SEEPAGE CONTROL AT TARBELA DAM
THROUGH
UPSTREAM BLANKET

By

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1. General

Tarbela Dam is the largest earth and rockfill dam ever built in the world. The volume of earthfill placed in the dam is 186 million cubic yards, which is for more than any other existing earth dam. The river valley on which the dam is founded is filled with several hundred feet deep alluvial deposits, which are highly pervious. In order to control seepage from the foundation of the dam, an upstream blanket of impervious material has been placed for a length of 7,300 feet. The maximum height of Tarbela Dam is 485 feet at an elevation of 1,565 and the maximum conservation level is 1,550 feet.

The construction of this gigantic dam was started in 1968 and water was stored in the reservoir for the first time in the year 1974. This year was in fact a trial year, and it was intended to check the behaviour of various structures of the project under the reservoir loading. The year 1974, however, produced many shocks for the project, and several components of the project, which were tested, showed mal functioning.

The major mishap occurred in the failure of upstream part of the No. 2 diversion tunnel. The seepage from the foundation of the dam and through the right abutment was also found to be very high. In order to repair the damages in the tunnels, the water in the reservoir had to be depleted very rapidly in the late August, 1974. This also provided an opportunity to inspect the upstream blanket. Upon depletion of the reservoir, the inspection revealed that the upstream blanket had cracked at several places and a number of sinkholes were found in the blanket.

In this paper an attempt has been made to analyse the behaviour of the blanket and to discuss the probable reasons which may have caused the cracks and sink-holes. Such an important technical happening is obviously a subject of great technical interest. But so far this subject has not been discussed in any technical forum and the full data is also not yet available to local engineers. This study, therefore, is based on some information which was made available to the Pakistani Panel of experts appointed by the Government of Pakistan to look into the Tarbela mishaps. The main purpose being to raise the interest of the engineers in the country about this subject and to invite some deep thought into the problem.

2. Foundation Condition

The river valley at the damsite is about 9,000 feet wide, of which obout 8,000 feet wide section is filled with alluvial deposits. The subsurface condition at the damsite were of complex nature and the Project Consultants put great emphasis on the investigations to determine the foundation stratigraphy and alluvium characteristics.

The investigations consisted of making seismic surveys, drilling a large number of bore hole and digging of test pits. A freeze shaft was also excavated in the blanket area to a depth of 90 feet for inspecting the insitu condition of the alluvium. The bore holes were from 100 to 700 feet deep, and fully define the bed rock profile in the river valley. In the blanket area, in addition to bore holes, about 450 shallow test pits were also excavated to sample and observe the foundation materials which will be adjacent below the impervious blanket. In addition to above, grouting and pump out tests were carried at different sections across the valley to get an idea about the permeability of the foundation materials. It can be safely stated that the foundation were quite throughly investigated. The design stage investigations were supplemented to a great extent during the construction period.

On the basis of the design stage investigations Consultants interpretted the following conclusion about the foundation materials:—

> "The major part of the Indus valley, at the damsite, is filled with deep deposits of rounded boulder-gravel-sand mixtures containing occasional starta of sand and silt which are believed to be discontinuous. Borings and tests made during the foundation investigation indicate that the boulder gravels are generally chocked with the fine to medium sand which limits the material permeability to that of the sand. In some locations, however, high

mud and water losses during drilling gave evidence of a sand deficiency, indicating an open work boulder-gravel structure. High mud losses were also noted in borings made along the left abutment. This may be evidence of an open-work condition in the talus deposits along the base of the steep valley walls.''

The investigation carried out during the construction stage revealed that the 'Open Work' gravels zones in the foundation alluvium are more wide spread than initially envisaged and such highly pervious layers are concentrated on the right side of the valley. The exploration in the construction stage also brought to the light that on the right bank the bed rock vertically drops from elevation 1,050 to 400.

In the design report the Consultants have stated that an idealized foundation profile was developed from the exploration and field test results to facilitate design of the seepage control measures. This simplified profile, together with the estimated mean permeabilities and other assumptions essential to the design of seepage controls, is as follows :

Zone	Depth (feet)	Material Description	Mean Permeability (cm/sec.)
A	0-15′	Loose silty sand, loose fine sand, and boulder-gravel choked with sand	0.02
B	15′-80′	Loose to medium-dense-boulder-gravel choked with sand and containing occasional discontinuous zones of open-work boulder gravel.	0.02
C	80′-110′	Same as B, except more open-work boulder-gravel.	0·04

D	110′-300′	Medium dense to dense boulder-gravel choked with sand and containing occasional discontinuous zones of silts, sand, and openwork boulder gravel.	0.01

However, it is believed that the actual permeability of the foundation alluvium, as investigated in the subsequent investigations, may be generally higher than the above figures, particularly the open work zones have probably a permeability coefficient of 0.1 to 1 cm/sec.

3. Seepage Control Measures

In the early stages of investigations for Tarbela Dam, it was realised that the alluviam in the foundation extends to a very great depth, i. e., over 600 feet. The alluviam was also known to be highly pervious, therefore, the problem of seepage control at this dam are of unprecedented magnitude and complexity.

At a site with a previous foundation three basic methods of foundation treatment are possible.

(*i*) Eliminating the seepage or reducing it to a negligible amount by constructing a complete vertical foundation seepage barrier or cut off.

(*ii*) Reducing the seepage with a partial cut off or with an upstream impervious blanket, and providing for the control of the water that does seep through. The seepage control is normally done through horizontal drainage blanket within the dam or through vertical drainage in the form of relief wells.

(*iii*) Taking no steps to reduce the seepage and only providing for its control.

The practice shows that before 1940, all high earth dams built on pervious soils were treated by the first method. However, in the last 30 years, confidence has grown in the safety of seepage control measures and a number of dams have been constructed all over the world, resting directly on pervious foundation at sites where complete cut off would have been very expensive.

At Tarbela Dam the installation of a vertical cut off was considered to be not feasible, due to the great depth of the alluviam, and its very high cost. The partial cut off would not be effective for the Tarbela Dam because the permeability of the foundation does not markedly decrease with depth. Therefore, the provision of an impervious upstream blanket was considered as the best alternative. At Tarbela Dam (Fig. I) the designed length of the imperviovs blanket is 7,300 feet and its thickness is 40 feet near the upstream toe of the dam and tapers down to 5 feet at its upstream end of the main blanket. Initially, the blanket was planned as 5,300 feet long, but in 1972 detection of additional highly pervious zones within the alluviam prompted the extension of the blanket by 2,000 feet. The extended blanket is also 5 feet thick. The head created by Tarbela reservoir is about 440 feet, therefore, the corresponding ratio of length of the blanket to head is about 17 : 1.

The horizontal upstream impervious blanket increases the horizontal length of the path of underseepage and thereby reduces the downstream pore water pressures and hydraulic gradient. If the blanket is very impervious, compared to the natural foundation, so that relatively little seepage occurs through the blanket, the reduction in the seepage quantities and pressures at the downstream toe is directly related to the length of the blanket. On the other hand, if the blanket is only slightly less pervious than the foundation material, there is a maximum length of the blanket, beyond which no appreciable benefit is obtained by increasing the length. Therefore, good practice for a blanket which is relied upon to control the underseepage requires that it be constructed of impervious soil in the same manner and with the same care as impervious core of the dam.

For determining the effectiveness of the blanket, a mathematical solution has been developed by P. T. Bennett for the condition where the foundation consists of a single horizontal pervious layer with a more impervious, surface blanket. In order to assess the effectiveness of Tarbela blanket, some computations have been made using the Bennet's solution and assuming different permeability coefficients for the blanket.

It has been assumed that foundation have an average permeability of 5×10^{-2} cm/sec, and effective blanket length for a 5,300 feet long and 7,300 feet long blanket have been computed.

The results are tabulated in the following table :

Effective Length of Blanket

K_f cm/sec	K_b cm/sec	$\frac{K_f}{K_b}$	Effective Length of Tarbela Blanket	
			for 7, 300 feet (extended)	for 5, 300 feet (original)
5×10^{-2}	10^{-3}	50	820	820
5×10^{-2}	10^{-4}	500	2,580	2,512
5×10^{-2}	10^{-5}	5,000	5,840	4,670
5×10^{-2}	10^{-6}	50,000	7,120	5,231

K_f = Permeability of foundation

K_b = Permeability of blanket

It is apparent from above figures that in order to make the blanket effective, it must be greatly impervious as compared to the foundation. The extended length of the blanket at Tarbela, for instance, could only be effective, if the blanket was 50,000 or more times impervious than foundation. If the $\frac{K_f}{K_b}$ ratio is for instance only 500, the extended length of the blanket would be almost useless.

Since the blanket only provides partial treatment, therefore, a large quantity of water still seeps through the foundation and emerges on the downstream side. In order to control the pressure of seepage water and to avoid piping conditions, relief wells are provided at the downstream toe of the dam. The wells are spaced at reasonable interval to keep the pressures below any desired level.

The relief wells are much more effective, if they penetrate through the full depth of pervious foundation, and effectiveness of the wells which penetrate less than 50% of the thickness of the layer is substantially reduced. At Tarbela, in addition to blanket, a line of relief wells at 50 feet centres have been provided near the downstream toe in order to safely control the exit gradients. There were 113 relief wells (which have been increased to 190 in 1975) with depths varying from 125 to 250 feet. The penetration of the wells, therefore, varies from 20 to 50 per cent of the total alluviam thickness. In view of this it is possible that substantial amount of seepage from the foundation may be bypassing below the relief wells and emerging somewhere downstream in the river bed.

The blanket has been constructed with a special mix of material designated as B2 (1) type. This material is graded from 12 inch downward, with allowable percent finer than No. 200 sieve size (silt size particles) to range from minimum of 20 per cent to a maximum of 50 per cent. These limits were apparently relaxed for the extended portion of the blanket, where random fill with variable gradation was placed. The exact limits for the material placed in the extended portion of the blanket are not fully known. It was considered that the special mix of the B-2 (1) material would be self healing and the migration of blanket material in the foundation soils will not occur. It was also specified that B-2 (1) material will be well graded within the overall specified limits, however, the term 'well graded' has not been adequately defined in the specifications.

Prevention of migration of fines from the blanket into the foundation materials is one of the major consideration in the blanket design.

Normally the blanket is constructed with fine grained material, while the foundation consisting of pervious gravels may have large voids where the fines from the blanket would penetrate under the pressure of reservoir water. If this phenomenon takes place freely and on large scale, the blanket is short circuited and becomes ineffective, which could ultimately lead to a piping failure. In order to safeguard from this situation, two measures may be adopted :

(i) to provide a transition layer between the blanket and the foundation material, which will act as a filter and prevent the migration of particles.

(ii) to construct the blanket with a material which is so well graded that it is resistant to erosion and migration. Where the foundation materials are very gap graded, it is usually difficult to manufacture such a mix for the blanket material.

At Tarbela the second alternative was chosen and a special mix of material was designed for the blanket construction. There are other problems associated with the blanket, such as differential settlement, cracking and local subsidence due to loss of support. For this purpose the blanket should be made sufficiently thick and flexible.

4. Behaviour of Tarbela Blanket

For a very large dam like Tarbela, it is extremely important to monitor the beheviour of various structures in order to ensure their proper functioning and safety. For this purpose, a large number of piezometers were installed under the blanket and dam foundation to observe the pore pressures and potential under the blanket. The piezometers consist of a porous filter, a cylindrical housing, a diaphragm and a vibrating strain gauge. The instrument measures the axial strain due to the outside pressure. A signal from the read-out sets the wire in vibration by an electromagnet while another magnet transmits the frequency of the vibrating wire to the read out set through another circuit. Frequency readings of the read out are converted into pressure by a calibration curve. These piezometers, which numbered over 100 provided very useful information during the first as well as second filling of reservoir.

Plots have been drawn (fig-2) showing the equipotential contours under the blanket for various levels of the reservoir.

These plots have heen made along three sections. Section AA is through the right bank, Section BB is in the middle of the valley and section CC is through the left bank. The potentials in terms of percentage reservoir head are plotted under the blanket for different reservoir elevations.

In the plot AA (fig.3) at reservoir elevation 1168 the percentage potential immediately downstream of the extended blanket was 17 percent. However, the potential at the same point at reservoir elevation 1460 become 58 percent. The plot BB, (Fig. 4) in the middle of the valley, shows very little potential drop in the extended portion of the blanket, and downstream of coffer dam 'C', there is an abruptly steep drop in the potential. The difference in the potential for higher reservoir elevation is not so significantly marked in the mid valley area. The plot CC (Fig. 5) on the left bank shows very little potential drop under the extended blanket and again downstream of cofferdam 'C' there is a steep drop. The potential lines also show a considerable shift from 1168 reservoir elevation to 1460 reservoir elevation, particularly in the area immediately downstream of the cofferdam 'C'.

The shift of the equipotentials for different reservoir levels under the blanket during the 1974 filling is quite significant. It shows adjustments were taking place within the foundations and the blanket. Normally, if the blanket stays intact and there is no internal errosion within the foundation, the equipotential contours under the blanket for the various reservoir heads shall also remain constant. However, if the blanket material migrates into the foundations, thereby reducing the effective thickness of the blanket, or there may be ruptures in the blanket at places, the short circuiting of seepage water will result in the increase of potential under the blanket. Similary, if the fines within the foundation material start travelling downstream due to the reservoir pressure, the voids in the foundation increase and accordingly the potentials go up. The phenomenon of change in equipotential levels with increasing reservoir pressures was quite pronounced during the 1974 filling. The potentials appeared to be stabilizing beyond 1380 elevation of reservoir, but the reservoir, did not stay at a high elevation for a sufficient period to indicate whether or not the condition was due to a permanent equilibrium.

It was also noticed that a number of piezometers stopped functioning with the rise of the reservoir.

In the late August 1974, it was decided that the reservoir will be repidly depleted, the maximum elevation of the reseavoir reached was 1,463. The reason for this decision was the collapse in the upstream part of tunnel No. 2. The entire depletion of the reservoir was completed on September 16, 1974 and the blanket was exposed. The inspection of the blanket revealed that it had developed a number of sink holes and surface cracks.

Sink-holes varied in diameter at the surface from few inches to 30 feet. These were concentrated mainly in three areas (Fig. 6). The largest of these areas is on the right side of the main blanket and blanket extension between main dam station 15 to 68 and between the main dam and auxiliary diversion channel. The second area is on the left side between the left bank tunnel intake structure and cofferdam 'C'. The third area which is relatively smaller is in the blanket extension between the main diversion channel and the auxillary diversion channel. The sink-holes are of circular shape with almost vertical walls, however, there were several sink-holes which were truncated cone type, with diameter increasing with depth. The investigations carried out by the Consultants revealed that none of the sink-holes penetrated to the full thickness of blanket in the main blanket area, although some of the vertical cracks were found to go down to the foundation materials. In the extended blanket between diversion channel and auxiliary channel, a number of sink-holes and subsidences were deep enough to penetrate through the small thickness of blanket in this area.

There were over 200 sink-holes in area between the main dam and auxiliary channel. The largest sink-hole was 19 feet diameter and the deepest one was 13 feet deep. In the left bank, there were over 50 sink-holes, with maximum diameter of 28 feet and with maximum depth of 5.7 feet. There were less cracks however substantial migration of fines from the blanket into the foundation materials was noticed in this area. In the blanket extension at right bank the number of sink-holes was over 50, and a number of these holes penetrated through the full depth of blanket. The maximum diameter being 18 feet and maximum depth was recorded as 8 feet.

The reason for the formation of sink-holes is not completely known and different hypotheses have been presented by the various experts. The following causes have been discussed.

Differential settlement and shear fracture due to the load of the reservoir.

Unfilled bore holes or open wells.

Erosion under the blanket.

Some other likely reasons like internal erosion of the blanket or migration of fines from the blanket into the foundation have apparently not been discussed.

Differential Settlement.

In view of the thickness of the alluviam in the valley of over 600 feet and uneven rock profile under the alluviam, the possibility of differential settlement is there. It is quite likely that some of the cracks which have appeared in the blanket may be due to this reason. It is also possible that the fines from the bottom part of the blanket were washed into the foundation open-work gravels through these cracks causing cavities, which resulted in local subsidence in the blanket. The sink-holes did not penetrate all the way into the blanket, because the foundation material have got choked with these fines. This situation may have been temporary, and it was likely that with higher reservoir pressure, at least, some of the sink-holes may have fully penetrated in the foundations.

Unfilled Bore Holes or Opon Wells.

Unfilled bore holes and improperly filled open wells or pits in the valley could have in some cases encouraged erosion in a vertical direction, but this explanation could not be applied to all the sink-holes, because these are consipiciously laid along the cracks and fissures. However, some of the large sink-holes on the left bank may by due to a number of open wells which were existing in this area. Another possibility which has occurred to the writer is that there was a large grave-yard on the left bank, which is now overlain by the blanket. It is likely that some of the graves were deep and not completely backfilled and therefore, resulted in local subsidence.

Washing Away of Sand

Fine sand underlies the blanket over limited area in an irregular pattern, except over a width of 500 feet immediately upstream of the upstream toe from where most of the sand was removed before the placement of blanket. It has been considered that such fine sand is easily removed by flowing water. In contrast the blanket, which is well graded and compacted, can bridge over narrow channels which may from in the surface of sand under the blanket. The erosion channels in the sand surface beneath the blanket can readily get started at any location where sand adjoins gravel with open voids into which the sand can pipe, thus causing a cavity under the blanket.

This cavity or loss of support under the blanket may result in the rupture of the blanket under the reservoir load, particularly where the blanket thickness is small. The rupture will cause a tension crack along the bottom of blanket. In addition to sand, the blanket material may also be eroded from the roof of these channels, particularly if tension crack has opened up at the bottom of the blanket. Seepage through the blanket in the plane of the crack will tend to disintegrate the compact structure of the blanket and with chunks of blanket material dropping into the channels. The fines from these chunks of the blanket will be eroded alongwith the sand while the coarsest particles would tend to pave to the bottom of the channel. Progressively, a shallow depression may form along the top of the crack in the form of a sink hole.

It has also been mentioned that due to the pressure of the reservoir, the sand from the voids of river bed boulder-gravel settled down on hourglass fashion, because the voids were not fully choked; with the result that open work boulder-gravel layers were formed immediately under the blanket. Washing of fines into the openwork gravel through the tension cracks in the blanket may have taken place, resulting in local subsidence of the blanket in the form of sink-holes.

Internal Erosion of Blanket

Although the specified limits of the blanket material may be such that the material appears to be well graded and erosion resisting. However, it is entirely possible that at places the blanket may be skip graded even within the overall specified limits, and this facilitated migration of fines from the blanket into the river bed boulder gravels. The cracks in the blanket will accelerate this type of internal erosion. The migration of fines from the skip graded blanket into the openwork river bed boulder-gravel will result in local subsidences in the blanket. This phenomenon will progress until the underlying river alluviam gets choked, or in the worst case, the skip graded portion of the blanket will be completely washed away creating big gaps in the blanket.

The sink-hole may have been caused for any or combination of the above mentioned causes. If the phenomenon of sink-holes formation would have continued, and the blanket was punctured to the full depth at a number of places, the seepage would have short circuited this blanket and it would have resulted in a major set back for the seepage control measures. During the 1974 ponding, whether or not this condition would have developed under a higher and prolonged reservior head, is something which is difficult to state. Although the equipotential contours under the blanket did indicate certain stability for a number of days, but the reservoir was not kept high for sufficient period to ensure that self healing state had reached. For this reason, it may be true that lowering of the reservoir due to the happenings in tunnel No. 2 was a blessing in disguise for the blanket.

A question will be asked in the future by the engineers that whether formation of sink-holes and possible short circuiting of blanket could have been avoided. The answer to this question lies in the realm of engineering judgement. For instance, if a properly graded transition layer was provided between the openwork river bed boulder gravel and the blanket material, the phenomenon may have been avoided. Quality control of the gradation of fill material and their proper placement plays very important role in its satisfactory performance. To fully ensure that blanket material is completely well graded throughout, perhaps it would have been better if the gradation limits of blanket material were more eleborately defined in the Tarbela specifications. The provision "that the material shall be well graded within the specified limits" may not suffice, unless the term "well graded" is defined.

5. Seepage Through the Foundations.

During the impounding season of 1974, the seepage from the foundations readily developed and rose to over 220 cusecs as measured from the discharge of relief wells. In addition to this, there may have been substantial additional quantity of seepage which by passed the relief wells and was not measured, specially in view of the fact that some of the relief wells only penetrated 20-30 per cent of the alluviam depth. The measured seepage was higher than estimated and relief wells which were designed for 1.5 cusec capacity, were being overloaded. However, no sand was noticed to come out of the relief wells and their filters were functioning effectively.

The higher than the anticipated seepage could be due to two reasons:

(*i*) the permeability of the foundation material is in fact higher than what was assumed in the design.

(*ii*) the blanket was in actual functioning not as effective as anticipated.

A rough computation of the seepage indicates that average foundation permeability may be as high as 10^{-1} cm/sec. while in the design assumption the maximum permeability was considered as 4×10^{-2} cm/sec.

As has been already mentioned in the earlier part of this paper, the effectiveness of the blanket is dependent to a great extent on its imperviousness as compared to the foundation alluviam. Provision of a very long blanket which consists of only semi pervious materials would not improve the capability of the blanket. In order to make an effective blanket, the blanket material must be many thousand times less previous as compared to foundation material. The solution lies in providing a well designed, properly constructed and impervious blanket. It appears that the extended blanket at Tarbela has not contributed much towards reduction of seepage or potentials. The measured seepage through the foundation at Tarbela is quite high, but it cannot be considered abnormally large. As long as the seepage potentials under the blanket are controlled within tolerable limits and no piping condition develops, this seepage can be effectively handled. However, it should be interesting to determine by measurements and through downstream piezometers, as to how much seepage is bypassing the relief well system.

6. Remedial Measure

The depletion of the reservoir in 1974 provided a very good and rare opportunity to inspect the blanket. The sink-holes, cracks and local subsidences in the blanket, associated with high seepage indicated that some measures should be adopted to ensure the long time stability of the blanket. This was further: more considered necessary, because the performance of the blanket in 1974 could not be tested for the high sustained reservoir level, and it was not ascertained whether or not the phenomenon of self healing had fully developed. If the sink-holes would have continued to get deeper and larger, the situation would have been critical due to the short circuiting of the blanket.

The situation was reviewed by a number of experts of international repute and several alternatives of remedial measures were considered. The proposals included such extreme measures as installation of a positive grouted cut off and laying of a water tight layer of bituminous concrete over the blanket. The final scheme which has been adopted, consists of increasing the thickness of the blanket by a substantial amount 5 to 10 feet in the areas which are underlain by open work gravel. The additional material has been placed where sink-holes had occurred and also in the areas which were known to be under lain by open work gravels. The additonal material consist of filter material over sink-holes and cracks and uncompacted material graded from silt to cobble sizes. The filter material was intended for choking cracks that might develop and placement without compaction was apparently done to minimise cracking and providing a flexible fill. In all 4.3 million cubic yards of additional blanket material has been placed. It is being considered that open work gravel beneath the blanket has already been chocked to a great extent and the increased thickness of the blanket will act as a deterrent against short circuiting the reservoir through the blanket, to the open work gravels.

In addition to blanket reinforcement, 77 additional relief wells have also been installed in order to limit the discharge per well to remain within 1.5 cusecs.

7. Reservoir Filling in 1975

The repairs of the blanket by filling up the sink-holes and making mounds over them, and the placement of the additional blanket was completed before the impounding season of 1975. In 1975, the reservoir was steadily filled and along with it the monitoring of the perfomance of the blanket is being continuously carried out. Additional piezometers have been installed under the blanket and a special sounding device called the Side Scan Sonar is imported to the site to detect the formation of sink-holes.

The reservoir level of 1,530 has been achieved this year. The results of the piezometer readings have indicated that under the main blanket, the potentials are generally lower than last year, there seems to be no particular change in the potential under the extended blanket as compared to last year.

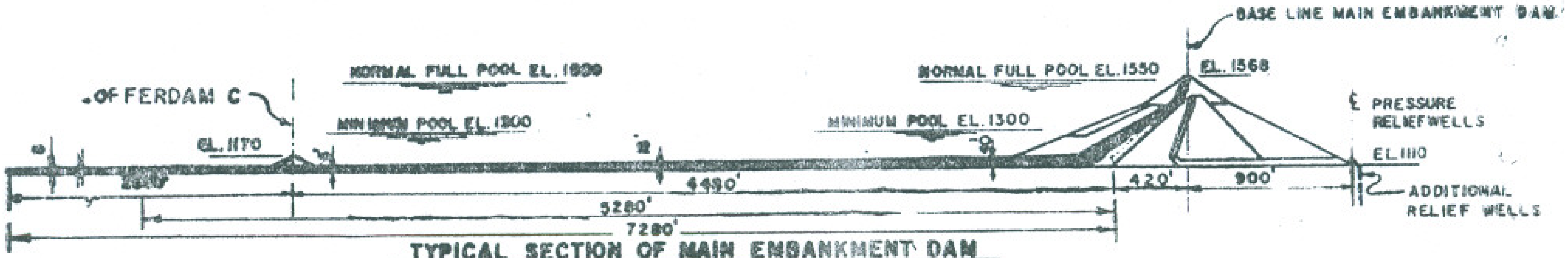
The sink-holes formation is, however, continuing, and the sink-holes are mostly being formulated in the same areas as of 1974. The Side Scan Sonar photographs the sink-holes under water, this instrument indicates the diameter of the holes, but it cannot give the depth of the sink-holes. Over 300 sink-holes have already been detected, and the surveys have indicated that some of the holes are getting enlarged. The surveys have also indicated that maximum development of new sink-holes occurred around reservoir elevation 1,260, while the enlargement of existing holes took place between reservoir elevation 1,360 to 1,480. Some of the subsidence areas have been measured to increase from 4′ x 4′ to 70′ x 10. The potentials have not shown many abrupt changes with different reservoir levels. The potential under the main blanket as compared to 1974 have been reported to be low to the order of 70-75% except on the left bank they seem to flatten out on the downstream side (Fig. 7). It would have been very useful if some instruments could be installed in the potential sink hole areas to measure the approach velocity of water percolating through such holes. This would have shown whether or not holes are getting deeper. However, no such instruments have been installed. The sonar survey has not been conducted so far in the extended blanket, therefore, the sink-hole formation in the blanket extension is not known, however, it is expected that a number of sink-holes must have also developed in this area.

The seepage through the foundation in 1975 is also relatively less (Fig. 8) and for the same reservoir level it is about 80% of 1974 value. It is, however, noticed that there appears to be a sharp rise in the seepage quantity beyond reservoir level of 1465, and maximum seepage intercepted through the relief wells at reservoir elevation 1530 has been reported as 360 cusecs. The reservoir will be maintained at the high elevation for a number of months and the monitoring of the blanket will keep providing the continuous information about its performance.

The sink-holes formulated are being filled up through a special bottom dump barge. A mix from silt to cobble size particles is prepared, moistened and dumped at the location of sink-holes indicated by Side Scan Sonar. It is being hoped that the sink-holes will be treated in this manner. The barge carries a load of about 100 cubic yards of material and 10 loads of the barge are dumped at each location of sink-holes. The process is slow and of some doubtful success, because dumping of material through 400 feet depth of water is succesptible to lose lot of fines on its way down.

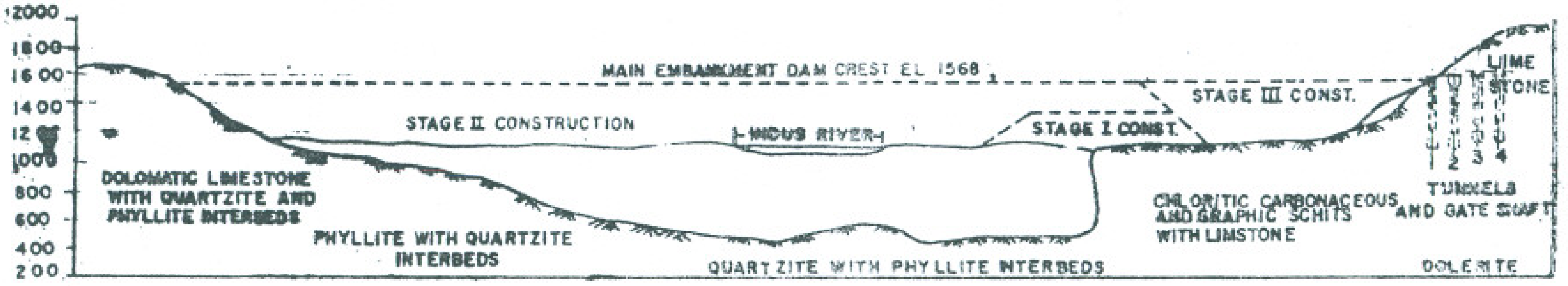
The real check on the behaviour of the blanket is through the piezometer readings and the measurements of quantity of seepage from the foundation. If the potential under the blanket remained constant and there is no abnormal rise in the seepage quantities, it will indicate that phenomenon of sink-hole formation has stabilised, and the blanket will work satisfactorily. The deposition of reservoir sediments should also help in sealing the sink holes. Let us hope that the continuous monitoring of the blanket this year will give such positive indications.

From the happenings at Tarbela, it is strongly indicated that research through Model and laboratory experiments should be conducted to determine the blanket and foundation material interaction under high reservoir heads and to find the most optimum solution to avoid such happenings.



TYPICAL SECTION OF MAIN EMBANKMENT DAM AND IMPERVIOUS BLANKET

500 0 500 1000
SCALE IN FEET



SECTION ALONG BASE LINE OF MAIN EMBANKMENT DAM

500 0 500 1000
SCALE IN FEET

Fig. 1

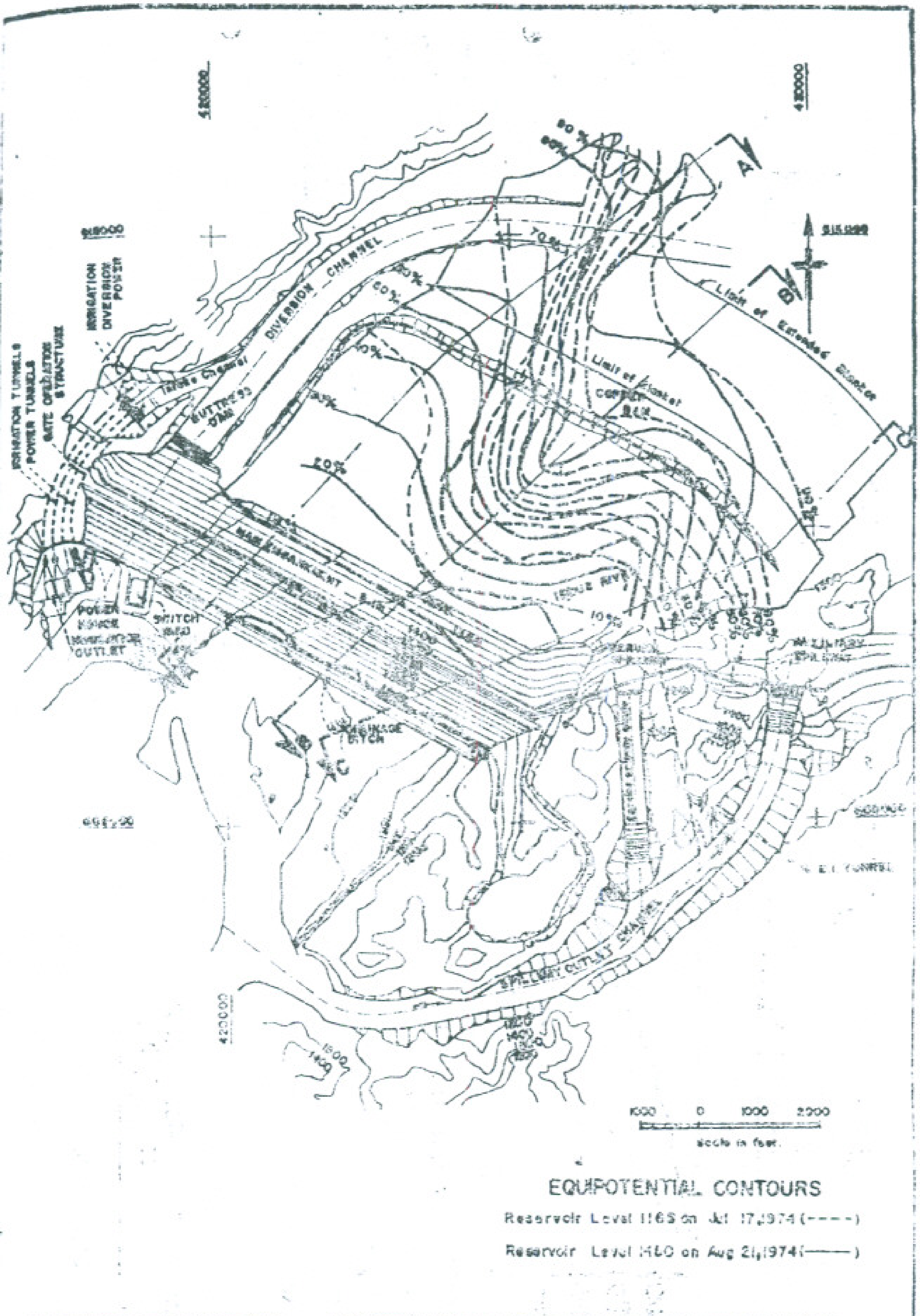

DIVERSION CHANNEL
Limit of Extended Blanket
Limit of Blanket
POWER HOUSE
SWITCH YARD
SPILLWAY OUTLET CHANNEL
1000 0 1000 2000
scale in feet
EQUIPOTENTIAL CONTOURS

Fig. 2

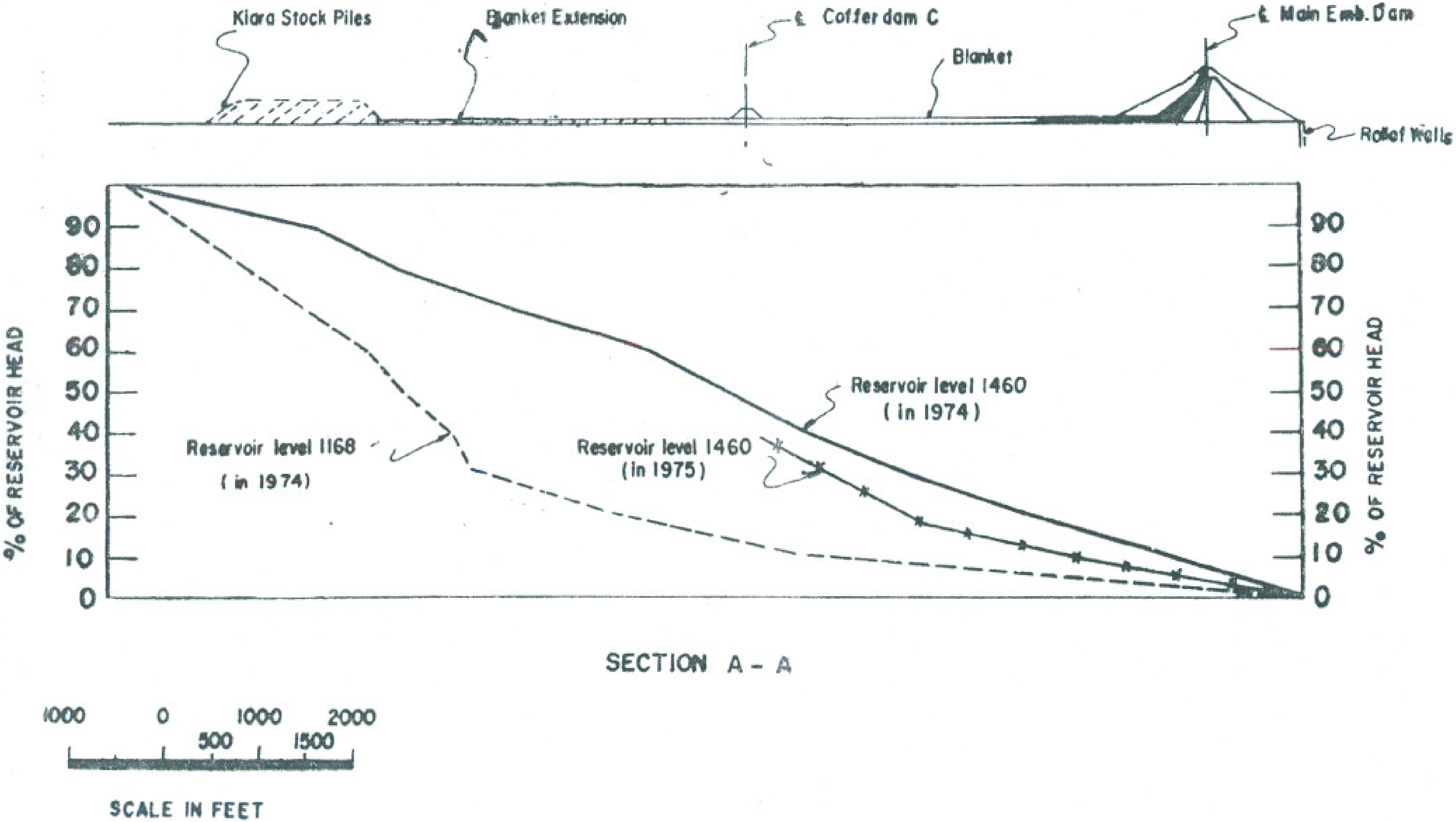
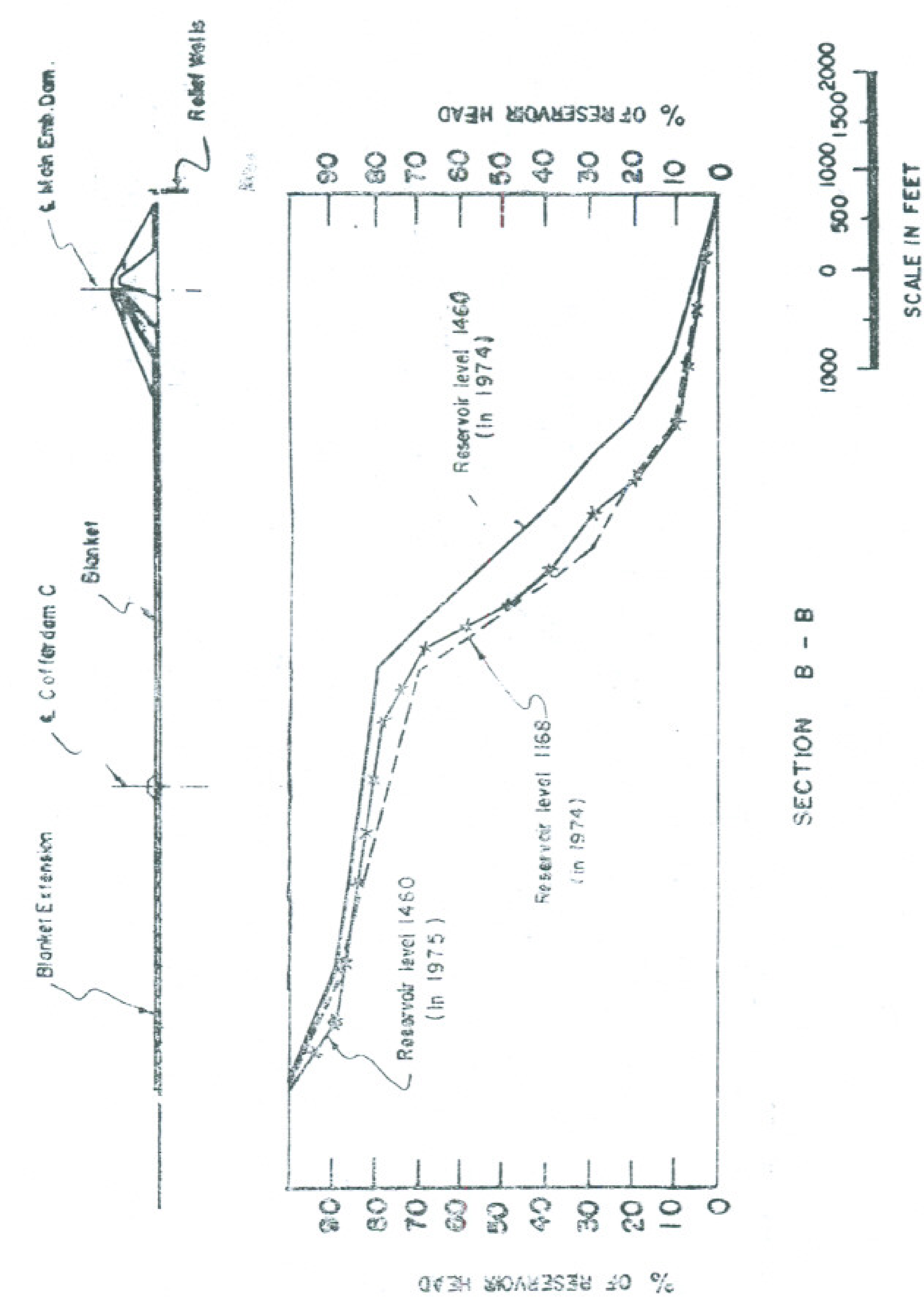
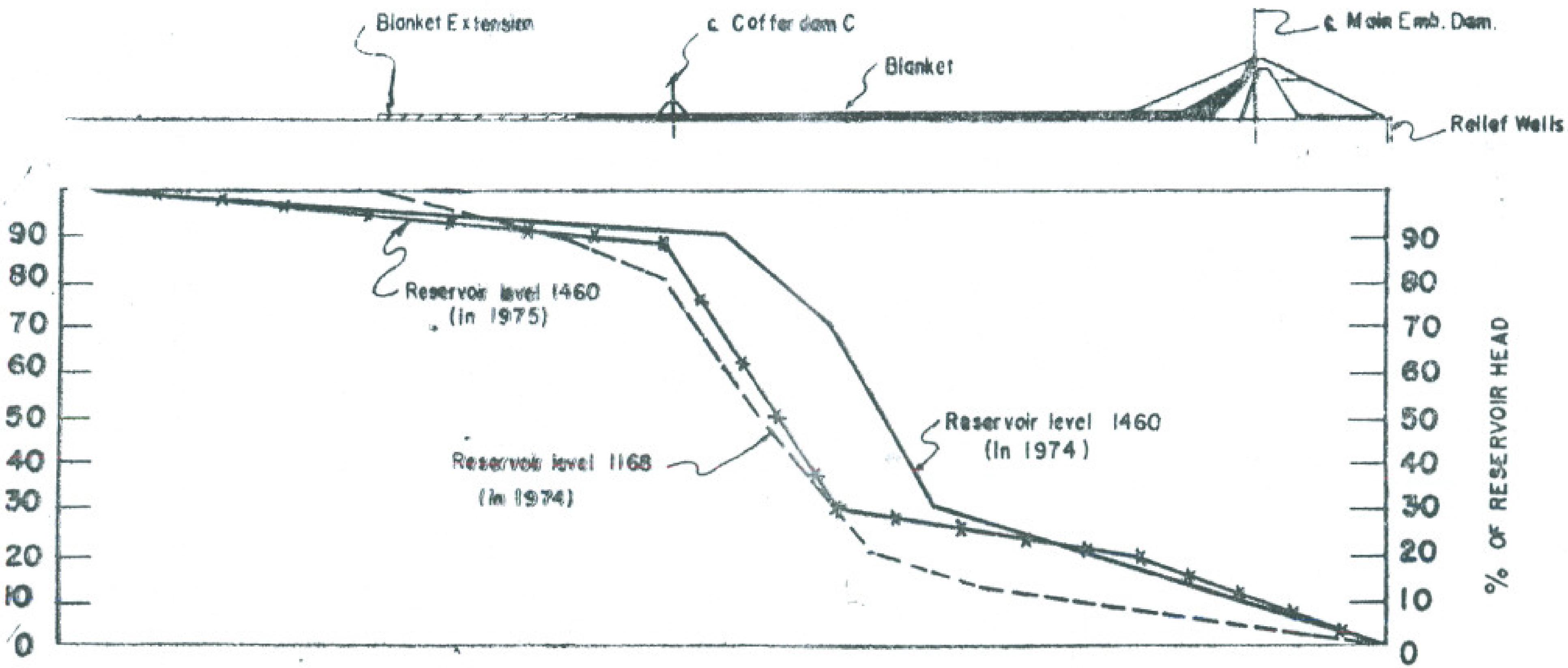

Kiara Stock Piles
Blanket Extension
℄ Coffer dam C
Blanket
℄ Main Emb. Dam
Relief Wells
% OF RESERVOIR HEAD
90
80
70
60
50
40
30
20
10
0
Reservoir level 1168
(in 1974)
Reservoir level 1460
(in 1975)
Reservoir level 1460
(in 1974)
SECTION A - A
1000
0
1000
2000
500
1500
SCALE IN FEET

Fig. 3



Main Emb. Dam
Relief Wells
Cofferdam C
Blanket
Blanket Extension
% OF RESERVOIR HEAD
90
80
70
60
50
40
30
20
10
0
Reservoir level 1460 (In 1974)
Reservoir level 1168 (In 1974)
Reservoir level 1460 (In 1975)
1000
0
500
1000
1500
2000
SCALE IN FEET
SECTION B - B

Fig. 4



SECTION C-C

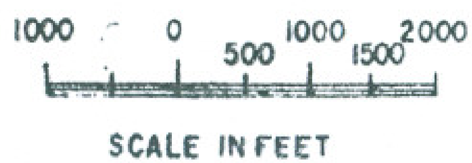


Fig. 5

Amjad M. Agha

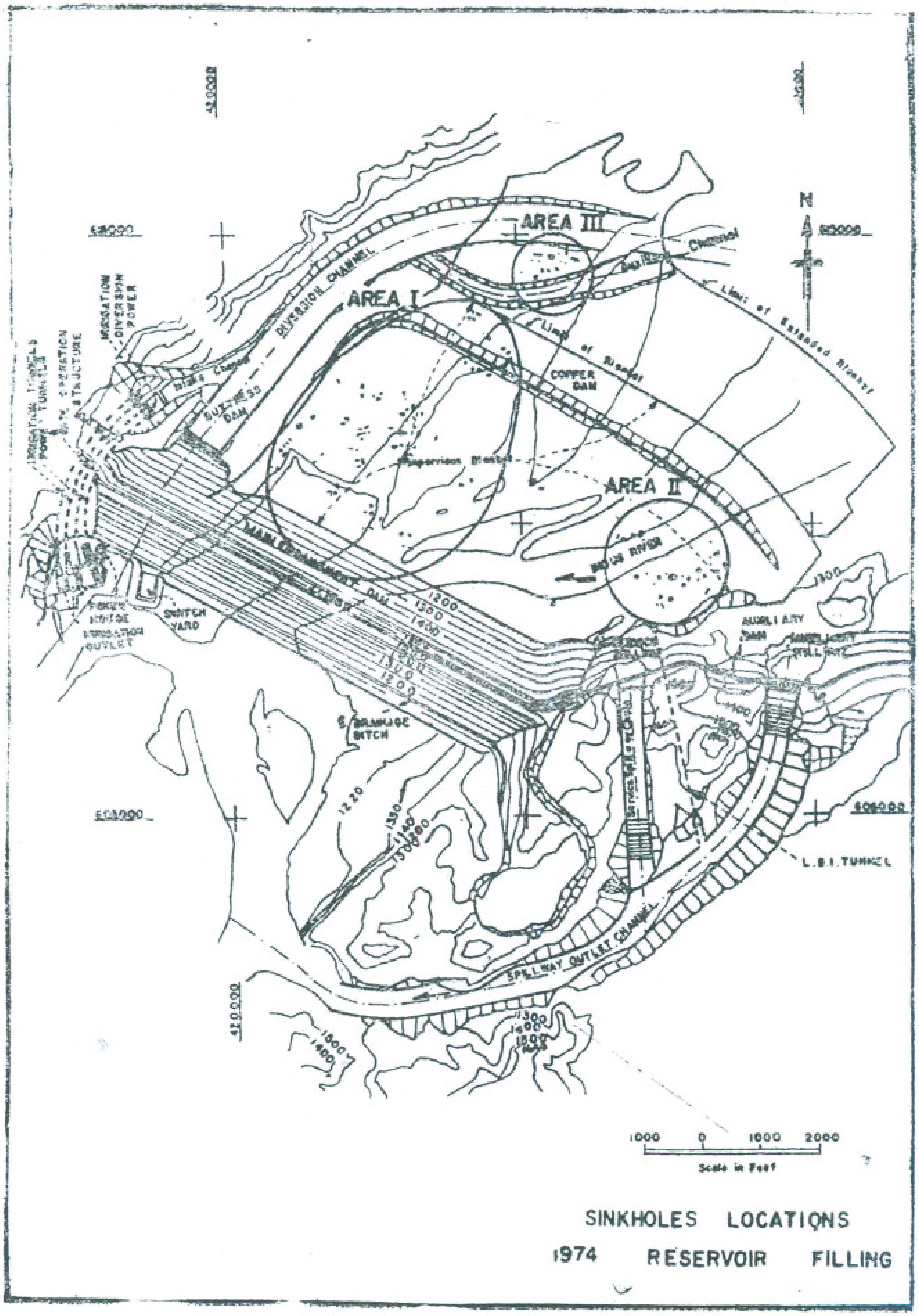

AREA III
AREA I
AREA II
DIVERSION CHANNEL
COFFER DAM
MAIN EMBANKMENT DAM
INDUS RIVER
AUXILIARY DAM
SWITCH YARD
POWER HOUSE
IRRIGATION OUTLET
DRAINAGE DITCH
SPILLWAY OUTLET CHANNEL
L.B.I. TUNNEL
N
1000 0 1000 2000
Scale in Feet
SINKHOLES LOCATIONS
1974 RESERVOIR FILLING

Fig. 6

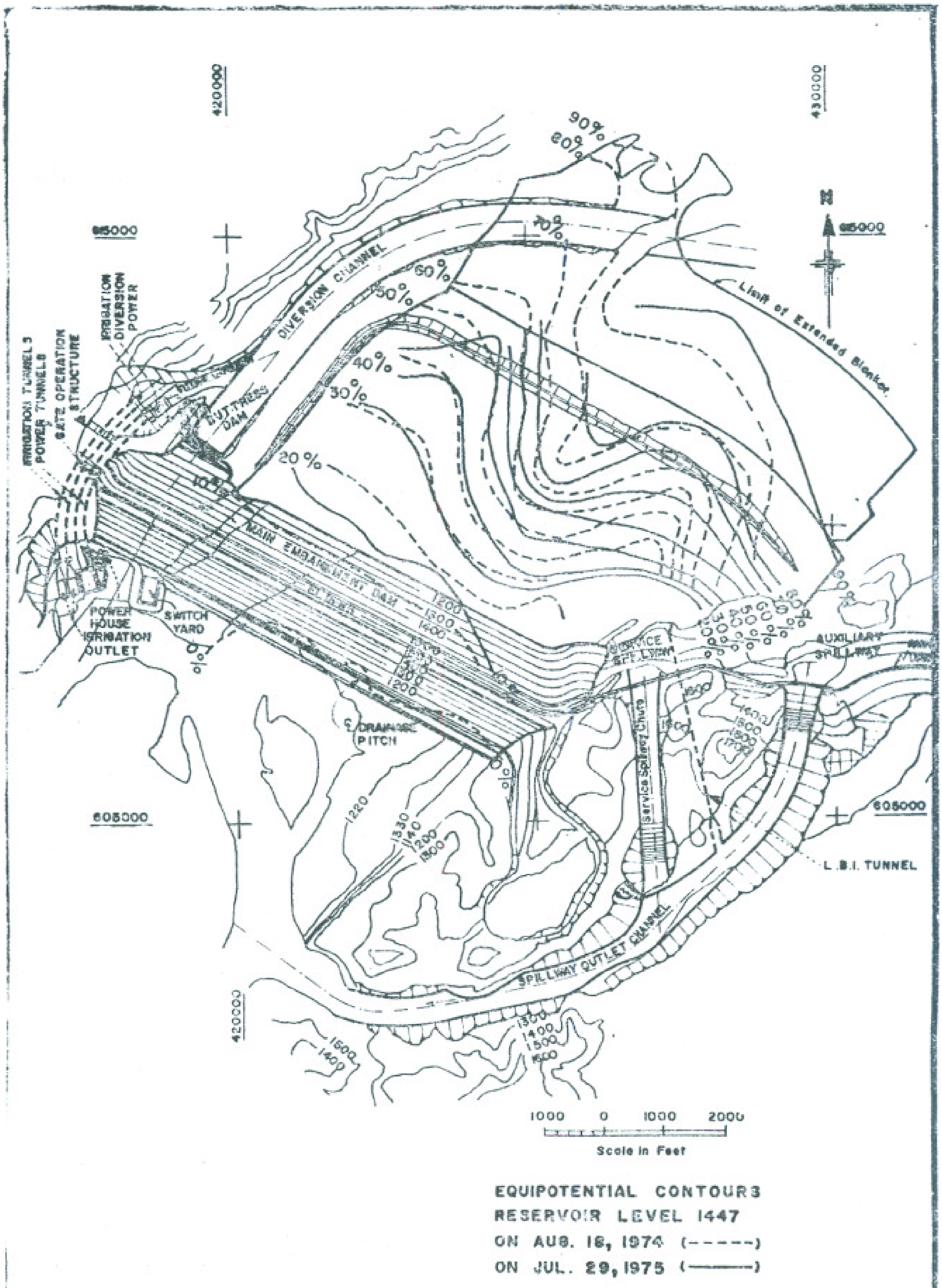
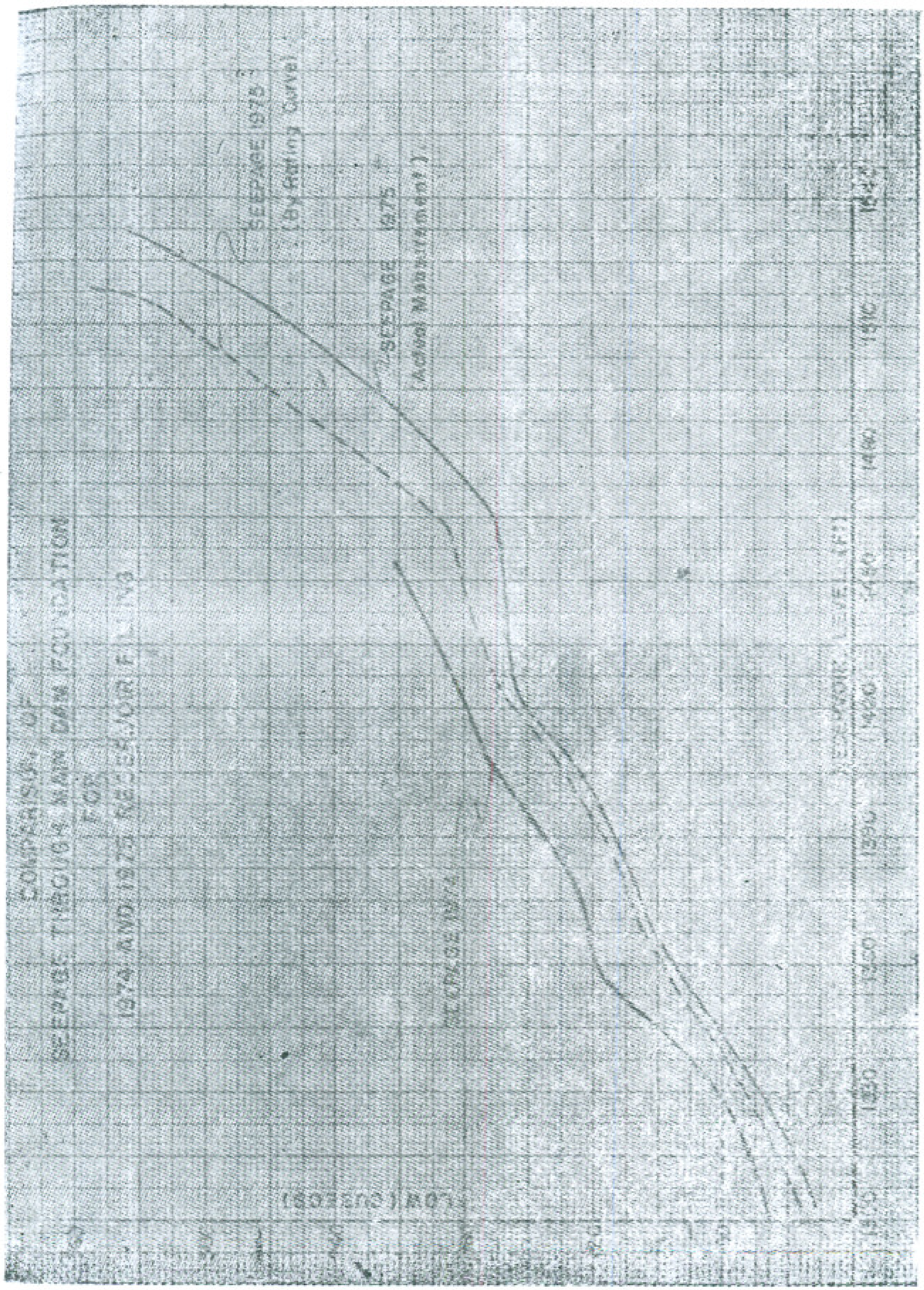

420000
430000
605000
90%
80%
70%
60%
50%
40%
30%
20%
10%
DIVERSION CHANNEL
Limit of Extended Blanket
IRRIGATION DIVERSION POWER
IRRIGATION TUNNELS POWER TUNNELS GATE OPERATION STRUCTURE
BUTTRESS DAM
MAIN EMBANKMENT DAM
POWER HOUSE
IRRIGATION OUTLET
SWITCH YARD
DRAINAGE PITCH
SERVICE SPILLWAY
AUXILIARY SPILLWAY
Service Spillway Chute
L.B.I. TUNNEL
SPILLWAY OUTLET CHANNEL
606000
1000 0 1000 2000
Scale in Feet
EQUIPOTENTIAL CONTOURS
RESERVOIR LEVEL 1447
ON AUG. 16, 1974 (-----)
ON JUL. 29, 1975 (———)

Fig. 7


SEEPAGE 1975
(By Rating Curve)
SEEPAGE 1975
(Actual Measurement)
SEEPAGE 1974