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ENGINEERING ECONOMICS OF THE DESIGN AND CONSTRUCTION OF DAMS

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Chapter I

INTRODUCTORY

Chapter II

GEOLOGIC INVESTIGATIONS

Chapter III

DESIGN

Chapter IV

RESEARCH—HYDRAULIC MODELS

Chapter V

CONSTRUCTION PLANNING

Chapter VI

CONSTRUCTION PLANT LAY-OUT

Chapter VII

CONSTRUCTION PLANT AND CONSTRUCTION METHODS

Chapter VIII

ALTERNATIVE CONSTRUCTION AGENCIES

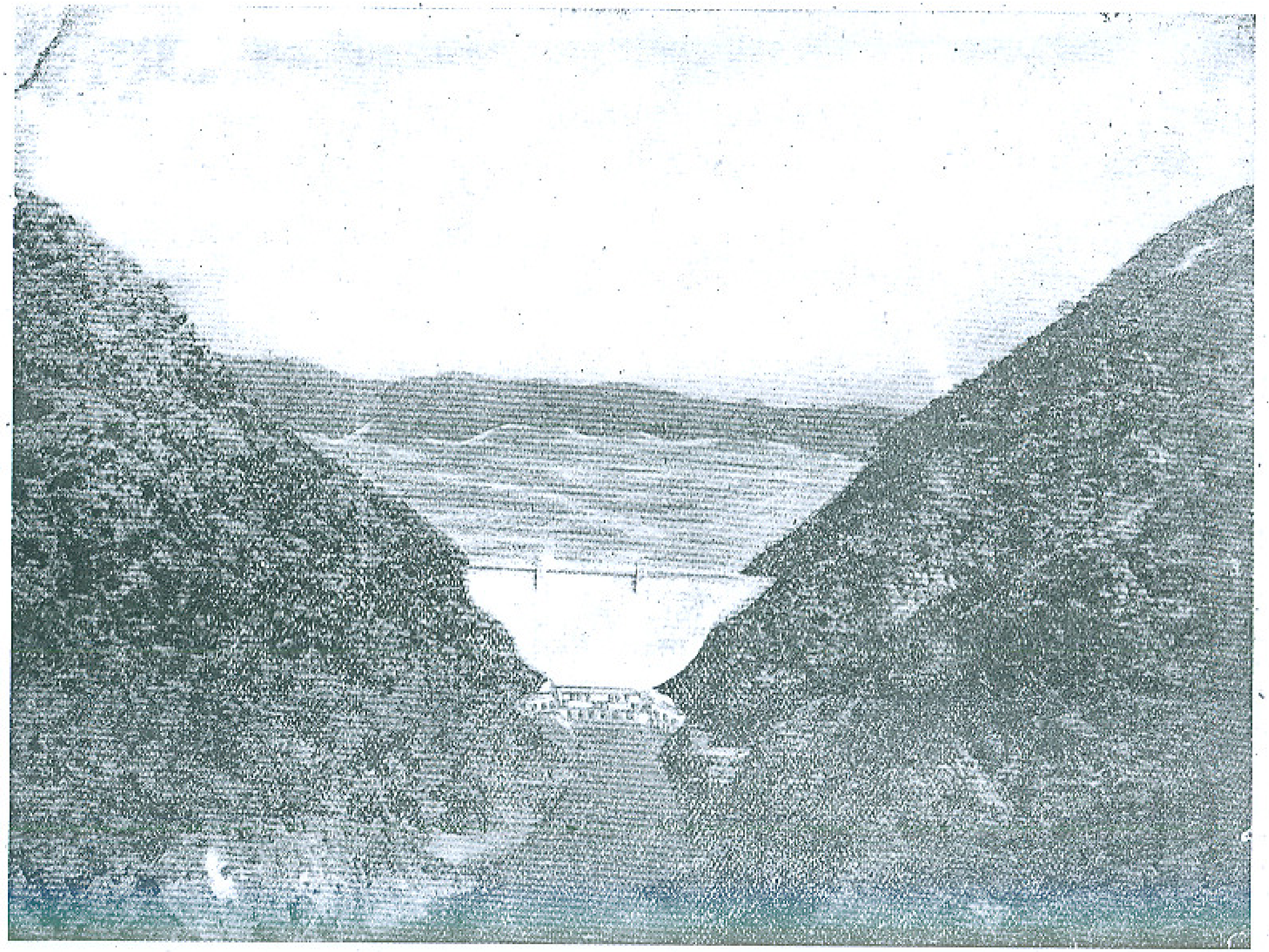
Chapter IX

PUNJAB PROJECTS

402

Appendices

List of Plates



Bhakra Gorge Showing the Proposed Dam.

CHAPTER I

INTRODUCTORY

1. **Authors' deputation to the States.** The authors were sent on deputation to the United States of America by the Punjab Government to study the design and construction of high dams in view of the proposed construction of Bhakra and other dams in the near future. While in the States * they visited most of the important dams in operation, as well as under construction and had access to a lot of useful literature on the subject including several unpublished reports by the Bureau of Reclamation and the Tennessee Valley Authority, which the authorities concerned were kind enough to place at their disposal. In addition, they had several interesting discussions with leading authorities connected both with the design and construction of high dams. They have, therefore, taken this opportunity of placing some of the information collected by them before the members of the profession, in view of the importance of the subject to this Province.

2. **India and its needs for industrial development.** The total area of India is 18,05,000 sq. miles and the population is estimated to be 400,000,000 or 222 per sq. mile. The yearly increase even on a conservative basis is estimated to be over 5,000,000. The present standard of living is one of the lowest in the world. The *per capita* income (before the war) was Rs. 66 a year in India as against 1,406 in U.S.A., 1,038 in Canada, 980 in United Kingdom and Rs. 792 in Australia. The mortality rate is very high particularly infant mortality. The expectation of life in India is 27 years against 59 years in Canada 60 years in Germany, 62 years in United Kingdom and U.S.A. and 65 years in Australia. The pressure on the land, on which 75 per cent of the people depend for their subsistence, is on the increase due to the increase in population, but there is no corresponding increase in the irrigated area. This must naturally result in further lowering of the standard of living unless some of the population can be diverted to industries.

In the Tennessee Valley Authority, with an area about $\frac{4}{5}$th of Punjab and a population of $4\frac{1}{2}$ millions, the total power generated at present is over 10 billion K.W. hours per annum which is equivalent to 120 billion men hours, representing 60 million people working 8 hours a day, for 25 days a month throughout the year. With this enormous increase in the effective man power, the increase in the productivity of the region can be easily visualised.

The economic potential of India is very high. The human factor which is considered a liability at present may become a great asset, especially as the resources of India are plentiful. These resources can be effectively tapped only by increased power output and industrialization

3. **Economic significance of irrigation.** In addition to industries, it is also necessary that more areas should be brought under cultivation

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* For Major Dam Sites in U. S. A. see Plate 6.

and the yield of crops increased where possible. The present yields are insufficient and capable of substantial increase. For instance, in 1939-40 the yield per acre of rice was 1·01 tons in U.S.A. and 1·61 tons in Japan and only ·35 tons in India. Similarly the yield of wheat was ·52 tons in India In respect of sugar cane, Java produced 54·91 tons, U.S.A. 20·06 tons and India only 12.66 tons per acre. The out-turn of raw cotton was 515 lbs per acre in Egypt, 246 lbs in U.S.A. and only 100 lbs per acre in India. There is thus considerable scope for increased yields with better seeds and manuring and the adoption of scientific methods of farming.

4. **Scope of the paper.** The construction of dams at suitable sites would afford considerable facilities for generation of cheap power as well as for extension of irrigation in various parts of India.

This paper covers the economics of the various aspects of design and construction of dams. It deals with the preliminary investigations necessary before the design of a dam can be taken in hand as also the general considerations governing the design of various types and the importance of model experiments in the design. The various aspects of construction planning are then dealt with in brief and by way of illustration one of the studies for the construction plant lay-out for the Bhakra Dam is given. The paper ends with the details of construction plant and construction methods, with special reference to dams and briefly outlines the alternative construction agencies employed in the States. A brief review of some of the possible Punjab Projects is also given.

5. **Acknowledgments.** A bibliography has been added to indicate the important references consulted. As most of the notes were compiled while the authors were on the move in the States there may be some omissions which, however, are not intentional.

The authors are grateful to Mr. T. A. W. Foy for various discussions with him which enabled them to clarify their ideas on the subject.

402

CHAPTER II

GEOLOGIC INVESTIGATIONS

1. **General.** The Engineer has to consider, early in the study of new projects, what effects natural conditions will have on cost and ultimate success of construction. It is now recognized that Geology provides a means to anticipate and understand these conditions. Thus essential foundation conditions can be determined in advance of construction to ensure that safe and successful dams may be built by providing the necessary foundation treatment.

2. **Geological work required for a large dam.** The Geologic work required for a large dam falls into three stages :—

(*i*) *Preliminary investigation.* This embraces more than a brief reconnaissance study as it includes the study of physiography, stratigraphy and geologic structure, of the area involved.

(*ii*) *Exploration.* In this stage the development of the details of structure, and rock conditions is involved. The work comprises drill holes, trenches, pits and tunnels.

(*iii*) *Construction.* Throughout the construction period, large scale drawings are made showing the details of geologic features that have bearing upon engineering problems.

3. **Points to be considered in the interest of large dam construction.** The following are the main points that need specific consideration in the interest of economic large dam construction :—

(*i*) Character and distribution of formations.

(*ii*) Structural features of rocks such as joints, contacts, sedimentary beds, folds, faults, fissures and shear zones and the altitude, spacing and openness of joints.

(*iii*) Extent and effects of weathering.

(*iv*) Thickness and character of over burden.

(*v*) Amount of stripping required in preparation of foundations.

(*vi*) Adequacy of support under probable operating conditions.

(*vii*) Identity and importance of soluble foundation materials or those readily entrained.

(*viii*) Special treatment of defective members.

(*ix*) Considerations involved in tunnels, spillways, outlet works.

(*x*) Opportunity for leakage and suggestions for control.

(*xi*) Elevation and shape of ground water table which may determine losses from reservoir.

(*xii*) Siesmic stability of region.

(*xiii*) Availability and kinds of construction materials.

(*xiv*) Effects of silt laden streams entering reservoir.

(*xv*) Scouring action of released water below dam.

4. **Core drilling and logging of holes.** To accomplish the above objects, the geologist has to undertake detailed surface mapping followed by exploratory work by means of core drills. These drills can bore holes up to 4 feet diameter and 300 feet depth in which the engineer or geologist can enter and visually examine the exposed section of the rock in place. The drilling is done by a rotating cylinder of the proper diameter employing shot as a cutting medium. The core is broken loose from the bottom of the hole by small charges of explosive.

Modern exploration practice employs the use of core boring, wherever core recovery is feasible. The choice of core-boring equipment —diamond drills, steel cutter, or shot drill—depends on the nature of material, time and cost factors.

Competent and careful attention should be given to the logging of the holes with adequate description of the condition of the material. Other pertinent data particularly the behaviour of water in the hole during drilling is important as loss of water or the encountering of the flow of water yields evidence of openings in the rock, thereby indicating that expensive foundation treatment would in all probability be needed.

Side by side with the drilling of exploratory holes, attention has to be given to grouting as this gives valuable information regarding the existence of openings in the rock. The pressure to be used for such grouting is generally limited to one lb per ft. of width so as not to enlarge openings by lifting the rock.

In certain phases of dam site exploration, geophysical methods have useful applications. Their function is the determination of thickness of the alluvium or overburden, including weathered rock. Concealed rock surfaces are determined by either the electrical resistivity method or the siesmic method.

It is very useful to record the results of drill hole explorations on three dimensional models showing the space relationship of the geological features. These may either consist of pegs on which the log of the hole is indicated or may be constructed of transparent celluloid.

In any rock whether granitic, metamorphic, volcanic or sedimentary, the main factors to be considered are : the bearing strength and elastic properties, resistancy to sliding, leakage beneath or around the dam and the effect of weathering.

5. **Preparation of foundations for various types of rocks.** The preparation of foundations on the various rocks generally involves the following procedure :—

(*i*) *Metamorphic rocks.* The excavation involves removal of disintegrated and decomposed rock and of all loose unweathered rock in which the joints, cleavage and other planes of weakness have been unduly opened by surface agencies. The main hazard in this case is sliding and added resistance may be given, where necessary, by providing a saw-tooth outline.

(*ii*) *Volcanic Rocks*. A secure dam can usually be built with provision only against uplift and piping if the lava foundation offers adequate support.

Various remedial measures have been successful, including grouting, concrete cut-off walls in the permeable layers and blanketing.

(*iii*) *Granitic Rocks*. The problems in this case resolve largely into questions as to depth of excavation and requirements for grouting and drainage.

(*iv*) *Sedimentary Rocks*. In the case of sandstone, the excavation of the overlying alluvial material and of all unsound rock is necessary. No special treatment is required to ensure good bond between the concrete and sandstone.

The above remarks also apply in the case of lime-stone except that in this case the removal of undesirably thin rock covers of solution openings and the cleaning of these openings prior to filling them with concrete may be required.

The preparation of foundations on shale presents special difficulty. The shortest possible time interval should be allowed between the foundation preparation of the rock surface and placing of concrete. As concrete applied to a partially or incipiently dried shale surface forms a mud or soft clay layer, a suitable coating of water-proofing material should be applied during this interval.

In brief, the development of a slaked shale zone between the masonry and rock must be rigidly avoided.

6. **Measurements desirable after the completion of a dam.** The above would clearly indicate that a conservative principle in construction is the adaptation of design to the foundation. As the selection of dam sites is in many cases governed by factors other than geological limitations, the best plan is to keep the unit load within safe limits so as to avoid endangering the stability of the structure. Since concepts of foundations are speculative as to the long time effects of load and submergence, continued measurements are desirable during operation following completion of the dam. This can be done by the use of pressure cells, stress metres, strain metres, tilt metres. etc.

CHAPTER III

DESIGN

1. **General.** The greater portion of the investment in a hydro-electric project (generally from 65 to 80 per cent), is in the dam, spillways, reservoir, lands and riparian rights. It is, therefore, desirable to investigate very carefully the possibility of savings in all items relating to dam construction. For any particular case, it is possible to utilise a type of dam which is specially suitable and economical for the given conditions. For example, a material saving can be effected in some cases if, instead of having a long spillway section of dam, provision is made for passing the flood water through section of gates and the rest of the dam is made a non-overflow masonry section or even an earth or rockfill dam.

Multiple arch and flat slab R. C. dams sometimes work out more economical under certain conditions, than other types. Alternative plans for various types of dams and spillways should thus be analysed to determine which type will give the lowest costs for the given conditions.

2. **Considerations governing the selection of types of dams.** As soon as the preliminary surveys for any dam site have been completed, the data regarding water supply studied and the foundation conditions investigated, the next point for consideration is the selection of the type of dam. The type will, in general, be governed by the following considerations :—

(*i*) *Availability of materials.* In a location away from railroads or highways, an earth or rockfill dam may be most suitable from an economical viewpoint. On the other hand a concrete dam may be more desirable where transportation facilities are available for cement and aggregate.

(*ii*) *Safety of the structure.* A consideration, of the question of safety or permanence of the dam would also influence the selection of type. In the case of dams located away from centres of habitation and valuable property, cheap and inexpensive type like earth dams are preferable even at some sacrifice in the degree of permanence.

(*iii*) *Suitability of foundations.* The perviousness, bearing power, erodability, homogeneity and continuity of the foundation material have all to be examined most carefully in view of their influence on the cost and permanence of a dam. Generally a flexible type of dam is constructed on a flexible foundation and a rigid type on rigid foundation. This would imply the building of earth dams and to a lesser extent rockfill dams on earth, sand, or gravel foundations on masonry dams on solid rock foundations.

(*iv*) *Height of dam.* Low masonry dams of 25 ft. or less can be successfully founded on silt and fine sand, of 30 ft. or less on clay, of

50 ft. or less on compact gravel or thick beds of clean course sand and generally up to 700 ft. on solid rock foundations. The highest dam in the world at present is the Boulder Dam which stands 726 ft. high above bedrock.

3. **Masonry dams.** The principal types of masonry dams in use these days are the solid gravity or single arch type. Of these, the solid gravity types are most popular except where narrow canyon widths make the arch type preferable. The limiting height of the gravity dam will be determined by the allowable working stresses in concrete and the type of foundations available. It may be possible to build a low gravity dam successfully and economically by using a suitable cut off even in pervious foundations. The arch gravity type is generally preferable where the canyon span is relatively narrow and the abutments consist of sound rock capable of taking the arch thrusts. The uplift of the water is also not so important in this type as in the gravity type. An arch gravity type is used sometimes where the arch length or the radius of curvature is not too great and where the abutments are capable of withstanding high pressure or where the foundation contours make it more economical to follow a curved plan. In regions of heavy seismic activity, gravity dams are considered safer than arch dams.

4. **Flexible dams.** The main types of flexible dams are rockfill and earthfill dams, the latter being further sub-divided into hydraulic fill and rolled fill types. These are generally used where the foundation material is relatively unstable and pervious or where the cost of a concret dam would be uneconomical. It may be remarked that these flexible dams are generally placed in locations where there is no possibility of their being overtopped by water overflow. Overflow spillways should not, therefore, be built on such dams. This feature would in some cases over-ride the considerations of economy.

5. **Development in the field of design.** There have been considerable advances in construction methods on large dam projects in recent years which have gone hand in hand with the evolution of design methods. The result has been a marked improvement in quality as well as economy in construction.

In the field of design, one of the most important developments has been the evolution in methods of analysing stress conditions coupled with an increase in the allowable working stresses. It has been recognised that the safety of a structure should be considered on the basis of the three dimensional state of stress rather than on the basis of the maximum direct stress in one direction as used to be done in the early days. This has led to a better appreciation of the methods of analysing effects of foundation and abutment deformations and methods of determining the true non-linear distribution of stress in the system.

This is done by what is commonly known as the trial load method of analysis. The horizontal waterload is divided between the arches and cantilever so that the calculated arch and cantilever deflections are equal at all conjugate points in the interior of the dam, and in a large foundation block which is included in the analysis, as an integral part of the structure. The load distribution required to fulfil this criterion is determined by trial which accounts for the name by which this method is known. When the deflections are in satisfactory agreement, the arch and cantilever stresses are calculated and considered to be the true stresses in the dam.

Local stress concentrations may be studied by theoretical analytical methods, by photo-elastic tests or by actual measurements, on small laboratory models; the results obtained by all these methods have been found to check satisfactorily.

Another marked advance in design has been a change in conception of the sliding factor, which used to be determined by simply calculating the ratio of the total horizontal force to the total vertical force. The new method, proposed originally by the late D. C. Henny in 1933, includes allowances for shearing strength also. The main uncertainity involved in evaluating the shear friction, factor of safety, is the determination of the average shearing strength of a material. Values of shearing strength used in calculating shear friction factor of safety for dams built by the Bureau of Reclamation have varied from about 300 to 700 lbs per square inch depending upon the characteristics of concrete and rock specimens as determined by laboratory tests. The value of the friction co-efficient is taken as ·65 and the minimum shear friction factor of safety is kept greater than 5 during the worst conditions of reservoir load and earthquake acceleration.

In the case of an arch dam an economical and relatively simple structure will result when the ratio of length to height does not exceed about 2·5 to 1. The ideal site for an arch dam is thus a canyon having a small ratio of length to height and having reasonably sound abutments which are nearly symmetrical. When the length to height ratio reaches 5 to 1, a considerable proportion of the waterload is carried by gravity action instead of being transmitted to the abutments by arch action and the arch becomes quite massive so that the suitability of this type becomes doubtful.

The economical central angle of an arch in accordance with the elastic theory is approximately 150° to 160° and special cases in which high temperature stresses are used, give values close to 180°. According to R. S. Lieurance, the most economical central angle can be obtained only for one set of working conditions, and the most economical angle can seldom be used due to the abutment and foundation conditions, as the angle of the resultant at the abutment may be of greater importance.

In an arch dam, the zone of higher stress is likely to occur at about 2/3rds of the height of the structure at which point most of the load is carried by arch action. The examination of a given section at this point using the full water load may disclose a weakness or overdesign in the structure, and eliminate the necessity of making a detailed analysis of the entire dam. It should also be noted that of the three adjustments required to be done in a trial load analysis, *viz.* radial, tangential and twist, the first is really the most important, and need only be carried out in the preliminary design of a dam. The complete analysis should be done to determine stresses in the design finally adopted.

6. **Economics in earth dam construction.** As a pre-requisite to the design of earth dams, the available material from both borrowpits and foundation must be explored and tested in the soil laboratory. Based on these soil tests and repeated field placement methods, safe average values for friction and cohesion are determined. On the basis of these data the dam is ordinarily proportioned by the so called Swedish Slip Circle method to give a factor of stability of at least 1 : 5 for normal conditions and 1 : 3 for the exceptional conditions resulting in the upstream face from rapid drawdown of the reservoir. In localities where the borrow material is deficient in friction and cohesion characteristics it is often advantageous to provide embankments consisting of a rolled fill core supported by external rockfill shells, as in the case of Anderson Ranch Dam, which was visited by the authors during construction.

A freeboard of from 10 to 15 ft. over the reservoir level for maximum flood conditions is provided against a minimum freeboard of 7 ft. for concrete structures. The assumed maximum floods are derived from runoff studies and the resulting flood magnitude may be summarised approximately by the formula :

$Q.=5{,}000\sqrt{\text{Drainage area}}$, in the case of dams in the U. S. A. Sufficient spillway capacity is thus provided to discharge floods without exceeding the normal maximum pool elevation.

7. **Drainage and inspection galleries.** Every large masonry dam is provided with inspection and drainage galleries. These usually run parallel to and at a distance of from 10 to 30 ft. from the upstream face of the dam and extend up the slopes along the abutments, within the dam to elevations within 25 to 50 ft. of the top of the dam.

8. **Cavitation effect in spillways.** The term " cavitation " is used to denote the phenomena of destruction and subsequent erosion of materials in high hydraulic structures due to the " sucking " action caused by the occurrence of very high velocities. The damage results from the formation of cavities or low pressure regions in the flowing liquid followed simultaneously with the impact of high pressure liquid masses on the surface of the material which gets " pitted." Cavitation has been variously attributed to chemical or electro-chemical action. There is, however, reason to believe that the action is largely mechanical and provision should, therefore, be made in the civil engineering design to minimise the risk of damage by this phenomena.

The harmful effects of cavitation in a spillway are :—

(*i*) Erosion of the concrete.

(*ii*) Reduction of the co-efficient of discharge and the consequent falling off of capacity.

(*iii*) Vibrations in the structure caused by the periodic nature of the formation and collapse of the cavities in the fluid.

An extensive study of the various dams in the United States leads us to conclude that the spillway problem is not yet fully solved. None of the spillways of the major dams has been tested to more than 40 per cent of the designed capacity and even then there has been trouble.

One prominent instance of damage has been the Arizona side spillway tunnel at Boulder Dam. This was first placed in operation in August 1941 and in December of the same year, an eroded area was discovered in the bottom of the curve connecting the horizontal and inclined portions of the tunnel. The hole was 115 ft. long 30 ft. wide and had a maximum depth of 45 ft. below the invert grade. All the damage occurred with an average flow of 13,500 cusecs whereas the designed capacity of each spillway is 200,000 cusecs.

The Bureau of Reclamation has since repaired the damage, the principal cause of which was believed to be misalignment of the tunnel a few feet upstream of the eroded area.

Pitting due to cavitation has also occurred on the Boneville Dam built by the Corps of Engineers. The spillway here consists of eighteen 50 × 50 stoney gates on a concrete ogee section about 75 ft. high. Water is discharged beneath the gates under a head of 50 ft. Erosion has occurred on the sides of spillway gate piers as well as on the crest. It could not be definitely concluded as to whether the cause was abrasion or cavitation.

The repairs were first executed by refilling the holes due to "pitting" with good sound granite made with standard Portland Cement but even this did not stand. The vulnerable area was then lined with ½ inch thick steel plates backfilled with concrete and anchored to the existing reinforcement. This has stood better but pitting has reappeared even piercing the plate and again attacking the concrete.

Damage by cavitation has also been experienced by the T.V.A. at the Norris Dam sluices. In order to safeguard against similar damage at the Hiwassee, Cherokee, Douglas and Fontana Dams, the Authority made model tests and modified the curvature at the entrance of sluices until the pressures at all points were high enough to avoid cavitation.

The best assurance against pitting in new structures can be secured only if "cavitation" is prevented. This can only be done if there is intelligent collaboration between the design office and the hydraulic laboratory. The designs have to be "streamlined" and sharp curvatures, vortices, eddies and high local velocities have to be avoided.

Due to the serious nature of the damage that can be caused by cavitation in an inclined tunnel spillway of the Boulder type, it is more essential to be conservative in the design of the spillway arrangements for Bhakra Dam. Accordingly extensive investigations are necessary to ensure the safest design and for this purpose a number of studies are being carried out.

402

The alternatives that appear to be suitable are :--

(*i*) Two tunnel spillways consisting of inclined tunnels as in the Boulder Dam discharging into the diversion tunnels which will be utilized as permanent spillways, after they have served to divert the river for construction purposes. The powerhouse would be located at the toe of the dam.

(*ii*) An overflow spillway and one tunnel spillway with the powerhouse located on the downstream left side.

(*iii*) Spillway arrangement to be the same as in (*ii*) above, but powerhouse would be located both on the left and the right sides in order to obtain the ultimate power development.

(*iv*) Another scheme under consideration is to drive two tunnels under the ridge about 17 air miles upstream of the present dam site and bypass the surplus discharge of the river through these tunnels into the parallel reach below. These tunnels will be about three miles long. They will help the initial diversion at the dam site and also prevent nearly half the silt load from going into the reservoir and thus protect it against sedimentation and loss of capacity. This scheme will be a more progressive feature than even the American high dams where no direct provision exists for desilting. In the absence of a detailed estimate, it is too early to say whether this scheme will be feasible from the point of view of cost and time involved.

Dissipation of kinetic energy of the water discharged through any type of spillway is one of the most essential features of a high dam, and is secured through the provision of a "bucket" which throws up the jet and thus kills a good deal of its force through the action of gravity. At the Boulder Dam, the velocity of the current through the spillway tunnel reaches a maximum volue of 150 ft. per second and this necessitates the utmost care in the design, construction and specifications for this portion of the job.

9. **Main types of spillways.** The main types of spillways generally used are :—

(*i*) *Chute spillways.* This is a type of spillway isolated from the dam having its crest normal to its centre line and having a discharge channel to the river in an excavated trench which is usually paved with concrete in whole or in part. This is generally used in dams composed of earth or rock, or for dams over which it is undersirable to pass floods.

(*ii*) *Side channel spillways.* In this type the flow after passing over a weir or ogee crest is carried away by a channel running essentially parallel to the crest. This is used for earth or rock fill dams in narrow canyons and for other situations where direct overflow is not permissible and where the space required for a chute spillway of adequate crest length is not available. Usually it is necessary to line the spillway channel with concrete and the channel should thus be selected in such a way that the wetted perimeter is minimum ; also the total combined cost of the concrete and excavation should be minimum.

(*iii*) *Shaft spillways.* This is also sometimes called a "Morning Glory" spillway and consists of a vertical flaring funnel which connects with an outlet conduit extending through or around the dam.

There are two types of shaft spillways, the first having a standard crest and the second a flat crest.

It is essential to have model tests in the case of these spillways to determine the location and amount of negative pressure obtained with different heads.

(*iv*) *Syphon spillways.* These are sometimes used in overflow dams where it is desirable to secure a large discharge of water with a small fluctuation of water level in the reservoir. These are of two general types ; the water sealing and the self-sealing type. The water scaling type has the outlet end of the syphon submerged in water. In the self sealing type, however, the water flowing through the syphon seals the discharge end.

10. **Selection of turbines.** The first problem that arises in planning a new hydro-electric project is the selection of the proper type of turbine and its speed to suit the given conditions of power capacity and effective head. This is done by the use of the specific speed principle of which the fundamental relation is

$$N = N_s \frac{H^{5/4}}{\sqrt{H.P.}}, \text{ where}$$

N = Rotary speed of any turbine.

N_s = is the specific speed or the speed of a homologous 1 H.P turbine under 1 ft. head.

H = Effective head.

The value of N can thus be readily determined on the results of tests on laboratory models of homologous turbines. For this reason manufacturers keep available, test records for an extensive series of designs of progressively varying characteristics and giving satisfactory performance.

Another basic characteristic governing the design of a turbine is the critical σ_c (sigma) or degree of resistance to cavitation, which occurs on the vanes of a turbine if the local pressure head becomes so low as to approach the vapour pressure of the water. This causes the alternate formation of a cavity filled with vapour and its subsequent collapse due to condensation, resulting in a series of sudden explosions, which in course of time cause pitting and wear away the metal.

The requisite margin of safety against cavitation of the turbine may be secured either by placing the runner relatively deep with respect to tail water with an attendant increase in cost for the deeper structure or by locating the runner fairly close to tail water and installing a turbine of larger diameter operating somewhat below its actual power capacity. In the last analysis, determination of this feature becomes a problem in economics. The increased cost of structures and the decreased cost of smaller higher speed generating machinery in the one case, is balanced against the less expensive structures and the larger diameter turbines and generating machinery operating at proportionally reduced speed in the other case.

For sites where the overburden is heavy and sound foundation rock is deep with respect to tail water, the design will naturally gravitate to the deep type of setting. However, for projects where the foundation rock occurs at a high elevation with respect to tail water, with comparatively small overburden, the natural choice will be the bigger slower wheel and the shallower type of structure.

It may be stated here that it is usual practice in the United States that manufacturers are co-opted in the design as well as the installation of the hydraulic runners and this procedure results in the latest knowledge and technique in this specialized subject to be incorporated in the final selection.

It is advisable to have all the units in any one plant of the same design and size, as this simplifies repairs and replacements and is more economical.

11. Economies in design cost. It is possible to effect considerable economies in the design costs by having a central organisation and a proper control over the operations in the field. In this connection it will be interesting to record that design costs on the T.V.A. projects decreased from 2 per cent in 1941 to slightly more than 1 per cent in 1942 although there was a marked increase in the volume of design work. This economy was the result of the following factors :—

(*i*) Exclusive use of the pool rather than the project system of design.

(*ii*) Insistence upon the principles of standardization in design on various projects.

(*iii*) Formulation and close observation of sensitive production indices.

(*iv*) Insistence upon complete definition and approval of all foundamental elements of the economic design before undertaking rapid mass production of detailed drawings.

(*v*) Rigid adherence to established lines of organization.

The general grounds were, of course, specially evolved at the T.V.A. because of the numerous projects that they tackled in their 10 years regional planning. The principles are, however, instructive and can, with modification, be applied to the design organization in the Punjab.

CHAPTER IV

RESEARCH — HYDRAULIC MODELS

1. **General.** A model has been defined as a system by whose operation the characteristics of other similar systems may be predicted. Hydraulic model studies are being used increasingly for checking and modifying the analytical designs of hydraulic structures.

2. **Conditions of similarity in model and prototypes.** The flow systems in the model and prototype are dynamically similar when boundary conditions and streamlines are geometrically similar and when homologous forces in the two systems bear a constant ratio to each other. The forces present in moving water in addition to inertia are gravity, viscosity, elasticity and surface tension. The dimensionless ratios derived from a consideration of the above forces are :—

(*i*) Froude's number (F) which expresses the condition for similarity of gravity and inertia forces.

(*ii*) Reynold's number (R) which expresses a similar condition for similarity of viscous and inertia forces.

Similar numbers relating to surface tension and elasticity are Weber's number and Cauchy's number.

These, however, are not of much practical importance.

The three types of flow commonly met with are :—

(*a*) Laminar flow as in smooth pipes at very low velocities or seepage through sand, etc., when R is less than 2,500.

(*b*) Turbulent flow in short pipes or open channels with higher velocities where R is greater than 2,500 and

(*c*) Shooting flow with very high velocities in open channels where v is greater than $\sqrt{g \times \text{depth}}$ = (critical velocity).

In the case of (*a*) Reynold's number is the criterion of dynamic similarity as the viscosity forces are dominant.

In the case of (*b*) and (*c*) however, the Froude number is the criterion as gravity forces are dominant.

As most of the hydraulic studies deal with turbulent flow, Froude's number is most important. A good practical criterion for ensuring turbulent flow in river models is to keep velocity in feet per second X depth in feet = .02 or more.

The dimensionless ratio for the Froude number is expressed as $\frac{V^2}{gL}$ where

V = velocity.
g = acceleration of gravity.
L = any length parameter influencing flow.

If Froude's number is the criterion for similarity and L_r the scale ratio of prototype to model then it can be easily shown that the

Velocity scale	$= (L_r)^{\frac{1}{2}}$
Discharge scale	$= (L_r)^{\frac{5}{2}}$
Time scale	$= (L_r)^{\frac{1}{2}}$
Slope scale	$= (L_r)^{2}$
Power scale	$= (L_r)^{7}$
Work scale	$= (L_r)^{4}$

The choice of either the length scale or the discharge scale thus fixes all other scales and the size of the models.

In the case of rivers where roughness of the channel plays a large part, it can easily be determined by using the Manning's formula that

$$n_p = n_m (L_r)^{6}, \text{ where}$$

n_m and n_p are the co-efficients of roughness in the model and the prototype.

3. **Distortion in models.** Sometimes on account of space limitations the model has to be distorted as the water surface slopes obtained in an undistorted model are so flat that these are not capable of accurate measurement. Distortion may be done by tilting the model arbitrarily, changing the discharge scale, by using different horizontal and vertical scales or by changing the roughness. In such cases

$$V_r = D_r^{\frac{7}{6}} / (L_r)^{\frac{1}{2}} n_r$$

$$S_r = D_r / L_r$$

$$\text{and } Q_r = (L_r)^{\frac{1}{2}} (D_r)^{\frac{13}{6}} / n_r, \text{ where}$$

V, D, L, Q and n represent velocity, depth, length, discharge and roughness respectively and r denotes the ratio of model to prototype.

In case where gravity and friction forces have to be satisfied simultaneously $h_r = (D_r)^{\frac{7}{6}} / L_r$,

which reduces to $(L_r)^{\frac{1}{6}}$ for undistorted models.

4. **Typical model studies.** Some of the typical model studies which have to be done in connection with a dam are :—

(*i*) *Spillway design.* The authors had an opportunity to study a model of the spillways of the proposed Bridge Canyon Dam in the laboratories of the Bureau of Reclamation where tests were being made in connection with the dimensions, shape and inclination of the bucket sections at the exit of inclined tunnel spillways. These model studies are also used for determining the type of spillways or the shape of the crest and the discharge co-efficient.

(*ii*) Design of penstocks and outlet works.
(*iii*) Gate discharge co-efficients.
(*iv*) Performance of valves.
(*v*) Stilling basin characteristics : to avoid scour and side erosion.
(*vi*) Tower intake structure.
(*vii*) Emergency gate loads.
(*viii*) Lockfilling system.
(*ix*) Design of turbines.
(*x*) Cavitation studies.
(*xi*) Fish ladder design.

5. **Limitations of modelling.** Any hydraulic model gives excellent results in cases in which friction plays a relatively unimportant part and if it is not built on too small a scale. In the case of river channels, a model can only be expected to indicate the probable direction and magnitude of velocities, the presence of underneath eddies, tendencies towards silt and scour and an approximation of back water effects.

A model designed in accordance with Froudes' Law will not represent the effects of friction and a model designed to stimulate friction forces may not be correct with respect to gravity forces.

This limitation of models should be clearly borne in mind. Phenomena involving waves are also very difficult to study on a model as gravity waves in the prototype may on scaling down, become capillary waves in the model, both of which follow different laws. In the case of distorted models, the distribution of velocities and water levels should be accepted only after very thorough consideration.

6. **The economics of models.** The proportion of the cost of models to the cost of proposed structures is naturally a variable factor. In the case of model tests on the dams of the Muskingum Conservancy District, the cost of model tests was only 0. 2 per cent of the total cost. The model tests for a single project are likely to be more expensive but it can easily be asserted on the basis of experience of both the Bureau of Reclamation and Tennessee Valley dams built in recent years that considerable economies can be effected by model testing which repay many times over the expenditure incurred on the model studies.

CHAPTER V

CONSTRUCTION PLANNING

1. Fundamentals of heavy construction planning

(*i*) *General.* The general trend in heavy dam construction to-day is towards closer co-operation between engineer, designer and builder, more through administration and control of construction equipment, more careful planning of plant and more studied attention to processes and methods. All these things make for finished structures of higher quality at low cost.

The importance of proper planning in a construction plant is being more universally recognised by the construction industry to-day than ever before. One of the basic principles early established in connection with equipment purchases in the T. V. A. was that the lowest construction costs usually result from the use of the best and not necessarily the cheapest equipment in the market. Specifications should therefore be written after a thorough study of the merit of all the different types of equipments on the market.

(*ii*) *Size of plant.* The size of the plant is of primary importance. A tendency to under-plant a job should be avoided at the same time not "overplanting" it.

(*iii*) *Impoɿtance of proper selection of plant.* Once the plant is designed and built, the entire job is practically fixed. If the plant is right the job has a flying start and will run smoothly. If wrong, it costs more to change as a general rule than can be saved. Errors in any selection of plant or equipment not only retard construction progress in general but also lower the morale on the entire job.

The heart of the construction plant on any large concrete dam project is the *concrete mixer plant.* The efficiency of this unit controls the output of concrete and determines the maximum rate of concrete placing. The other parts of the construction plant should be built to maintain the capacity determined upon for the mixer plant in order to ensure a balanced installation.

The control of the cement and waterbatching is automatic in modern plants. This tends to simpler plant design and simpler maintenance with only small additional operating cost.

(*iv*) *Importance of standardization.* One important principle to be kept prominently in view is that special equipment is an essential part of heavy construction, but on every individual job there are opportunities for employing standard equipment or hand labour for maximum economy. Careful planning and experienced judgment will keep these methods in proper balance.

(*v*) *Model tests.* The use of models is also necessary for a proper planning of the job, specially in connection with the layout of coffer dams and other connected problems. The highest flood conditions anticipated should be reproduced to check upon the spillway conditions provided, to verify that adequate freeboard actually obtains on the model and to confirm that the arrangements for flood disposal are adequately taken care of. The cost of protective works necessary will, of course, have to be evaluated against a periodic shut down involving a delayed completion of the job.

(*vi*) *Sequence of operations.* An examination of the sequence of starting various sections of the work is a very important consideration as this may lead to considerable economies.

(*vii*) *Safe access facilities.* In the general planning a suitable provision for safe access facilities to all points on the job should be invariably provided for the workmen.

(*viii*) *Maintaining continuity of employment of labour.* A basic and essential requirement of all large construction jobs is the desirability of keeping *unskilled labour employed at all times* to form a reserve from which emergent demands may be readily met. It is customary, for example, on a headworks construction to employ labour on the excavation of the head reach of the canal during slack periods on the headworks. This needs to be prominently kept in view during a dam construction to compensate for seasonal fluctuations of labour requirements ; the actual items for absorbing labour will depend on each particular case.

(*ix*) *Provision for safe custody and storage of materials.* Adequate space for safe custody and storage of materials is an obvious necessity on any large construction job. This should be provided keeping in view the fact that the haulage involved should be the minimum.

(*x*) *Reserve of spare parts.* The desirability of keeping adequate *reserves of spare parts* available at all time has also to be permanently kept in view as the economies resulting therefrom are obvious. This not only obviates undesirable delays but considerably simplifies the job due to the easy interchangeability of the operating and maintenance crew.

(*xi*) *Use of small tools.* The desirability of using small tools in places where these can be worked more economically than the heavy duty equipment should not be lost sight of.

(*xii*) *Design of special equipment.* The economic advantages sometimes obtainable by developing and designing special equipment for a particular job call for continual engineering study and experiment. Not only does thorough engineering planning offer a plant capable of economical sustained trouble-free operation and effective administration, but it also tends to provide a finished structure of higher quality at lower cost.

2. Main factors affecting selection of plant.

(*i*) *Topography.* On a large dam project the topography of the site is one of the controlling factors in determining the construction procedure. Topography conditions will largely govern the location of suitable foundations for screening plant, mixing plant, cable ways, access roads and miscellaneous plant buildings.

A canyon site would, in all probability call for a cable-way layout whereas a long low head dam in a flat river valley would probably require a construction bridge and cranes.

On general grounds, lowering is cheaper and faster than hoisting when placing concrete in a dam. Where topography requires the quarry and aggregate storage to be located at approximately normal river level, it is generally better to elevate the raw material by belt conveyors to one upper mixing plant so located as to permit delivery of concrete to the dam somewhere within the upper half of its total height.

(*ii*) *Geological conditions.* A study of geological conditions is of equal importance. Where manufactured aggregate is to be used, the selection of the most suitable quarry site definitely ties down the plant layout and defines one of the principal construction costs.

(*iii*) *Availability of materials.* To enable the prevailing natural materials of the region being used as far as possible some of the question to be considered are :—

(*a*) Can the excavation for the dam be used for concrete aggregate ?

(*b*) If earth dams are to be built, is the material sandy or full of clay ? How will it handle ?

(*c*) What kind of equipment should be used ?

(*d*) In the case of rock for rockfill, how will it break ?

(*e*) How will the equipment stand up ?

(*f*) What size of equipment is needed ?

(*g*) Over what kind of surfaces must it travel ?

(*iv*) *Rate of production.* Every job has a certain best rate of production ; either a slower or a faster schedule means higher costs. As a rule the first cost of a plant is a relatively small element of the total cost of doing the job. The day to day costs are what count and where these can be reduced by a more expensive plant, within reasonable limits, such opportunities should not be overlooked.

(*v*) *Reliability of equipment.* In the selection of equipment, the reliability of the epuipment is even more important than the first cost. This will apply equally if used equipment is being procured.

3. Schedules required in construction planning.

(*i*) *Construction schedule.* In planning a job one of the first things to be done is the framing of a construction schedule after taking into account the hydrograph of the river. It may be mentioned in this connection that a general idea of the equipment required is necessary so far as the type and output of the equipment concerned is involved.

(*ii*) *Labour schedule.* Another important schedule which has to be framed on the basis of the construction schedule is the labour schedule which indicates the monthly personnel requirements of all types of labour.

(*iii*) *Material schedule.* A material schedule based on the construction schedule is also necessary to enable the requisite quantity of material such as steel, cement, gates, generators, turbines etc., to be arranged and delivered in time. It is often found more advantageous to order well in advance even the permanent hoisting equipment like gantry cranes, etc., which is eventually needed for operating the gates. This permanent equipment obtained somewhat in advance of final designs is a material help during construction as problems of handling and erecting heavy construction equipment have to be frequently faced in the early stages of every large job. This precaution has also the advantage of certainity in view of possible delays due to fluctuating conditions in the heavy equipment market where supplies cannot generally be arranged at shorter notice.

(*iv*) *General.* In framing all these schedules, due provision must be allowed for the labour being comparatively untrained in the early stages of the job and equipment also not being properly turned in, to give the best out-turn. Also unavoidable delays in the receipt and installations of the various items of equipment should not be overlooked as these do occur in spite of careful planning.

A proper planning in the early stages of the work and ironing out on paper the major problems involved, is of very great importance to ensure economical and efficient construction. It is not convenient to have to make adjustments in the field.

4. Record of construction equipment.

(*i*) *Record cards.* It is of great importance to get the best out of each machine, and discover ways and means of improving the reliability and increasing the out-turn. *A record card* should be kept in the field or in the shops indicating its general description and manufacturer's specification such as serial number, price, horsepower, principal dimensions and weight etc.

(*ii*) *Equipment use report.* It is also desirable to have an equipment use report showing for each day details of all equipment which is working, is being maintained as a standby or is under repair. This would enable the engineer-in-charge, to see if the number of idle units is unnecessarily high.

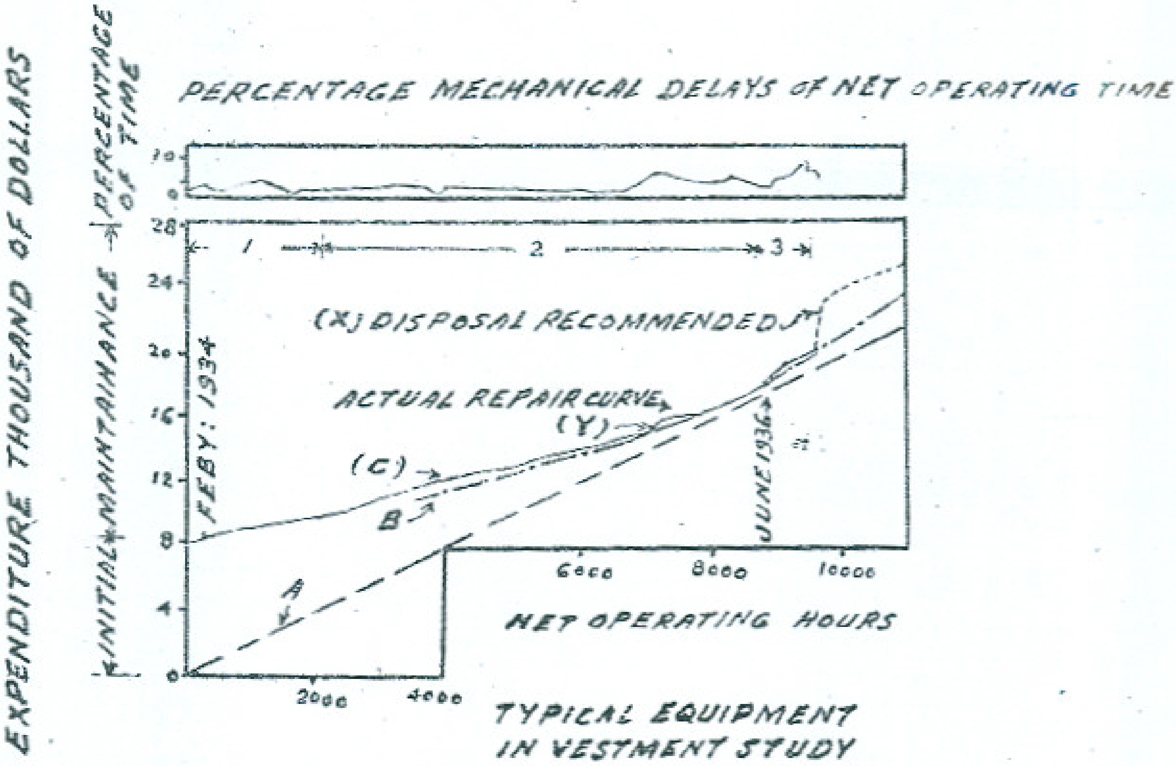
(*iii*) *Record of operations.* Real control over equipment performance is obtained by recording its operations continuously—generally on graphical meters. One of the commonly used type of recorder is the Service Recorder. This is driven by clock mechanism and can easily be installed on a truck or any other equipment which vibrates sufficiently when in operation ; by actuating a small stylus attached to a sensitive pendulum. This would give an indication of the frequency of use, time of operation, average speed, frequency and extent of delays. Another type of meter is the Watt-meter which can be easily connected to the motor element of the particular machine, *e.g.* concrete mixer, hammer-mill etc.

(*iv*) *Major replacement record.* Another useful record is the *major replacement record* specially where large supplies of replacement parts have to be kept in hand.

TYPE OF SERVICE

(1) FOUNDATION
(2) LEVEL QUARRY 12 % GRADE RAMPS
(3) MISCELLANEOUS

A. EQUIPMENT RATE FOR NET OPERATING HOUR
B. EXPECTED REPAIR TREND
C. ACTUAL REPAIR CURVE
X. POINT AT WICH DISPOSAL IS RECOMMENDED
Y. POINT AT WHICH IT COULD BE TRADED



TYPICAL EQUIPMENT
IN VESTMENT STUDY
12 CUB: Yd: DUMP TRUCK.

(*v*) *Record of repair trend and depressions.* An up-to-date chart should also be maintained showing the first cost, expected and actual repair trend, equipment use rate, hours of use and type of service. A typical curve as given by Mr. R. T. Colburn in his article in " Civil Engineering " for August 1939 is shown in the graph below. This indicates a 12-yard truck the first cost of which was 8,236 dollars, the sloping line drawn from O tangent to the repair curve represents the use rate which for this unit is 2 dollars per net operating hour. This particular case shows that after 9700 hours of operation, a heavy overhaul is required and the future cost of ownership is greater than the use rate upto this point. The truck should be sold at this point or traded in for replacement. The curve also indicates that the truck could have been traded in at 7000 hours at no greatly increased ownership expense and probably with reduced mechanical delays.

(*For graph see opposite*).

5. **Improvement in equipment for effecting economy.** The following are the *improvements* developed by manufacturers of *equipment* during the last few years for ensuring *economy* :—

(*i*) Change over from slow manually operated levers to easily manipulated hydraulic air or electric controls on excavating and hoisting machinery.

(*ii*) Change over from petrol engines to diesel engines which are cheaper in operation and maintenance costs.

(*iii*) Introduction of special alloys and metals such as aluminium booms or draglines for increasing the reach, speed, and capacity of the machines.

(*iv*) Improvement in safety features.

CHAPTER VI

CONSTRUCTION PLANT LAYOUT

1. **A study for the proposed Bhakra Dam.** It is not possible at this stage to make the final layout of construction plant for the Bhakra dam as further detailed surveys and decisions regarding the programme of construction have yet to be made. However by way of illustrating the method, a plan is attached in Plate IV showing a construction layout scheme which is in some measure on the lines of the Fontana Dam layout of the T. V. A. and may be taken as indicating the scope of the problem. It must be noted that this represents just one of the authors' studies and in no way expresses the views of Government on the subject.

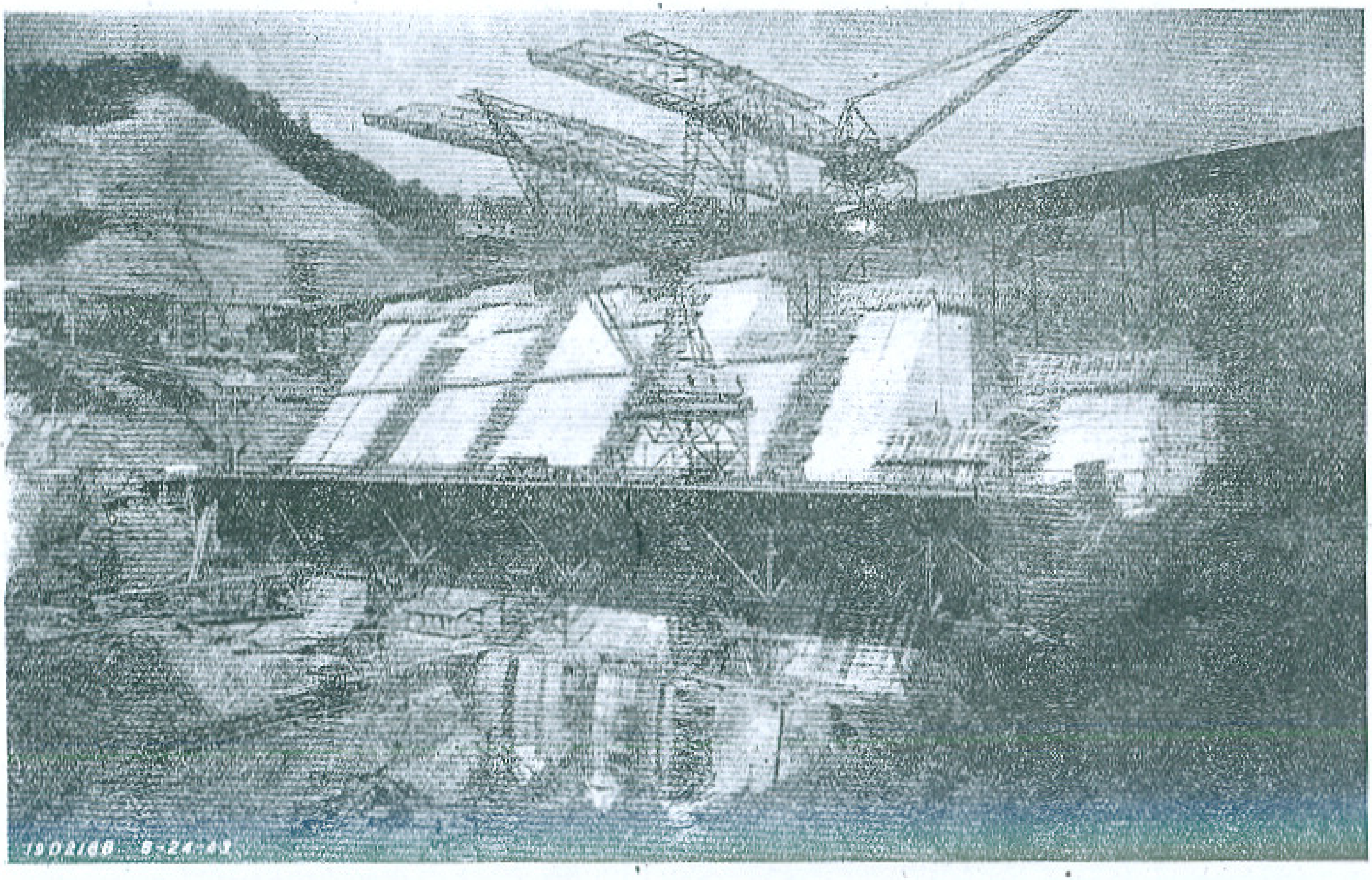
The following points may be noted in connection with this general layout :—

(*i*) Two alternative locations for the concrete mixing plant are shown one on each side of the river. Further study at the site would be necessary before a final exact location can be fixed.

(*ii*) Concrete placing is shown as being done with revolving cranes and hammerhead cranes from a steel construction bridge. This is the method that was used at Fontana. It should be noted that a cableway placement scheme could also be used with advantage and this will have to be studied before a final decision is made. In this connection attention is also invited to the remarks regarding cableways versus trestles. The principal reason that the cableways were not used at Fontana was the high speed with which it was necessary to build the project, and the impossibility of operating enough cableways over the restricted area to maintain the schedule. The Fontana scheme was predicted on using conveyors for carrying concrete to the three bridge levels. This method of carrying concrete however, does not find favour with some technicians of the Reclamation Bureau. (See photograph)

(*iii*) The aggregate storage pile is shown in a location downstream from the dam on the left bank which appears to be a suitable location from the topography. Conveyors are used to carry the aggregate from the stockpile to the mixing plant and also from an unloading point to the stockpiles and concrete conveyors are used to carry the concrete from the mixing plant to the various levels of the construction bridge. These conveyors are shown on the plan roughly to conform with the contours and keep within the slope requirements for conveyors. An aggregate conveyor should not slope more than 18 degrees, and a concrete conveyor should not slope upward more than 12 degrees, or downward more than 11 degrees. The final location and design of the conveyors will naturally be made after a more careful laying out at the site.

(*iv*) The method of transportation of aggregate and sand is not covered on this drawing, but it is assumed that no matter how it is brought to the dam it will be unloaded at the unloading point into a hopper which will feed the conveyors to the stockpile.



Fontana Dam under Construction
Showing Hammer Head and Revolving Cranes (Courtesy of T. V. A.)

(*v*) A temporary construction bridge has been shown across the river near the stockpile, which would be essential to maintain access to both sides of the river and provide a support for the conveyors. It would also be possible to obtain access across the coffer dam at a later stage in the work. This is also shown on the drawing.

(*vi*) It is assumed that cement will be hauled in trucks to the dam site. The recommended unloading point is chosen close to the mixing plant. The cement is dumped into a large hopper and conveyed by belt and bucket elevators to the silos, from which it can be reclaimed and transported by belt conveyors to the mixing plant. The advantages of this scheme are that no compressed air is required for conveying the cement and also that cement loss due to blowing is eliminated. The steep grade the trucks have to negotiate may be a disadvantage. An alternative scheme for handling and storing cement has been indicated on the drawing. In this scheme the unloading point is located below the mixing plant and near the coffer dam which eliminates the steep grade but requires compressed air for blowing the cement. Cement is blown in either direct to the mixing plant or it may be stored in the silos and reclaimed as needed.

(*vii*) A shop area has been indicated downstream on the right bank. It will be necessary to have a machine shop, warehouse, carpenter shop, garage and repair shop, field offices, etc. in this area. The location shown is only provisional.

(*viii*) An air compressor plant is shown close to the alternate location for cement unloading facilities. This is also close to the dam. Most of the air consumption will be for the excavation work in the dam itself, tunnel construction, and for cement conveying if it is blown. It is therefore desirable to locate this plant close to these units.

(*ix*) A raw water pumping station is shown downstream from the dam. The location of this can be altered to suit field conditions but it will have to be located at a point where water will be available at all times and pumped directly into a raw water piping system with tanks located at a high elevation.

(*x*) It will be necessary at a later time to provide access to the spillway structures on both sides of the river upstream from the dam, and to provide facilities for concreting and excavating at these points. This could probably be studied after the main work is under way.

(*xi*) The first work on the project will normally be the completion of the diversion tunnels, which are shown on the drawing, and the building of the coffer dams. This work can be carried on at the same time that the construction plant facilities are being installed and the dam excavation carried on.

(*xii*) A small crushing plant has been indicated below the shop area. This plant will be required if gradation of the natural aggregates and sand is not in the correct proportion. The major part of the material may be by-passed.

(*xiii*) A steam electric generating plant is shown on the plan with sub-station and switch house for supplying power to the project. This should be as centrally located as possible.

This layout and the above discussion covers only some of the principal problems which will come up in connection with Bhakra construction plant. All of these will require further analysis and study to determine the final decisions. Some of these points will no doubt need partial or radical modification depending upon major decisions as to the location of the access railway track and road. In view of the importance of the matter, it has been considered that the inclusion of this study in this paper would be instructive as indicating a practical over all approach to the design of the construction layout, which comprises one of the most specialized items of high-dam construction " know-how."

CHAPTER VII

CONSTRUCTION PLANT AND CONSTRUCTION METHODS

1. **Coffer dam design and construction.** The following considerations are important in coffer dam design and construction :—

(*i*) The flood characteristics of the river.

(*ii*) The hazards and risks that should be reasonably assumed.

(*iii*) The type of channel suitable for handling the river during construction and diversion and final closure. An economical balance has to be stuck between the discharge capacity of diversion passage ways and their construction cost inclusive of gates and other component parts.

(*iv*) For the most economical type and height of coffer dam, an analysis should be made of locally available materials, foundation conditions, and liability to scour around or under the coffer dams. Methods of water proofing and pumping requirements to deal with probable leakage have also to be gone into. It may not thus be necessary to provide for the maximum flood conditions on record.

(*v*) The most economical sequence in building the various stages of the structure with a view to ensure that there is always a place available to deposit concrete thus allowing the plant to operate continually at a high rate of production.

In short, the total of plant cost, operating cost, river diversion cost and other incidental costs should be a minimum for the project.

The area to be enclosed within coffer dams for each stage of construction must be carefully planned after running model tests of various alternatives.

The following are the main types of coffer dams in general use :—

(*a*) *Earth-fill.* This is the simplest type and can be used if the material is stable, compact and impervious. It is, however, unsuitable for a long period of time.

(*b*) *Rock-fill.* This is useful in cases where a supply of rock is economically available, as it also enables disposal of the excavated material. Water-proofing is done by a layer of clay deposited on the waterside with some form of mattress at the water line to protect the clay from wave action.

(*c*) *Rock-filled cribs.* This is especially useful in high velocities and where there is a risk of over topping. The cribs are made watertight by dumping earth-fill against the water side.

(*d*) *Steel sheet pile.* These types are adopted in the construction of locks or dams on pervious foundation. In the Cellular type, circular compartments are interlinked by connecting arches. This type is costly but efficient. It is not suitable for use in India due to non-availability of sheet pile and their high cost. The type best suited for the Bhakra Dam seems to be the rock-filled.