SOME LABORATORY TESTS OF TETON DAM CORE SOIL ILLUSTRATING WELL FRACTURE, INTERNAL EROSION, VOID MIGRATION, AND INTERACTION BETWEEN FRACTURES AND FILTERS.

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1. Introduction

This is an illustrated review of a series of centrifuge and other tests, mostly conducted in the Cambridge University Engineering Department (England) on specimens made of soil from the core of Teton Dam.

Following the failure on June 5th 1976 an Independant Panel reviewed the cause of failure and reported to the U.S. Department of the Interior and the State of Idaho in December 1976. The Independant Panel's report included an analysis of hydraulic fracturing and its possible role in the Teton Dam failure. This present review begins with a comment that that analysis did not consider the tensile strain conditions necessary for fracture.

That comment originally made in April 1977 led to centrifuge model tests of well fractures. First models were tested by a research student Gillogley at the University of California at Davis in 1977, and subsequently models Teton I, II and III were tested in early 1978 in Cambridge. While Gillogley's tests generated internal channels and voids the fractures in the Cambridge tests were self healing to such an extent that they were invisible on subsequent 'site investigation' of the models, except in one case where a fracture surface was stained. We reached no clear conclusion about the difference between the UCD and Cambridge model tests, and a continuing technical difficulty with these centrifuge tests was the accurate measurement and control of small seepage flow rates in models: the analysis of these well tests by Arulanadan, Gillogley and Schofield remains to be completed. However, when the wet seams in Teton Dam remnant were reported the suggestion at Cambridge was that the wet seams were evidence of small fractures that healed, while the erosion channel that formed at Station 13 was evidence of a large fracture that was unable to heal and led to the rapid failure of the dam.

In 1977-8 a series of centrifuge model tests of mine waste heaps for the U.S. Army Corps of Engineers at Cambridge showed features of seepage through-flow, surface erosion and gully formation. This led to a further series of tests on the interaction between transient groundwater mounds and drained embankment slopes. This study also remains incomplete until seepage flow rates are better controlled in the centrifuge, but the plane model test equipment was used early in 1980 for models Teton IV and V.

A feature of the plane model package is that there is a vertical plane transparent perspex (plexiglass) face behind which a section of the embankment can be seen. The idea of models Teton IV and V was to test the vertical face of a compacted embankment section as if it were half of a vertical crack transversely through the embankment. The progress of erosion could be observed through the perspex. Other fractures were induced and erosion on them was seen to generate open channels such as had been seen in the 1977 UCD centrifuge tests. Then a reverse filter was placed over the channel outlet and self healing of the voids was observed. This was performed twice; once at 1g on the laboratory floor in model Teton IV and again at 100g in the centrifuge in model Teton V. The upward migration of voids, the collapse of overlying filter layers plugging voids, and the self healing of large voids are all illustrated in this review. Some features of these tests resemble features photographed after the Baldwin Hills reservoir failure.

The 1980 Rankine Lecture introduced simple concepts of tensile cracking and fissuring of stiff soil. Two studies of tensile strains to fracture Teton Dam core specimens will have been completed by Cambridge students by September 1980. These studies remain incomplete at present but some concepts of the application of tensile strain cracking criteria to the safety of dams such as Teton Dam are discussed at the end of this review.

2. The fracture analysis by the Independant Panel

The principle proposed in Chapter 12 page 12.12 of the Report of the Independant Panel is as follows:

".. compute the minimum total compressure stress (σ_n) at any point within the dam and . . . compare the sum of this stress and the tensile strength (t_s) of the fill material with the pore water pressure. If the sum of the normal stress and the tensile strength is less than the pore water pressure the possibility exists that cracks will develop by a mechanism of hydraulic fracture," (parenthesesadded). The calculation is shown in Figure 10 of Appendix D page 18

".. fracturing occurs if $u > \sigma_n + t_s$."

This principle would not apply if the case under consideration were the transportation of a similar dam made of compacted clay with a similar key trench and rock foundation to the bottom of the ocean. The dam would experience an increase in σ_n in all directions as it was immersed and the water pressure increased all around; this would then be followed by a decrease in effective stresses in the soil as the clay began to swell. The rock foundation would not allow lateral strain and the width of the key trench would not increase so the net horizontal strain would be zero. The bouyant dam would experience vertical stress relief when totally immersed in water and there would be some reduction in the lateral pressure across the key trench. However, in that case there would not be a fracture of the key trench even though the final u at the ocean bottom was very much greater than the initial normal stresses σ_n in all directions in the soil compacted in the key trench.

In general a principle of superposition works in cases of a statically determinate structure free to strain in all directions. The fracture analysis by the Independant Panel takes the inital stress σ_n before reservoir filling and subtracts the water pressure u after reservoir filling without considering what restraint the rigid walls of the key trench impose on the strains, and what change there will be in the total stresses σ_n during reservoir filling.Of course there are many examples of simple calculations giving reasonable answers even though approximate, and the case of increase of water pressure in jointed rock on the upstream face of the key trench could possibly approximate to the analysis by the Independant Panel. A vertical crack in the rock ending at the key trench, with water levels and pressures steadily rising in the crack, resembles a well with water levels and pressures rising before hydraulic fracture. The calculation made in 1979 for that well fracture case is that the tensile strength t_s of the soil is determined as the difference between the water pressure u at which levels in the well fall dramatically and the minor initial principal total stress σ_n. Since the Independant Panel accepted the calculation $u = \sigma_n + t_s$ for the interpretation of the data of well fracture it was reasonable for them simply to extend that calculation as they did in their analysis. However, the principle involved in the calculation does not have universal application because it does not apply to total immersion of a dam on a rock foundation. This comment was made to Professor Seed in April 1977 and the following model tests then proposed.

3. Teton well models

Problems where self-weight is important attract the interest of geotechnical centrifuge research workers. A feature of the fracture analysis of the Independant Panel was the arching of pressure away from the soil at the bottom of the narrow key trench, allowing a crack path to run preferentially through the soil at the bottom of the trench where σ_n was least. A centrifuge analogue of the Independant Panel analysis is suggested in Figure 1. In the well model tests there are one or more vertical or inclined wells, cased over an upper length and open over a lower length, with a simple falling head water supply. Each well is thought of as an open vertical crack in the rock on the upstream face of the key trench, providing sources of water under pressure at one face of the key trench. Not far from the lower end of the wells a body of gravel or of cracked brickwork provides an easily accessible sink. If a crack began at a well and ran to that sink then it would be eroded by through-flow, there being no filter to prevent loss of solids from the eroding soil into the voids of the gravel or the cracked brickwork. A special feature of the Teton III model with cracked brickwork was that there were steel surcharge plates above the soil and high pressures arching across the trench. The wells are thought of as representing fissures in the upstream face of the key trench, and the sink with voids represents the downstream face, but in the Teton III model the trench had twice the width of the corresponding key trench at Station 13 in the Teton Dam with flow from the wells possible in either direction.

In planning exploratory tests such as are being described here the idea is simply to try first to produce the physical phenomenon of interest (in our case a fracture from a well to a sink); elaborate instrumentation can be planned better once the phenonomenon has occurred in two or three repeated tests.

The first well models were made and tested on the Schaevitz centrifuge at the University of California at Davis Figure 2; the first specimen was compacted into a 18 inch diameter steel ring with a segment cut out and replaced by gravel. The three wells in that case were set at varying distances from the gravel sink. The model held at the end of the centrifuge arm Figure 3 could be viewed in flight by a closed circuit television camera. The inclined well casings were sealed in their upper length with epoxy resin and then drilled out beyond the casing Figure 4. To observe the flow of water to the well an inclined mirror was fitted Figure 5 so that the height of water in the header vessel was visable from the central television camera: the soil surface is foil covered in this photograph. After a complex series of well tests a sink hole appeared Figure 6. Excavation showed an oblique fracture with erosion of a channel visible at the pencil point in Figure 7. Eroded soil had been washed into the gravel.

The next step was to attempt to repeat this phenomenon on the Cambridge centrifuge, Figure 8, which operates with packages of up to 900 kg mass swinging up in flight at 4m radius at up to 125g. Teton Dam core soil was shipped over to Cambridge, England. The specimen that formed model Teton I was compacted into a 850 mm diameter 400 mm deep tub Figure 9, and a segment was cut out Figure 10 and filled with gravel. The inclined wells were drilled and cased Figure 11, and in order to apply a falling head and observe it from a central television camera an inclined ramp was constructed from slotted angle, and on the ramp plastic pipes were fitted Figure 12. In the first phase of the tests the head in these plastic stand pipes was raised in stages and the rate of fall was observed with each well in turn until each well fractured. Fractures clearly ran up to the surface, as seen in Figure 13 and 14 with the model Teton I still on the swinging platform at the end of the test. When the specimen was examined after removal of the gravel it was clear that there had been no erosion or channel running to the gravel sink Figure 15 and the fracture rose vertically from the well tips: perhaps there had been a little lateral movement of the fractured block towards the gravel sink. When the specimen was jacked out of the tub Figure 16, and sectioned Figure 17, there was no sign of the vertical fracture that had been so evident originally from above: the fracture had self healed and was invisible in section.

In the next model Teton II in order to eliminate any movement of a fractured block towards the gravel sink a single well was drilled Figure 18 and the gravel sink took the form of a rectangular vertical drain Figure 19. To form the gravel drain as each layer of soil was compacted in the tub a rigid rectangular block of wood was placed in the drain position, the soil was compacted firmly beside the block of wood, the block of wood was eased out of position, and gravel was compacted into the slot, forming a vertical drain through all layers. The gravel was close to the well, but the fracture ignored the gravel and once again ran vertically to the surface. The specimen was jacked out after the test Figure 20, and the gravel removed Figure 21, but once again there was no sign of a fracture from the well to the gravel sink. As the investigation proceeded the horizontal layers of compaction were evident Figure 22, but even when the well casing was reached Figure 23 the fracture was invisible. This model Teton II had three total stress cells near the well to measure stress components Figure 24.

The third model Teton III was made with a plastic lining sheet inside the tub Figure 25 and with two blocks of bricks laid with cement mortar to either side of the tub. The bricks were oiled to prevent bonding and when the mortar had set it was easy to break the brickwork apart, remove some of the mortar joints to create open voids filled with coarse sand and re-assemble the blocks of cracked brickwork. The soil was compacted into the tub with pore pressure and total pressure cells in the trench, the surcharge plates were placed above the compacted soil Figure 26, and the wells drilled into place. With this Model Teton III provision was made to saturate the cracked brickwork and the trench soil, and two plastic pipes can be seen rising from the edge of the tub which allow air to escape from the brickwork. The falling head supply to the wells can be seen in figure 27. The tests on the wells continued over a number of days. In order to make the water in the stand pipe visable it was stained with potassium permaganate. In one of the tests on a Saturday morning the supply of potassium permanganate ran out and as a temporarary expedient instant coffee was used. The test involved a succession of many runs in each of which the head in the stand pipe was raised and then the rate of fall was observed. The potassium permanganate stained water was not very clear, and a better indicator of the level was then devised, which was a white plastic float in the plastic stand pipe tube. After a succession of many increments there was ultimately a sudden drop of level and a clear fracture of each well in turn. Because of the presence of the surcharge plates it was not clear if the fractures had run from the wells to the cracked brickwork until after the site investigation.

The presence of the greased plastic liner bag made it easy to remove the tub after simply inverting the model Figure 29. When the bag was removed the cracked brickwork was revealed Figure 30: it was also clear that in removal of the tub there had been a sidewise movement that sheared the specimen on horizontal planes where compacted soil slipped most easily. There was no sign of any soil washed into the brickwork voids, even when the brickwork was carefully removed, Figures 31 and 32 (note in Figure 32 that the specimen is upside down and the ridge of soil seen on the top is really the bottom key trench soil). Soil was carefully removed without any sign of a fracture Figures 33 and 34 even near the wells. The load cells were removed Figure 35. Then, unexpectedly, near one well a dark coffee stain was seen Figures 36 and 37. Excavation revealed that the stain was approximately circular and planar and extended beside and above the length of open well Figure 38. As excavated Figure 39 the well and the stain are seen above the surcharge plate but in the test of model Teton III the well should be thought of as extending vertically below the surcharge plate Figure 40. In these tests at the time the coffee was introduced into that well there was still an increasing head being carried in the stand pipe. The event described as well fracture occurred during a later increment by which state there clearly was a plane vertical circular crack which began to extend away from the well at a stage of the well test earlier than the stage called well fracture.

At the end of the Teton well model tests at UCD and Cambridge there was no clear explanation why a horizontal erosion channel occurred in the UCD test and not in any of the Cambridge tests: the research student Gillogley continued with further tests at UCD and is now (June 1980) about to submit his thesis. All the well tests require further detailed analysis, but for the purpose of this review it is sufficient to state first that in the well tests the point at which there was a distinct fall of head did not signify the first occurrence of tensile strain cracking in the soil in the uncased hole wall, and second that all three Cambridge well tests showed fractures in a vertical plane rising towards the free surface and not running across the key trench, whereas the UCD tests showed fractures in other planes.

4. Internal erosion on fractures, void migration, and filters

The equipment used for the drained slope models Figure 41 had a source of water at the lower right hand side of the package over which a bank of fine sand was placed. At the toe of the slope a reverse filter prevented erosion and back-sapping, so that a ground water mound could be introduced and rise within the plane section and flow safely away from the toe. To observe pore pressures in the bank in flight six stand pipes seen on the left of the package are connected to pressure tappings in the sand. At the bottom of each stand pipe the white reflective float can be seen, which is clearly visable by television as it rises or falls during a test. The upper phreatic line of a transient ground water mound is visable by television. In order to see failure clearly by television diagonal stripes of black paint are sprayed on the sand face and diagonal stripes of white paint are sprayed on the back wall of the package. The flow of water to the source and the plastic pipes connecting the pressure tappings to the stand pipes are seen round the back of the package Figure 42. A typical slope failure due to a ground water mound approaching a slope is seen in Figures 43 and 44. This equipment was adapted for use with models Teton IV and V, involving sections of compacted core, Figure 45.

In model Teton IV there was a small gap between the compacted core soil and the vertical transparent perspex face. The source from which water entered the package is being pointed to in Figure 46. Water was poured rapidly into the box and in Figure 47 the column of falling water is clearly visible; this water flowed through the gap between the core soil and the perspex. Erosion of the soil widened the gap, the rate of pouring of water was reduced, and in Figure 48 the upstream water level is falling. In Figure 49 the appearance of a compacted face eroded by water is evident.

A small flow of water was then introduced. The dispersive nature of the compacted soil was such that the lower part of the gap healed, and Figure 50 points out the upstream level which is held back by the 'healed' gap. The process of infilling of the gap removed a quantity of soil from a distinct channel which by then had formed. In Figure 51 the channel is stable but there is no supply of soil to infill it: the core is in a dangerous state because any increase in flow rate through the channel will rapidly remove the soft soil infilling the gap below the base of the channel.

To close the channel a screwdriver was then driven into the top of the core, causing the cracks that are pointed out in Figure 52. The upstream level could now be raised Figure 53, as is pointed out in Figure 54. However, by the time the water had reached the crest of the core Figure 55 there was a new flow of water through the core: some of the fractures caused by the screwdriver were connected with the gap behind the perspex. A wet patch appeared half way up the core. The flow from the wet patch increased Figure 56 and soon a heavy flow of eroded soil began to appear in the gap behind the perspex Figure 57. At first the eroded soil succeeded in filling the gap but then the full upstream pressure appeared behind the perspex at the point shown in Figure 58. There was a rapid flow, flushing out the soft soil already deposited in the gap and lowering the upstream water level Figure 59, leading to formation of a large channel and void.

At this stage a coarse sand filter was loosely deposited over the downstream exit of the channel, Figure 60. The upstream water level was again raised and soft mud began to infill the gap Figure 61, but the water pressures were more than the downstream filter could stand and it washed out Figure 62, leaving an even larger void. The filter was reinstated and the upstream level was slowly raised Figure 63, and the layer of sediment which filled the gap Figure 64 backed up to the point Figure 65 where the reservoir pressure had broken through. The level was raised to full upstream height Figure 66 and left overnight Figure 67. Next morning Figure 68 the upstream water was clear, the upstream face had sloughed, there had been a little seepage, but the core and all the voids had become water tight. The model was stripped down Figure 69 and the original steel former within which the core had been compacted was forced back into place Figure 70: the very soft nature of the infilling mud is clear from the way it deformed when the steel former was forced into it.

The next model Teton V introduced some refinements and was conducted at 100g: the gap was reduced but a distinct saw cut was made across the face of Figure 71. Gravel was placed upstream and downstream to prevent slope failure under self weight at 100g: as an after thought a small circular cavity was bored near the crest and the upstream face to see how such a void would migrate. The centrifuge test began and a water flow was provided at 100g, which almost immediately caused a collapse of soil above the saw cut and an upward movement of the void Figure 72. When the test was stopped it was clear that the soft soil infilling the gap had not completely plugged all the channels - discontinuous channels remained near the upstream toe Figure 73 and near the downstream toe 74, where soil had been washed into the voids between the gravel. The perspex face was removed so that once again a downstream filter could be placed Figure 75.

The downstream gravel was removed, Figure 76 and in order not to alter the balance calculation in the middle of the test the total mass of downstream filter was kept equal to the removed mass. A lightweight but strong polyethelene block was inserted Figure 77 and a graded filter was built up with fine sand next to the core face, and medium and coarse sand downstream of it, Figure 78. The centrifuge test was restarted and a flow from the upstream gravel shell, through the damaged core, and into the graded filter, was established.

The television monitor picture shows data of the test in the top left hand corner. Note that the view is of a mirror image, so where Figure 78 shows the white polyethelene block to the left the television picture in Figure 79 shows it to the right of the photograph. The test took place on the 10th January 1980 and was at 101.4g at the time the photograph was taken, so the first line of data reads 10:01:80 G101.4. Figure 79 is a photograph taken just after 7 minutes to 4 in the afternoon so the second line reads 15:53:23.0. There is provision for a transducer signal such as a pore water pressure in the format after T, but this was not connected, so the information T009.7 is not significant.

At the stages shown in Figures 79, 80 and 81 the channel had migrated up from the original saw cut and a steady flow through the channel was entering the downstream filter. In the filter the flow can be seen in free fall to the phreatic line, about a quarter of the way up from the base. The water flows freely away through the coarse and fine sand. For a time not much movement of the eroded channel was apparent, and the flow rate was then increased, so at the stages shown in Figures 82 and 83 the filter is completely flooded below the erosion channel. Note that there is a void at the end of the channel in direct contact with the filter, and in Figures 84 and 85 a portion of the downstream filter collapses and plugs the void, leading to an infilling of the erosion channel and further upward migration; at this stage the flow rate was cut back and once again the through flow can be seen in free fall in the filter. The erosion channel slowly filled in Figures 86 to 90, and finally in a period from 15.53 hrs to 16.36 hrs, with a variable through flow and with collapse of part of the downstream filter the dam core became water-tight. Site investigation after the test showed the infilling to be soft, and a potentially dangerous but discontinuous erosion channel is evident low in the face in Figures 91 and 92.

The principal features of the test of 1g model Teton IV could be repeated in the 100g model Teton V, because the soil was strong enough. The voids seen in the model Teton V would be large enough for a man to walk about in them at prototype scale, but the soil was so strong that there was no question of the sides squeezing in and the floor heaving. The soil was strong enough for a vertical fissure to remain open over heights more than one hundred times greater than the 10in high model.

When a large void or channel in this fine grained non-plastic core soil contains air it follows that there is a water meniscus forming a membrane across the roof the void and preventing particles falling down. If water fills right up to the crown of the channel or tunnel then particles will begin to sedement down rapidly, but if the air is trapped as a bubble the void will not fill with sedement. If the trapped air later dissolves the void will infill and migrate upwards.

In general the nature of dispersive soil is such as to heal and infill cracks with soft mud which is watertight. An essential feature of the healing process is that soil particles need time to sediment before any water flow removes them from the void system. There can still be a modest flow rate provided the depth of soft mud in the channel base is increasing and the particles are not being removed. A dangerous event occurs when a crack or channel transmits the full upstream reservoir pressure to a weak zone downstream which is unable to contain the pressure, because this releases a flow that causes rapid erosion. The healing process is not a full strength repair - only a soft infilling.

5. Comments

Some features of the model tests were comparable to what was visible immediately after the failure of the Baldwin Hills Reservoir in Los Angeles. In that case a small vertical displacement on an underlying fault was evident from a crack in the distribution pipes. The failure caused a narrow breach in the embankment, Figure 93. The down throw to the west of the fault was evident right across the reservoir floor Figure 94, but the lining was supposed to remain water-tight with much larger displacements on the foundation fault. The narrow breach in the embankment Figure 95 had been in the process of cutting back Figures 96 and 97 when the flow ended. Within the breach there was still a small pool of water to be seen directly above the fault Figure 98, and a look at the fractured foundation rock below the pool Figure 99 showed no sign of seepage along the fault, so in general the fault was not providing a flow channel.

The Baldwin Hills reservoir lining Figures 100 and 101 which extended up the slope of the embankment rested on a cemented pea gravel drain. The soil compacted above the pea gravel drain was fine enough to wash into the pores of the drain; instead of a filter there was a skin of gunnite which was supposed to form a permeable membrane, allowing water to enter and preventing soil from entering the voids in the pea gravel, On the whole there was no evidence of failure of the gunnite or movement of soil into the cemented pea gravel Figure 102. However, at a number of places along the line of fault there were sink holes through the lining Figure 103, where it appeared that soil had been washed down into the pea gravel drain and a void had slowly migrated upwards through the lining. The final report showed photographs of a few voids and discontinuous channels found along the fault, Figure 104, which seem to indicate a early period of smaller flow in a channel such as was seen in models Teton IV and V. The underdrain probably cracked and void migration probably began years before the failure, perhaps even on first filling of the reservoir. However, it would not be until the sink holes broke through the lining and the full head of the reservoir acted in the voids and channels that the process of erosion of infilling accelerated and it then only took a matter of hours before failure. The Baldwin Hills reservoir breach was narrow and in that respect resembled the initial break in Teton Dam Figure 105. In both cases the soil seems succeptible to upward migration of voids.

The general character of the behaviour of such soil was clear in the model tests. Physical models can be informative even if they are not representing in precise detail every feature of a prototype event. They demonstrate features of behaviour and sequences of phenonmena which theoreticians do not consider - not because they disbelieve the evidence but because they have not upgraded their theoretical models to embrace all the evidence. In this respect it is a pity that the critical state models of soil behaviour are so little understood. They explain many features of soil behaviour such as the index properties and they give insights into the use of soil in model tests. Of course, there are not yet many analyses using the new models, and engineers have a lot of experience of using older models and adjusting parameters to suit circumstances, but the critical state models provide a rational basis for making such judgements. A recent exposition and development of critical state was given in the 1980 Rankine Lecture.

The 1980 Rankine Lecture mapped soil behaviour on axes of liquidity index against logarithm of effective pressure Figure 106.At any given liquidity, as effective mean-normal pressure increases the mode of failure changes from fracture or fissuring, to Coulomb rupture, and to yield with plastic volume change. The stress ratio q/p' that can be carried by the soil increases as pressure and liquidity fall - the insert shows a section across the map at constant p'. This increased strength and stiffness leads engineers to compact soil more and more, until they meet a new problem. When stiff soil becomes fissured it's permeability increases very greatly. A fracture will involve open voids and channels, whereas Coulomb rupture preserves soil still in a relatively impermeable mass. In this sense it is safer to have softer and more ductile soil construction which remains water-tight even when ruptured.

Considering a body of soil initially at LI = 0.5 and subject to elastic compression the map suggests that at shallow depths where $p' < 5\ kN/m^2$ there may be cracks, but for depths where $5 \leqslant p' < 50\ kN/m^2$ the soil will remain water-tight while deforming. In contrast a body of soil initially at LI = 0 will be susceptible to fracture at depths for which $p' < 50\ kN/m^2$: taking account of elastic compression it could require an overburden depth of say 50m of drained soil or 100m of bouyant soil to ensure that deformations caused water-tight rupture planes rather than open permeable cracks in such soil. In this view the steep vertical face of the breach in Teton Dam Figure 107 can be seen as an open fracture in very strong soil, standing to a height of 50m to 100m. Heavy compaction brings soil into a state where fractures and fissures must generally be anticipated.

Unjacketed compression tests and split cylinder tests of compacted Teton Dam core soil indicate the tensile strain for cracking to be 0.05 per cent Poissons ratio being 0.1 and E being 26 MN/m^2. The air permeability of jacketed split cylinder specimens increased significantly when continuous specimens reached this tensile strain. This is a small strain which would occur if for example there were changes of slope along the level crest of the dam by as little as one part in one thousand on filling. On the evidence of the compacted Cambridge models even less strain would be needed to separate successive layers of compacted soil. The compacted soil compresses on first wetting, and perhaps nothing more than that is needed to explain horizontal partings of layers within the core near the top of the key trench. Such tensile strain fractures generally would lead to wet seams, but it is not fully clear from the reports what was the actual position and inclination of the wet seams in the remnant of Teton Dam.

If all such dam cores have been and remain susceptible to tensile strain cracking, and if the past cracks have been small and well distributed and self healing when previous dams were slowly filled, then the improvement of compaction could lead to wider cracks open over greater lengths in stronger soil. The more rapid filling of the Teton Dam could well lead to these larger cracks mostly healing and forming wet seams: it would only need one of them which eroded to lead to failure. One way to test this hypothesis would be to study the distribution of wet seams in the remnant of Teton Dam, and to look for healed cracks in other similar dams. It would also be interesting to observe accurately the deformations of new prototype structures, to back calculate what internal strains were consistent with the observed deformations, and to look for healed cracks in regions of greatest tensile strain.

The protection of dams made from compacted non-plastic soil clearly requries all voids below or beside the dam into which core material could be transported to the infilled or closed with filter layers. Where it is suspected that voids are in the process of migrating through such soil the placing of a filter and a downstream berm may allow healing and plugging of voids provided that the filter layer is sufficiently thick, or possibly is provided with mesh reinforcement layers.

Given better control of water flow rates in our centrifuge it would be well worth undertaking more model tests in the centrifuge to study the effect of small distortion and tensile strain cracking in core material and the erosion of dispersive soil due to flow through cracks. Some similar experimental study could be well worth undertaking at some appropriate scale in the laboratory at Denver: the events observed in model Teton IV were informative even without a centrifuge.

Cambridge June 6th 1980

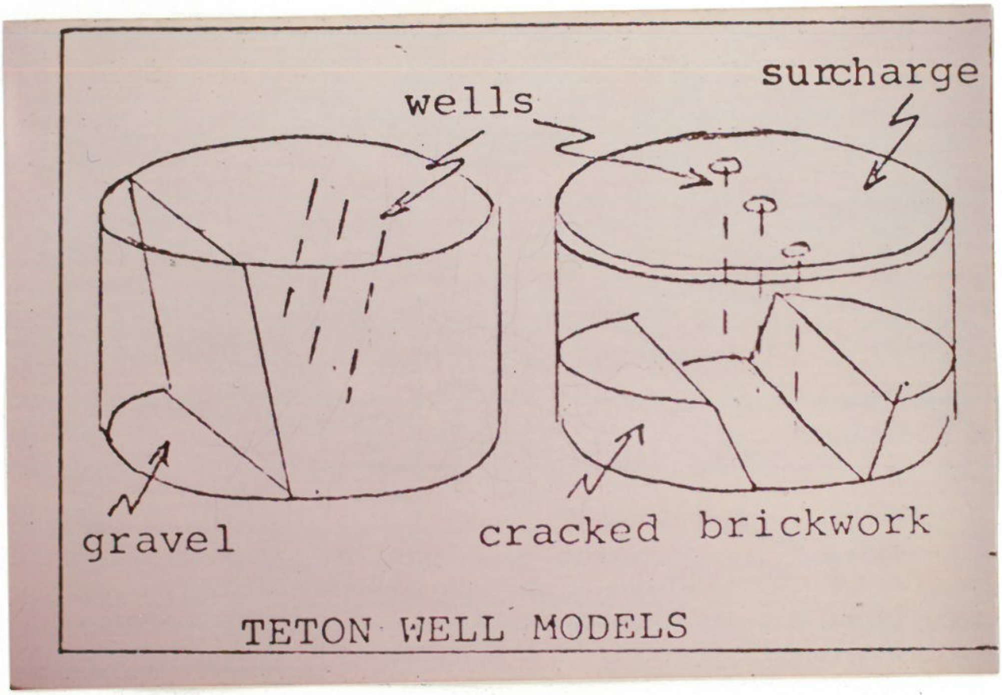

Figure 1

Figure 2

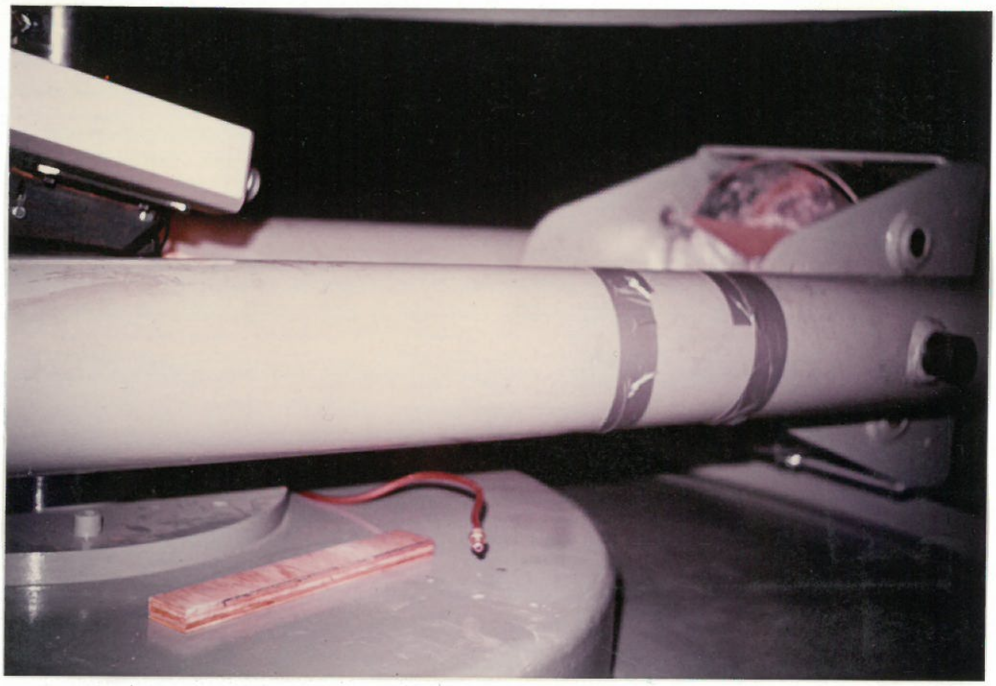

Figure 3

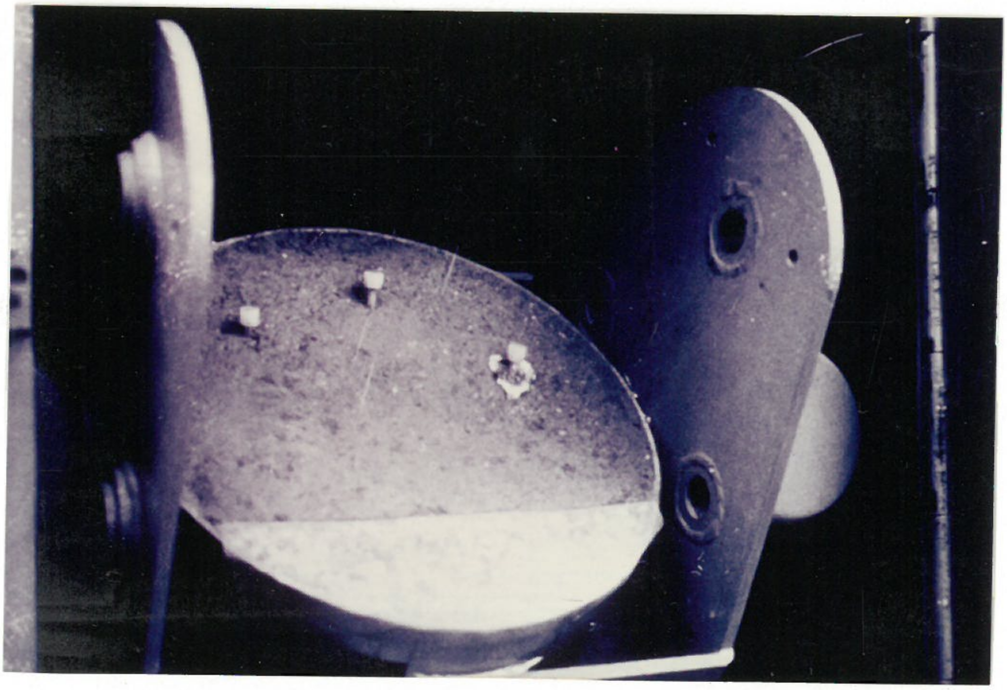

Figure 4

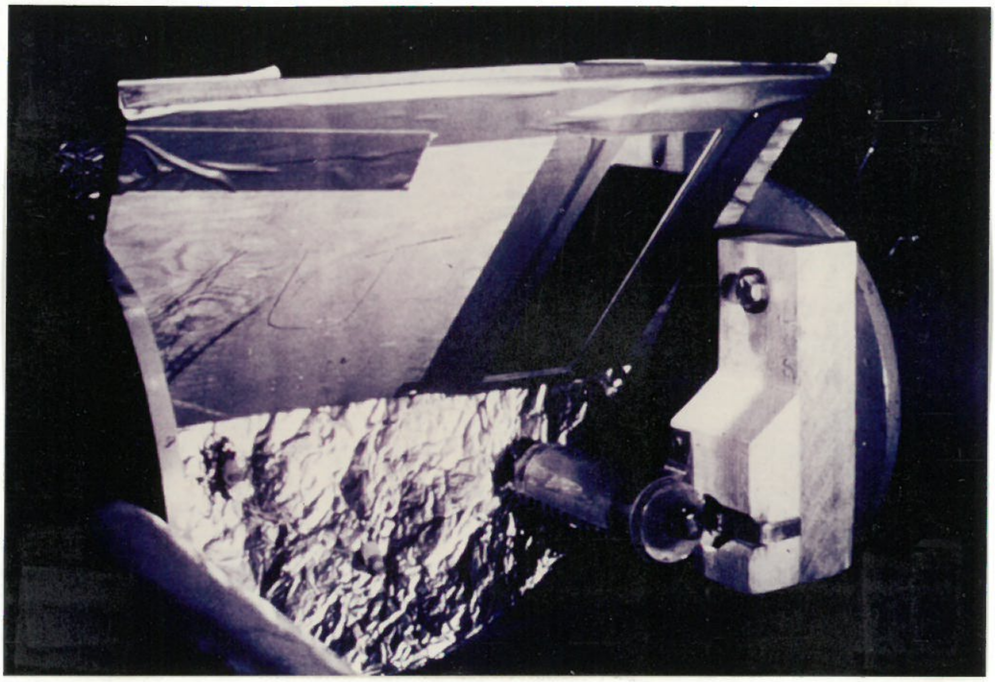

Figure 5

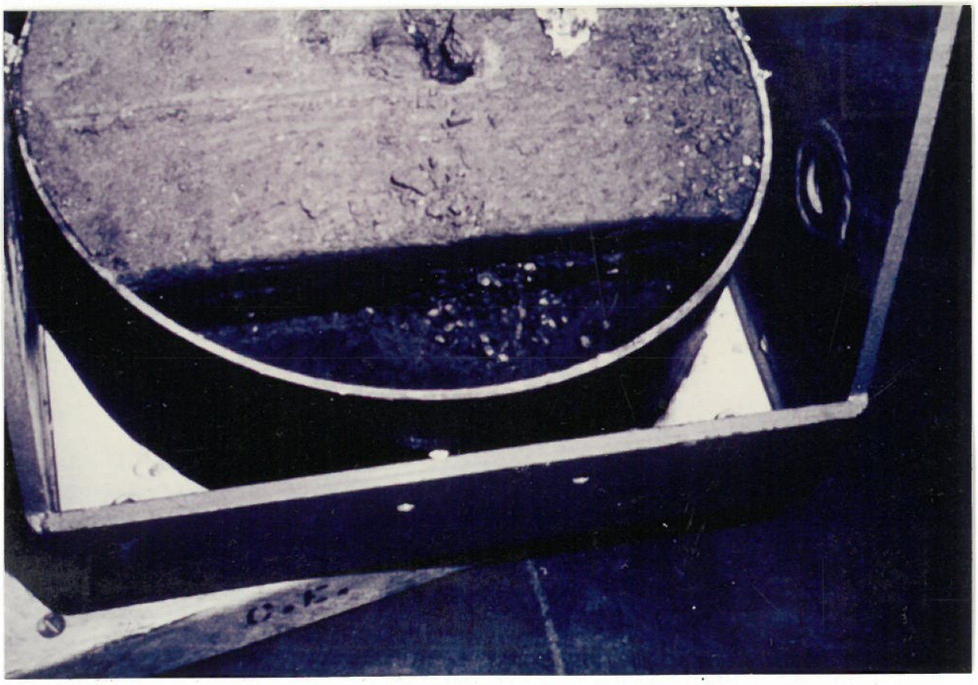

Figure 6

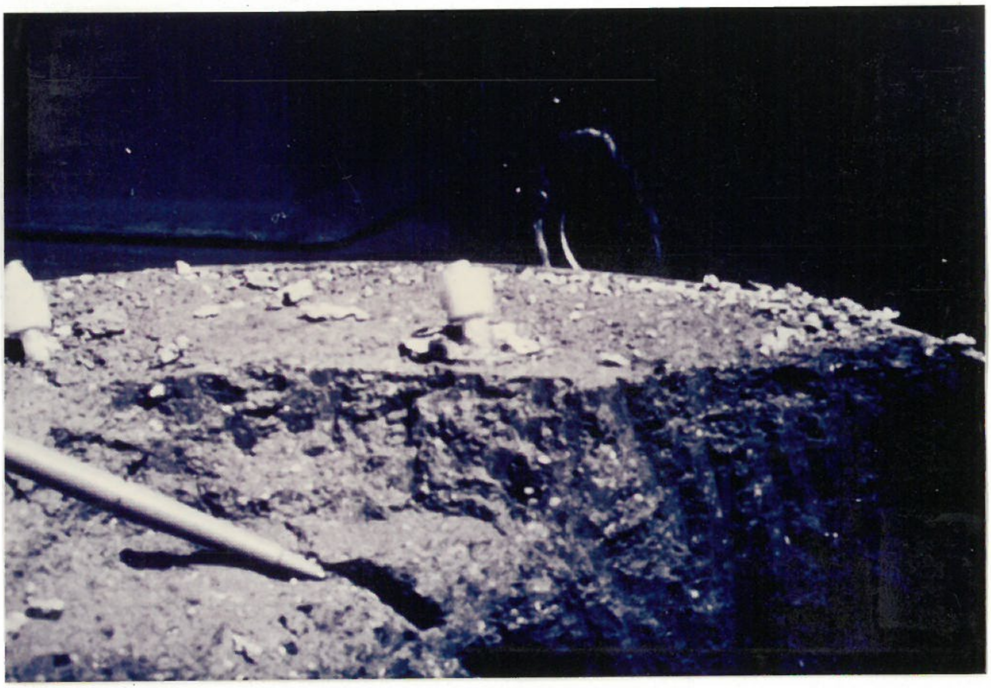

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

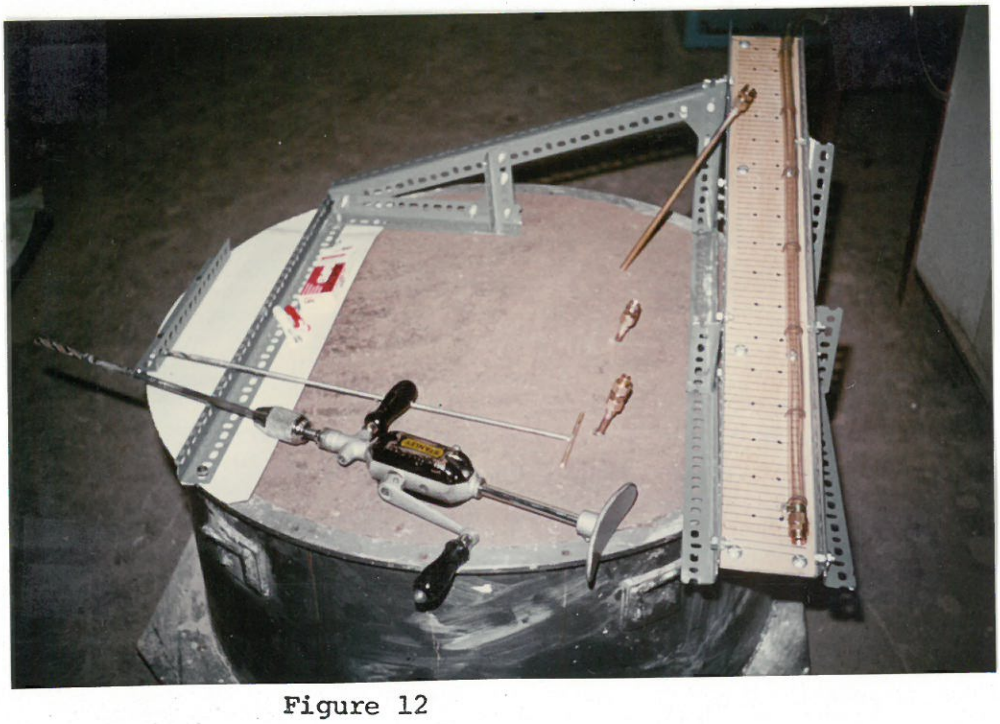

Figure 12

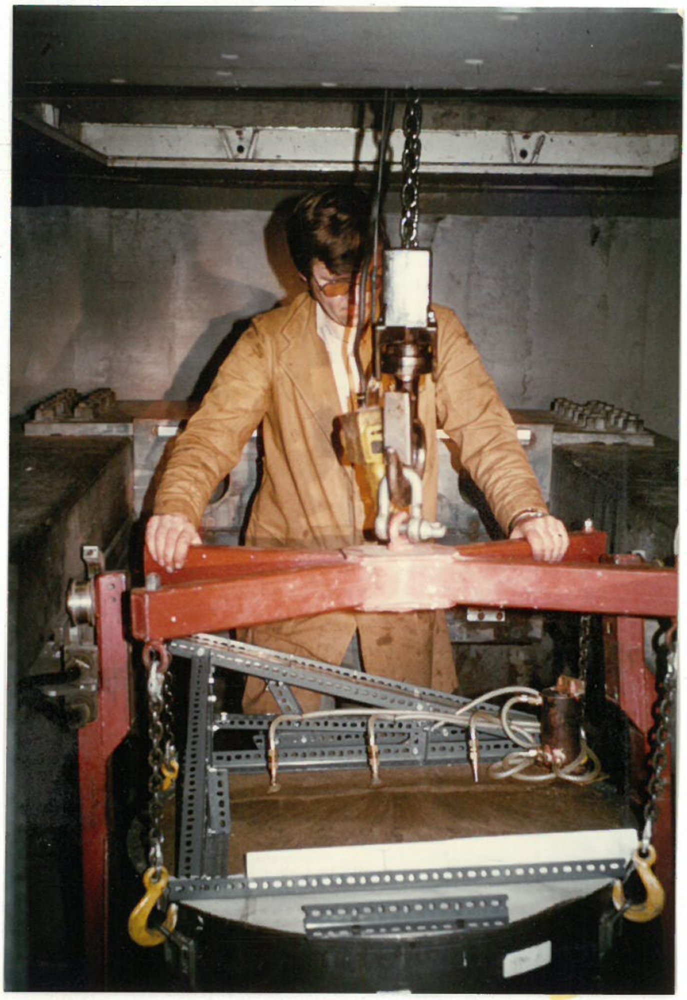

Figure 13

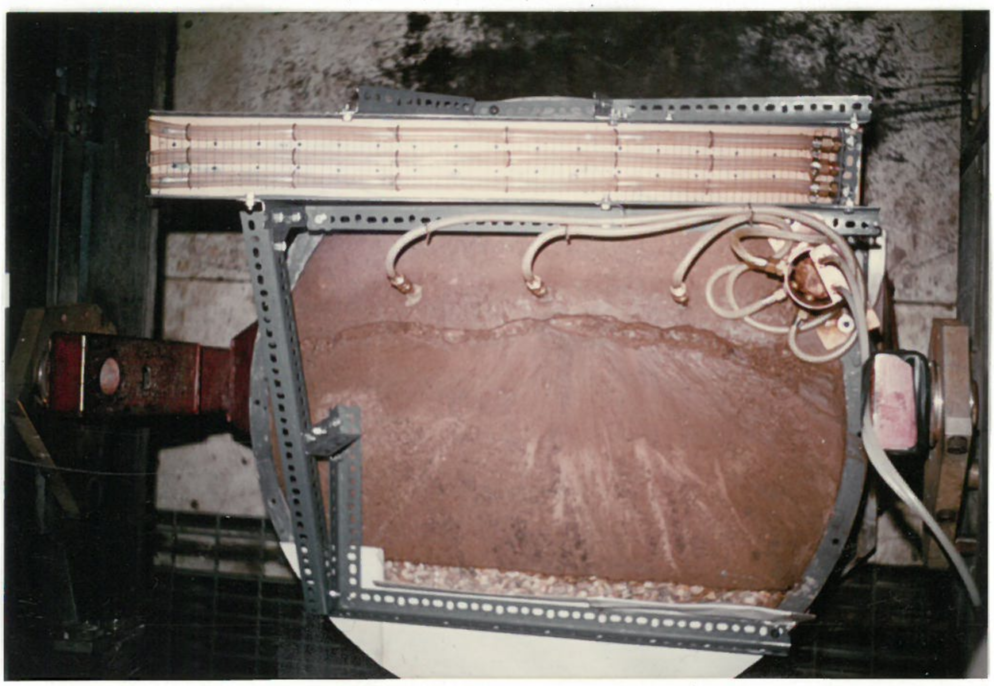

Figure 14

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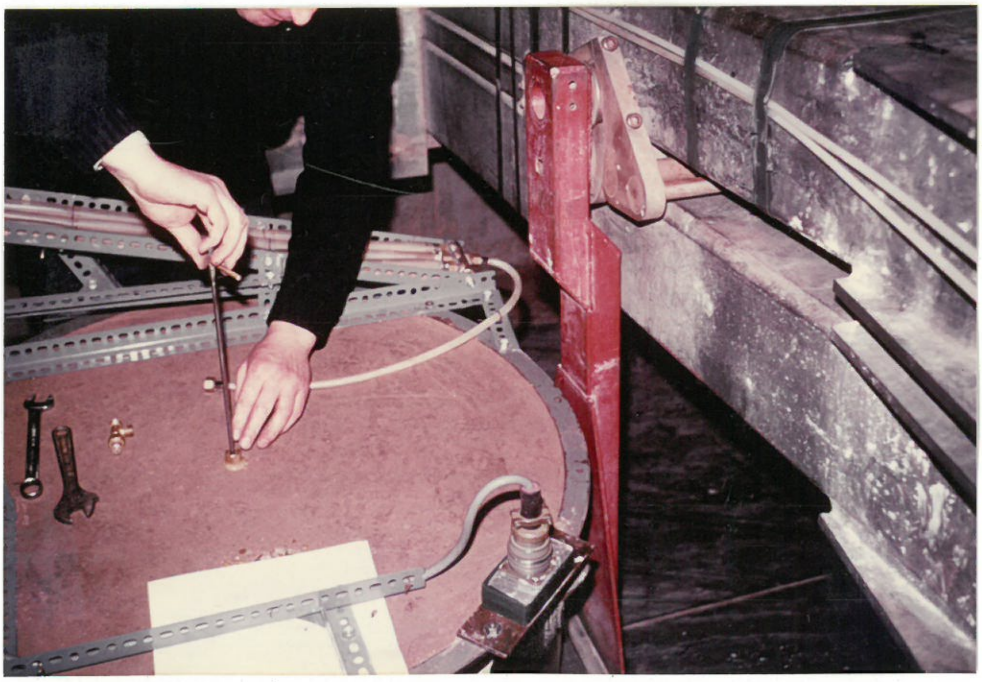

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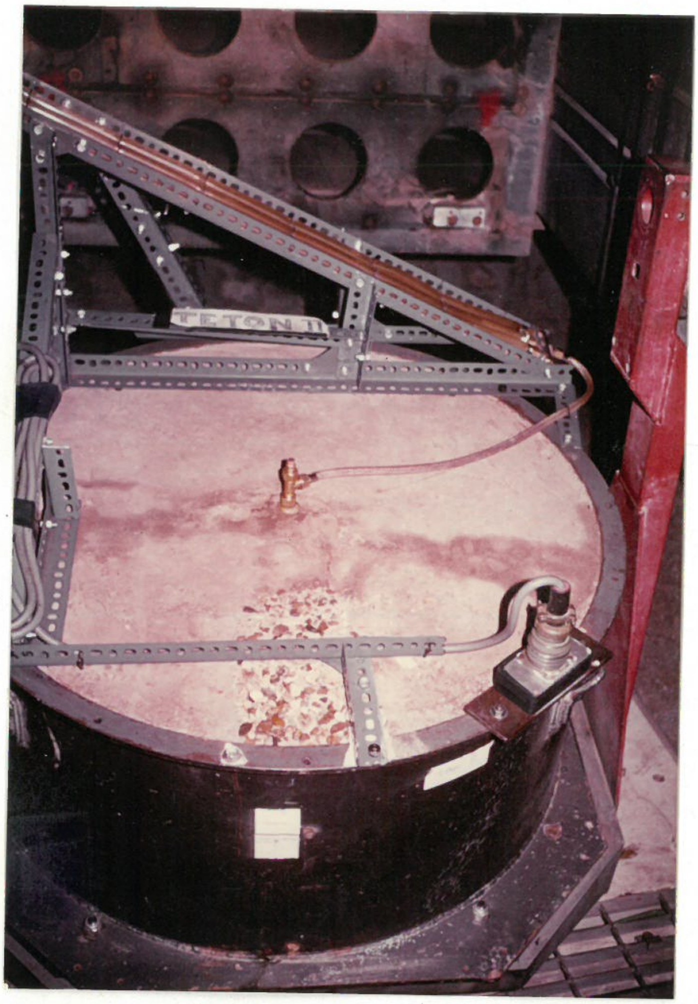

Figure 19

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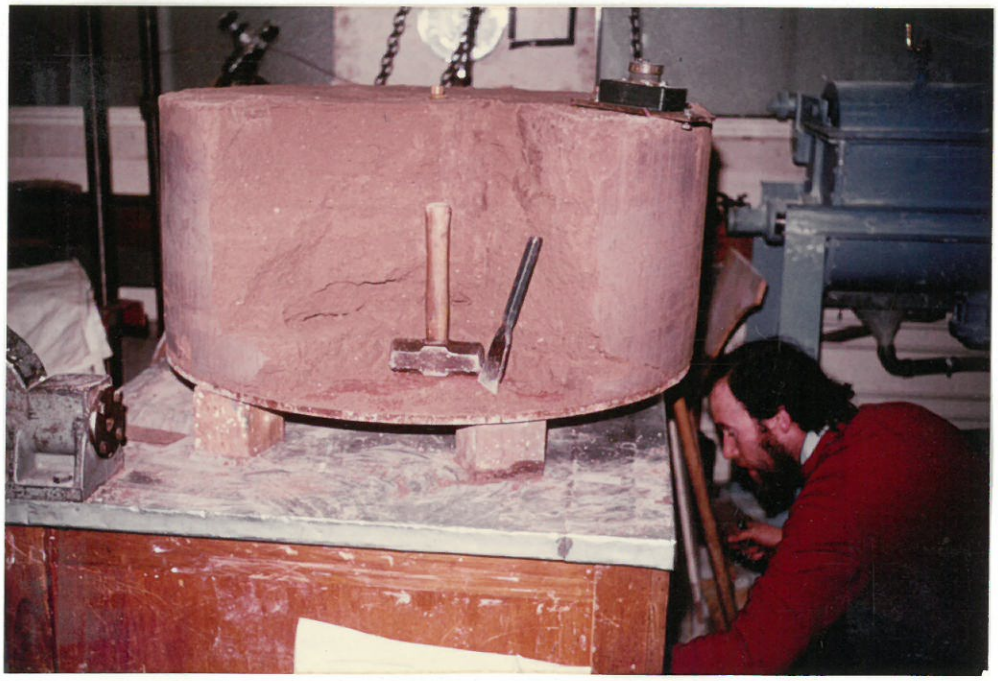

Figure 22

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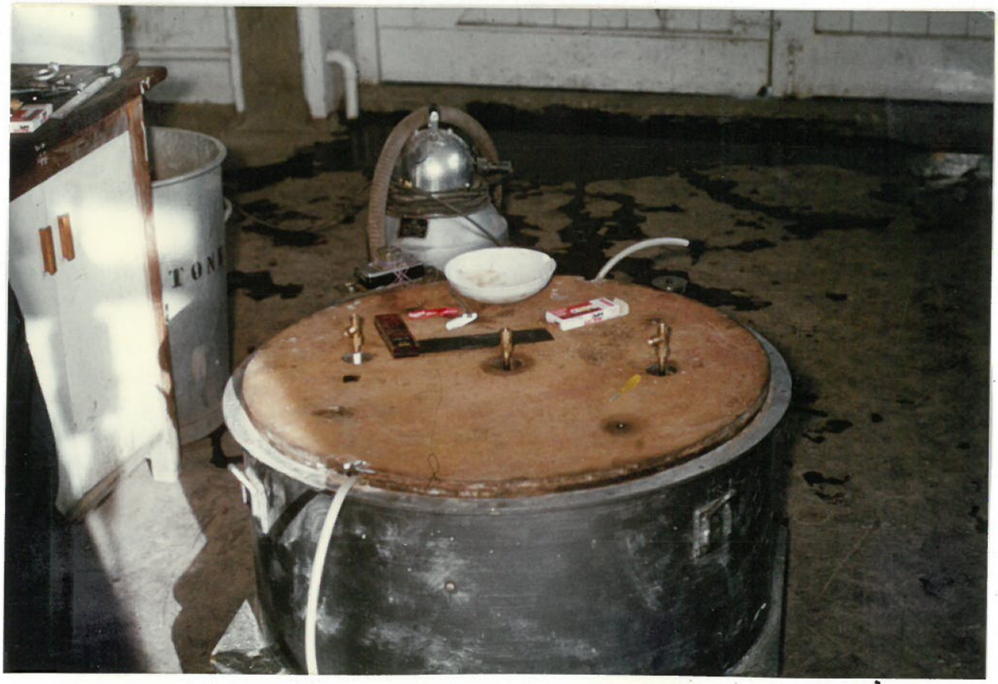

Figure 26

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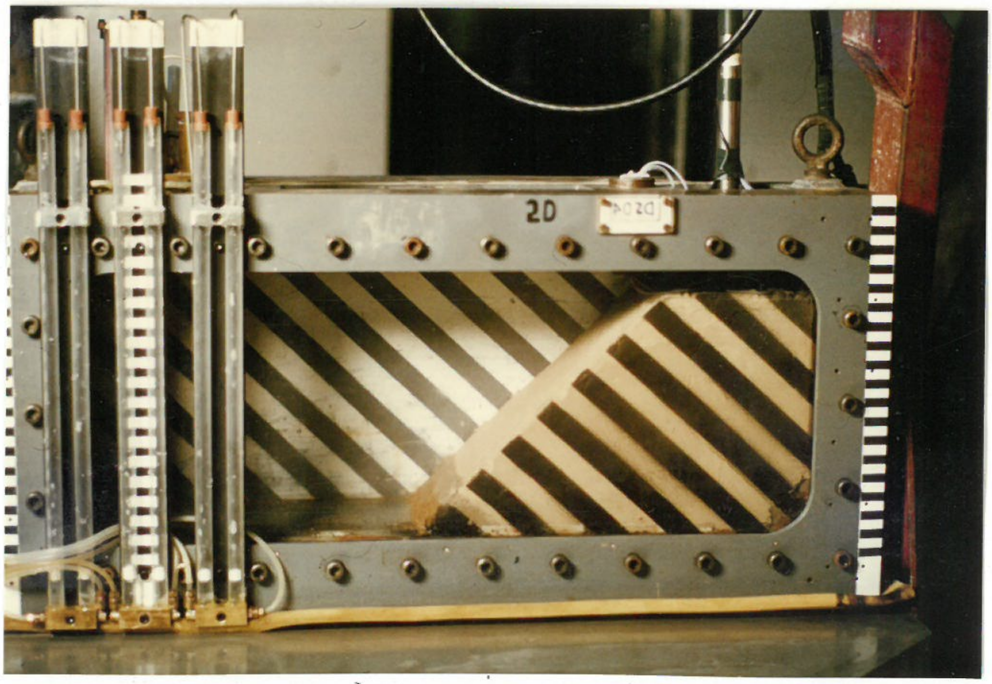

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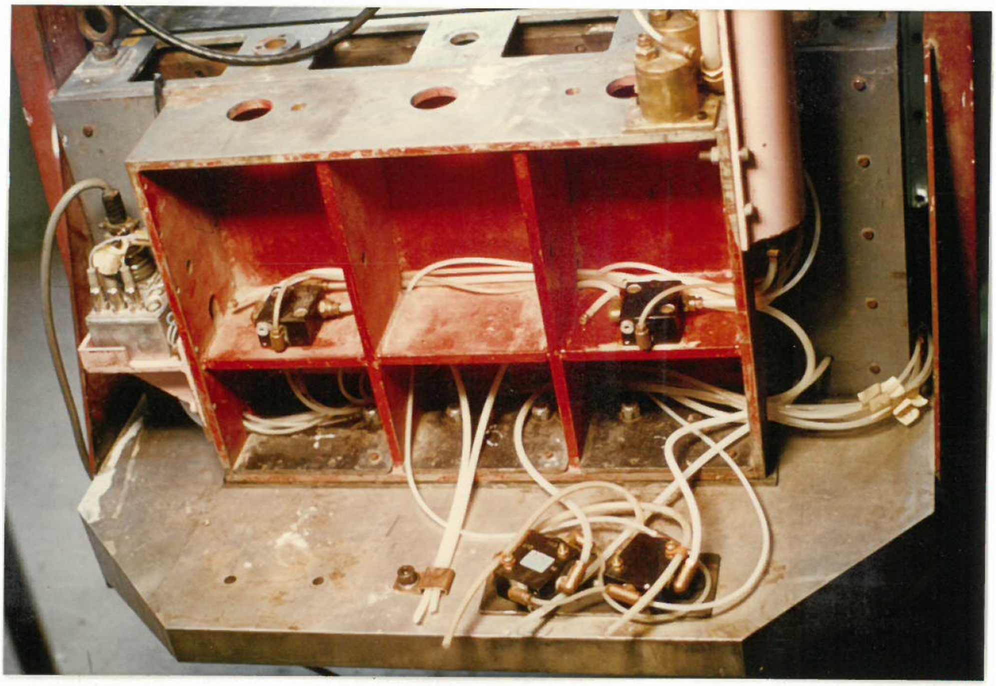

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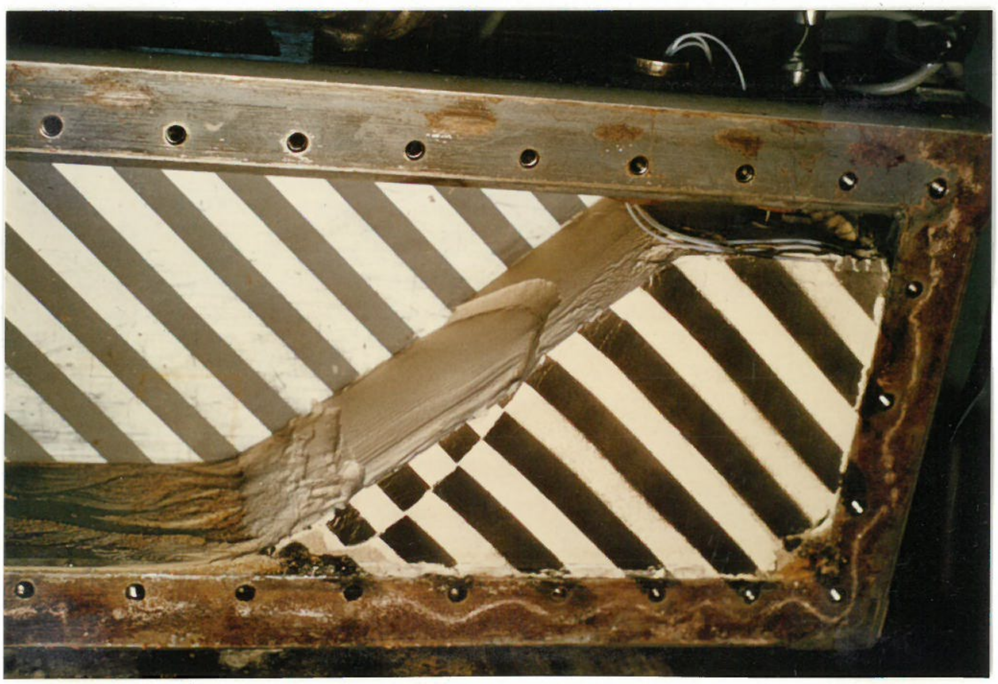

Figure 43

Figure 44

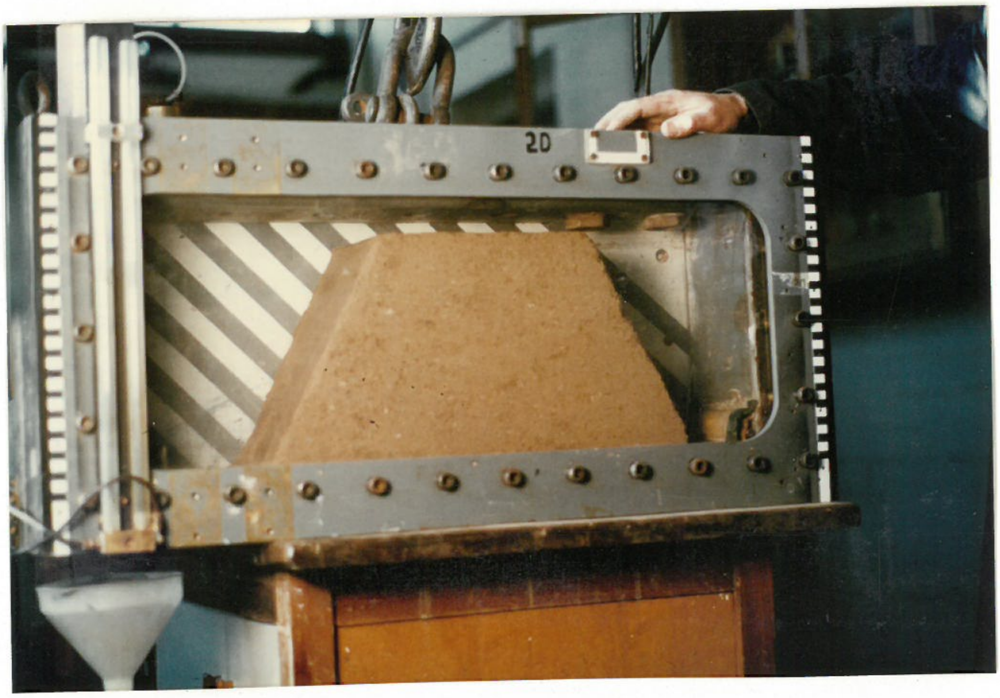

Figure 45

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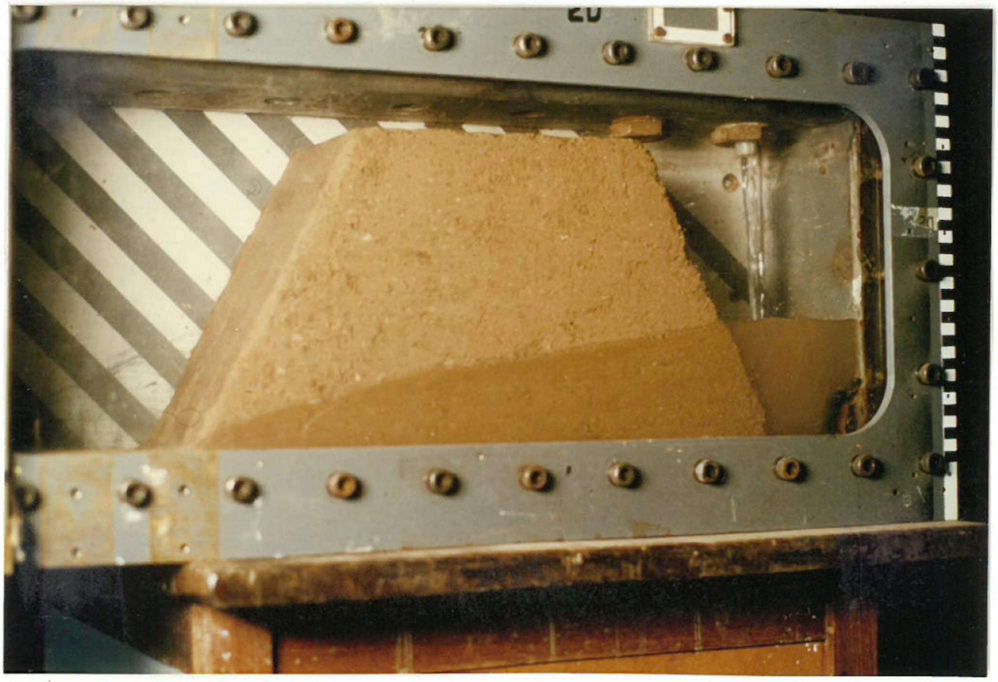

Figure 47

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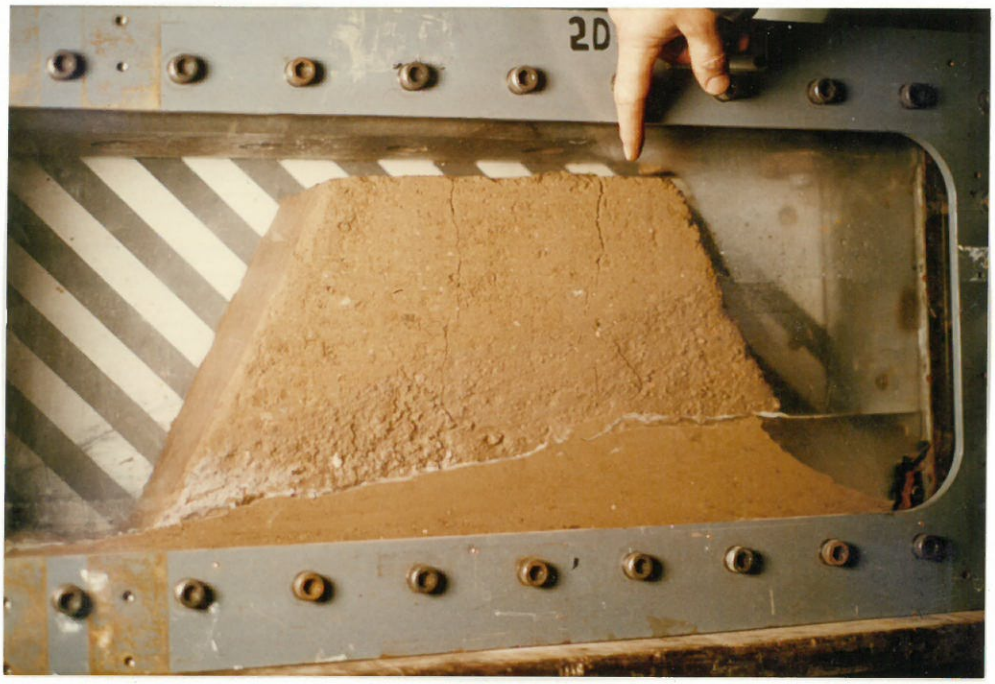

Figure 52

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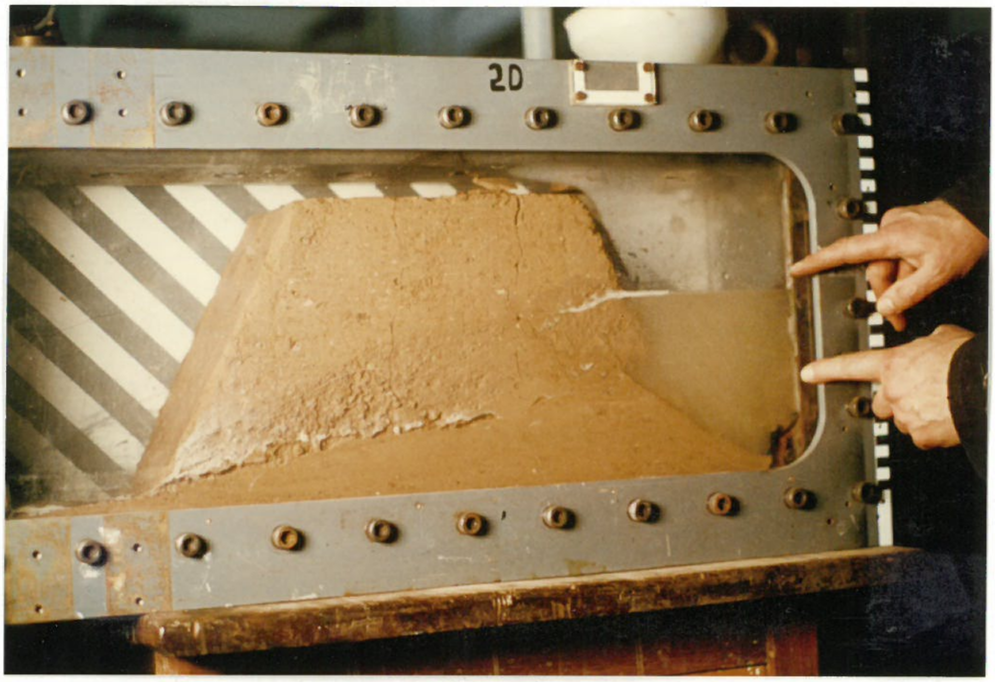

Figure 54

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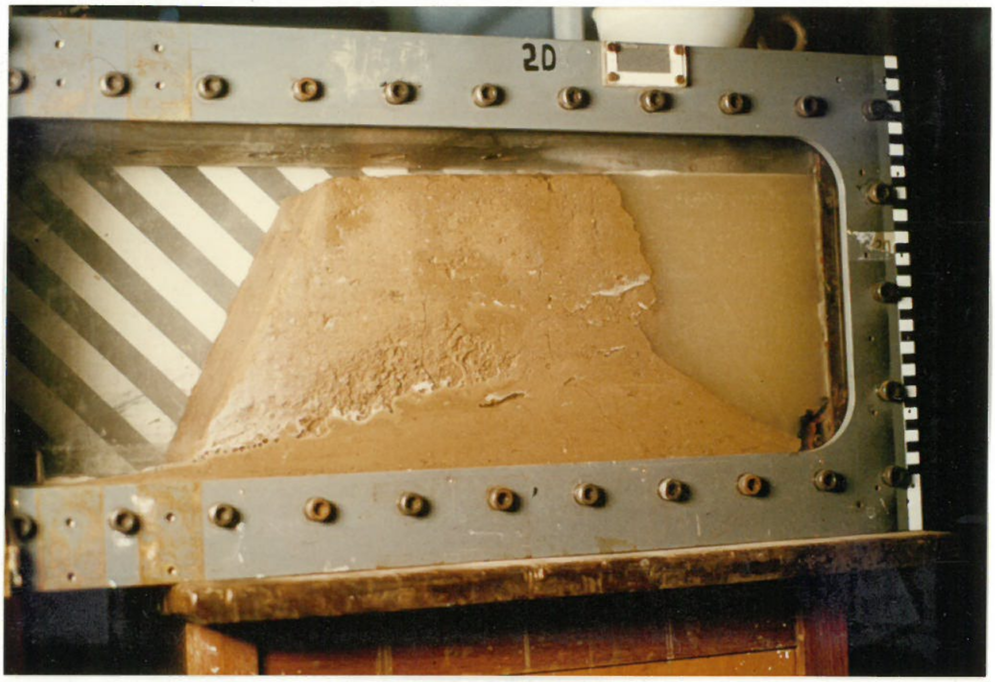

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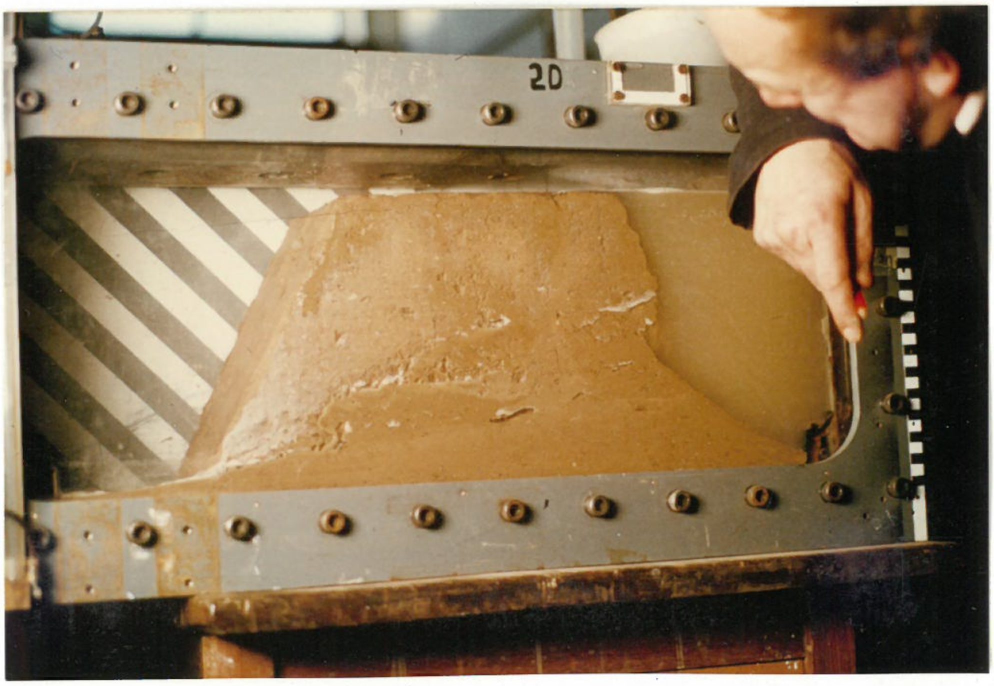
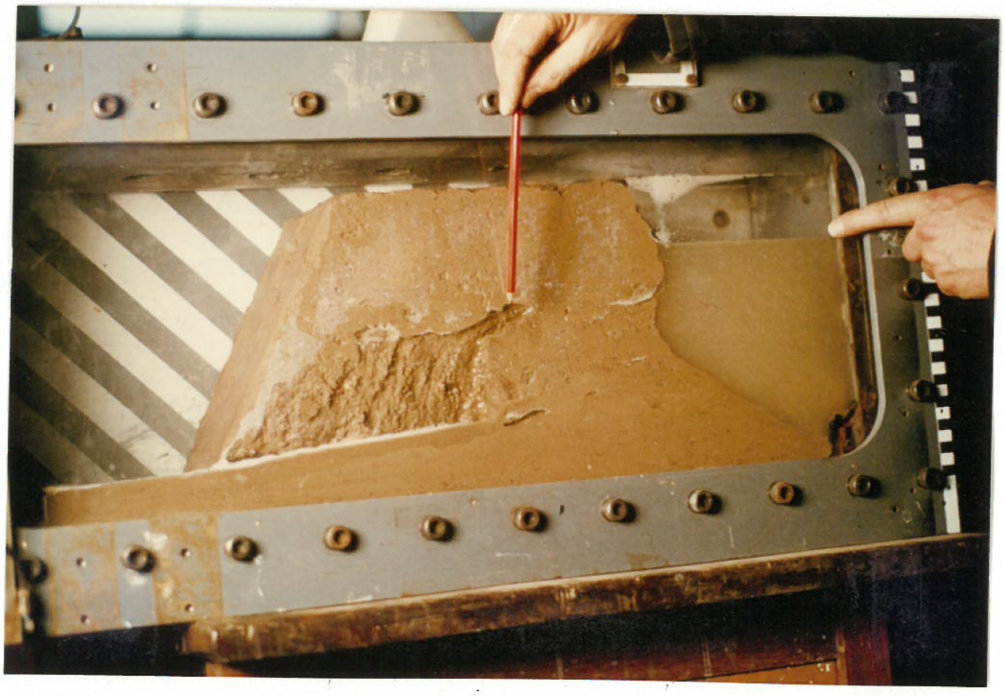


Figure 57

Figure 58



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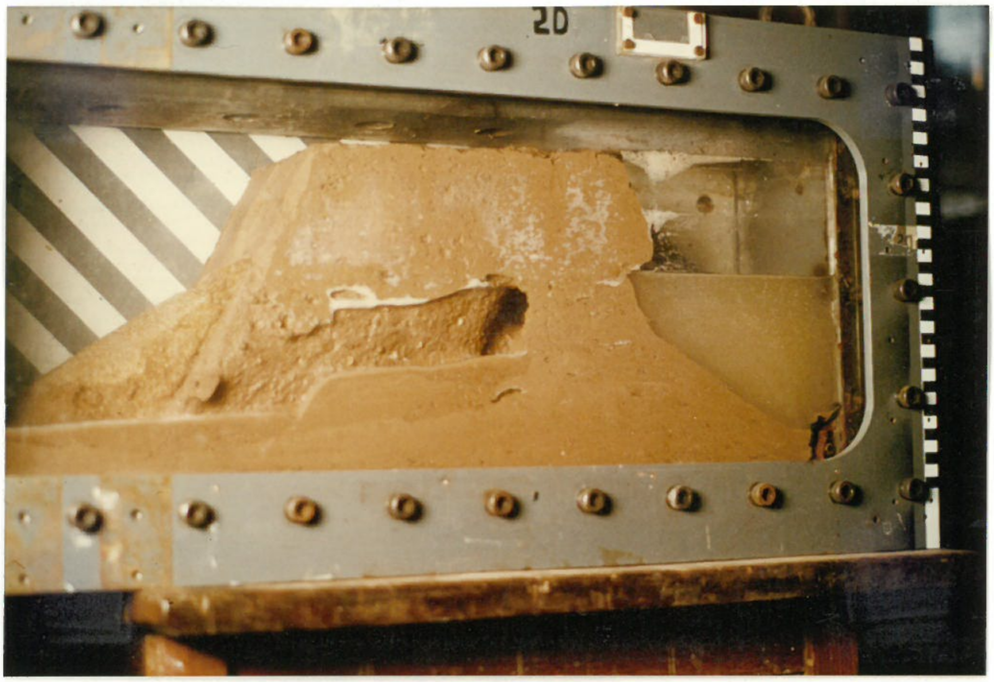

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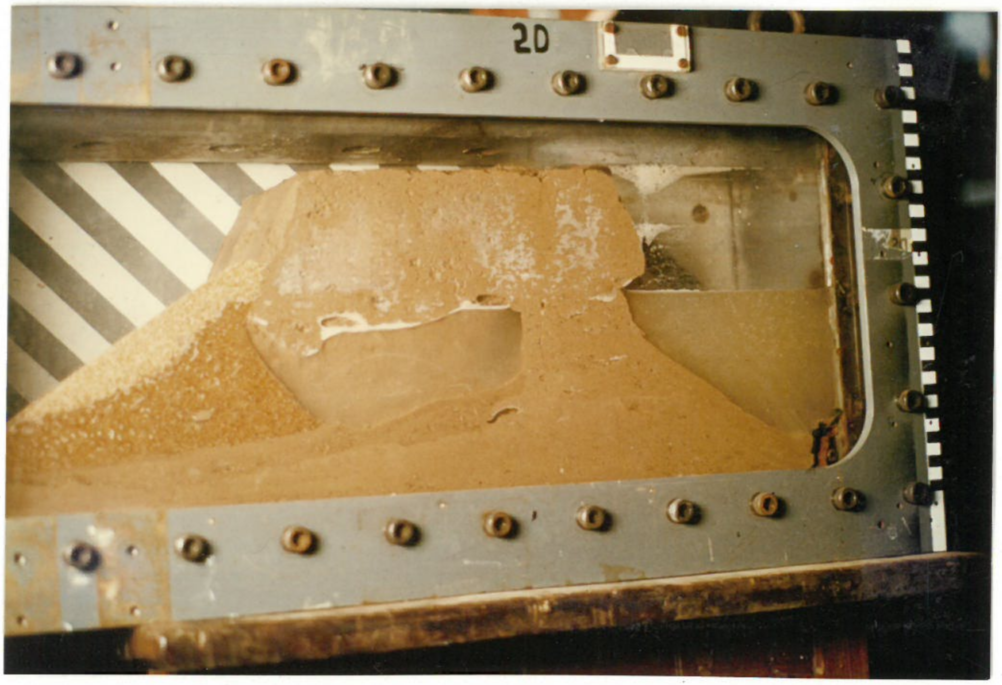

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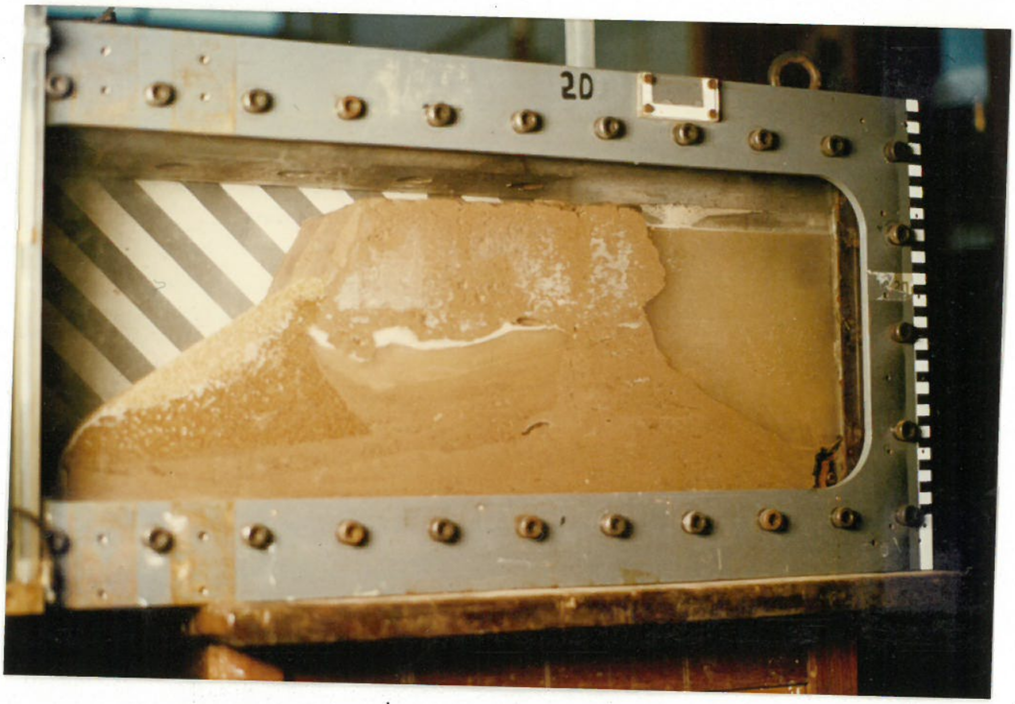

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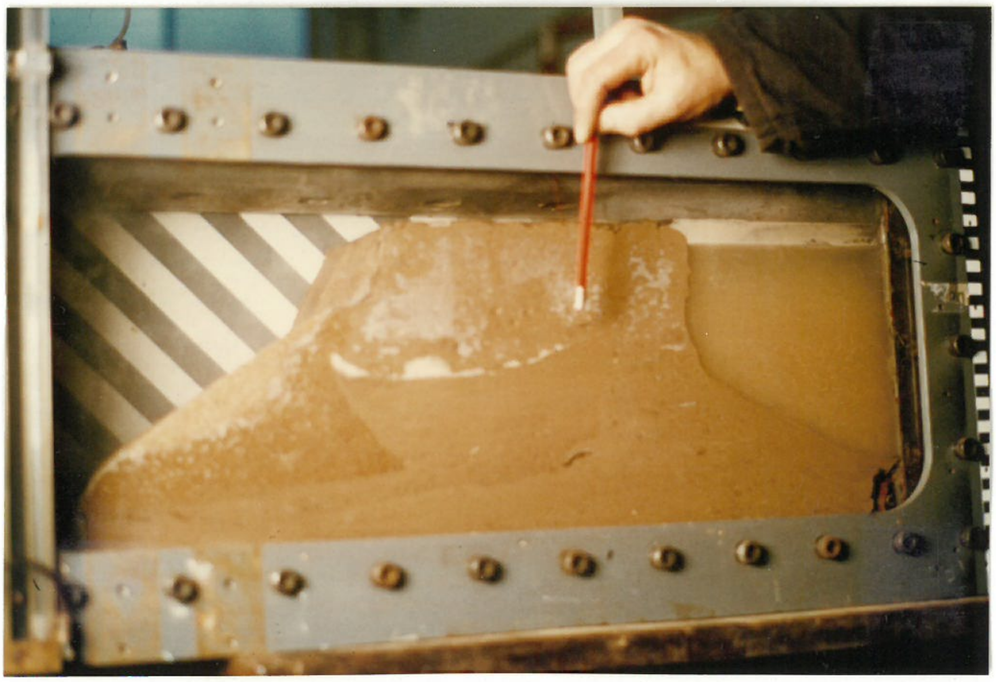

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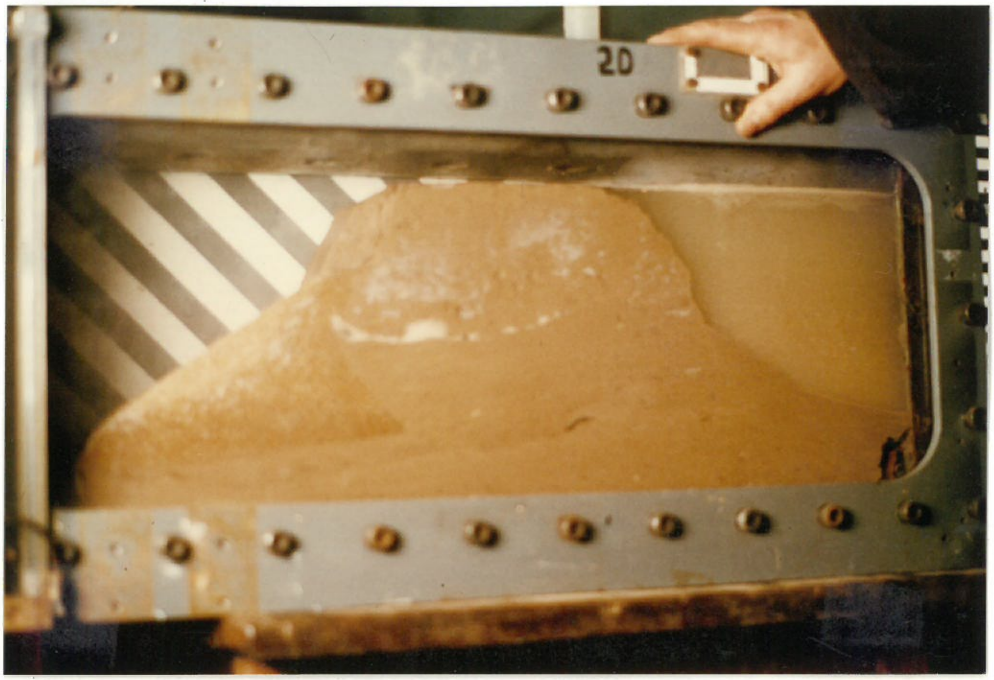

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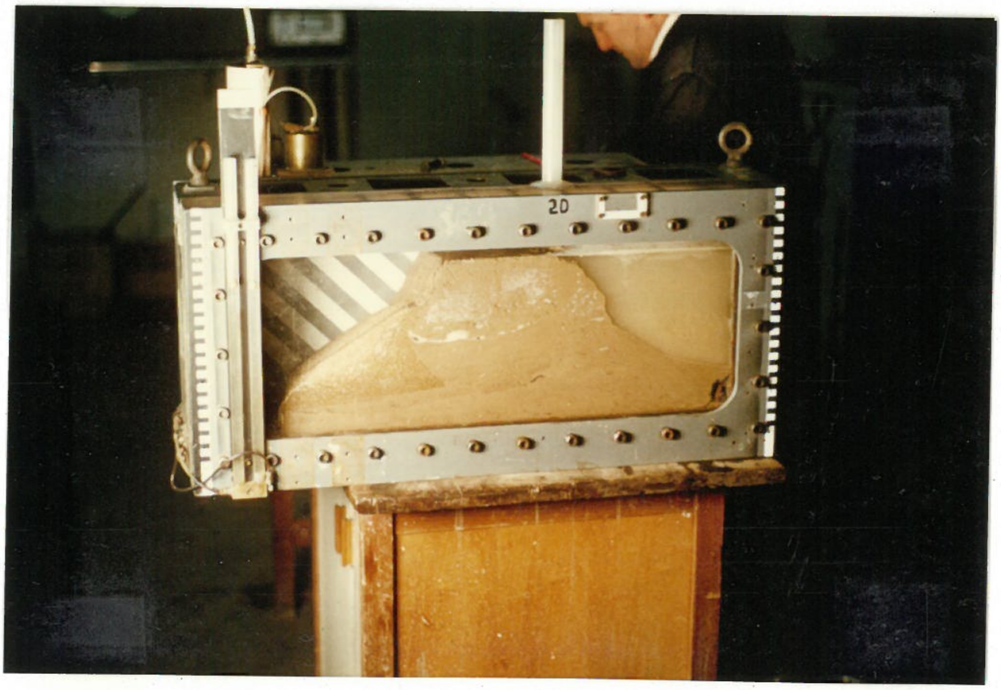

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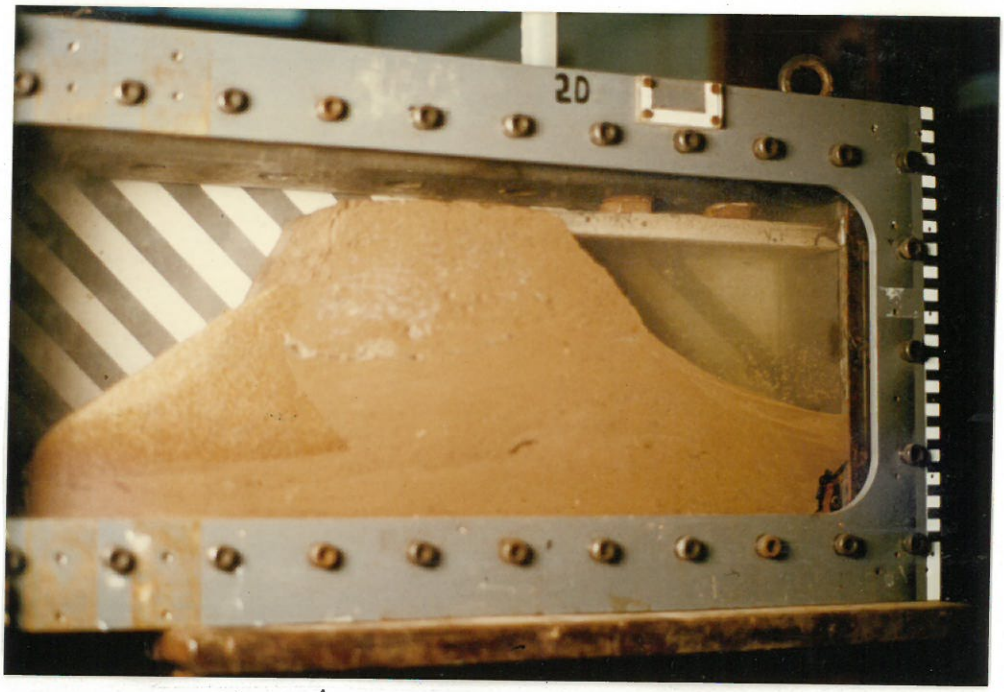

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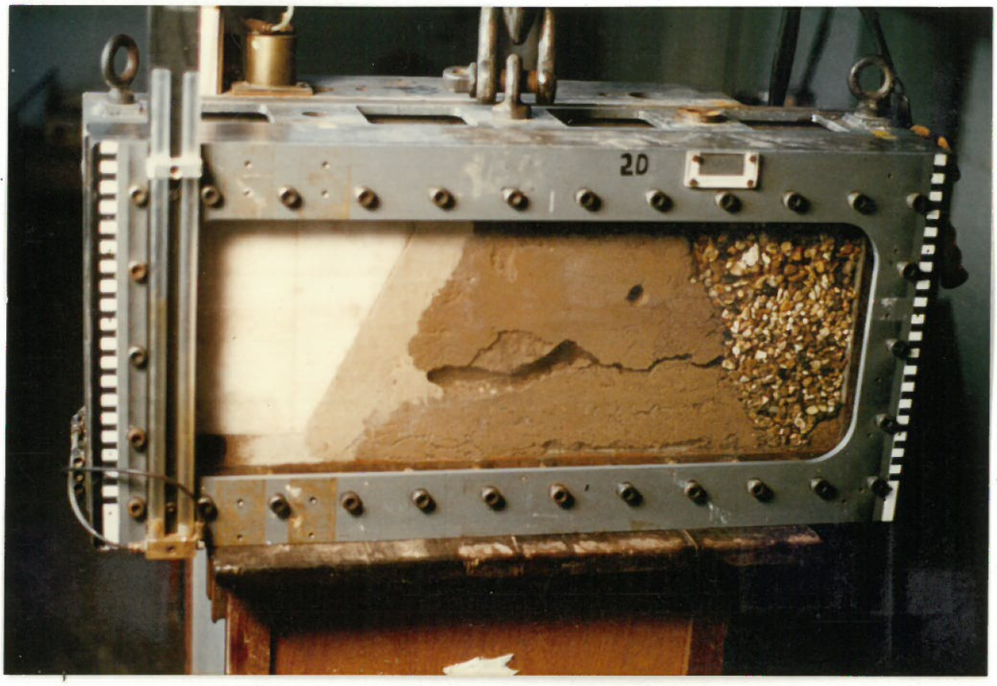

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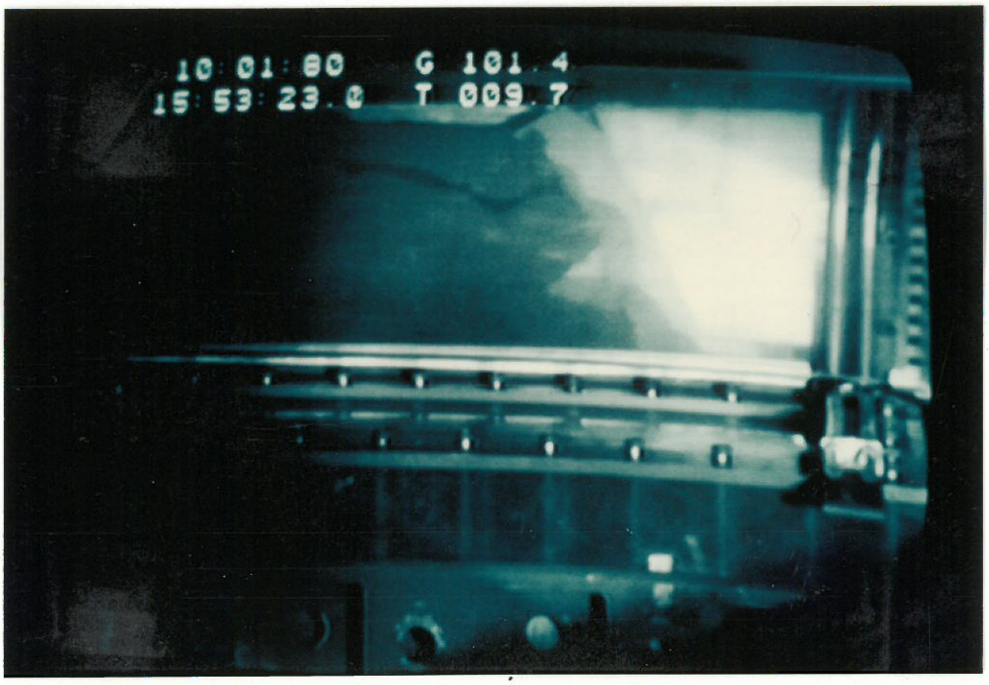

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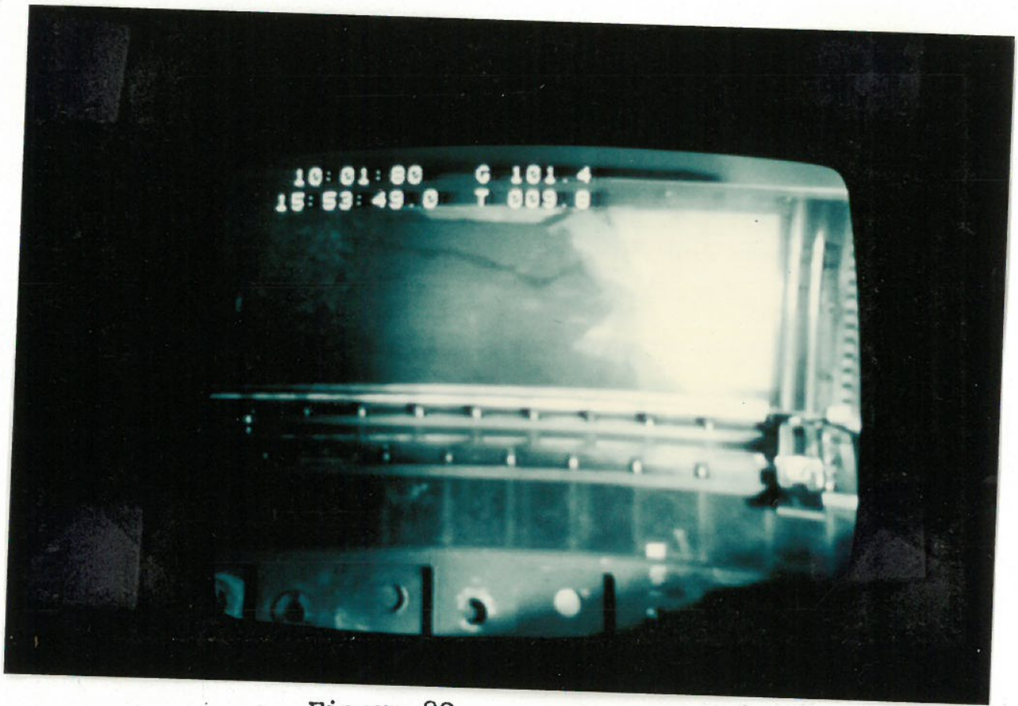

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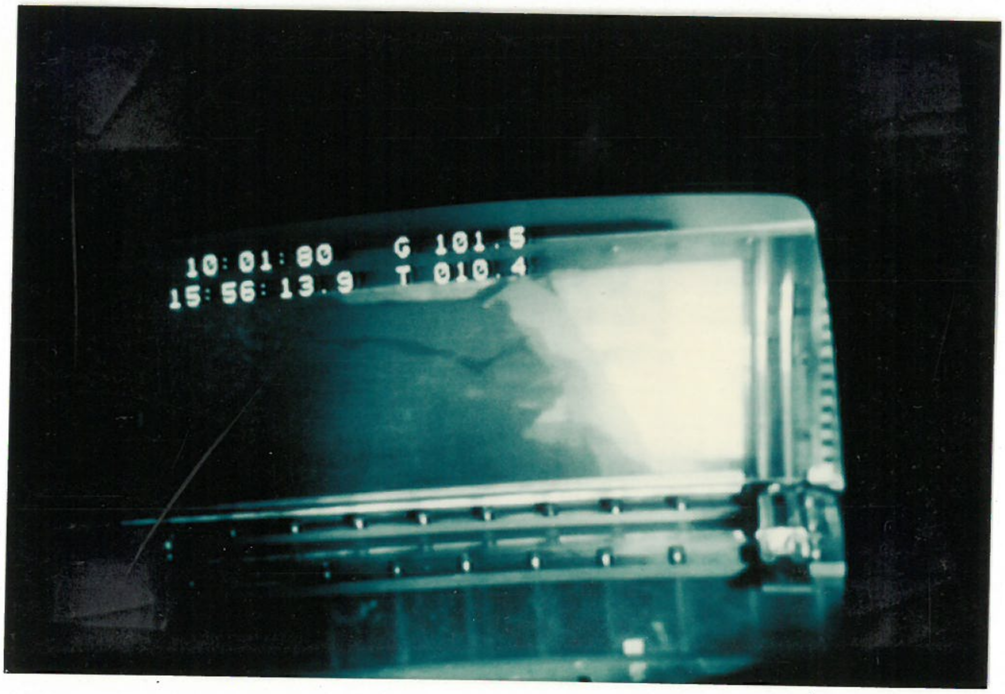

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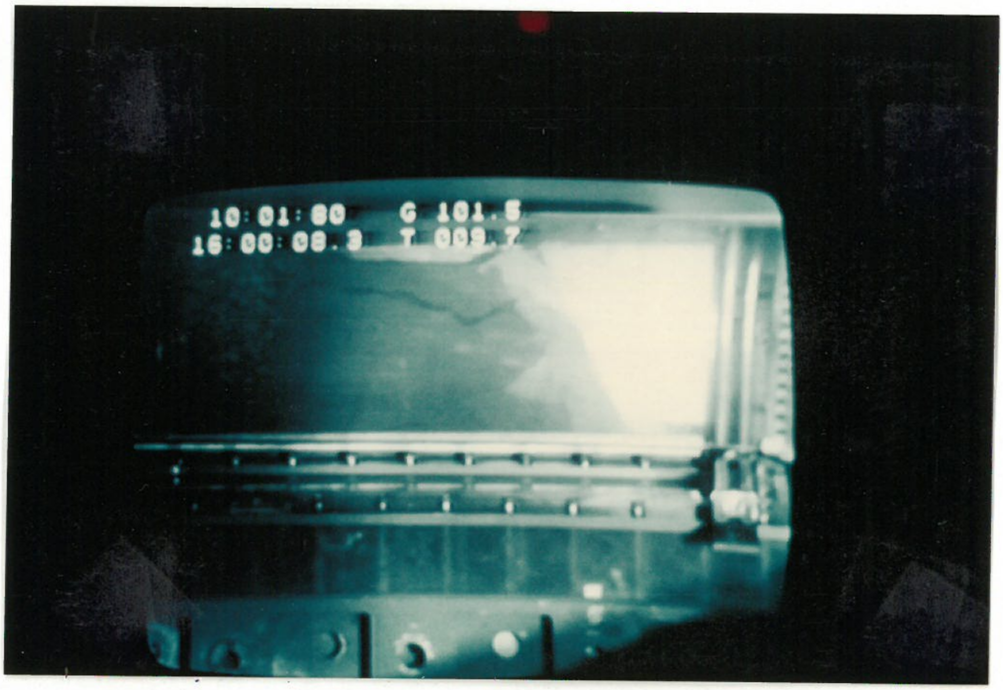

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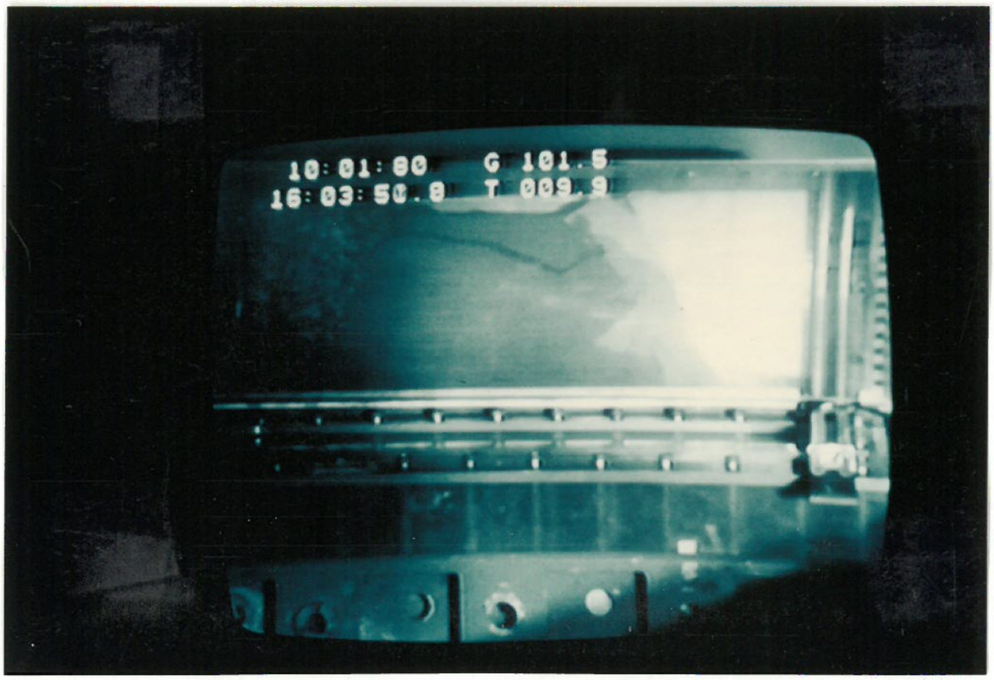

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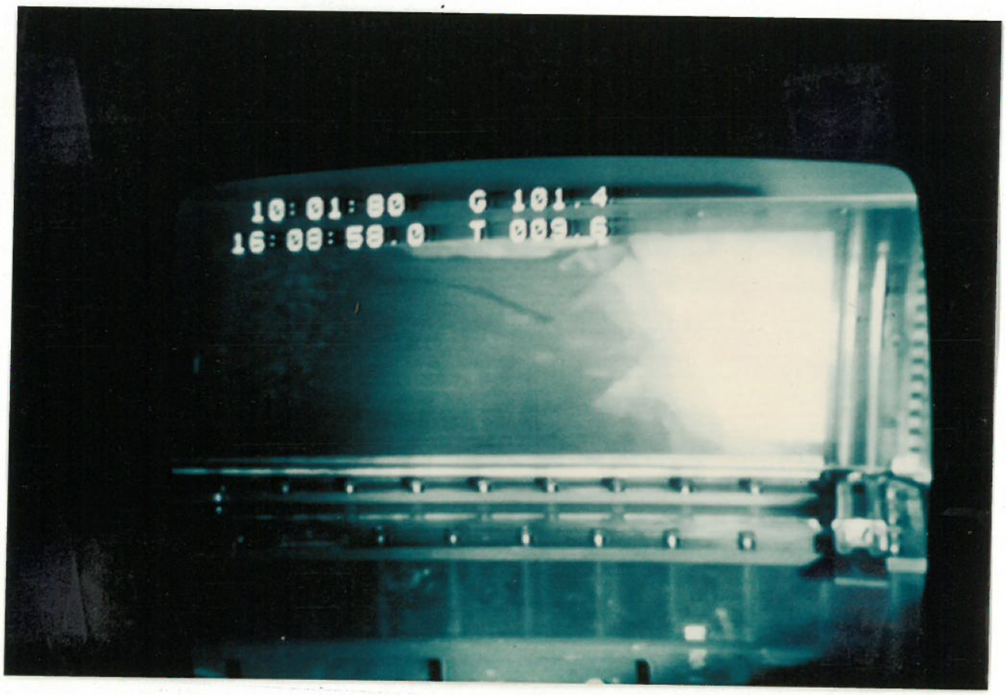

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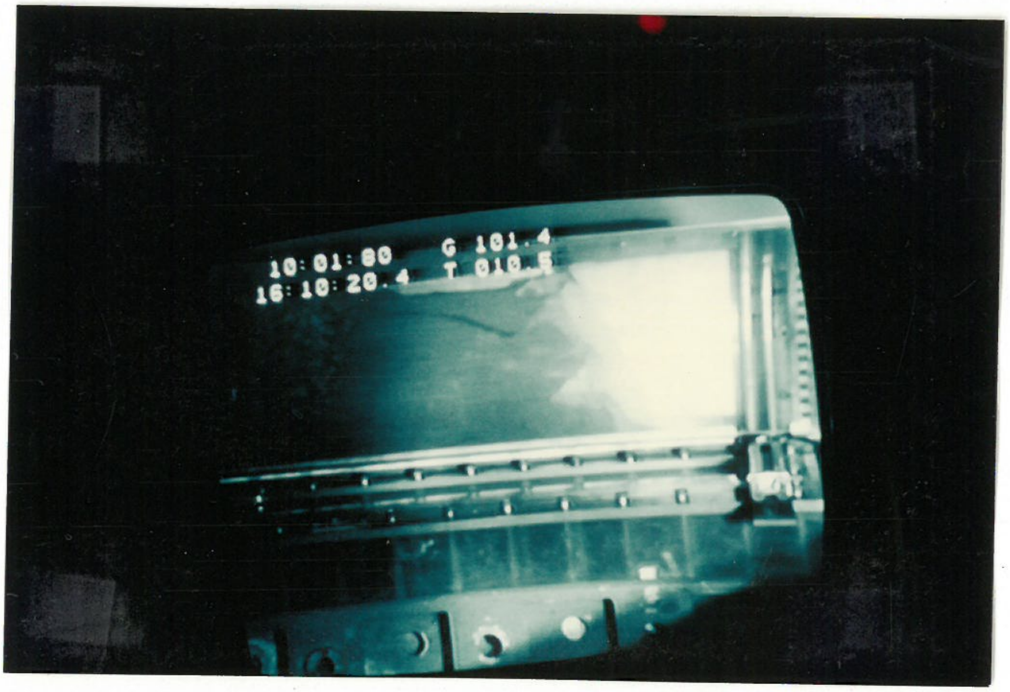

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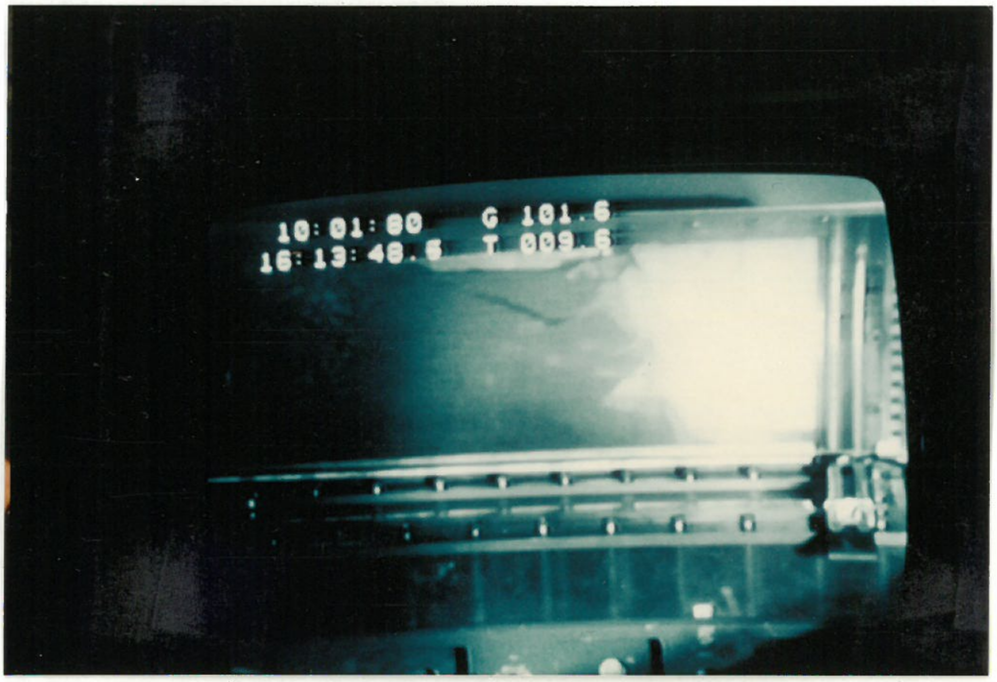

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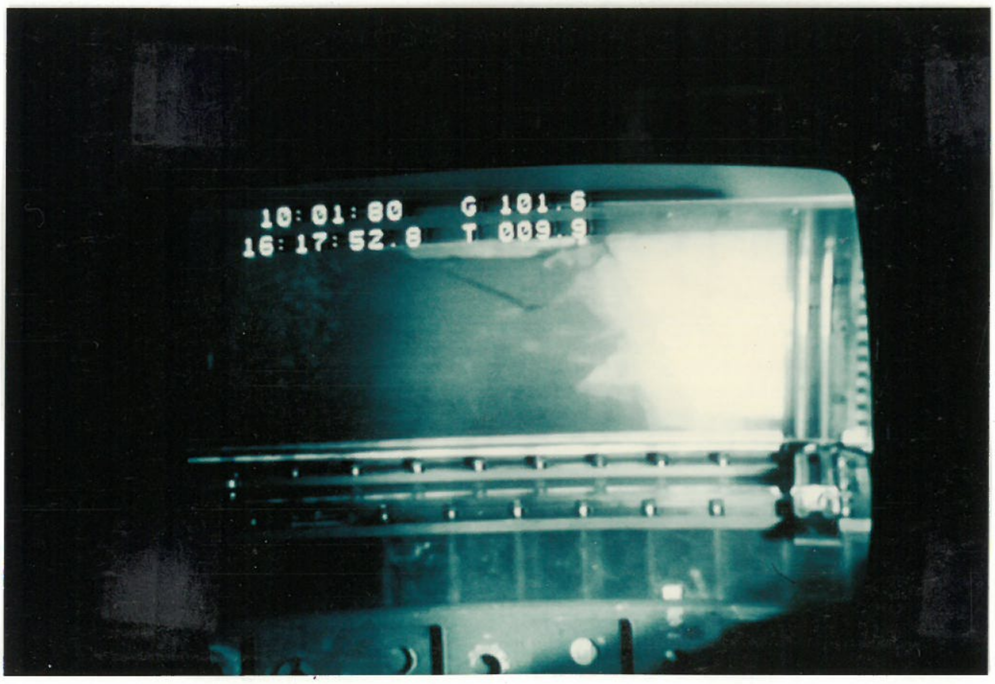
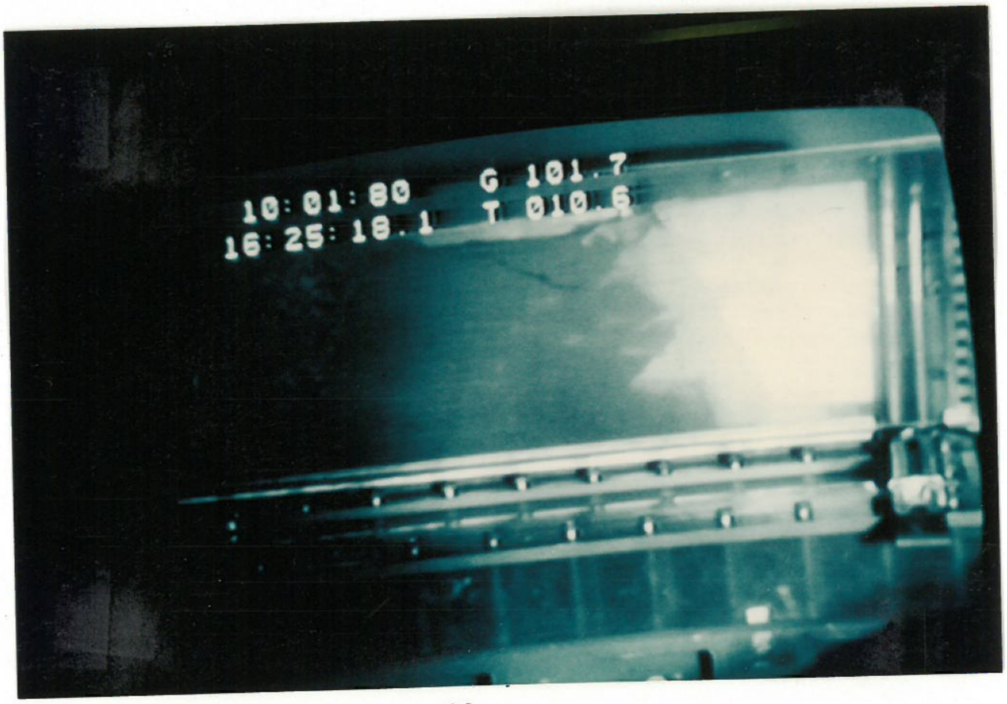


Figure 87

Figure 88



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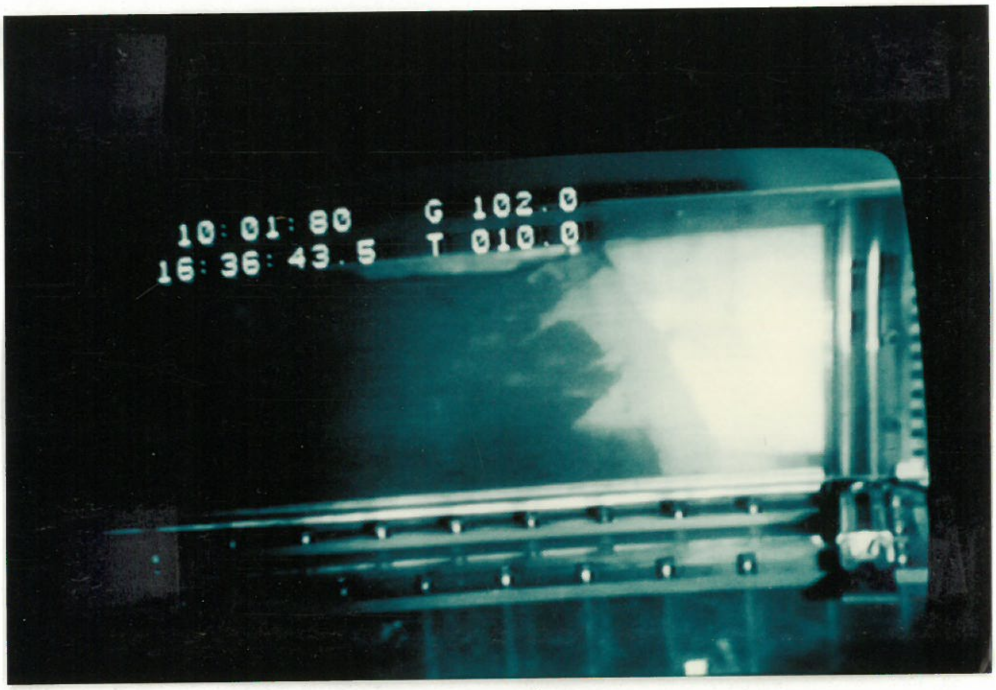

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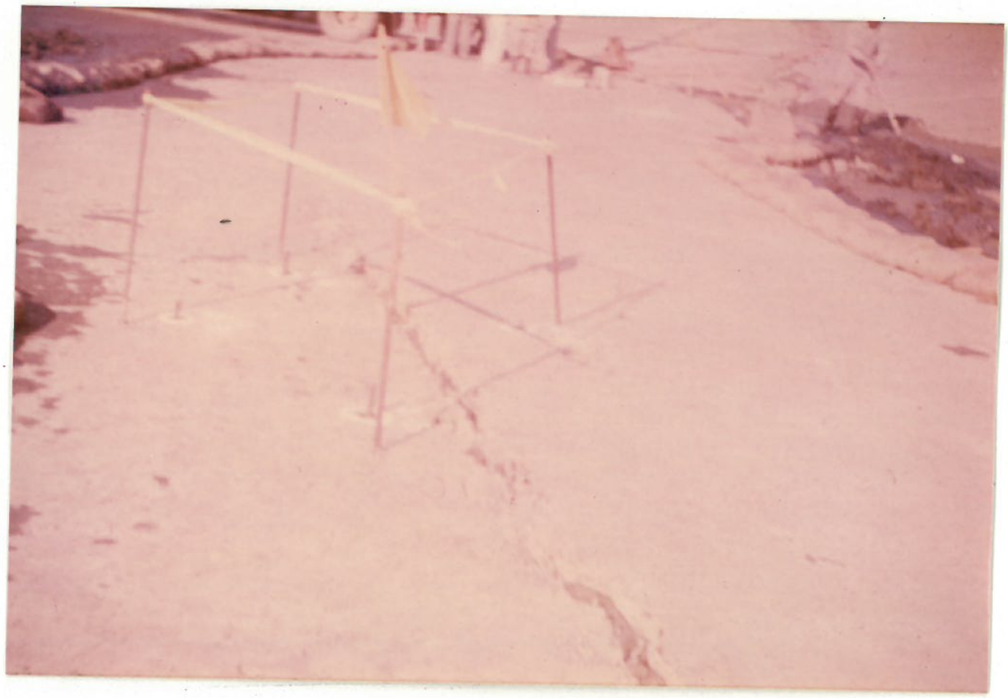

Figure 94

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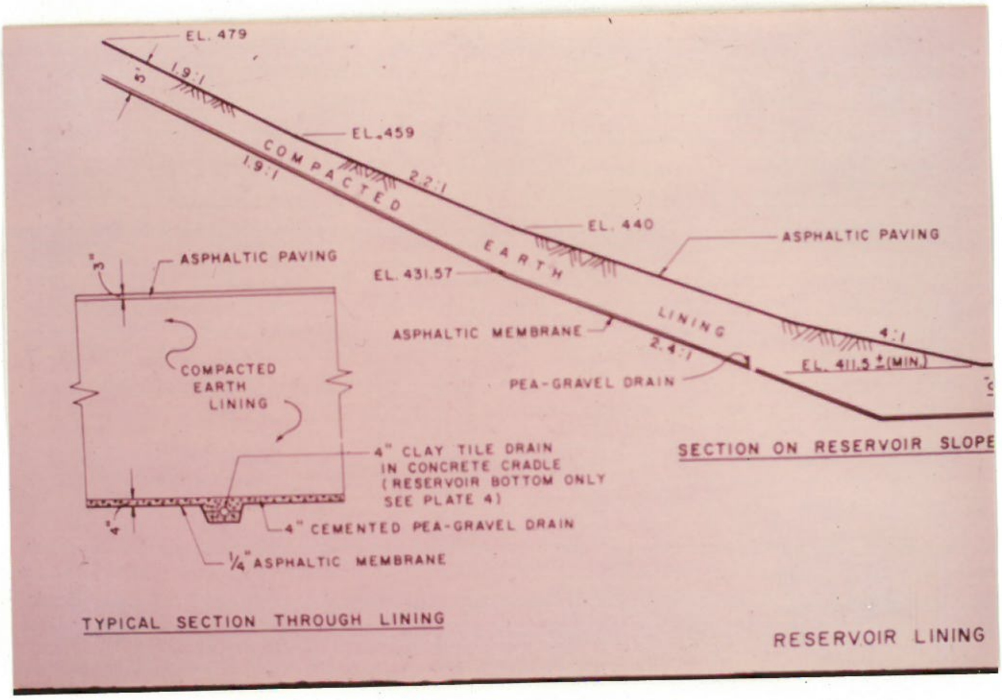

Figure 101

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Figure 105

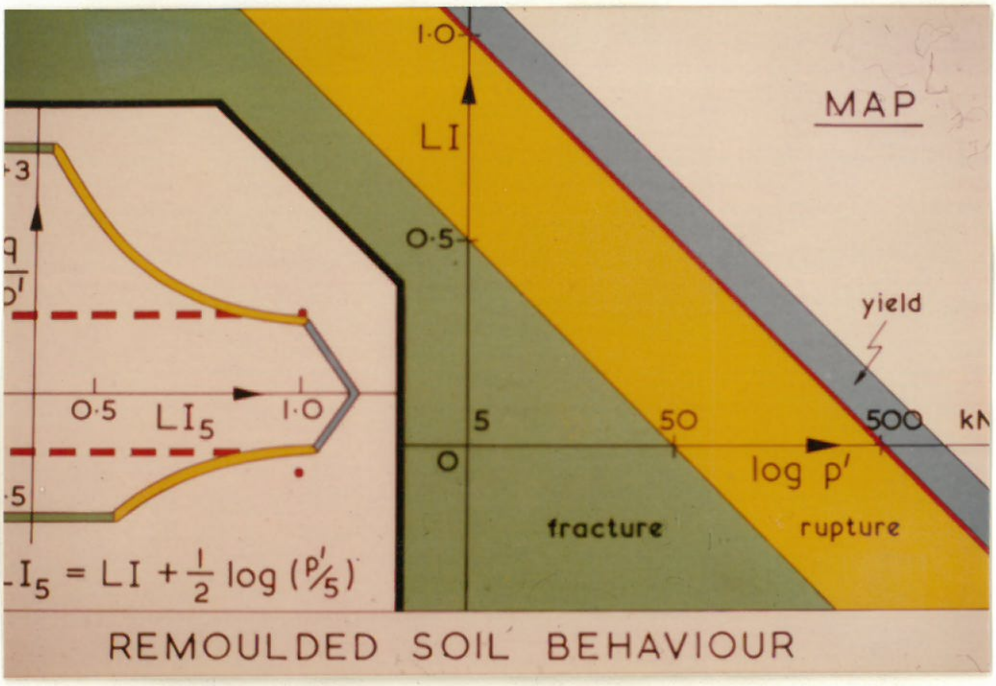

Figure 106

Figure 107