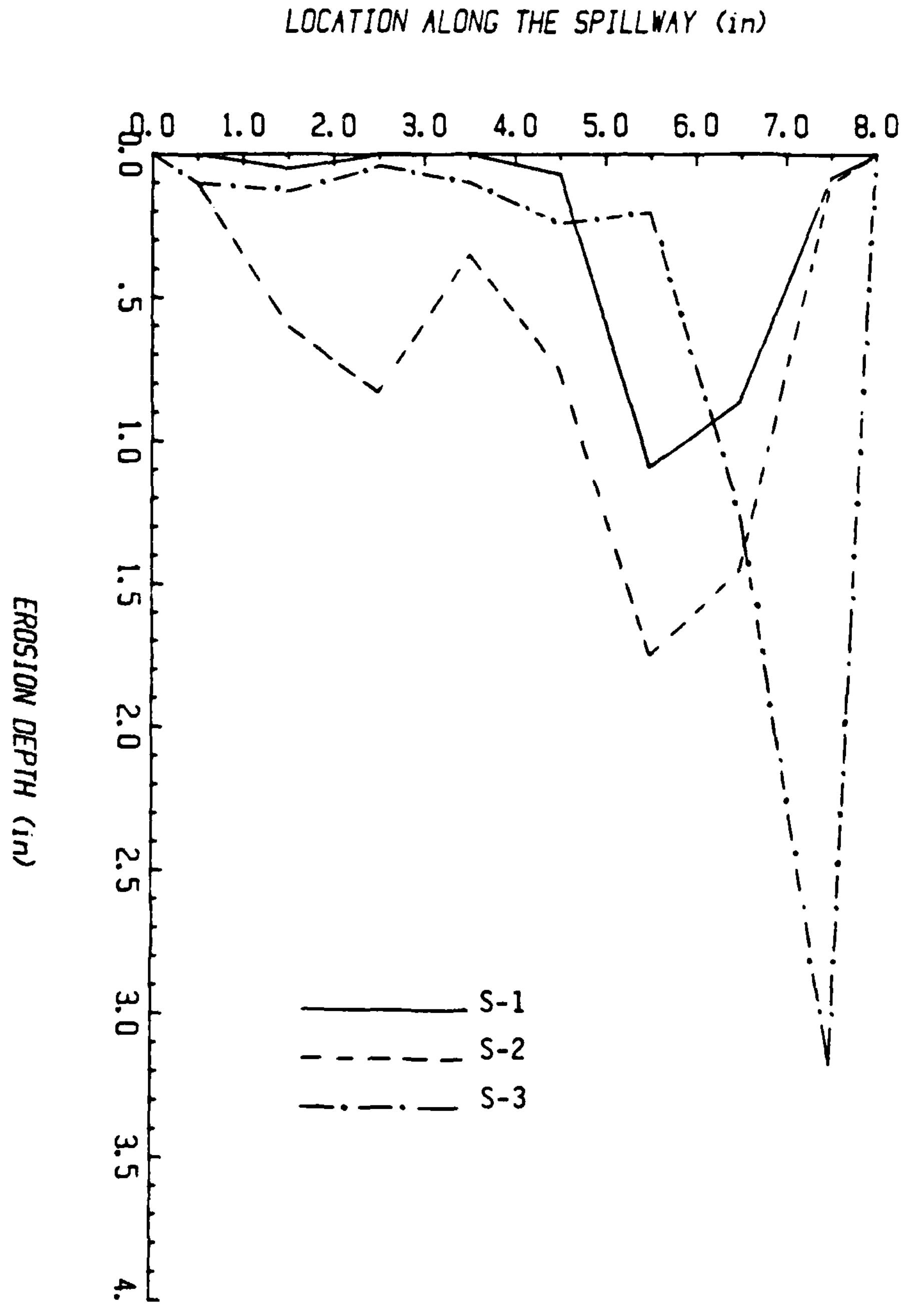


Fig. V.4 (a) Comparison of crushed rock embankment erosion profile cross sections at row A determined from manual measurements

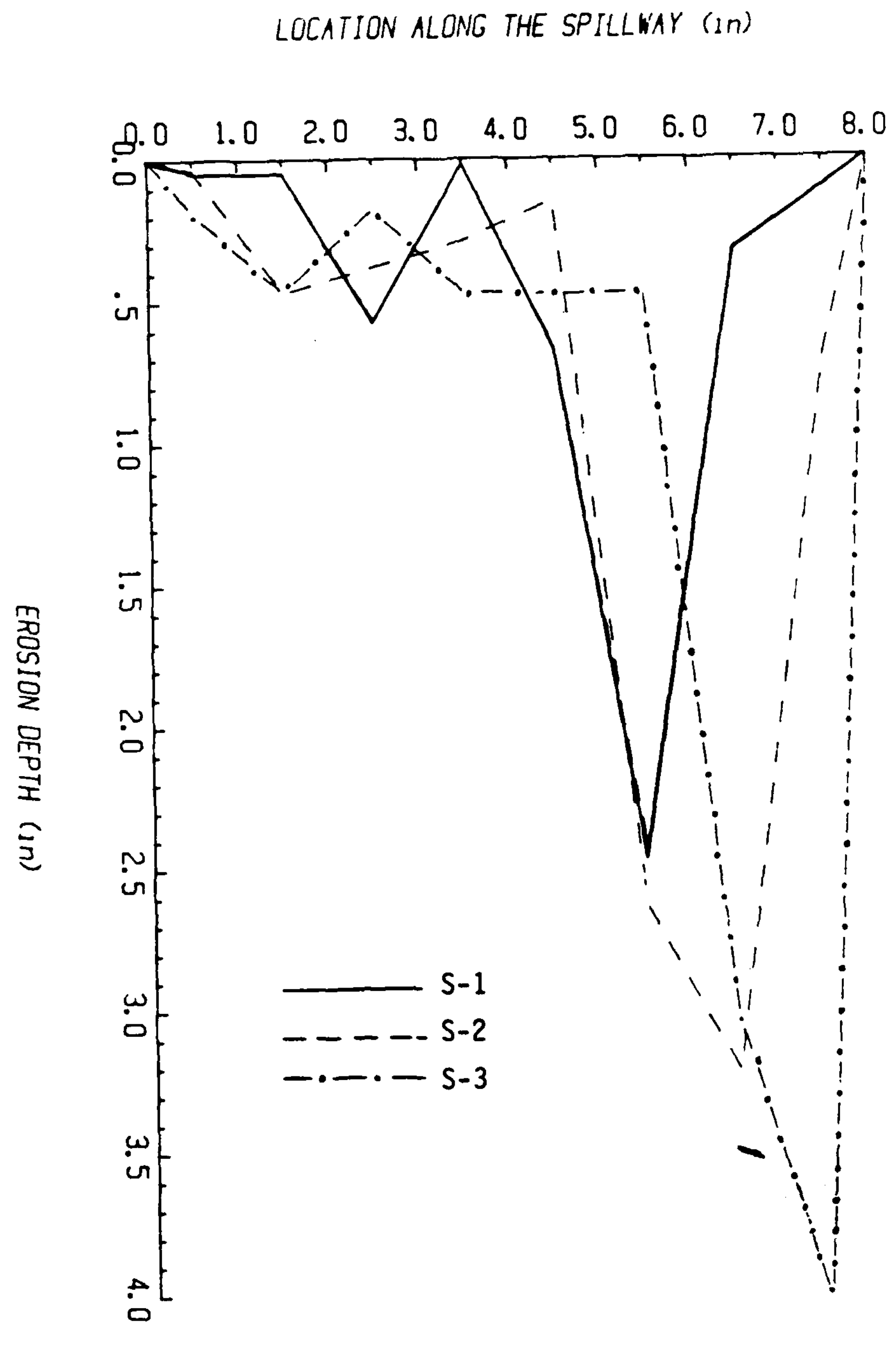


Fig. V.4 (b) Comparison of crushed rock embankment erosion profile cross sections at row B determined from manual measurements

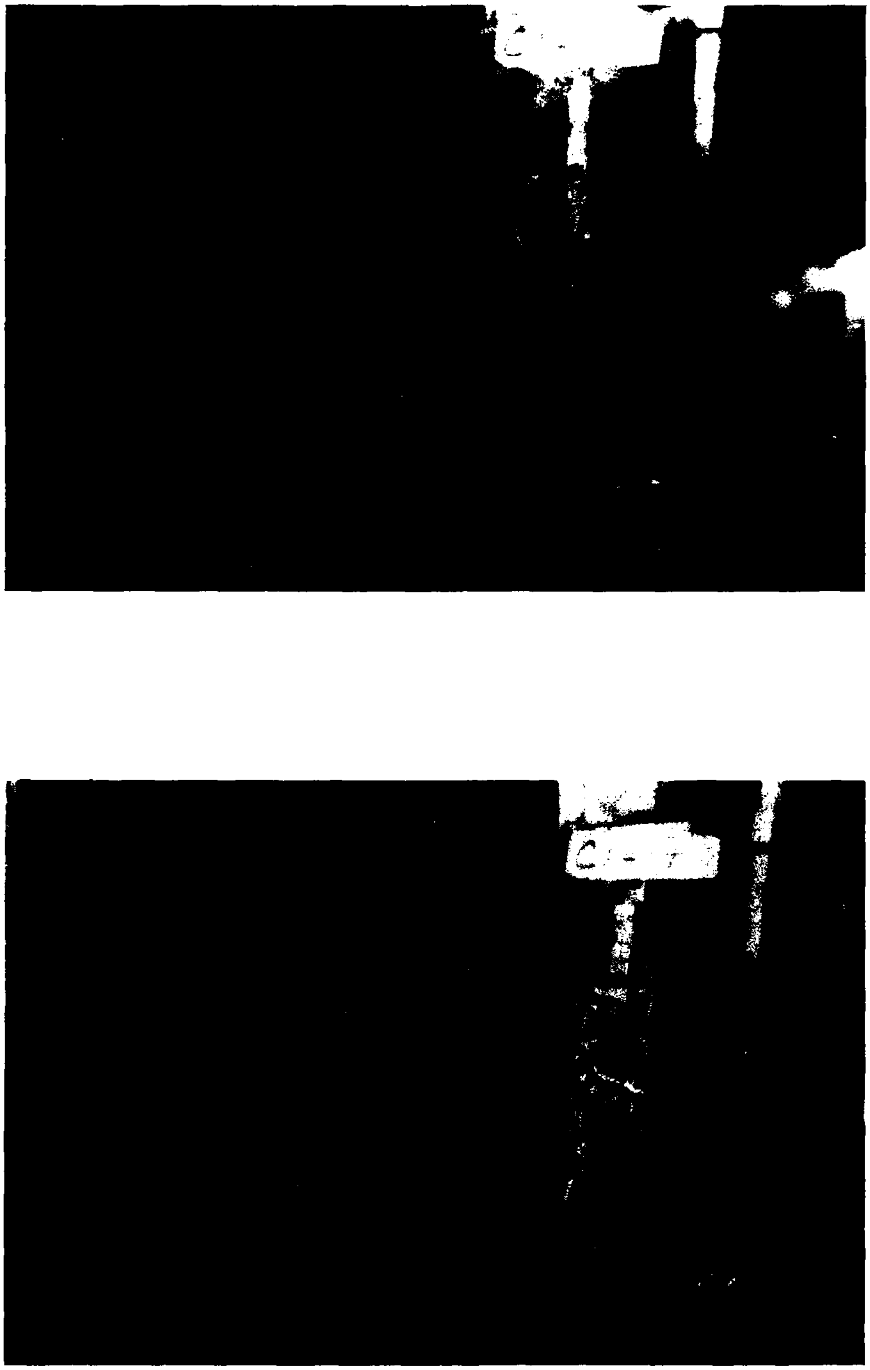
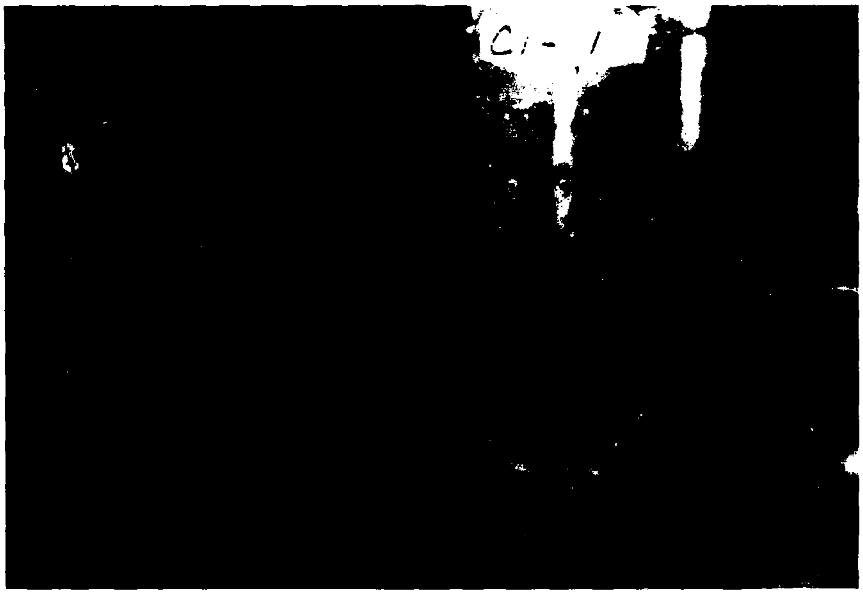


Fig. V.5 (a) Stereo photographs of clay embankment C-1 prior to overtopping



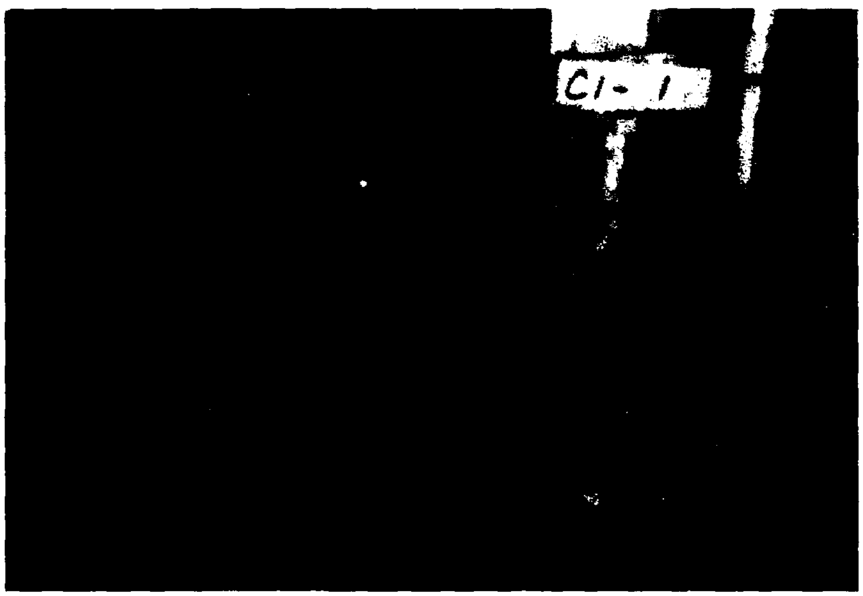


Fig. V.5 (b) Stereo photographs of clay embankment C-1 after 4 minutes of overtopping

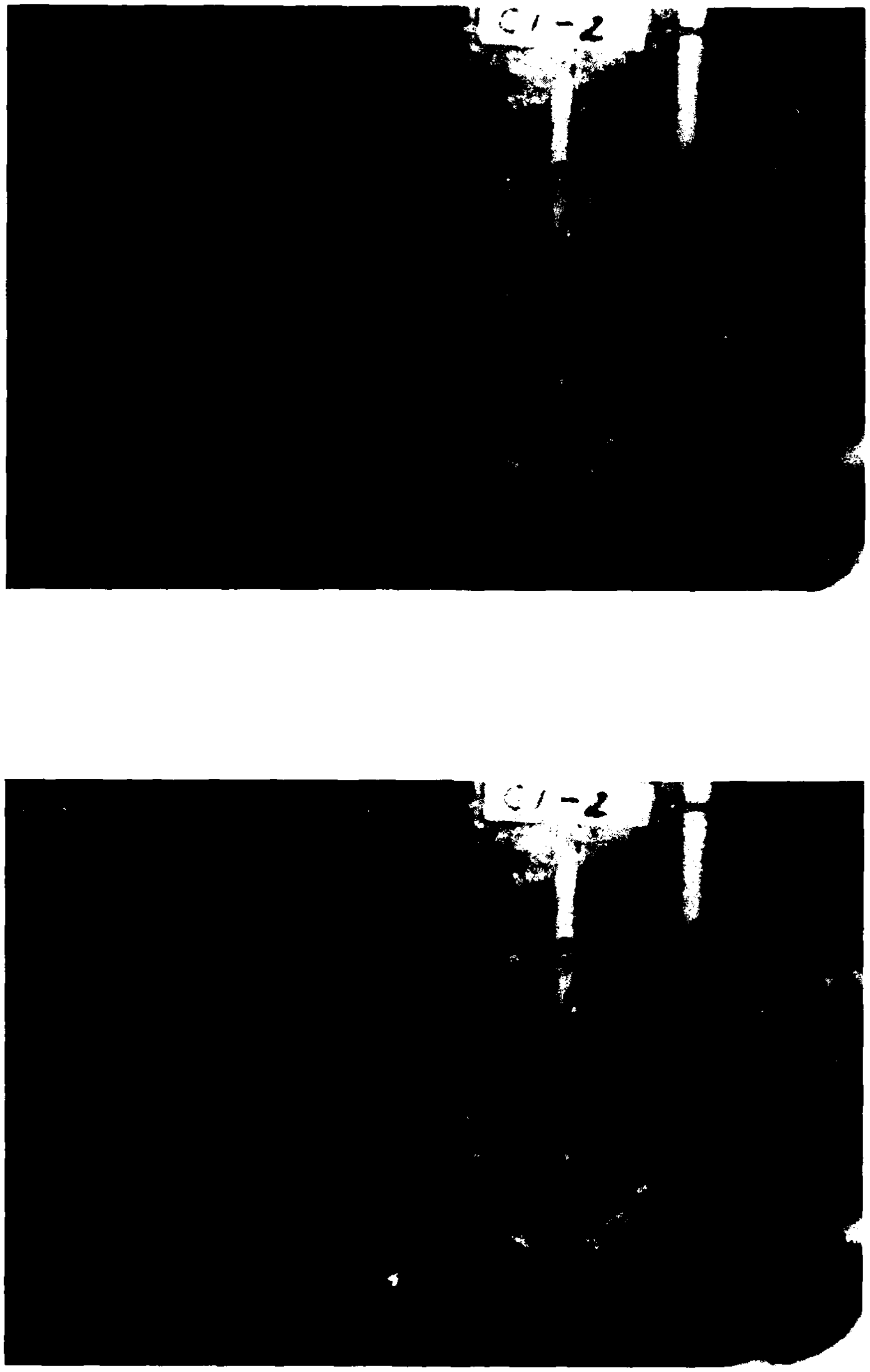


Fig. V.5 (c) Stereo photographs of clay embankment C-1 after 8 minutes of overtopping

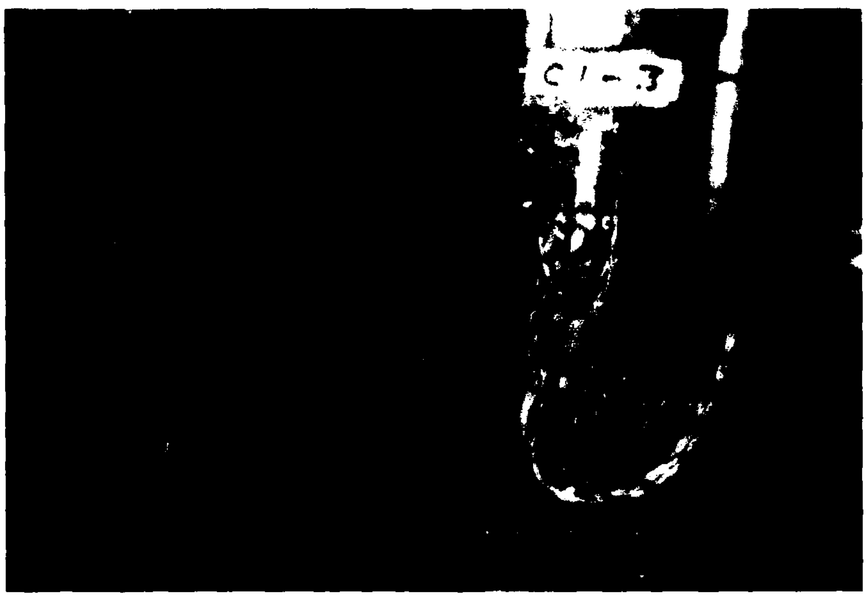
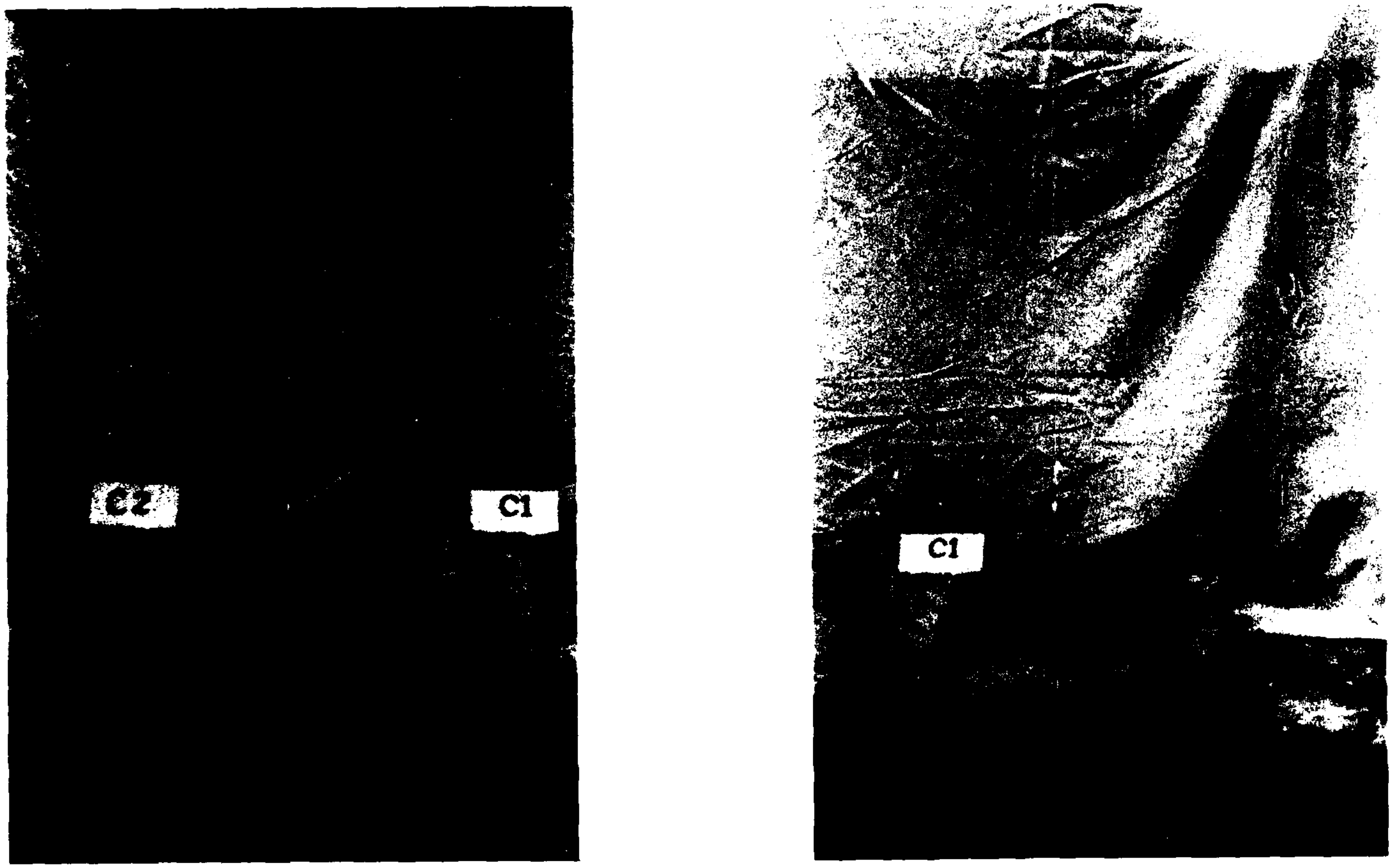


Fig. V.5 (d) Stereo photographs of clay embankment C-1 after 12 minutes of overtopping

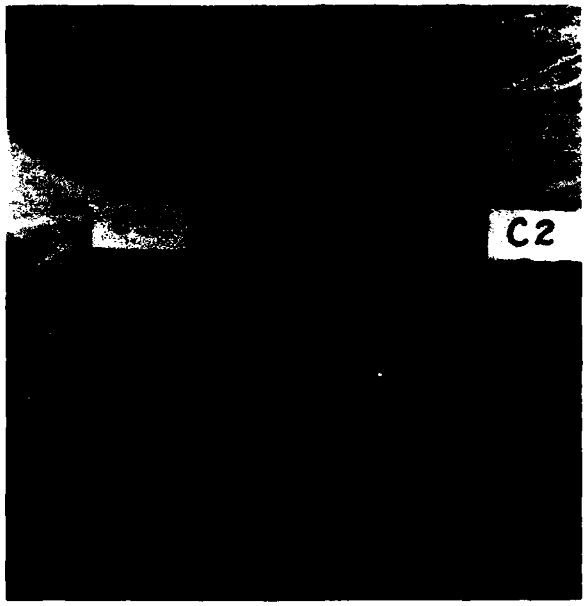
Fig. V.5 (e) Stereo photographs of clay embankment C-1 after 16 minutes of overtopping



(a) (b)

Fig. V.6 Photographs of clay embankments after completion of 16 minutes of overtopping, (a) Embankment C-1, (b) Embankment C-2

(c)



(d)

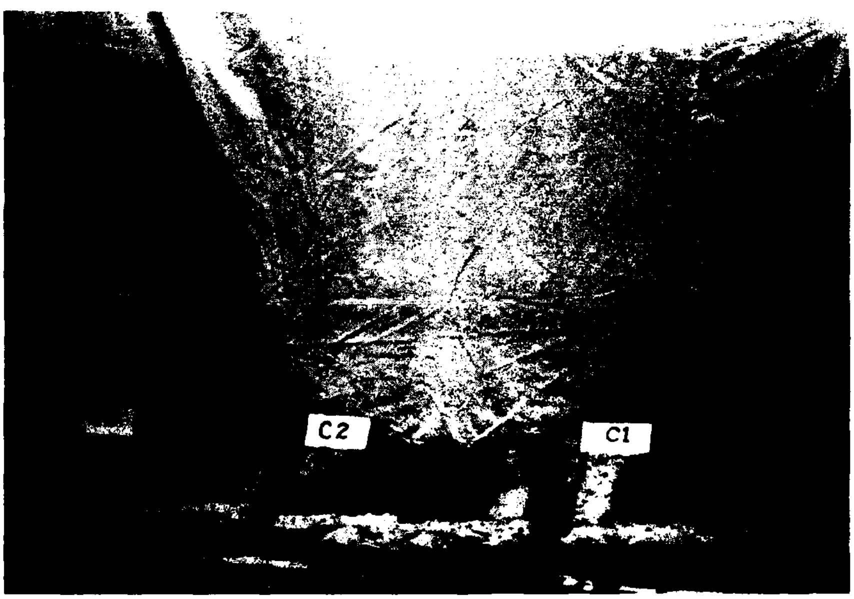


Fig.V.6 Photographs of clay embankments after completion of 16 minutes of overtopping, (c) Embankment C-3, (d) Embankments C-1, C-2, C-3

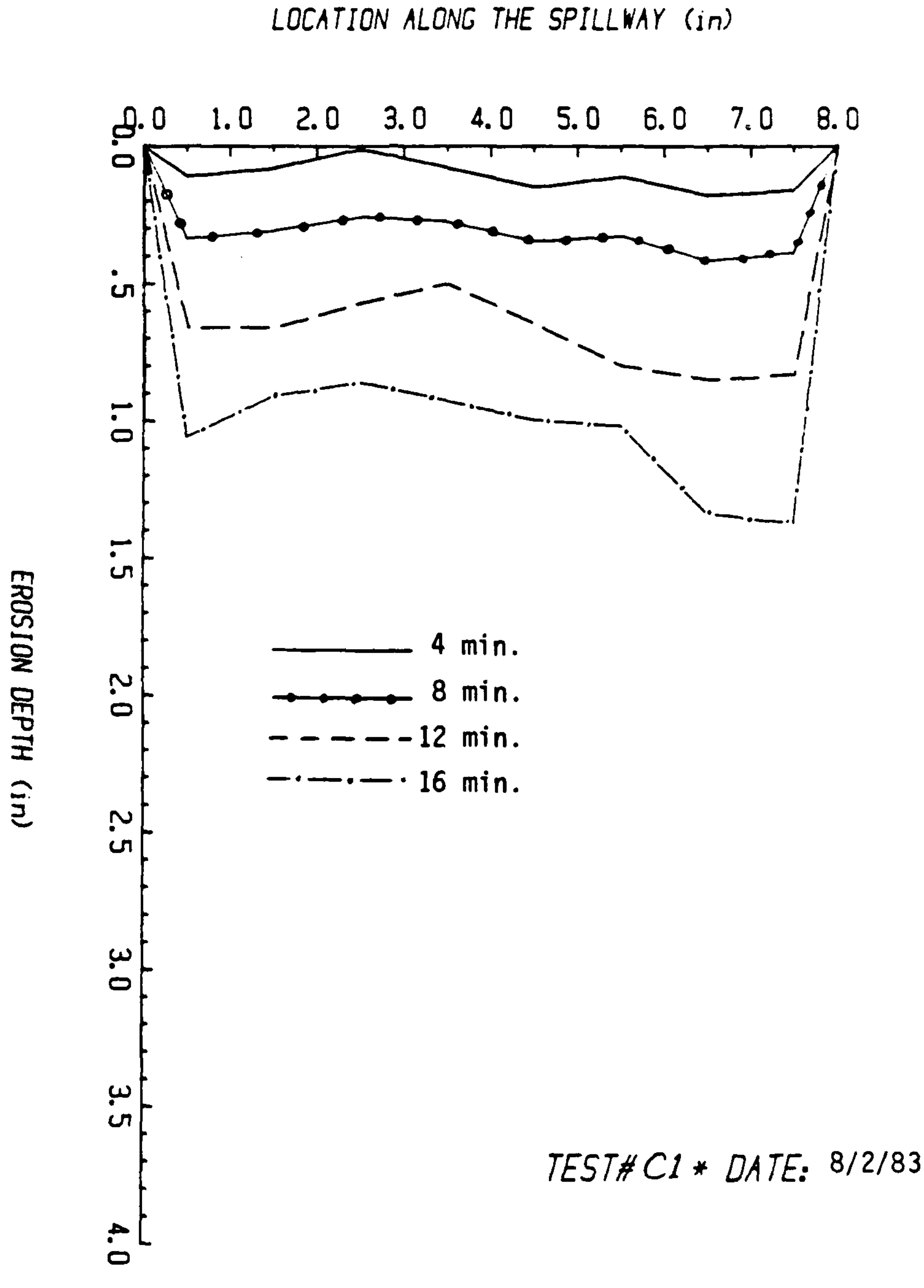


Fig.V.7 (a) Erosion profile cross sections of C-1 determined from manual measurements at row A

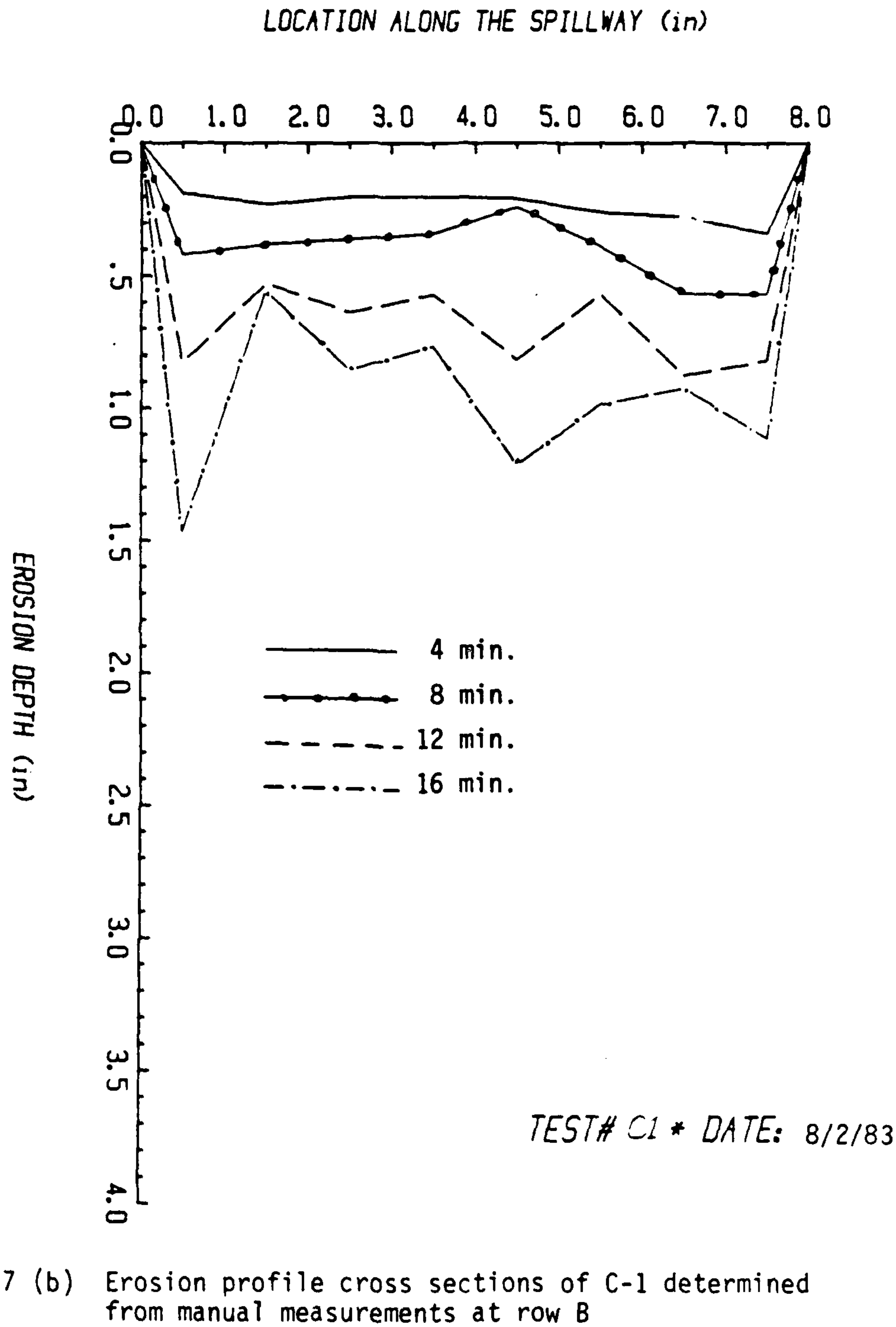


Fig. V.7 (b) Erosion profile cross sections of C-1 determined from manual measurements at row B

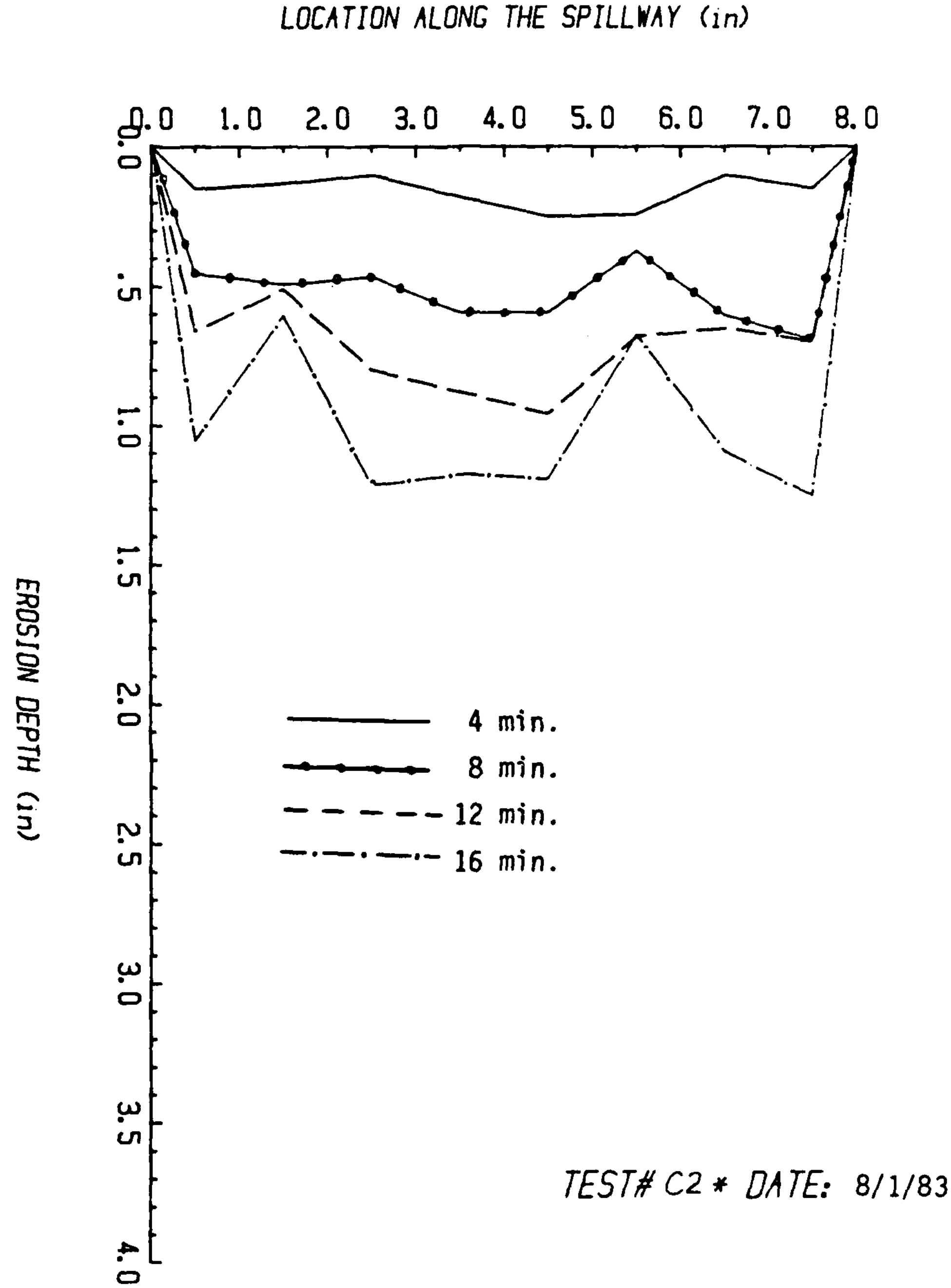


Fig. V.7 (c) Erosion profile cross sections of C-2 determined from manual measurements at row A

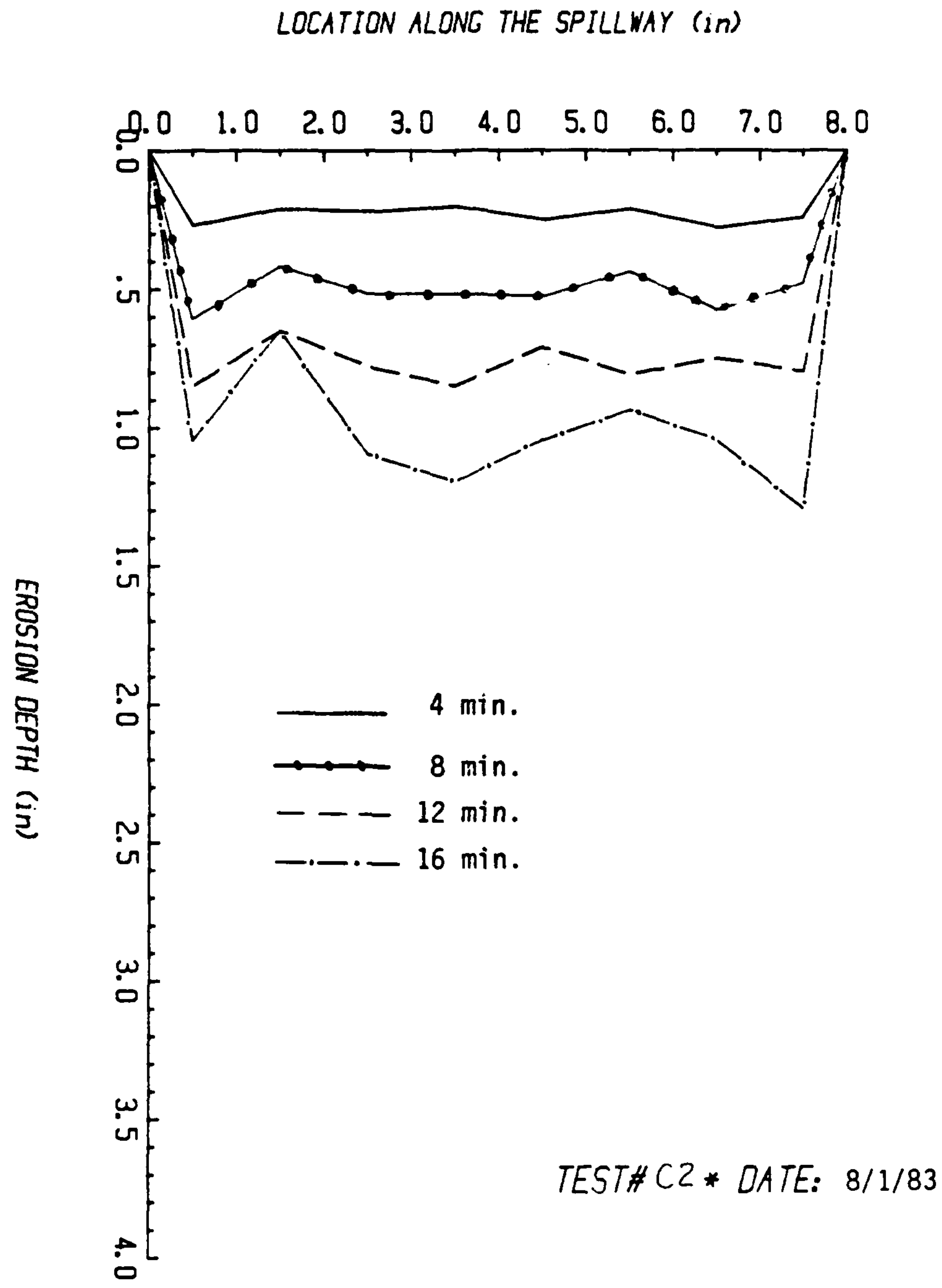


Fig.V.7 (d) Erosion profile cross sections of C-2 determined from manual measurements at row B

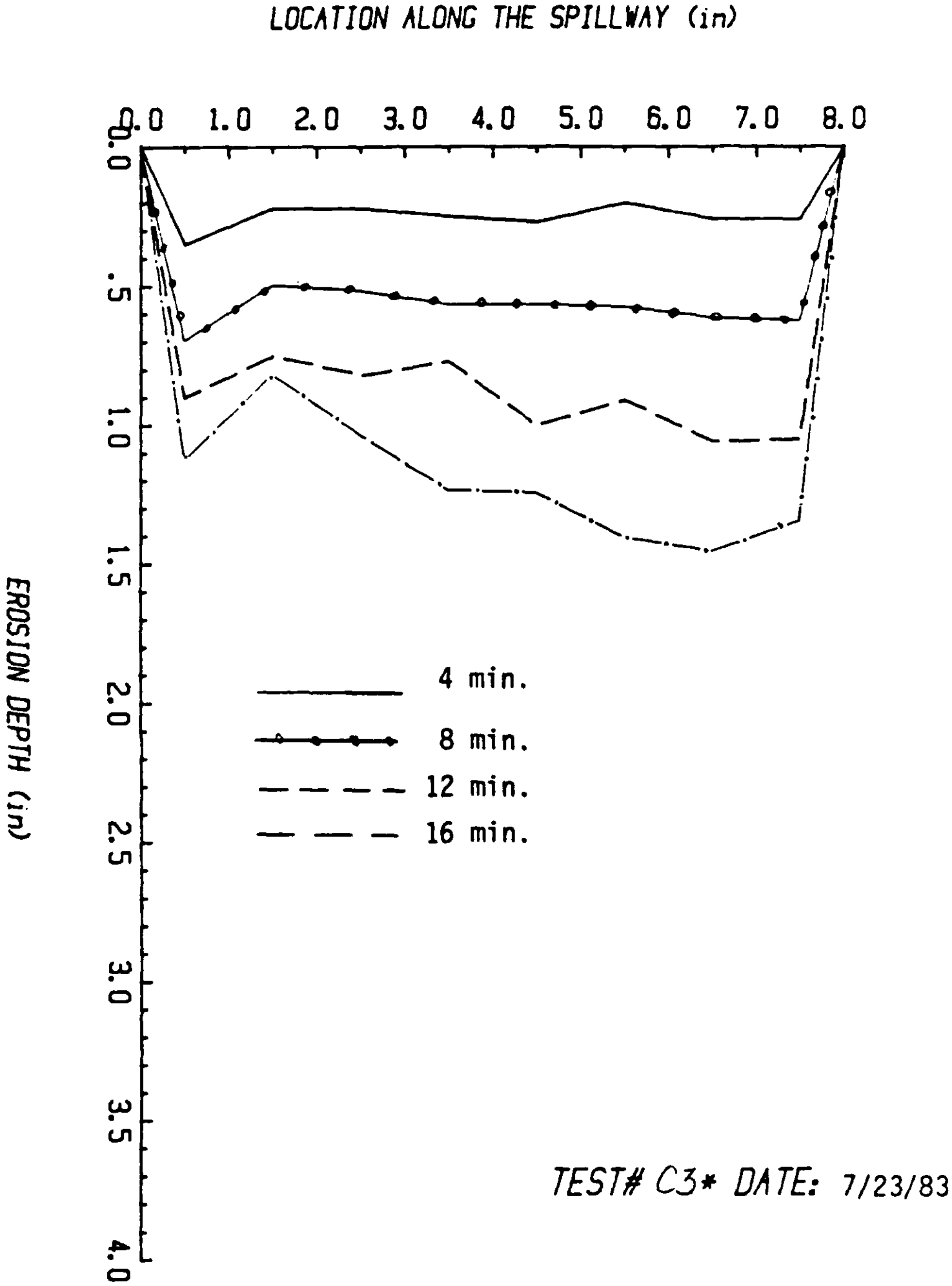


Fig. V.7 (e) Erosion profile cross sections of C-3 determined from manual measurements at row A

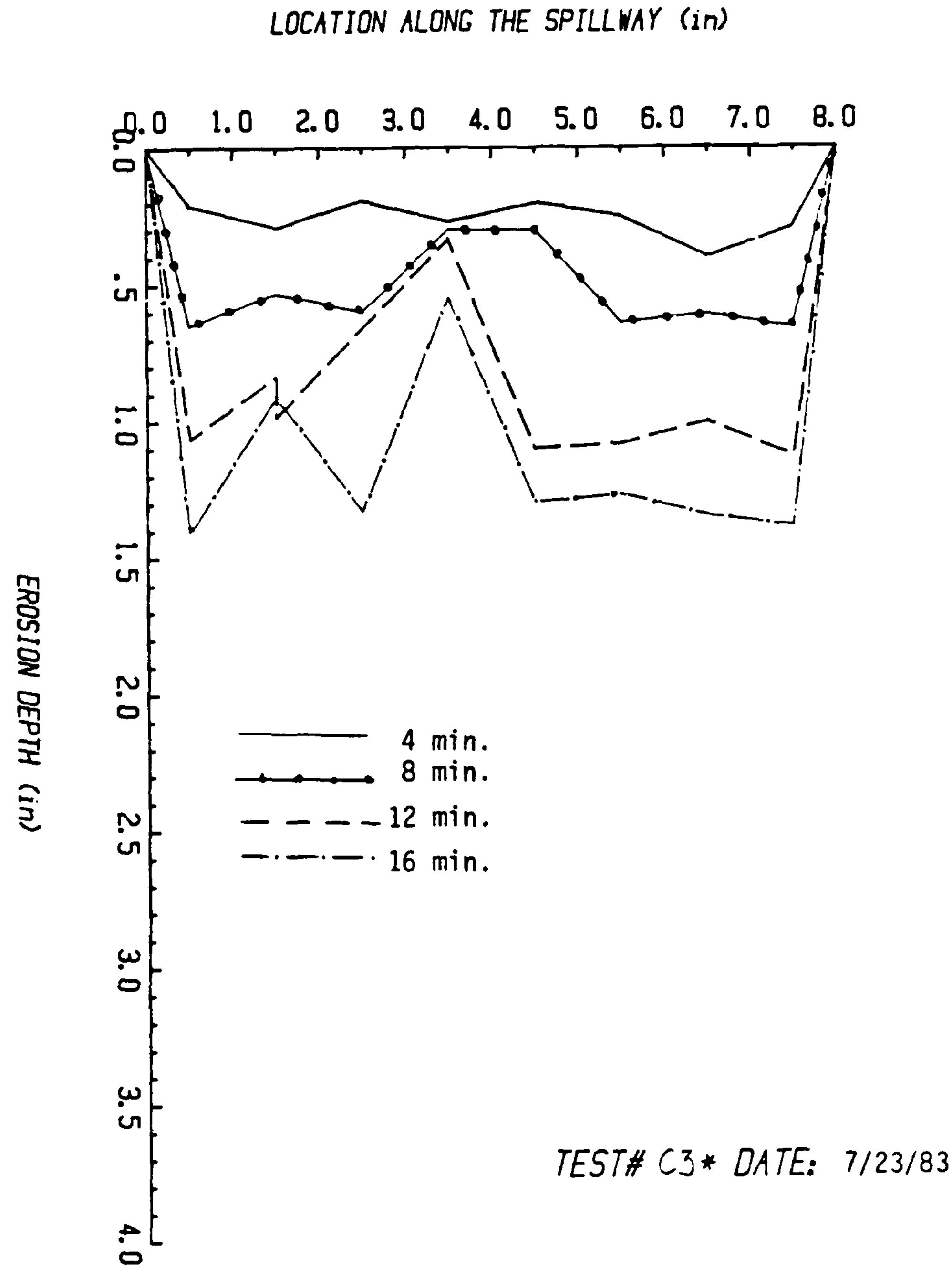


Fig. V.7 (f) Erosion profile cross sections of C-3 determined from manual measurements at row B

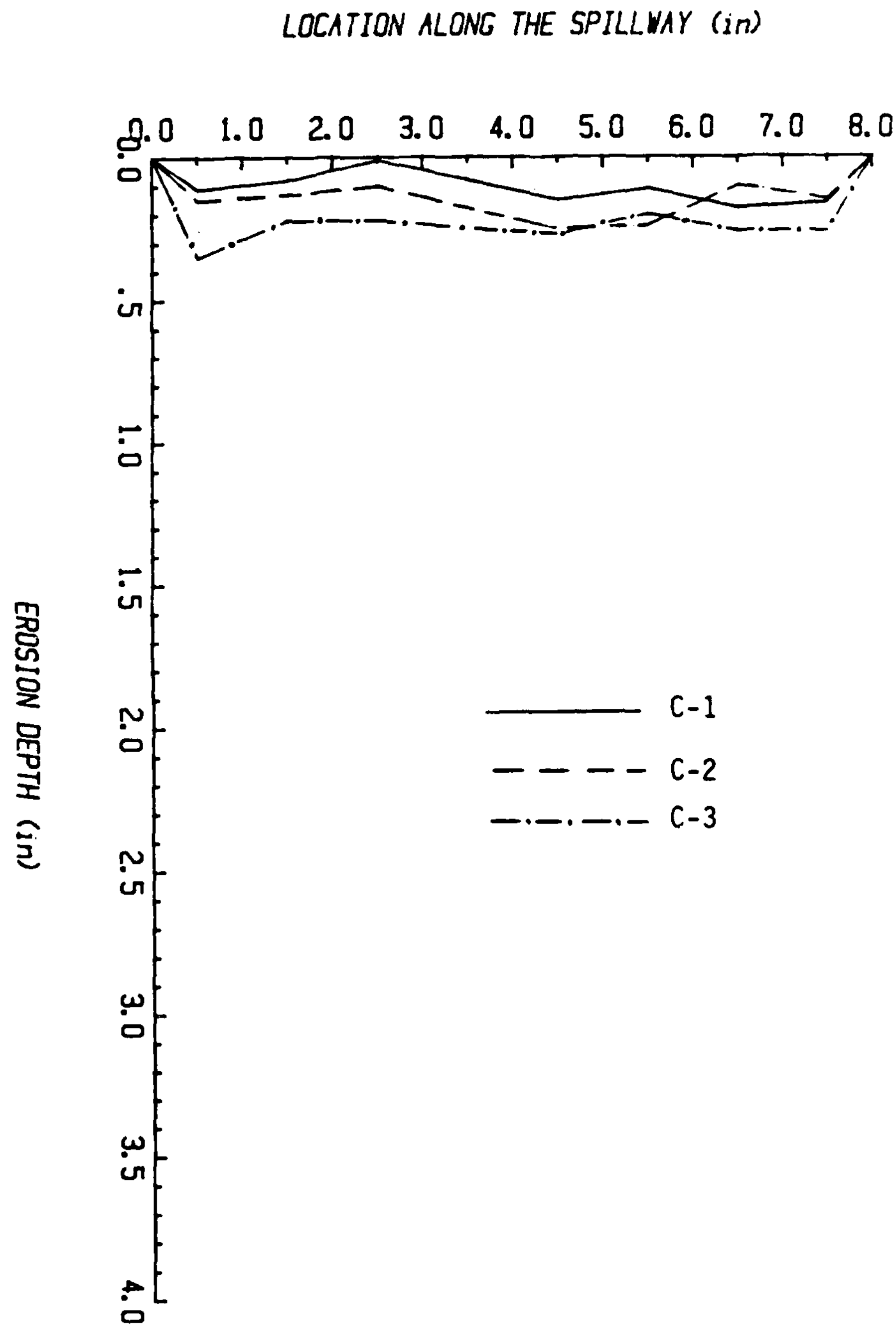


Fig.V.8 (a) Comparison of clay embankments erosion profile cross sections for row A after 4 min. of overtopping

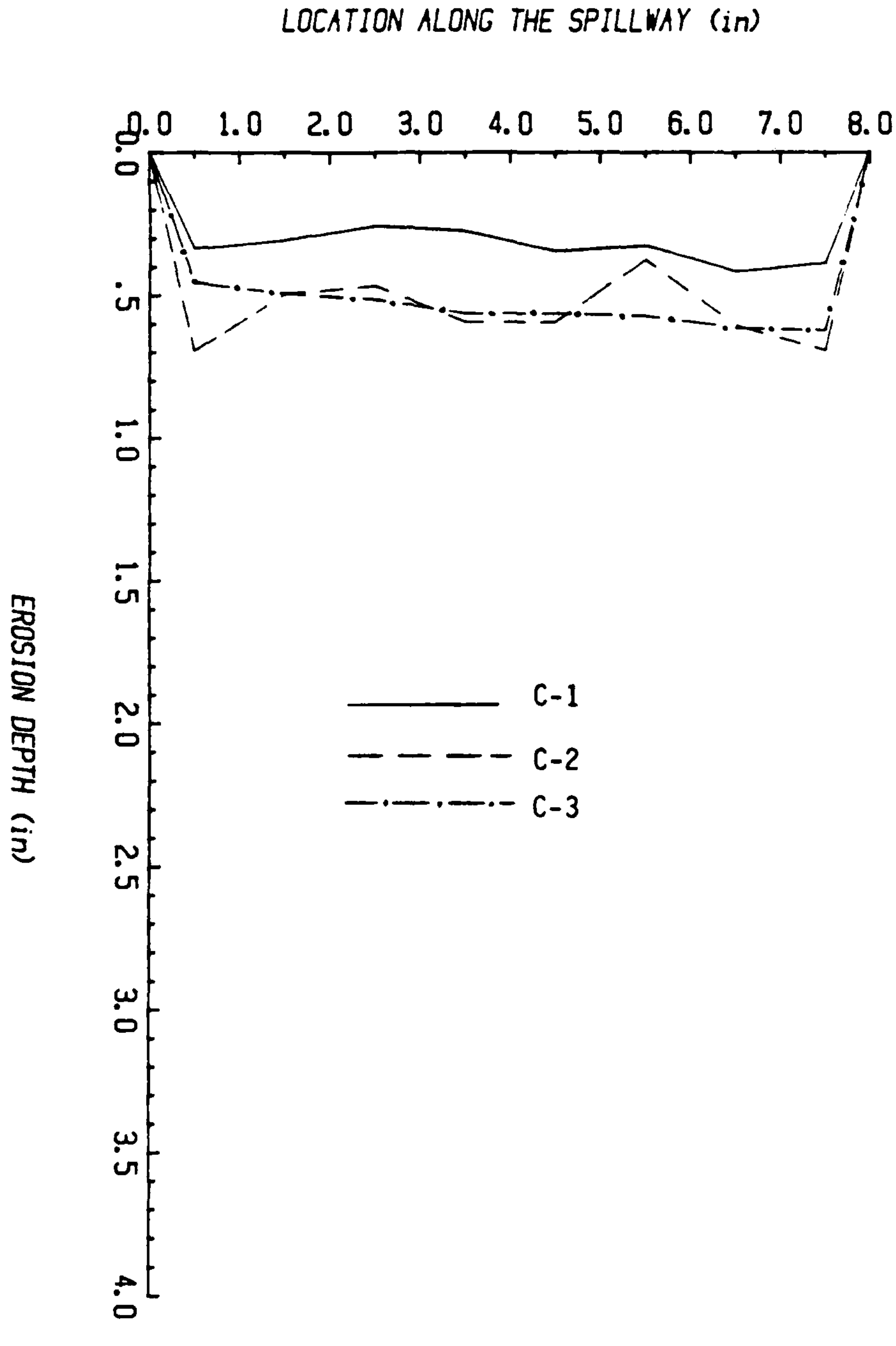


Fig.V.8 (b) Comparison of clay embankments erosion profile cross sections for row A after 8 min. of overtopping

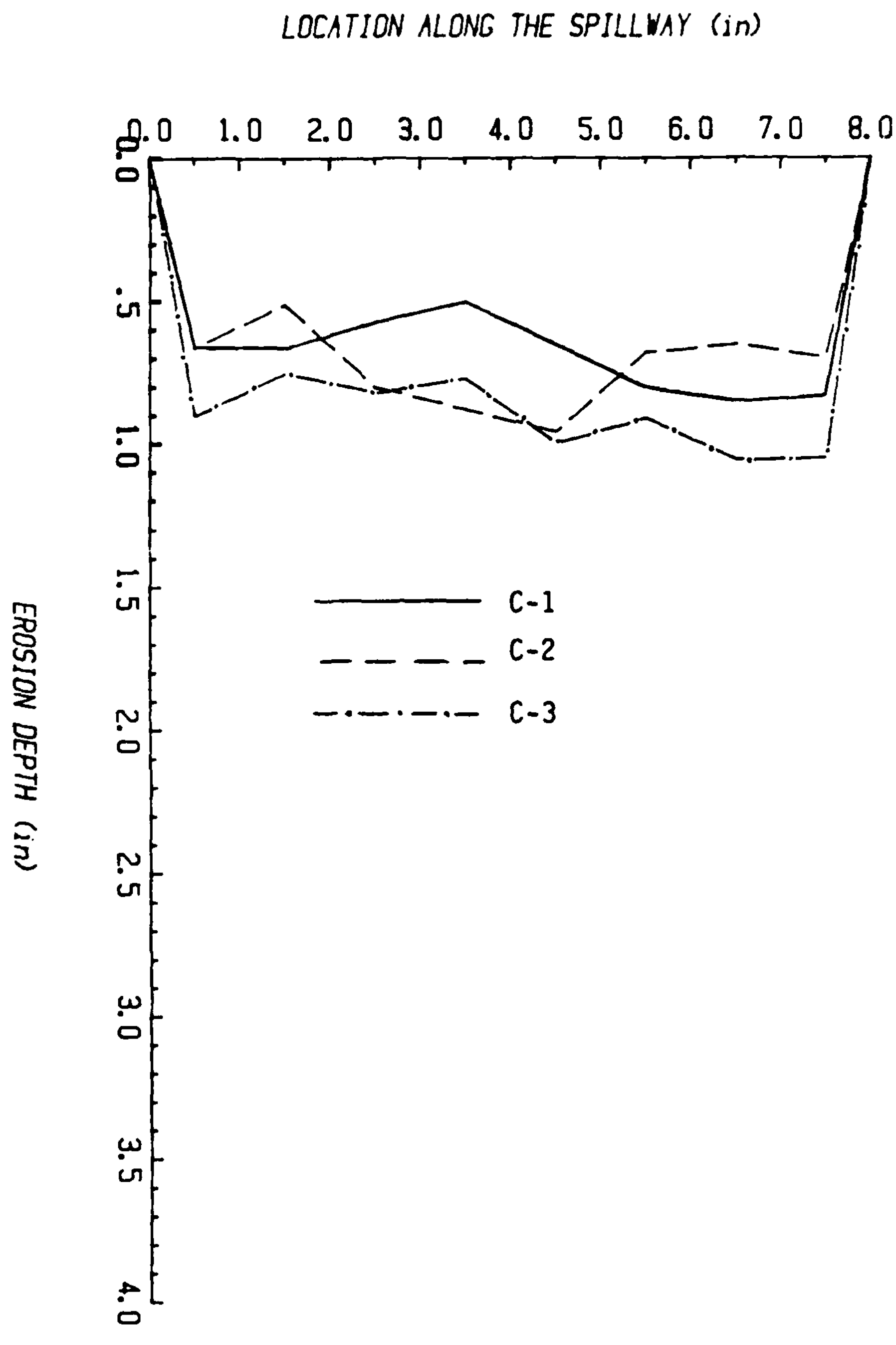


Fig. V.8 (c) Comparison of clay embankments erosion profile cross sections for row A after 12 min. of overtopping

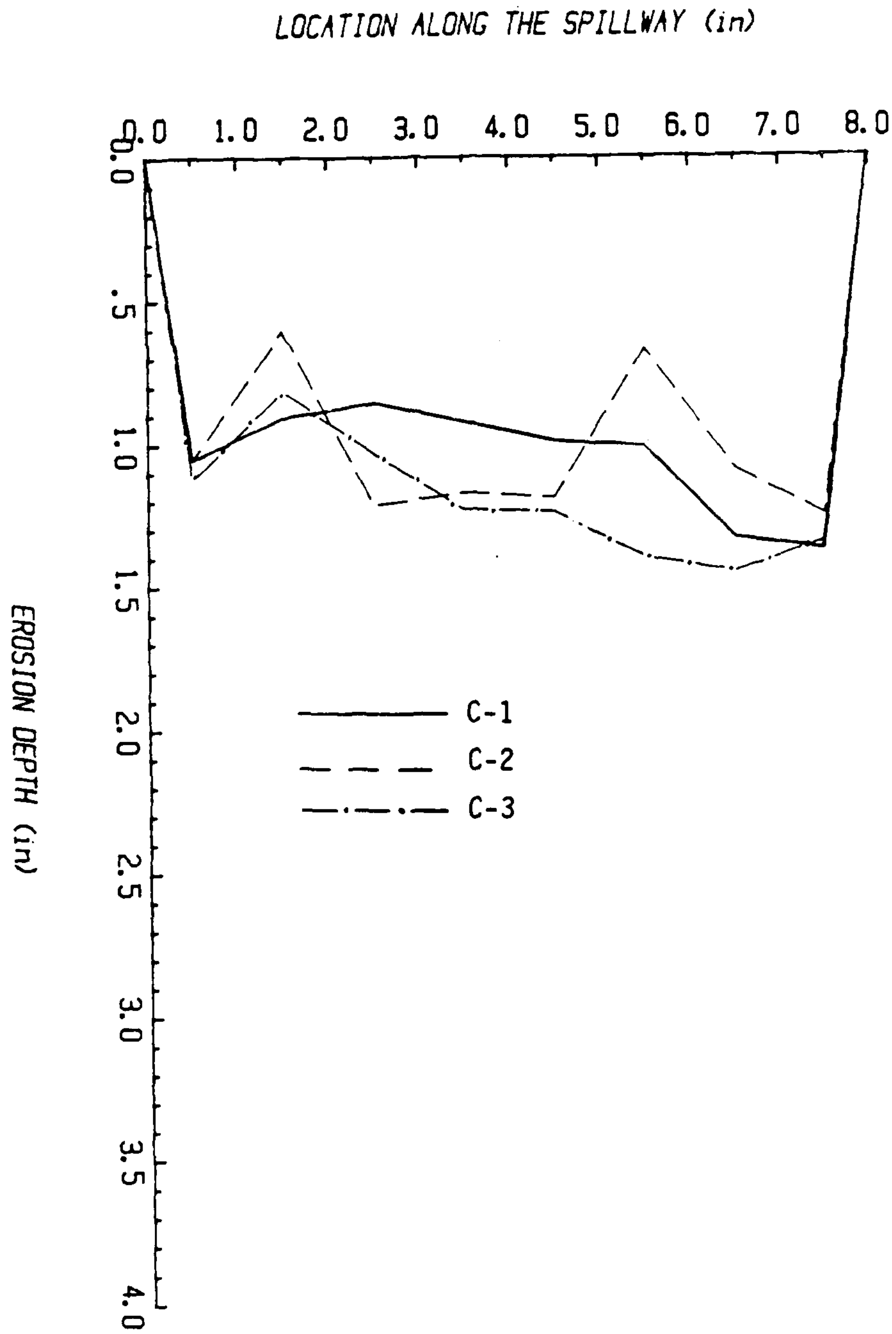


Fig.V.8 (d) Comparison of clay embankments erosion profile cross sections for row A after 16 min. of overtopping

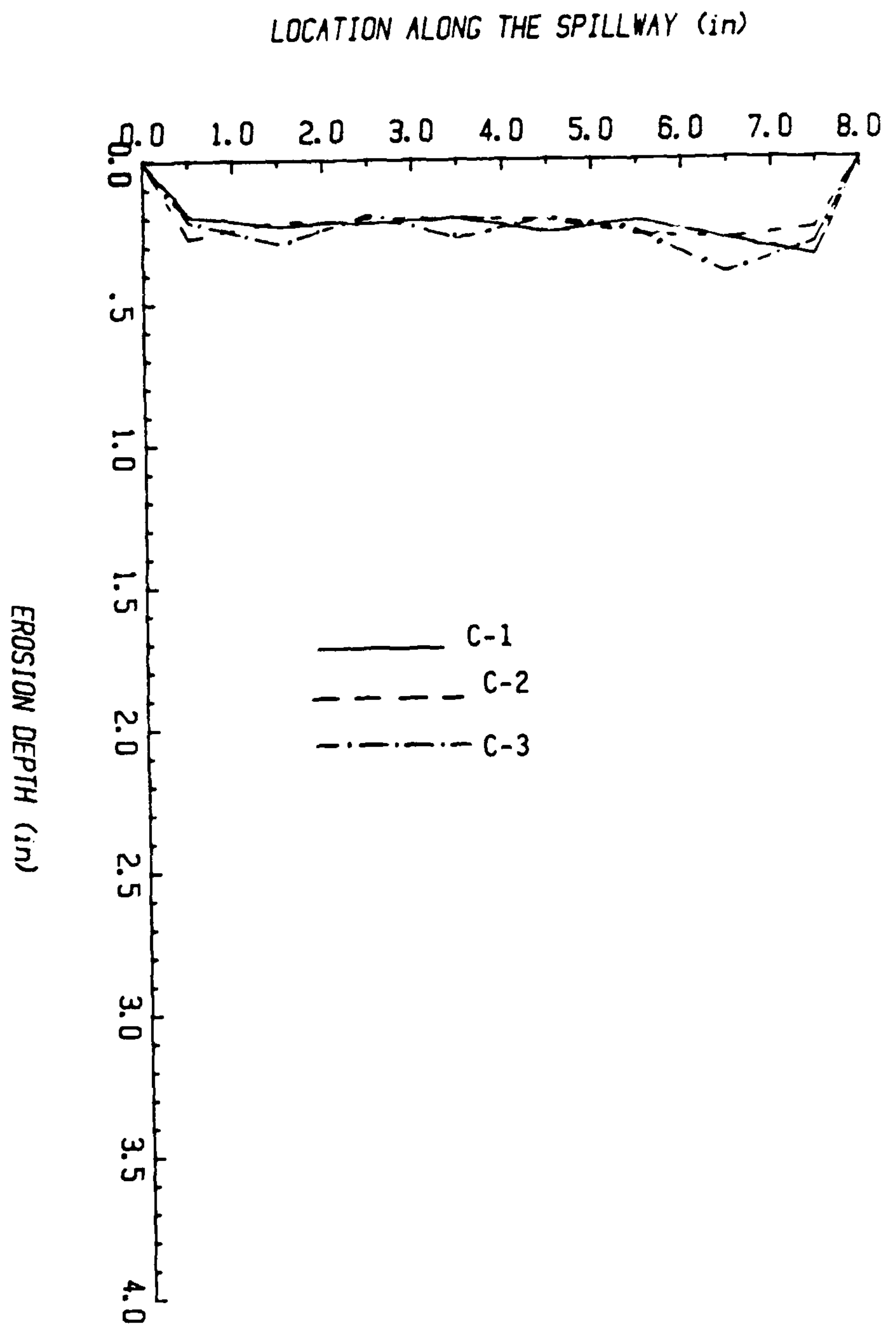


Fig. V.8 (e) Comparison of clay embankments erosion profile cross sections for row B after 4 min. of overtopping

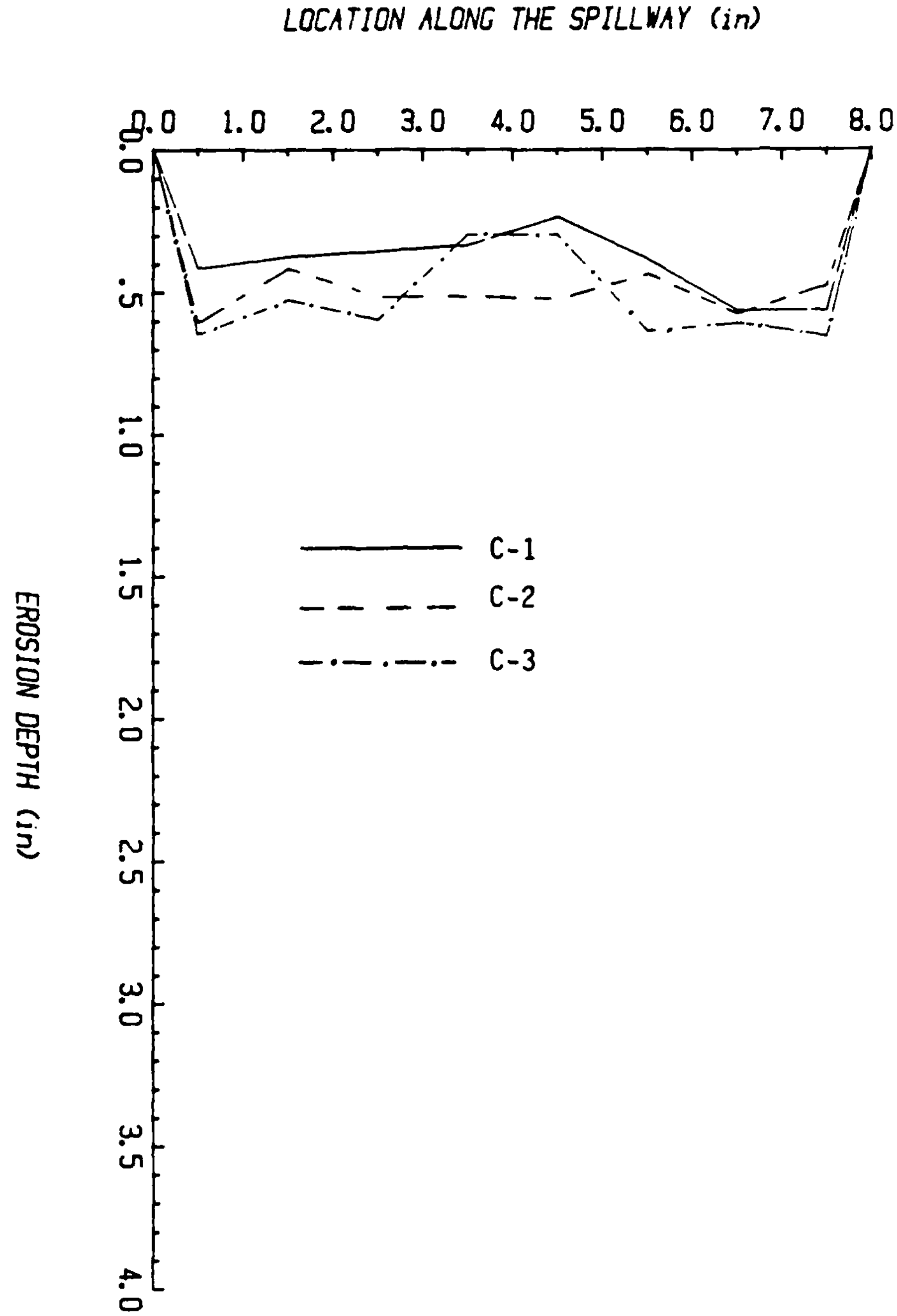


Fig. V.8 (f) Comparison of clay embankments erosion profile cross sections for row B after 8 min. of overtopping

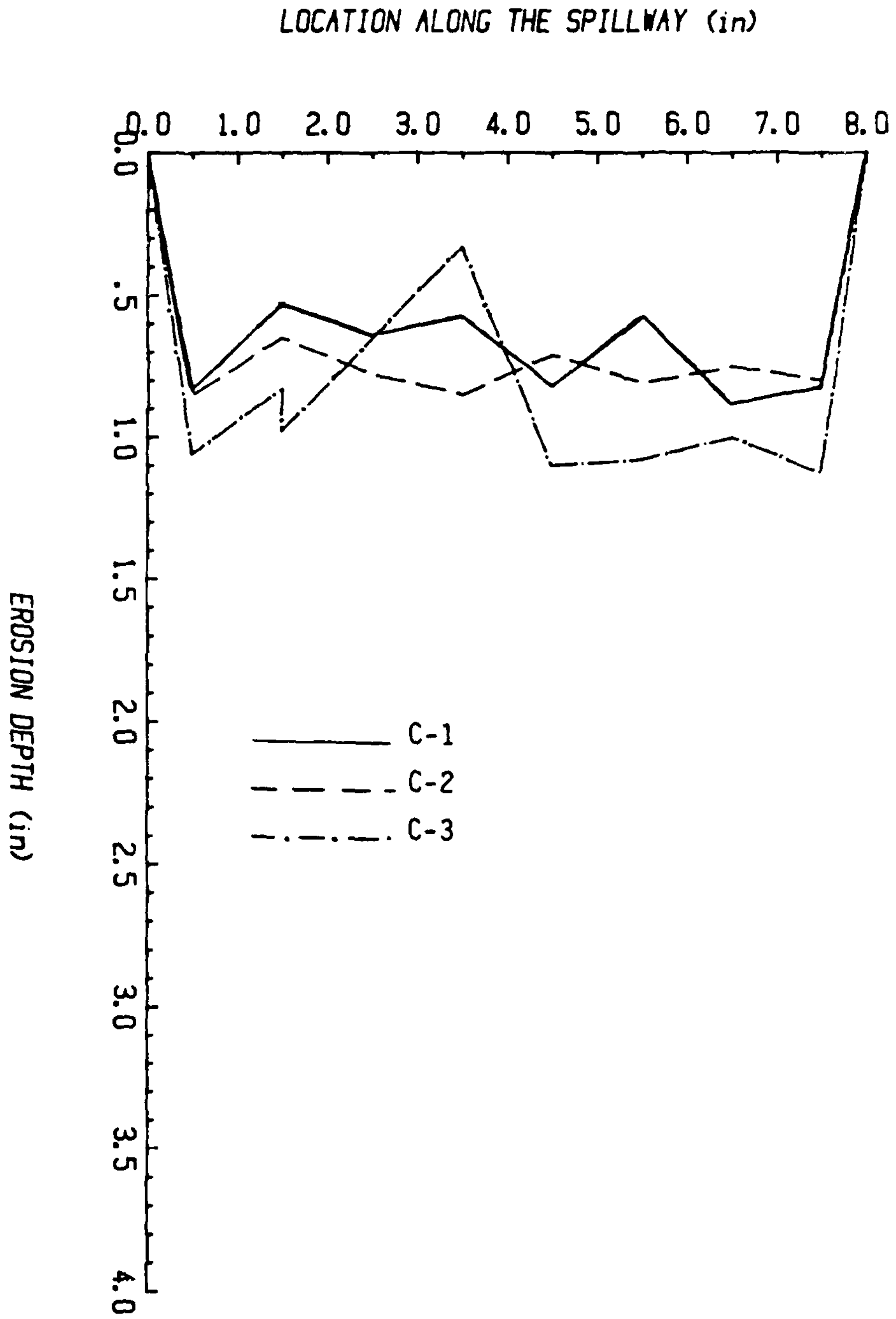


Fig.V.8 (g) Comparison of clay embankments erosion profile cross sections for row B after 12 min. of overtopping

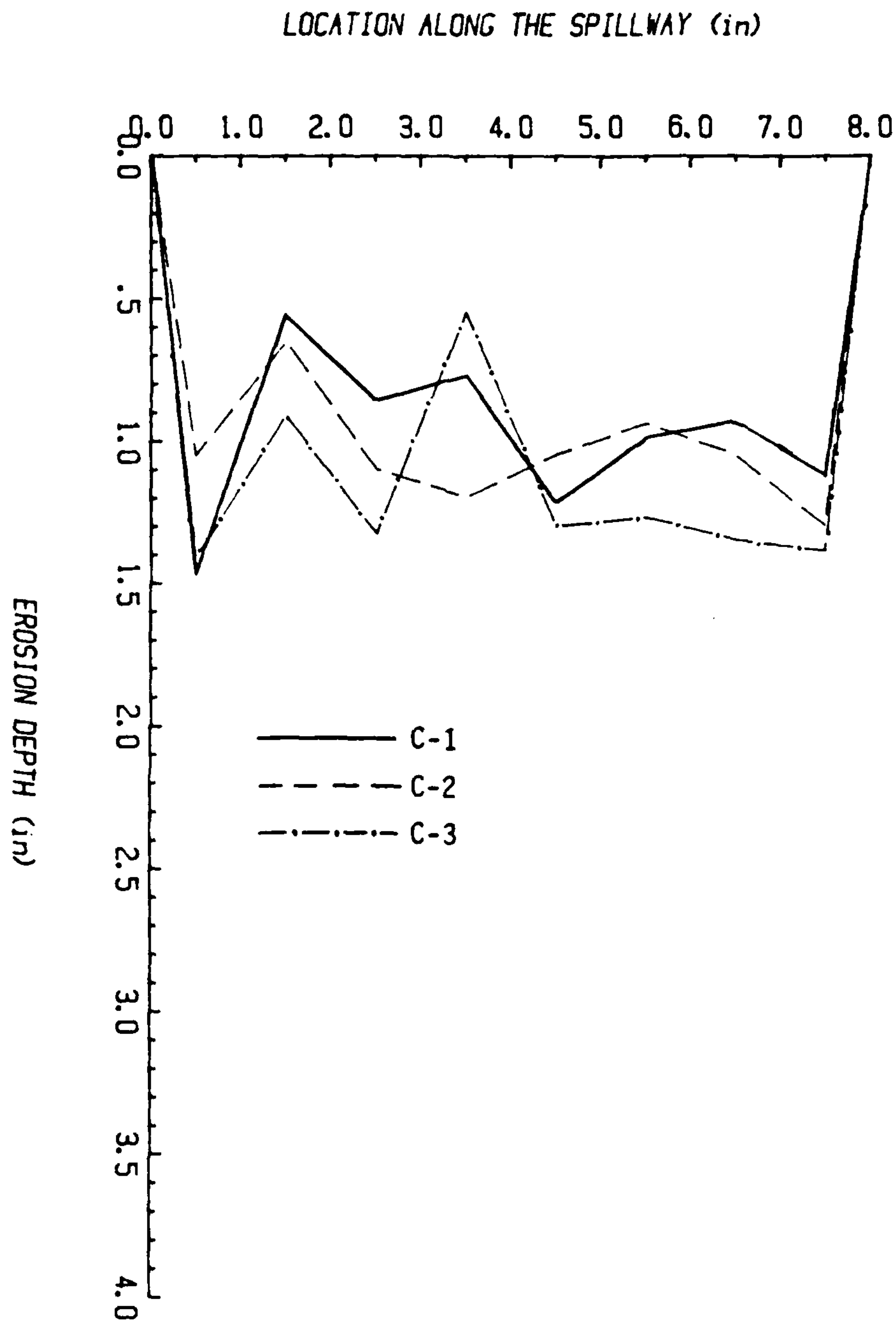
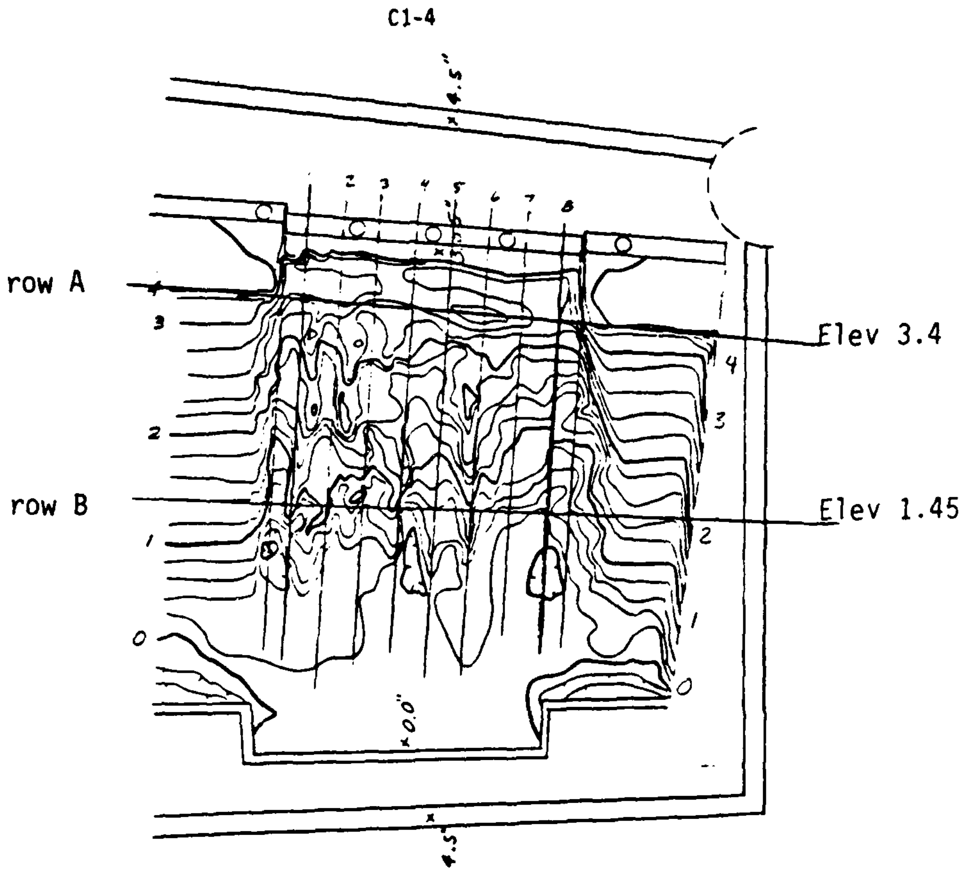


Fig.V.8 (h) Comparison of clay embankments erosion profile cross sections for row B after 16 min. of overtopping



Contour interval = 0.2" , Scale = 1:4

Test date: 8/2/83

Fig. V.9 Contour map of clay embankment C-1 after 16 min. of overtopping

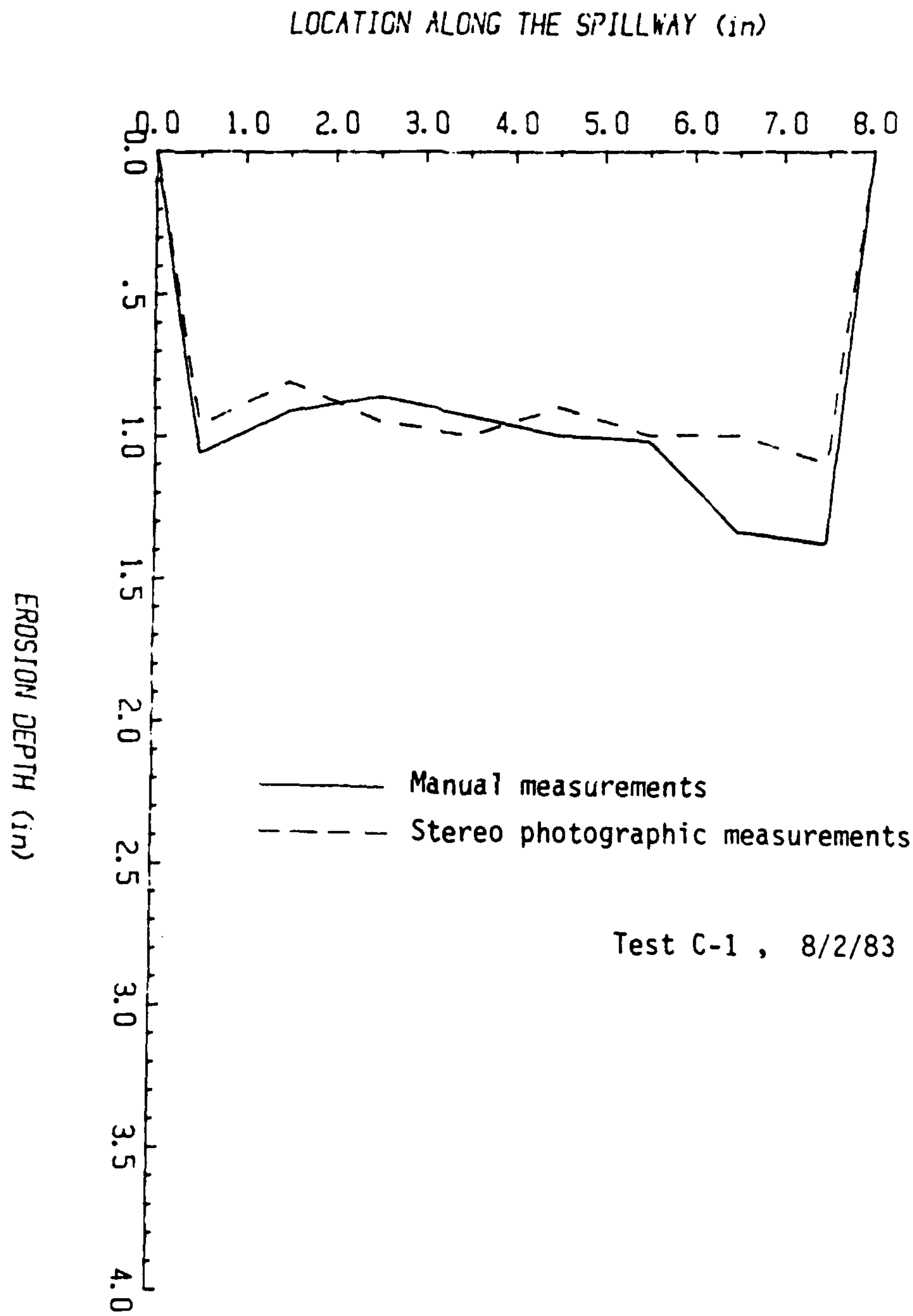


Fig. V.10 (a) Comparison of manual vs. stereo photographic measurements at row A in clay embankment C-1 after 16 min. of overtopping

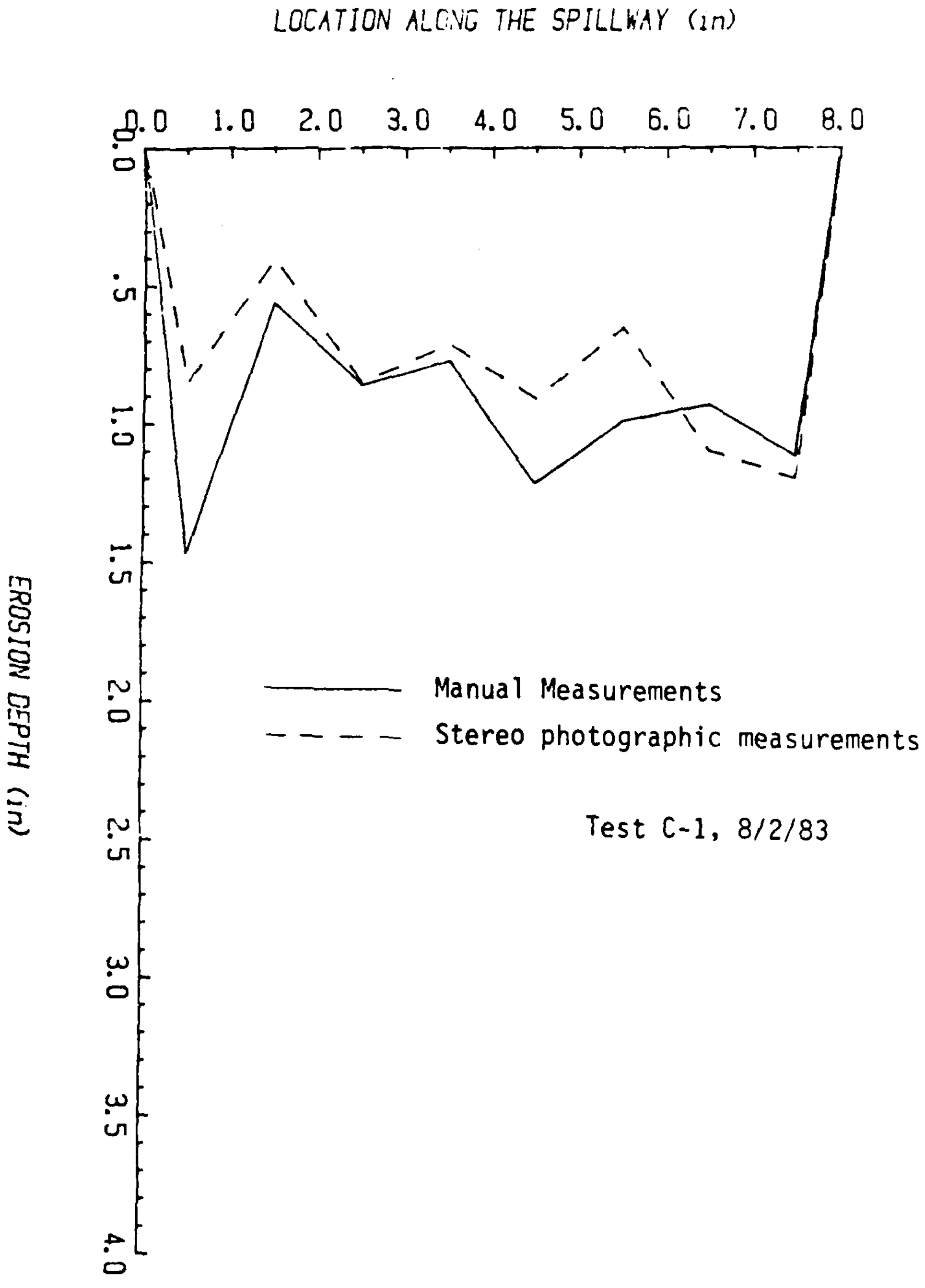


Fig. V.10 (b) Comparison of manual vs. stereo photographic measurements at row B in clay embankment C-1 after 16 min. of overtopping

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Feasibility of Using the Centrifuge For Study of Embankment Overtopping Phenomena

43. In order to show that the centrifuge is a useful tool for modeling of overtopping phenomenon, several objectives had to be met. They were:

- a. Introduction of large quantities of water into the centrifuge.
- b. Measurement of overtopping flow depth.
- c. Development of methods to measure erosion depth and volume.

44. Objective a was achieved by installation of the toroid water catchment system on the underside of the centrifuge arm. Objective b was met by installation of depth measurement gauges at different locations and elevations along the embankment spillway. Objective c was achieved by the use of stereophotographic techniques, and manual measurements with comparison of the two methods. The dimensions of the breached area can be determined from the erosion contour maps, and the volume of embankment erosion can be easily calculated by digitizing the data obtained from contour maps into a computer. However, we did not pursue that goal in this study. Based upon an achievement of the above named objectives, we feel that the centrifuge is a very useful tool for modeling of embankment overtopping phenomena.

Recommendations for Further Research

45. The validity of any modeling experiments is best demon-

strated by comparison with the full scale prototype performance. At the present time, Simons, Li, and Associates (SLA) of Fort Collins, Colorado are conducting a series of full scale tests of embankment overtopping for the Federal Highway Administration (FHWA). It is possible to duplicate the SLA tests in the University of Colorado centrifuge thus allowing direct comparison of the model and prototype test results.

46. In addition, to validate scaling laws, a modeling of models study should be conducted. In this study 3 different scales of the SLA tests should be tested at three different gravity levels, for example, 25g, 50g, and 75g, and the results related to the 1g full scale prototype. This will allow prediction and validation of the relevant scaling laws.

47. Questions have been raised regarding the appropriateness of using the centrifuge to model hydraulic phenomena, such as open channel flow. In conjunction with the above concept of simulating the SLA soil erosion tests, an additional test series should be conducted on an embankment model with a rigid (non-erodable) surface. This will allow the hydraulic parameters applicable to open channel flow to be measured. Again, a series of modeling of models tests like that described above will be required to verify the scaling relations for these parameters. The modeling of models study of both rigid and erodable embankments is currently underway as part of the extension to the contract.

48. To model larger dams, for example, over 100 feet high, a larger centrifuge is required. The centrifuge presently in operation

at the University of Colorado is optimal for modeling the SLA tests. It, however, is limited in size. Because of this limitation in this study, only the downstream half of the embankment dams was modeled. If a larger centrifuge, with a larger radius and experimental basket size were available, larger embankments could easily be modeled. Additionally, the need for high RPM's to achieve necessary g loadings on the models would be circumvented, making the operation of instrumentation and cameras much easier.

REFERENCES

1. Ladd, R.S. "Preparing Test Specimens Using Undercompation," ASTM Geotechnical Testing Journal, Vol. 1, No. 1, March 1978, pp. 16-23.

2. Suga, K., Ishikawa, T., and Kasai, T. Abstract from Proceedings of the 25th Japanese Conference on Hydraulics, 1981.

3. Winterkorn, H.F., and Fang, H.Y. Foundation Engineering Handbook, van Nostrand Reinhold, New York, 1975.