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Applications of Soil Mechanics in River Structures (India)

Application de la mécanique des sols aux travaux de rivière

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Summary

A large number of dams and barrages are under investigation or construction in India, with a view to overcoming the present shortage of food and electric power. Their economic scheme involves the application of Soil Science at various stages. This Paper reviews some of the problems that have arisen and the way they have been solved as well as those needing further investigation.

Sommaire

Les Indes ont décidé la construction d'un grand nombre de digues et de barrages afin de surmonter la présente pénurie de denrées alimentaires et d'énergie électrique. Ces ouvrages – les uns en construction, les autres à l'état de projet – impliquent l'application de différents aspects de la mécanique des sols et l'objet de cette communication est de passer en revue les problèmes soulevés par leur construction, les solutions apportées et les recherches entreprises.

Investigations

The 6,600-foot long Rampadasagar Dam to be built across River Godavari about 100 miles above its confluence with the sea, is to be a concrete gravity structure; in the river bed, the foundation rock is overlaid with sand and at places with lenses of clay, for depths varying from 100 to 200 feet. Near the right abutment, for a length of about 800 feet, the overburden, over 50 feet deep, consists of slicken-sided clay. The prevailing soils at the dam site are coarse sand, silty clay and fine clean or silty sand. The investigations were for determining: depth and nature of overburden, minimum slopes for excavation in clay and other soils in the river bed, permeability of the overburden sand determined by pumping tests to estimate the extent of dewatering required during foundation excavation, and suitability of various injections or groutings to water-proof the proposed sheet-pile cofferdam. Sand samples were obtained by split spoon samplers and clay by Denison samplers.

These investigations, carried out under the guidance of Dr. *Terzaghi*, are briefly described below.

To determine the depth of overburden along the axis of the dam, and the cofferdam alignment, *penetrometer sounding* was very successfully used. The penetrometer consisted of $1\frac{1}{2}$-inch diameter rods in 6-foot lengths with a 2-inch diameter conical driving point (Fig. 1) and was driven with a 100-lb. weight dropping through 30 inches. The number of blows required for every foot of penetration indicated the type of overburden. When the penetrometer reaches rock or clay layer, it becomes noticeably difficult to drive it any further; but the layer can

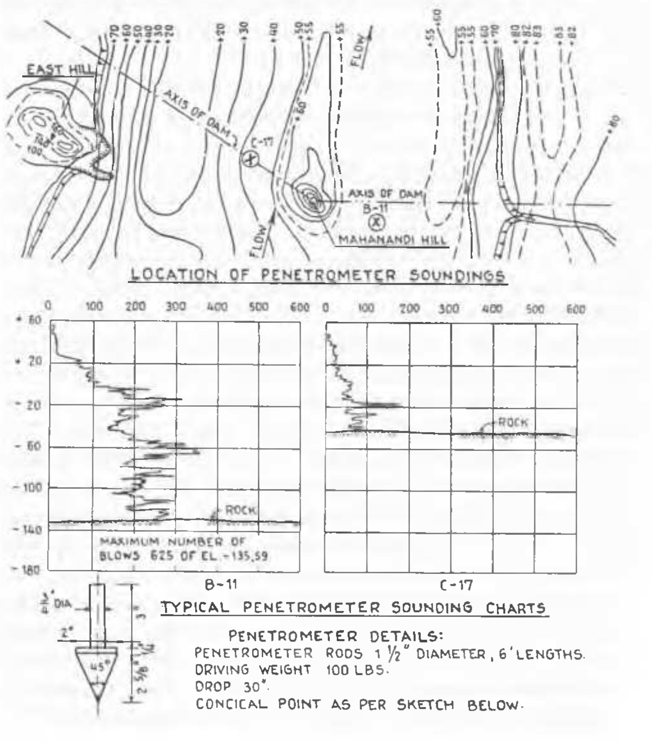

Fig. 1 Typical Penetrometer Charts
Résultats typiques des essais au pénétromètre

be indentified from the fact that the penetrometer rebounds only on rock. The soundings covered an extensive area and gave valuable results. These were checked by putting in casing pipes and taking out core samples with calyx drills. A typical plot of soundings obtained is shown in Fig. 1.—These soundings were of further value as they showed to what depth the river bed was scoured and back-filled. This back-fill is only loosely laid and so offers practically no resistance to the conical point; the depth of scour was deduced from these observations as 50 feet. A direct determination was also attempted to determine the depth of scour, by placing an annular disc concentric with a pipe buried securely. The disc was held over pulleys by a small weight moving inside the pipe. When the soil under the disc was scoured the disc would fall down and raise the weight inside the pipe. A number of these pipes had been set up at intervals in the river bed; but unfortunately as the river has very high discharges ranging up to 2½ million cusecs, most of these pipes were washed out and could not be traced. In a few that held, the discs went down only by 4 feet.—The penetrometer tests were further verified by geophysical exploration employing electrical resistivity methods (*M. B. Rao*, 1947). It must be admitted that penetrometer tests proved more reliable than geophysical methods in this subsoil prospecting.

It was essential to determine, to prevent failure during excavation, the exact *slopes* to which clay, or sand with clay lenses has to be excavated and the precautions to be taken for proper drainage. A shaft 6 feet in diameter was sunk nearly 80 feet deep and soil samples were collected at different levels. The soil was found to be uniformly slickensided clay. A funnel shaped pit was dug about 30 feet deep with different slopes. It was found that the 1¼:1 slope collapsed after a depth of 30 feet was reached. The clay closely resembles London Clay and has the following characteristics: Liquid limit 60 to 90%, Plastic limit 32 to 35%, Natural moisture content 25 to 40%, Unconfined compressive strength 1 to 6 tons/sq.ft. The shearing stress on the surface of sliding was roughly equal to 0.25 ton per sq.ft. If the rest of the soil was not better than in this place, it was concluded that the slopes could not be steeper than 4 to 1 for a critical height of 50 feet.

The large coarse sandy overburden (effective size of sand 0.6 mm) constitutes a large underground reservoir making dewatering a difficult problem. To get an idea of the permeability of the sands in places, several *pumping tests* were carried out. In one test, a pit 100 feet diameter was excavated and attempts were made to dewater it by pumps placed along the periphery of the pit; it was not possible to lower the water appreciably beyond 5 feet, though water was being pumped out at the rate of 10,000 gallons per minute. The coefficient of permeability calculated ranged from 20 feet to 40 feet/hour. With the outer pipe of 20 inches diameter sunk to rock level (i.e. 50 feet below bed level) a strainer well of 15 inches diameter was inserted and the annular space filled with shingle, ¼ to ⅜ inch size. The casing was withdrawn; pumping at the rate of 18.00 gallons per minute depressed the water level 7 feet. The effective grain size of sand at this site is 0.36 mm except for the lower portion where it is 0.57 mm. Unfortunately the location of the test well was such that on the south side water edge was 105 feet away while on East side it was 500 feet. Observations of the water table in the neighbourhood were recorded from 1½-inch diameter pipes located at varying distances from the well in two directions at right angles to each other. There was no depression beyond 700 feet. The value of the permeability coefficient was computed as 70 feet per hour.

It was evident from these tests that very large pumping installations would be necessary to do the main excavation. Apart from this, there will be danger of erosion from excess flow. The sheetpile cells of 60-foot diameter, proposed to be driven along the cofferdam alignment, could not be expected to penetrate all the 200-foot overburden. At best they may go from 75 to 100 feet. Hence the problem still remained regarding the probable *leakage* from underneath the sheet piles.

Chemical injections were out of question on account of excessive cost. Bitumen emulsion injections similar to those carried out at Esna Barrage in Egypt were considered. Preliminary experiments were carried out with the Godavari Sands at Amsterdam Laboratories (*Laboratorium B.P.M., Amsterdam*, 1947). The proposal was to inject emulsified bitumen under low pressure in front of the cells. The bitumen globules would fill the interstices, permeate the entire treated area and prevent flow of water. It was found that permeability could be reduced from 20 to 4 feet/hour. The laboratory experiments showed that the permeability of the impregnated soils decreased with time. The values were not altered even at gradients of 30. Under high gradients like 135, the coefficient of permeability increased, perhaps due to turbulence in water, but decreased again when the gradient was decreased.

On further examination when it was found that bitumen grouting might prove costly, Dr. *Terzaghi* suggested field experiments with *clay injections*. At a site where the sand was 50 feet deep, a pumping test was done with a 8-inch well. Clay was then injected through 1½-inch pipes at the four corners of a square 5 × 5 feet. The specific gravity of clay suspension was 1.1, and the proportion of various chemicals used was as follows: Clay 1000 cm^3; Gum Arabic 150 cm^3 (2% strength); Sodium Silicate 100 cm^3 (50 cm^3 in 100 cm^3 of water); Hydrochloric Acid 100 cm^3 (10 cm^3 of acid in 100 cm^3 of water). The pressure of injection was 30 lbs./sq.inch; clay was injected at every 2-foot intervals; a total of 10,000 gallons was injected. Five days after the injection, pumping tests were again carried out at the centre of the area treated. For the pumping rate of 700 gallons per minute, the depression in the well was 10.85 feet, nearly double of what it was before treatment. Sampling of the treated soil showed clay contents varying up to 6.4%.—A further test was done by driving a 20-foot diameter sheet pile cell to rock level through 40 feet of overburden. Clay was injected around the periphery of the cell at its junction with the rock. Pumping tests carried out before and after injected clay, showed considerable stoppage of leakage flow.

Similar investigations (geophysical prospecting and penetrometer soundings) carried out at the site of the proposed dam across the *Pennar* (maximum discharge of half a million cusecs) showed that sound rock was about 100 feet below bed. The characteristics of the sand in the river bed are determined to be: Sand 95%; Silt 5%; D_{10} 0.2 to 0.35 mm; Permeability coefficient 20 feet/hour. The necessity for heavy pumping during excavation was indicated by the high value of permeability coefficient revealed by pumping tests. As a result of these investigations, the design was changed from a concrete gravity to an earth dam, as the site conditions permit locating the spillway section to the left abutment side on an outcrop of rock.

There are a large number of similar examples in India where deep overburdens of sand and silt in the river bed make it a difficult problem to decide on the type of structure. Also diversion of the river is not always easy or possible, as generally rivers in India carry very large amounts of water during monsoon months. Thus the Barakar, whose summer discharge will be about 50 cusecs, carries 300,000 to 400,000 cusecs in monsoon months; and, site conditions at Maithon dam do not permit diversion of the heavy discharge. At the same time the 100-foot overburden of sand in the river bed makes it impossible to adopt any but an earth dam. This necessitates the placing of nearly 2.8 million cyds of earth in the river bed right to the top of the dam in a single nonmonsoon period which may vary from 6 to 8 months.

Soil Selection, Slopes and Pore Pressures

The practice in India before the advent of the British, in the *construction of earth dams* very closely approximated to the standard present day practice; the British in their time, however, introduced the practice of utilising clay-puddle core in the hearting of the earth dam and adopting flatter slopes on the downstream rather than on the upstream side. This practice conflicts with the present practice of controlling the water content in the hearting soil, rejecting rich clays and using flatter slopes on the upstream rather than on the downstream side.

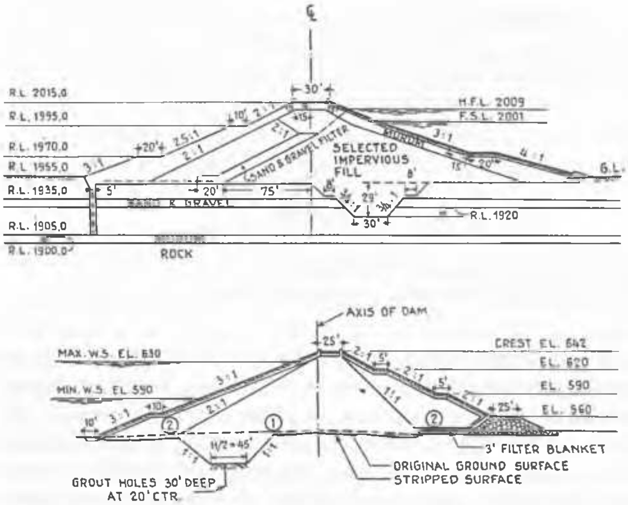

Fig. 2a Typical Cross Sections through Modern Earth Dams
Sections typiques des barrages en terre modernes
Gangapur Dam above / en haut
Hirakud Dam, below / en bas

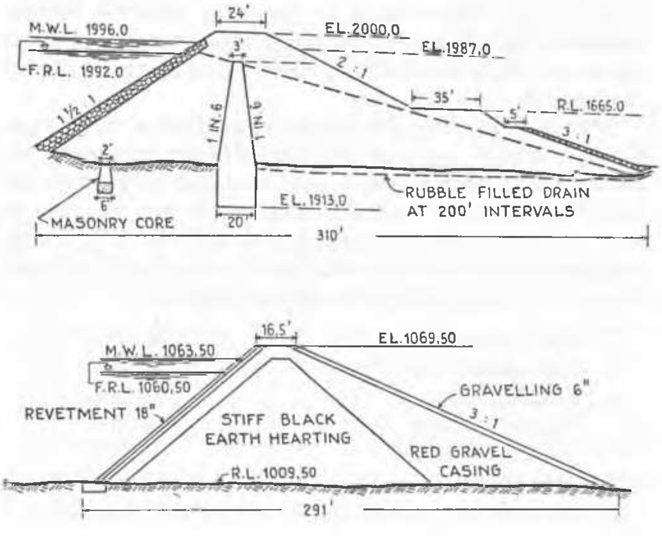

Fig. 2b Typical Cross Sections through Ancient Earth Dams
Sections typiques de barrages en terre anciens
Anjanapur Dam, Mysore State, above / en haut
Siddapur Dam, Madras State, below / en bas

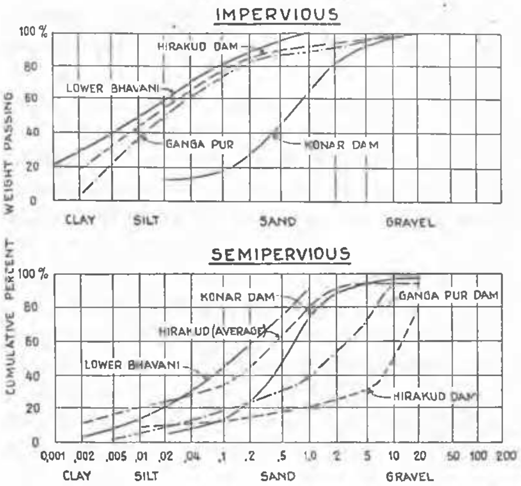

Fig. 3 Typical Analysis of Soils Used in Earth Dams
Analyse typique des sols employés pour la construction des barrages en terre

Figs. 2*a* and 2*b* show examples of these two practices in India. This change is due to the development of soil science; at any rate, while quite a large number of Indian engineers are against steeper slopes for the downstream side there is unanimity on the need for careful selection of soils and avoidance of rich clays in the hearting.

Fig. 3 shows typical *analyses of soils* used at Hirakud, Konar and Lower Bhavani Dams, etc. Hirakud Dam is across the Mahanadi where the main earth dam is 10,000 feet long with a maximum height of 200 feet, about 100 feet being the average height; and the earth work is 24 million cyds. Konar Dam is 9,800 feet long and will have 5.8 million cyds of earth in it; the Lower Bhavani is 28,000 feet long and will have 4.5 million cyds of earthwork. At Hirakud there is only a slight distinction in most of the soil used for the impervious and semipervious zones; the soil is designated "average impervious". This is available in large quantities and has to be utilised, there being not much of ideal semipervious material.

At Konar the soil contains a lot of micaceous material and its effects on the stability of slopes have been taken into account.

The *dry density* of the different soils at optimum moisture contents used at the above three dams are, 116, 117 and 128 lbs./cu.ft. respectively for Hirakud, Konar and Lower Bhavani Dams. The dry density of impervious soil is less by 8 to 10 lbs. in Hirakud and Lower Bhavani soils but at Konar there is hardly any difference in densities, though the permeability of the material in hearting is 2.6 feet per year and the permeability of the material in casing is 6.5 feet per year.

The *slopes* adopted in the different earth dams under construction are shown in Fig. 4. It will be noted that flatter slopes are adopted in the case of Gangapur Dam. This is an earth structure (12,500 feet long, maximum height 140 feet) across the Godavari near its source. The characteristics of the soils available in the vicinity are as follows:—

	Impervious	*Semi-pervious*
Clay content	28%	3%
Liquid limit	58%	—
Plastic limit	32%	—
Plasticity index	26%	—
Maximum dry density	104 lbs./cu.ft.	132 lbs./cu.ft.
Cohesion	600 lbs./sq.ft.	—
Angle of internal friction	$\tan^{-1} 0.30$	$\tan^{-1} 0.63$

The clay is slickensided and is not amenable to any scientific design procedure. In view of these uncertainities, slopes as flat as 1 in 3 and 1 in 4 are adopted.

In the case of Hirakud Dam, the angle of internal friction and cohesion of impervious soils at optimum moisture contents are 20° and 1,000 lbs./sq.ft. respectively but in saturated condition, the angle of friction reduces to 12° and cohesion, to 800 lbs./sq/ft., and if these values are adopted in the analysis for slopes, the factor of safety decreases. It is considered that due to high impermeability of the soil, it will never attain the state of complete saturation.

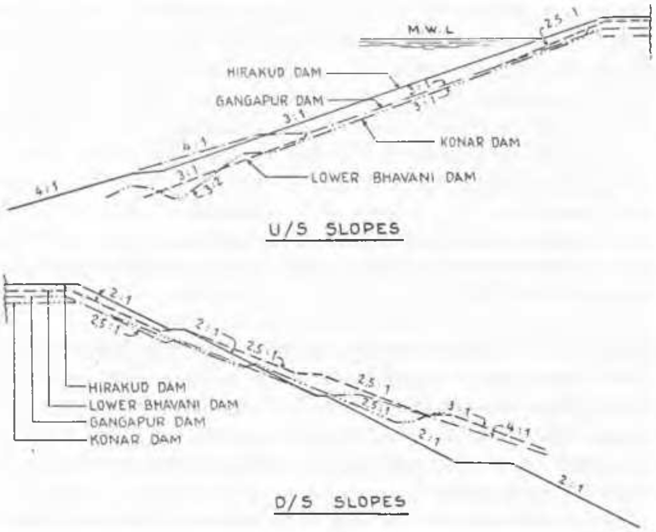

Fig. 4 Slopes of Some Earth Dams
Inclinaison de certains barrages en terre

One of the important observations on earth dams is with regard to *pore pressures* developed during construction. It is assumed that soils with coefficient of permeability less than 0.3 feet per year will develop pore pressures when subject to rapid construction operations; field observations show extreme ranges; while at Anderson Ranch Dam, pore pressures up to 70% of the height of overburden are observed, at Davis Dam no pore pressure was observed. The reason stated was that the soil was placed at slightly less than optimum moisture content. If the pore pressures are so sensitive as this, it will be necessary to develop some method of relieving these even during construction instead of adopting flat slopes that increase cost. There is great obscurity regarding the pore pressures developed in natural overburden overlying the rock. But some engineers in India assume that pore pressures develop in this overburden just as in the earth fill built over it; this results in very flat slopes. An example of this is Koyna Dam in the Western Ghats of Bombay State. A 266 feet high dam is to be built across a river to form a reservoir, the water of which is led through a tunnel to generate electricity of half a million kW, taking advantage of an abrupt fall of 1,500 feet in the country towards the Arabian Sea. The earth overburden in some places is 110 feet above foundation rock and to design an earthen embankment, this entire overburden was taken as developing full pore pressure with the result that the slopes to be adopted became excessively flat and led to the adoption of a masonry structure. It is, therefore, important that pore pressure measurements must be recorded at every possible damsite. At Hirakud, measuring devices are being installed at a large number of places to record field observations.

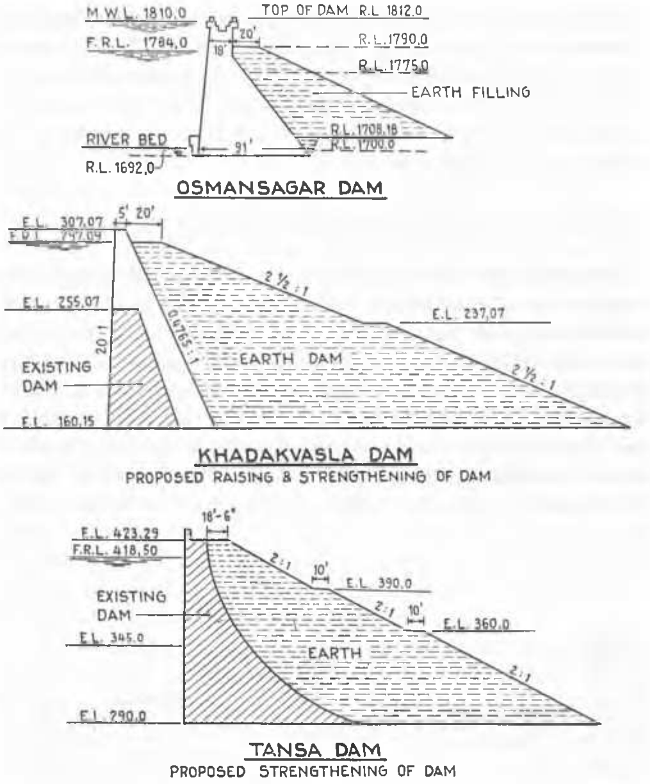

Fig. 5 Typical Composite Dam Sections
Sections typiques de barrages composés

In some recent dams, high *retaining walls* forming the junction between earth and concrete dams are being employed instead of transition sections, as being more economical. At Hirakud Dam Project on the left side, a 140-foot high retaining wall is being constructed. Care was exercised in specifying the type of earth to be filled in behind the retaining wall, since relatively more pervious soil would reduce the length of percolation path between concrete and earth dams. It was decided to use semi-impervious soil in the upstream side up to lowest water level of the reservoir and, above that, pervious soil to the full reservoir level to ensure that no excessive pore pressures develop when the water level fluctuates violently between maximum and minimum reservoir levels. Measuring instruments are being installed to observe the pressures on the retaining wall.

At Pykara, located 6,000 feet above sea level in the Western Ghats, a gravity dam was proposed between abutments, but during actual construction, it was found that on the right hill side, the foundation rock was deep and it was necessary to excavate nearly 100 feet for the foundation. But this was not possible as the earth composing the hill was a highly saturated clayey soil with the following characteristics:—

Clay content	20–40%
Silt content	20–30%
Liquid limit	40–50%
Plasticity index	20–30%
Natural moisture	40–50%
Dry density	70 lbs./cu.ft.
Unconfined compressive strength	1,600 lbs./sq.ft.
Cohesion	400 lbs./sq.ft.

The high moisture content made it impossible to excavate the hill side with any reasonable slopes. Electro-osmosis was tried to reduce the moisture content of the soil but not with success. Finally it was decided to replace the end gravity portion by a retaining wall and earth dam in continuation with the abutment hill.

Utilization of Earth Pressure

In India, the method of having for the dam section a *masonry wall with earth fill* behind it is in wide use specially where the foundation rock is not good. Fig. 5 shows a typical example of the Oosmansagar dam at Hyderabad. In such a composite section, the masonry retaining wall insures impermeability and the earth bank provides stability to the wall against the water pressure.

Tansa Dam, 8,961 feet long and 133 feet high as it was built is believed to be not sufficiently stable against possible uplift pressure, the existence of which has been indicated by holes drilled on the downstream side of the dam. Remedial measures are, therefore, sought to strengthen the dam. Various alternatives are being considered, including *Coyne*'s process of prestressing with cables. Providing earth backing as shown in Fig. 5 which gives the necessary counterpressures to ensure stability of the structure is also one of them.

This method of strengthening and raising dams by providing earth backing is also proposed for the Khadakvasla Dam, 130 feet high and 4,827 feet long (Fig. 5).

Structures on Permeable Foundations

A number of hydraulic structures, constructed on sand foundations as far ago as 100 years, are functioning quite satisfactorily, but these which were intended for diversion of river water, are low structures with not more than 10 to 20 feet of hydraulic head difference. Even for these the analysis always assumed homogeneous sands underneath the structure. But using the recent method indicated by the author (*K. L. Rao*, 1951), it will be easy to calculate the seepage pressure even though the stratum may be extremely heterogeneous. The method consists in solving the equations of flow by relaxation methods. A practical application arose in the design of a barrage across the Sutlej. The stratum underneath the 15-foot high structure consisted of lenses of clays and silts. A cross section is shown in Fig. 6 and the net work of pressure computed in the stratum is also given in the same figure.

Maithon Dam on River Barakar, represents an example of an earth dam on deep river sand as foundation material. A great deal of consideration led to the use of a sheet pile cut-off. The proposed eighty-foot high dam across the river Kosi, presents similar foundation problems. A number of alternate studies are under way but it looks as if it would be best to have the concrete spillway located in the river bed itself. This would mean economic design of a concrete over-flow dam on permeable foundations with a maximum difference between upstream and downstream water levels of about 80 feet. Such a design entails close study of seepage flows in soil under great heads and time effects on these flows.

Power Houses Founded on Soils

The construction of the three power houses at Sarda, Pathri and Bhakra-Nangal No. 1 involved difficult problems of dewatering foundations. The details of installations and foundation are given below:—

	Units	*Proposed*	*Foundation details*		
	No. of Units	*Capacity each in kW*	*Pit in feet*	*Depth below G. Level in feet*	*Depth below: Natural water table in feet*
Sarda	3	13500	193 × 91	85	63
Pathri	4	4000	176 × 155	60	33
Bhakra Nangal No. 1	3	24000	230 × 125	110	65

The soil stratum in each of the stations was highly permeable with a high ground water table. Dewatering the foundation

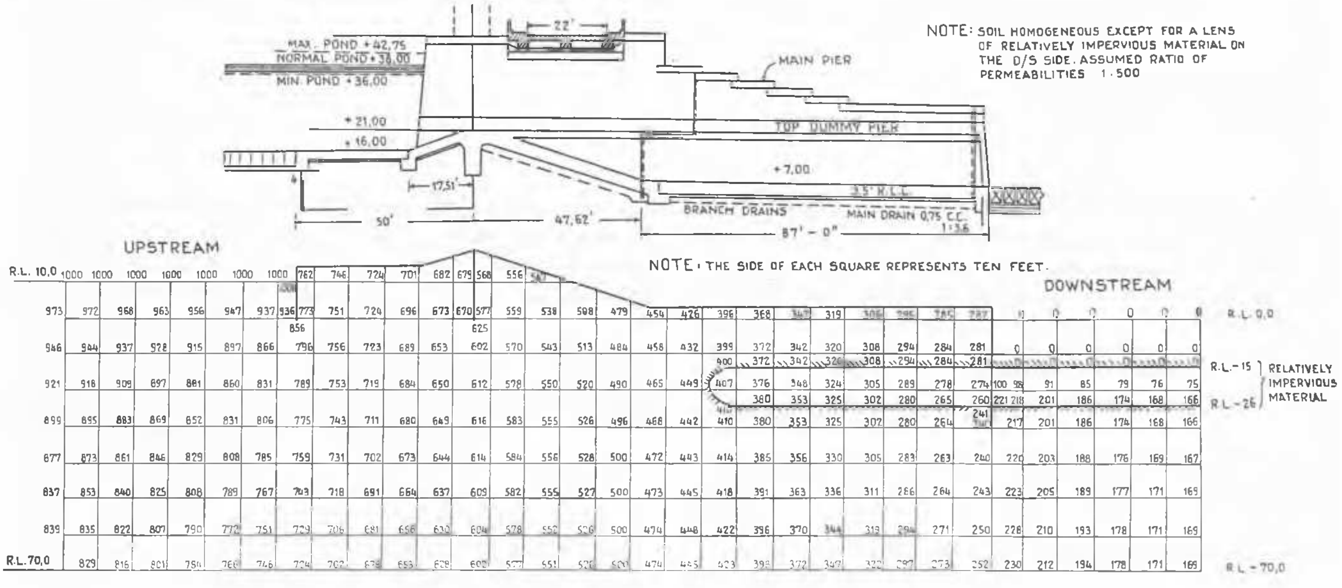

Fig. 6 Seepage Pressures Under Barrage by Methods of "Successive Approximation"
Pressions de l'infiltration sous un barrage par la méthode d'approximations successives

pit required in each case great skill and was achieved mainly through the use of tube wells. The maximum water pumped out was between 23 and 26 cusecs. Clay lenses were removed and the foundation rafts were laid on sandy soils. Special precautions adopted included provision of expansion joints for the penstocks before their entry into the power house to eliminate effects of differential settlement.

Conclusions

The above discussion, while it shows how soil science has entered practically into every phase of investigation, design and construction of dams, draws attention to the urgency of solving some problems if soil science has to find a still wider application in river structures. The pressing problems pertain to the value and effect of pore pressures in embankment and in the natural ground soils above rock, measures to eliminate these during construction and value of cut-off underneath earth dam founded on sands and possible effects of omission of these cut offs.

Acknowledgment

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