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TUNNELLING IN CONNECTION WITH THE UHL RIVER HYDRO-ELECTRIC PROJECT

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Introductory.

The Uhl River Hydro-Electric project is designed to meet the existing needs of the Punjab for electric power and to provide further supplies to keep pace with and facilitate the industrial development of the Province. The site at which power is to be generated, is located in Mandi State, about 200 miles north-east of Lahore. A high ridge, an off-shoot of the Dhauladhar range, separates the basins of the Uhl and the Rana, and the general level of the latter is much lower than that of the Uhl. The difference in level in the neighbourhood of the site chosen for operations is approximately 2000′, vide plate I. In order to utilize this difference in level for generation of power, it is necessary to divert the water of the Uhl through the ridge separating the two valleys, and to achieve this purpose, there is no practical alternative to the driving of a tunnel. This tunnel is the vital factor in all present and future power development in this area, of which the stages proposed are briefly as follows :—

In the first stage now under construction, the normal flow of the Uhl River—stablilised by a storage of sufficient capacity to afford half a day's reserve supply—will be utilised. This will permit a development of some 36000 K. W.

In the second stage the output can be doubled by means of additional storages in the Uhl Valley, and for this purpose the construction of a dam some 250 ft. high is projected.

In the third stage,[which, however, is equally capable of development as a second stage if found more suitable, the water from the first power house can be conducted in a flume for a distance of about 3 miles down the Rana alley, to a point from which a further fall of 1200′ can be utilized for production of an additional 48000 K. W.

It is therefore clear that the tunnel, complete at the end of the first stage of construction, will already have constituted an essential feature of a much greater development.

The preliminary works, required before a start could be made on the construction of the tunnel itself, were very considerable and occupied the major part of the first two years of construction. No detailed description of these will be given in this article, but some may be mentioned.

Nothing beyond rough mountain tracks connected the Uhl and Rana Valleys at the outset. Communications over the 8000′ ridge were therefore one of the first considerations, and the construction of the Haulageways and Hill Top Tramway was the result.

The point on the south (Rana Valley) side, where the tunnel emerges is about 1500 feet above the existing cart road, and communications were obtained with this altitude by means of the Pipe Line Haulage and Adit Tramway—the former of which is the first link in the communications with the Uhl Valley, besides being an essential instrument in the construction of the Pipe Line.

Accommodation for a staff of considerable size had to be provided.

An exact survey of the tunnel alignment had to be completed, and the general scheme of driving decided on.

Power for transport and construction purposes was required and therefore two small water power plants were installed, giving a combined total output of 1080 K. W.

Concurrently with the above works, the Kangra Valley Railway was in progress, but the commencement of tunnelling was not dependent on this.

This article does not deal with any other parts of the scheme beside the tunnel, but in order to give an idea of the general relations of the tunnel to other details, the following brief note is included.

The following are the main divisions of the project from a construction point of view.—

The Headworks, where water will be extracted from the tributaries of the Uhl river by two weirs connected by a 4′ 4″ dia, pressure duct.—From the intake situated on the Uhl river, the water will pass through the decantation chambers, the object of which is to make the water travel at a gradually decreasing speed, which will ulimately fall to 1 ft. per second, suspended matter being, therefore, deposited on the floor of the chambers, which are formed of inclined louvres covering rectangular scour ducts. Particles will fall through the inclined louvres, through the openings of which, during the rainy season, there will be a continuous flow of water running to waste back to the river, and it is anticipated that this under-draw will remove silt as fast as it is deposited. In the winter when the river is low, it is also clear, and therefore, no silt will be deposited in the decantation chambers, and no water will be wasted. The portion of the chambers built for the first stage of the project, is capable of delivering 305 cusecs of clean water. Leading out from the decantation chambers there is about a mile of reinforced concrete duct and rapids. A diurnal reservoir has been provided adjacent to the north tunnel portal, which has a storage capacity of 7 million c. ft.

The Main Tunnel, some 14000 feet in length, connecting the head works with the surge shaft.—This tunnel can be fed either direct from the forebay, which is located at the upper end of the diurnal reservoir, through a reinforced concrete duct 8′ in dia. which passes beneath the bed of the reservoir, or from the diurnal reservoir, the intakes being controlled by a pair of butterfly valves, capable of working against a maximum head of 50 ft. If the dam is built, it will also be possible to supply the tunnel with water from the main reservoir through the valve adit, in which case a second high pressure valve would be located in the valve chamber near the northern portal of the tunnel. Owing to the height of water in the reservoir, it would be necessary to sink a shaft from 250 to 300 ft. deep, in order to control these valves, but for the first stage of the project this shaft has been omitted, and access will be obtained to the single high pressure valve in the main tunnel through the valve adit, which also at present forms the shortest and most convenient exit for the mucking tubs proceeding to the spoil dump on the bank of the river. For the first stage, the second high pressure valve is not being installed, the end of the pipe being blank flanged off.

The surge shaft and pipe tunnels are the connecting links between the main tunnel and the pipe line. The shaft is some 386′ deep, and its function is to serve as a pressure relief, when the flow of water in the pipe line is checked more or less suddenly, by a diminution of load, and also to act as a storage to supplement the tunnel flow for short periods, when the load increases suddenly.

The pipe tunnels are really the commencement of the pipe line and consist of two 1000′ tunnels which are lined with 6 ft. diameter steel pipes backed with concrete.

The pipe line commences at the point of exit from the hill of the pipe tunnels, and connects the latter to the power house some 1600 ft. lower down. Two lap welded 55″ pipes are connected to each 6 ft. tunnel pipe, but in the first stage, only two pipes are laid throughout to the power house. Each of these carries 200 cusecs and bifurcates at the power house into two 100 cusec pipes each of which serves one machine. The lower portion of the pipe line, designed to stand pressures up to 1000 lbs. per square inch—are constructed of reinforced pipe, weldless rings surrounding a lap welded core pipe. Valves for controlling the supply are located at the top and the bottom of the pipe line.

The power house will in the first stage contain four Pelton wheels, designed to drive alternators of 12,000 K. W. capacity. During the first stage, three units only will be in operation, with one as spare.

Last in order, though first in cost, is the transmission system. The generator voltage will be transformed to 132 K. V. to feed the trunk lines, of which over 200 miles are under construction. Substations at important centres will distribute the power to bulk consumers.

Geology.

The general geology of the ridge through which the tunnel is being driven is shown on plate II. The main feature is a wide syncline, over-folded slightly to the south-west, with the axis of this syncline running approximately parallel to the main ridge and the change of dip occurring at about R. D. 4000. It was at first thought that the granite gneiss, which forms the heart of the hill, was a normal igneous intrusion, expanding in depth, but the geologists reported that this theory was incorrect, and that this granite gneiss was probably originally an intrusive rock underlying the mica schist strata of the tunnel alignment, but that it, along with the adjacent strata, had suffered much folding and thrusting. Further, it was stated that the main mineral components, i.e., the large white felspar crystals and the mica flakes in particular would be found, owing to the forces to which they had been subjected, to be crystallized out in parallel bands, conforming with the dip and folding of the adjacent mica schist. In general, the geological predictions were found to be correct, the dips conforming to those shown in plate II, and the junctions of the granite gneiss and mica schist being sharp and clearly defined. The rock encountered in the southern section did not however come up to expectations, being very much shattered and being heavily charged with water. The quantity of water flowing in through crevices in the rock at the working face of the mid-point heading alone, was often in excess of 1000 gals. per minute, whilst the total discharge of this section was over 2000 gallons.

Survey and Layout.

The triangulation was carried out with 6″ micrometer and vernier theodolites, and the work was started from a base line 900 feet long; the proposed tunnel centre line being connected to it near the north portal and at surge shaft and tunnel exit. The triangulation was carried right over the hill, the vertical angles being read as a check on the double precise levelling which connected up the power station and headworks areas. This D. P. levelling, involving a combined rise and fall of something over 6000 feet agreed with the levelling of the original surveys for which a very short space of time was available, to within 4½ inches. The vertical angle readings gave a further check and agreed with the D.P. final levelling to within 5 inches. None of the portals could be seen from the top of the ridge, hence it was necessary to set out additional trig. stations as near as possible to the portals, from which the necessary lines could be run. A point was chosen on the ground surface to mark the junction of the south adit and the main tunnel. The computed angles that the adit made with the main tunnel to the surge shaft, and with the main tunnel centre line to Brot, were laid off from this point and the centre lines produced on the ground to the surge shaft trig. station, and to that on the tunnel centre line in the Brot area. As the lines passed through these points the computed angles and length of the south adit checked with the survey. A similar procedure was adopted in the layout of the pipe tunnels, and the north and valve adits, suitable reference points being fixed near each portal on the centre line of the adits (produced), and the centre lines being transferred from the surface to below ground. The lengths of the adits to the junction with the main tunnel were measured by subtense bar, and checked by a 100 ft. invar tape. The tunnelconnecting F. A. J. and surge shaft was mainly driven fromF.A.J.; but a heading some 130 ft. long was driven from the surge shaft, the alignment of this heading having been set out using four eight pound plumbobs suspended by piano wire from the top of the shaft. On completion of the works, the alignments of these two headings met with an error of 5/32 inch. This proved the accuracy of the survey work, as the meeting occurred at distance underground of nearly a mile from the south adit entrance, and the surge shaft was 380 ft. deep. Reference marks have been fixed at approximately 50 ft. intervals in the pipe tunnels and at 100 ft. intervals in the main tunnel. They give distances, line and level and consist of steel plates embedded in concrete, the point being indicated by a punch mark on the plate. Distances along the tunnel are measured with 100 ft. steel tapes compared from time to time with a 100 ft. invar tape and levels are taken using small precise pattern instruments.

Location of tunnel.

The choice of the exact location of the tunnel was a matter in which a large number of factors had to be taken into consideration. The general topography of the district shows that the tunnel length must, assuming the tunnel roughly horizontal, lie between two and three miles. The intake had of course to be placed downstream of the junction of the Uhl and Lambha Dag streams and considerations which finally fixed its position on the north side were the location of the diurnal reservoir and of the proposed dam site. On the southern side it was imperative to select suitable positions for the surge shaft and pipe line. A pipe line on the type of ground met with in the Kangra valley is best sited in such a manner that any slips which may develop on the slope on which it is sited, will tend to move parallel to the pipe line and not across its track. This means that the pipe line should preferably run down the backbone of a ridge or down the steepest grade of an open slope. The choice of position is also influenced by its suitability for the construction of haulage facilities. When these requirements had been duly considered little latitude was left for the position of the tunnel. The surge shaft which is at the point at which the main tunnel delivers its water into two six foot pipes was fixed within narrow limits by hydraulic considerations. The bottom of the shaft must be below the lowest possible hydraulic gradient and the top must be at least as high as the maximum static water level.

The intake and the surge shaft being fixed, a straight tunnel between the two might appear at first sight to be the obvious course. Here, however, the methods and time required for driving the tunnel have to be considered. The important question of time required for a tunnel depends upon the number of places at which excavation can be started. Side entrances (or adits) and shafts to enable additional driving faces to be opened up are employed wherever possible. In this case the Wyre nallah offered the only possible line of approach for an adit. There was no possibility of splitting up the work any further. Additional shafts could not be employed owing to the great depth that would have been necessary. The Wyre nullah adit offered a means by which two extra driving faces could be operated but it was found on completing an exact survey that it would require to be some 2000 ft. in length, if a straight tunnel from the surge shaft to the intake were adopted. It was then observed, however, that by deflecting the tunnel in the manner shown in plan on plate II, its total length was increased by approximately 80 ft. only, while that of the adit was decreased by nearly 700 ft. It was for this reason that a bend was introduced in the tunnel.

Design of Tunnel.

The tunnel section has been designed of circular shape 9′ 3″ internal diameter to carry 300 cusecs in the first stage and 600 cusecs at 9ft. per second after the dam has been built. With a frictional co-efficient of N 0.14 the friction loss per 1000 ft. when discharging 600 cusecs is calculated to be 2.22 ft.

Owing to the poor nature of the rock through which the tunnel has been driven, and also to that fact that it will be liable to heavy internal hydrostatic pressure, a circular section has been adopted throughout, except in the granite gneiss where it was originally hoped that the rock would be sufficiently sound to require no lining.

Starting from the northern portal in the Uhl Valley, a circular section as shown on plate III has been adopted throughout the mica schist and for 550 ft. into the granite gneiss. In order to prevent leakage where the overburden is small, a section of the tunnel 677 ft. long from the north portal to a little beyond the valve chamber has been lined with reinforced concrete. An effort was made in December 1930, by which date the granite gneiss in the neighbourhood of R. D. 3500 improved in quality appreciably, to drive to the 12′-9″ dia. necessitated by the increased frictional co-efficient of an unlined tunnel. Progress however dropped to an alarming extent and reached the very low figure of 115 ft. for the month, the costs rising correspondingly. The fall in progress was mainly due to the increase in quantity to be mucked out, which rose by over 28 per cent. and the increased cost was largely due to the increased consumption of explosives the cost of which rose by Rs. 25 per ft. run.

As the improvement in the quality of the granite gneiss was not maintained (actually it frequently deteriorated to such an extent that steel sets had to be erected to secure the roof against heavy rock falls) and as the reduced progress would have had a serious adverse financial effect it was decided to line throughout and to reduce the cross sectional area again adopting a plain arch section, as being easier to drive than a circular one. It may be noted that conditions had changed very considerably, as in the mica schist heavy pressures were likley to develop, at places, both at the sides and particularly in the roof, whereas in the granite gneiss, side pressure was practically unknown, but the decomposed felspar in the joints was very apt to weather and get washed out by water, necessitating roof support to prevent large pieces of rock falling. The type of lining for this section of the tunnel is shown on plates IV & V.

It was found that for a cross sectional area of approx. 100 sq. ft., the plain arch section possesses many advantages over the circular as sidings and passing places have to be specially excavated in the circular section causing much "overbreakage" which has to be filled in when lining, also pumping stations with their sumps require appreciably more excavation than is necessary when the pavement is horizontal.

The circular section is more difficult to trim to correct shape, from which it follows that the overbreakage in this section is likely to be heavier than in the plain arch ; while in the plain arch section some of the services can be laid on the ground, in the circular, unless secured by holdfasts in the rock, they are liable to slide down and foul the track.

Where, however, heavy pressures either internal or external have to be dealt with, the circular section possesses many obvious advantages and on the south side of the ridge, the lining has always been finished to a circular shape, although the placing of the steel sets automatically forced the excavation to assume the plain arch shape.

Owing to the likelihood of large "gushers" of water being met in the granite gneiss, it was decided to change the easy grade of 0.899 per cent. originally projected for the northern heading, to $3\frac{1}{2}$ per cent. and to drive down at this grade over a length of 662 feet, in order that the greater portion of the progress through the granite gneiss might be at 0.2 per cent. down; on which grade the water difficulties at the face could be reduced appreciably, by overcutting the floor in a series of steps between each of which the floor could run uphill, back to grade. It was originally intended to utilize an arched lining 12′ wide and $11\frac{1}{2}$ ft. in height in places, as considerable saving in concrete would be affected, but this could not be done, without the probability of air pockets forming in the roof, the depth of which would probably be about 15 inches. While owing to the large area of cross section, there was no danger of the carrying capacity of the tunnel being reduced, there was, however, the grave danger of air bubbles, compressed to a very high pressure, being carried along from these pockets to the surge shaft, where they might be released with explosive force, with the risk of damage to the intricate work of the surge shaft.

At R. D. 6543 which marked the probable limit of progress from the north end, the grade to the junction with the south adit is 1.25 per cent. which gives a good drainage gradient for the midpoint heading. From the adit junction to the surge shaft the grade is uphill to the extent of .599 per cent. Thus both south headings have natural drainage and the arrangement also makes it possible to empty the entire tunnel through the adit should this ever be necessary. No other arrangement would, in fact, be practicable, as the south adit runs on a 3 per cent. up grade from its portal to the junction, and due to the topographical conditions, it was not possible to bring it in at a higher level.

Plant and Equipment.

A total of 1080 K.W. has been installed for all construction purposes in two interconnected water driven stations, one in the headworks area at Brot, and one at Dhelu near Jogindarnagar. Power is generated and transmitted at 11,000 volts. to the tunnel substations, of which there is one at each portal. From these the tunnel headings are supplied with power at 400 volts, A. C., three phase, for mucking machines, concrete mixers, placers and pumps, carried by 3 core 19/.083 V. I. R. cable; current at 220 volts D. C. from motor generators, for charging the loco batteries and for running the locos by overhead trolly wire outside the tunnel portals is carried inside the tunnels by means of 37/.083, V.I.R. cable, so that loco batteries may be charged while waiting for trucks in the tunnel ; also current at 220 Volts three phase A. C. for lighting is supplied, each phase cable being of 19/.064 V. I. R. The tunnel is sectionalised so that each phase illuminates about 1/3 of the total length driven.

Compressed air has been used in many different ways on the project and it is almost impossible to imagine the execution of the work without its aid. Compressors are located along with the sub-station plant at each portal. The machine principally used has been the Browett and Lindley reciprocating type, two stage compressor of 600 c.ft. per minute free air capacity. The compressor is driven by a three phase induction motor of 140 B. H. P. at 365 R. P. M. current being taken at 400 Volts. Air is delivered at 120 lbs. into a receiver of 160 c.ft. capacity from which a connecting pipe runs to the heading.

Two of these machines are maintained at the north portal station and three at the south portal station which is located about 1000′ from the south adit entrance. The service main in the north heading is of 4″ victaulic jointed steel pipe. On the southern side where the demand of two headings has to be met simultaneously a 6″ Mannesmann flange jointed pipe connects the compressor station to the adit junction and from this point a 4″ victaulic pipe serves each heading.

In December 1930 one rotary air compressor of the Swiss Locomotive Co. manufacture was added to the equipment on the south side to deal with increasing demands for air for the pipe line and power house and also for grouting in the main tunnel. This machine which can supply air up to 150. lbs sq. in. is driven by a 145 B. H. P. synchronous induction motor at 500 R. P. M. and takes its power at 400 volts A. C. like the others.

A pair of blowers made by Messrs. James Keith and Blackman, is located in each compressor station. They are driven by a direct coupled induction motor located between the two blowers, which are of different characteristics, being designed to deliver 3000 c.ft. of air at 12″ and 20″ water gauge respectively, when running at 1500 revs. per minute. When run at 2950 revs. per minute they can exhaust 6,000 c.ft. of air per minute at $40\frac{1}{2}$″ and $65\frac{1}{2}$″ water gauge respectively. These two blowers require 210 B. H. P. when run at full speed but only 39 B. H. P. at low speed. The blowers are connected with the headings by means of a 17″ dia. steel flanged duct made up in lengths of 10 ft. which are bolted together with asbestos insertion packing.

The ventilation of the tunnel has on the whole proved to be very satisfactory. After each blast, both the blowers are run exhausting at high speed and the fumes are generally cleared from the heading and work commenced within 45 minutes. It has been found in practice that the best results are obtained throughout the tunnel by continuing exhausting at low speed rather than blowing, though the latter appears theoretically the right course to adopt. This, however, was found to cause considerable discomfort in the actual heading where the air exhausted from the drills was found to be very beneficial provided the fans were exhausting.

During the excavation of the south adit a smaller single blower of similar type was employed. This was rated at 3,000 c.ft. of air against 18″ of water. After commencement of the main tunnel headings the larger machine took over the work the smaller being retained as a standby. It was intended to use this machine for the surge shaft heading by means of a separate duct but this was found to be unnecessary. A "Y" piece was fixed at the junction of the adit and the main tunnel connecting with the ducts in each heading. Dampers were fixed so that the large machine could operate on one heading at a time. As the length of the headings increased the double task proved rather severe as in order to keep both headings ventilated it entailed much more high speed blowing than was originally anticipated. However, the machine stood the strain and the holing through of the surge shaft heading immediately eased the situation as a natural draught was thereby created between the adit entrance and the surge shaft and pipe tunnels. When the shaft and the pipe tunnels were both open the circulation of air was a somewhat complicated matter and the direction of the draught in the surge shaft heading evidently depended on varying atmospheric conditions outside, sometimes causing the draught to pass from the adit to the shaft and sometimes in the opposite direction in considerable strength. By regulating the draught in the pipe tunnels however by means of wooden doors with adjustable air louvres it was found possible to maintain a steady draught from the adit to the surge shaft and no further artificial ventilation was necessary in this heading except in cavities above the roof which were ventilated by jets of compressed air while work was in progress inside them.

A smithy has been provided in the vicinity of each portal. Each is equipped with two No. 50 Ingersoll-Rand drill forging and sharpening machines. These are operated by compressed air at 80-100 lbs. and have worked very satisfactorily. The drill steel shanks are tempered in oil and the bits are quenched in water. Charcoal and oil furnaces are provided in each smithy.

The average daily output of sharpened drill steels for each smithy has been about 500 and the maximum about 750. One trained operator with one assistant can turn out a maximum of 250 in an 8 hour shift.

In the south headings 2″ and 4″ centrifugal pumps have been used mainly for water-supply to concrete work and occasionally for diversion of water while laying the invert. Although the inflow of water in the south headings was much greater than in the north heading, the problem of drainage, though troublesome for concreting, did not affect excavation as the grade was always away from the tunnel face. In the north heading natural drainage was towards the face and considerable quantities of water particularly in the granite gneiss had to be pumped out of the tunnel. For this purpose one 8″ suction and 6″ delivery centrifugal pump capable of delivering 750 gallons per minute against a head of 30 ft. was located alongside the tunnel portal to deal with surface water and a 4″ centrifugal pump capable of delivering 350 gallons a minute against a head of 75 ft. was provided as a standby.

In the tunnel eight 4″ pumps of the same specification as that given above and four 2″ centrifugal pumps capable of delivering 100 gallons a minute against a head of 25 ft. are in use.

The delivery main from these pumps consists of a 6″ steel pipe on to which flanges have been screwed and in view of the considerable friction head involved while heavy pumping is going on, it has been found advisable to form pumping stations along the length of the tunnel and to pump out in stages each with a head of about 70-90 ft. In general these pumping stations are equipped with two 4″ pumps, one of which runs almost continuously, the other serving as a stand-by. Recesses have been cut in the sides of the tunnel in which it is possible to locate a 4″ pump and these have been installed within 50 ft. of the heading, a 2″ pump being located in a similar recess close up to the face. Failure of the heading pumps has to be avoided at all costs as a shut-down for a couple of hours could cause the water to bank up to a depth of about 2 ft. against the face rendering mucking practically impossible until this water had been cleared. The pumps have, therefore, been protected with heavy timbers from the force of the blast, but nevertheless the suction pipes have frequently suffered damage.

The working of the mucking machine with water at the face was extremely difficult, as it was found almost impossible to keep the track clear particularly after a blast when rock would be scattered over it for a length of anything up to 400 ft. This difficulty was got over to some extent by dropping the tunnel grade suddenly for about $2\frac{1}{2}$ ft. at a point where a pump could be located and then driving uphill at a very easy grade for about 200ft. To keep the rails to grade however, it was necessary to pack them up considerably where the step in the pavement took place.

Method of excavation and plant employed underground.

Methods of tunnel driving are dependent on the size of the cross section to be excavated, the nature of the rock and the type of plant available. If mucking methods are slow, it may not pay to blast out too much at one time as work on the face is thereby much delayed. In this case, however, the tunnel section is a comparatively small one and rapidly working mucking machines were available. In general, therefore, when in good ground the entire section has been drilled and blasted in one operation. This has been modified at times in the north heading where a top heading with a low bench was more satisfactory on account of water which tended to drain towards the tunnel face. In the south heading the modifications necessary have been due mainly to bad ground. When the rock penetrated is of a nature likely to fall in large masses, the expedient is frequently adopted of proceeding by means of a small heading approximately 6′ × 5′ which is afterwards enlarged to full size.

A top heading is usually adopted in loose rock, *i.e.*, the roof of the small heading is kept at the level of the roof required for the main tunnel or slightly higher. This method renders it possible to keep the roof of the tunnel securely strutted while enlargement and the placing of the full size timber sets or steel-work is in progress. Enlargement follows the top heading at about 20′ distance.

A bottom heading has occasionally been used where mucking or haulage were interrupted by other work in the tunnel. By this method a low heading is pushed forward 50′ or so and the track extended. The roof can then be blasted and allowed to fall on the track from which it can be rapidly removed by the mucking machine. The method was found suitable only in good rock.

Another method in bad ground which has been used is to excavate two narrow side galleries leaving a solid central bench. Uprights for sets are placed in each side gallery and the sets are completed one by one, the bench being gradually removed.

In very loose ground the needle bar and face board method has been tried. Briefly this consists of provision of head cover by driving steel channels into the face at roof level, the outer ends being supported on steel sets or single R. S. beams strutted from the tunnel floor. Excavation proceeds under the channels, sets being placed as soon as sufficient space is gained. If the face of the tunnel will not stand vertically, it is boarded up completely and worked on one foot at a time commencing from the top. The top board is taken out and enough muck excavated to enable it to be replaced and held by struts 6″ or so further forward. The process is repeated with each board in succession.

This method which is a standard one for loose ground, and particularly for plain earth, was found to give great difficulty except when the ground could actually be worked by hand. Where masses of loose boulders were encountered as in some of the cavities it proved definitely unsuitable as blasting had to be resorted to at times and this usually wrecked the sets already erected. A far more suitable method which gave good results was obtained by injections of cement grout ahead of the face. For this process the tunnel face was completely closed with planking and 2″ G. I. pipes were driven into the loose ground as far ahead as possible. Cement grout was then injected from a Canniff tank at 100 lbs/sq. in. Solidification of an area about 6′ in depth round the tunnel section was aimed at. In practice the grout also penetrated the actual section intended for excavation but the expenditure of cement was usually surprisingly small in view of the results obtained. It was usually possible to go ahead with excavation after a delay of a few days and no serious fall was ever experienced from rock which had been previously grouted.

The work at the face was split up into a cycle of operations, details of which together with the approximate average time taken during each 8 hours shift are given below :—

Drilling	3—5 hours.
Charging holes	1 hour 15 minutes.
Firing and exhausting fumes	45 minutes.
Clearing track and mucking	6 hours.

In general drilling was restarted as soon as the face could be cleared and hence the time allowed for it overlapped that of mucking. In addition to the above, track had to be laid, to keep the tubs right up to the face, this was usually done in 10 ft. lengths, these being replaced by 40 ft. rails as found necessary.

Timbering was carried out wherever possible without interrupting the above cycle though in bad ground drilling had frequently to be interrupted in order to advance the permanent timbering and to permit of the erection of temporary timber sets in the face itself for the safety of the drillers.

The various operations will now be described in detail.

Drilling.

The depth and spacing of holes to be drilled for blasting a tunnel face are always dependent on the quality of rock being excavated. Typical drilling diagrams for the mica schist and the granite gneiss are shown on plates VI (a) and (b). In long stretches in the shattered quartzite of the surge shaft heading no hole was ever drilled above the tunnel centre line as the roof came down only too readily when the lower half of the face was lightly blasted.

In all headings C. P. 10 Jack-hammers weighing 55 lbs. have been used almost exclusively though latterly Ingersoll-Rand No. S. 49 jack hammers have also been tried. These tools have been run by all a crew consisting of 1 head driller, 1 asstt. driller and 1 miner, 7/8″ drill steel being employed. It was originally intended to utilize the Jack-hammers only in the softer portions of the mica schist, Leyner drills working either from a drill carriage or from vertical or horizontal bars being brought into use as soon as hard rock was encountered.

Whilst the normal depth of the drill holes for the Jack-hammers ranged from $2\frac{1}{2}$ to 6 ft. that for the Leyners was intended to be from 8 to 10 feet, necessitating heavy charges of explosive and the use of $1\frac{1}{4}''$ cartridges. The latter drills weighed 150 lbs. and utilized $1\frac{1}{4}''$ drill steel.

The Leyner drills were tried out both in the mica schist and in the granite gneiss and it was soon established that the lighter Jack-hammers were more suitable for the conditions met.

In order to compensate for the extra time taken in setting up the heavy drills the rock must be of such a nature that long holes can be drilled and heavy charges used. This condition has never been fulfilled in either of the southern headings and very seldom in the north heading. Moreover men unused to handling these drills require considerable training before they can become proficient in their use. Men of powerful physique are essential and are not easily obtained in this country.

In view of the above, and the poor progress which was obtained with Leyner drills under the conditions met with, it was decided to withdraw them from the work and the suppliers kindly agreed to exchange the unused machines for Jack-hammers and stoppers.

Four of the latter tools were in use in the northern heading, two supplied by the Consolidated Pneumatic Tool Co. and two by Ingersoll-Rand and they were found to be extremely useful, as, being fitted with an automatic feed, the tool could be rested on a piece of board on the floor of the tunnel and a couple of men could easily control it and drill holes for holdfasts for services, "stope" down the roof where trimming was necessary, or do excavation work in the walls or roof of the tunnel where blasting was not permitted.

Working three 8 hour shifts it was possible to get off 3 face blasts per day but simultaneous bench blasts frequently could not be arranged, as for instance, when the pavement was being trimmed prior to track laying. Considerable difficulty was therefore experienced in maintaining the necessary progress in the bench. In the south headings the whole section was blasted at once, except when a small advance heading had to be resorted to. This was found necessary for about 10 per cent. of the length of each south heading and was always slower than the full face work. Further delay was caused by the fact that the gelignite deteriorated comparatively rapidly under Indian climatic conditions and therefore the danger from misfires was considerably enhanced. That this danger existed is clear from the fact that as much as 100 lbs. of unfired gelignite cartridges were removed in a month from the muck pile.

As the geologists had predicted that considerable quantities of water might be met with in the fissures of the granite gneiss, pilot holes running from 12 ft. up to 16 ft. in length were drilled in the north heading, to give warning of such water, which might have been under very heavy pressure and have caused loss of life or serious damage. These pilot holes were driven by the C. P. 10 drills fitted with a $\frac{7}{8}'' \times 3\frac{1}{4}''$ shank, the steels being made up in multiples of 3 feet with a decrease of bit diameter of $\frac{1}{8}$ inch for each 3 feet increase in length, as follows :—

Length of drill steel	Bit diameter.
2′ 6″	$2\frac{1}{4}$″
5′ 6″	$2\frac{1}{8}$″
8′ 6″	2″
11′ 6″	$1\frac{7}{8}$″
14′ 6″	$1\frac{3}{4}$″
16′	$1\frac{5}{8}$″

The C. P. 10 drills also worked satisfactorily for holes from 5 to 6 ft. in length, when made up with $1\frac{1}{4}$″ bits, in order to use up the $1\frac{1}{4}$″ gelignite cartridges, which became surplus after the decision to exchange the Leyner drills.

For the ordinary drilling work the smallest size bit made was $\frac{7}{8}$″ to take the $\frac{7}{8}$″ gelignite cartridges.

The consumption of drills and drill steel varied considerably in the different types of rock, being on the average as follows :—

Material.	No. of steels reqd. per shift	Length drilled per shift in ft.	Length drilled per steel.
Mica Schist ..	80—90	200	18″—24″
Fissured Granite Gneiss	120	200	18″
Hard Granite	150	160	9″

Blasting.

The principal explosive used in all headings has been 60 per cent. gelatine dynamite commonly known as gelignite. A certain quantity of blasting gelatine has also been used and being more powerful is better suited to the harder type of rock.

Gelignite is suitable for work in wet conditions and it produces less carbon monoxide on detonation than other types of dynamite. For these reasons it is most suitable for underground work where considerable quantities of explosives are required and ventilation is difficult.

Electric detonators were used throughout, except for minor trimming work after excavation had gone ahead, when time fuse and commercial caps were occasionally employed for small blasts. No. 6. low tension electric detonators were used of three types, *viz.*, instantaneous, 5 second delay, and 10 second delay, and latterly No. 8 low tension instantaneous have been almost entirely used and appear to give more satisfactory detonation.

The original idea was to use instantaneous detonators for the cut holes, five second delay for the easers and ten second for the ring or side holes. Thus each blast would take place in three stages, each stage clearing away the resistance for the next and making it more effective. The idea is attractive in theory but, though there is no intention of denying the value of delay action detonators in certain circumstances, it cannot be stated that they were a great success in the tunnel. For one thing a blast with only instantaneous No. 8 detonators was found to give very much the same amount of progress as a successful blast with both instantaneous and delay action. Further the number of misfires with delay action detonators was surprisingly high. This was partly attributed to defective or deteriorated detonators as in some cases it was proved on examination that the waterproofing compound had flowed into the detonator cap and had masked the platinum bridge the fusion of which should light the match-head of the time fuse. The cause of this has been the subject of considerable discussion and it is still open to question whether the fault occurred during the process of manufacture or whether it is due to exposure to heat during transit. One fact which can be stated with certainty is that the detonators have never, while in storage in the magazines on the project, been exposed to heat sufficient to melt their waterproofing compound.

There are, however, other causes which may produce partial misfires with delay action detonators. It is quite possible especially in the softer types of rock that the explosion of the cut holes may displace the charges in the easers to an extent sufficient to cause only partial detonation. In such a case the detonator may do its duty but the continuity of the charge being interrupted by shearing of the rock, some unexploded gelignite may be left in a socket. Similar interruption may be caused by the fact that the delay action detonators are never precisely accurate in their timings. It is only necessary to listen to a blast in order to prove this. It would be quite impossible to ensure that all holes are always so placed that the explosion of one will never affect another. With instantaneous detonators no such trouble can arise.

It is of course of great importance to ensure that no unexploded gelignite is left in the face after a blast and a careful inspection is always made before drilling recommences. Drilling on to unexploded gelignite is about the worst thing that can happen to a driller and even a slight explosion naturally shakes the confidence of the whole gang. It is sometimes a matter of great difficulty in highly jointed or soft rock to make certain that no gelignite is left as all trace of the drill holes is liable to disappear and unexploded gelignite may get squeezed into crevices. In cases where the sockets of all the drill holes can be accounted for there is, generally speaking, little risk.

In loading a hole the detonator was placed in the last cartridge to be loaded as this was found to give the best results besides making loading easier. Loading was often difficult on account of the heavy pressure of water in the hole. In extreme cases two holes had to be drilled close together for one charge ; one hole being loaded and the other acting as a vent to ease the water pressure. In other cases the charge had to be jammed in the hole with a wooden plug through which the firing leads passed. The latter were occasionally enclosed in a thin reed or a bamboo rod in order to protect the insulation.

All electric detonators of one type were connected in series. Delay action and instantaneous were also usually in series with each other though at times the instantaneous and delay action were connected in separate series circuits which were then connected in parallel to the firing mains. Firing was done with 110 volt current produced from the 220 volt lighting mains by means of a small portable transformer. As many as 48 No. 8 detonators could be fired at one time.

On an average the progress per blast amounted to about 3′ and explosive consumption was as follows :—

North Heading. Mica schist 9.7 lbs. per ft. run.
Granite Gneiss 22 lbs. per ft. run.

These figures correspond to a consumption of about 5 lbs. per cubic yard allowing for overbreakage.

South Heading.	Pounds of Gelignite per ft.	Per cubic yard.	Detonators per ft.
Adit	5.7	1.9	8.1
Surge Shaft ..	6.25	1.4	6.3
Midpoint ..	13	2.7	13.3

again allowing for overbreakage.

A comparison of these figures illustrates clearly the difference in quality of the rock on the north and south sides of the hill though as the midpoint heading approached the north heading the quantity of explosive used corresponded very closely to that in use in the north heading.

Overbreakage in the south heading was inevitable owing to the state of the rock and was greater than in the north heading. Even here, however, it was found very difficult to keep down the overbreakage and in the early days it was found to account for an excess excavation of about 36 per cent. over the theoretical quantity necessary for a tunnel of 11′ 3″ diameter. This caused a corresponding excess of over 100 per cent. on the quantities of concrete required for lining. Contributory factors over and above that of unstable rock are :

(a) the stoping down of loose rock from roof and sides in order to prevent falls. This was particularly necessary in granite gneiss and wherever overhead protection was not provided.

(b) widening for the purpose of providing sidings and emplacements for machines.

(c) excavation for concrete beams to hold the beams for the raised platform helped to increase quantities.

In the south heading overbreakage was to some extent neutralised by repacking cavities with dry stone after erection of overhead protection this being grouted up at a later date. Occasionally plum concrete was used instead.

No heavy blasting was permitted within 800′ of the lining in order to avoid any likelihood of damage to the concrete. The rule was only relaxed in exceptional cases when charges of 1 to 2 oz. of gelignite were permitted one at a time for special trimming.

Timber was extensively used in the early days both in the north heading and in the south adit. It was found however that it decayed quickly in underground conditions and moreover specifications demanded that timber should not be concreted in along with the lining. The object of this is to avoid leaving a zone of perishable and soft material between the concrete and the natural rock. Greater security is obtained both from external and internal pressure if the concrete lining can be laid in intimate contact with the rock. The removal of timber was duly observed throughout the tunnel with practically no exception though it was realised that in soft and yielding ground, not easily solidified by grout, the point was of less importance. For example at points in the surge shaft heading where the ground is little better than soft clay the presence of an extra layer of soft material could not be of much consequence.

As the removal and replacement of timber sets was expensive and dangerous it was decided to utilize steel sets in all headings. Five piece steel sets as shown on plate VII (a & b) were made up in the Shanan work shops from 6″ × 3″ steel joints. These were linked together with 4″ × 4″ angles and roofed with precast reinforced concrete slabs. These sets proved entirely satisfactory and it is doubtful if their cost exceeds the provision of timber sets and the maintenance thereof which would otherwise have been necessary. In any case their use was inevitable if timber was not to be left in the lining.

In the north heading the granite gneiss conditions changed and as there was but little heavy distributed loading, as in mica schist, but concentrated loading due to the weight of individual and comparatively small masses of rock, a cheaper form of rail setting was tried and proved successful. This was made up by bending either 24 lb. or 18 lb. rails, each set being fish-plated up in one place only at the crown, and strutted apart with scrap material.

In both cases reinforced concrete slabs 10″ wide by 3″ thick made up in either 4 or 6 ft. lengths were used as lagging outside the steel sets These slabs having a very high percentage of reinforcement with ¼″

rods both top and bottom, gave ample warning before failure, and immediately a crack occurred, it was generally an easy matter to insert an additional steel set in the middle of the span of the slab.

It was found advisable to reduce the cross section of the tunnel appreciably when bad ground was met with, opening out again as soon as conditions improved. In general, however, much difficulty was experienced in widening out and putting in steel sets if these restricted areas were timbered and left to be opened out until just before the concreting parties came along, as weathering almost invariably took place and the timbers were found to be carrying extremely heavy loads. Hence every endeavour was made to carry out the enlargement, and to fix steel sets as soon as the heading had proceeded sufficiently far to enable this to be done.

Muck-dykes about 1 ft. in thickness and containing a wet plastic material were occasionally met with in the mica schist, and these very rapidly weathered forming a soft clay. As they were generally dipping at an angle of about 60°, it was found absolutely essential to steel set and concrete them up immediately, to prevent the formation of cavities. Where this was done but little serious trouble was experienced, as the ground was caught and supported before movement could take place. Where timber had to be removed after several months had elapsed however it was frequently found that cavities were formed involving the removal of large quantities of muck. A cavity at R. D. 1500 is a typical example. This extended at a maximum height of 35 ft. above the track, was about 15 ft. in width and 50 ft. long. Starting from the northern end the timber sets were removed, being replaced immediately by steel sets, which were then concreted in at the sides and roof. Notwithstanding this the sides started sloughing away and roof falls occurred causing very heavy loading on the remaining timbers, which, as they showed signs of failure, had to be supported from the middle of the track, close timbering having already been resorted to. Wheeled traffic to and from the heading was thus cut off. As much as possible of the muck lying on the timbers was then removed, though a considerable amount remained, and a flexible pipe from the concrete placer was fixed facing towards the heading, concrete being placed until it was considered that an arch of sufficient thickness had been formed over the timbers. This concrete was given 3 days to set before the timbers beneath it were removed and the muck, "sandwiched" between the timbers and the concrete taken out. In the meantime the southern end of the cavity was opened up, timber being replaced by steel which was immediately concreted up and these steel sets were carried forward beneath the concrete arch, the intermediate space being concreted up solid. During this work traffic was held up for 15 days and 10,000 c.ft of 1: 4: 8 concrete were placed, plums being added wherever conditions permitted. Plate VIII shows a method adopted when the sides started falling in.

The concrete placer was found invaluable, as the labour was only exposed to the danger of falls during the time that the delivery pipe was being fixed in position or now and then when shovelling over some of the concrete. In addition falls became much less frequent once the placer had come into action, owing to its "guniting" effect the walls and roof of the cavity being covered by cement plaster driven on by the compressed air used to discharge the concrete. The result was that where the sides could be held, it was possible on several occasions to dispense with the arch concrete referred to above and to span the cavity with steel rails over a gap of from 12′ to 16′ from the steel setted work at one end of the cavity to that at the other, these rails being covered with reinforced slabs, after which traffic could proceed with a reasonable degree of safety, whilst additional sets were being fixed beneath the rails and concreted in.

In the above work it always paid to fix the steel sets at least 6″ too high, to ensure against the possibility of encroaching on the lining.

Reverting to the south heading, the adit was timbered with the ordinary three piece sets, 9″ and 10″ diameter round timber being employed and covered with 3″ lagging. As this showed signs of decay within two years it was replaced by five piece steel sets similar in design to those employed in the main tunnel but of smaller span. Reinforced concrete slabs were used for lagging. The placing of these steel sets was comparatively simple as there was no necessity to remove all timber in the case of the adit.

In the main tunnel the surge shaft heading was timbered with steel sets and concrete slab lagging practically throughout. As is evident from the geological section the rock changed in quality several times and the dip was very flat. The rock throughout the whole of this heading was in a very highly jointed and in some cases a pulverised condition. This was particularly the case in contact zones of different strata. In such conditions blasting had to be very light and steel sets were kept practically flush with the face. Cavitation above the steel sets was practically unavoidable and timber had frequently to be used for packing as stone packing could not be placed quickly enough to hold the roof.

Although water appeared at many points in this heading during the monsoon of 1930, causing numerous slides and falls, it was fortunately not continuous except at two points where the work was, in consequence, especially difficult. These points were located at each end of the quartzite zone at R. D. 500 and 1600 respectively measured from F. A. J. At R. D. 500 a heavy and continuous inflow of water was struck. This washed out the loose rock and formed a cavity 96 feet and 30′ high. Steel sets were here placed at 2′ intervals and were preceded by the needle bar and face board process which has been previously referred to.

In the midpoint heading it was hoped that excavation would very soon penetrate the main granite of the ridge as it was expected from the earliest geological report that the granite zone expanded with depth. The reverse however was found to be the case and for nearly 4000′ this heading has passed through micacious schists and gneisses. The heading has been wet from the start to finish, the average inflow of water varying from about 2 cusecs to about 5 just after the rains. To some extent the water tended to follow the tunnel face as it advanced but steady springs remained in numerous places. At R. D. 290 after the excavation had passed, a sudden increase in the inflow of water took place which washed out sufficient stones and debris from the roof to block the tunnel. Luckily the tunnel face was quite close and the driving gang was just able to escape across the pile of debris before it filled the tunnel. This point was shored up with timber sets which were subsequently replaced with steel and about 15′ of concrete filling was placed above the tunnel section the remainder of the cavity being filled by grouting.

The most formidable cavity in the whole tunnel was however met with between R. D. 507-525 measured form F. A. J. in the midpoint heading. This stretch of 18′ which took 4 months to pass consisted of a natural fissure filled with loose rock and boulders to an unknown height and heavily charged with water. Unluckily the point was reached just after the start of the monsoon of 1929 with the result that the water increased continually. The tunnel at this point passed only about 500 ft. under a *nullah*. The first indication of trouble was after a blast when material flowed in and filled up the tunnel for 25 feet. Several methods were tried. A small heading heavily timbered was put through but was crushed by the pressure and had to be abandoned. Unfortunately the grouting plant had not yet arrived so that cement injection which would probably have solved the difficulty speedily could not be tried. The fissure was at length passed under cover of 12″ × 4″ steel channels supported on steel frames at 1′ intervals. Two large boulders which had jammed overhead in the cavity helped to relieve the pressure during the final stages. After arrival of the grouting plant the walls and roof were carefully covered by means of planks fixed between the steel sets and all crevices were stuffed with gunny bags. A thorough grouting was then applied and nearly 10,000 c.ft. of cement and sand were forced into the cavity through numerous pipes. A depth of about 10′ was solidified and a cover of at least this height obtained overhead. It was subsequently found possible to remove the supports and enlarge the tunnel to full size without any difficulty and the final lining has now been in position many months. Water still flows from the grout pipes but no signs of pressure have been noticed.

After this experience prompt measures were taken to apply cement injection at difficult points before large cavities could develop and in this way some half dozen places have been passed which would otherwise have proved much more difficult.

On the whole conditions in the midpoint heading have seldom been favourable to progress though in May 1931 at the driest time of year the driving shifts proved their capabilities by achieving a progress of 357′ in the month which is a record to date for all headings. Even in this stretch, however, water penetrated later during the monsoon and steel sets had to be erected practically throughout. On the average in this heading one steel set has been placed every 7′ as compared with every 3.7′ in the surge shaft heading and every 25′ in the north heading.

Mucking (north heading).

Two Myers-Whaley type 4 mucking machines driven by 20 H. P. motors and equipped with cable drums and 250 ft. of 3 phase trailing cable and travelling under their own power on 2'6" gauge track were employed in the northern heading. The No. 4 machine which has a capacity of about 40 c.ft. per minute consists essentially of an automatic power shovel mounted upon the forward end of a swinging jib which is pivoted at its rear end to the main frame of the machine. The jib section carries an armoured belt conveyer which receives the material from the automatic shovel and delivers to a second armoured belt conveyor which is also pivoted for lateral movement at the same point of the main frame and by which the machine can load trucks directly behind it or on parallel tracks. The driver operates two levers one to move machine backward or forward on its track and the other to swing the jib. These two movements give complete control and enable him to direct the shovel just as a man would direct a hand shovel. Due to the pivoting of both back and front portions the machine is easily adopted to tunnel clearance and curves. The machines proved satisfactory in dry conditions, for the first two years of the work, but when considerable quantities of water were met with, serious delays were caused owing to fact that water accumulated at the heading while the fumes from the blast were being cleared and the machine could not be moved back into the face, until the water had been cleared and the whole of the track thoroughly cleaned up. The wear and tear on these machines was considerable and in addition to minor repairs, which were carried out in the tunnel they had to be taken out and completely overhauled once a month, which caused delays, when the tunnel was upwards of a mile in length. Mucking machines of this type, to work most economically, require that the track should be laid right up to the face, in order there may be no man handling of muck after the blast, and this was found difficult to arrange owing again to water difficulties. In 1931 therefore the mucking machines were taken out of the north heading and hand mucking was resorted to.

Mucking (south headings).

One machine of the same type was provided for each of the south headings and both gave good service although maintenance charges were high. Conditions here favoured the use of the machines more than in the north heading, although their advantages would have been more fully emphasised if more rapid progress had been possible in drilling and blasting. In the south headings the gradient was away from the driving face so that accumulation of water did not impede mucking. As far as possible the face was kept vertical and track was laid right up to the face before blasting. Moreover on account of the down gradient it was possible to haul the muck out of the tunnel much more rapidly than on the up grade of the north heading. A loco could take out 12—14 loaded trucks at a time as compared with only 6—8 in the north heading.

Considerable saving of time could therefore be effected by loading trucks quickly and this was, of course, always important though more particularly so when drilling and blasting could proceed rapidly.

Regarding costs of mucking it was found that neglecting depreciation and interest charges on the machines, there was very little difference in the cost per foot of tunnel excavated whether hand or machine mucking was employed.

Haulage.

50 lbs. rails on wooden sleepers laid at 2′6″ gauge and to maximum grade and curve of $3\frac{1}{2}$ per cent. and 55′ radius, respectively, have proved to be very satisfactory, the number of derailments being negligible.

10 ton electric locomotives of the combined battery-trolley mining type have supplied the traction in all headings. These machines run with an overhead conductor between the tunnel portal and the muck dump and on battery inside the tunnel. They are fitted with two motors of 25 H. P. each and are specified to give a maximum tractive effort of 4000 lbs. at 4·8 miles per hour or to haul 25 tons up a 3·5 per cent. grade.

The batteries consist of 112 Edison alkaline type A/6 cells each of a voltage of 1·5 on open circuit. They are charged with a current of 45 amps. at 220 volts D. C. supplied by a motor generator. They have given good service and appear to be quite satisfactory provided they are overhauled at regular intervals and discharged and charged strictly in accordance with the maker's instructions.

There are two electric locos in the north heading and one spare battery has been provided. This is kept on a table outside the tunnel portal so that a loco coming out of the tunnel with a discharged battery can have it changed without delay leaving the discharged battery to be recharged.

On the long up grade it was found best to haul 8 loaded trucks only at a time. When the ramp of the raised platform was laid on the $3\frac{1}{2}$ per cent. grade between R. D. 1700 and 2312 the combined grade became 7 per cent. and it was then found advisable to reduce the number of trucks to six to avoid overloading the battery and for a time a cable which was mounted on a drum was plugged into the loco. This method proved satisfactory but necessitated elaborate precautions to avoid damage to the cable.

The south headings employ two combined type locos and one trolley type which does all outside work. It was originally proposed to run a trolley line through the tunnel but this idea was abandoned as the restricted height of the heading would have made it a constant danger to labour carrying drill steels, etc., and further because interruption would have been frequent as the bare conductor could not have been kept live in the presence of grouting and other parties at work at various points in the tunnel.

Trains of 8-10 loaded trucks on up grade and of 12-14 on down grade were easily operated on all grades in the south headings.

Labour organisation and methods of payment.

As the methods finally adopted on the north and south sides varied considerably they will be described separately. The adoption of different methods was largely due to different conditions of work. On the north side although many difficulties had to be overcome working conditions for the labour were for the first 4000 feet or so distinctly less severe than on the south side. The rock was of a nature which lent itself to steady progress and the inflow of water though serious enough for a down grade heading was not such as to cause great physical hardship. Conditions generally were such that hard work usually produced corresponding results in good progress. On the south side the rock was far more shattered and in the midpoint heading the driving crews have practically never worked under dry conditions. On the surge shaft side although wet conditions were mainly confined to the first 600′ the intensely shattered and varying nature of the rock gave great trouble and on account of the small overburden the monsoon rains caused additional difficulties. An indication of the state of the ground in this heading is that strong overhead protection had to be provided except for about 100′ throughout the whole 3000′ length, many of the steel sets being placed at 2′ intervals. Cavities were numerous in both southern headings, one of them in the midpoint heading taking four months to pass. Thus on the south side the hardest and most dangerous work was done at times when little progress in actual footage was effected and a system had therefore to be adopted which gave adequate remuneration to the men who faced the conditions, irrespective of total length driven.

In the northern heading, once some idea had been obtained of the conditions, all work was carried out by daily labour, the labour employed on the tunnel driving being paid a bonus corresponding to the footage driven each month. The following were the main principles of this scheme.

The foremen were cut 20 per cent. of their pay, such cut being the first charge on the total bonus earned. The balance of the bonus earned was then divided in the proportions of 25 per cent. to the foremen and 75 per cent. to the labour.

For a monthly progress of less than 100 ft. no bonus at all was paid, the bonus for a drivage of from 100 ft. to 150 ft. amounted to Rs. 6 per ft. for over 150 and up to 175 ft. it was Rs. 12 per ft., for over 175 and up to 200 ft. it was Rs. 24 per foot, for over 200 and up to 225 ft. it was Rs. 30 per ft., finally for over 225 ft. Rs. 36 per ft. was paid.

The labour employed in the heading consisted chiefly of Gurkhas, Garwalis and Pathans and once the work was in full swing no difficulty was experienced in obtaining ample supplies of labour. On an average about 700 men were employed in the northern heading and these were split up into three shifts of 8 hours each, except on Sundays, when the work was carried out in two shifts of 12 hours, each to enable the working hours of the gangs to be changed over. The driving in this heading was supervised by one head tunnel foreman, three tunnel foremen one for each shift and three heading foremen, who, as their designation implies, were solely employed at the face.

At the south heading the ordinary muster roll system of payment was adopted at the outset and later a bonus system similar to that in use in the north heading was tried. This, however, was almost immediately opposed by the labour as it was soon found that men working in difficult and dangerous conditions, and who undoubtedly deserved special encouragement, would thereby earn less than those working in easier ground. Reversion to the daily wages system was undesirable. Flat rates for the various types of work would not meet the case.

It was essential to pay wages which had some relation to the physical conditions of the work and the risks which had to be taken, if any progress was to be obtained. A system was required under which any man who showed marked tenacity and personal bravery in dealing with a difficult job, could be awarded an extra day's wages on the spot. Any attempt to apply such a system departmentally would have presented considerable difficulties, even if it had not been promptly strangled by red tape. A solution was, however, found by engaging a suitable contractor who took over tunnel labour in both headings and was paid on a footage basis on monthly work orders. It was not possible to adopt different systems in each heading as these were served by the same line of communication, *i.e.*, the adit, but there was an advantage in giving the contractor both, in that he was generally able to balance his losses in one heading by his profits in the other, while he was of course quite free to vary his rates of payment to labour according to the conditions of work, the particular conditions where special rates were required being indicated by the Department. The department was freed from the onerous task of maintaining muster rolls for 1500 men working over the 24 hours with the result that supervision could be better concentrated on the actual performance of work.

Regarding rates paid it was reckoned that with departmental labour in average ground at rate of progress of 150′ per month labour and explosives would cost approximately Rs. 60 per foot run. This rate was paid to the contractor the cost of explosives being recovered from him. To cover the cost of additional wages in wet ground an additional Rs. 20 per foot was allowed the payment being made only on the personal certificate of the Superintending Engineer that wet conditions prevailed. In addition to this a considerable bonus for progress was offered on the month's work. For excess footage over 150′ four annas per foot of excess was added to the rate paid for the whole month's progress and eight annas per foot of excess of over 200 up to a maximum of 250′. It was many months before the contractor earned any appreciable bonus ; at length however better progress was achieved and after a couple of months of this it was found possible to make a fresh agreement on the same lines which called for greater progress before bonus was paid. The system has worked well and there has been no discontent among the labour although monthly footage has varied from 10′ to 357′. It can also be stated that when the cost of the vastly greater amount of timbering is taken into account the costs of the south headings compare not unfavourably with that of the north.

Labour shifts were on the same lines as already described for the north heading.

Progress.

Plate IX shows a portion of the tunnel diagram which was maintained and which was found to be very useful, as it shows the location of springs, cavities, over-breakage, reinforcement in lining, progress and geological features, etc.

In the northern heading to the end of October, 1931, an average progress of 5.4 ft. per day has been maintained, the average for the work done in the mica schist being 5.1 ft. and in the granite gneiss 5·78 ft. per day. The best continuous progress was obtained in the year 1931 when up to the end of October, 2035 ft. were driven, at an average of 6.69 ft. per day.

Compared to these rates, the average progress to the end of October 1931 in the midpoint heading was 3.6 ft. per day and in the surge shaft heading was 4.2 ft.

Cost of driving.

The total cost to the end of October, 1931, per ft. run of drivage in the northern heading amounts to Rs. 145 and in the southern headings to Rs. 178 and 179 . These costs are inclusive of all timbering and steel setting. They include the reinforced concrete slabs, which are used as lagging for the steel sets, but do not include concrete required for filling cavities and other over-breakage, which is charged to lining. Interest and depreciation charges on machinery are not included.

The following table shows the cost of the work, by sub-heads, in the different headings :—

TABLE OF DRIVING COSTS.

COSTS IN RUPEES PER FOOT RUN.

Sub-head.	Northern Heading.				Southern Heading.						Remarks.
	In Mica Schist.		In Granite Gneiss.		In Adit.		In Surge Shaft.		In Mid-Point.		
	Labour	Materials	Labour	Materials	Labour	Materials	Labour	Materials	Labour	Materials	
Drilling and Blasting.	14	25	17	54	12	25	24	24	31	41	
Timbering.	8	8	7	12	5	14	20	49	9	18	
Mucking.	8	3	16	9	10	4	20	2	22	6	
Haulage.	5	2	9	3	6	2	12	2	12	6	
Maintenance of Services.	13	18	17	22	7	5	13	4	16	8	
Work-Charged Establishment.	10	—	13	—	3	—	8		10		
Totals :—	58	56	79	100	43	50	97	81	100	79	
Grand Totals (Labour & Materials)	Rs. 114/-		Rs. 179/-		Rs. 93/-		Rs. 178/-		Rs. 179/-		

It should be noted that conditions in the two headings varied very considerably and that the Southern heading was one foot larger in diameter than the Northern.

General conditions governing the lining of pressure tunnels.

The forces acting on a pressure tunnel require very careful consideration as numerous failures have occurred, up to quite recently, owing to the general principles not being sufficiently well understood; examples of this are seen in the Angalbag power station tunnel, built between 1903 and 1905, which failed owing to cavities being filled with dry stone masonry and timber being left outside the concrete lining ; similarly the Sand-Canyon tunnel of Los Angeles failed, due to water finding its way through many cracks in the lining, into the mountain, where it travelled to the surface land caused and slides, notwithstanding the fact that the lining was about 12″ thick and had been grouted. It is now generally admitted that a plain concrete lining is only suitable where the movements in the rock due to internal pressure in the tunnel do not exceed fractions of a mm., or where the rock is compact and homogeneous, or where it contains water at a pressure approximating to the internal water pressure of the tunnel. Reinforced concrete is not the ideal material for the lining of pressure tunnels, owing to its liability to crack and enable water to escape, but at the present time it is the most suitable available, and hence it is frequently used, with the proviso that the steel is only very lightly stressed, The percentages required and the resultant costs are, therefore, very high, the work being troublesome owing to the difficulties experienced in absorbing in the concrete the full quantity of steel, including joints. For this reason, it is usual to employ a cement gun to place the concrete and it may be considered advisable to weld the joints, instead of overlapping them. Another system which is frequently adopted is a combination of the two mentioned above, in which case the plain concrete lining is placed to take the external pressures and the reinforced lining or "mantle" (as described in this paper) takes the internal water pressure.

The following forces acting on a tunnel must be considered :—

1.—The pressure of the materials through which the tunnel is driven.

2.—The external water pressure.

3.—The internal water pressure.

4.—The stresses due to changes in temperature.

Under the influence of pressure, rocks are apt to deform in two ways ; firstly that within what may be termed as the elastic limit, which is of a temporary nature ; and secondly the plastic deformation, which is of a permanent character. It has been found by test that in certain materials such as gneiss, the plastic deformation has been so small that it could not be measured, whereas in certain slates, the plastic movement was estimated at 50 per cent. of the toal movement. Experiments in Germany have shown that the movements under pressures of only a few atmospheres may be sufficient, even in rock of fairly good quality, to destroy and crack a concrete lining, and in the Ritom tunnel under a pressure of 4.2 atmospheres very serious losses were experienced over a length of 8250 ft., where the average width of the cracks on the concrete was 0.4 mm., corresponding to an average increase in the diameter of the tunnel of 0.5 mm. showing that the lining was fractured under movements of a quarter of a mm. Cracks and crevices may exist naturally, or be caused by blasting, which must loosen the rock around the bore-hole, particularly if it is badly fissured.

It is, therefore, obvious how necessary it is to prevent movements during driving, which may lead either to the development of very heavy pressures or to the movement and resultant cracking of the lining, when the internal water pressure comes into operation. Hence it is advisable to prevent movement of the rock, whilst the timbering is being removed, and to execute the lining as soon as possible after the excavation, though the effect of heavy blasting on new laid concrete has to be borne in mind.

During the driving of a tunnel there is always the possibility of striking fissures both large and small, which may contain water; the pressure in these fissures, immediately they are struck, being that corresponding to the height of the water in the overlying rock. If the fissures are small, the pressure may soon diminish due to the friction losses, though the supply may not diminish very appreciably unless the storage in the hill is small. On the sealing up of these small fissures by the lining, the external water pressure may build up and become a very important factor. On the other hand a large discharge of water into the tunnel, during the construction, would not necessarily correspond to a heavy external water pressure on the lining of the finished tunnel; as this would entirely depend on the height of the water level in the fissures. Owing to the fact that where the exernal water pressure is considerable, there is little risk due to leakage, pressure tunnels are now usually located as deep as possible below ground level.

The internal water pressure has to be provided for wherever it exceeds the external pressure with the tunnel empty. Many authorities now maintain that it is almost impossible to calculate the share of the stresses to be taken by the lining and the rock respectively; as the lining of the tunnel has no rigid support, but rests on a base which yields in an indeterminate manner.

In general, during the driving of a tunnel the exposed rock will be brought into contact with air at a lower temperature and will, therefore, be liable to contraction, which may form cracks. Furthermore if the water passed through the tunnel is colder than the air, further contraction will take place, resulting in a decreased diameter of the tunnel and a consequent decreased support to the lining. Experiments have shown that the influence of variation in temperature does not reach more than about 10 ft. beyond the lining. The following shows that temperature variations in the Uhl River tunnel, during driving, were negligible :—

R. D.	Temp. Fahr. on 17-11-31.	REMARKS.
Portal	66.0°	
1000	62.0°	Air.
,,	62.0°	Water from grout pipe.
2000	64.0°	
2850	66.0°	Centring car.
2900	67.5°	Near fresh concrete.
3200	69.0°	,,
3460	68.5°	
,,	62.0°	Water from grout pipe.
4000	68.0°	
5000	64.0°	
5555	60.0°	Water from fissure.
5650	66.0°	In heading, concrete being laid.

The rises in temperature recorded above, appear to be almost entirely due to the heat given out by setting concrete.

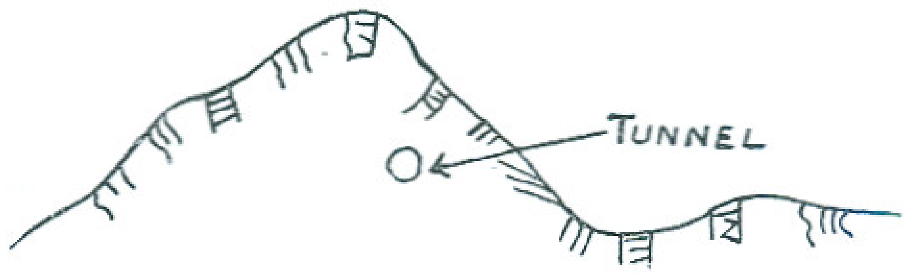
The temperature of the river water on the same day was 46.5°.

The tunnel mantle.

From the above it follows that the first consideration in the lining of a tunnel is to provide a lining capable of withstanding any external pressure which may be exerted by the surrounding rock. In the present case, this has been met by the installation of a circular ring of concrete of a minimum thickness of one foot. A lining of this type with a finished internal diameter of about 10 ft. may be relied upon to take any pressure likely to arise, provided that all cavities which have occurred in the rock, during excavation, are carefully filled. The complete filling of cavities assures, as far as possible, that any pressure on the lining will be of a uniform nature, and of a type which the circular form is well adapted to resist, whereas if numerous large cavities are left empty, there is a serious danger of local movement in unsound rock, which may bring heavy concentrated pressures to bear.

Even after all possible precautions have been taken, however, in dealing with external pressure, there still remains the question of the effects of internal hydrostatic pressure.

In any pressure tunnel lined with plain concrete there is liable to be a saturated zone of rock round the lining caused by the passage of water through cracks, which in turn are caused by the internal pressure. Whenever the strain caused by the latter is beyond the elastic limit of the concrete and the surrounding rock, cracks are inevitable, but their importance depends greatly on the nature of the surrounding rock and also on the topographical position of the tunnel. When the tunnel lies below a steady water table, similar to that previously referred to, the internal hydrostatic pressure may often be balanced by external water pressure and in such a case, there is no necessity for a waterproof lining; but in the present case, when the height of the water table obviously depends on the season of the year and more especially when the tunnel runs inside a ridge as in the following diagram, which represents conditions in the Surge Shaft heading, any escape of water is likely to be serious, both from the point of view of actual loss of water and also from the danger of heavy slips being started on the hill-side.



In this connection, it was noted during construction, that the percolation of water into the unlined tunnel usually increased, during and just after the monsoon, and furthermore a spring situated some 300 ft. above the adit portal and which for some time supplied water for all purposes in the adit and tunnel exit areas, dried up ; the only possible explanation being that it has been drained out through the tunnel.

Various means for counteracting the internal pressure were suggested, among them high pressure grouting of the surrounding rock and reinforcement of the concrete lining. It was decided that the former though invaluable for consolidating loose rock, and thereby easing external pressure, could not be wholly relied on to prevent leakage ; while the latter presented great practical difficulties which would retard progress very considerably, and from results on other tunnels, has often failed to give satisfaction. A more satisfactory solution based on expert advice from Switzerland, where considerable experience of the problem has been gained, has been adopted and consists of the provision of an inner layer of reinforcement added after the execution of the main concrete lining. The reinforcement is covered by means of gunite —a fine mixture of approximately 1 part cement to $2\frac{1}{2}$ parts sand, applied by means of a cement gun. This system has several great advantages. No centring is needed and a high rate of progress can be obtained. Moreover gunite has a considerably greater tensile strength than ordinary concrete and is considerably more dense, more elastic, and more watertight.

Types of lining adopted in various sections of the tunnel.

From the north portal to R. D. 3500, the standard type of lining consists of a 12″ thick ring of plain concrete, this being reinforced with 1″ rods placed at 8″ centres, with $\frac{3}{4}$″ longitudinals at 18″ centres; from the north portal to just inside the Valve Chamber; in which section, though the rock consisted of sound mica schist, it was considered advisable to take additional precautions to ensure against the possibility of cracks occurring, and water leaking back into the river. Similar reinforcement was used beneath cavities in the northern heading, where they had not been completely filled with concrete.

The reinforcement was provided to take the bursting stresses resulting from a head of 50 ft. of water acting on the tunnel due to the head of water in the forebay with the reservoir empty, the steel being stressed to 12,000 lbs. per sq. inch.

Several of the cavities in the northern heading ran up to 35 to 40 ft. above rail level, and in all cases at least 5 feet of concrete was placed on top of the slabs in such places. It was considered, in this heading, where owing to the heavy overburden the risk of leakage was but slight, that the wedge action of this plug of concrete, together with the reinforcement in the 12″ ring, would be sufficient to prevent the bursting stresses, resulting from the building of the dam, cracking the lining.

In the granite gneiss, the original intention based on the assumption that a good solid rock would be encountered in the heart of the mountain, was to gunite the surface of the rock with a skin of cement mortar from 1″ to 3″ thick, to reduce friction losses and prevent excessive weathering. In this it was intended to leave weep-holes to provide for the excessive external water pressures likely to be encountered. The rock was found, however, to be so fissured and jointed, that there appeared to be great danger of rock-falls, if gunite only were relied upon. It was, therefore, decided to put in the arch section lining shown on plates IV & V, using old 18 lbs. and 24 lbs. rails surplus from the works, made up for use as forms, of standard height of 9′ 10$\frac{1}{2}$″ and widths of 9′ 3″ and 11′ respectively, and as reinforcement.

The rail uprights are placed at 3 ft. centres and prove to be very cheap, being used over and over again, and the setting up of them being greatly facilitated by leaving slots in the berms. Rail reinforement is used, as shown on the drawing, where the roof overbreakage is heavy or where the rock is very badly fissured. The larger sized shuttering is used at places where the overbreakage is excessive, and though it necessitates special transitions, nevertheless it saves 14 c.ft. of concrete per ft. run over that required for the 9′ 3″ shuttering. The resultant saving amounts to Rs. 11 per ft. run of tunnel.

In the central portion of the tunnel from about R. D. 6500 to R.D. 8800 the standard 12″ ring of plain concrete will be used, as it is anticipated that there will be considerable external water pressure, and in any case leakage could not be very serious, the cover being very great. Beyond the latter point right through to the surge shaft, the internal diameter of the ring has been increased to 10′ 3″ to accommodate the 6″ thick mantle. Plate X shows the type of mantle adopted for the tunnel, and this consists of two circular rows of 7/8″ steel rods at 4″ centres, embedded in six inches of gunite. In the first two months of work, a speed of 600 ft. per month of completed mantle was obtained, Swiss operatives being employed on the gunite application, assisted by unskilled labour supplied by the department.

The steel is bent outside the tunnel, two lengths to a ring and an overlap of 40 diameters is allowed for the joints. The outer layer of steel is first placed and covered with gunite, which is applied in very thin coats, five to seven applications being made before the steel is covered. The second layer of steel is then fixed and the process repeated the surface being smoothed off with trowels after the final application. The method of fixing the steel is illustrated in plate X. The hook bolt is placed when laying the original concrete lining, and the clips supporting the longitudinal bars are added later, the circular reinforcement being wired to the longitudinal bars.

Method.

With nearly 11,000 ft. of drivage between the north portal and adit junction, there would have been very great delay, probably of at least a year, in the completion of the tunnel, and therefore of the whole project, unless the lining had been carried on simultaneously with the driving ; hence a type of centring had to be adopted, through which the services could be passed, and which could take all traffic without causing any delay. Plate XI shows the type of centring car which was adopted, together with the provision made for services and traffic.

In placing the circular lining using the car, first of all two berms were laid in 1 : 4 : 8 concrete at the sides of the tunnel, on which R. S. joists 10″ × 6″ × 10′ 8″ and timber beams 10″ × 10″ × 10′ were laid alternately, 4 ft. apart. Originally R. S. Joists only were used, but latterly when considerable lengths running up to 350 ft. of track were raised at a time, these had to be supplemented by beams, which were found most convenient, as the track could be spiked direct to them. This elevated platform was laid $2\frac{3}{4}$ ft. above finished invert level, and ramp cars capable of being pulled along the normal track were provided at either end. Originally a symmetrical turn-out was located at either end of the raised platform, but these gave trouble, particularly in the section where the tunnel was driven downhill at a $3\frac{1}{2}$ per cent. grade, as the total grade up the ramp was then about 7 per cent. and a straight pull-out was necessary for the loco. In addition, there was but little clearance for the two tracks on the platforms, owing to the services, which took up considerable space. These ramp cars were readily moved by the elec. locos, but they gave a certain amount of trouble owing to the track on which they had to stand, not being absolutely true, and hence they had to be packed up, to make them sufficiently rigid.

The trimming of the invert followed, the labour working beneath the raised platform ; then the invert concrete was placed using curved templates 6' apart and finally the ramp cars were pulled forward and the elevated platform re-erected ; 2' 6" gauge track being then laid on the completed invert. In addition, 5' 2" gauge track on special steel sleepers was laid on the invert, this track carrying the centring car. In order to prevent any vibration due to passing traffic reaching the centring car and affecting the "green" concrete, this 5' 2" gauge track was entirely separate, and not connected in any way with the ordinary track carrying traffic. With the above arrangements 150 ft. of invert were laid in 24 hours. The best results were obtained by laying several hundred ft. of the invert, and gradually dismantling the raised track, as the centring car was moved forward. It was soon found possible to shift the centring car with the aid of an electric loco, without causing any delay to operations in the heading as all the electric cables were slid through a timber casing on one side of the centring car, the air supply pipe slid through the car in a similar manner, on the other side, and the fresh watersupply pipe together with the rising main from the pumps being accommodated in the middle of the track, *vide* plate XI. It was thus only necessary to break the joints in the ventilating duct for about 1 hour and 45 minutes, which could be done without serious interference to the ventilation in the headings.

The shifting of the forward ramp car and erection of the elevated platform was the work which took the most time, but with careful organization it was found possible to raise 350 ft. of track in 18 hours and during this time, arrangements were usually made for a large number of tubs to be accommodated in sidings close to the heading, so that mucking might not be delayed ; and for such jobs as laying of track, excavation of pump sumps, and the fixing of bench marks and centre lines, to proceed.

Except occasionally for invert work, the concrete was machine-mixed with the aid of $\frac{1}{4}$-yard mixers, located either on the second track of the raised platform, or in any convenient place where there was overbreakage. The concrete was then transported by hand, either into the invert or to the centring car, in which planks were laid to form scaffolding. As the sides were built up the steel plates were bolted on to the frame of the car, up to well above springing level ; after which the concrete was laid in the crown from end to end, special transverse plates being bolted into position as the work proceeded. To strengthen the joint between the invert and ring concrete, $\frac{1}{2}$" steel bars, 2 ft. long, were placed at 6" intervals when laying the invert.

Where the overbreakge in the crown exceeded about 12", the main 12" concrete ring was laid first, and the overbreakage concrete was laid above it. Some difficulty was experienced in placing the concrete in the crown of the arch, up against the steel joists, hence this concrete, consisting of a narrow prism, was placed in advance. Where conditions permitted, the steel sets were removed from the work, during the time that the lining was being placed, and this could be done fairly easily after taking the weight of the slabs on temporary timber supports, fixed on the outside of the steel centring car. During the laying of the concrete, grouting pipes were jammed between the car and the rock, to save drilling the concrete at a later date. These pipes ended flush with the inner surface of the lining, and were fitted with screwed sockets.

In the northern heading a certain quantity of water flowed into the tunnel through the open grout holes and then travelled along the finished invert towards the face. A temporary bund was, therefore, built across the invert, in which a pipe was laid, the water being carried across the invert work which was in progress, and thence drained down to the nearest pumping station. Much more water was encountered in the southern heading, which fortunately was driven uphill ; but nevertheless this water, which amounted to over 2000 gals. per minute, gave much trouble and necessitated special methods being employed to deal with it. Precast concrete pipes 15″ in diameter were, therefore, laid in a trench in the floor of the tunnel and outside the 12″ thick invert, hand holes being provided at every 40 ft. through which connections were made from the various springs to the main drain, and which will finally be used for grouting up the drain pipe. During the excavation for the drain and the invert, a temporary steel pipe made up from lengths of 17″ dia. vent. duct, was fixed below the elevated platform between a bund erected at the upper end of the platform and the last hand hole. This pipe functioned until the invert concrete had hardened.

When the reinforced lining was laid from the portal to beyond the valve chamber, the valve adit was available for traffic, and hence it was found most convenient to lay this concrete in 3 stages :—

(*i*). The invert.

(*ii*). Up to springing, using a semi-circular form.

(*iii*). The arch, using a similar form, wedged up off wall plates, which rested on the lower form.

For the lining in the granite gneiss, a timber platform was erected at springing, which allowed ample clearance for the passage of traffic.

Underground water.

Underground water caused considerable hindrance both to driving and lining. It was encountered in two different forms, firstly as a concentrated flow when spouting out from a rock fissure, in the form of a jet, and secondly where the rock was shattered and the water flowed in through many crevices, distributed over an appreciable area. The method adopted in both these cases, was to divert the water through pipes or weep-holes installed before the laying of the concrete commenced. To deal with concentrated flow, a hole 3 to 4 ft. deep was drilled so as to intercept the flow of the water, and a 1″ G. I. Pipe, having the end well perforated, was fixed into the hole, a flexible hose pipe being attached to the other end of the pipe, and being led to the nearest hand hole in the main drain pipe. The bulk of the water usually flowed through the pipe or weep-hole, but sometimes it was necessary to insert strips of gunny bag into the crevices, and to gunite the rock around the pipe, as soon as the leakage had been sufficiently reduced. Where scattered flow was encountered, flat iron sheets were used to keep the water away from the concrete which was being laid, and special arrangements were required to make a satisfactory contact between the iron sheets and the rock, due to the very uneven surface of the excavation. The following method, details of which are shown on plate XII, was, therefore, adopted.

The outer portion of the 12″ concrete ring (D) was made up of a specially rich mixture, which was laid against a smooth sheet iron shuttering (E), which rested on the concrete berm (F), already constructed for the elevated platform. On top of this berm, a chamber (H) of suitable size, and a drain (I) across the berm, were provided. In this drain, a pipe was laid long enough to protrude through the lining. At the time of laying concrete behind the centring car, a vertical notch (J), in the concrete was provided, and the water flowed down this notch and out to the drain through the chamber (H). To keep the water off the concrete whilst it was being laid, the chamber and the drain were covered with flat iron sheets. Concrete was laid each side of the notch, in order to give a smooth and more or less water-tight joint between the iron sheet and the rock. The notch and drain were afterwards grouted up.

When a spring was struck in the invert, a notch leading to the drain pipe was chiselled out in the rock and covered with G. I. sheet, the contact between the rock and the sheet being obtained as described above. Plate XII shows the method adopted when water was encountered in the roof of the tunnel, the centring in the crown being kept open until the side concrete had been brought up as far as possible. The concrete over the transverse top plates, was then laid in short strips, under the protection of C. G. I. sheets (K) which were fixed above the 12″ ring and removed after the concrete had hardened. The space between the concrete and the tunnel roof was then packed with stone (L), and eventually grouted up solid. The adoption of this method necessitated an overbreakage of 6″, and this was amply justified by the results obtained.

Overbreakage and cavities.

During excavation, steel sets were erected wherever the rock was loose or liable to fall in ; but afterwards, when lining, it was found possible to remove some of the sets and utilize them again. Where steel sets were required, the theoretical cross sectional area required to be excavated amounted to 134 sq. ft. whereas in sound rock, it was 118 sq. ft. only. In practice, the shape of the tunnel was irregular and the quantity of concrete, including that laid in cavities in the surge shaft and in the mid-point heading, amounted to 100 c. ft. and 85 c. ft. respectively per ft. run of tunnel, against an estimated figure of 67 c. ft. The various reaches of the southern heading, where steel sets were erected, could be sub-divided as follows:—

(*i*) Where the steel sets could be removed altogether, before placing the lining.

(*ii*) Where the tunnel over the length of the centring car, could not be left without supports, even whilst the concrete ring was being laid. In such cases the uprights were concreted in but the slabs and some portions of the sets were gradually removed one bay at a time; packing, if any, above the slabs being replaced with concrete.

(*iii*) Where the ground above the slabs was loose and threatened to cause considerable trouble if disturbed. Here the placing of the upper part of the lining ring was done under the slabs, and later on, the packing of timber or stone over the slabs was replaced with concrete and hand packed stone, up to the natural rock, through "windows" left in the concrete. It was sometimes found necessary to solidify the loose ground above the packing, before it could be taken out and replaced with concrete, and this was done by grouting,

Cavities, both large and small, formed over about $\frac{3}{4}''$ of the total length of the surge shaft heading. The formation of these cavities could have been prevented, if the ground had been solidified foot by foot, as the tunnel driving proceeded, but the cost and the time involved in this grouting, would have been excessive. During the excavation, timber and stone packing was, therefore, placed in the cavities of the southern heading, these being replaced at a later date by concrete and hand-packed stone. In the early stages this was done ahead of the lining but it was soon found unsafe to tamper with cavities, when men were working up at the face and hence the cavities were attended to through "windows" or manholes left in the lining ring. As a further precaution, every effort was made to speed up lining as much as possible, three centrings being erected in the different reaches of the southern heading, "windows" about 4 ft. × 6 ft. being left in the concrete at intervals of about 40 ft. The locations of these "windows" were carefuly chosen where the natural rock was not very high above the lining ring. Through these "windows" the cavities were attended to, the slabs covering the "windows" being broken one at a time, allowing packing and loose muck to fall through into the tunnel. From each "window" a heading 8 ft. long was then excavated in one direction and after this had been well secured, work was started in the opposite direction as well, the rock above the "window" being well supported in order to provide a safe entrance to the cavity. This having been done, a small sized tunnel was excavated in the loose ground lying on top of the finished lining. The size of this heading was dependent on the height of the cavity, and varied from 3 ft.

to 7 ft. in height and 3 ft. in width. The sequence of the work, as illustrated in plate VIII, was as follows :—

1. Remove the slabs and provide a safe entrance to the cavity.

2. Excavate 4 ft. of top heading through the loose ground, and timber.

3. Under protection of the top lagging, remove loose stone and timber down to the concrete lining, first on one side, then on the other, and place concrete side walls forming a passage 3 ft. wide.

4. Cover the passage with reinforced concrete slabs.

5. Extend the heading by 2 ft. packing the space over the slabs with stone up to the natural rock (in some cases where the cavity was high, 2ft. of concrete was laid over the slabs prior to stone packing, which in places extended 30 ft. above the tunnel roof).

6. Fill up the passages with concrete.

The "window" itself was finally closed up with the aid of a concrete placer.

When the rock in the cavity was loose and the above method could not be adopted without considerable loss of time and the probable enlargement of the cavity ; the upper layers of loose ground were solidified and then the packing was removed and concrete placed instead.

Concrete.

Aggregate was obtained direct from the Crushing Plants located close to the portals ; where roofed-in mixing platforms were provided, on which considerable quantities of mixed aggregates of the various gradings required, were kept available for issue. In general, a fixed water-cement ratio was adopted, but this could not always be adhered to, as the slump had sometimes to be varied according to where the concrete had to be placed, and the quantity of water had to be reduced according to the length of time that the aggregate was stored in the tunnel. The aggregate was measured by volume, and the cement by weight, and these materials were despatched into the tunnel in bags, the cement being kept separate from the aggregate, until the materials were loaded into the mixer, at which time a measured quantity of water was also added. When the weather conditions were variable, the moisture content of the fine aggregate was taken frequently, additional quantities of cement and aggregate being added to the bags at the mixing platform, in order to keep the water-cement ratio constant. Frequent sieve analysis tests of the aggregate were also carried out, to ensure that the grading was correct. The following are the average results of a very large number of tests of various types of concrete.

Type.	Conventional proportions.	Ratio of cement to mixed aggregate.	Fineness modulus.	Specified slump,	Specified strength at 28 days in lbs. per sq. inch.	Average actual strength in lbs. per sq. in. at	
						7 days	28 days
C.L.	1:1.86:3.72	1:4.65	5.35	2½" to 3"	1830 to 2100	2302	3225
C.E.	1:2.1:4.36	1:5.45	6.1	2½" to 3"	1830 to 2100	2217	3058
C.T.	1:3.22:6.44	1;8.09	6.25	2½" to 3"	700 to 800	1301	1635
1 : 4 : 8				1½"	620 to 710	1109	1658

The values for C.T. type concrete are based on 7 tests only.

Mixers and placers.

Quarter-yard concrete mixers have been used in the tunnel and it has been possible to accommodate them without interfering with traffic, or making special preparations other than removing the water tanks. Three Ransomes concrete placing machines have been used from time to time. They are designed on the principle that when concrete is fed into a compressed air main by means of a worm drive, the air pressure builds up and forces the concrete along the delivery pipe; this in turn causes the pressure to fall and another "slug" of concrete is admitted into the air main. This process is continuous, and theoretically, the concrete should arrive at the end of the discharge pipe in a series of shots. Actually, this was not found to be the case, and care had to be taken to keep the end of the pipe close up to the work, to prevent the separation of the coarse and fine materials. This machine is driven by a $7\frac{1}{2}$ H. P. motor and has delivered concrete in considerable quantities to a height of over 20 ft. above the tunnel floor. To obtain the best results, it was found necessary to keep the discharge pipe at a fairly steady rising gradient, and to utilize air receivers when the distance from the compressor station exceeded about 1000 ft. Air receivers of about 14 c.ft. capacity were used in the vicinity of R. D. 1200 and of 77 c.ft. near R. D. 3000.

Cost of lining.

The first section from Portal to just beyond the valve chamber which was 9′ 6″ in dia., and heavily reinforced, cost Rs. 153 per ft. run, and progressed at the average rate of 4 ft. per day.

The expenditure in the northern heading per ft. run, to the end of October 1931, on the circular type of lining from R. D. 403 to R. D. 3500, amounted to Rs. 27.3 for the invert and Rs. 87.3 for the ring making a total of Rs. 114.6 per ft. run. By this date 55,462 c.ft. of concrete had been poured in the invert and 1,61,857 c.ft. had been poured in the ring, over lengths of 2574 and 2387 ft., respectively. The total quantity of concrete required per ft. run amounted to 21.5 c.ft. for the invert and 67.8 for the ring making a total of 89.3 c.ft., as against the net theoretical requirement of 32.2 c.ft. The costs of this concrete were Rs. 126.9 and Rs. 128.7 per c.ft. for invert and ring, respectively. In addition to the above, 1,57,429 c.ft. of plum concrete had been poured in the filling up of cavities, overbreakage, etc., the cost of this amounting to Rs. 1,28,449, corresponding to an additional cost of about Rs. 46 per ft. run, hence the total cost per ft. run, to the above date was Rs. 160.6. It is anticipated that this over-all figure will be further decreased when the work is completed, as both overbreakage and cost of concrete have been appreciably reduced, as the work has progressed, and the labour has become experienced.

An average progress of 5 ft. per day could easily be obtained with one centring car, and this figure could have been increased had the