Beas Dam Embankment Pore Pressures During Construction and Post-Construction Period*

by

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Introduction

The Beas Dam is a rolled earth-core gravel-shell dam containing 36 million cubic metres of total fill placement comprising of 11.7 million cu. m of impervious and 24.3 million cu. m. of pervious material. The dam has a height of 103.6 metres above stream-bed and 132.5 m above the bottom of the 9.14 m wide cut-off trench. Measured from the rock-foundation, it is the highest earth-fill dam in India. The dam embankment is zoned to produce an impervious centre section supported by filter zones and pervious sections on both sides.

In recent years, the necessity for instrumentation in earth and rock-fill dams has increased because of the utilization of dam sites having weaker foundation strata and the construction of high earth and rock-fill dams. Also, more reliable measuring devices have been developed for recording the behaviour of the embankment and its foundation. The type, number and location of required instrumentation depend on the complexity of the project.

Between the small closely packed particles that make up the impervious section of the dam embankment, there are interconnected pore spaces that permit the flow of air and water through the material. This Pore Pressure affects the stability of the embankment. Special attention is therefore given to pore-pressure development in the dam embankment and also to possible development of pore pressures in the dam foundations, particularly in stratified compressible materials including varved clays. High pore pressures may be induced in the foundation beyond the toes of the embankment, where the weight of the dam produces little or no vertical loading. Thus, the strength of foundation soils outside of the embankment may drop below their orginal in-situ shear strength. The necessity of measuring the amount and distribution of pore water pressure in the dam embankment and in the foundation cannot therefore be over-emphasized. The measurement of the pore water pressure is regarded as being the most important measurement in an earth dam. Today, the construction of an earth dam is inconceivable without provisions for measurements of the pore water pressure.

The construction of the Beas Dam up to the full height was completed in June 1974. The construction pore-pressures in the dam embankment

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The discussion is open till the end of May 1976.

and foundations were observed as the construction proceeded, at monthly intervals or earlier, even daily in some cases. The pore-pressures were continued to be observed during the filling of the reservoir from July 1974 onwards at 15 days intervals or earlier when the reservoir elevation rose by 6 m during the first two years of reservoir filling. The pore pressures were observed at longer intervals subsequently as determined by the dam behaviour.

The paper mentions briefly the pore-pressure instrument installations made in Beas Dam and the summary of the pore-pressure instrumentation data observed in the dam embankment during the course of construction of the dam in the pre-reservoir filling period preceding the completion of the dam in June, 1974 and also in the post construction reservoir filling and depletion period thereafter. A critical review and evaluation of the data has been presented and the experiences gained narrated briefly.

Instruments

The following pore-pressure measuring instruments have been installed in the dam embankment and foundations of the Beas Dam to observe the behaviour of the dam and its foundations during construction and subsequent reservoir operation.

Pro-Pressure Piezometer Installations

Piezometer installations designed to measure pore pressures developed by consolidation of the dam foundations and the embankment during construction of the dam and later due to settlements and seepage pressures during operation of the reservoir have been installed at three planes; one on the left abutment and two in the river section. In addition, 5 foundation type piezometers were provided for and installed along the plastic seams in clayshale band No. 4-A in the dam foundations which is in direct contact with the deep channel overburden at the upstream end of the core base, on either side of the key trench, as warranted during the course of actual treatment of the dam foundations during construction.

The apparatus consists of USBR type Piezometer tips with an inlet and outlet tube extending to the terminal well near the downstream toe of the dam. The purpose of the Piezometer tip installations was to hold a porous disc over an otherwise unprotected piezometer opening to prevent embankment material from entering the tubing.

A total of 145 USBR type piezometer tips (58 foundation type and 87 embankment type) have been installed as indicated in Figure 1.

Piezometers were installed as the fill was being placed and were simply buried in the same fill material. Along tube trenches across the core around 46 cms wide and 46 cms deep dug for installing the piezometer tubing, and backfilled with the same fill material properly compacted by hand tampers and pneumatic tampers, puddle-clay/bentonite cut-offs were provided about every 15 m. The trenches for the tubes in pervious material were around 4 m wide (blade width of dozer) and 0.9 m deep and were back-filled with impervious material compacted with pneumatic tampers. Tube trenches, 46 cms × 46 cms were dug in this impervious material for installation of piezometer tubing to protect the same from damage.

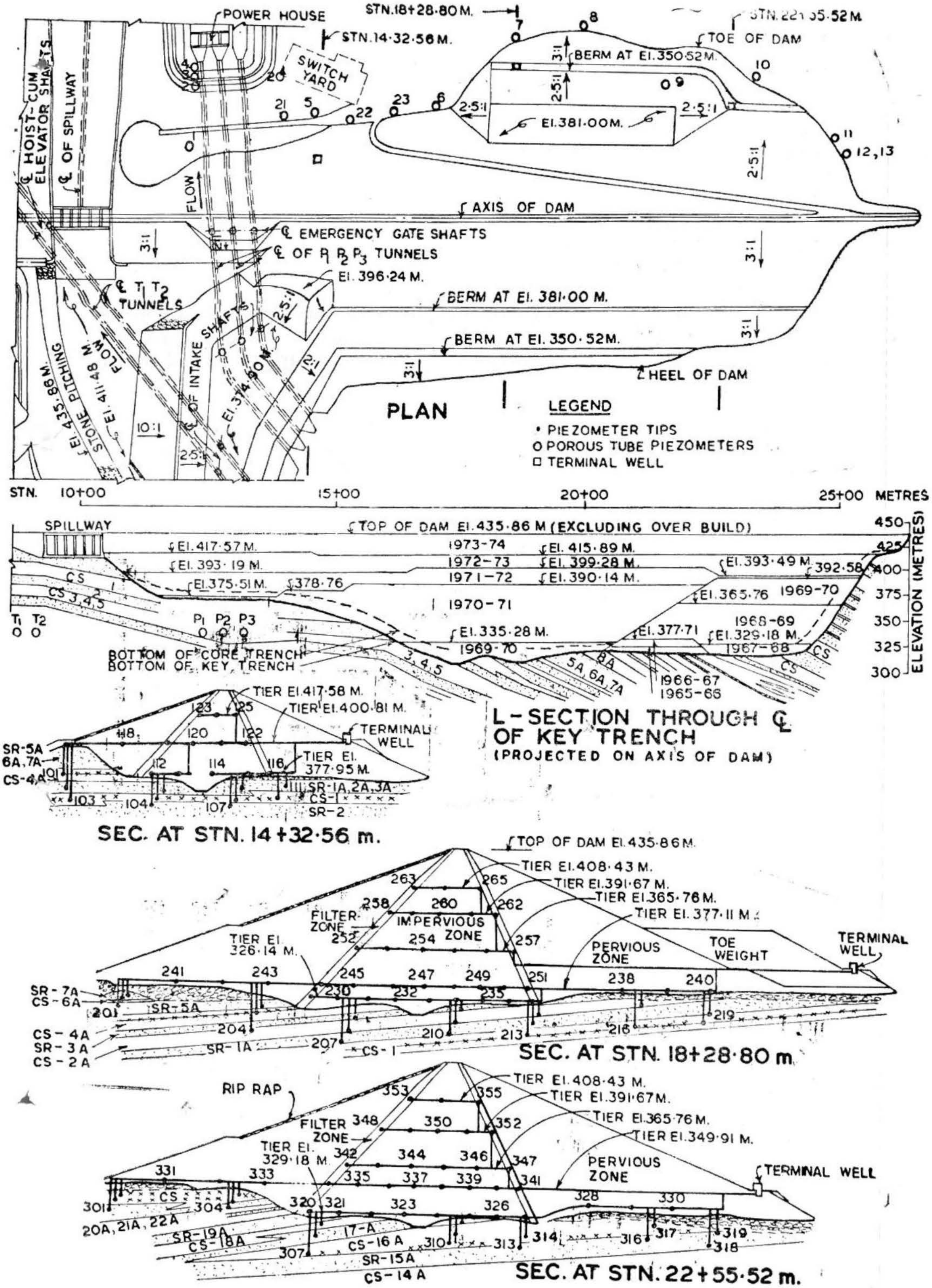

FIGURE 1. Soil Instrumentation for pore-pressure measurement Installations in the Beas Dam at Pong

Observed Data

Pore Pressure Readings in Dam Embankment

(*a*) Construction Pore Pressures used for the original design during 1965 were based on the results of one dimensional consolidation tests carried out in the Laboratory on specimens from exploration samples of sandrock decided to be used, compacted to maximum dry density at different moisture contents above and below optimum moisture content. Theoretical pore pressures based on a no drainage assumption were calculated from these test results using the Hilf's method. The construction pore pressure at any point within the impermeable zone for the original design thus determined worked out to around 30% of total vertical stress as indicated in Figure 2, against the usual arbitrary assumption that the pore pressures are equivalent to 1.25 times the height of the embankment above the point under consideration in terms of hydrostatic head, which works out to around 67% of the overburden load. The total vertical stress for this purpose was taken to be equal to load per unit area of overlying embankment. It was then stipulated that on availability of further information regarding placement characteristics of the fill material from the test section of the dam, a more definite picture of the construction pore pressure would be determined and stability of slopes for construction conditions verified.

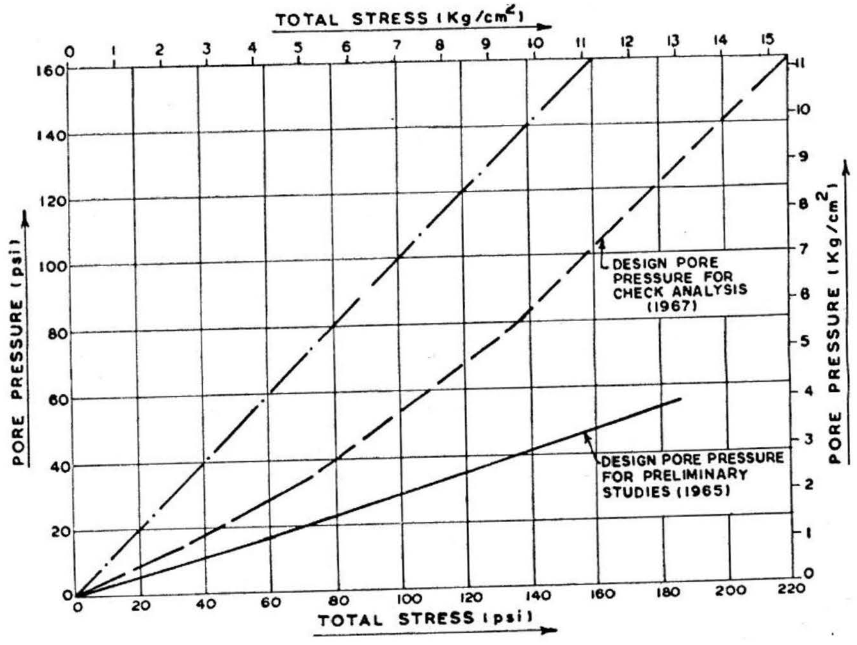

FIGURE 2

A plot of the actual construction pore pressures calculated by the Hilf's method from one dimensional consolidation test results on all the 9 number undisturbed samples taken from the dam during the course of construction up to the end of the working season 1966-67 versus the total stress, indicated that they are higher than the adopted design construction pore pressures. The stability of the downstream slope of the dam which is the critical case under construction conditions was therefore re-analysed on electronic computer using the actual maximum calculated pore pressures of the embankment fill. A factor of safety of 1.33 was obtained with earthquake and 1.69 without earthquake which is very satisfactory as the minimum acceptable values are 1.10 with earthquake and 1.50 without earthquake. The 1967 design Pore Pressures for this check analysis also indicated in Figure 2 enveloped all except stray results with minor deviations.

The plots of total stress versus pore pressures determined by Hilf's method from one-dimensional consolidation test results of undisturbed specimens taken from the actual embankment fill during construction were considered at the end of each working season. They were found to more or less conform to the 1965 design pore pressures for preliminary study, at the end of the 1967-68 working season excepting one sample in which case the results appeared to be erratic. The pore pressures similarly determined at the end of working seasons 1968-69, 1969-70, 1970-71, 1971-72 and 1972-73 were found to be less than the new design values adopted in 1967.

(*b*) In the Beas Dam Project, disturbed samples were taken from the location of Piezometer tips installation and tests were performed in the laboratory to check dry density, moisture content. Atterberg's limits, grading analysis and specific gravity.

In all 205 undisturbed samples were taken from different locations in the impervious zone of the dam during the course of its construction. The construction pore pressures for these undisturbed samples were calculated by the Hilf's method on the results of one-dimensional consolidation tests at a normal stress of 3.5 kg/cm^2, 7.0 kg/cm^2, 10.5 kg/cm^2, 14.0 kg/cm^2, 17.5 kg/cm^2 and 21 kg/cm^2. The plot of total stress versus pore pressure for these samples on a single sheet (Figure 3) revealed that only 3 samples gave pore pressures slightly higher than the 1967 design pore pressures for check analysis. The Pore Pressure test results of undistrubed samples taken from fill placement in the dam at different periods during construction cannot obviously be compared with the Pore Pressures indicated by the tips installed at different locations in the embankment due to hetrogeneity of the soil and different moisture and placement conditions.

Triaxial tests were also conducted on 205 samples prepared from undisturbed samples from the embankment, in consolidated undrained conditions. In the undrained triaxial tests, the specimens were subjected to lateral pressures of 2.1 kg/cm^2, 4.2 kg/cm^2 and 6.3 kg/cm^2 and sheared at an axial strain rate of 0.127 mm per minute. Pore pressure measurements were also made and accounted for while drawing Mohr's stress diagram.

(*c*) The pore pressure readings of the piezometer tips installed, taken during the course of construction of the dam generally at one month intervals, were plotted against overburden pressure and analysed regularly.

The piezometer data have been summarised by plotting pore pressures as percentages of the overburden load against time as indicated in Figure 4.

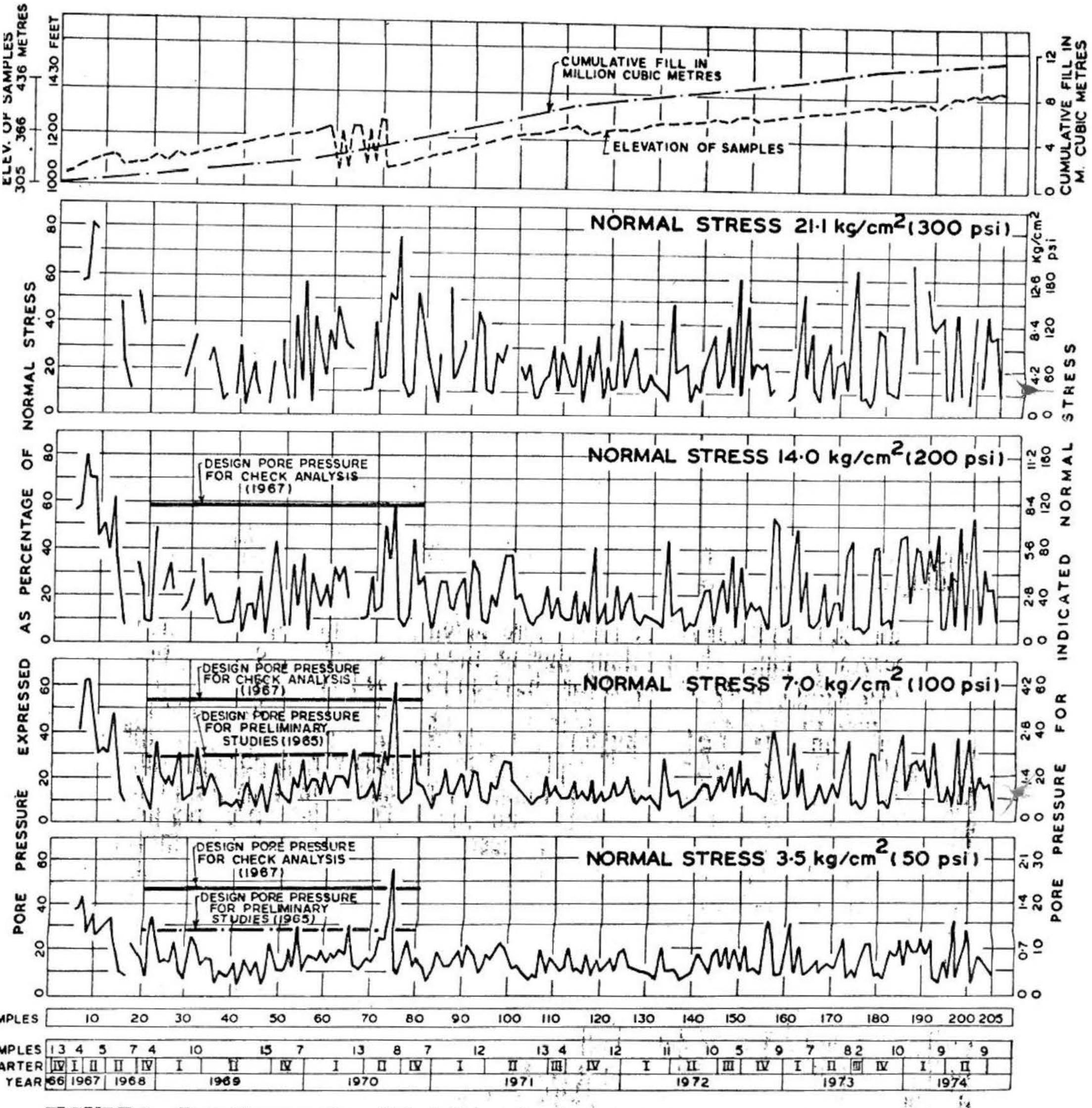

FIGURE 3. Pore Pressures in undisturbed samples from impervious fill tested at different normal stresses as determined by Hilf's method in Beas Dam Soils Laboratory

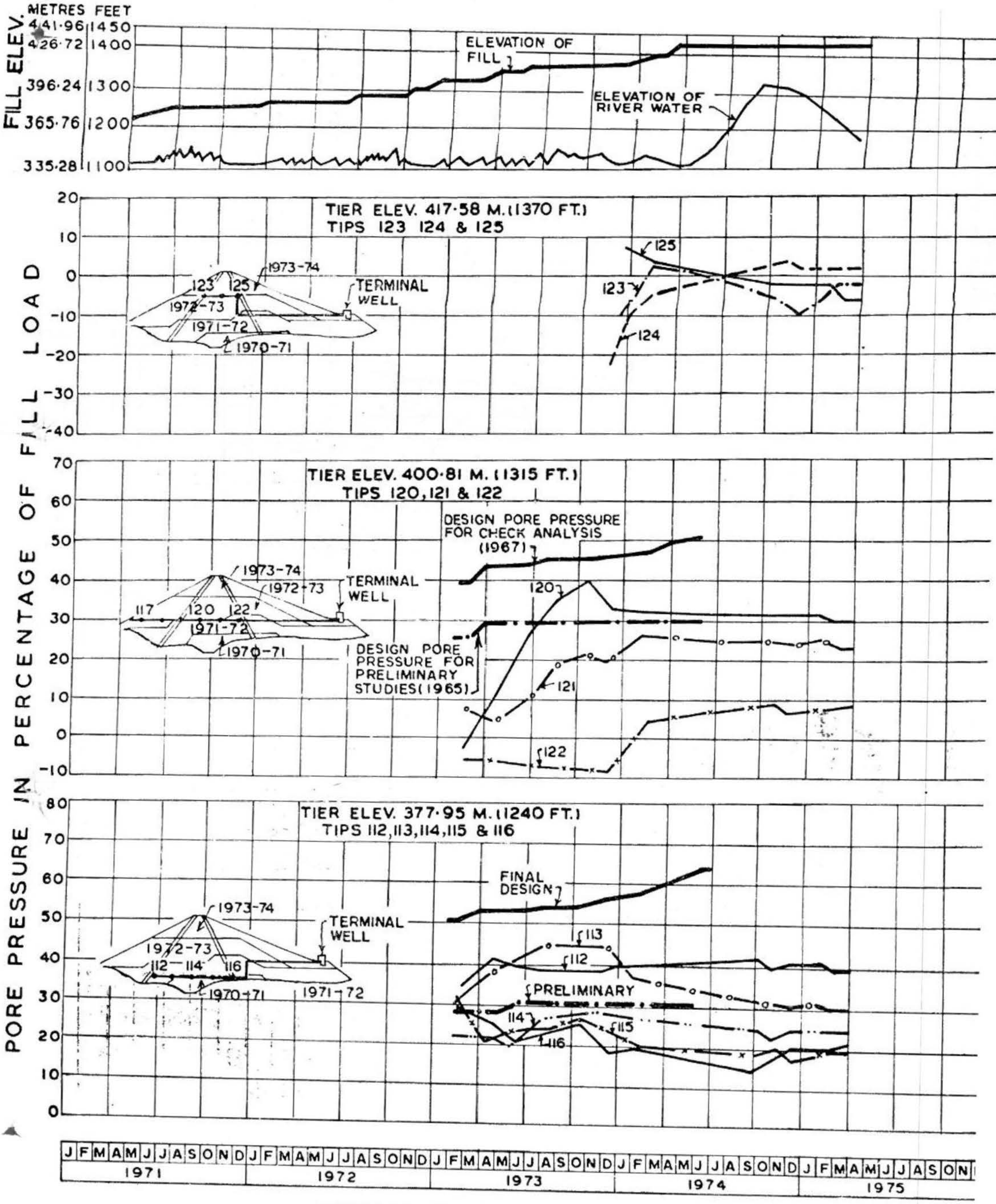

FIGURE 4. Pore Pressure Installation

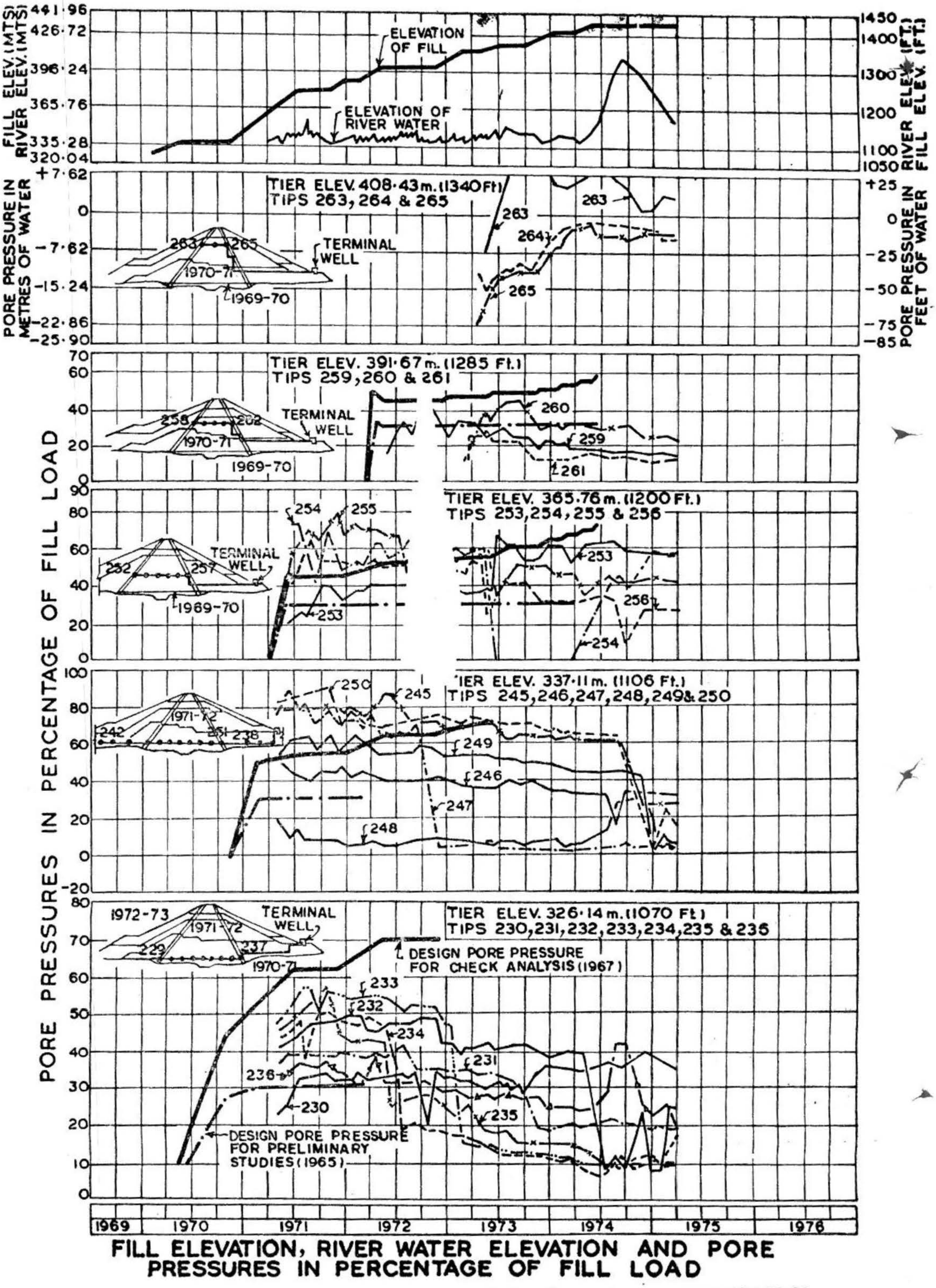

FIGURE 4. (Contd) Pore Pressure installation observations at station 18+28·80 m

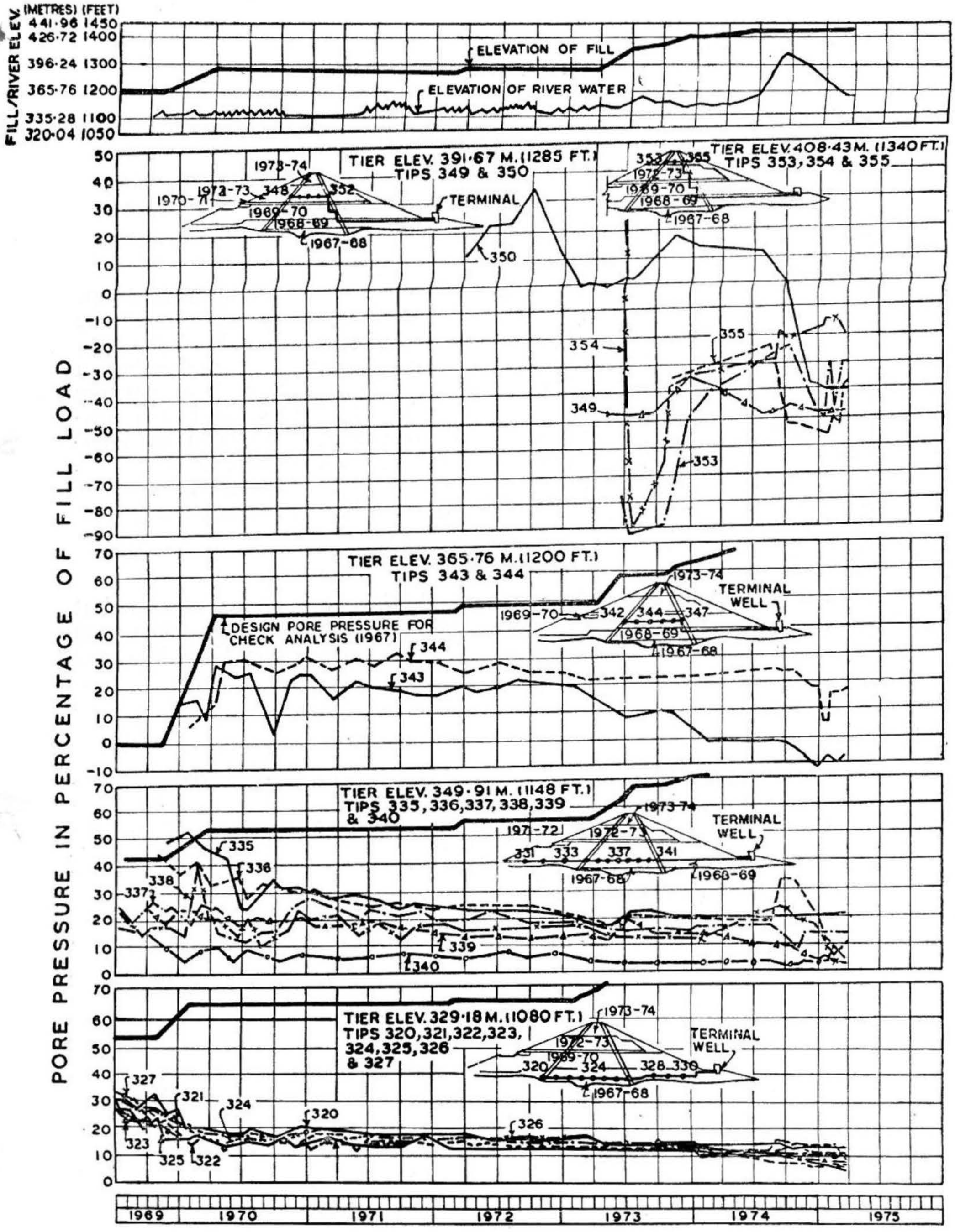

FIGURE 4. (Contd) Pore Pressure installation observations at station 74+00

Another curve is also plotted in these figures at the top showing the top elevation of the progress of embankment placement alongwith a curve for river water elevation against time, so that the Pore Pressure observations could be correlated with the fill placement height. The 1965 design pore pressures for preliminary studies and the new 1967 design pore pressures for check analysis for the concerned heights of fill placement have also been plotted against time to indicate at a glance the relative values of the observed pore pressures.

The piezometer data at different stages of dam construction was also summarised separately by indicating water level elevation or total head at the location of the piezometer tips on a cross section of the dam. This is simply the elevation to which water would rise in an open stand-pipe whose bottom is at the same elevation and location as the corresponding piezometer. These Pressure diagrams of the sections of the dam containing the installations were prepared periodically to show the pressure distribution to aid in the study of Pore Pressure behaviour. The pore pressure contours in terms of the water level elevation of total head and equipotential lines (equal stand-pipe elevations) were thereafter drawn by interpolation at different stages of dam construction. Figure 5 shows the distribution of the recorded pore pressures in the embankment (pore pressure contours and equipotential lines) at different stages of construction.

Construction Pore Pressures in Dam Embankment

Consolidation of the Beas Dam embankment has been measured at between 1 & 2.5 precent. Tests on 205 undistrubed samples taken from the dam embankment during the course of construction have indicated that initially the air in the soil voids varid from 1.9 percent to 13.2 percent of the volume of soil particles, with an average of 6.8 percent while water in the soil voids varied from 27.8 percent to 28.1 percent of the volume of soil particles with an average of 27.6 percent. Thereafter, unless there is drainage, pressures within the pores must result from the consolidation. Soils which show such pressures are found to have percolation rates less than 7.6 mm per year. The rate of percolation in the impervious core in the Beas Dam as per permeability tests on 11.4 cms diameter 13.7 cms high samples prepared from 205 field undisturbed samples and tested by the falling head method varied from 0.25 mm per year to 17.5 mm per year with an average value of 3.3 mm per year. The rate of percolation from 10 field permeability tests varied from 1.45 mm per year to 44.7 mm per year. Only nine tests results in the Soils Laboratory out of a total of 182 tests on undisturbed samples taken from the dam indicated a percolation rate greater than 7.6 mm per year. Only 2 field permeability tests out of a total of 10 field tests on the Beas Dam indicated a percolation rate greater than 7.6 mm per year. The test results therefore indicate that the soil is susceptible of developing pore pressures.

The recorded pore pressures show an increase during the loading of the embankment over the point until finally a constant pressure was sustained for prolonged periods. This residual pressure is a function of the material within the embankment and the applied load.

Pore pressures equal to 20 to 40 per cent of the total weight of the overlying embankment are common in the central part of the core. For the central deepest riverbed section of the dam where construction proceeded

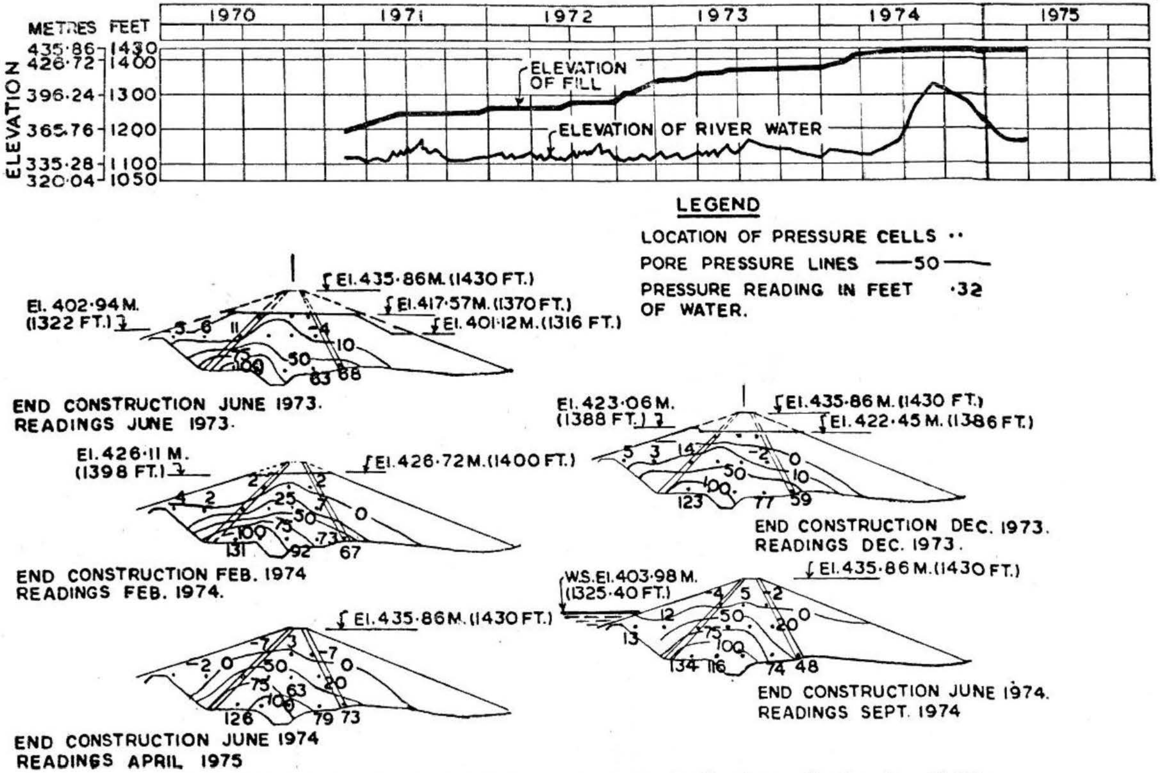

FIGURE 5. Construction Pore Pressure Diagrams for Section at Station 14+32.56 m

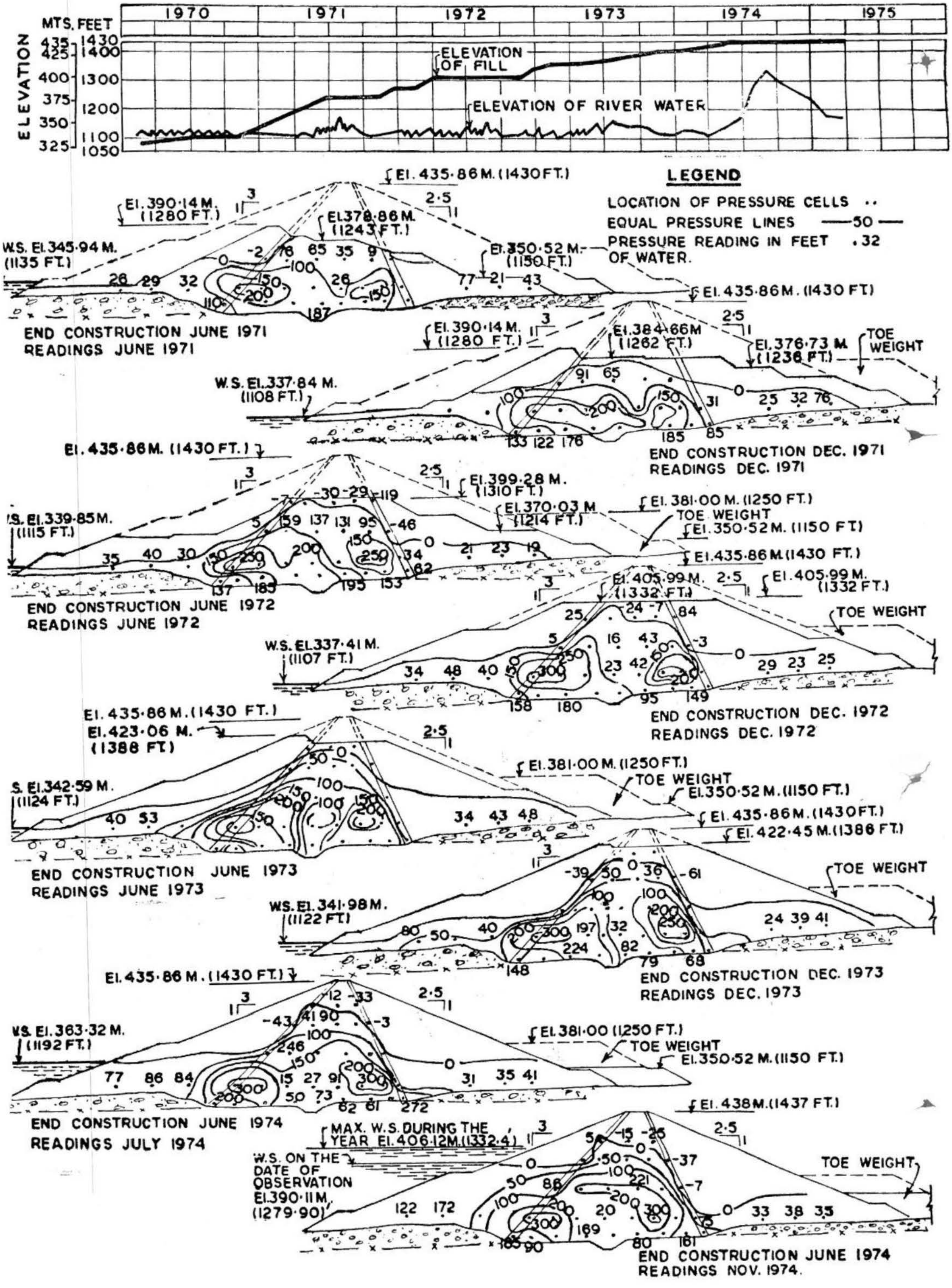

FIGURE 5. (Contd) Construction Pore Pressure Diagrams for section at station 18+28.80 m

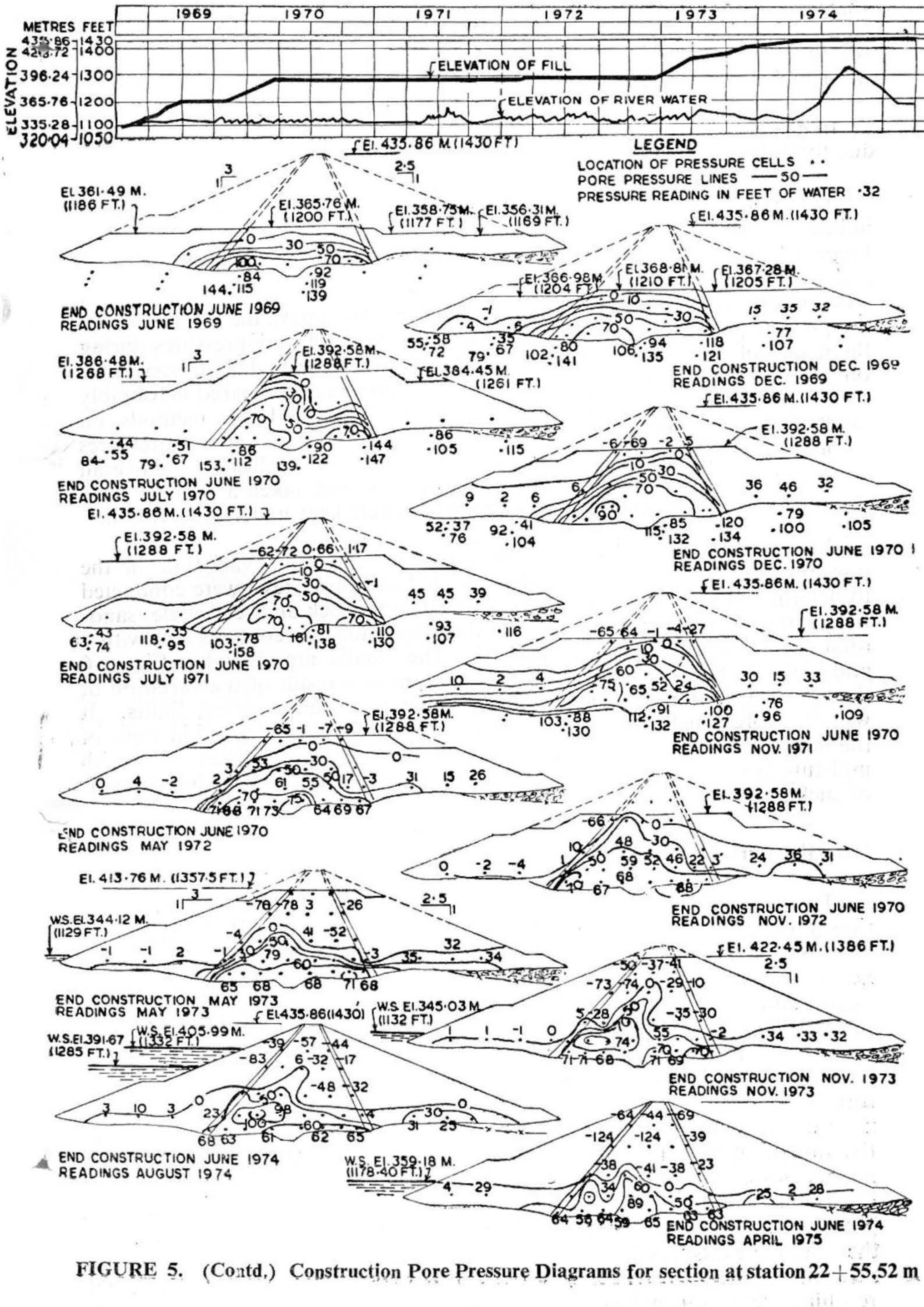

FIGURE 5. (Contd.) Construction Pore Pressure Diagrams for section at station 22+55,52 m

continuously except for the slowing down or short break during the rainy season from July to September each year, the construction pore pressures varying from 10 per cent to 60 per cent at various stages of construction were quite common and pressures exceeding 80 per cent were also measured in a few isolated cases.

In general pressure pattern isolated high or low pressure points may be due to faults in the system.

The pore-pressures observed at stations 14+32.56 m and 22+55.52 m indicated values within the 1967 assumed design pore-pressures. The Pore-Pressures observations for tips 245, 247, 249, 250 at tier elevation 337.11 m and tips 254, 255, 256 at tier elevation 365.76 m at the deepest river bed section at station 18+28.80 m indicated values above the 1967 assumed design pore pressures. Strict watch was kept on these pore pressures during the course of construction of the dam embankment by even daily observations on the concerned tips. The observed pore pressures compared favourably with the laboratory determination of pore-pressures by Hilf's methods on undisturbed field specimens. These stray isolated cases of pore pressures higher than design were not considered to have an effect on the overall stability of the dam section and were therefore not taken a serious note of, but further development of pore pressures were kept under observation.

In an endeavour to determine the causes for the wide variation in the pore-pressure values observed in Beas Dam, Laboratory tests were conducted to determine the pore-pressures on clayshale, sandrock and clayshale sandrock samples mixed in 50:50 ratio at different moisture contents and with a total normal stress of up to 20 kg/cm². The results are plotted in Figure 6 and highlight the vast pore-pressure variations as a result of the variation of the soil composition and the moisture content within practical limits. It was therefore concluded that the higher pore pressures observed in some of the piezometers were a result of the predominance of clay-shale soils with moisture contents slightly above the optimum moisture content in the areas of such piezometer tips.

Pore Pressure Contours in Dam Embankment

The Pore Pressure contour diagrams showing the pore-pressure distribution in the dam section at Station 14+32.56 *m station, 18+28.80 m and* station 22+55.52 m at the close of the construction season in June and at the end of December each year were plotted to examine the development and also the relatively small dissipation of Pore-Pressures. Pore-pressure contours shown in Figure 5 indicate that the pressure pattern is approximately centered in the impervious zone. The configuration of equal construction pore pressure lines within the impervious section appear as a series of deformed ovals conforming to the shape of the central impervious zone of the dam. The higher pressure occurs near the lower third level of the embankment. The highest pressures develop in the portion of the impervious core, where the overburden pressures are highest and the effect of drainage to the adjacent pervious zones is least. Below this point, pressures drop toward the foundation but do not entirely disappear. At the side, the pressures fall off rapidly at the boundary of the impervious section. In the upper part, the reduction in pressures is more gradual, reaching zero somewhere in the upper 6 m or 9 m. The structure being large, two or more such whorls have been observed. A particular whorl occurs immediately above the foundation.

Pore Pressure Analysis

The records were summarized, the data presented graphically was then critically evaluated and further judgement was exercised in interpretation as necessary.

Measured Versus Predicted Pore Pressures

The measured pore pressures were compared with those which would have been predicted from the test results of undisturbed field samples on the basis of the USBR Theory and found that the two agreed roughly, and that the main difference between the predicted values and the pore pressures measured could be explained reasonably from the construction history. For example, the measured pressure was higher than predicted when concentrations of wet and compressible soil had been placed in the embankments. Drainage relief and surface tension in the pore-water caused the pore pressures in the impervious zone to be lower than predicted, and differential settlements led to different pressures than predicted because they caused transfers of total stress within the embankments.

Influence of Construction Water Content

As per analysis of USBR Dams reported by Gould, with only two exceptions, in every dam built by USBR in which the average water content exceeded 0.6 percent above Standard Proctor Optimum, substantial pore pressures developed. In embankments compacted a few percent drier, no significant pressures developed.

The Beas Dam specifications provide that the moisture content for the impervious core shall be within 2 percent on the drier side to 1 per cent on the wetter side of the optimum. The percentage moisture content test results on 10000 field tests revealed that the moisture content generally ranged between +0.4 percent of OMC and —2 percent of OMC with extremely rare cases when it was beyond these limits. The average water content in 86 per cent of the test results was below the Optimum Moisture Content and in 75 per cent cases it was below 0.6 per cent below Standard Proctor Optimum. (Figure 6)

As was excepted, the primary factor governing the development of pore water pressure during construction was found to be the average water content at which the embankment was constructed.

Influence of Drainage and Surface Tension

As per analysis of USBR dams by Gould, in dams where the foundation permeability was equal to or lower than that of the impervious core, the highest construction pore pressures occurred at or just above the foundation. The Beas Dam foundation permeability and the permeability of the impervious zone of the Beas Dam embankment could be considered as being generally of the same order and the highest construction pore-pressures were found to occur at or just above the foundation.

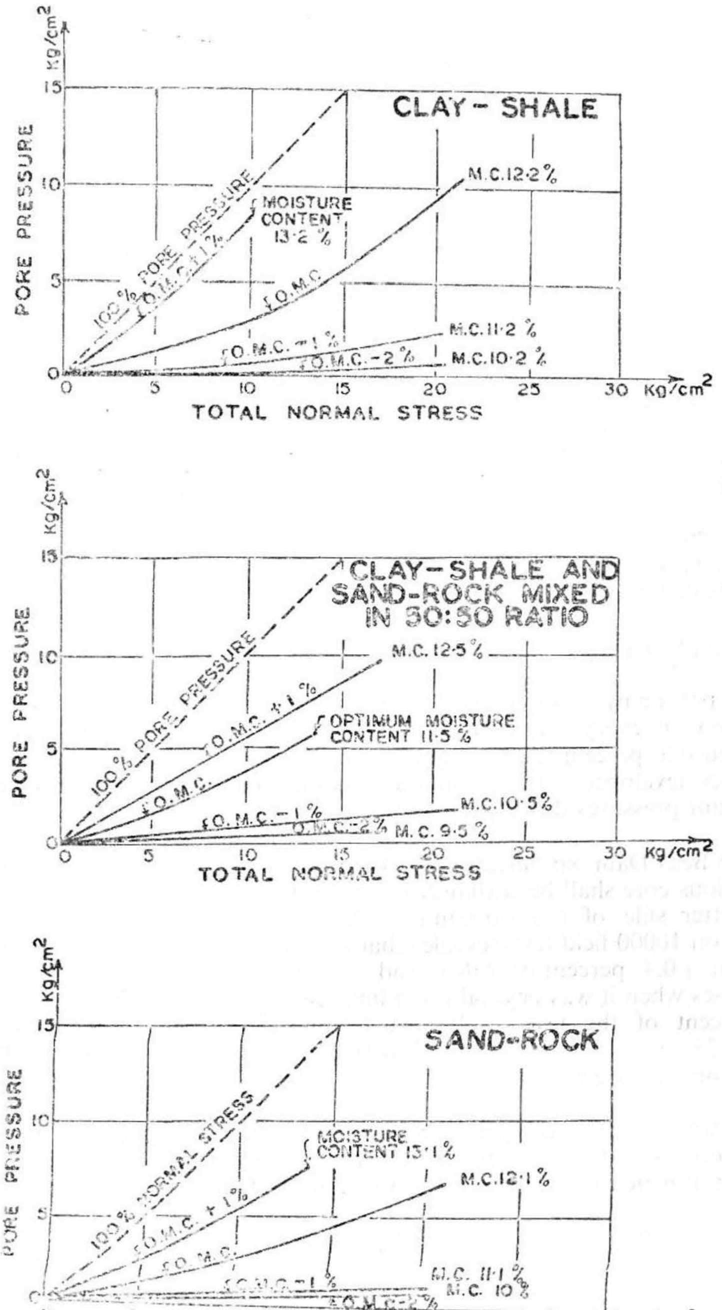

FIGURE 6. Dependence of pore water pressure on the moisture content of the sample

The accurate measurement of pore water pressure in partly saturated soils as in the case of the Beas Dam impervious zone is important as difference between pore air and pore water pressure is significant. The importance of the error due to inadvertent measurement of air pressure depends on the soil type, the placement water content and the height of the fill above the piezometer.

There are difficulties in measuring correct pore pressures and in defining effective stress in partly saturated compacted fills with both air and water present in the voids. The pore water pressure in such fills is lower than the pore-air pressure due to the effects of surface tension or capillarity. In compacted clay soils this pressure difference may have a magnitude of several atmospheres even at relatively high degree of saturation and it is this pressure *difference which is the cause of many of the difficulties in the* measurement and interpretation of pore pressure. For a given compactive effort the pressure difference depends both on soil type (particularly clay fraction) and on placement water content.

If drainage of both air and water from the sample is prevented, an increase in confining pressure leads to an increase in both the air pressure and water pressure, the difference between them decreasing as the stresses increase.

Influence of Soil Type

While the water content is the primary factor governing construction pore pressures, there is also a strong co-relation with the embankment soil type. Both theory and the measurements on USBR dams indicate that the highest pressures are generated in embankments constructed of well-graded gravel mixtures with clayey fines, in which the original air content is relatively low and the compressibility relatively high. Conversely, theory and measurements also both agree that embankments of uniform silts and fine silty sands with little or no plasticity are the least susceptible to the development of high pore pressures because of their high initial air content and relatively low compressibility. Other measurements suggest the possibility that because of high capillary forces and the relatively large air contents the construction pore pressures in embankments of very fine-grained clayey soils may always be low. The highest pore-pressures in the Beas Dam embankment were generated in areas consisting predominently of clay-shale soils as compared to other areas having sand-rock or sand-rock/clay-shale mixtures.

Influence of Periods of Work Stoppage and Drainage on Pore Pressure Development

When fairly high pore pressures develop within the core of a dam during the early part of construction and then are later dissipated to some degree by drainage during a period of work stoppage, they subsequently increase at a rate which is appreciably smaller when construction commences again. Hence, delays in construction may have a doubly beneficial influence on the stability of earth dams during construction. The reason for the decrease in the rate of pore pressure development after periods of work stoppage is that the embankment becomes denser and less compressible as the result of the consolidation which occurs. When work starts again, the soil structure is stiffer than before, and a smaller percentage of the added weight of the new embankment is thrown to the pore fluid.

The above fact was borne out by the Pore-Pressure observations on the Beas Dam embankment.

Conclusion

(*a*) The piezometer installations have proved to be a generally reliable means of measuring the pore pressures. Subject to the requirement for periodic flushing and de-airing, most of the piezometers have behaved satisfactorily since installation except a few.

(*b*) Flushing of piezometers at and soon after the time of installation may have contributed to some of the relatively high initial pore pressures recorded at some points. Despite repeated flushing and de-airing certain piezometers gave obviously incorrect readings for several months following the installation. In other cases obviously erratic and erroneous readings could not be explained.

(*c*) Drainage effects play a significant part in reducing the construction pore pressures even in the central portion of the impermeable zone.

(*d*) Due to the wide variation in theoretical curves and in the recorded pore pressures, it is not possible to make general comparisons between actual pore pressures and those calculated from or measured in laboratory tests.

(*e*) Pore-pressure measurements enabled the stability of the embankment to be analysed in terms of effective stress during construction. The observations made continuously during the construction stage and thereafter have provided information for a continuing check on departures from the design assumptions. The instrumentation observations of Pore water pressures have indicated that the actual rate of fill placement as per programme has been quite reasonable.

The instrumentation has given a reliable indication of the behavior of the embankment during the construction period and there-after during the post-constrnction period so far. The instrumentation data hasfurther indicated that the structure will function as intended and further observations of piezometer readings shall provide continuing suveillance of the structure towards any developments which may endanger its safety.

(*f*) The instrumentation gave security by furnishing the true data of conditions and their chronological variations, by eliminating inaccuracy of factors entering calculations, permitting correct ascertaining of influences which could not be taken into account by calculation and finally for helping to recognise moments of danger for avoiding catastrophes by taking security measures in time.

(*g*) The information obtained will also be useful for future design criteria for high dams as the same will depend upon detailed and reliable knowledge of the behaviour of embankment dams both during construction and operation stage.

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