REINFORCED CONCRETE SIPHONS ON THE LOWER SWAT CANAL.

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Use of reinforced concrete -- siphon on the Hazarkhani Branch—Bara siphon—Island siphon—Description of false work—Experiments—Construction of long siphons—Grouting of leaks—Summary of suggestions—Rates—Reinforced concrete versus steel siphons—Calculations for uniform pressure—Appendix.

Use of Reinforced Concrete.

During the past year and a half, three tube siphons and a drainage culvert under a canal have been constructed of reinforced concrete, while, at the time of writing, the false-work for a small aqueduct of large span is under construction, and will have been completed by the time the Congress meets.

Siphon on the Hazarkhani Branch.

The construction of a siphon of $2\frac{1}{2}$ feet diameter, near the tail of the Hazarkhani branch of the Kabul River Canal, was first undertaken. The length of the tube was 117 feet, with a thickness of shell of three inches, designed to resist an internal pressure corresponding to a head of fifteen feet. The reinforcement consisted of circumferentials of $\frac{3}{8}$ inch diameter mild steel rods, spaced 12 inches apart, and of longitudinals of the same size, spaced $11\frac{1}{2}$ inches apart. The tube was enclosed in lime concrete up to the horizontal diameter.

This tube was moulded in advance in sections of four feet length, the concrete being laid in moulds, with the axis of the tube vertical. After setting for some time, the sections were placed in position and cemented together. This is the simplest method of construction, and undoubtedly gives the best results, as by laying the concrete in vertical moulds it is possible to get it thoroughly compact and watertight. The objection to this method is the possibility of leakage at the joints, but this can be made negligible by exercising a little care in cementing up the joints, and by a small collar round the joint. Moreover, seepage at the joint could have no ill effects where there is no reinforcement to rust. This method is, however, only feasible for pipes of small diameter, unless machinery is available for lifting heavy weights. Katni cement was used in this siphon, and the proportions of

the concrete were 1 of cement, 1½ of sand, and 3 of fine gravel. In order to increase the rigidity of the reinforcement in the mould for this tube, it was found necessary to introduce some spirals of cheap fine wire, which were tied to the hoops and longitudinals at the corners of the rectangles formed by the latter. The reinforcement, thus triangulated, kept its proper shape in the mould.

Bara Siphon.

The Kabul River Canal at present crosses the Bara river in a wooden aqueduct, which was built in 1892, but as in 1916 this aqueduct shewed signs of failing, a design for a permanent structure had to be prepared. The aqueduct is 280 feet long, and the bed of the canal about 25 feet above the bed of the river, while the high flood level is above the floor of the trough of the aqueduct. A masonry aqueduct would have been objectionable, owing to the great obstruction it would offer to floods, the velocity of which is very high, and accordingly, designs both for a reinforced concrete aqueduct of large spans with open spandrils, and for a reinforced concrete tube siphon were made out. It was found that the cost of the aqueduct would be double that of the siphon, even though the latter design necessitated raising the full supply level and the banks of the canal for some five miles upstream, in order to get the head necessary to develop the requisite velocity through the siphon. An internal diameter of seven feet was chosen, giving a velocity of 5½ feet per second, which would be sufficient to keep the tube clear of silt. The crown of the siphon was kept five feet below the lowest point in the river bed, so that the height of the hydraulic gradient above the crown was thirty-five feet. The reinforced concrete tube, both in the case of this siphon and in that of the Island siphon, (to be mentioned later) was supported up to the horizontal diameter in a cradle of lime concrete, of which the outside was in section a rectangle, two feet wider than the external diameter of the reinforced concrete tube, with its base a foot below the bottom of the exterior surface of the tube.

The calculations for finding the stresses in the shell, caused by the bending moments due to the difference in pressure at the top and bottom of the tube, are given in the appendix.

So far as is known, calculations for the bending effects on pipes are not described in books on reinforced concrete, nor does the necessity for them seem to be realised, though an American periodical in 1912 described a large steel tube which

failed from not being stiffened sufficiently against circumferential distortion. The method of arriving at the stresses is an adaptation of the theory of elastic arches, but, owing to the shell of a pipe being of uniform thickness, the moment of inertia is constant, if the metal keeps the same position throughout. If the hoop reinforcement were placed eccentrically, the moment of inertia would not be constant, and rigorously accurate calculations would have to be of the lengthy type required for arches. Assuming the moment of inertia constant, the calculations come out very simply by the use of the integral calculus, and a general equation can be obtained for a particular method of supporting the pipe, applicable to pipes of all diameters and subjected to any head of internal pressure and with any depth of earth over the crown, supported in that particular way.

The calculations given in the appendix assume that the pipe is held rigidly in place below the horizontal diameter, but the calculations would be very similar for any other method of supporting it. It will be noticed that the bending moments are independent of the head of water in the pipe, and vary only with the diameter and method of support. An American periodical has lately shewn a very neat method of using single reinforcement to resist bending moments in a pipe. The reinforcing hoops are circles (as it is most difficult to make them of any other shape) and the concrete tube is made slightly elliptical so that the position of the metal in the thickness of the shell varies as is required to resist the bending moments. Great economy results from this method, where it is necessary to take the bending moments into account, as double, symmetrically placed, reinforcement can be dispensed with. In this case, the moment of inertia is not quite constant, and the shell is not quite a circle, so that accurate calculations would be lengthy, but, if based on the assumption that the tube is circular and the moment of inertia constant, they are probably sufficiently accurate for practical purposes

The seven foot tube, as finally designed, had a shell thickness of seven inches (following the usual rule of thumb which gives one inch thickness for every foot of diameter) and was reinforced by hoops of $\frac{3}{4}$ inch diameter, round, mild steel rods spaced nine inches apart, and by longitudinals of No. 8 S. W. G. wire spaced at the same distance. The proportions of the concrete were one of cement to two of sand, and four parts of gravel, Bundi cement being used.

As it was important to lose as little head as possible at this site, the entrance and exit were designed to give an easy flow, with the circular section of the pipe gradually merging into a square section, and the approach wing walls ogee shaped in plan, with a batter varying from a half to one at the junction with the earthen channel of the canal, to vertical at the entrance and exit of the pipe. It may be mentioned here that no difficulty whatever was found in constructing this entrance and exit, and it is well worth doing where the saving of head is a matter of importance.

Expansion joints were not provided in the case of this or of the other siphons, since being always under water, they are not exposed to appreciable changes of temperature. After construction, care was taken to keep the concrete wet and cool till the siphons had been covered in.

Island Siphon.

Owing to the opening of the Upper Swat Canal, the Swat river, below the lately constructed Abazai weir, will be dry in the winter, and the arrangements for carrying on the irrigation from the numerous private canals taking out from this reach of the river, necessitated the passage of 182 cusecs of water from a canal on the left bank to a large island formed between two branches of the river. This canal was some thirty feet higher than the level of the island, so that almost any velocity could be generated through a siphon.

Originally a steel siphon of 3·8 feet diameter was designed for this place, the velocity through it being about 15½ feet per second. The diameter was chosen as being about the smallest for a tube of considerable length, through which a man could pass for inspection purposes. Enquiry had elicited the statement that no one could be induced to go through a siphon a thousand feet long and 2½ feet in diameter, near Peshawar, not only on account of the difficulty of movement, but also because of the foulness of the air, while the same informant stated that no such difficulty had been experienced in the case of another siphon of 3·8 feet diameter. The first statement was however subsequently disproved, by the passage of the author himself through the smaller tube.

Owing to the great increase in the price of steel, especially of mild steel plates, due to the war, it was found that a reinforced concrete tube could be made at much less cost, and a tube of the latter material was then designed, on the lines of an article

in Engineering News, which stated that, given a smooth surface and no sharp bends, velocities of twenty to thirty feet per second could be allowed to pass over cement concrete without danger. The article quoted the case of a concrete lined tunnel in connection with a dam, where heavily sand laden water had passed through the tunnel, with these high velocities, for three years without any signs of erosion. The Government of India, however, ordered the velocity to be reduced to eight feet per second, and the diameter to be increased to $5\frac{1}{2}$ feet, and in spite of this great increase in the diameter, and of the fact that, owing to the smaller head through the larger pipe, an extra fall of some twelve feet upstream of the siphon had to be provided, the cost of the reinforced concrete tube was estimated to be only four per cent. more than the pre-war cost of the steel siphon. The final design of this tube shewed an internal diameter of $5\frac{1}{2}$ feet, a thickness of shell of six inches, circumferential reinforcement of $\frac{3}{4}$ inch round bars spaced fourteen inches apart, and longitudinal reinforcement of No. 4 S. W. G. wire spaced seven inches apart. The proportions of the concrete were 1 : 2 : 4, as in the case of the Bara siphon, and Bundi cement was used.

Description of Falsework.

Plate I shews the falsework for the Island siphon ; that for the Bara siphon was practically identical, save that the ribs were closer. (The spacing of the ribs must be a multiple of the spacing of the circumferentials). It was found, in practice, advisable to make continuous ribs with scarfed joints, as otherwise there was not only delay in fitting the laggings, but the laggings did not fit properly the second time they were used. The circumferential reinforcing bars were passed through holes in the top longitudinal split beam, which kept them rigidly in place at the crown. Slips of wood, with V shaped nicks, were lightly nailed to the longitudinal wall plates, which rested on the previously constructed lime concrete cradle, and by fitting the circumferential bars into the nicks in these pieces of wood, it was found that the former were kept accurately in position in the top half of the tube. The process of laying the concrete had a tendency in some cases to lift the hoops slightly near the bottom of the tube, so that they were brought closer to the inside of the shell, but the displacement was slight and so local that it did not affect the strength of the tube, and fixing the hoops in three places was found to be sufficient. The laggings were $1\frac{1}{2}$ inches thick and 10 inches wide. Little

difficulty was found in curving the faces of these wide laggings and they were used because they necessitated less fixing during the construction of the tube. The laggings in the lower half of the tube were kept in place by tying them to the ribs with wire, a pair of staples being fixed at each end of a lagging and wired to similar staples in the ribs. In the upper half of the tube, outside as well as inside laggings were required. Here the inside laggings required no fixing to the ribs, while each outside lagging could be kept in position by a pair of little wooden struts, in length equal to the thickness of the shell. When a certain amount of concrete had been laid between the inside and the outside lagging, it pushed the outside lagging into position, when the wooden struts could be removed. It was neither necessary nor advisable to carry the outside laggings up to the crown. By using a template, and with a fairly dry concrete, the top sixty degrees or so could be laid more easily without outside laggings.

When the concrete had been laid to within about forty-five degrees of the crown on each side, the tie bars, which suspended the ribs from the top cross beams, were removed, as well as the longitudinal split beam, and the last inside laggings were then placed in position. It was found necessary to make the crown lagging at site, as it was impossible to keep the laggings quite true, with the result that the last lagging had as a rule to be wedge shaped in plan. This should be fitted fairly loosely, as, if tight, it is difficult to take out the laggings when removing the centering.

The top cross beam was found to be too low, with the result that it was a little difficult to consolidate the concrete immediately beneath it, and in future designs the cross beam should be kept six to twelve inches higher, though this will necessitate some packing between the longitudinal split beam and the cross beam, and also a longer bolt. Some planks laid longitudinally on the cross beams are necessary for inspecting the work, and help to keep the framework of the centering rigid longitudinally.

At first diagonal braces were used in every bay, so as to give longitudinal rigidity, but these hampered the work, and it was found sufficient to put these braces into the two end bays, of a length of as much as a hundred feet.

Measures must, however, be taken to keep the longitudinal wall plates, which rest on the top of the lime concrete, rigidly

in position, and struts from the wall plate to the excavation will serve this purpose. On one occasion, when no such struts were used, it was found that the whole falsework in three bays had moved slightly to one side, owing to the wall plates not being fixed. This was caused by uneven ramming of the concrete on the two sides of the lower part of the tube.

Experiments.

In order to obtain some experience in the laying of concrete under actual working conditions before undertaking the construction of the siphons, it was decided to make a 15 feet long culvert, of exactly the same design as the 5½ feet Island siphon tube, in a place at Abazai, where a bridge was required over a large watercourse. This was started at 11-30 A.M. and finished about 4 P.M. the same day. After allowing the concrete to set for four days, though it was afterwards found that two days were ample, inspection showed that, whilst the upper portion of the tube was perfect, the bottom 90 degrees was very bad, the inner surface of the concrete for a depth of about an inch or less being little better than loose gravel. This was attributed to—

(*a*) The concrete not having been wet enough.

(*b*) The aggregate being too big (gravel up to 1½ inches having been used).

(*c*) The concrete not being sufficiently mixed.

(*d*) The fact that only two laggings should have been laid at the bottom, and one lagging at a time added, instead of four laggings being laid and added, as was done in the experiment.

The joints of the circumferential bars were welded, and not overlapped and tied, because when joined in the latter way the hoops were inclined to open out. In erecting the reinforcement, the welded joints were kept in the bottom 120 degrees of the tube, where, owing to the grip and friction between the cement and lime concretes, there would be little or no tension in the steel.

A further experiment was made in a drainage work on a small nullah, where the tube was again 5½ feet diameter, but 70 feet long and with two elbows and sloping ends (slope 2 to 1). In this case, too, the concrete was bad as long as it was dropped into place from the level of the horizontal diameter of

the tube : it was decided, therefore, to hand the mortar pans down to the masons, and to make the latter empty them at the place where the concrete was required. Narrow, shallow shovels were accordingly manufactured and used. The method of mixing the concrete recommended in Marsh and Dunn's book was employed, namely, mixing the mortar first, both wet and dry, spreading the gravel over the mortar, and mixing again both with shovels and long-pronged rakes. This gave better results, though it was not until a finer aggregate was used that really good results were obtained.

Construction of Long Siphons.

In construction, the choice lies between undertaking a great length all at once, leaving a horizontal joint somewhere below the horizontal diameter (where the surrounding lime concrete would help in making it watertight), and in completing short lengths each day, having comparatively frequent circumferential joints. The former plan was adopted, but experience shews that circumferential joints give no trouble from leakage when the old concrete was carefully picked away and washed, and a little mortar plastered over the old face before the new concrete was laid. The expense of falsework is much reduced by a system of short lengths; and the extra room available for the masons and coolies also tends to good work.

The masons were offered prizes as follows :—Rs. 15 in addition to their pay for the best pair, Rs. 10 in addition to their pay to the second pair, similarly Rs. 7-8, 5 and 2-8 to the third, fourth and fifth pairs, and nothing,—not even their pay, to the worst pair. These prizes made the masons remarkably keen, but they had to be watched or they would try and get coolies to bring them surreptitiously pans of neat cement to improve their mixture. A pair of masons were employed to every two bays on a 120 feet length of the Bara siphon, and in the portions at the elbows and on the slope ($1\frac{1}{2}$ to 1 in this case) a pair in every bay. A wooden mixing floor was used, and the gravel was passed through a $\frac{3}{4}$ inch, instead of through the one inch screen used for the Island siphon. This length was finished in two days, with longitudinal joints one foot below the horizontal diameter.

Some points about the construction of the elbow may be mentioned here. The top longitudinal split beam of the falsework, which must be curved to suit the curvature of the elbow, should be made in short lengths, otherwise it is impossible to remove it without sawing it. A slope

of 1½ to 1 is about the steepest slope which can be laid comfortably, even with fairly dry concrete, unless outside laggings are laid right up to the crown, as with a steeper slope the concrete towards the crown will not stay in position.

The result, when the falsework was removed, was, in the author's opinion, as near perfection as it is possible to attain. The circumstances which contributed to this result were the finer aggregate, and the smooth, wooden, mixing floor, as well as the large diameter of the tube and the greater thickness of the shell (seven inches as against six inches in the case of the Island siphon) which gave great freedom of movement to the masons.

One inch gravel was used in the first eighteen bays of the Island siphon, but the finer gravel from a ¾ inch screen was used for the rest, which in practice meant that practically nothing over half an inch went into the aggregate. In one length of the Island siphon the invert of the tube was made before putting in the laggings. This method is not considered a good one, as while giving a good invert, it leaves a nasty joint on each side, since the invert has to be allowed to set for a couple of days before laying the rest of the concrete.

Towards the bottom of the tube, the masons were inclined, when the concrete came to the top of a lagging, to pile it up above the level of the top of the lagging on the outside of the shell, and leave it level with, or slightly lower than, the top edge of the inside lagging. The result in such cases was that, when the next lagging was added, a wedge shaped hollow had to be filled in with concrete, and the aggregate failed to find its way into the apex of the wedge. Much the same is apt to occur towards the top of the tube, but here the apex of the wedge is at the outside of the shell. The masons are inclined to do this when the concrete is being brought to them faster than the carpenters can fit the laggings.

Grouting Leaks.

When water was allowed to pass over the Island siphon, twenty-two pin hole leaks shewed themselves, though the rest of the inside surface of the tube was quite dry. These were grouted up with neat cement with a grouting machine consisting of a small air compressor from which the compressed air was led away in a flexible rubber pipe to a steel cistern. The latter had a small manhole at the

top through which liquid cement was poured in, and blades working inside the cistern, and rotated by hand by means of a handle on the outside, kept the cement agitated. From the bottom of the cistern another flexible rubber pipe, fitted with a cock, allowed the cement to be led away to any required spot.

The grouting machine, as received, was quite unsuited to grouting against pressure. In the first place it was necessary to fix a saucer-shaped cap round the nozzle, and the rim of this cap was kept airtight against the inside surface of the tube by means of rubber or cotton waste packing. On the first attempt the cement was successfully forced into the leak, but when the compressor was stopped, the outside pressure blew all the cement back again. A cock was then fitted to the nozzle so as to retain the pressure after the compressor was stopped, and a screw jack fitted to the nozzle, which, by bearing on the side of the tube opposite the leak, kept the nozzle tight in position. When a sufficient quantity of cement had been forced into the leak, the cock in the nozzle was closed and the nozzle was left in position for half a day. The result was entirely satisfactory. In some cases, when a leak was closed, a new leak formed in the vicinity, but by the exercise of a little perseverance, all the leaks were eventually stopped.

Summary of Suggestions.

1. 1½ inch laggings are stiff enough for spacing ribs 5½ feet apart, and in fact were used for 5 feet 10 inches spacing.

2. The laggings at the elbows have to be specially cut and numbered.

3. At a bend in the tube, the top, split, longitudinal beam (which is curved) should, for ease in removal be made in short lengths equal to the spacing of the ribs at the bends.

4. The top cross beam of the falsework should be kept well above the top of the tube.

5. Several wooden gauges should be kept to facilitate spacing the reinforcements.

6. The mixing floor should be smooth, preferably of wood.

7. For pipes whose shell thickness is about six or seven inches, use an aggregate which has passed through a screen with a mesh not larger than ¾ inch square.

8. The mortar should first be mixed, and the gravel then spread over the mixed mortar.

9. Only small heaps should be mixed at a time. This ensures greater continuity of work.

10. Appoint some jamadars to see that the masons are supplied with concrete evenly, otherwise smart masons will get themselves supplied faster than stupid ones, and the work will not progress regularly.

11. Put the two best pairs of masons at the two ends of the length which is being done ; also put good masons at the elbows.

12. Provide the masons with a curved iron rod for shoving the concrete into place, and a small wooden tee something the shape of a small T square, for ramming it.

13. Do not throw the concrete in from a height.

14. Make the masons give the concrete in the mortar pans a final turn over with their trowels before emptying them.

15. When laying the bottom concrete, watch that the masons do not push all the concrete underneath the circumferentials. They try to do this, as it is easier, but it has the effect of forcing up the reinforcement.

16. Make the masons finish off each layer of concrete with its top level with the top of the laggings, and as nearly radial as possible, before fixing the next lagging.

17. Avoid a complete interval for the midday meal by letting only half the men go at a time.

18. Watch the carpenters, or they will let sawdust blow on to the concrete when the latter is being laid.

Rates.

Neglecting the cost of the falsework, which was separately estimated, the analysis of the rate per cubic foot of finished reinforced concrete in the Bara siphon was as follows :—

					Rs.
·23 cubic feet	cement @	Rs. 3·48	per cubic foot	...	0·8
·46 ,, ,,	sand ,,	·10	,, ,,	...	0·046
·92 ,, ,,	gravel ,,	·08	,, ,,	...	0·074
·039 cwt.	steel ,,	30·00	per cwt.	...	1·17
Labour	,,	·20	per cubic foot	...	0·2
		Total	... ...		Rs. 2·29

The labour rate worked out almost exactly to Rs. 0·2 per cubic foot, and the total rate of the concrete in the Register of Works was about Re. 1-14 per cubic foot.

Reinforced Concrete versus Steel Siphons.

A reinforced concrete tube, where gravel and sand are easily available, is much cheaper than a steel tube. Assume the cost of falsework as eight annas per cubic foot (it can be made as little or as much as one pleases, according to how often it is used), and take pre-war rates for steel. Steel, in the shape of reinforcement, would cost Rs. 15 per cwt. in the work, while in the shape of a tube it would cost at least Rs. 20 per cwt. Calcutta and Bombay firms were quoting, in 1913, rates of over Rs. 20 per cwt. for steel tubes, exclusive of erection and riveting. In these circumstances, the shell of the Bara siphon would have cost Re. 1·05 per square foot, which would have been the same as the cost of a square foot of steel plate 9/64ths inch thick, or, when the extra cost of angle iron stiffeners is included, of 1/8th plate. 3/16ths for small, and ¼ inch for large, diameter pipes is the very thinnest plate which can be used, while in the case of some large nine feet diameter pipes on the Upper Swat Canal, ½ inch plates were used. In the latter case there would have been no comparison in cost between the two pipes, while, in every case, a tube of reinforced concrete would be cheaper than one of steel. The reinforced concrete pipe should also have a longer life than the steel pipe, being practically everlasting if well made. There will also be less friction head than through a rivetted steel pipe with lap joints. In practice, however, experience goes to show that the greatest advantage which a reinforced concrete siphon possesses over one of steel is that the engineer is independent of the firm making the steel work. Whenever his foundations are ready he can immediately construct his reinforced concrete tube, and he can construct the latter with extreme rapidity, which may be a factor of the very greatest importance where there is a danger of floods. On several occasions the author has experienced disaster in the construction of steel siphons, owing to the contractors in charge of the steel work, in spite of promises and agreements, not having the steel tube ready before the flood season.

In the case of a new canal, where a large number of culverts are required, probably reinforced concrete tubes of one or two stock diameters would prove cheaper, while they would certainly take less time to construct, than masonry culverts. The same centerings could be used over and over again. In the case of dry

firm earth it would be quite unnecessary to have a surrounding cradle of lime concrete. As in the case of the experimental drainage culvert, referred to above, the earth could be excavated to a semicircle and plastered over.

Calculations for Uniform Pressure.

The calculation of the circumferential reinforcement necessary, on the assumption of uniform pressure round the tube, is extremely simple.

If p be the internal pressure in lbs. per square inch, R the radius of the pipe, and T the tension in lbs. per inch run of the pipe, then $T = pR$. If 15,000 lbs. per square inch be taken as the safe tensile stress in the steel, then $\frac{T}{15,000}$ is the area of metal required per inch run. If the circumferentials are spaced l inches apart, then the area of each should be $\frac{Tl}{15,000}$ square inches.

One is very much inclined to make an arithmetical mistake in the units, and it is recommended that everything be reduced to inch units, taking the head of pressure in inches, and the weight of water in lbs. per cubic inch.

The calculation for the longitudinals is a little longer. Take an inch width (measured along the circumference) of the shell, then this inch strip forms a continuous beam supported at the circumferentials (the longitudinals, in the case of internal pressure, being placed inside the circumferentials) and resisting the uniform load of p lbs. per inch run. The maximum bending moment occurs at the points of support, *i.e.* at the circumferentials, and is $\frac{pl^2}{12}$ where l is the spacing of the latter in inches. Here compression is at the outside of the shell, so that the effective depth of the beam is the distance from the outside of the shell to the centre of the longitudinal. Midway between the hoops, the compression is at the inside of the shell, and the effective depth of the beam here is the distance from the inside of the shell to the centre of the longitudinal. As the bending moment here is only half that at the hoops, it is economical to lay the longitudinals more towards the inside than the outside of the shell, and this result is obtained by placing the circumferentials in the centre of the thickness of the shell.

APPENDIX.

Calculations for bending due to differences in pressure at different levels in a tube.

The first part of the calculations is applicable to arches in general, and may be of interest to those who are unacquainted with the theory of elastic arches. For this reason the theory of elastic arches is proved *ab initio* although the proof can be obtained from books The proof given here has been obtained partly from Marsh and Dunn's, and partly from Taylor and Thompson's books on reinforced concrete. Neither of these books alone gives a complete demonstration of the theory. The introduction of integral calculus is a modification, not given in these books, which in the case of a tube simplifies the calculations and gives a general formula. The theory of elastic arches is a simple one, and should really be applied to all arches, and certainly to large span masonry and concrete arches, in order to obtain the line of pressure, as the methods ordinarily used for obtaining the line of pressures in an arch are only approximate. For the benefit of sceptics it may be mentioned that the correctness of the theory of elastic arches has been proved by a method in which polarized light is used to shew visually the actual stresses in an arch.

The use of the integral calculus in these calculations need not frighten anyone. It is not absolutely necessary, and in ordinary arches it is not possible to use it. It can only be used here because of the fact that the moment of inertia of the shell is the same all the way round the circumference. In an ordinary arch, the two equations immediately before equations (4) and (5) become:—

$$\Sigma \frac{M y s}{E I} = 0 \qquad \text{and} \qquad \Sigma \frac{M s}{E I} = 0$$

where s is the length of a section of the arch rib which is divided up into m sections. An ordinary arch has to be divided up into some twenty or forty sections such that $\frac{s}{I}$ is constant, so that $\frac{s}{EI}$ can be taken outside the sign of summation, leaving the equations: —

$$\Sigma My = 0 \qquad \text{and} \qquad \Sigma M = 0$$

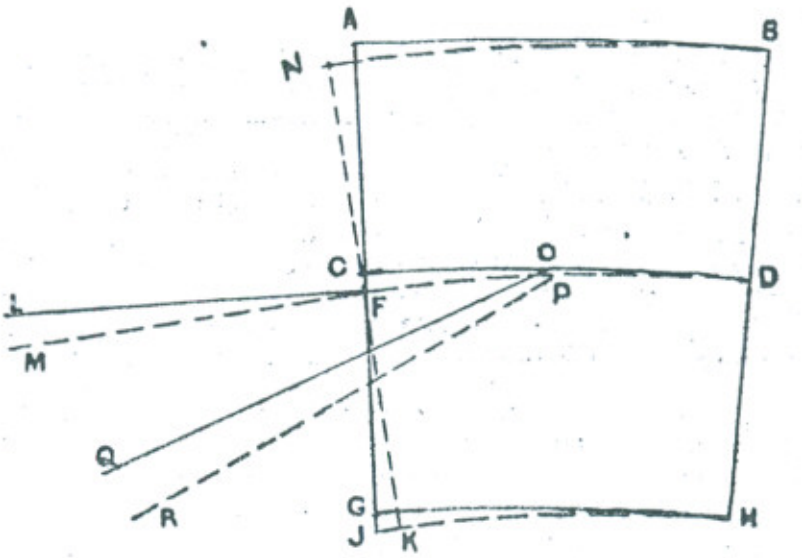
For unsymmetrically loaded arches the method is just the same, but there is a vertical component of the thrust at the crown for which an equation can similarly be obtained from the vertical movement of the crown.

In Fig. (1) let $A\ B\ H\ G$ be an infinitely small length of the shell (or arch), $A\ J$ and $B\ H$ being the ends of the radii of curvature. $C\ D$ is the neutral axis of length ds.

When bent, due to a bending moment M, this piece of shell will assume the shape shewn dotted, $N\ B\ H\ K$; $N\ K$ is now the end of the new radius of curvature. Draw $F\ L$ at right angles to $A\ G$, and $F\ M$ at right angles to $N\ K$, then these lines are the tangents before and after bending. Let $d\theta$ be the angle between them, *i.e.* let $d\theta$ be the change in the inclination of the tangents due to bending. (It may conveniently be stated here that if a line $O\ Q$ be drawn in any direction from O, the centre of this small length of shell, for instance a line drawn to the crown of the pipe—if

the latter is supposed to be free to move—then, after bending, $O\ Q$ will take up the position $P\ R$. and the angle between $O\ Q$ and $P\ R$ will be equal to the angle between $F\ L$ and $F\ M$, *i. e.*, it will be $d\theta$. This is obvious, and can easily be proved).

FIG. I



Now the inner surface of the shell has been compressed from the length $G\ H$ to the length $K\ H$. The shortening in length is $J\ K$. If f be the intensity of stress at this surface, then the strain is the stress divided by the co-efficient of elasticity, and therefore

$$\frac{J\ K}{G\ H} = \frac{f}{E} \text{ therefore } \frac{J\ K}{ds} = \frac{f}{E}$$

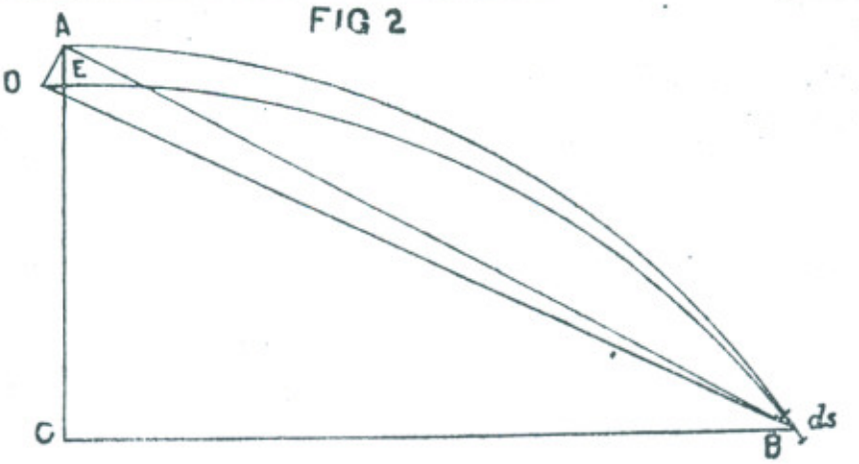
Now if y is the distance of this surface from the neutral axis, $f = \frac{M\ y}{I}$, therefore $\frac{J\ K}{y} = \frac{M\ ds}{E\ I}$ but $y = K\ F$, and $\frac{J\ K}{K\ F} = \angle\ J\ F\ K = \angle\ L\ C\ M = d\theta$

$$\therefore d\theta = \frac{M\ ds}{E\ I} \text{ .... Equation (1).}$$

In Fig. 2 let A be the crown of the pipe, and let B be any point in the shell. Imagine the pipe to be cut into two halves at the crown so that the latter is free to move. Take A as the axis of co-ordinates, so that $AC = y$, and $BC = x$. Let the short length of the shell, ds of which B is the middle point, be subjected to a bending moment M; then due to the bending of ds, the crown point A will move through a small arc AD to D. As already stated $\angle\ A\ B\ D = d\theta$. $\angle\ D\ A\ B$ is a right angle, and $\angle\ C\ A\ B = \angle\ C\ B\ A$ = a right angle, therefore $\angle\ D\ A\ E = \angle\ C\ B\ A$, also $\angle\ D\ E\ A = \angle\ A\ C\ B$, therefore the triangles $D\ E\ A$ & $A\ C\ B$ are similar, therefore $\frac{D\ E}{D\ A} = \frac{A\ C}{A\ B}$, therefore $D\ E = A\ C \times \frac{D\ A}{A\ B}$, but $A\ C = y$, and $\frac{D\ A}{A\ B} = d\theta$, therefore $D\ E = y\ d\theta$.

But $D\ E$ is the horizontal movement of the crown, therefore horizontal movement of the crown, due to the bending of ds, $= y\ d\theta$.

FIG 2



The total horizontal movement of the crown, due to the bending of the infinite number of small lengths to the right of the crown

$$= \int_{\text{crown}}^{\text{right springing}} y \, d\theta$$

Similarly, the horizontal movement due to bending on the left of the crown

$$= \int_{\text{crown}}^{\text{left springing}} y \, d\theta$$

These movements are equal, but opposite in sign (for instance, if the crown moves from A to D, bending on the right causes movement away from the right springing, while bending on the left causes movement towards the left springing) therefore

$$\int_{\text{crown}}^{\text{right springing}} y \, d\theta = - \int_{\text{crown}}^{\text{left springing}} y \, d\theta$$

For a symmetrically loaded pipe therefore

$$\int_{\text{crown}}^{\text{springing}} y \, d\theta = 0 \quad \text{.....Equation (2).}$$

Again, the change in the inclination of the tangents at the crown $= \angle A B D = d\theta$

Therefore total change of inclination of the tangents at the crown, due to the bending of all the sections to the right

$$= \int_{\text{crown}}^{\text{right springing}} d\theta$$

and that due to the bending of all sections to the left

$$= \int_{\text{crown}}^{\text{left springing}} d\theta$$

These are equal, but opposite in sign, therefore

$$\int_{\text{crown}}^{\text{springing}} d\theta = 0 \quad \text{.....Equation (3).}$$

Substitute in equations (2) & (3) the value given for $d\theta$ in equation (1)

$$\therefore \int \frac{M y \, ds}{E I} = 0 \qquad \text{and} \qquad \int \frac{M \, ds}{E I} = 0$$

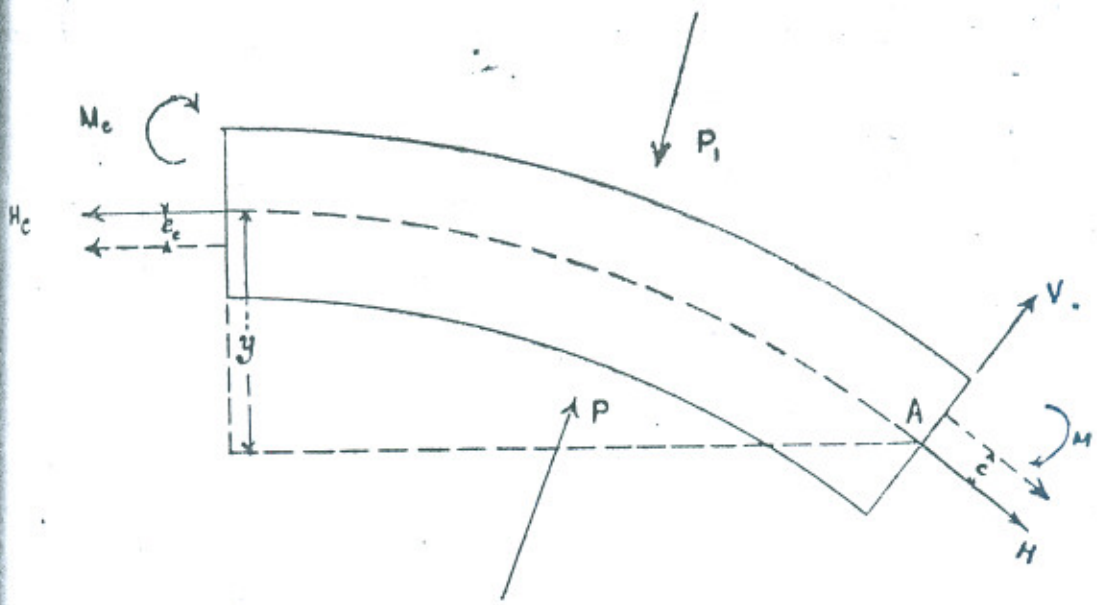
If the thickness of the shell is constant, and the position of the metal in the shell is always the same, then $E\,I$ is constant, and may be taken outside the sign of integration

$$\therefore \int_{\text{crown}}^{\text{springing}} M\,y\,ds = 0 \quad \text{.....Equation (4).}$$

$$\text{and} \int_{\text{crown}}^{\text{springing}} M\,ds = 0 \quad \text{.....Equation (5).}$$

Fig. (3) shews a portion of the shell to the right of the crown. This portion is kept in equilibrium by the tension H_c at the crown, acting eccentrically at a distance e_c from the neutral surface in some such position as shewn by the dotted arrow, by the external forces P and P_1, and by the tension at the right hand end of the section, of which H, acting eccentrically at a distance e from the centre, and shewn by the dotted arrow, is the tangential component, while V is the radial component (which is the shear).

FIG. 3



The tensions H_c & H, which act eccentrically from the neutral surface, may be replaced by tensions H_c & H acting at the neutral surface (and shewn by the full arrows) and by moments M_c & M.

Take moments about A, and let the moment about A of the external forces, P & P_1 be called M_p. Call clock-wise moments positive.

$$\therefore \quad Mc - H_c y + M_p + M = 0$$

$$\therefore \quad M = H_c y - M_c - M_p \quad \text{.....Equation (6).}$$

Substituting this value of M in equations (4) & (5), we get

$$\int (H_c y - M_c - M_p)\, y\, ds = 0$$

$$\int (H\ y - M_c - M_p)\, ds = 0$$

H_c & M_c, being constants, can be taken outside the sign of integration and we get :—

$$M_c \int y\,ds - H_c \int y^2 ds + \int M_p y\,ds = 0 \ldots\ldots\ldots\ldots\ldots (7)$$

$$\& \; M_c \int ds - H_c \int y\,ds + \int M_p ds = 0 \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Now $\int ds = s$ = length of shell from springing to crown therefore from (8) we get :—

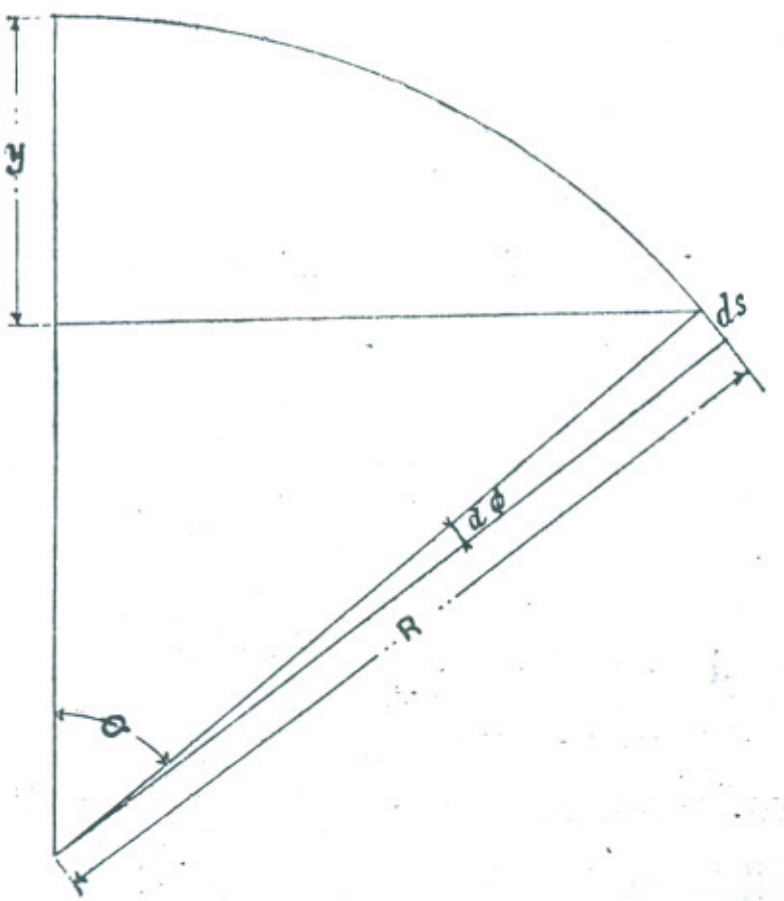
$$M_c = \frac{H_c \int y\,ds - \int M_p ds}{s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Substitute this value for M_c in (7) and multiply throughout by s

$$H_c = \frac{s \int \angle\, M_p y\,ds - \int M_p ds \int y\,ds}{s \int y^2 ds - \left\{\int y\,ds\right\}^2} \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Using polar co-ordinates, instead of rectilinear, *vide* Fig. (4), let R be the radius of the pipe. Then $y = R\,(1 - \cos\phi)$ and $ds = R\,d\phi$

FIG. 4



In the case of the Bara siphon the shell is kept rigidly in place below the horizontal diameter, so that the springing is at the end of the latter, and the limits of integration are O and $\frac{\pi}{2}$

(In the calculations which follow, space does not permit of the various intermediate steps in integration and in simplification being given, accuracy of the intermediate steps can however be guaranteed.)

Equation (10) becomes

$$H_c = \frac{1}{R} \times \frac{s\int_0^{\frac{\pi}{2}} M_p (1-\cos\phi)\, d\phi - R\int_0^{\frac{\pi}{2}} M_p \phi \int_0^{\frac{\pi}{2}} (1-\cos\phi)\, d\phi}{s\int_0^{\pi/2} (1-2\cos\phi+\cos^2\phi)\, d\phi - R\left\{\int_0^{\frac{\pi}{2}} (1-\cos\phi)\, d\phi\right\}^2}$$

$$\text{or } H_c = \frac{1}{R} \times \frac{\int_0^{\frac{\pi}{2}} M_p (1-\cos\phi)\, d\phi - \cdot 5708 \int_0^{\frac{\pi}{2}} M_p\, d\phi}{\frac{\pi}{2} \times \cdot 3562 - \cdot 5708^2}$$

$$\text{or } H_c = \frac{1}{\cdot 2337R}\left(\int_0^{\frac{\pi}{2}} M_p\, d\phi - \frac{\pi}{2}\int_0^{\frac{\pi}{2}} M_p \cos\phi\, d\phi\right) \quad \ldots\ldots\ldots\ldots \quad (11)$$

and equation (9) becomes :—

$$M_c = \frac{H_c R^2 \int_0^{\frac{\pi}{2}} 1-\cos\phi)\, d\phi - R\int_0^{\frac{\pi}{2}} M_p d\phi}{\frac{\pi R}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

Let m = height of hydraulic gradient above crown
„ n = „ „ level of earth filling „ „
„ w = weight, per cubic unit, of water
„ w_1 = „ „ „ „ „ earth filling

Horizontal intensity of pressure of earth, where α is the angle of repose, is $\frac{1-\sin\alpha}{1+\sin\alpha}$ × vertical intensity.

Let $\frac{1-\sin\alpha}{1+\sin\alpha} = a$

The moment, M_w, of the water pressure above any point whose angular distance from the crown is k, *vide* Fig. 5, is

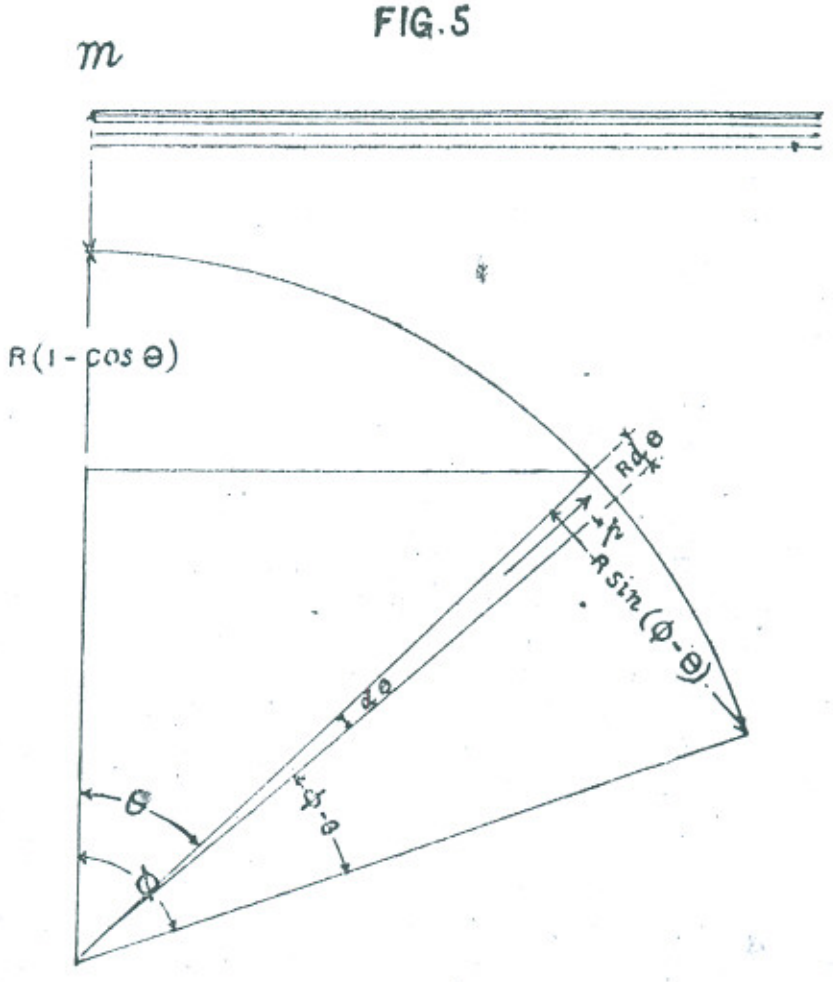
$$\int_0^{\phi} p \, R \, d\theta \times R \sin(\phi - \theta)$$

$$Now \; p = w \left\{ m + R(1 - \cos\theta) \right\}$$

$$\therefore M_w = wR^2 \int_0^{\phi} \left\{ m + R(1 - \cos\theta) \right\} \sin(\phi - \theta) \, d\theta$$

$$\therefore M_w = wR^2 \left\{ (m + R)(1 - \cos\phi) - \frac{R\phi \sin\phi}{2} \right\} \quad \ldots\ldots\ldots\ldots (13)$$

FIG. 5



In computing the moment of the earth pressure it is simpler to take the vertical and horizontal components separately, *vide* Fig. 6. The vertical intensity on a length of shell $R\,d\theta$ is $w_1 \left\{ n + R(1 - \cos\theta) \right\}$. This acts on an area of $R\,d\theta \cos\theta$. Its lever arm about A is $A\,C$, or $A\,H - B\,G$, or $R(\sin\phi - \sin\theta)$, therefore the moment about A of the vertical

component of the earth pressure on a length of shell $R\,d\theta$ is

$$w_1 \left\{ n + R\,(1-\cos\theta) \right\} \times R\,d\theta \cos\theta \times R\,(\sin\phi - \sin\theta)$$

or $$R^2 w_1 \left\{ (n + R) - R\cos\theta \right\} \cos\theta\,(\sin\phi - \sin\theta)\,d\theta$$

The horizontal intensity of pressure $= a w_1 \left\{ n + R\,(1-\cos\theta) \right\}$. This acts on an area $R\,d\theta \sin\theta$. Its lever arm about A is BC, or $FG - FH$, or $R\,(\cos\theta - \cos\phi)$. Therefore its moment about A is

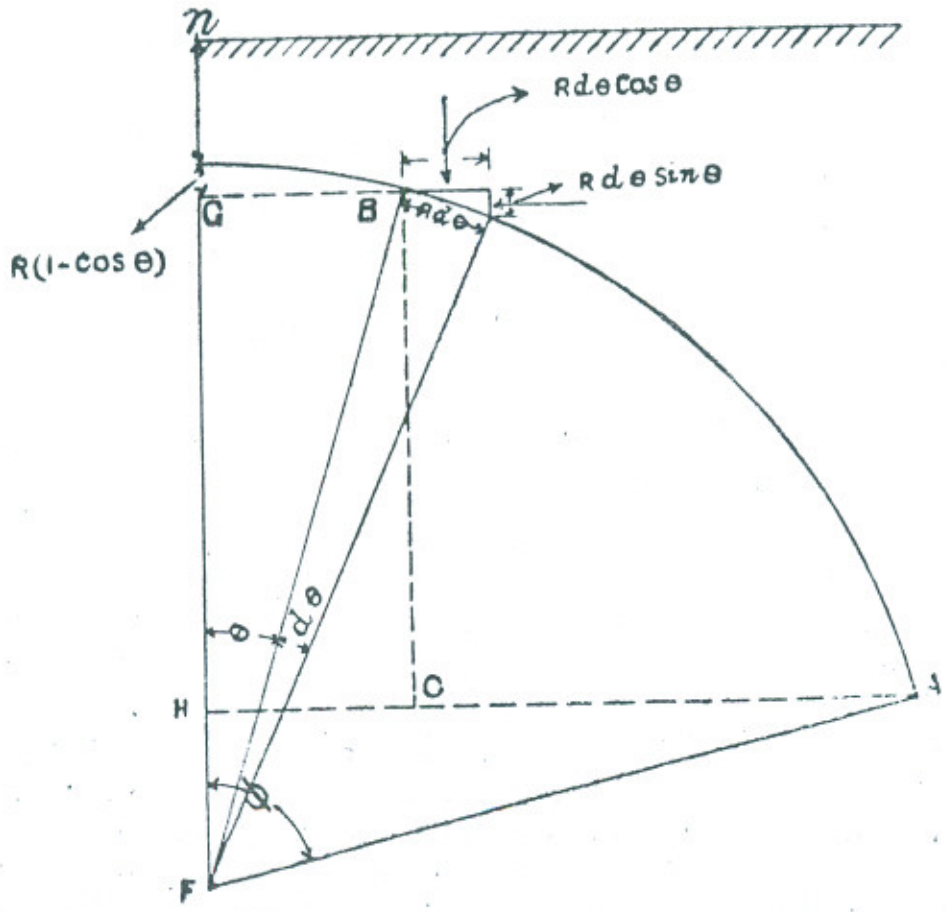
$$R^2 a\, w_1 \left\{ (n + R) - R\cos\theta \right\} \sin\theta\,(\cos\theta - \cos\phi)\,d\theta$$

The moment of the earth pressure from crown to A about A is therefore :—

$$w_1 R^2 \left[\int_0^{\phi} \left\{ (n + R) - R\cos\theta \right\} \cos\theta\,(\sin\phi - \sin\theta)\,d\theta + a \int_0^{\phi} \left\{ (n+R) - R\cos\theta \right\} \sin\theta\,(\cos\theta - \cos\phi)\,d\theta \right]$$

$$\therefore M_e = w_1 R^2 \left\{ \frac{R\,(5+a) + 3n(1+a)}{6} - \frac{2an + R\,(1+a)}{2}\cos\phi - \frac{(n+R)\,(1-a)}{2}\cos^2\phi + \frac{R\,(1-a)}{6}\cos^3\phi - \frac{R\phi\sin\phi}{2} \right\} \quad \ldots\ldots(14)$$

FIG. 6



This is a counterclockwise moment and therefore negative. Combining (13) and (14) we get :--

$$M_p = R^2 \left[\left\{ w(m+R) - w_1 \frac{R(5+a)+3n(1+a)}{6} \right\} - \left\{ w(m+R) - w_1 \frac{2an+R(1+a)}{2} \right\} \cos\phi + w_1 \frac{(n+R)(1-a)}{2} \cos^2\phi - w_1 \frac{R(1-a)}{6} \cos^3\phi + \frac{R(w_1-w)}{2} \phi \sin\phi \right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$$\therefore \int_0^{\pi/2} M_p \, d\phi = R^2 \left[\cdot 5708wm + R \left\{ \cdot 0708w - (\cdot 0274 + \cdot 0434a) w_1 \right\} - n w_1 (\cdot 3927 + \cdot 1781a) \right] \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$$\& \int_0^{\pi/2} M_p \cos\phi \, d\phi = R^2 \left[\cdot 2146wm + R \left\{ \cdot 0182w - (\cdot 0091 + \cdot 0091a) w_1 \right\} - n w_1 (\cdot 1667 + \cdot 0479a) \right] \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

Substitute in equation (11) the values given in (16) and (17), then the tension at the crown is given by the following equation :—

$$H_c = R \left[wm + R \left\{ \cdot 1805w - w_1 (\cdot 0561 + \cdot 1245a) \right\} - n w_1 (\cdot 5600 + \cdot 4400a) \right] \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

In equation (12) substitute the values given in (16) and (17) and we get :—

$$M_c = \frac{5708 H_c R - R^2 \left[\cdot 5708wm + R \left\{ \cdot 0708w - (\cdot 0274 + \cdot 0434a) w_1 \right\} - n w_1 (\cdot 3927 + \cdot 1781a) \right]}{\frac{\pi}{2}}$$

Substitute the value given for H_c in equation (18), and we get the following equation for the bending moment at the crown :—

$$M_c = R^2 \left[R \left\{ \cdot 0205w - w_1 (\cdot 0015 + \cdot 0176a) \right\} + \cdot 0465 n w_1 (1-a) \right] \ldots (19)$$

In equation (6) substitute the values given in equations (15), (18) and (19), and we get the following equation for the bending moment at any point whose angular distance from the crown is ϕ :—

$$M = -R^2 \left(R \left\{ \cdot 8400w - w_1 (\cdot 7787 + \cdot 0598a) \right\} + \cdot 1065 n w_1 (1-a) - \cos\phi \left[R \left\{ \cdot 8195w - w_1 (\cdot 4439 + \cdot 3755a) \right\} + \cdot 5600 \, n w_1 (1-a) \right] \right.$$

$$+w_1\frac{(n+R)(1-a)}{2}\cos^2\phi - w_1\frac{R(1-a)}{6}\cos^3\phi + \frac{\cos R\phi\sin\phi}{2}(w_1-w)\Big)\ldots\ldots(20)$$

This equation shews the fact that the bending moment is independent of the head causing the internal pressure. Also if $a=1$, or $\frac{1-\sin\alpha}{1+\sin\alpha}=1$, that is if the material round the pipe, on the outside, were fluid, then the bending moment for exterior fluid pressure would also be independent of the depth.

In the case of the Bara siphon $R=42$ inches, $w_1=\cdot063$ lbs. per cubic inch, $w=\cdot036$ lbs. per cub. in., and $a=\frac{1-\sin20^\circ}{1-\sin20^\circ}=\frac{1}{2}$. Then our equations become:—

$$H_c = 42\,(\cdot036m-\cdot0101-\cdot0491n)$$

$$M_c = 6\cdot6679+2\cdot58n$$

$$M = -42^2\left\{(\cdot00335n-\cdot8694)-\cos\phi(\cdot01764n-\cdot4322)+\cos^2\phi\right.$$
$$\left.(\cdot01575n+\cdot6615)-\cdot2205\cos^3\phi+\cdot567\phi\sin\phi\right\}$$

Assume the river bed scours down to the level of the top of the tube, then $m=35\times12=420$ inches, and $n=0$

$$\therefore H_c = 637 \text{ lbs. per inch run of tube}$$

$$M_c = 6\cdot668 \text{ inch lbs. } \quad " \quad " \quad "$$

$$\& M=42^2\left(-\cdot8694+\cdot4322\cos\phi+\cdot6616\cos^2\phi-\cdot2205\cos^3\phi+\cdot567\phi\sin\phi\right)$$

Put different values for ϕ and we get the follᵒwing table:—

ϕ	0°	15°	30°	45°	60°	90°
M	−6·67	−8·29	−11·11	−8·88	+2·29	−37·4

The maximum bending moment therefore occurs at the end of the horizontal diameter and $=-37\cdot4$ inch lbs. per inch run of pipe.

Note.—If there were only internal water pressure, *i.e.*, if the river scoured down to the horizontal diameter, then putting $w_1=0$ we find that $M_c=54\cdot68$, $M_0=-54\cdot68$, $M_{60}=+61\cdot85$, & $M_{90}=-145\cdot6$.

The tangential component of the tension at springing is the vertical water pressure on the shell between crown and springing minus the weight of earth above this shell $=625$ lbs. per inch run.

The eccentricity, e, of the "line of tensions" is $\frac{M}{T}=\frac{-37\cdot4}{\cdot625}=-\cdot06$ inch at this point. The minus sign for e means that the resultant tension acts towards the inside of the shell, following the convention adopted in fig. (3).

The remaining calculations, to get the reinforcement necessary, are given in reinforced concrete books under some such heading as "direct pressure combined with bending," only here tension has to be substituted for pressure.

Equation (20) is a general equation for a circular tube rigidly fixed at the extremities of the horizontal diameter, and can be used either for interior

or exterior water pressure, or for exterior earth pressure, or for any combination of these, and is therefore suitable for the design of a culvert set in lime concrete, or in hard virgin earth, below the horizontal diameter.

For instance, in the case of a drainage culvert under a canal, two cases would have to be considered :—

(1) Tube empty.

(2) Tube full of water to the crown (when the Lullah is in flow).

In the first case all terms involving w in equation (20) would be zero.

[*Note.*—Stresses are also caused by the change in length of the shell due to the tension, but where the thickness of the shell is small compared with the radius of the pipe, the effect of these stresses is found to be negligible].

DISCUSSION.

MR. BURKITT, in introducing his paper, said he had nothing to add to what he had written, but would be glad to listen to the criticisms and try to reply to them in due course.

MR. CARNE pointed out that it was stated that a concrete pipe should, if properly made, outlast a steel tube, but it was difficult to say whether the work had really been well done. In the Island siphon there were several leaks which were subsequently stopped by grouting, and, in undertaking this class of work, arrangements had to be made for personal supervision at every stage by a competent engineer. Steel pipes had stood the test of time, and the speaker only knew of one instance in the North-West Frontier Province, where there had been trouble, and that was not due to corrosion, but to deposit, or rather incrustation, to which steel pipes were sometimes liable, and he understood that this had caused a lot of trouble in the hydro-electric power supply at Mussoorie. He would be glad if the author could give the approximate cost per foot length of each of the tubes he had mentioned, and would also compare the cost of the concrete tube used for the Island siphon with that of the steel tube as originally estimated, as well as the cost per foot run of the tubes used on the Upper Swat Canal, taking the steel at pre-war rates.

LALA WAZIR CHAND CHOPRA said he would be glad if the author could give some idea of the cost of ferro-concrete as compared with brick siphons, when built in the plains at a distance from the railway. In 1909 he had occasion to design a siphon for the Raya branch of the Upper Chenab Canal, where the bed width was sixty-five feet, and the depth 6·7 feet. The place was eighteen miles from the nearest railway station, and the siphon was designed to discharge 350 cusecs at five feet per second. The ferro-concrete siphon worked out to Rs. 15,000 as compared with Rs. 14,000 for the ordinary brick siphon, which had been built, and had given no trouble. That the reinforced siphon design had not been unduly conservative would appear from the fact that the thickness proposed was only seven inches, as against nine and a half required under the author's rule, while the circumferential reinforcement consisted of 7 16″ rods placed four inches apart in the 9½ feet tube, or twenty-two per cent. less than the quantity used by the author in his seven-feet tube. The longitudinal reinforcement merely consisted of quarter inch rods a foot apart. These figures were not quoted in order to criticise the author's design, but merely to show that brick siphons were cheaper

when the materials for ferro-concrete work had to be carted some distance from a railway station.

MR. LIVINGSTONE-LEARMONTH said the cost of the Bara siphon, as completed, was approximately Rs. 2 per cubic foot for reinforced concrete and Re. 1 per cubic foot for falsework. He promised to hand in a detailed statement* of the cost, comparing steel with reinforced concrete, and showing that, in this case, with a pre-war overall rate for steel of Rs. 23 per cwt., the cost would have been about double that of the reinforced concrete siphon constructed. Mr. Burkitt had mentioned the concrete mixture as being one part of cement to two of sand and four of gravel, which was the mixture laid down by higher authority, but the actual tests made at the site shewed that the best graded mixture would have been one part of cement to half a part of sand and four of gravel, the reason being that the natural gravel used was so well graded that very little fine sand was needed. The tests made were the ordinary water tests for interstices, which, though not absolutely accurate, were better than the arbitrary determination of a mixture without any testing. The author had mentioned † the difficulty of laying the concrete in the bottom segment of the tube, but the speaker had found from experience, gained in constructing both the Bara and Island siphons, that much the best way was to lay the bottom segment to template without any laggings, and if this portion were left fairly dry, there was no necessity to wait before laying the upper portion, and the whole circumference of the tube could be completed in one day. This method was quick, and had the further advantage that the surface could be smoothed off if necessary before completely setting, as there were no bottom laggings to be removed.

As regards the author's summary of suggestions;‡ it had been found cheapest and most satisfactory to increase the number of ribs at the bends, and to use half-inch laggings, bent as in boat building. while a wood floor was absolutely essential for mixing the concrete, the convenient amount for each group to mix being eight cubic feet. Doing away with the bottom laggings also eliminated the danger of the measures forcing all the concrete under the circumferentials. It was found that at least as many carpenters were needed as masons. On further experience, he did not think it necessary or expedient to give prizes. It was better to put all the men on a backward piece of work, especially on the slopes. A system of prizes led to fighting among the masons as to who would get mortar quickest, etc., and this resulted in unevenness in the work.

* Appendix, page 92b. † Pages 75 and 77. ‡ Pages 78 and 79.

MR. QUINN-YOUNG complained of the absence of a specification, and of any explanation as to why a 1 : 1½ : 3 mixture had been used in the Hazarkhani siphon, where the head was only fifteen feet, while the mixture was 1 : 2 : 4 at the Bara siphon, with thirty-five feet head. No mention had been made of any stiffening against lateral movement, which was necessary for long tubes, unless the soil was such as would offer considerable resistance to subsoil water pressure, and the river bed was stable. When the head works of the Lower Bari Doab Canal were first designed, a siphon was proposed under the Ravi at Balloki, but was abandoned, partly on account of the great difficulty combined with the excessive cost of stiffening it against lateral movement. He hardly considered that cradling a siphon, only three inches thick, in a lime concrete bed, was safe. Most of the soil of Northern India was impregnated with alkaline salts, which would quickly find their way through the concrete into close proximity with the reinforcement in the cement concrete shell, and he suggested a layer of brick in cement as offering better protection. He thought that the trouble experienced with some of the Lahore buildings, where the rusting of the iron beams supporting the roof forced out the walls, proved conclusively the danger of having steel in contact with lime. He disagreed with the author in thinking 1½ inch aggregate would be too big, provided the gravel had been thoroughly graded from ¼ inch upwards. Thorough grading both of the gravel and of the sand, in order to reduce the percentage of voids to a minimum, was the secret for water tightness and strength. Also using a sloppy in preference to a dry mixture ensured better protection to the steel work, and such a mixture combined with good workmanship rendered the addition of any water proofing substance unnecessary.

MR. HARFORD said that, after listening to the discussion on making reinforced concrete siphons, he was surprised that an important department like the Irrigation Department should attempt to carry out such a big work by hand, when it could be carried out by a mechanical process. All those who had not heard of the Jagger table should get acquainted with it. At home in England, nobody attempted to make by hand reinforced pipes, or any class of reinforced concrete that could be made by a mechanical process. By the Jagger process a perfectly homogeneous concrete, free from voids, could be obtained. In 1914 the Improvement Construction Company of London had sent out a representative, who travelled

throughout the whole of India for the sake of introducing the process, which he now wished to bring to the notice of the Congress, because it had only recently been realized how important a process it was for the manufacture of standardised concrete. The North-Western Railway had recently introduced a Jagger table, and were now manufacturing concrete slabs for lining oil tanks at Karachi. His object in speaking was to inform the Congress that the Railway Department would be glad to give full information on the subject, and detailed drawings as well, if any gentleman was interested in it.

As the reinforced concrete pipes were made in a factory, all falsework was done away with—the pipes were made in any lengths up to twelve feet, and were laid with a plain butt joint and a collar to cover the joint; the space between the collar and the pipe being filled in with neat, liquid cement, making a perfectly watertight joint. He had seen reinforced concrete pipes, only three inches thick, which had been standing under a continuous pressure of a hundred pounds to the square inch for eighteen months, without the slightest sign of leakage or loss of pressure. When made by this mechanical process, the concrete was so good that it was possible to make a considerable reduction in the thickness of the pipes designed to be made by hand, and thus a considerable saving was effected, which in time more than covered the cost of the installation.

MR. LINDLEY gathered from the discussion that modern practice had not been followed in testing the various materials for voids, and thereby finding out what proportions were needed. Another point he wanted to bring forward was the wetness. It was stated that, in the first experimental tube, the bottom part was found faulty, owing to the mixture having been too dry. He had seen the design of the reinforced concrete work, with a specification in which it was specified that the mortar should be made with so much water, but it was a very dry mixture, and he thought that while there was a demand for a dry or a wet mixture, there was no standard of what was called dry or wet. One possibility was to include in the specification the amount of water per cubic foot of concrete, but that was not a definite standard when evaporation varied enormously. Another method was to measure the angle of repose of a tipped quantity. His point was that the wetness of the concrete wanted defining, and should not be left to the judgment of the men on the spot.

MR. HADOW said, with reference to the remarks in the paper as to the relative cost of reinforced concrete and brickwork

siphons, that he had had to make comparative estimates for twelve or fourteen such siphons on the Upper Jhelum Canal, and it was found that, in each case, except those of single barrels, the masonry siphon was the cheaper, though it should be noted that the works were some distance from a railway. On page 65 Mr. Burkitt stated that he had buried the welded joints of the steel in the bottom of the siphons, from which it might be judged that he did not place much reliance on them, but could he give any information as to what strength could be safely allowed to such welded joints ? As regards a system of prizes for good work, the speaker had had some experience of offering a bonus for progress on work, but had almost invariably found it a failure.

MR. WOODS pointed out that the diameters of the tubes, and the heads of water pressure in them, were as follows :—

Hazar Khani	Diameter	2·5 feet.	Pressure	15 to 17·5 feet.
Bara	,,	7·0 ,,	,,	35 to 42 feet.
Island	,,	5·5 ,,	,,	over 30 feet.

In each case the diameter of the siphon tube was only about one-sixth of the head of pressure against it, so that the principal stress in each tube was hoop-tension, and the metal necessary to resist this hoop-tension or bursting pressure would take care, incidentally, of the relatively negligible bending moments due to the difference of pressure against the top and bottom of the tube respectively. If, however, the bending moment round the shell of the tube were an important stress, it would be wrong to place the metal reinforcement, intended to resist this stress, at the centre of the shell, for in that position it could exert only about half the resistance that it could have done if placed near the tension surface. Investigation of the stresses induced in the shell of a tube, whether by water pressure inside the tube acting radially outwards, or by water pressure outside the tube acting radially inwards, shewed that if the tube were laid with its longitudinal axis horizontal, and if the water pressure against its bottom were greater than that against its top, the tendency would be for the tube to bend inwards at the top and at the bottom. The metal reinforcement necessary to resist the tension due to this bending moment, ought to be placed at the inner circumference of a tube. If it were placed at the centre of the tube, it meant that the arm of the moment of resistance was only half what it would be if the metal were

placed at the soffit, and therefore twice as much metal would have to be placed in the centre as would suffice if it were placed at the soffit.

If the upper half of the tube were regarded as an arch, supporting a superincumbent load of earth and water, with a horizontal extrados, the tendency of the elastic arch would be to bend outwards at the haunches ; the maximum bending moment being at points thirty degrees above the horizontal diameter, and to meet this bending stress metal reinforcement was required at the outside of the tube shell. The author had mentioned an American device for varying the thickness of the tube shell, so as to vary the relative position of the metal reinforcement in the shell in order to resist varying bending moments, but it would probably be more correct to say that this was a device for getting rid of some of the bending stresses, by making the concrete of the tube shell thick enough to form a stiff or rigid arch, in which tension could be obviated by keeping the line of resistances within the middle third of the thickness of the shell. In such a case, if the bending moments and the hoop-tension in the tube due to radial water pressures, were provided for by a single circular reinforcement placed round the inner circumference of the shell, the tendency to bend outwards at the haunches, above and below the horizontal diameter, due to earth pressures outside the tube, could be met by making the tube shell thick enough at the haunches to keep the line of resistences to these pressures within the middle third of shell thickness.

It was well to note, also, that the subsoil in which the tubes were laid was saturated with water ; and the pressures of the water inside the tubes, acting radially outwards, were met by corresponding preasures outside the tubes, acting radially inwards ; so that the only stress, due to radial water pressures, which the tube was called upon to bear, was a uniform radial outward pressure producing simple hoop-tension in the shell. In these circumstances there could be no circumferential bending stress at all, except on the rare occasions when the tube might be unwatered for inspection and repairs.

The reinforcing metal bars had been placed needlessly far apart. Thus, in the case of the Bara siphon, the circular reinforcement consisted of $\frac{3}{4}$ inch bars, spaced nine inches apart ; when $\frac{3}{8}$ inch bars spaced $2\frac{1}{4}$ inches apart would have been more useful, and similarly No. 14 S.W.G. wires, spaced $2\frac{1}{4}$ inches apart

would have been better longitudinal reinforcement than No 8 S.W.G. wires spaced nine inches apart. In reinforced concrete work it was essential for the metal and the concrete to act together, as though they formed a homogeneous material, and this result was more likely to be achieved by using bars of small diameter, placed relatively close to each other, than by thicker bars, aggregating the same weight of metal, spaced farther apart, since the strength of reinforced concrete was proportionate to the cohesion of the concrete to the metal, and to the bearing surface. The thickness of the longitudinal reinforcement, in the case of the Bara siphon, had been calculated by regarding the tube shell as a series of longitudinal beams of concrete, seven inches deep, supported across spans of nine inches, by the metal hoops of the circular reinforcement, but this was an erroneous method of calculating the dimensions of the longitudinal reinforcement, since, if the reinforcing hoops had been spaced only $2\frac{1}{4}$ inches, instead of nine inches apart, there would have been no need to anticipate bending of a concrete beam, seven inches thick, across a span of only $2\frac{1}{4}$ inches. No expansion joints had been provided along the length of the siphons, on the ground that, being always under water, they would not be exposed to appreciable changes of temperature, but experience had shown, in the case of the reinforced concrete siphons of the Upper Chenab Canal, that such expansion joints were very necessary, and there was no indication in the paper that use had been made of the experience gained by engineers on the reinforced concrete construction used on this canal about ten years ago.

MR. ASHFORD, at the request of Mr. Woods, said that it was impossible to give any definite figure for the strength of a welded joint, as the result depended so much on the personal factor, and the skill of the workman. It was stated that the joint was about seventy-five to ninety per cent. of the strength of the bar, and was the best that could be done, though mechanical joints might prove more satisfactory. Would it not, however, be possible, to make these siphons in short lengths, and then to erect them at site? These short length pipes could be made in a yard under supervision, where each stage of the work could be inspected as it was completed, and all doubtful work rejected. By this method it would be possible to carry out the work in a more satisfactory and expeditious manner, and with much less anxiety to the officer in charge.

MR. FOY, referring to Mr. Ashford's suggestion that siphons should be built up of short length, moulded pipes, with flanges, gave his experience with short length pipes on the Machai branch of the Upper Swat Canal, which had, in the end, proved more expensive, and took longer to make, and said that perhaps Mr. Harvey could tell the members something about their present condition. (Mr. Harvey replied that they had stood all right.) Mr. Foy continued that it had been found cheaper in the end to make the siphons straight away, using collapsible moulds. The moulded pipes were four feet long, three feet diameter, and four inches thick. The total length of the completed siphon was about eighty or ninety feet.

MR. DUTHY said that the discussion had developed into a question of brick *versus* concrete siphons, and in this connection, the fact should not be lost sight of, that a reinforced concrete siphon was usually given more supervision than a brick one ; a single officer being usually considered capable of supervising the construction of six or seven brick siphons at a considerable distance apart, so that it was hardly fair to condemn brick siphons if one or two of them had failed.

MR. SANGSTER thought it might be of interest to members to know that a large amount of reinforced concrete work was being done in the remodelling of the head regulator of the Lower Jhelum Canal. The new crest wall and breast wall were being built entirely of reinforced concrete, and in this work the specification used was that framed for the Upper Chenab Canal siphons, with the following modifications :—

Sand,—In the Lower Chenab Canal specification the following processes are required :—

(1) To pass the material through a quarter inch mesh screen, and reject all material retained on this screen.

(2) To pass the material through an eighth inch mesh screen, and mix it in the proportion of three parts of what passed through the screen to one part of what was retained on it.

(3) To pass the mixture through a twelfth inch mesh screen, and accept all that was retained on the screen.

(4) To again pass the material which had passed through the twelfth inch mesh screen through a forty-eighth inch mesh screen, and to add the material which passed through to the material obtained in process (3), in the proportion of one to two. These processes seemed unduly complicated,

and it was decided as a *modification* that the following would be sufficient :—

(1) as (1) above

(2) To pass the material obtained from (1) through a forty-eight inch mesh screen, and mix the materials in the proportion of two parts of what was retained on the screen to one part of what passed through.

Ballast.—(1) Ballast to be passed through a three quarter inch mesh screen, and all ballast retained on the screen to be rejected.

(2) The material obtained from this process to be passed through a screen of $\frac{1}{4}$ by $\frac{1}{4}$ inch mesh, and all material passing through this screen was to be rejected and used as sand.

MR. BURKITT, in reply, said that mixtures which would have given the best results in a laboratory would not by any means have given the best results on the work. The best laboratory mixture, *i.e.* fairly dry, and containing a proportion of large aggregate, would have resulted in the occurrence of voids on the work. The reason for the richer mixture in the case of the smallest pipe, objected to by Mr. Quinn-Young, was "funk" : this was the first pipe constructed, and no risks were taken. He did not see why a reinforced concrete tube, which was stiffer longitudinally than a steel tube, should be more liable than the latter to failure from problematical lateral stress. The large steel tubes of a siphon on the Upper Swat Canal cost about Rs. 1,60,000, at pre-war rates for steel, while the same tubes could have been constructed of reinforced concrete for about Rs. 80,000 at war rates. The statement made by several members that reinforced concrete required an excessive amount of supervision, was not quite correct. While actually being laid, it undoubtedly required a lot of supervision, but this did not take long. The concrete of the first half of the Bara siphon, *i.e.* a length of about a hundred and ninety feet, was laid in four days, and during this time, three engineers were present for two days, and one for the other two days.

In the North West Frontier Province reinforced concrete siphons might be constructed once in a hundred years, and the cost of the Jagger table, recommended by Mr. Harford would probably have been as much as that of the siphon

while the use of a table necessitated the erection of plant for lifting and placing the sections of the pipe in position.

As regarded the comparative costs of brick culverts and reinforced concrete pipes, his experience was that the former were in most cases much the cheaper.

Regarding the welded joints, these had been made under skilled supervision, and he had full confidence in them when placed at the bottom of a tube which was itself laid in a cradle of lime concrete. In the case of a tube, however, without a cradle, he would use the usual overlapping joint. He quite agreed that there were advantages in moulding in advance in the case of small tubes, but with tubes of large diameter, lifting and placing of the sections would, in most cases, require formidable plant.

He agreed with Mr. Woods that in the depressed part of the tubes, where the head was great, the hoop reinforcement was capable of looking after the bending stresses, as here the lever arm of the bending moment was negligible, but this was not the case in the sloping parts of the tube, where the head was small and the lever arms of the bending moment great. A tube with a small head of pressure on it would undoubtedly fail if the hoop reinforcement was only designed to resist uniform pressure. Placing the reinforcement in the centre of the shell, when practicable, as in the cases in question, ensured the protection of the metal against rust. He entirely disagreed with Mr. Woods's suggestion for a closer spacing of the hoops, as the only advantage was that the longitudinal reinforcement could be smaller, but in any case the cost of the longitudinal reinforcement was always negligible, while the overwhelming advantage of spacing the hoops nine inches or more apart, lay in the convenience of being able to pass the pans of concrete between the hoops to the masons inside.

He was sceptical about the necessity for expansion joints in cases where the pipes were always under water. The tubes under discussion had been built a year, and not even a single hair-crack had been observed. He had not copied the siphons on the Upper Chenab Canal, mentioned by Mr. Woods, as he understood that these had not proved satisfactory, having developed numerous cracks.

APPENDIX.

Comparative cost of reinforced concrete as compared with a steel tube for the Barai siphon on the Kabul River Canal.

REINFORCED CONCRETE.

Material.	Quantity.	Rate.	Total Cost.	Cost per cubic foot of concrete	
			Rs.		
Steel	165 cwt.	Rs. 15/12/- per cwt.	2,596	0·46	0·75
Freight and carriage			508	0·09	
Bending and fixing ...			1,141	0·20	
Cement	46 tons.	Rs. 57/8/- per ton.	2,631	0·47	1·18
Freight and carriage			837	0·15	
Gravel	6,300 c. ft	Rs. 8/- % c. ft.	504	0·09	
Sand	2,760 c. ft	Rs. 12/- % c. ft.	331	0·06	
Labour			2,364	0·41	
TOTAL ...	...	...		1·93	
Falsework	...		Rs. 5,578	0·99	

The cost of reinforced concrete per c. ft. was	Rs.	1 15 0
The cost of falsework per c. ft. was	Rs.	1 0 0
Total quantity of concrete		5,655 c. ft.
Length of siphon		346 feet.
Quantity per running foot length		16·34 c. ft.
Cost per running foot length of reinforced concrete		Rs. 31·54
Cost per running foot length of falsework		Rs. 16·17
Total cost per running foot of the seven foot siphon		Rs. 47·71

STEEL TUBE.

Taking a quarter-inch plate as the minimum thickness practically admissible, with two longitudinal overlaps of six inches and one transverse overlap of six inches in a six foot length, thirty five square feet of plate would be required per foot run, as well as one 2½ inch by 2½ inch by 7/16

inch angle stiffener per four foot length, which was equal to six feet of ang stiffener per running foot length of tube.

Weight of 35 sq. feet of ¼ inch plate at 10·2 lbs per sq. foot	3·18 cwt
Weight of 6 ft. angle stiffener at 7 lbs. per running ft.	0·38 cwt
Total weight per foot of tube ..	3·56 c

while the most favourable pre-war quotation for steel tubes, including la rivetting, &c., was Rs. 23 per cwt. which gives the cost as Rs. 82 per fo tube as compared with Rs. 48, which was the actual cost of the reinf concrete tube on the Kabul River Canal under the Bara river. In pra at least Rs 8 would be deducted from this Rs. 48, as half the false charges could be debited to another siphon, where the same wood could be utilised again.