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Experiences of engineering geological problems of major dams in Pakistan

Mansur Ahmed
Geotechnical Division, National Engineering Services Pakistan (Pvt) Limited
1-C, Block-N, Model Town Extension, Lahore, Pakistan

ABSTRACT

There are about 79 dams in Pakistan, which meet the ICOLD criteria of 'large dams'. This paper deals with certain engineering geological problems of dam construction that are peculiar to Pakistan. These include difficult foundations, reactive aggregates, deep alluvial filled valleys, and seismically unstable areas. In addition, associated problems including very high floods and phenomenal sedimentation are also discussed.

Owing to the complex geotectonic setting, various critical problems of engineering geological nature occurred during the construction of such large dams as the Mangla and Tarbela in northern Pakistan. Some of these problems were beyond the boundaries of experience. Appropriate solutions, which sometimes required untried techniques, were devised and successfully implemented. The paper also discusses special foundation treatment provided in the design of a proposed large dam.

INTRODUCTION

Agriculture forms the largest single sector of Pakistan's economy. Pakistan has one of the largest and most intricate irrigation systems in the world with about 700 km of major canals and 79 dams and barrages (Agha 1980). The Tarbela and Mangla are among the largest dams in the world. Another very large dam is the 80 m high Kalabagh Dam, which has been designed on the Indus River about 190 km downstream of the Tarbela (Fig. 1). The Warsak, Khanpur, Simly, and Hub Dams are more than 50 m high.

Certain problems of dam construction are peculiar to Pakistan. These are costly nature of surface water storages with difficult foundations, reactive aggregates, deep alluvial filled valleys, very high floods, phenomenal sedimentation, and seismically active areas. Some of the major problems that threatened the very construction of dams in Pakistan, include:

- The soft Siwalik rocks at the Mangla and Kalabagh Dams have undergone intense tectonic deformation creating shearing within the clays, which are illusive and sometimes difficult to detect during the investigation. As discussed later, these shear zones can be a nightmare for the designers. On the other hand, tectonic deformation has transformed hard igneous and metamorphic rocks at Tarbela into a discontinuous and pulverised rock mass requiring a costly foundation treatment.
- The presence of gypsum at Hub and Tarbela has caused dissolution of rocks, where it was necessary to introduce special design modifications.
- Some of the major rivers are flowing through igneous and metamorphic rocks and transport a large quantity of siliceous sediments. They have to be used with great care as the alkali-silica reaction in aggregates, with time, can cause serious deterioration of concrete.
- Rivers have eroded deep valleys and then backfilled them with the alluvial deposits transported from the mountains. The Khanpur and Tarbela Dams are constructed on deep alluvial filled valleys. At Tarbela, the longest blanket in the world had to be constructed.
- Geotectonic setting of the country is very complex with several tectonic boundaries of different interacting plates and microplates (Fig. 2). Some of these boundaries are characterised by long active faults.
- Pakistan is characterised by several seismic zones, which are capable of generating large destructive earthquakes. Dams have to be constructed by taking into account the very high seismic factors. A re-evaluation of seismic risk for some of the older dams indicates that they require further strengthening of such structures (Agha and Ahmed 1986).
- Very large spillways had to be constructed to take care of high floods, and elaborate diversion works had to be built during construction. At Mangla and Tarbela, 20% of total construction cost was spent on the large spillways.
- The rivers transmit a phenomenal amount of sediment load. The Indus and the Jhelum Rivers annually transport about 350 and 110 million tons of sediment, respectively. This results in rapid depletion of storage capacity of the reservoirs.

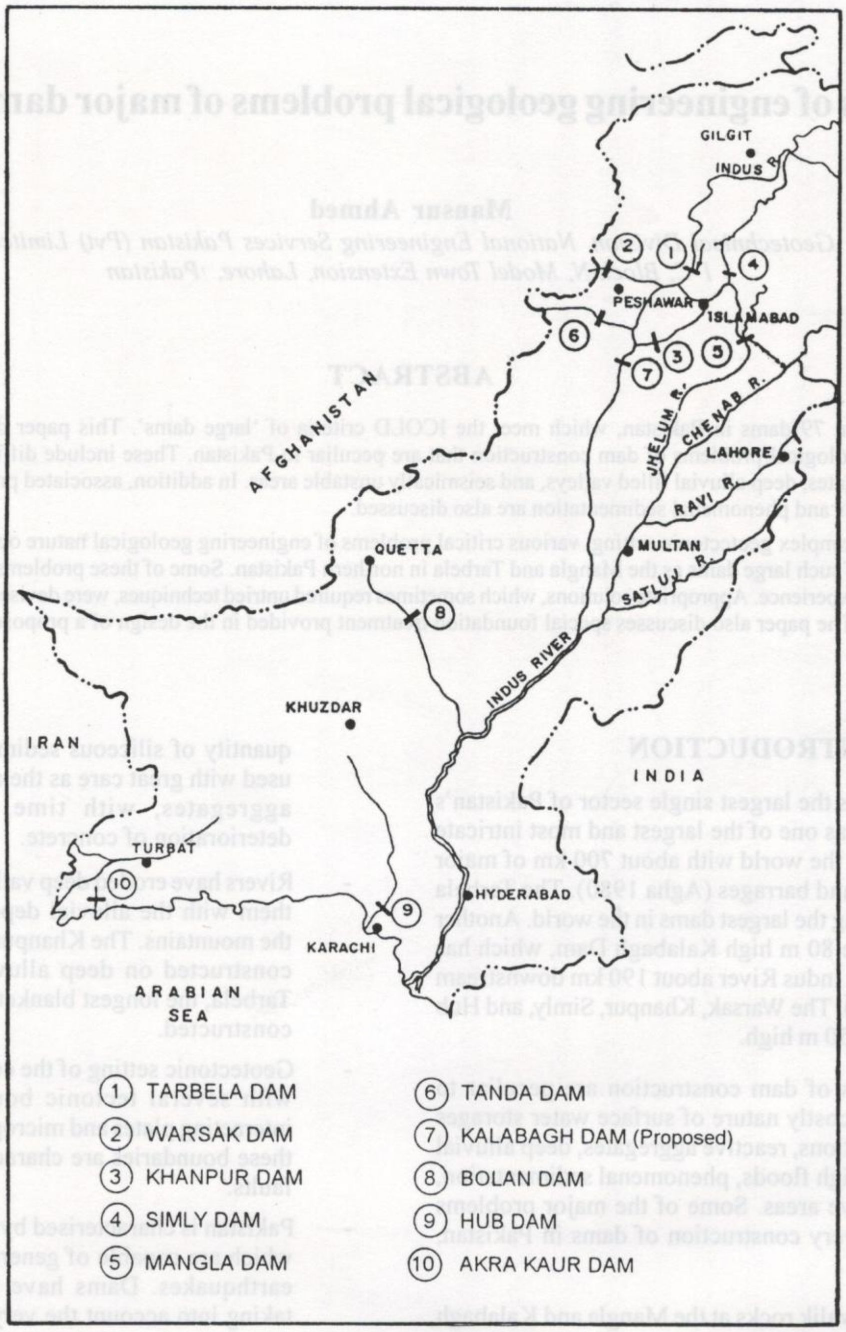

Fig. 1: Location of major dams

This paper discusses some of the problems outlined above, which had to be faced in a very complex geological environment of Pakistan. These problems associated with design, construction, and performance had to be confronted at an unprecedented scale both at Tarbela and Mangla, where many aspects of dam engineering were on or beyond the boundaries of experience at that time. The experience of design, construction, and monitoring of these dams has made a major contribution to the profession of dam engineering.

GEOTECTONIC SETTING OF PAKISTAN

In Pakistan, the following two types of active plate boundary are conspicuous:

- Convergent boundaries characterised by continent collision, subduction, and thrusting in the northern regions of the Himalayas, and oceanic crust subduction in the southern region of Makran and Chaghi; and
- The Chaman Transform Zone, which is characterised by a very large strike-slip movement, connects the Mekran Convergence Zone, where the oceanic lithosphere is being subducted beneath the Lut-Afghan microplates, with the Himalayan Convergence Zone, where the Indian plate is subducting under Eurasia.

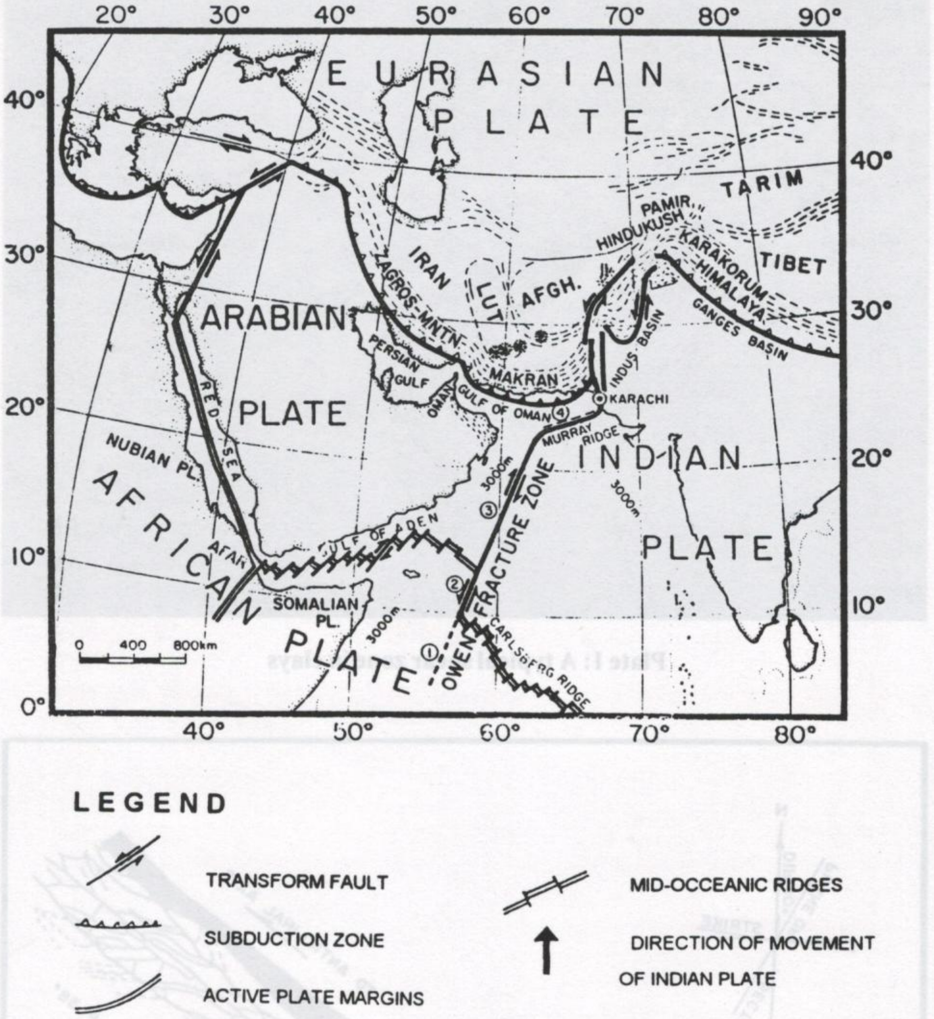

Fig. 2: Geotectonic setting of Pakistan

Several large dams including such gigantic projects as the Mangla and Tarbela had to be constructed in the tectonic scenario described above.

SHEARED CLAYS

Sheared clays in the Siwaliks had a major influence on the design of two large dam projects in Pakistan (Plate 1). In the first case of the Mangla Dam, changes in design were made when sheared clays were detected during the construction. In the second case of the Kalabagh Dam, the project planning had taken full consideration of the presence of sheared clays in the bedrock. Case histories of these two projects are presented below.

Mangla Dam Project

The main features of the Mangla Dam Project (completed in 1967) include three rolled earthfill embankments, spillways, power and irrigation tunnels, and power station. The total crest length of the embankments is about 12,700 m with the maximum height varying from 42 to 139 m. The clays are well stratified and are intersected by a number of discontinuities (Skempton and Patley 1967) such as:

- Fissures typical of most over-consolidated clays, which are polished and occasionally slickensided;
- Thrust shear joints, which occur as a result of beds adjusting to folding under compressive stresses; and
- Shear zones are the bedding plane slips, which have occurred as a result of folding.

The presence of shear zones in clays and siltstones of the Siwaliks at Mangla (Fig. 3) was not detected during the design stage, as it is difficult to recover the weak sheared clays in core drilling. It was during the excavations for construction when some of the structures had been partially constructed that the presence of sheared clays and their significance was fully realised (Binnie & Partners 1968).

Plate 1: A typical shear zone in clays

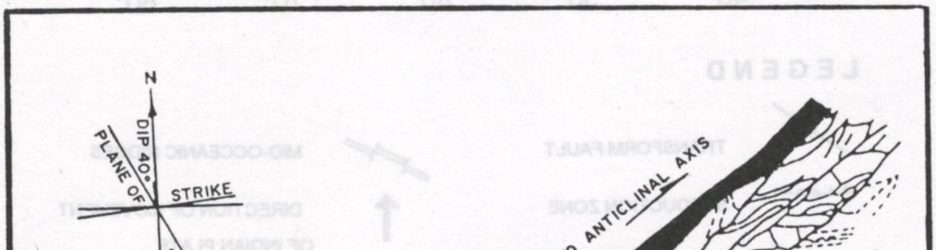

Fig. 3: Shear zone in Siwalik clays at Mangla Dam

Extensive field and laboratory investigations were carried out to assess the engineering properties of sheared clays. Multi-reversal direct shear tests were devised to determine the residual strength of shear zones. The friction angle used for clays in the original design varied from 28 to 32 degrees, and the values dropped to 13–18 degrees in the revised design parameters. Therefore, due to this change in strength parameters, some modifications had to be undertaken for various structures of the Mangla Dam, such as:

- On the main embankment, additional downstream toe weights had to be added;
- Slopes under the intake embankment were modified and additional toe weights had to be provided on the upstream side;
- At the 4 km long Sukhian Dyke, some of the weaker sheared clay beds were excavated and backfilled by sandstone, and toe weights were provided in certain reaches;
- Stability of the intake embankment and power station foundation was improved by providing additional drainage through a system of wells and drainage galleries to control the pore pressure development;
- The tunnels were steel lined to prevent any leakage from them into the surrounding rocks and the development of high pore pressures; and
- An additional low-level adit was added at the spillway and pumped wells were installed on the flanks.

Kalabagh Dam Project

Another example of designing a major dam in foundations containing sheared clays is the Kalabagh Dam Project. The experience gained at the Mangla was extremely useful in adopting appropriate measures design where sheared clays were expected.

The Kalabagh Dam Project is being constructed on the Indus River about 190 km downstream of the existing Tarbela Dam. The project elements include an 80 m high earthfill main dam and an auxiliary embankment with total crest length of more than 1,500 m, two spillways, four diversion conduits, eight power conduits each of 11 m in diameter, and an indoor power station (Kalabagh Dam Project 1985–1987).

The claystone and siltstone beds underwent intense shearing during folding of rocks. These beds like those at Mangla contain a variety of shear features (i.e. thrust joints, oblique shears, flattened shear lenses, and fully developed bedding shears). The intensity of shear increases with clay fraction. Displacements have taken place along all the discontinuities to an extent sufficient to significantly reduce the rock mass strength. The extent of shearing of the clay and siltstone was studied through careful logging of exposures in excavated trenches. Samples were also taken from these trenches for index tests and shear tests. The shear tests conducted included multi-reversal shear box tests on cut-plane samples, and natural slip surfaces and ring shear tests on remoulded samples. Based on the index properties and the results of a series of shear tests, correlations were established between the clay fraction and the residual strength.

The design strength parameters established on the basis of degree of shearing and the residual strength of clay beds did not always give the required factors of safety during the stability analysis of the various embankments and structures involved in the Kalabagh Dam Project. Therefore, the following special treatment measures were recommended to achieve the desired degree of safety at such places.

i. To achieve the desired level of stability of the main embankment dam, the sheared clay beds in certain areas under the downstream shoulder will be excavated up to the depth of 75 m from the ground level and replaced with rolled sand fill.

ii. Under the auxiliary dam, the replacement of sheared clay beds with rolled sand fill will be carried out up to 30 m.

iii. In the power complex area, sheared clay beds were intersecting the power tunnels, and any large displacements in shear zones in case of an earthquake could rupture the conduits. Huge excavations are now planned to remove sheared clays from the power complex area and replace power tunnels with conduits. A 22 m thick RCC pad will accommodate the power conduits of 11 m in diameter (Fig. 4).

iv. Permanent cut slopes expose the sheared clay beds at numerous other locations causing instabilities on these slopes. Therefore, these exposed clay beds will be cut back and replaced by rolled sand fill to improve the stability up to the desired levels.

Substantial costs will incur on the above mentioned ground improvements to achieve a safe design and to mitigate the potential problems of sheared clays.

GYPSIFEROUS ROCKS

The presence of gypsiferous rocks in the foundations and abutments posed serious problems in two major dams in Pakistan.

Gypsum (as secondary deposits) occurs in the left embankment foundation of the Hub Dam (Hub Dam Project 1988, 1995). The deposits are in the form of gypsiferous beds, veins, and veinlets mostly in the top 5 m. The main concern is its dissolution under the shoulders and the core, which may cause cracking of the embankment. For the clay beds containing gypsum, collapse potential was determined, so as to ascertain the behaviour of clay beds on dissolution of gypsum. It may take several years for cracking to occur. However, a system of observations has to be adopted to be aware of any adverse development. At present, seepages

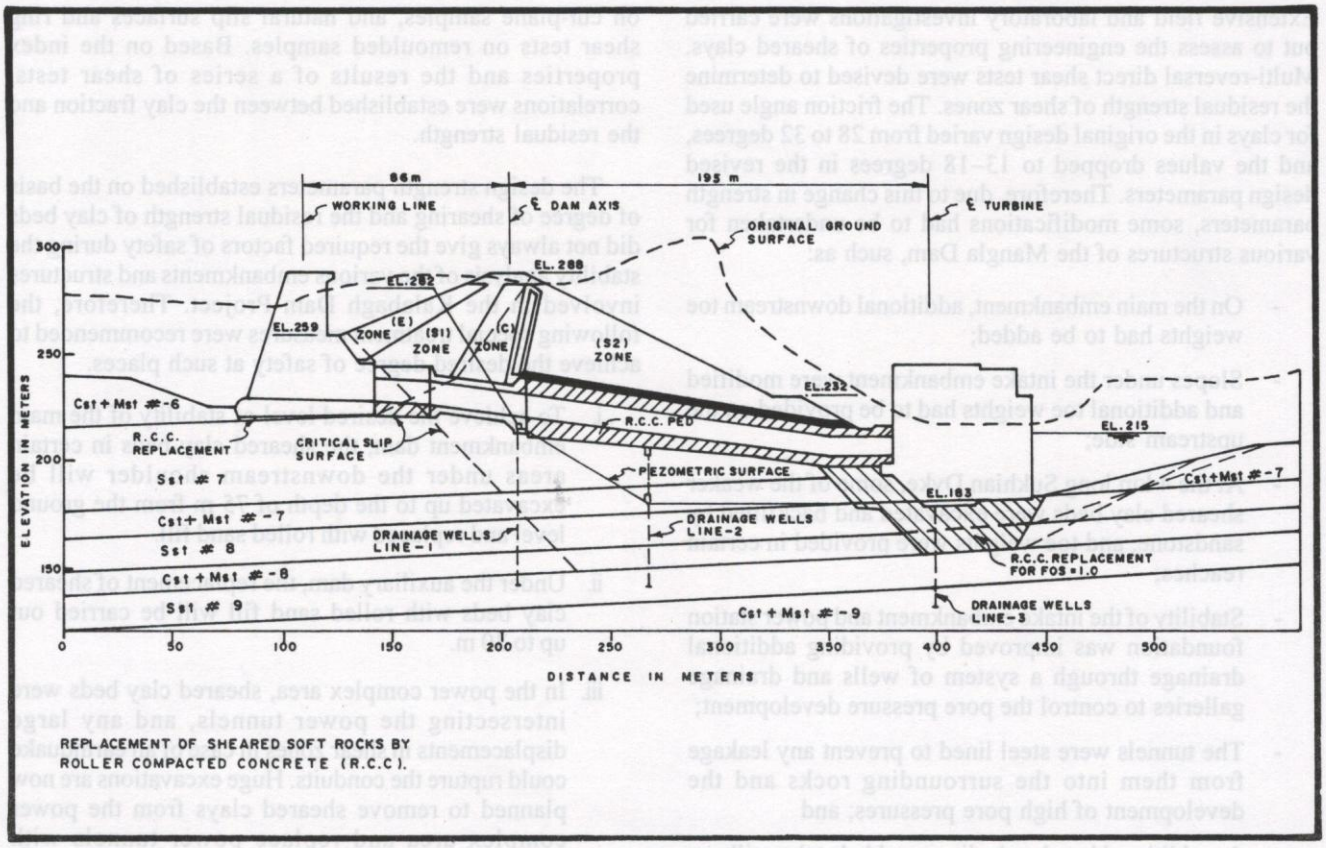

Fig. 4: Kalabagh Dam intake embankment cross section through unit no 5

are being monitored with chemical testing to estimate the removal of gypsum. It is proposed to have inclinometers to monitor the deformation in the gypsiferous beds and monitor the development of any cavities by geophysical methods (i.e. cross-hole observations). The cross-hole observations will be repeated periodically to determine the behaviour of the gypsiferous zones and any possible dissolution of gypsum veins.

At the Tarbela Dam, (Tarbela Dam Project 1984) gypsum is a secondary deposit in the right abutment and occurs in the matrix of various strata of carbonaceous schist, basic igneous rocks, especially in the brecciated zone, chlorite schist, and phyllite. However, massive beds of gypsum are also present in the outlet area of the tunnels. It is estimated that about 55,000 tons of gypsum has been removed through seepage water from 1974 to date. The removal of gypsum occurring in disseminated form is not alarming in the sense that a volume change will not occur and the structure of the rock will remain intact. However, this is leading to open up the paths of seepage. To counteract this, a network of grouting adits is provided to reduce the seepage and consequently cause less dissolution of gypsum. The seepage has also been controlled by treatment of exposures in the intake area to prevent the ingress of water. These measures have been effective in reducing the seepage considerably. In the areas where gypsum occurs as beds, there is an apprehension that cavities may develop with the gradual dissolution of gypsum. It is therefore proposed to have a geophysical survey to detect any cavities along the tunnels. The survey conducted will also act as a reference for detecting any future anomalies.

PROBLEMS OF REACTIVE SILICEOUS AGGREGATES

As mentioned earlier, the major river valleys in the northern part of the country have an abundance of concrete aggregates, which are transported in large quantities by the rivers flowing through the Himalayas. In addition to this transported material, there are several rock quarries spread all over the country.

Over the last two decades, it has been recognised that some of the important structures have been built with reactive aggregates, and an important dam built in the late fifties has suffered from considerable damage because of the alkali reactive aggregates.

The aggregates of concrete are normally considered suitable if they have requisite properties such as gradation, abrasion, soundness, specific gravity, water absorption, and permitted amount of deleterious materials. However, the extensive cracking of concrete works in several parts of the world has been observed, although these structures were constructed with aggregates of excellent physical properties. Such cracking has been attributed to the alkali-silica reaction (ASR) (Hobbs 1988).

ASR at the Warsak Dam

In Pakistan, the worst affected project is the Warsak Dam (Fig. 1) completed in 1960 where no precautionary measures were taken to use low-alkali cement or avoid reactive aggregates, as the concept of ASR had not developed yet.

The power station structure is undergoing a slow movement of about 1 mm per year over the last three decades. The floors of the building have cracked and roof beams have sheared. Penstocks have moved and tilted the generator blocks. The substructure and draft tube roof has been anchored to prevent any further movement.

During the design of the Kalabagh Dam, another large dam proposed to be built on the Indus, some of the tests indicated that the aggregates available in the economical haul distance were reactive. Therefore, an extensive research was carried out for finding a solution to this problem.

Methods of controlling ASR

The ASR can be controlled or reduced to an acceptable level in the following ways.

- Avoiding the use of reactive aggregates where non-reactive aggregates are available in the vicinity;
- Blending for dilution of reactive aggregates with non-reactive aggregates;
- Using low alkali cement; and
- Partial replacement of the Ordinary Portland Cement with pozzolana or slag.

The first two alternatives were not possible at Kalabagh owing to non-availability of good quality material within an economical haul distance. The low alkali cement is not produced in Pakistan. The clay deposits at site were not suitable for manufacturing pozzolana, since the alkalis in these clays were more than the permitted limits. The only alternative available under the prevailing circumstances was the use of slag produced in the steel mills of Pakistan.

Use of slag

Slag is a non-metallic product, consisting essentially of silicates, aluminium silicates, calcium, and other bases. It is developed in a molten condition simultaneously with iron in a blast furnace. The granular blast furnace slag is the glassy granular material formed when molten blast furnace slag is rapidly chilled. Granular slag from the Pakistan Steel near Karachi is the only source of blast furnace slag in Pakistan. The steel mills when operated at full design capacity can produce 270,000 tons of slag annually, but the average production of slag is about 180,000 tons per year. The slag can be grounded to fineness of 3,000 cm^2/gm (blaine) or even further. A number of mortar bar and other tests were carried out using the slag and Ordinary Portland Cement along with the local aggregates. Studies on this slag indicated that about 40% replacement of Ordinary Portland Cement by ground slag could control ASR. Accordingly, for all mass concrete in the proposed Kalabagh Dam, slag will be added to the Ordinary Portland Cement. The use of slag reduces the short-term strength of concrete, which is gained with time, however for most concrete structures this was not considered as a problem.

DAMS ON DEEP ALLUVIAL FILLED VALLEYS

Two major dams in Pakistan had to be located on deep alluvial filled valleys. One of these is the gigantic Tarbela Dam on the Indus River and the other is the Khanpur Dam on the Haro River (Fig. 1), where the experience gained from the Tarbela Dam was utilised for its design and construction.

The depth of alluvium at the Tarbela Dam site is over 200 m (Fig. 5) and the valley is about 3,400 m wide. For the underseepage control, the alternate solutions of providing a positive vertical cut-off or partial cut-off, grout curtain or a slurry curtain were technically impracticable and economically prohibitive. The design of an upstream blanket with vertical drainage at the downstream toe appeared to be the only possible solution. However, the profession neither had any previous experience of providing a blanket for a maximum head of 145 m nor any knowledge on the behaviour of open work gravel zones in the alluvium.

Design of Tarbela blanket

The original design of the blanket consisted of the following features (Sir Alexandar Gibb & Partners 1980).

- An upstream impervious blanket connected to the sloping impervious core of dam with a thickness of about 13 m at the toe of the main dam to about 1.5 m at the end, about 1,830 m upstream (Fig. 6 and 7). The length of this blanket was about 20 times the head of water.
- A horizontal drainage blanket under the downstream shell of the dam.
- A line of deep drainage wells at the downstream toe of the dam.

The above features of the project were designed for anticipated behaviour under most probable conditions. The blanket was well instrumented to monitor its performance including piezometric levels (pore-pressures), temperatures, abutment and foundation seepages, and seismic events, which might occur upon reservoir filling. It was intended that should any problem develop, the designers would review the data and decide on the remedial measures.

After about one month of the first impounding when the reservoir elevation was about 450 m, an upstream end of a power tunnel collapsed and the reservoir had to be emptied. This dramatically revealed that serious problems had already

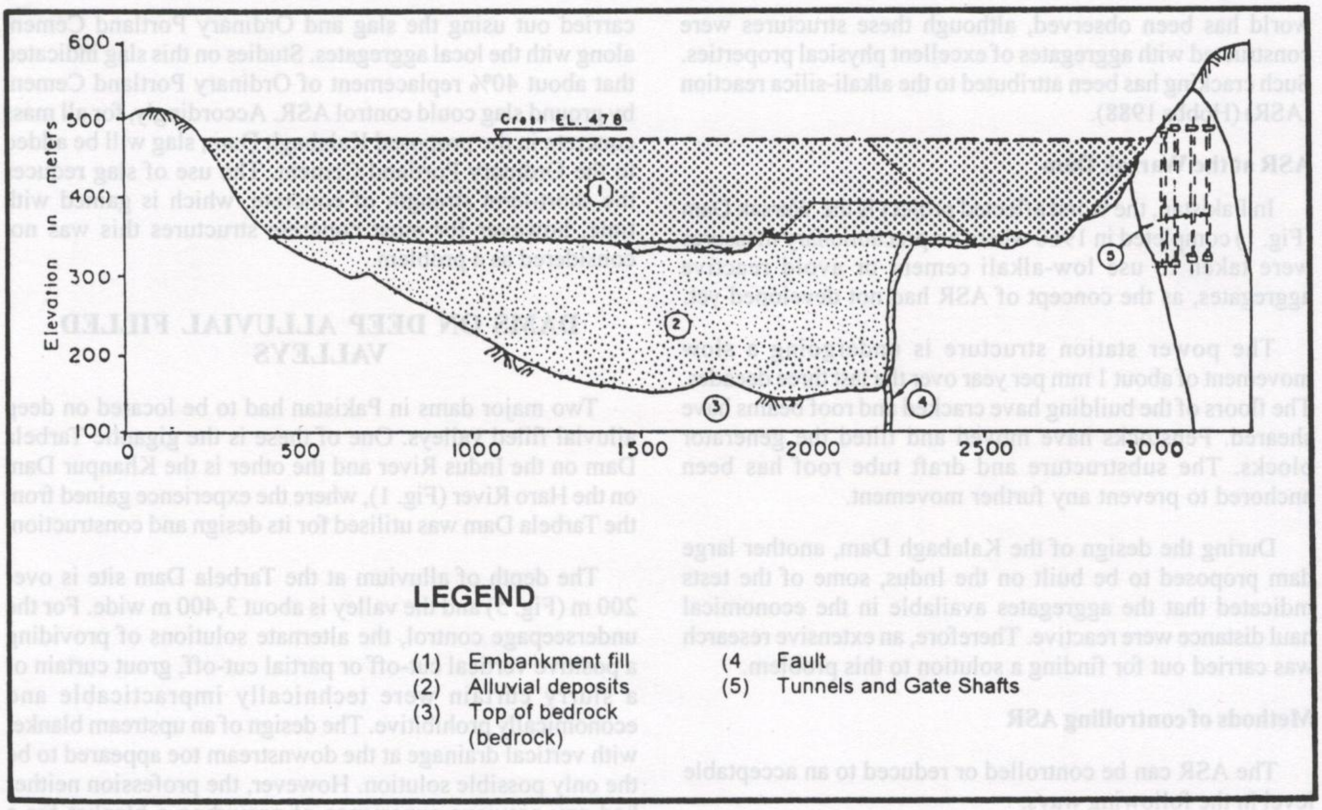

Fig. 5: Deep alluvial filled valley at Tarbela Dam

developed in the upstream blanket. Depleting the reservoir provided an opportunity of direct observation of the blanket in addition to regular instrumental monitoring.

On examination of the blanket, a total of 362 sinkholes were detected together with about 140 cracks as well as several compression ridges. In most of the cases, these sinkholes were located along the cracks. Many of the sinkholes had diameters in the range of 0.3–4.5 m and depths in the range of 1.2–1.8 m. The largest had a diameter of 12.2 m and the deepest a depth of 4.0 m, but none of them punctured the blanket entirely.

Causes of sinkhole development

Several test pits and trenches were excavated at sinkholes to investigate their nature. These pits and trenches penetrated down to the underlying alluvium and indicated that the fines of the blanket material migrated into the alluvium, and generally a thin layer of open work gavels was found immediately underneath the blanket.

The detailed study and investigation of these sinkholes led to the following hypothesis of sinkhole development process.

- The blanket experiences unavoidable irregular settlements due to reservoir loading, and cracks develop at the thumps or ridges created by this settlement.
- Appreciable seepage occurs through these cracks and at places where the sand choking the gravels may not be dense i.e. less than 14 per cent. The seeping water causes downward migration of the sand in the voids to act as a filter in the lower part of the gravel deposits.

This process causes the development of a thin layer of open work immediately underneath the impervious blanket. Consequently, the fine fraction at the bottom of the blanket and along the sides of the lower part of the crack migrated into the open work.

- Thus, when the fine fraction is leached from the bottom portion of the blanket, the remaining coarse fraction occupies less space than the originally placed intact blanket material and a void develops in the bottom portion of the blanket. Material from the roof of the void falls to the floor of the void, and thus the sinkhole develops by stooping action.

Remedial measures

- Repairs of the sinkholes consisted of filling them with filter material, then constructing a mound of additional blanket material over them (Binger and Wilson 1978).
- The original blanket thickness varies from 12.8 at the toe of the main embankment dam to 1.5 m at the upstream end. The whole area of the upstream blanket

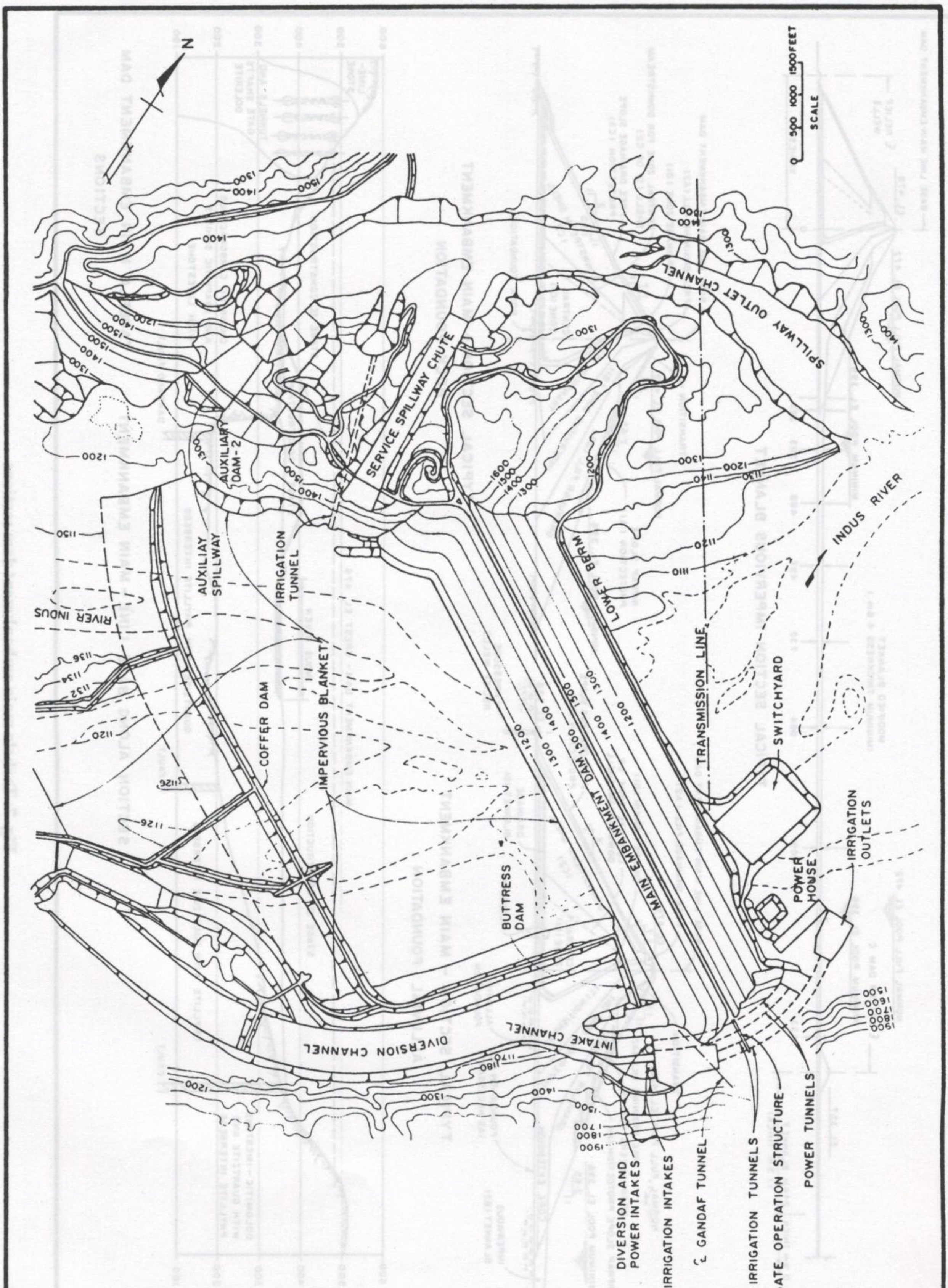

Fig. 6: General layout plan of Tarbela Dam

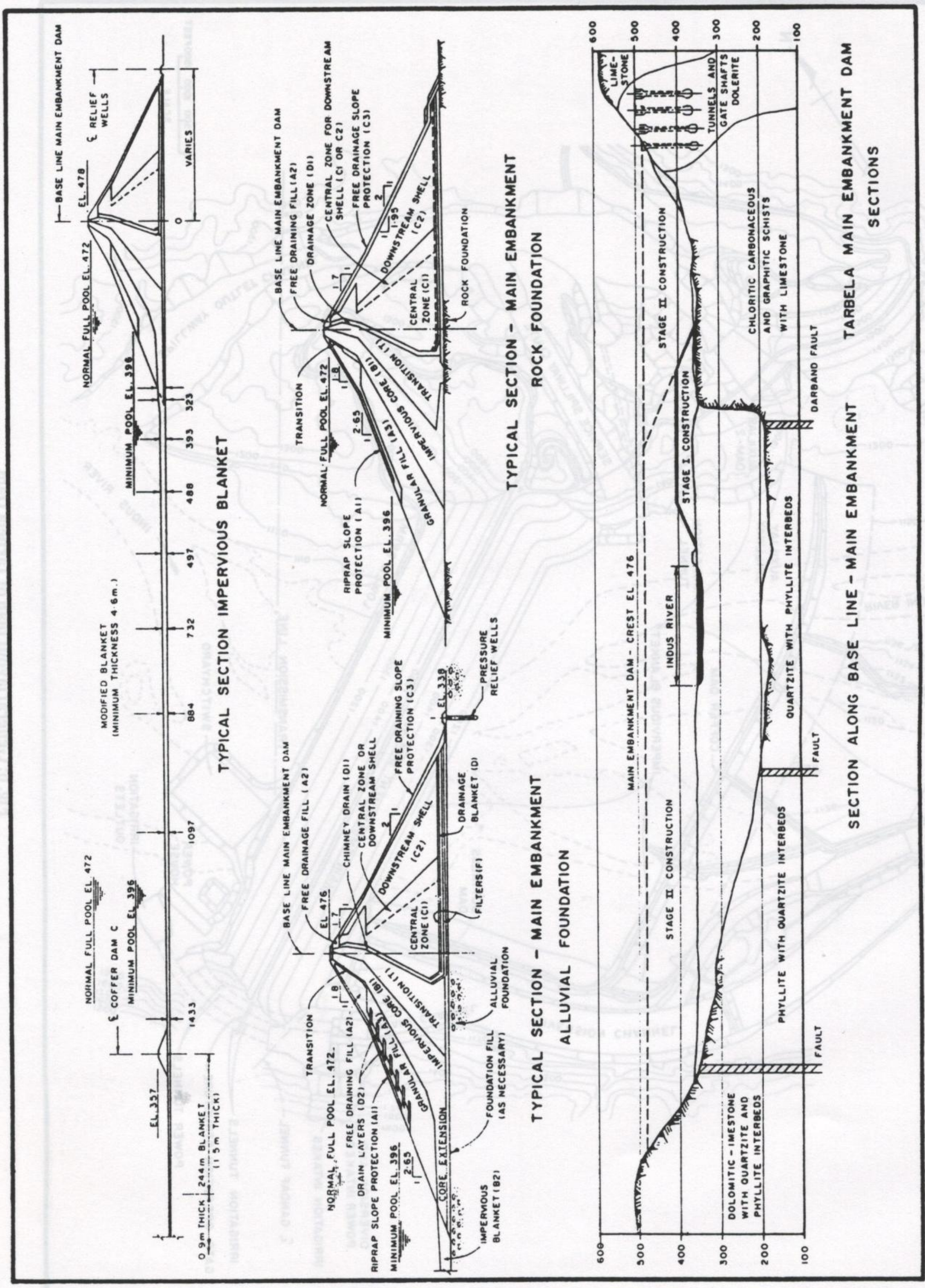

Fig. 7: Tarbela main embankment dam sections

was thickened to an overall minimum thickness of 4.5 m using less compacted fill to avoid cracking.

- Upon subsequent filling of the reservoir, further uneven settlement of the blanket and new sinkholes were expected to develop. To detect these new sinkholes under considerable depths of water, the side-scan sonar (working on the principle of reflected sound waves) was used.

To treat the sinkholes that developed after reservoir was filled, the material was dumped from self-propelled bottom-dump barges of 80 m^3 capacity each.

As a result of barge dumping of material over sinkholes and thickening of the blanket due to natural deposition of silt from the reservoir water, the underseepage has reduced from over 8.5 m^3/s to a negligible amount. Moreover, further development of new sinkholes has also almost completely stopped, indicating the effectiveness of these remedial measures.

Experience gained at Tarbela

As a result of this experience of sinkholes and other observations of the Tarbela Dam operation, the following new advancements were made to the geotechnical engineering aspects of hydro-project design (Lowe III John 1978).

Advancement in filter design criteria

From the mechanism of sinkhole development, it became clear that in addition to other established filter criteria, the material should be checked to see whether the coarse fraction of the material satisfies the D85/D15 criterion with respect to its fine fraction.

Avoidance of knuckles in embankment dams

It is preferable to have steeper angles in the core configuration of the embankment dams to increase the overburden pressure on the knuckles between the core and the blanket.

Blanket design

- Blankets should be constructed to be as flexible as possible to reduce the risk of cracking in differential settlements. The material should be compacted wet of optimum or only lightly compacted if optimum moisture content is preferred.
- Piezometers should be provided to monitor behaviour. Airflush or other methods of drilling liable to create openwork in sandy gravel or boulder should be avoided if possible. Where they have to be used, holes should be drilled before laying the blanket and backfilled with grout above the response length.
- In some cases transition layer may be necessary between the coarse openwork gravel and the blanket.

Provision of sonar and barges

Where there is significant open-work, preparation should be made at least tentatively for the provision of side-scan sonar and bottom-dump barges to locate and treat any sinkholes that may develop on the first filling.

Indicators of sinkhole

The indicators for development of sinkholes are:

- Sudden rise in piezometric pressure under the blanket, and
- Significant increase of seepage from the drainage blanket and relief wells.

Application of Tarbela experience at Khanpur

The Khanpur Dam is founded in a valley, which has over 70 m deep gravelly alluvium (Khanpur Dam Project 1985, 1993). For underseepage control, 870 m long (19 times the water head) upstream blanket was provided on a 1 in 19 gradient (Fig. 8).

Following the Tarbela experience, the blanket was thickened and also the knuckle zone was loaded. After reservoir impoundment, sinkholes were also experienced but were not significant. Moreover, now it was known how to treat them. Vertical drainage at toe was provided, and boiling was experienced on the first impounding severe. Additional wells at toe as for the Tarbela were provided but at closer spacing. The dam has been functioning satisfactorily for the last 14 years.

HIGH SEISMICITY

The mountainous regions of western and northern Pakistan comprise a segment of a major plate boundary along which the Indian and Eurasian plates converge. The Indian plate is moving northwards at an average rate of about 3.6 cm/year. This motion amounts to about 360 km of relative movement across the plate boundary over a period of 10 million years, a short period on a geological timescale. This large relative movement between the Indian and Eurasian plates results in a dominantly convergent collisional tectonics with the development of thrust faults in the Himalayan ranges (Jacob and Quittmeyer 1979). It also results in a sinistral transcurrent motion along the north-south striking faults of the Balochistan Arc (Khirthar and Sulaiman Ranges) and on parallel faults of Pakistan-Afghanistan borderlands, the Chaman-Gardez-Kunar Faults (Fig. 9). Studies of Quaternary sediments in Pakistan have revealed several areas where deformation is found in alluvium (Plate 2), implying that the large earthquakes in the recent past have displaced the alluvium. Therefore, another important problem faced in building dams in Pakistan is the hazard of earthquakes. In recent years, the environmental safety demands have become far more stringent. Dams have to be safeguarded against the risk of surface faulting, strong ground shaking, rockslides in reservoir triggered by large shocks etc. The geographical position of Pakistan happens to be within the syntaxial bends of the Himalayan orogenic belt. This belt is well known for its seismic instability, having been the locus of four earthquakes exceeding the magnitude of 8.3 in the past 75 years, two of which were among the greatest ever recorded.

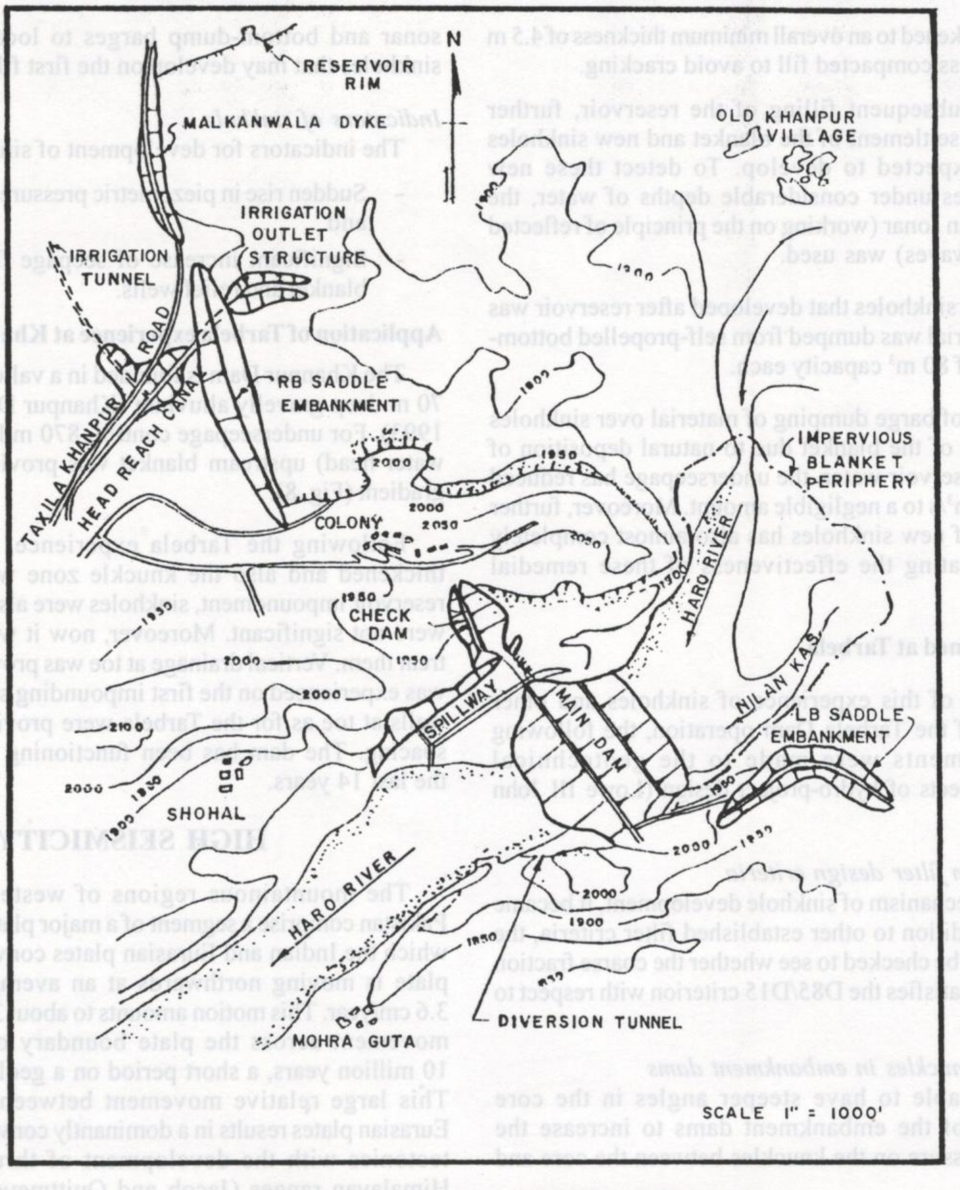

Fig. 8: General layout plan of Khanpur Dam

During known history, this part of the world has experienced some disastrous earthquakes, causing a colossal loss of life and property (Fig. 10). To mention a few, an earthquake ruined the historic city of Taxila in Northwest Pakistan in about 25 A.D., which led to basic changes in the architectural design of the new city. In the current century, the destructive earthquakes of Balochistan and particularly the Quetta Earthquake of 1935 are well known, in which 30,000 lives were lost. More recent event was that at Pattan in December 1974, killing about 5,000 people.

The northern and western mountainous areas of Pakistan are still undergoing a phase of seismic activity. Destructive earthquakes have occurred in this region in the past and are likely to continue in the future. Both the Mangla and Tarbela Dams, and most of our future dam sites including Kalabagh are in zones of recent seismic activity.

The proposed Kalabagh Dam site happens to lie in the vicinity of an active fault. This requires the structures to be designed on a high seismic factor, which is likely to increase its cost.

Increasing attention is being paid for realistic evaluation of seismicity. The Tarbela Dam Project is being extensively monitored by a micro-seismic network installed to cover the tectonic features in the critical range of the project. The dam was designed to withstand an acceleration of 0.15 g. Recent seismotectonic studies carried out for re-evaluation of seismic risk at Tarbela indicate more stringent values. A dynamic analysis is now underway to check its stability against the revised seismic parameters. Microseismic networks were set up for certain other important existing projects and for the proposed Kalabagh Dam Project. Therefore, in the years to come Pakistan would have an

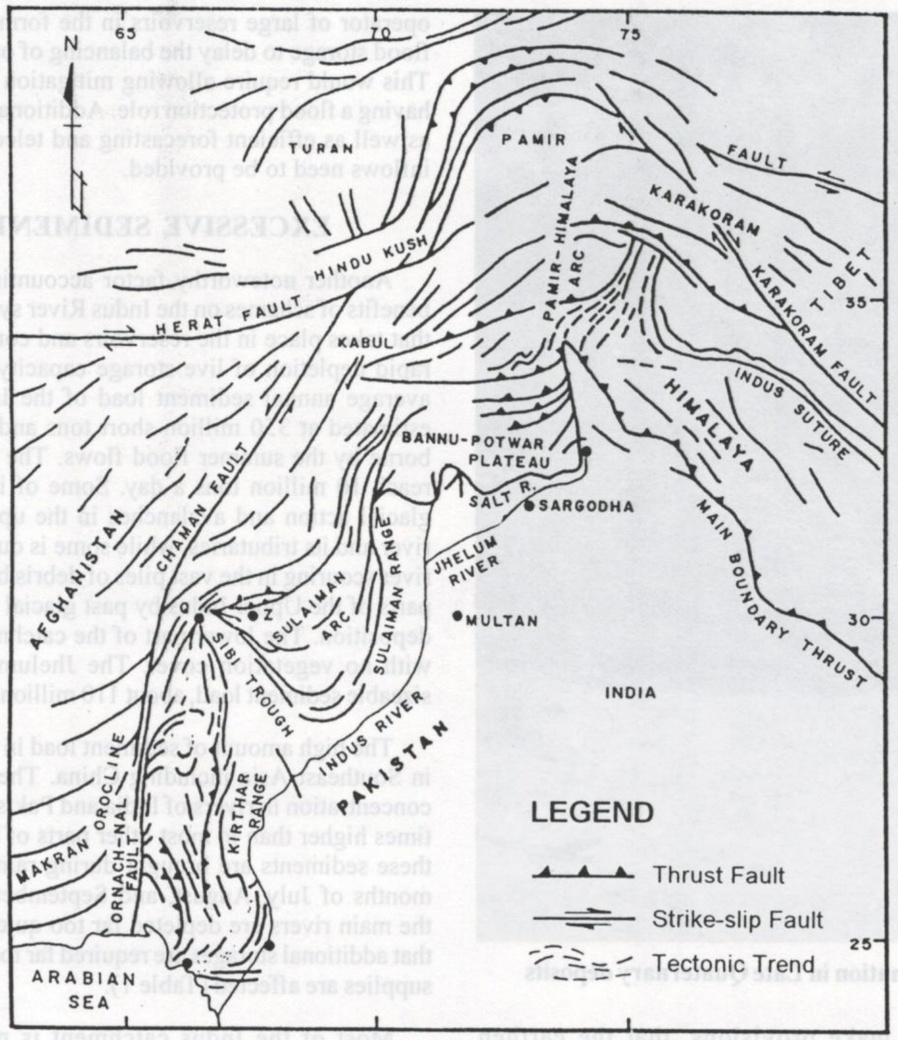

Fig. 9: Major tectonic trends around northwest part of Indo-Pakistan subcontinent

extensive network covering most of the region so that the hazard from earthquakes to dams and other important structures could be evaluated with greater assurance.

The seismic risk evaluation of the proposed Kalabagh Dam, the under-construction Ghazi-Barotha Project, and the re-evaluation of seismic risk to Tarbela Dam have revealed that the seismic potential is quite high.

HIGH FLOODS

Floods are consequences of large storms due to the phenomena of monsoon developing in the bay of Bengal and travelling to Pakistan, which cause a great deal of damage in the downstream areas. The other types of flood peculiar to the Indus River are due to the glacier lake outburst, i.e., a sudden release of storages created by Ice dams and avalanches in the large snow-covered area of the upper reaches. The avalanches not only destroy any habitat in their path but also block the river inundating the valley upstream. Once the dam is overtopped, large floods occur like the 1876 flood of over 56,640 m^3/s at Attock. These types of flood are avoidable now due to better communication about the blockage and early depletion of the lake so formed by bombing or blasting.

Those rivers that experience large floods require large spillways and embankment dams become more expensive as almost 20% of the project costs are to be provided for spillways. At Mangla and Tarbela, design flood peaks are 73,632 m^3/s and 61,454 m^3/s, respectively. Whereas two spillways of total 42,480 m^3/s capacity have been provided at Tarbela. At Mangla a flood storage space of 8 m had to be provided over and above the conservation level in addition to an orifice spillway of 25,488 m^3/s and an emergency spillway of 6,514 m^3/s.

The floods cause huge damages. The 1992 flood at Mangla with peak flow of 30,896 m^3/s caused a loss of US$ 2.0 billion in property and facilities. Several hundred persons died.

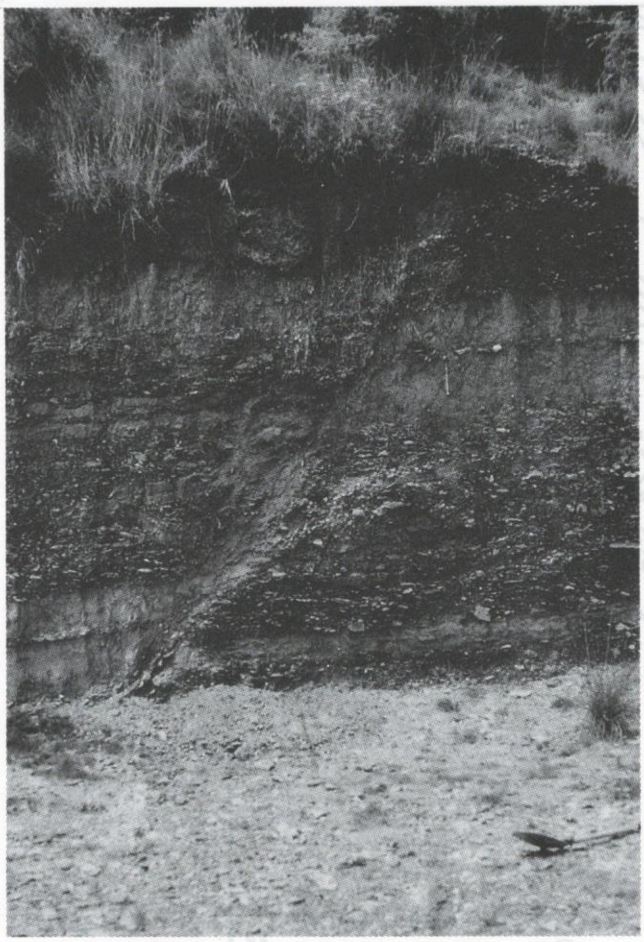

Plate 2: Deformation in Late Quaternary deposits

The designers make provisions, that the earthen embankments are not overtopped and are only concerned with the safety of embankment and route the flood by balancing outflows to inflow. In actual routing, the operator has to issue warnings downstream and sometimes wait for evacuation of people working or residing in the immediate downstream channel. Therefore, it is necessary to allow the time for decision-making by providing some flexibility to the operator of large reservoirs in the form of a few hours of flood storage to delay the balancing of outflow with inflow. This would require allowing mitigation of floods by dams having a flood protection role. Additional surcharge storage as well as efficient forecasting and telecommunicating the inflows need to be provided.

EXCESSIVE SEDIMENTATION

Another noteworthy factor accounting for the reduced benefits of schemes on the Indus River system is the siltation that takes place in the reservoirs and consequently leads to rapid depletion of live storage capacity. For instance, the average annual sediment load of the Indus at Tarbela is estimated at 350 million short tons and almost all of it is borne by the summer flood flows. The sediment load can reach 10 million tons a day. Some of it is due to current glacial action and avalanches in the upper reaches of the river and its tributaries, while some is due to landslides and river scouring in the vast piles of debris built up in the lower parts of the Upper Indus by past glacial movement and silt deposition. The lower part of the catchment has soft rocks with no vegetation cover. The Jhelum River also has a sizeable sediment load, about 110 million short tons per year.

The high amount of sediment load in rivers is a problem in Southeast Asia including China. The average sediment concentration in rivers of India and Pakistan is almost 4 to 5 times higher than in most other parts of the world. Most of these sediments are brought during rainy season viz. in 3 months of July, August, and September. The storages on the main rivers are depleted far too quickly with the result that additional storages are required far too early as irrigation supplies are affected (Table 1).

Most of the Indus catchment is not susceptible to watershed management. This is a long-term process and may not significantly contribute to sediment control in the life of the project. The watershed of Mangla Reservoir is being afforested and treated since 1967 without any apparent reduction in sediment delivery ratio of the inlet streams. The Indus has only about 11,268 km^2 of the rain-fed catchment, which is also being afforested.

Table 1: Original and present storage capacities of the Mangla and Tarbela Dams

Project	Year of completion	Original capacity 10^6 m^3 Gross	Original capacity 10^6 m^3 Live	Present capacity 10^6 m^3 Gross	Present capacity 10^6 m^3 Live	Remarks
Mangla on Jhelum River	1967	7,260	6,593	6,112	5,778	Sept. 1993 Survey
				5,946	5,724	Sept. 1997 Survey
Tarbela on Indus River	1974	14,322	11,976	11,482	10,136	Sept. 1995 Survey
				11,114	8,955 @ W, 1369	Sept. 1997

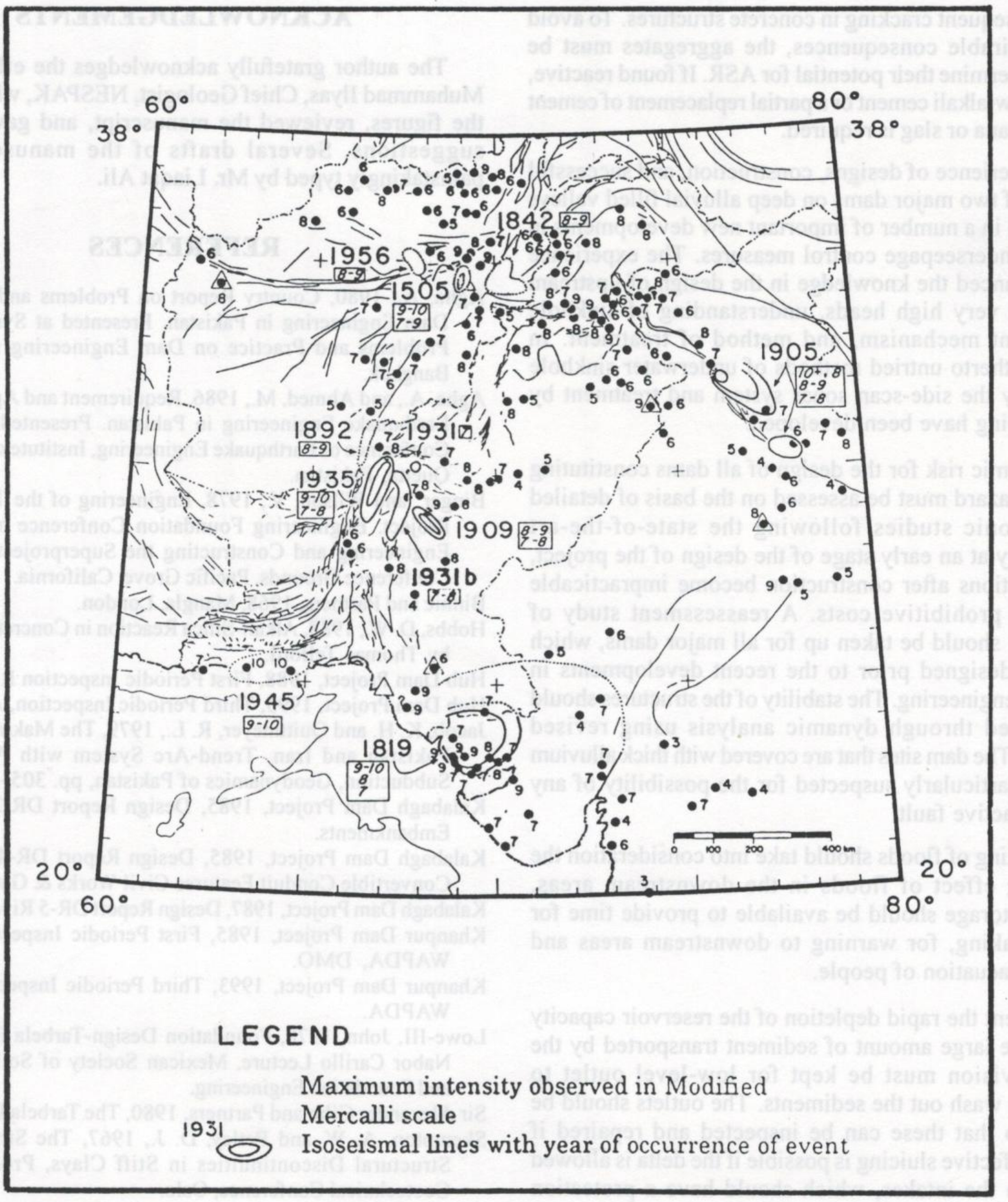

Fig. 10: Map of maximum observed intensities

CONCLUSIONS

The presence of shear zones in soft rocks can cause serious design problems. These problems were very bitterly realised and appreciated during the construction of the Mangla Dam Project. The concept of using residual strength along sheared surfaces instead of the peak strength was developed at this project and later utilised during the design of the Kalabagh Dam, where a great deal of further research on this aspect was carried out. In fact, the Mangla experience has universally changed the state-of-the-art in dealing with overconsolidated clays, especially in tectonically disturbed areas.

Gypsum as secondary deposit generally occurs in some rock formations. The removal of gypsum by dissolution can increase the seepage underneath the dam foundations and in dam abutments. To counteract this, a network of grouting and drainage needs to be provided to isolate the gypsum deposits from the seepage path.

The aggregates for concrete are considered suitable if they have requisite properties such as gradation, abrasion, soundness, and specific gravity. However, it should be realised that alkalis of cement react with the siliceous constituents of aggregates resulting in expandable silicate gel and subsequent cracking in concrete structures. To avoid such undesirable consequences, the aggregates must be tested to determine their potential for ASR. If found reactive, the use of low-alkali cement or a partial replacement of cement with pozzolana or slag is required.

Our experience of designs, construction, and successful operation of two major dams on deep alluvial filled valleys has resulted in a number of important new developments in design of underseepage control measures. The experience gained advanced the knowledge in the design of upstream blanket for very high heads, understanding of sinkhole development mechanism, and method of treatment. In addition, hitherto untried methods of underwater sinkhole detection by the side-scan sonar system and treatment by barge dumping have been developed.

The seismic risk for the design of all dams constituting major life hazard must be assessed on the basis of detailed seismotectonic studies following the state-of-the-art methodology at an early stage of the design of the project, as modifications after construction become impracticable because of prohibitive costs. A reassessment study of seismic risk should be taken up for all major dams, which have been designed prior to the recent developments in earthquake engineering. The stability of the structures should be rechecked through dynamic analysis using revised parameters. The dam sites that are covered with thick alluvium should be particularly suspected for the possibility of any subsurface active fault.

The routing of floods should take into consideration the devastating effect of floods in the downstream areas. Surcharge storage should be available to provide time for decision-making, for warning to downstream areas and probable evacuation of people.

To prevent the rapid depletion of the reservoir capacity owing to the large amount of sediment transported by the rivers, provision must be kept for low-level outlet to periodically wash out the sediments. The outlets should be designed so that these can be inspected and repaired if required. Effective sluicing is possible if the delta is allowed to approach the intakes, which should have a protection wall so that coarser sediments do not damage the power installations.

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