HISTORY OF TARBELA FROM INCEPTION TO SUBSTANTIAL COMPLETION

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INTRODUCTION

History of Terbela (location in fig. 1) from inception to the present stage of substantial completion (September 1975 is replete with the mighty Indus, unleashing its powerful forces to resist man's attempts to control it, and of a young nation using the knowledge of engineering and technology to tame the river for the service of humanity.

Indus has so far inhibited all efforts to harness the sites in its upper reaches where the access problems are acute (now improving somewhat with the Indus Valley Highway), and the elements of nature over-powering and hostile. Even in the lower reaches (through being looked into presently) it frustrated all efforts with the threat of flooding fertile lands and important towns.

Present Tarbela site was selected as the last resort, but here again serious problems have cropped up from time to time. Some significant problems encountered so far and those still outstanding can be grouped as below:—

I. **Planning Stage**

1. Conceptual Evolution.
2. Inclusion Amongst Indus Waters Treaty.
3. Appropriate Siting.
4. Financial Crisis.
5. Technical Feasibility.
6. Tendering.

II. DESIGN AND EXECUTION

7. Project Construction.
8. Design Changes During Construction.
9. Reservoir Operation.
10. Damages During Initial Impounding and Dumping.
11. Additional Works for Satisfactory Performance.
12. Remaining Problems.

Notwithstanding the above list of almost unending problems, this Project has progressed and is now substantially completed. The object of this presentation is to recount the history of various problems encountered since inception of the Project, the efforts put in for coming to grip with the events and the present state of completion and further out-look.

II. CONCEPT OF DAM

Reconnaissance

Soon after Independence India shut off supplies from the Eastern Rivers to irrigation canals in Pakistan. This closure was a rude shock as denial of vital irrigation water was a sure way to turn the fertile plains of the Punjab into a veritable desert. It was clear indication of Indian intentions and Pakistan's survival threatened unless new water was created by constructing storage dams on the Western Rivers. This led to initiation of a series of studies in search of suitable dam sites.

Storages on Chenab were not possible as all the dam sites on this river including the one investigated at Dhiangarh before Independence were in Jammu and Kashmir territory which was under Indian occupation. The next choice was Jhelum. A multi storage scheme for a dam at Mangla and from it the development of off-channel storages on the Kanshi river 16 miles belew Gujjar Khan and on the Kahan river at Rohtas was investigated and planned. It was obvious that these storages would exhaust all surplus flows of Jhelum and Indus soon would need to be dammed as this was the only hope for the future of irrigated agriculture.

First obvious choice on Indus was Attock where physical conditions favoured construction of a high concrete dam to create about 20 MAF reservoir in the broad Indus Valley between Tarbela and Attock. This hope was soon dashed upon realising that such a reservoir would inundate most of the fertile lands in the Peshawar Valley including the city of Peshawar. The next attractive site was the narrow gorge above Kalabagh where a medium/high concrete dam would create 5-8 MAF of reservoir without extensive submengence of the Peshawar Valley. But very soon this turned into disappointment when a world known expert on dams (Dr. Savage) declared the site unsuitable for a concrete dam. Another attempt was then made (1949) for a scheme of 900 foot high concrete dam acrose the Indus gorge at Darband to create about 9 MAF storage. Indian plans to increase the height of Bhakra dam to 750 feet (the highest concrete dam in the world), inspired optimism for this scheme, but no significant headway could be made.

In September 1952, a partv of 5 engineers including Mr. R. J. Tipton (Consulting Engineer), proceeded on a reconnaissance tour of the Indus Valley with the ambition of finding a suitable site to regulate the Indus. The first target was Darband site, but reconnaissance revealed the river diversion during construction would impose a formidable problem. The geology of the abutment was complex and the river bed was covered with large gravel and boulders. Under the circumstances, a 900 foot high concrete dam would be prohibitive in cost and probably not feasible.

At Tarbela village (a little lower than Darband) Siran/Dor rivers joined the Indus and the valley was quite wide. If a dam were built in the reach below Tarbela (near Dal village with about 2 miles width to store water up to 300 feet in depth, the reservoir would extend into the Siran valley almost to Haripur and into the main Indus to about 20 miles north of Darband.

Perliminary reconnaissance indicated that the site was suitable for construction of an earth and rock-fill dam to impound water to a depth of approximately 300 feet. Although Tarbela village was a mile upstream of the proposed site, it was named as Tarbela dam.

Dams Investigation Circle.

In 1953, Government of Pakistan established the Dams Investigation Circle (DIC) to carry out detailed investigation of Mangla, Tarbela and other dam sites. Tipton & Hill (T & H) were appointed as Consulting Engineers and a Consulting Board was formed with Raymond A. Hill, Roger Rhoades and Thomas M. Leps as members to advise DIC. The Board visited Tarbela site in March 1953 and outlined a programme of investigations. The data from field investigations was later reviewed and location of the principal works comprising Tarbela project were determined.

Tipton and Hill Proposal

In Ootober, 1954, T & H submitted a report concluding that Tarbele Project was feasible of construction as well as economically viable. It was estimated to cost between Rs. 85-90 crores for a 4.2 MAF reservoir (live capacity 3.3 MAF) and 600 MW power plant with an annual output of 4,000 million Mwh. The total direct benefits from the Tarbela project were estimated to average Rs. 17. 5 crores annually during the first 50 years of operation and indirect benefit would be atleast as great.

Revised Storage Capacity

Considering 300 feet as the limit to which water should be raised in view of the pervious foundations of the dam, T & H fixed crest level of the dam at elevation 1440 with maximum conservation level of 1390 which was also the crest level of the spillway. Gross reservoir capacity at elevation 1390 was 4.2 MAF which gave an effective storage of 3.3 MAF. In 1955, Project was revised by increasing the maximum reservoir level to elevation 1420 in order to increase the gross capacity to 5.1 MAF and the efective storage to 4.2 MAF. This was accomplished without raising the height of the dam by installing gates on the spillway at a small incremental cost. T & H endorsed the proposal and revised Tarbela reservoir capacity was adopted for negotiations on the water dispute.

III. INCLUSION AMONGST INDUS WATERS TREATY

Breakdown of Negotiations

During the seven years of protracted negotiations with India and the World Bank, Pakistan suggested several alternative plans to find a solution of the water dispute and every one of them included Tarbela as an essential component. In 1957 Pakistan submitted the "Aide-Memoire Plan" which included a 5.1 MAF reservoir at Tarbela and 2 MAF reservoir at Rohtas on the Kahan river. Mangla was not included in the plan as Pakistan reserved it for her own development. A note-worthy feature of the plan was the inclusion of the Upper Indus Link connecting Tarbela to Kanshi river as the first step in the development of side-valley storages in the Potwar Plateau for an integrated development and use of the waters of the Western Rivers. India refused to accept the plan. At the subsequent meetings held in Rome in May 1958 and later in London in July 1958, Pakistan submitted other 'less costly, alternative plans by eliminating the 'costly' Upper Indus Link but retaining Tarbela. Again India refused to accept any of them on grounds of high costs. The engotiations broke down when Pakistan was told that India had neither the willingness nor the ability to foot the bill for such costly works.

The Settlement Plan

As the tripartite negotiations failed to produce an agreed plan, the World Bank initiated bilateral negotiations separately with India and Pakistan to evolve a "Settlement Plan". In May 1959, Mr. Eugene Black, President and Sir William Illiff Vice-President of the world Bank visited Pakistan to discuss a plan of works for settlement of the dispute. This plan included two reservoirs at Mangla and Rohtas with live storage capacities of 4.75 MAF and 2.10 MAF respectively but omitted Tarbela Dam. Pakistan made it clear that no plan would have her un-reserved approval unless it included Tarbela. Pakistan also demanded compensation for the recurring costs and other consequential works required in respect of channel deterioration and loss of sailab. The Bank ultimately agreed to substitute Tarbela Dam in place of Rohtas on condition that Pakistan would waive her claims in respect of the recurring costs. Pakistan accepted the Modified Settlement Plan after the Bank agreed to make adequate arrangements for its financing. Indus Waters Treaty was finally signed in September 1960, and the Indus Basin Development Fund (IBDF) was created with contributions from the friendly countries to under-write the cost of the plan which was then estimated at Rs. 400 crores. The Settlement Plan became to be more familiarly known as the Indus Basin Project (IBP).

IV. APPROPRIATE SITING

Alternative Tarbela Sites

In January 1960, Water and Power Development Authority (WAPDA) the agency designated for implementation of IBP, appointed TAMS as Consulting Engineers for the Tarbela Dam. Three sites in the vicinity of Tarbela were selected for detailed investigations. Of these, the Bara site originally investigated by T & H proved most favourable with a potential storage of 11 MAF. The second site at Kiara, 2 miles upstream of Bara, had a potential storage of 10, MAF without any other significant advantages. The third site at Kirpalian, 15 miles upstream of Kiara, was relatively less expensive because of its narrow gorge but its storage potential was only 4.3 MAF. These studies led to the selection of the Bara site.

Excessive Sediment Load

Tarbela Project included in IBDF was based on T & H's Report of October 1954 with the reservoir capacity revised to 5.1 MAF. As actual sediment observations were not available, T & H estimated the annual sediment load of the Indus river as 165 million tons on the analogy of the Mangla data. On this basis the effective storage of 4.2 MAF would be depleted to about 1.0 MAF after a period of about 77 years. The residual storage of 1.0 MAF was expected to remain unaffected almost indefinitely as the trap efficiency of the reservoir would be considerably reduced and almost all the sediment brought by the river would escape through the spillways and outlet works. In terms of water benefits, this reservoir would have provided a total volume of 200 MAF-years of storage water which was equivalent to 4.0 MAF on the average for about 50 years.

Actual Observations.

Actual observations carried out during 1960 and 1961 and the resulting rating curves developed to estimate the life of the reservoir indicated that Indus carried an annual sediment load of 390 million tons against the original figure of 165. Sediment analysis also showed that its density was 85 lbs per cubic foot against the assumed figure of 95 lbs. Both these adverse factors indicated that 4.2 MAF Tarbela reservoir would be depleted to 1.0 MAF in a period of 35 years against the original estimate of 77 years. No other river in the world had such devastating power to choke its reservoirs. This shocking revelation shattered the hopes but strengthened the conviction that indirect storages in the side-valleys would be the key to economic development of the Indus for which Tarbela was a must.

Tams Project Planning Report (1962)

In January 1962, TAMS submitted the Project Planning Report indicating the following alternative sizes of reservoir which were feasible of construction:—

TABLE—I

ALTERNATIVE SITES OF TARBELA RESERVOIR

Reservoir level (SPD)	Maximum Dam Height (Feet)	Capacity (MAF) Gross	Live	Life (years)
1445	380	6·0	4·2	35-40
1490	425	7·8	6·0	45-50
1500	435	8·4	6·6	50-52
1530	465	9·8	8·0	55-60
1550	485	11·1	9·3	65-70

WAPDA suggested that the size of Tarbela reservoir to be constructed under IBDF should be 8·4 MAF to provide the same benefits in terms of volume of water viz., 200 MAF-years, as envisaged by the original project. However, as natural storage sites on the Indus were extremely limited, Tarbela should be constructed to maximum height and the cost of increasing the reservoir capacity from 8·4 to 11·1 MAF should be at the expense of Pakistan.

Board of Special Consultants.

WAPDA appointed a Board of Special Consultants comprising Dr. A. Casagrande, E. B. Burwell, Hibbert Hill Byram, W. Steele and Dr. Francis B. Slichter, eminent world experts on large dams, to review the Project. The Board after inspecting the site and examining all data and designs in 1961 and in 1965 confirmed that Tarbela Project was technically feasible and economically sound.

V FINANCIAL CRISIS

Revised IBP Cost (March 1962)

But all was not well for Tarbela Dam. Revised cost estimates of IBP prepared by WAPDA in March 1962 indicated that the total cost of the programme would be nearly Rs. 900 crore against the availability of Rs. 400 crore in the Fund. A serious financial crisis followed. The Bank explored ways and means to bridge the gap but found the prospects dismal. In April 1962, the Bank conveyed to Pakistan the views of contributing Governments that Tarbela reservoir, Taunsa Panjnad Link and the Tubewells and Drainage Programme should be dropped from IBP. Further commitments on the remaining projects in the programme were withheld pending resolution of the crisis. Pakistan strongly opposed any changes in the system of works as they would knock down the very basis of settlement. Questions were raised whether IBDF was committed to build Tarbela Dam regardless of economic consideration and alternative storage sites on the Indus; in particular the Kalabagh Dam, was suggested for investigation. Project description in IBDF which referred to "a dam on the Jhelum river" and "a dam on the Indus river" instead of the Mangla Dam and the Tarbela Dam was quoted in support of this contention. Pakistan contended that the dams on the "Jhelum river" mentioned in the Agreement were Mangla and Tarbela. All the plans, list of works and cost estimates prepared independently as well as jointly by Pakistan and the Bank specifically mentioned Mangla and Tarbela. Pakistan also referred to the circumstances which led to the project description in the treaty. In the course of drafting the Treaty and IBDF, India objected to any reference to Mangla Dam by name as the site was located in the disputed territory of Jammu and Kashmir. The Bank did not like to get involved in any disputes over territorial rights and proposed that the Mangla Dam be described as 'a dam on the Jhelum river'. Both India and Pakistan accepted the suggestion. There was no controversy on the name of Tarbela as the site was wholly in Pakistan, but in order to have a uniform project description it was also referred to as 'a dam on Indus river'. Pakistan, therefore, informed the Bank that Terbela was vital and integral part of the Settlement Plan, and technical infeasibility apart, IBDF was committed to it and that the inclusion of Tarbela in the plan was the basis for her acceptance of the Treaty.

Supplemental Fund Agreement (1964)

The crisis consinued for nearly two years during which the Bank made persistent efforts to find a solution. Questions were raised whether Tarbela was economically viable and whether it would not be wise to invest a much smaller sum on other water development projects, principally tubewells, to achieve the same results. Finally on November 14, 1963 an understanding was reached between Pakistan and the Bank according to which the Bank would undertake a Study to determine, inter-alia the place of Tarbela in the development of the water and power resources of the region. This understanding led to the solution of the impasse and a Supplemental Fund Agreement was signed to increase the total resources of the Fund to $1208 million after Pakistan accepted responsibility to meet the rupee costs from its own resources. It was also agreed that the augmented resources of the Fund would be applied first to meet the cost of the Indus Basin Project excluding Tarbela and the balance used on Tarbela provided it was found technically sound and economically justified on the basis of the Special Study to be arried out by the Bank.

VI. TECHNICAL FEASIBILITY

Bank's Special Study

Under terms of the Supplemental Fund Agrement, a Bank Group initiated intensive study of the water and Power resources of West Pakistan and in particular of Tarbela and its alternative on the Indus. Work commenced in April 1964, and extensive reviews were carried out of designs and cost estimates of Tarbela and other potential storage sites on Indus, agricultural benefits resulting from the use of storage water and detailed studies of power forecasts and alternative means of meeting the demands for energy and power in the area. In February 1965, the Bank Group completed its first report on Tarbela and arrived at the following conclusions :—

(*a*) Tarbela Project is technically feasible.

(*b*) Financial requirements for the construction of the Project of a gross storage of 11.1 MAF including power installations of 1400 MW will amount to $900 million.

(*c*) Project is economically viable and the economic return from agriculture and power benefits will be about 12 per cent per annum.

As regards alternative dam sites, the Study concluded that it would be difficult to develop potential storage sites on the upper Indus. It confirmed that Tarbela with a potential gross storage of 11.1 MAF and a power potential of 2100 MW was the most promising site on the main Indus. The life of the reservoir would be relatively short (about 53 years) because of siltation but the development of side-valley storages to offset the loss of storage capacity was technically feasible and very attractive. These schemes involved the construction of reservoirs at Ghariala on the Haro river and Dhok Pathan on the Soan river which would provide gross storage of 8.2 MAF and 12.0 MAF respectively. Power installations at these sites were technically feasible, and Dhok Pathan site alone had a power potential of 1600 MW.

As regards benefits, estimates were made of the probale costs and benefits associated with the agricultural development that would result from the increased water availability from Tarbela. A notional area of six million acres within the canal commands was selected for the study where 4 MAF of Tarbela storage could be utilised. The Study showed that with Tarbela the irrigation intensity in the area could be increased from the existing 75 % to above 150%. When these results were projected for the total storage water from Tarbela the agricultural benefits alone justified the project.

The power aspects of Tarbela were equally attractive. Its generation capacity of 2100 MW would be sufficient to meet system requirements through 1985 with only minor additions to the system. Considering that a sub-stantial part of the total system energy requirements by 1975 would relate to pumping load from tubewells, Tarbela would make an important contribution to the development of ground water resources for reclamation and irrigation.

Final Report of the Bank was completed in 1967 which further confirmed the strategic place of Tarbela in the integrated programme for development of the water and power resources of the region. The Report concluded that unless construction of Tarbela Dam was taken up immediately there would be serious shortage of water and power in the Fourth Five year Plan and beyond.

VII. TENDERING

Having received a clean bill of health' the stage was set for implementation of the Tarbela Dam. Once again the Bank played a leading role in obtaining financial support for the project. Pakistan's outstanding success on the Indus programme provided the incentive and the carry over of some $324 million from IBDF for application to Tarbela made the task less difficult. During November 1966, the Bank presented to Pakistan Consortium the estimated financial requirements for Tarbela, the anticipated surplus available from IBDF and asked the member countries to offer loans to meet the gap. On the basis of the under-standing received from the Pakistan

Consortium tender documents for Tarbela were issued to four pre-qualified consortia of contractors on March 23, 1967. The date for receipt of tenders was, however, kept open pending final-ization of financing arrangements.

Pakistan Consortium met at Washington in July 1967 and made tentative commitments to meet the gap, following which Tarbela tenders were opened at Lahore on November, 30, 1967. The tender prices were as follow :

TABLE—2

COMPARATIVE TENDERS FOR TARBELA

(Million Rs)

Tenderer	*Sponsor*	*Total Price*	*Foreign Exchange Component*
GSJV	Hochtief	2,598	1,556
TJV	Impregilo	2,969	1,718
IRC	Morrison Knudson	3,663	2,366
Atkinson	Atkinson	3,844	2,107

Though it was the largest single contract in the history of civil engineering construction, considering Engineers Estimate of Rs. 3750 million (foreign exchange Rs. 1678 million), the competition was unbelievable.

Everything looked bright for Tarbela but again an unexpected crisis resulting from a qualification in the lowest tender delayed the award of the contract. The lowest bidder demanded increase in the tender price on the ground that his estimate was based on a schedule in the Tender Documents which was 'misleading'. A series of conferences followed and in view of the international import of the issue, three independent legal opinions were sought which established beyond doubt that the contention of the lowest bidder was untenable. The lowest bidder was asked to withdraw the qualification and on receiving a negative reply, the 'Letter of Intent' to award the Contract was issued on April 2, 1968 to the Italian-French Consortium (TJV) sponsored by Impregilo, the next low bidder.

Pakistan Consortium met again in Paris on March 5, 1968, and the Bank finally established the Tarbela Development

Fund (TDF) with the following foreign exchange contributions after Pakistan agreed to meet all the rupee costs:—

TABLE 3

COMMITED FOREIGN EXCHANGE RESOURCES OF TARBELA DEVELOPMENT FUND

Contributor	*Amount $ Million*	*Type*
IBDF (Estimated unspent balance).	324	Untied
Canada	5	Tied
U. K.	24	Tied
France	30	Untied
Italy	40	Untied
U. S. A.	50	Tied
World Bank	25	Untied
Total	498	

TDF was formally consummated on May 2, 1968, and Tarbela contract awarded to TJV on May 14, 1968.

VIII. TARBELA PROJECT

Principal Statistics.

Tarbela Dam Project as finally evolved and contracted in 1968 comprised the following salient features:—

1. Over 2½ miles of earth and rock fill embankments (main * 2 Auxiliary Dams) varying in height from 220'-470' and a fill volume of about 180 million cubic yards, thus making it the largest in the world.
2. Two Ogee type concrete and gated spillways (Service and Auxiliary) with design capacity of about 1·5 million cusecs to adequately handle the maximum record/probable floods and having a concrete volume of about 1 million cubic yards.
3. About 2 miles long four diversion tunnels on tha right side with inlet diameter of about 45' to provide deversion capacity during construction and irrigation/power outlets during the operational stage.

4. Initial power installed capacity of 700 MW (4 units of 175 MW each) with built in facilities for ultimate development to 2100 MW.

5. Reservoir resulting from the project construction having gross storage capacity of 11·1 MAF (live capacity 9·3 MAF) at maximum conservation level of 1550, extending to about 50 miles above the dam site, sub-merging an area of about 80,000 acres and uprooting about 16,000 families.

Layout plan of various components is attached as fig. 2 while basic data of the Project are listed in Appendix I.

Main Embankment and Auxiliary Dams

A special mention is warranted of the principal element namely enbankment dam which contains the largest fill volume in the world. In addition to the main embankment dam the Project has two small embankments to close a side valley and a saddle in the reservoir rim.

Main embankment dam (fig. 3) has a sloping core which is supported on the upstream and downstream sides by well graded granular shells. Continuous with the core, an impervious blanket, extends for about $1\frac{1}{2}$ miles in the upstream direction. It has been provided for under-seepage control because the foundation of the dam is composed of deep (upto 700 ft.) cobble gravel and fine sand alluvial deposits; where construction of a positive cut-off was found to be impracticable.

The sloping core makes a more natural connection with the impervious blanket than a central core and requires somewhat less core material. At Tarbela, large quantities of good quality, angular cobble gravel and sandy silt were available for blending together to form a well-graded core material capable of developing the high strength required for a sloping core.

Upstream shell zones are constructed of good quality granular material; the free draining zone is for stabilization of the upstream slope upon drawdown. Immediately downstream of the core, is a transition zone which is high enough in fines content to serve as a secondary core.

Downstream shell adjacent to the transition zone is composed of well graded, well compacted granular materials of low compressibility to give firm support to the core.

Upstream slope is protected against wave action by a rip-rap zone and the downstream slop against rain water erosion by free draining slop protection.

The larger of the two auxiliary dams, Auxiliary Dam I, is similar in design to the main embankment dam; the most important difference is that this dam has only a short upstream impervious blanket terminating in a cut-off trench to bedrock. Auxiliary dam 2 (fig. 3) is situated on a rock foundation, and it is essentially a centre-core dam with free draining upstream and downstream shells.

The major dimensions and quantities of the originally designed embankment dams are shown below:—

TABLE 4

Embankment quantities and dimensions at Tarbela

Item	Main Embankment Dam	Auxiliary Dam No. I	Auxiliary Dam No. 2	Main Embankment Impervious Upstream Blanket
Length At Crest (Ft.)	9000	2340	960	5,700
Maximum Height (Ft.)	470	345	220	5′-50′
Volume Million Cub. Yd.	138·0	18·0	4·0	21.0

IX. PROJECT CONSTRUCTION

Initial Mobilisation

After award of the contract in May 1968, TJV quickly got engaged with the initial mobilisation and logistics. As a result, the work at site commenced before end of 1968 and the Project got off to a promising start.

Diversion Sequence Planning

In order to proceed with orderly execution of the Project, river diversions presented serious problems. After considering number of alternatives a sequential diversion plan was evolved. The plan envisaged completion of the job in stages (depicted in

Fig: 2) spread over the construction period of about 7 years. Various stages of this diversion sequence were planned in the following manner:

Stage I (1968-September 1970):—River flow in natural channels with start of work on i) tunnels, ii) diversion channel excavation including buttress dam for Stage II diversion and iii) initial section of the dam within coffer dam area.

Stage II (October-1970-September 1973):—River confined to the excavated right bank diversion channel-cum-buttress dam and continued construction of main dams; start of work on the auxiliary dams, spillways, power house and completion of right bank tunnels to get into Stage III.

Stage III (October 1973)—Closure of the buttress dam across the diversion channel to force the river through low level intakes of Tunnels 1 & 2; completion of final section of the main embankment across the diversion channel just downstream of the closed buttress dam together with the spillways, power station etc.

Actual Execution:

Stage I—For more than two years after the Contractor's prompt start in 1968, Indus was left to flow in its natural channels. In this duration the Contractor excavated a diversion channel on the right bank bench, began the excavation of the four tunnels through the right abutment and placed a small section of the embankment situated between the diversion channel and the natural river channel. All of this was carried out behind an earth cofferdam extending 13000 feet along the river velley.

Stage II—As scheduled, in October 1970 the work entered Stagt. II. The river was diverted into the excavated diversion channel-cum-concrete buttress dam and the three natural river channels were closed off, thus allowing construction to proceed on the entire length of the main embankment, save the small section which (in Stage III) would plug the final gap across the diversion channel just downstream of the closed buttress dam.

Three mile long diversion channel had a bottom width of 650 feet throughout most of its length, and was designed to carry 750,000 cusecs, adequate to cope with the greatest historic flood over the period of record.

The most notable feature of Stage II diversion was perhaps the Buttress Dam across the channel near the future upstream toe of the main embankment. This Dam was to ensure dependable rapid and on schedule closure of the diversion channel and facilitate Stage III diversion into the four right bank tunnels.

With river confined to the excavated diversion channel on the right bank, construction of the main embankment continued using material from the right and left bank borrow areas and from the Spilway channel. Construction of Powerhouse and Auxiliary and Service Spillways was in hand and the Auxiliary Dams constructed. Construction of the tunnels including intake and outlet works completed and Stage II concluded on schedule by the end of September 1973.

Stage III:—Closure of buttress dam across diversion channel on October 1, 1973 forced the river flow through the low level intakes of the power Tunnels 1 and 2 and completed irrigation Tunnels 3 and 4. This allowed the completion of final section of the main embankment across the diversion channel just downstream of the closed Buttress Dam together with the two Spillways. With the main embankment substantially finished about the end of June 1974, diversion intakes gates of Tunnel 1 and 2 were closed. This was about 1 year ahead of schedule substantial completion of the dam (but subsequent events as explained elsewhere upset this).

Material Processing and Handling.

Construction of the three embankment dams at Tarbela required excavation, transportation and placement of 300 million tons of earth and rock. Approximately one-half of this total amount was supplied by the Project excavations, and the other half was to be obtained from borrow.

The major excavations on the right bank (yielding about 63 million tons of earth and rockfill) were diversion channel, tunnels including intakes and outlet channel. Excavated materials from these sources were transported by trucks to earth and rock processing plants from which they were directed either to the dams or to stockpiles.

In Stage I construction, the quantity of material from required excavations exceeded the needs of contemporaneous embankment construction, and the excess was stockpiled upstream of the Stage I embankment for use in later stages. Except for riprap, fill materials were transported from the plants to the fill by one of the most elaborate conveyor belt system (explained later).

On the left bank, excavations for the two spillways and the spillway channel yielded 89 million tons of material which was hauled to processing plants or directly to the embankments by trucks or bottom dumps.

After processing, rock materials were transported by trucks to the embankments; earth material passing 8" grizzly was transported to the main embankment by conveyor; +8" material was handled by trucks,

Major borrow area of the Project was located about 3 miles to the west, on a plateau beyond the ridge which is the right abutment of the main embankment. Many millions of tons of well graded sandy boulder gravel, containing some layers of silt, were present at this source. Southern portion of the plateau contained large deposits of silt which was primarily used for blending with the boulder gravel to obtain core material.

Boulder gravel was removed in 50 feet lifts with 15 cubic yard electrio shovels, and was transported from the excavation faces to three receiving plants by 110 ton bottom dumps where the oversize material was crushed to 12'' to permit transportation by conveyor belts.

Silt was excavted and transported by scrapers to a receiving plant where it was also fed onto a conveyor.

These two conveyors carried the material from the receiving stations to a major processing plant located in the south-east edge of the plateau.

This computer-guided plant was capable of separating the excavated material into components O -$\frac{1}{2}$",$\frac{1}{2}$-4" and +4", sending it to stock and surge piles and recombining it later in desired proportions. It could also send material without processing directly to the dams.

One of the operations of the plant was to blend boulder gravel with silt, regulate the moisture content of the blend and send it to the embankments for the construction of the cores and blanket zones.

Transportation to the main embankment dam was by two three-mile-long conveyors, one with a capacity of 1200 tons/hour and the other 2400 tons/hour. The smaller conveyor was for blended core and blanket material which had a maximum particle size of 4" , and the large was for coarser material for other zones of the dam.

En-route, this major conveyor link passed through a 5800 feet long tunnel.

1200 tons/hour converors traversed the upstream face of the main Embankment Dam. They discharged into hoppers on top of the fill from which bottom dumps were loaded for distribution of the fill materials over the lenght of the embankment.

Immediately upstream of the Main Embankment, core and blanket material was transferred to other conveyors for transportation across the river valley to the Auxiliary Dams. The shell zones of these dams, however, came from left bank sources.

Adjacent to the spillway channel, an additional borrow area was opened which supplied about 25 million tons of angular boulder gravel material.

X. DESIGN CHANGES DURING CONSTRUCTIONS

An important consideration in the design and construction of an earth and rockfill dam is to make optimum use of available materials and this was used with advantage in case of Tarbela.

The properties and quantities of materials obtained from project excavations at time differ somewhat from what is expected from pre-construction explorations; also more is known about foundation conditions from underground works, excavations, and additional explorations. The design of a dam should, therefore, be modified to take advantage of this additional information. On the same basis several design changes were introduced and carried out at Tarbela during construction.

As already indicated, a Board of Special Consultants (comprising renowned figures such as Dr. Cassagrande Dr. Einstein. Mr. Johnson, Dr. Nichol, Mr. Slitcher Mr. Snyder) had been engaged by WAPDA for Tarbela. The Board assembled regularly to review technical problems arising from design modifications, studies, information and data collected during the course of construction.

In the tender drawings, the embankment contained a horizontal draiage blanket and a series of relief wells along the downstream toe of the embankment. A chimney drain located downstream of the transition zone and connected to the horizontal drainage blanket was added design during construction.

There were two reasons for this change, the presence of the newly discovered underground escarpment, and the extent of open-work zones in the foundation of the main embankment, increased the possibility of differential settlement which could cause core cracking. Also, material used for construction of the downstream shell zones was less pervious than originally thought and consequently its drainage characterietics were poorer.

The chimney drain would intercept all seepage passing through the core and transition zones, even if some cracking should develop, and thus ensure that the downstream shell zones do not become saturated and cause a subsequent reduction in undrained strength.

Actually, cracking was not expected in the vicinity of the escarpment because of the sequence of construction proposed. Also, lengthening of the impervious blanket was provided to prevent possible internal erosion. Similarly, cracking at the abutments was unlikely because of the low and rapid compressibility of the bulk of the embankment materials.

Crest width of the dams was increased from the 30 to 40 feet. Experience with dams recently constructed in siesmically active regions, like Tarbela, had shown that a wider core in the top portion of the dam provides effective defence against cracking. Thus entire top portion of the dams had to be widened, which also accommodated wider core.

The free draining downstream shell zones and part of the free draining upstream shell were replaced by well-graded granular but non-free draining material. Free draining rock and boulder gravel fill was in short supply, but good quality, well-graded granular fill was abundant.

Introduction of the chimney drain eleminated the need for free draining fill in the top portion of the downstream shell. In the upstream shell, the incorporation of layers of free draining materials at about 20 feet spacing was to provide satisfactory drainage of the granular but non-feedraining shell material at time of drawdown.

Addition of the chimney drain to the auxiliary dams necessitated addition of horizontal drainage blankets, as drainage blankets were not originally incorporated in these auxiliary embankments.

Initial design included a weight berm at the downstream toe to provide additional stability should sand zones in the foundation be loose and become weakened by liquefaction under seismic leading. This downstream weight berm, together with a concrete drainage gallery was eliminated as additional exploration and testing during construction had revealed that the sand zones were dense and in no danger of liquefaction. Also, the sand layers were of limited extent.

Filter material produced by the contractor was in short supply and of marginal gradation, and to alleviate the shortage, natural sand was used in a multi-layered filter arrangement. At less critical locations, the dimensions of the filter zones were reduced.

Exploration carried out during the construction period revealed a continuous, highly-pervious zone of openwork cobble gravel located in the foundation of the main embankment dam. This zone, like the rest of the Indus River alluvial deposits, was composed of rounded boulders and gravels, but the voids were not filled with fine sand.

A critical openwork zone about 1000 feet wide was located at a depth of approximately 100 feet near the right bank, and extending from upstream of the impervious blanket to downstream of the line of relief wells at the toe of the dam. A Similar zone existed in the vicinity of the left abutment, but this did not appear to extend to the upstream edge of the blanket.

In addition to conventional borings, an extensive programme of test grouting using grout containing the fine river sand, as well as a 100 feet deep shaft in frozen alluvium, was employed to define the extent and nature of these openwork channels.

Extension of Impervious Blanket.

In order to control seepage and prevent excessive migration of fines under the possible gradients, the original blanket had to be extended. This could be achieved by blanket placing in dry, underwater fill operations, sedimentation in the left and centre sections using training dykes, and sedimentation over the entire upstream area by operating the reservoir at low levels in the initial period. Of these, the conventional dry fill placing was finally selected because it could be well controlled resulting in a blanket with high degree of reliability. Blanket extension was divided into two areas. In the right bank area, where the openwork was known to be more extensive, a 5 ft thick blankat was extended over the diversion channel and tied into the spoil piles located at the right side of the channel, resulting in about 4500 feet extension of the existing blanket. In the left bank area, having less openwork and in general higher bedrock elevations, the blanket was extended by about 2,000 feet with a 3 ft layer of impervious material.

Fifth Tunnel.

The contracted Tarbela Project included 4 right bank tunnels (as mentioned already) which were to:—

(a) Cope with the diversion requirements during the construction stage.

(b) Provide power intake for eight 175 MW each hydro-electric units (initially) with facility for ultimate installation of 12 units, and

(c) Provide low level outlet capacity (between the Spillway crest elevation 1492 and the dead storage level 1300) for meeting the downstream irrigation demands in conjunction with outflow from power units.

Provincial Irrigation Department of the West Pakistan, objected to this outlet capacity on the premise that serious restraint would be caused to the early Kharif (upto mid June) river run-off which otherwise would be needed for crop sowing. This issue remained under debate fot over 3 years during which a lot of material was brought forth for and against the adequacy of low level outlet capacity at Tarbela. This ultimately led to the appointment of Panel of Experts under the chairmanship of the Chief Engineering Adviser, Government of Pakistan (GOP).

The panel, after looking into the pros and cons of the problem came out with the recommendation that augmentation of the low level capacity at Tarbela would be advantageous for the downstream irrigated agriculture. Consequently, in 1971 GOP ruled in principle that the capacity be augmented by providing a fifth tunnel on the left bank of Tarbela.

As a result of GOP's decision, TJV was asked to construct 700′ long stub portion of the fifth tunnel on the left bank with the same diameter (45') as for the four right bank tunnels. After subsequent studies and economic considerations, a fifth left bank tunnel was incorporated in the Project having the following salient features:—

(a) Type Concrete/steel lined (similar to right bank tunnels).

(b) Diameter (after Stub) 36'

(t) Length 1838'

(d) Discharge Capacity:—

(i) Dead Storage Level (1300)-48000 cusecs.

(ii) Maximum Conservation Level (1550)-93,000 Cusecs.

In order to impart technical know-how to local talent, the contract was awarded to Pakistan Tarbela Consortium (PTC). a joint venture between National Construction Corporation (NCC) and TJV with effective participation of NCC. Similarly, engineering of fifth tunnel was taken away from Project Consultants (TAMS) and assigned to newly created National Engineering Services of Pakistan (NES PAK).

After fulfilment of initial formalities, the contract was awarded in 1973 The work started soon aftar and is poised for on-schedule completion in May 1976.

XI. RESERVOIR OPERATIONS

Planning for First Year (1974-75).

In the Board of Special Consultants meeting held at Tarbela in December 1972, one of the subjects reviewed was the initial reservoir impounding in 1974 in the context of the safety of the dam and the associated works. Previously the Board had recommended that no impounding above dead storage level be permitted during 1974 by operating reservoir at a level of ±1300. After further veview of all the data and relevant studies, as well as insistence by WAPDA that some partial storage for subsequent irrigation use must be created during 1974, the Board agreed that the reservoir level could be raised to an elevation in the vicinity of the Spillway crest (elevation 1492) and kept as such for an approximate period of 3 months. This was considered essential to avoid development of excessive foundation seepage in accordance with "Observational Method" briefly outlined in Appendix-2.

Initial Impounding:

The Board suggested that raising of the reservoir to elevation 1492 should be accomplished in two steps. The first stip would comprise raising the reservoir to elevation 1300-1350 by operating the gates of Tunnels 3 and 4 from July 1, 1974. The filling operation could last for a few days simultaneously ensuring adequate release of water for downstream irrigation needs. The object of this operation would be to permit early evaluation of the behaviour of dam foundation under partial head. In case the foundation behaved satisfactorily, further raising would be permitted. Otherwise the reservoir would be immediately drawndown to a safe level and kept as such till completion of the remedial measures. In case of such an occurence it might not be possible to create any Tarbela storage during Kharif 1974.

The second step of reservoir impounding, after initial testing of the safety of Tarbela embankment, would be Stage-IV diversion. It will commence by closing Tunnels 1 and 2, depending upon the completion of the closure section of the main embankment and auxiliary dams No. 1 and 2 to elevation 1520. According to available indications, the earliest date for this stage could be August 15, 1974.

After Stage-IV diversiun i. e. closure of Tunnels 1 and 2 through the closure gates at the head, construction would proceed to convert, these two tunnels to power use.

With the diversion tunnels closure planned for August 15, 1974, the two irrigation release Tunnels 3 and 4 would be operated as necessary to control the storage level in the reservoir as well as release supplies required for downstream uses. Thus the active first filling of the reservoir, above the initial testing level of 1350, would commence in an endeavour to create maximum possible partial storage during late Kharif of 1974. As Spillway gates were unlikely to be installed by the end of Kharif 1974, elevation 1492 represented the maximum limit of reservoir impounding with a utilizable storage of about 6·1 MAF.

Initial Drawdown.

If during the testing period of 1974 reservoir impounding the piezometer observations and the performance of the relief wells demonstrated that the dam was safe, WAPDA would proceed with the planned completion of the Project and the operation of the reservoir for irrigation/power needs. If on the other hand, there were any indications of development of unfavourable trend in the foundation of the dam, the reservoir would have to be lowered as rapidly as possible to a safe level first by means of Tunnels 3 and 4 followed, if necessary by opening of Tunnels 1 and 2. Remedial measures would them be initiated. To cater for such a contingency, it would be necessary to keep Tunnels 1 and 2 operable by putting off the plugging of the river intakes till the remedial measures have been completed.

Following initial reservoir filling, to a possible maximum elevation of 1492 as agreed to by the Board of Special Consultants, the reservoir ievel would be kept constant for approximately 3 months to observe any development of the foundation seepage. If during this test period, the performance of piezometer and relief wells demonstrated that the dam was safe, the project would be completed as planned and operation of reservoir started for irrigation/power needs. in other words, following end of the testing period in December, 1974, Tarbela partial storage could become available for supplementing the river inflows during the remainder period of Rabi and early Kharif.

First Reservoir Filling (1975).

Following the first drawdown of the reservoir, to the minimum pool level of 1300 in early Kharif, the reservoir impounding would start to achieve its first filling to capacity. This filling would be accomplished on the basis of the normal Rule Curve Criteria being prescrible by the water Management Cell of WADPA for IBP reservoirs. As per normal practice, these criteria take due congnizance of the anticipated river inflows, realistic irrigation needs, the constructional requirements and other related factors. It was expected that, all going well, a smooth and efficient first filling to capacity of the reservoir would be accomplished during 1975 high run-off period. This filling will mark the end of the interim reservoir operation period of 1973-75 and bring the reservoir to its substantial completion stage.

ACTUAL OPERATION DURING FIRST YEAR (1974-75)

Initial Impounding (1974).

Factual reservoir operation started with Stage-III diversion on October 1, 1973 when the river water started flowing through the tunnels. However, uptil end of the June 1974 this was essentially run-of-the-river passing through the tunnels with head just sufficient to push through the gradually increasing discharge (Refer to Appendix-3 on 10-daily reservoir operations).

From July 1974, initial reservoir filling commenced to bring it up gradually to the Spillway crest elevation of 1492 for observing reservoir foundation behaviour against excessive seepage in accordance with the "Observational Method". Control of the reservoir levels was achieved through gate manipulation of Tunnels 3 and 4.

The filling process continued satisfactorily through July and end of the month elevation was 1350. However, from eary Alugust some trouble started with the tunnels. Initially stainless steel liners downstream of Tunnels 3/4 outlets got ripped off. These warranted closure for inspection and repairs. Soon after some rock chunks started coming out of Tunnel 2. The situation went on further complicating with increasing reservoir level. Finally it was decided to completely shut-off the tunnels to avoid further damage and let the reservoir rise to the spillway crest level of 1492. In this process, unfortunately, in take gates of Tunnel 2 got stuck-up and resulted in its rupture on August 21. This necessitated dumping of the reservoir by opening other Tunnels 1, 3 and 4 in which process they sustained further damage (ex-plained later).

Initial Drawdown (Emergency).

On occount of the unfortunate mishap to Tunnel 2, the reservoir dumping was started on August 23, 1974 with elevation of 1462.7. This continued through September 20, 1974 when reservoir finally attained the lowest level of 1133.2

(Appendix-3). In this process stored water to the extent of 6.7 MAF had to be dumped for emptying the reservoir to safe level. It was a national clamity that, besides extensive damage to the tunnels, a sizeable amount of stored water was lost which could provide tremendous boost to the following Rabi crop. However, this unfortunate incident had also a bit of silver lining.

Due to unprecedentally low supplies during Kharif 1974, all the rivers had fallen to such a low level that escapage below Kotri was reduced to nil on August 24. Not only that, but filling of Mangla reservoir was not in sight despite concerted efforts to conserve every possible drop of water. By that date Mangla had only come up to an elevation of $\pm$ 1172 which represented about 70% of capacity (that year Mangla could only fill up to about 75%).

In view of this precarious water supply condition, almost all the canals in the Indus Basin Irrigation System (IBIS) had been put on to share supplies for an equitable distribution of shortages. This was the time when dumping of Tarbela started. Thus it proved to be a blessing In disguise and enabied substantial improvement of canal supplies in the remainder Kharif period of August to September 1974. In addition, it made possible filling of Chasma storage to capacity which had been almost depleted during the preceeding period to make up for the seriously constrained Tarbela outflows for meeting the irrigation uses.

On the basis of daily data on the system operetion, it was computed that Tarbela dumping in Kharif 1974 proved instrumental in providing over 2 MAF of supplemental water to IBIS at a time when maturing of Kharif crop was in real jeopardy.

Rabi 1974-75 Operation:

According to the original plans, it was anticipated that-after successful testing at constant level of $\pm$ 1492 for 3 months-Tarbela reservoir drawdown would commence to provide supplemental irrigation supplies during Rabi 1974-75. This, however, could not meterialise due to the emergency of reservoir dumping towards the end of Kharif 1974. In stead, during Rabi 1974-75 the reservoir was kept at the minimum possible level, consistent with available low level outlet capacity, to pass run-of-the-river. This was essential to carry out the crucial repairs to the right bank tunnels as well as to complete the remedial and restoration works necessary for recommissioning of the reservoir in the next spring. In this process the reservoir level fluctuated between elevation 1121 and 1188 (10-daily operational data in Appendix-3).

First Reservoir Filling After Repairs (1975)

Planning—During winter 1974-75, the necessary repairs, restoration and remedial measures were pursued on emergency basis. Thus in early February 1975, river was diverted through Irrigation Tunnels 3 and 4 after completion of essential repairs. While repair work on damaged Tunnels 1 and 2 continued through May/June 1975, some involuntary reservoir impounding started effective February when the river flows were diverted through Tunnels 3 & 4.

Keeping in view the programme of repairs and the state of preparedness at site, the Board of Special Consultants advised that the reservoir filling during 1975 should be carried out carefully and gradually with constant monitoring under the "Observational Method". Further, the reservoir may not be filled to the maximum conservation level. On this basis, the following filling criteria were evolved for the first reservoir filling during Kharif 1975:—

(*a*) Tunnels 1 & 2 should not be operated but kept available for emergency drawdown in case of adverse indications under the "Observational Method".

(*b*) Reservoir should be brought up gradually by September 1975 in accordance with a prescribed rule curve by gate manipulation of Tunnels 3 & 4 (asymmetrical gate operation of the 2 outlets on each tunnel to be strictly avoided).

(*c*) Impounding should be limited to elevation $\pm$ 1510 and then reservoir kept constant (for about a month) to watch for any adverse indications on pore pressures, underseepage, sink holes, etc.

(*d*) After safe testing of the reservoir and clean bill of health (as under (c) above), the reservoir drawdown could commence for supplemental irrigation supplies, during the following Rabi period of 1975-76.

Actual Reservoir Operation:

Active reservoir filling above elevation ± 1200 started from late April 1975. Concurrently close watch was kept through the "Observational Method", and by the end of June reservoir level raised to elevation ± 1350.

With progressive increase in reservoir levels, the observational indications kept on giving satisfactory results. In fact the things were so promising by mid July that filling plans were revised to attain an elevation above the stipulated level of ± 1510 and possibly attempt maximum conservation (1550) if the conditions so permitted, Thus impounding was somewhat accelerated from then on and a level of ± 1530 attained by August 19, 1975 having a gross storage content of 10·2 MAF. This was attained by commissioning of the Service Spillway as well as short testing of the Auxiliary Spillway. At this stage, reservoir filling plans were reviewed again in the light of observational results and other related factors. It was decided, primarily as a matter of caution, that the reservoir level should not be exceeded during the current season. Further, the Project be tested at this level of × 1530 for at least one month, and all going well its drawdown commenced for supplementing Rabi 1975-76 irrigation supplies.

By late September the reservoir had withstood one month test and observation at the maximum impounded level of × 1530 (10 daily details in Appendix-3). According to available indications it was poised for a drawdown in the forthcoming Rabi season of 1975-76 starting from October.

1975 Instrumentation Indications:

Regular monitoring of piezometer reading during 1975 filling of the reservoir in both the right and left abutments showad no significant change in piezometric levels over the last 100 feet rise in reservoir level. Temperature measurements of seepage water in the right abutment Indicated that this water was still old ground water and suggested that a direct path between the reservoir water and the drainage adits had not occurred. In the foundation alluvium piezometer levels followed closely the rise in reservoir level, which was similar to last year except that the potential increases were somewhat lower this year. Monitoring of the piezometers along the line of the downstream relief wells also showed a generally improved situation compared with last year. Very broadly, it could be said that the situation had improved over last year.

XI. Damages during initial impounding and Dumping (1974)

It has been briefly mentioned in the preceeding (Section-X) that the reservoir had to be dumped in the initial impounding season of 1974, after having attained a level of + 1462 in late August.

Events—From July 1974, active reservoir impounding started above elevation + 1167. It was to be gradually brought up to the Spillway elvation of 1492 by storing from amongst the Indus water in excess of downstream irrigation requirements.

An important object of the initial impounding was to test the safety of embankment and related structures against excessive underseepage through an eleborate programme under the "Observational Method".

Filling began on sceedule, and initially went according to plans, except that for a short period, the rise of the reservoir had to be slowed to allow some of the 80,000 people, who had been slow to move out of the reservoir area, to get away from the rising waters. Though the out-pouring of the waters from the tunnels caused unexpected damage to temporary works, filling proceeded normally as the Indus began to rise from the waters of the monsoonal rains and the annual melting of snow.

On July 27, however, a gate of Tunnel 2 could not be closed. While various attempts were made to force the gate down, two earthquakes in the nearby Hindu Kush mountains occurred. A few days later (around August 8 or 9) rocks were seen to be coming out of Tunnel 2. It was also observed that water coming out from this tunnel changed colour from time to time. At the same time the gates of the other diversion tunnel No. I jammed at small openings.

On August 13, there was a loud noise below the outlet gate of the irrigations Tunnels 3, in which many of the stainless steel liner plates in the outlet passage were ripped off. The irrigation tunnel (3 & 4) were closed immediately, both as a precaution and to permit the damage to be inspected. The water level in the reservoir rose fast, and was only about 30 feet below the Spillway crest level when a few minutes before midnight on August 21, there was an explosive sound in the inlet area of the tunnels and the flow of water through Tunnel 2 suddenly quadrupled to 140,000 cusecs bringing with it some debris.

It was first thought that the inlet gates of Tunnel 2 had given way, and after anxious deliberations by the Federal Provincial Governments and WAPDA, the momentous decision was taken to 'dump' the reservoir. To do this, all the operable tunnel gates were to be opened, but the three gates of Tunnel 1 could not be fully opened.

For three anxious weeks, the water roared through the tunnels, causing the huge structures to viberate and oscillate.

Damage

As the reservoir emptied, small eddies appeared on the surface of the lake, but they were at the wrong place. Instead of being above the intakes, they were incongrously located between the intakes and the dam (it took until mid-September for the reservoir to be drawndown and the mystery explained).

After emptying of the reservoir to elevation+1133 on September 20, an inspection of the damages was started. It indicated that gates of the diversion Tunnel 2 had not been swept away, but what had happened was far worse ; some 250 feet of the tunnel had collapsed within the abutment, and about 500,000 cubic yards of the hill above it had been swept through the tunnel. It also became clear that a number of sink holes had been punctured in the impervious blanket of the reservoir. Seepage through the relief wells had been somewhat more than expected, but otherwise, the main embankment dam stood up very satisfactorily to the filling of the reservoir and to its exceptionally rapid drawdown.

The damage to irrigation Tunnels 3 & 4 had been of the following order :

(a) Stainless Steel liners at the flour and along side walls in Branch A of Tunnel 3, downstream of the outlet gates had been ripped and the anchors broken mostly at weld joints. The steel liners in Branches 3B, 4A & 4B appeared to be intact although they sounded hollow underneath at a number of places.

(b) Tunnel 3 & 4 had to be run asymmetrically during 20 day dumping operation with branches 3A & 4A completely closed and 3B & 4B full open. This caused pitting in the painted surface downstream of the bifurcations in Branches 3B & 4B.

(c) Same damage was also noticed to the concrete in the chute portion below the outlet structures on Tunnels 3 & 4.

Causes of Tunnel 2's collapse are still uncertain, although it is clear that 'cavitation', the demon of fast hydraulic flows, played a key role in rushing waters, unstable vacuums developed which 'imploded' against the tunnel walls acting like chisel blows and dug holes which themselves caused the phenomenon to worsen.

Rather than spend time in allocating blame, the Federal Government wisely took the view that the first priority was to repair the damage so that the filling of the reservoir in the next summer could take place safely, and so that water and power benefits of this gigantic project could accrue with little or no delay.

Repairs and Restoration

To this end, WAPDA with the help of Project engineers, contractor and various experts, devised a complex programme of works to repair/restore damages and to provide an additional margin of safety for the Project. To remove any bottlenecks as well as to be in constant touch with the developments, the Federal Government for their part sat up a Cabinet Committee consisting of the Minister for Provincial Coordination as Chairman and Minister of Finance, Planning and Development and Minister for Fuel, Power & Natural Resources as Members. During the course of repairs and restoration works, the Cabinet Committee met regularly and ensured that Tarbela received the highest priority in respect of goods, services and other local resources necessary to achieve the final programme of work without delay.

Repair to Tunnels :—

The outlet passages to the irrigation Tunnels (3 & 4) were first repaired and strengthened. The seriously damaged Tunnel 2 was repaired by constructing a 'sleeve' to bridge the gap in it. The face of the abutment affected by the cave-in was stablized, and the gap was restored by placing 180,000 cubic yards of rollcrete a lean mixture of gravel and cement, at a record rate. On top of the rollcrete was placed more fill so as to restore the profile of the abutment to what it was before (Greater details in Appendix-4) ?

Restoration of Impervious Blanket :

As indicated earlier, a number of sink-holes had developed in the impervious blanket of the reservoir. The Special Board of Consultants advised that additional blanket material be placed upto a depth of about 5-15' for repairing the sinkholes and furrows. Originally quentum of this additional material was estimated as 3·5 million cubic yards. Subsequently, it was revised to 5·5 million cubic yards but finally limited to 4·5 million cubic yards as accomplished upto the closure date of Tunnel I on February 2, 1975. This quantity was, however, considered reasonably adequate for the purpose.

XII. Additional Works

As a result of damages and results obtained from the Observation Method during 1974 reservoir filling, certain additional works were deemed necessary for satisfactory performance of the Project both in the immediate future and in the long term. Most of these works were programmed for completion by July 1975 and were substaintially completed, but some items would need to be continued in future. The position in this regard was as explained hereinafter.

Tunnels I and 2

To permit operation of the hydraulic systems of the intake gates during the 1975 filling operation if dumping of the reservoir became necessary, the steel towers on top of the concrete intake towers were extended by 65 feet up to elevation 1515. This work was completed by mid-April, 1975. The installation of the conical chokes at the downstream end of each tunnel (required to ensure that the tunnels flow full with reduced risks of cavitation) was completed at the end of May and the associated concrete support and grouting work was completed by early July.

Outlets to Tunnels 3 and 4

The additional anchors required for the liner plates in the outlets, except for those at higher levels, were completed by the end of January 1975. The higher level anchors would be installed when the supply of the irrigation requirements through the Spillway (s) would enable the irrigation gates to be closed. Additional stabilization and erosion protection of the river bank downstream of Tunnel 4 stilling basin was considered prudent, and precast concrete 'dolosse' blocks were used for the purpose. By the end of July, 1340 such units had been manufactured, and 618 placed in position.

Reservoir Blanket.

A contrast was awarded in March 1975 to a specialist firm to undertake an underwater sonor survey for monitoring the behaviour of sinkholes. Soon after sonar survey work started within the side scanner. Initial survey revealed development of a number of sinkholes though their sizes and quantity did not show significant subsequent development.

As a precaution against the possibility of such sinkLole's recurrence, two 150 cubic meter bottom-dump barges has been procured in March 1975. These barges were utilised to dump suitably graded material in the critical sinkhole areas located by the sonar survey. Check observations on the in-situ results of these dumpings, with actual bed sampling and sonar surveys, gave encouraging results. More efficient methods of loading the barges were developed at site and the 2 barges were expected to place a total of about 75,000 cubic yards per month. In fact it was being seriously considered to acquire two additional barges for fully handling this remedial work.

Relief wells Downstream of the Main Embankment.

1974 observation had revealed that the existing relief wells downstream of the Main Dam received more water than expected. It was, therefore, decided to provide additional wells. Work on 77 such wells started slowly, but output improved during April and, with some modifications to the well sizes, the wells were completed on schedule at the beginning of June. A further 11 wells were completed by July 31.

Left and Right Abutments.

Drainage Adits and Grouting.

A programme of new adits for drainage and grouting in both left and right abutments of the main embankment was adopted in December 1974. A crash programme to complete the work by August 1975 was organized.

Work on the left abutment proceeded satisfactorily and with the exception of some check grouting, work was completed by the end of May.

Driving of the adits on the right abutment was hampered by blasting restrictions while the intake cut was being stabilized. By late July work in the main adits was substantially complete and only a small amount of grouting and some drilling for additional instruments and exploration remained.

Geology.

A detailed review of the geology of the right abutment, recommended by the Special Board of Consultants, was taken up which indicated the need for more exploratory drilling to fill in the gaps in present knowledge. Once this review had been completed a further programme of grouting could be implemented.

Tunnel 3 and 4-Repair of Stilling Basins.

Stilling basins of Tunnels 3 and 4 had been seriously damaged, (presumably) due to a symmetrical operations during 1974 reservoir dumping. This damage, however, could not be properly assessed till about May 1975 when ovet 50 feet of sediment deposits over the area were washed away by tunnels operation following February. At that stage the constrained low level outlet capacity did not permit taking up of the repairs. It was, therefore, decided to run the calculated risk of using Tunnels 3 and 4, with periodic soundings to moniter the damage and wait till after the reservoir exceeded the Spillway crest elevation of 1492. Unfortunately, however, this unavoidable operation of Tunnels 3 and 4 resulted in serious extension of damage (specially in Tunnel 3) to the stilling basins. On the basls of initially assessed damage (as guessed from soundings and diver's reports), the contractor had indicated completion by end December 1975. Consequently, construction of the coffer dam was taken up in August to permit dewatering of the stilling basins. After its completion, it transpired that the damage had been extensive and so dewatering should not be attempted. Consequently, the plans had to be revised for carrying out the initial work under water through tremie concreting. On this basis, the contractors latest estimate was to complete the work (subject to no increase in the presently assessed damage) not earlier than April 1976. As indicated earlier this was fraught with the possibility of denying Tarbela storage water below elevation 1500 for the Rabi of 1975-76. Efforts were, however, still on to improve upon this repair schedule to enable utilisation of some additional Tarbela storage for benefit of the crops.

XIII. REMAINING PROBLEMS

Except for the outstanding grouting in Tunnels 1 and 2 the main items of the Original programme of work have been successfully completed. However, the problems described below remain unresolved:—

(i) The significance of the recurrence of sinkholes in the upstream blanket and the development of a programme using dumping barges to repair them. The development of sinkholes in the blanket as they occur is being successfully monitored with the sidescan sonar survey equipment. Dumping of materials from barges is also continuing. At the same time the blanket and foundation instrumentation array is being monitored daily to watch for any adverse trends or anomalies in piezometric readings.

(ii) a. Effectiveness of the additional grouting and drainage works in the right abutment and the possible need for further works to provide a long term solution.

b. The effectiveness of the additional right bank grouting will be monitored with the present instrumentation array. The need for and urgency of implementing any further measures would depend on the outcome of the present review of the geology of the area and the performance of the abutment generally during filling.

(iii) Effectiveness of and the need for further grouting in Tunnels 1 and 2. The originally programmed grouting measures in Tunnels 1 and 2, which have been suspended, will be completed as soon as the need to be able to lower the reservoir has passed. Exploratory grouting to date has not revealed any large cavities. While this is reassuring, it is possible that a more extensive programme of consolidation grouting, particularly under the rebuilt section of Tunnel 2 may be necessary.

(iv) Repair procedures and programming of the repairs to the Tunnels 3 and 4 stilling basins, particularly in relation to the need to provida stored water for Rabi crop of 1975-76.

(v) Contingency plans, in case subsequent raising of the reservoir to maximum conservation level of 1550 becomes problematic on the basis of observational tests.

XIV. RECAP

Foregoing history of Tarbela Project from inception to the present state of completion is undoubtedly a chain of problems. On the other hand, it is a concerted effort on the part of all concerned, with a reasonable amount of success, to get over them. According to the indications as of now, the Project has crossed the 'hump' thus paving the way for realisation of the charished dream to revolutionise the regional economy by the impact of gigantic Tarbela Dam Project.

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5. Irrigation Release Requirements From Tarbela During the Period 1973-75—Unpublished Note by Water Resource Management Directorate WAPDA—October, 1973.

6. Tarbela Dam Project—Third Special Report by the Administrator following a Visit to Tarbela From February 10-15, 1975—March, 1975.

7. Tarbela Dam Project—Fourth Special Report by the Administration following a Visit to Tarbela From July 28 August 1, 1975 August—1975.

8. Tarbela Dam Mishaps Repaired, is Beginning to Fill Once Again.

   By

   B. Chadnet and C. Melmoth in 'Bank Notes of July-August, 1975.

APPENDIX—I

BASIC DATA OF TARBELA DAM PROJECT

Hydrology of Indus at Tarbela

Catchment area—655,000 sq. miles.
Mean annual flow—64 MAF.
Maximum probable flood—1,773,000 cusecs,
Diversion design flood—750,000 cusecs.

Reservoir

Full pool Level—El: 1550.
Gross storage—11·1MAF.
Live storage—9·3 MAF,
Dead storage—1·8 MAF.
Length of reservoir—48 miles.
Area submerged—80,000 acres.
Population affected—16,000 families.

Main Dam

Type—Earth & Kock fill.
Crest Level—El: 1565 S. P. D.
Length at crest—9,000 feet.
Maximum height above foundation—470 feet.
Total volume of fill:
Embankment—138·0 million cubic yards.
Blanket—20.0 million cubic yards.

Auxiliary Dam No. I

Type—Eearth & Rock fill.
Crest Level—El: 1565.
Length at crest—2340 feet.
Maximum height above foundation—345 feet,
Total volume of fill—18·0 million cubic yards.

Auxiliary Dam No. 2

Type—Earth & Rock fill.
Crest Level—El: 1560.
Length of crest—860 feet.

Maximum height above foundation—220 feet.
Total volume of fill—2·0 million cubic yards.

Coffer Dams

Type—Earth fill.

Total volume of fill—7·0 million cubic yards.

Service Spillway

Type—Ogee Crest and flip Bucket.
Top Level of spillway—El: 1560.
Crest Level—El: 1492.
Crest gates (width & length)—7 No. ('50'x58').
Type—Radial.
Length—820 feet.
Maximum height above foundation—125 feet.
Total volume of concrete—416,000 cubic yards.
Discharge at full pool—615,000 cusecs.
Design discharge—650,000 cusecs.
Reservoir Level at design discharge—El: 1552·2.

Auxiliary Spillway

Type—Ogee crest.
Top Level of spillway—El: 1560.
Crest Level—El: 1492.
Crest gates (width & length)—9 No. ('50x58').

Type—Radial.
Length—1330 feet,
Maximum height above foundation—260 feet.
Total volume of concrete—535,000 cubic yards.

Discharge at full pool—795,000 cusecs.

Design Discharge—840,000 cusecs.

Reservoir at design discharge—El: 1552·2.

Diversion Channel

Length—15,200 feet.

Design discharge capacity—750,000 cusecs.

Width upstream of Buttress Dam—650 feet.

Width downstream of Buttress Dam—694 feet.

Buttress Dam

Top Level—El: 1187.

Maximum height above foundation—105 feet.

Openings between buttresses (width x length)—28 No. (19′x58′).

Stop long panels—28 No. (19′x44′).

Gates—28 No. (19'x32·5').

Type of gates—Radial.

Total volume of concrete—25,000 cubic yards.

Tunnels (Original)

Number—4

Length—2400 to 2700 feet.

Inside diameter upstream of gate shafts (concrete lined) 45 feet.

Inside diameter downstream of gate shaft (steel lined):—

Tunnels 1, 2 & 3—43·5 feet.

Tunnel 4—36 feet.

Diversion gates, each of Tunnels 1 & 2 (width x length)—3 No. (13·5′x45′).

Service gates, each tunnel, (width x length)—2 No. (13·5′x45′)

Bulkhead gates for all 4 tunnels (width x length)—2 No. (13·5′x45′).

Outlet gates, each of Tunnels 3 & 4 (width x length)—2 No.

(13·5′x45′).

Irrigation discharge capacity, Tunnels, 3 & 4.

At Maximum drawdown El: 1300—136,000 cusecs.

At the Spillway Crest Level—196,000 cusecs.

Total volume of concrete—1·78 million cubic yards.

Power Plant

Turbo-generator units—4@ 175,000 K. W.

Sphericial inlet valves, (diameter)—4@ 192 inches.

Relief by-pass valves, (diameter)—4@ 96 inches.

Transformers—12@ 71 MVA.

Appendix—2

TARBELA DAM PROJECT

OBSERVATION METHOD FOR MONITORING BEHAVIOUR DURING INITIAL RESERVOIR FILLING IN 1974.

Concept.

Under normal design procedures a foundation treatment should be designed to be safe beyond any reasonable doubt under conditions which are the worst conceivable consistent with the sub-surface information available and geologic conditions at the site. When the worst conceivable foundation conditions result in a very expensive design and when further subsurface explorations to prove that the subsurface conditions are more favorable than assumed would be too expensive and/or time consuming, the use of the observational method is advantageous.

The observational method embodies the following ingredients :—

(*a*) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.

(*b*) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.

(*c*) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.

(*d*) Selection of quantites to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.

(e) Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.

(*f*) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.

(*g*) Measurement of quantities to be observed and evaluation of actual conditions.

(*h*) Modification of design to suit actual conditions.

Situation at Tarbela

In early 1974, (before start on initial reservoir filling) the situation at Tarbela with respect to each of the above ingredients was as follows :—

(*a*) Subsurface exploration had been carried out to a reasonable degree to establish the general nature, pattern and properties of the alluvial deposits and rock forming the foundation of the main embankment dam.

(*b*) An assumption had been made of the most probable foundation conditions and the most unfavourable conceivable deviations from those conditions established as well.

(*c*) Design of the impervious blanket extending upstream as well as the drainage blanket and relief wells at the downstream side of the dam based on a working hypothesis of behaviour anticipated under the most probable conditions.

(*d*) Quantities selected to be observed as construction proceeds and calculation of their anticipated values on the bases of the working hypothesis had been made. The quantities included piezometric levels, quantities of seepage, and seepage velocities. Piezometric levels would be determined from analysis of water temperature measurements (recent thermonic studies had indicated that temperature can be used as a tag for tracing the seepage of water through the foundation).

(e) Calculation of values of the same quantities (piezometric levels, seepage quantites and seepage velocities) under the most unfavourable conditions compatible with the available data concerning subsurface conditions had also been made.

(*f*) If significant deviasions from the design assumptions were indicated by the observations, the course of action to be taken would include immediate lowering of the reservoir and then extension of the impervious blanket upstream by various means plus construction of additional relief wells if necessary. In order to permit the lowering of the reservoir to a suitably low level, no work would be done in Tunnels one and two until January 1, 1975 at the earliest so that if necessary these tunnels could be re-opened for rapid lowering of the reservoir to minimum level.

(g) Measurement of quantities to be observed had already started in those piezometer which have been installed to date. Additional piezometers and thermometers were in the process of being installed and observations were to commence in them as soon as they were available. Quantities of seepage would be measured as soon as the reservoir filling progressed sufficiently to cause discharge of water from the relief wells or drainage blanket.

(*h*) Hopefully, no modification of design would be required, but if the observations indicated that actual conditions deviated significantly from those assumed then modifications as indicated in (f) would be carried out.

APPENDIX 3

TARBELA DAM PROJECT

10-Daily Operational data From October 1973 to September 1975

Month and 10-day period		1973-74 Mean Inflow (1000 x Cusecs)	1973-74 Mean Outflow (1000 x Cusecs)	1973-74 Reservoir Level (SPD)	1973-74 Reservoir Gross Content (MAF)	1974-75 Mean Inflow (1000 x Cusecs)	1974-75 Mean Outflow (1000 x Cusecs)	1974-75 Reservoir Level (SPD)	1974-75 Reservoir Gross Content (MAF)
Oct.	1	54·4	53·6	1124·80	0·004	40·2	40·7	1132·85	0·006
	2	41·8	42·1	1121·33	0·004	30·9	30·3	1139·55	0·007
	3	33·2	33·4	1118·44	0·003	26·4	26·9	1134·96	0·006
Nov.	1	28·7	28·9	1116·15	0·003	22·4	22·7	1131·56	0·005
	2	25·3	24·5	1126·30	0·004	19·5	19·9	1127·70	0·005
	3	23·1	23·0	1127·40	0·005	18·8	18·9	1126·62	0·004
Dec.	1	20·7	20·9	1124·76	0·004	17·6	17·7	1125·00	0·004
	2	19·4	19·2	1127·28	0·005	16·9	17·0	1124·15	0·004
	3	17·3	17·5	1124·52	0·004	16·2	16·2	1124·52	0·004
Jan.	1	16·2	16·2	1124·20	0·004	15·0	15·0	1122·65	0·004
	2	15·6	15·6	1123·60	0·004	14·7	14·7	1121·25	0·004
	3	15·5	15·5	1122·45	0·004	14·4	14·4	1121·60	0·004
Feb.	1	15·9	15·9	1122·48	0·004	14·4	5·5	1177·88	0·130
	2	15·0	15·7	1113·94	0·002	15·3	13·8	1181·57	0·150
	3	17·3	17·1	1115·95	0·003	14·5	14·4	1181·82	0·150
Mar.	1	16·9	16·8	1117·75	0·003	17·4	16·8	1183·88	0·170
	2	16·9	16·9	1117·40	0·003	15·8	15·9	1182·89	0·160
	3	24·3	24·2	1118·25	0·003	21·4	21·2	1188·20	0·200
Rabi (MAF)		8·4	8·4			7·1	6·9		

APPENDIX 3

TARBELA DAM PROJECT

10-Daily Operational data From October 1973 to October 1975

Month and 10-day period		1973-74 Mean Inflow (1000 x Cusecs)	Mean Outflow (1000 x Cusecs)	Reservoir Level (SPD)	Reservoir Gross Content (MAF)	1974-75 Meen Inflow (1000 x Cusecs)	Mean Outflow (1000 x Cusecs)	Reservoir Level (SPD)	Reservoir Gross Content (MAF)
Apr.	1	25·8	25·7	1124·20	0·004	24·4	23·2	1190·95	0·220
	2	25·7	25·7	1126·90	0·005	22·6	22·7	1190·46	0·220
	3	37·2	37·1	1135·28	0·006	38·8	29·4	1205·02	0·350
May	1	48·6	48·6	1139·78	0·007	37·5	35·8	1207·05	0·380
	2	51·4	51·5	1131·72	0·005	64·3	39·8	1240·03	0·780
	3	61·6	61·3	1151·22	0·010	78·8	59·3	1256·80	0·060
Jun.	1	108·7	108·9	1148·35	0·008	109·1	104·3	1262·15	1·150
	2	121·4	114·5	1180·92	0·150	165·2	114·9	1311·55	2·150
	3	118·7	125·1	1154·80	0·020	182·8	135·5	1349·76	3·090
Jul.	1	117·8	115·5	1167·80	0·070	138·9	127·0	1358·46	3·330
	2	209·3	141·8	1276·50	1·420	240·3	149·7	1416·60	5·140
	3	260·3	182·9	1350·45	3·120	185·3	99·4	1465·20	7·030
Aug.	1	177·7	110·9	1396·12	4·450	212·8	98·3	1514·10	9·330
	2	165·2	55·7	1455·95 a	6·640	259·4	217·7	1530·98	10·220
	3	125·8	247·2	1380·60	3·970	237·0	239·6	1529·92	10·160
Sep.	1	100·3	283·7	1200·20	0·300	137·8	136·5	1530·40	10·190
	2	67·9	82·8	1133·20	0·006	97·3	97·8	1530·22	10·180
	3	57·0	56·9	1138·45	0·007	71·3	69·0	1531·03	10·220
Kharif (MAF)		38·2	38·2			46·6	36·5		
Annual (MAF)		46·6	46·6			53·7	43·4		

(a) Maximum attained reservoir level was 1462·7 on August 23.

Appendix—4

TARBELA DAM PROJECT

DETAILS OF REPAIRS TO TUNNELS DAMAGED DURING INITIAL RESERVOIR OPERATIONS OF 1974

Intake to Tunnel I

The erosion damage in the intake was repaired using conventional concrete and all lost reinforcing steel was replaced. The concrete plug downstream of the central intake gate was also constructed. Good progress was made and the work was substantially completed by early March 1975.

Grouting of the intake was confined to grouting of the tremic concrete placed under the intake, and to exploratory grouting of the rock below the centre-line of the intake. The original scope of the work for this grouting was halved in the light of experience and by the end of June 1975, 95% of the modified programme had been completed. In late June a decision was taken, as a precaution, to seal all the grout holes and prepare the tunnel for use in an emergency draw-down, should the need arise during the later stages of filling the reservoir. The outstanding grouting work was left to be completed later.

Tunnel I

The major in the tunnel was a programme of exploratory grouting below the tunnel floor into known zones of sugary lime-stone. This posed many problems because of high water pressures caused by the rising lake level and some difficult ground conditions. The work was taken up but suspended in early 1976, and the need for further grouting reviewed. This would be carried out, when after 1975 filling/testing operations, the risk of drawing down the reservoir through the tunnels was sufficiently remote to permit work to re-start.

The installation of the service gates in the mid-tunnel gate shaft slots commenced immediately after the closure of Tunnel I, Concreting of the pier was completed by mid-April 1975. Installation of gate guides, a time-consuming operation, followed and this work was completed in June. Gate installation and testing was completed at the beginning of July. Final touching up and epoxy treatment of the concrete surfaces was completed by mid July, which was on schedule.

Intake to Tunnel 2

Grouting of the Tunnel 2 intake foundation, particularly in the area of the tremic concrete, and the final epoxy repair of the remaining areas of minor erosion continued intermittently but was suspended at the end of June with about 85% of the assigned work complete. The extent of further grouting work was being reviewed.

Tunnel 2

Rise in lake level after (February 2, 1975), closure of Tunnel I increased the problems of dealing with the inflow of water. By drilling a series of drainage wells and pressure relief holes and installing pump lines, the inflow was brought under control. These wells and pressure holes were subsequently grouted. Construction of the 36 feet diameter tunnel sleeve section inside the tunnel remnant was successfully completed in April, with other major concrete work being completed soon afterwards. The work of drilling and grouting of the rebuilt section had to be done in three stages of depth with each stage having to be sub-stantially complete before the next stage could commence. The drilling, particularly through the remnant section of the tunnel, proved very difficult. As work did not start till late in April 1975, after reservoir levels had begun to rise, increasing external water pressures added to the difficulties of the work and various measures were devised to cope with this situation with differing degrees of success. When the decision to suspend grouting was taken in late June 1975, so as to make the tunnels ready if dumping of the reservoir was required, the progress position was :—

(*i*) All skin grouting complete, about 60% of the contact grouting complete and 30% of the consolidation grouting complete. Work would be resumed as soon as it had been established that the reservoir had been filled safely.

(*ii*) Because of the problems encountered with the grouting of the new tunnel section, work fell behind schedule on the exploratory grouting in the upstream section of the tunnel. Only about 25% of the originally assigned work had been done when operations were suspended. Work would be resumed late so that the programme of work could be completed in full.

(*iii*) Construction of the mid-tunnel service gate pier continued on schedule and the installation of the gates was completed in July 1975.

(*iv*) General repairs and finishing work continued into July and filling of the upstream section of the tunnel started on July 24 and was completed on July 29. Welding and grinding repairs to the steel lining in the downstream portion of the tunnel and final painting was deferred until 1976.

Abutment Area of Tunnels 1 and 2

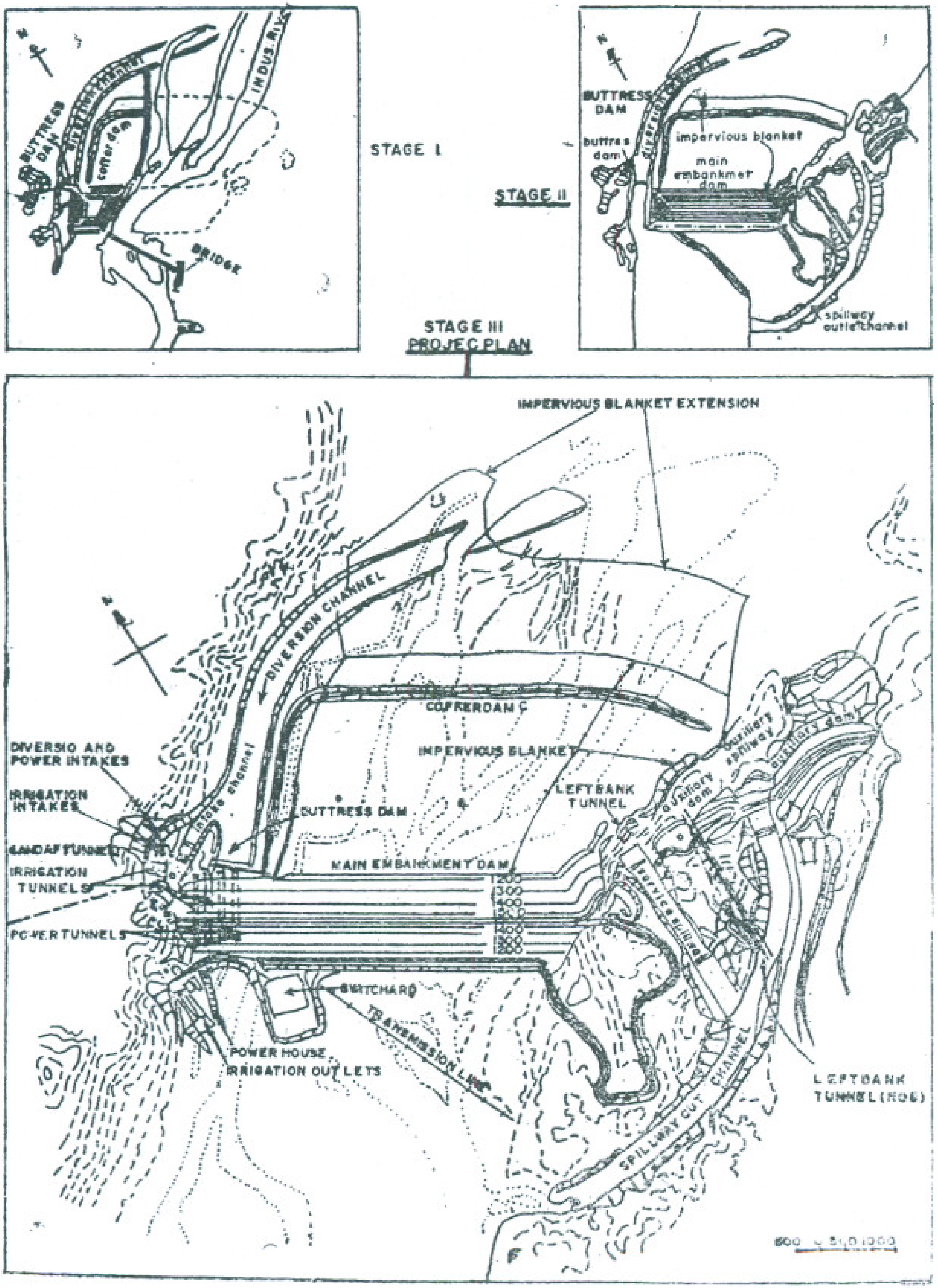
By February 2, 1975, the rollcrete level was high engough to permit closure of Tunnel 1. Work continued without interruption and the rollcrete was completed by February, 24, well ahead of programme. Placement of the granular fill material above the rollcrete was completed by the end of March, about 6 weeks ahead of schedule. All other necessary work was completed before the reservoir level reached about 1194 in April.

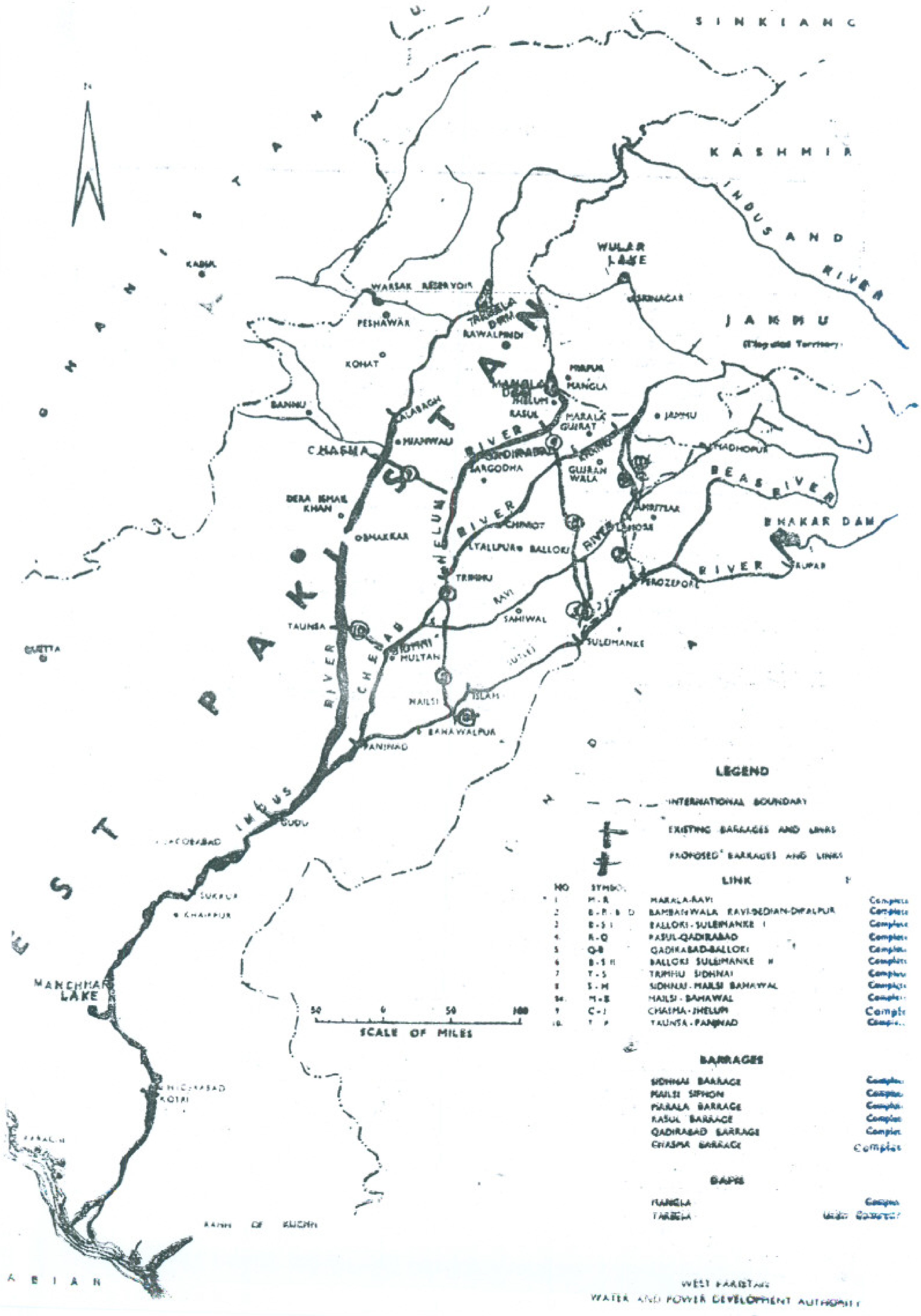
Outlets to Tunnels 3 and 4

Except for some epoxy painting in the outlets, no work was done since the diversion of the river through Tunnel 3 and 4 in early February, 1975.

TARBELA DAM PROJECT PLAN

STAGES OF CONSTRUCTION

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KASHMIR
INDUS AND RIVER
WULAR LAKE
SRINAGAR
JAMMU
WARSAK RESERVOIR
PESHAWAR
TARBELA DAM
RAWALPINDI
KOHAT
MANGLA DAM
MANGLA
JHELUM
RASUL
MARALA
GUJRAT
BANNU
KALABAGH
MIANWALI
CHASMA
QADIRABAD
SARGODHA
GUJRANWALA
MADHOPUR
BEAS RIVER
DERA ISMAIL KHAN
BHAKKAR
JHELUM RIVER
CHINIOT
LYALLPUR
BALLOKI
LAHORE
AMRITSAR
BHAKAR DAM
FEROZEPORE
RIVER
RUPAR
TRIMMU
RAVI
SAHIWAL
TAUNSA
SULEMANKE
QUETTA
MULTAN
SUTLEJ
MAILSI
ISLAM
BAHAWALPUR
PANJNAD
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GUDU
JACOBABAD
SUKKUR
KHAIRPUR
MANCHHAR LAKE
KOTRI
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PAKISTAN
WEST PAKISTAN
AFGHANISTAN
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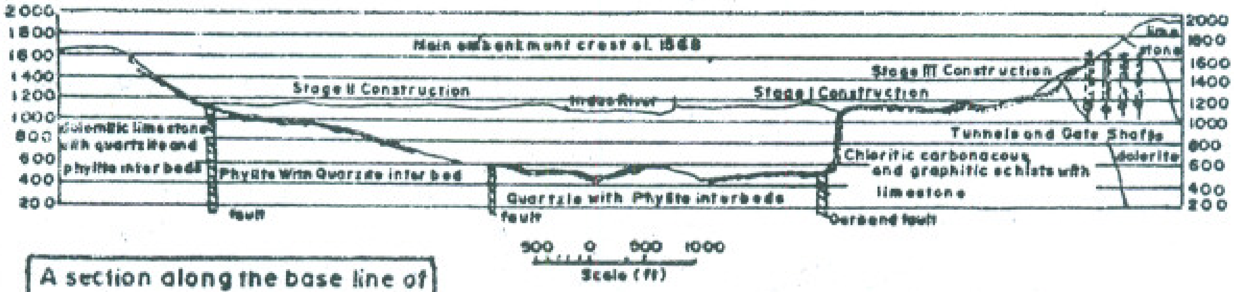
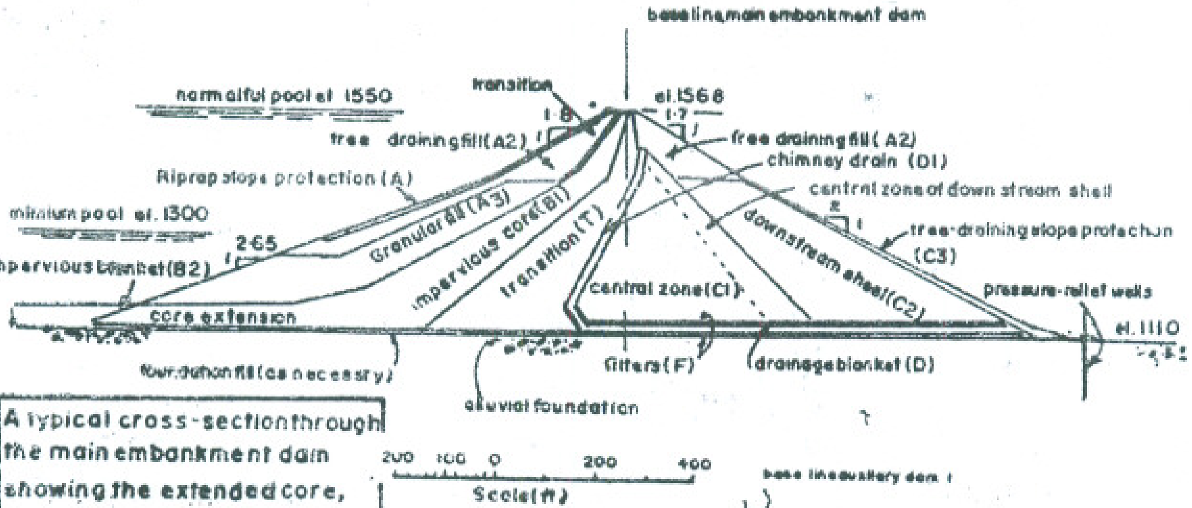
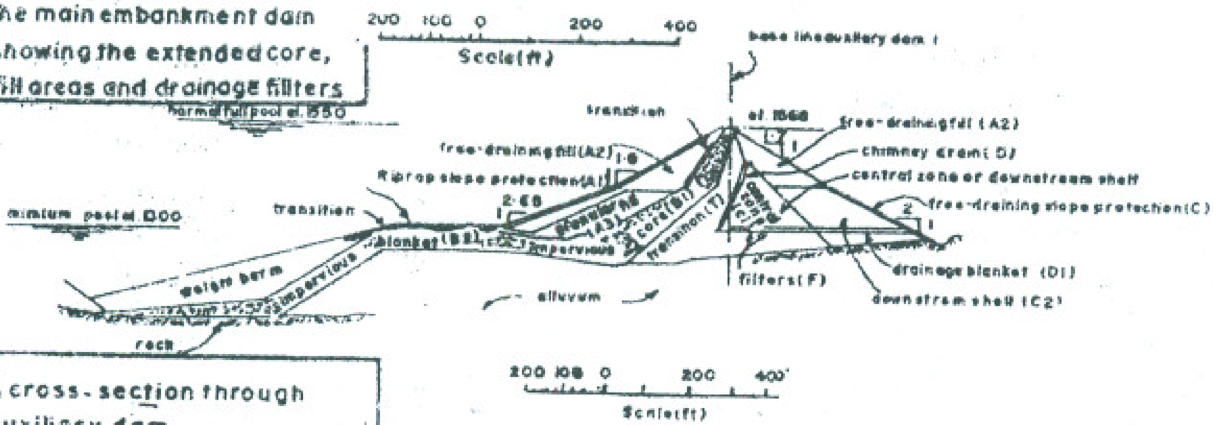
PROPOSED BARRAGES AND LINKS
NO
SYMBOL
LINK
1 M-R MARALA-RAVI Complete
2 B-R-B-D BAMBANWALA RAVI-BEDIAN-DIPALPUR Complete
3 B-S I BALLOKI-SULEIMANKE I Complete
4 R-Q RASUL-QADIRABAD Complete
5 Q-B QADIRABAD-BALLOKI Complete
6 B-S II BALLOKI SULEIMANKE II Complete
7 T-S TRIMMU SIDHNAI Complete
8 S-M SIDHNAI-MAILSI BAHAWAL Complete
M-B MAILSI-BAHAWAL
9 C-J CHASMA-JHELUM Complete
10 T-P TAUNSA-PANJNAD
BARRAGES
SIDHNAI BARRAGE Complete
MAILSI SIPHON Complete
MARALA BARRAGE Complete
RASUL BARRAGE Complete
QADIRABAD BARRAGE Complete
CHASMA BARRAGE Complete
DAMS
MANGLA Complete
TARBELA
WEST PAKISTAN
WATER AND POWER DEVELOPMENT AUTHORITY



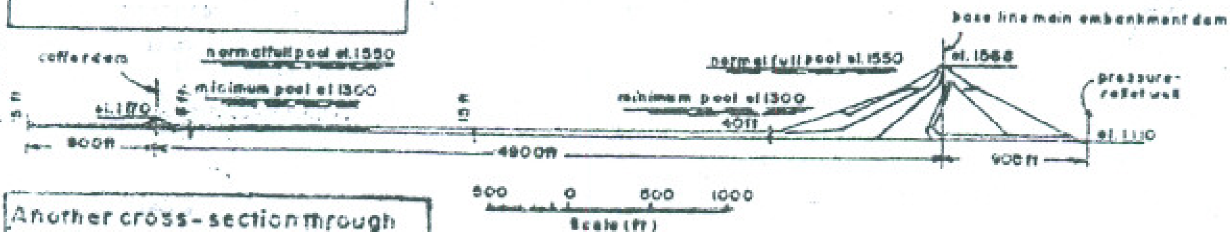
A section along the base line of the main embankment dam



A typical cross-section through the main embankment dam showing the extended core, fill areas and drainage filters



A cross-section through auxiliary dam



Another cross-section through the main embankment dam showing the impervious blaket