

(1) Number of pages _____

(2) Date of repair _____

(3) Initials of the Referencer _____

MADRAS RECORD OFFICE

Government of Madras

Public Works

DEPARTMENT

G.O. No.	2486	Press
B.P. No.		Mis.
158-159		
Dated	10-10.	1951/8.73

Not to be folded or roughly handled

*Proceedings of the Madras Government, Public Works Department,
10th October 1873.*

No. 158. Read the following Proceedings of the Government of India in the Public Works Department, (Irrigation,) dated Simla, 19th June 1873, Nos. 370—98 I. :—

Analyses of water movements on impingence, and of the nature and scope of the scour action developed at bridges and other obstructions in rivers and canals.

Read the following paper—

From Dr. J. P. Stratton, to Foreign Department, dated 31st March 1873, and enclosures.

OBSERVATIONS.—Dr. Stratton has described the results of his observations in an intelligent and instructive manner. The publication and circulation of the papers will doubtless prove very acceptable and useful to the Department of Public Works generally, and the Irrigation Department particularly, and will, in all probability, elicit valuable information on the several points adverted to. The Governor-General in Council considers that Dr. Stratton should be warmly thanked for his communication.

ORDER.—Ordered that the papers, including this Resolution, be printed and forwarded to the several Local Governments and Administrations in all Branches of the Public Works Department for circulation amongst, and consideration by, the Officers of the Department, with a request that the opinions educed, be abstracted and submitted, with a review, to the Government of India for information.

Ordered also, that copies of the printed papers be forwarded to the State Railway Officers marginally mentioned for the same purpose.

Chief Engineer, Punjab Northern (State) Railway.
Engineer-in-Chief, Indus Valley (State) Railway.
Superintending Engineer, Agra District, Rajpootana (State) Railway.
" " Delhi " " "
" " Holkar (State) Railway. " "
" " Neemuch " "

Ordered further, that copies of the printed papers

be forwarded to the Foreign Department for information and transmission to Dr. Stratton, with a request that the acknowledgments of Government may at the same time be conveyed to that gentleman, and with intimation that the results of the circulation of his observations will, in due course, be communicated to him.

Ordered lastly, that this Resolution, and the correspondence referred to, be published in the *Gazette of India* for general information.

(Signed) F. H. RUNDALL, Colonel, R.E.,
Offg. Depy. Secy. to the Govt. of India.

No. 159. ORDER THEREON, 10th October 1873, No. 2,486.

IRRIGATION, No. 12.

ORDERED that the spare copies of these papers on "water movements on impingence," etc., be circulated to District Engineers who will, when the subject shall have received due consideration, submit to the Chief Engineer for Irrigation any observations they may wish to offer.

(True Extract.)

Colonel, R.E.,
Secretary to Government.

To the Chief Engineer for Irrigation.
To District Engineers.
Spare Copies

GOVERNMENT OF INDIA.
PUBLIC WORKS DEPARTMENT.
IRRIGATION.

SIMLA, JUNE 19, 1873.

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R. E. E.

Colonel, R. E.,

Offg. Depy. Secy. to the Govt. of India.

No. 370 I.

*To the Secretary to the Govt. of Madras
Public Works Department*

GOVERNMENT OF INDIA
PUBLIC WORKS DEPARTMENT.
ILLUSTRATION.

Nos. 370-98 I

Dated 31st March 1873.

From P. W. D. Secretary, 1873.

Enc. 1.

Analyses of water movements on impingence, and of the nature and scope of the scour action developed at the bridges and other obstructions in rivers and canals.

P. W. D. Press - 26-8-73 - 510.

Enclosure to P. W. D. Resolution Nos. 370-98 I of 1873.

Dated 31st March, 1873.

From—J. P. STRATTON, Esq., M. D.,

To—Secretary to the Government of India, Foreign Dept.

Having last monsoon unexpectedly had opportunity of seeing in progress the scour action which occurs at bridge piers and similar obstructions in sandy channels during flood, I noted the points observed, and made sundry experiments thereon.

Ordinarily, the process is concealed from view by the turbidity of flood-waters.

Conditions unusually favourable for observation were thus evidently before me; for, so far as I have found, the explanation hitherto given in Engineering Publications is *from theory*, and it does not correspond with what I actually and repeatedly saw.

The principle thence deduced seemed, if correct, bound to explain so many other matters in hydraulic experience, that I was staggered by the largeness of the field opened up.

But apparently it leads nowhere that it does not simplify and define our understanding of water action and the mode of practically meeting its effects.

2. Before making the matter public, I wished the opinion thereon of a professional Engineer of experience in that Province, viz., the Punjab, from which, of late years, news of flood-damage to bridges had been most frequent.

Accordingly I sent an abstract of my Notes to the Superintending Engineer at Umballa, Mr. Login, F. R. S. E., for his opinion as to the newness and value of the points brought forward.

He has returned them with an Introduction and sundry Notes appended.

From these it will be seen that, in his opinion, the principle indicated is newly applied to the subject, and though he does not concur in all my deductions, yet he corroborates many of the observations from his own experience, and states that the subject is really of high engineering importance; while, as regards the central fact of the movements of water on encountering an obstruction, and the mode of its then scouring its channel, which I have described from *ocular observation*, he has, in employing this in his Notes, considered it to commend itself to acceptance in lieu of the theories hitherto employed to explain the action from the time (I may say, at any rate) of Colonel Abbott's Treatise on Indian Bridges.

3. As the apparently important bearings on river and canal works of this new analysis of water action can be fully investigated only by professional Engineers, I venture to forward my Abstract of Observations and Experiments, accompanied by Mr. Login's Introduction and Notes, so that if Government should think the matter of sufficient importance, the papers can be issued for consideration and circulation in the Public Works Department.

4. As the means of judging in a new and intricate matter of this kind can alone be furnished by giving experiment and induction with a detail that only Engineers or others interested will follow at leisure, and thus even the Abstract is voluminous, I attach to this letter a separate *resumé*, in which the chief points arrived at can be more readily seen divested of those preliminary particulars.

Chief points in Analysis of Water-movements on impingement and scour-action at obstructions.

[Summarised from fuller Abstract of Observations and Experiments.]

Dated December 1872.

FIRST:—Ordinary scour in free channels. Usual theoretical explanations of scour at obstructions.

In ordinary or general scour in an unobstructed channel, the current sweeps or rolls, lifts and carries along particles of sand or clay in some proportion to its velocity and their fineness, being favoured in the former case as regards its rapidity of action by their want of mutual cohesion.

Scour at bridges or other obstacles is usually described as an aggravation of ordinary scour as follows:—

The piers, &c., obstruct the water-way. This causes afflux, i. e., a heading-up or raising of the water above the bridge. Consequently there is increased velocity through its openings to the lower water on the down-side.

From this increased velocity arises the intensified scour.

See, e. g., Roorkee Treatise on Civil Engineering, 2nd Edition, Vol. II, 1871, pages 77, 78 and 79; and Professional Papers, 2nd Series, Vol. I, No. 4, April 1872, pages 338 and 339.

But on close examination it is not easy to trace out fully the connection between the scour result and those undoubted conditions.

Thus the heading-up and extra velocity are general across the whole channel, and that velocity doubtless produces proportionate ordinary scour where it operates.

But the dangerous special scour does not occur across the whole bed.

It is local and confined to the immediate borders of the piers, abutments, wing-walls or other obstructions.

(2)

The worst scour is at the very cut-water, and at stream base of these obstacles, *i. e.*, where the current is first checked and partially turned up, while the consequent increased velocity is acquired a little farther on between the piers.

Again, the velocity in that situation is greatest, in the mid-stream between them, or at a little distance from the obstacle side, while the scour is deepest close along the side of the pier, &c., shallowing off from the up-stream aspect where it is deepest of all.

In this special or local scour at obstructions there is a comparatively abrupt deep excavation, differing thus from the general lowering of the bed by scour in a free channel.

These points are difficulties in the explanation from increased velocity which I have not seen discussed.

Special scour is also sometimes referred to *eddies*, but without explanation, so far as I have seen, as to how these are supposed to act. See, *e. g.*, Roark's Professional Papers, 1st Series, Vol. II, No. LXIX, May 1865, page 190; and Vol. IV, 1867, page 76.

SECOND:—*Scour process at up-stream base of bridge piers and other obstructions as actually seen in progress.*

At velocities sufficient for scouring, the current is almost always so turbid that the bottom is not visible, and it is doubtless owing to this circumstance that the mode of action has not hitherto been described from ocular observation, but from theory, as above explained, in Engineering Publications.

Conditions which I must therefore regard as exceptionally favourable for observation, gave me last monsoon (1872) repeated demonstration of the real process during its actual progress.

A current on meeting an obstacle, which it first passes laterally (or sometimes below), splays out and is deflected, part of it swelling and curling up on the surface close against the obstacle, and distinctly above the general surface, part sweeping out to the side, and part turning into a down-sweep.

The plane of the bottom is parallel to the line of movement of the general current on its lower aspect, but it is transversely opposed to that of this deflected down-sweep, which thus acts as a body impinging rather than frictionally.

Friction is a more diffused, and impingence a more concentrated action. Abrupt scour-pools are excavated at obstructions to a depth sometimes of 20, 30 or 40 feet, or even more, although their superficial area may be limited.

Except friction be the impingence of lateral roughnesses, there is a practical difference in result, as familiarly exemplified by the graze and the fair-on blow of a cannon ball.

So with fluids: falling water rapidly hollows out; running-water rubs and wears away.

A current entering a channel at a right, or any considerable angle, strikes and specially scours the opposite bank, much more than is done by the side rub of the current moving parallel with the bank.

The down-sweep at a pier, &c., similarly plays on the transversely opposing bottom, stirs up the sand, &c., turns back or off from the cut-water, or other obstructing surface, sweeping the disturbed material with it; scooping out thus a hollow, and then turning up again, throwing out the sand, &c., and finally, ending with a lateral and onward tendency. By these three latter movements most of the ejected sand is thrown within the influence of the onward current above and to the side, and so is swept or carried away, while a portion falls or slides back to be again expelled.

The scour hollow is below the bottom of the current proper, and below the level of the general bed, however much it may be lowered by the ordinary onward scour of the current.

It constitutes a primary zone of true scour excavation around a pier-stem or other obstacle, which hollow has steeply sloping sides; while the sand falling in at the periphery seeking its angle of repose, produces an outer and secondary zone of infill at a gentler incline. In coarse gravelly sand these zones are well marked; in fine sand there will be differences of degree rather than of kind.

The action at the scour bottom may be looked on as a second impingement and deflection, the first being on the pier itself.

The more transverse the obstacle to the line of current, the more direct backwards are the deflected movements; while the more oblique it is, the more of onward tendency is blended with them, as, *e. g.*, at the shoulders of piers, at wing-walls, and along the concavities of a winding river bank, where similar special scour prevails. In these situations the distinction of the zones is less marked.

Of progressive sand terraces, their relation to the outer zone, and their mode of levelling up hollows, as described in my paper Abstract of Observations, I need not give details here.

THIRD:—*Producing conditions of scour at up-stream base of bridge piers and other obstructions.*

Observation and experiment show that the scour effect varies with variations in the amount and mutual proportions of the several producing elements, *viz.*, the velocity and depth of current, the width and receiving angle (as to transverseness or obliquity) of obstacle, as also the fineness and looseness of bed material, and possibly also the degree of its previous adhesion with the current.

Some as yet undetermined proportion is doubtless most effective.

Of the whole, the effects of velocity and fineness and incohesion of bed material seem the most simple and direct.

(3)

Those of transverse width and receiving angle of the obstruction appear intricately involved in the mutual proportions of these elements with that of the current volume as regards general velocity and depth.

Within certain limits of proportion to current, increase of width and direct transversity seem to increase the action, but with the current continuing the same, a very disproportionately broad obstacle is scoured only near the corners of the opposing side, and not at the middle, at which place, indeed, scour action would then be favoured by obliquity.

In a certain current a particular breadth of obstacle causes active scour, while a disproportionately narrow obstacle has little effect.

If the measure of both in either case be equally multiplied, the interproportion will remain the same, and there is nothing *a priori* to show that the results will differ from the proportion due merely to difference of scale.

In the second case, supposing the multiplication has increased the very narrow obstacle to the dimensions of an average bridge pier, the disproportionate current will be much beyond a medium river in depth, &c., and if the proportion as to result hold good as above, the scour will be slight.

With a uniform width of pier, but differences of current, the scour may thus increase with increase of depth, &c., up to a certain proportion of the latter to the fixed width; but increase of depth beyond this proportion may bring about the result found experimentally on the small scale, with an obstacle disproportionately narrow to current, *i. e.*, it may produce comparatively little scour.

This may, perhaps, be explicable as follows:—

For a force of limited intensity to scour deeply, a certain area of action is requisite effectively to oppose the in-fall.

The onward current at the sides interferences with the down-sweep, so that if the latter, from the obstacle being very narrow, has too small a cross-stream measure compared with its length down to the bottom of the current proper, it may, by the time it reaches that point, be so laterally reduced as to be practically ineffective for much scour excavation against the filling-up tendency at any narrow and limited hollow, of the ordinary bottom on-sweep of sand by the general current.

But it is not clear that there may not be some other element of interference, or a deficiency (for the purpose of effective scour) of some other requisite interproportion between the producing conditions already named, from the gradually increasing operation of which interference, or want of effective proportion in very deep streams, the scour force in them at obstructions may be lessened, as is said to occur with increasing depth in the case of ordinary onward unobstructed scour.

A turbid, *i. e.*, an already laden, condition of the current is described in ordinary scour to lessen its power of taking up fresh material, and the same may, to some extent, be the case also in pier scour.

At the up-stream base of continuous obstructions like weirs, there is little, if any, tendency to down-sweep and its excavating action, seemingly from the want of subsequent lateral or inferior passage. That is with a direct current,—for obliquity there favors such tendency,—finding issue at last by rising to the overfall.

At such works the danger is from the impingement of the over-fall or rapid on the down-stream base.

But where an under-passage exists, or can be forced at an obstacle, the down-sweep turns forward in it producing a strong under-scour.

Similarly, if the down-sweep can descend to the very base of an obstacle, and find loose material there, it turns ahead and scours out beneath, at first and chiefly at the up-stream margin or toe, so that if a bridge-work thus attacked yield before wholly undermined, it tends to fall upwards or against the stream.

Bridge-works have been known to sink bodily a certain way, showing thus complete undermining ere they sank. Others have been pushed over by the thrust of the stream flood.

Or, if the down-sweep or other current, gain, by any crevice however small, an entrance beneath floorings, or into compound foundations, the interior of which, with drop-walls, &c., resembles broad-closed chambers, it begins to act with force, as in a hydraulic press, and may hollow out, disintegrate, or even burst them.

Interchange the position of movement and resistance, and the same effects are found.

Thus with a bulky boat driven at high speed in a canal, the uproll at its bow is visible, as familiar also in the case of ships, but the down-sweep and outplay are also indicated by the injurious action on the bed and sides of the canal.

FOURTH:—*Scour on down-stream side of bridges, and under corresponding circumstances.*

But a special scour is also found on the down-stream aspect of bridges, and the stream, which had disclosed so much, did not fail here.

The contracted archway stream dashes with its superior velocity into the wider and slower water below.

An up-curling wave or breaker rises on the surface, and backward eddies appear laterally. Here are, in three directions, visible indications of impingement and deflection, while at the bottom a deep pool is scoured out, implying down-sweep in the fourth.

As on the surface, the water, at any one moment in the re-curling breaker, is rising and seeming to tend backwards, but yet, in the next instant is rushing ahead; so doubtless below

also, while the downward deflection may first tend a little back, it stirs up the sand and soon turns onward in a strong bottom scour.

Such pool tends to retrograde to the bridge foundations, especially if there be a flooring higher than the ordinary scour level of the bed, and to elongate also in the stream-line.

When first the idea suggested itself of deflected movement, and its consequences, from impingement of a current on still-water, or even on another current proceeding in the same direction, but more slowly, I hesitated at its adoption.

But farther investigation seems to show that it is a well-marked action elsewhere also as, e. g., in canals just *ahead of the foot* of ogee falls and of rapids, where the destructive action on the bed and sides may be explained by the down-sweep and out-sweep from the impingement of the current with some of its previously acquired velocity on the slower water in the leveller channel ahead.

The known use of sunken reservoirs at foot of canal falls thus receives *farther* explanation; as, besides the familiar function of retaining a buffer of water to break the primary impingement of the fall, the *front wall of the depressed cistern checks the forward portion of the outplay* which would otherwise enter the canal level at great velocity and, impinging on its slower water, be deflected and scour the bed and sides, as occurs beyond the foot of rapids and ogees.

The down-sweep, thus occurring at the junction of a greater with a lesser slope, constantly erodes the toe of the former, shortening and making that slope steeper, and hence seems to account for the *retrogression of levels* and accompanying aggravation of the scour experienced in these cases, as, e. g., in the Eastern Jumna Canal before its levels were adjusted.

What is called the regimen of a river appears of similar nature.

The instances of special scour above noticed may be found scattered through Engineering works, but without, so far as I have seen, explanation beyond general reference to velocity, or eddies, or pressure, and certainly without any connective explanation, such as is afforded by the present analysis of impingement, deflection, and secondary impingement.

Eddies, merely as such, and distinguished from a direct current, seem to have no special scouring energy.

Usually derived from a prior impingence and deflection of an ordinary current, they are weaker than it both in frictional and impinging force, and it is only when they meet an obstruction more or less transverse to their line of movement at the place of contact that scour effect is marked.

But here the distinction, before adverted to, between impingence and friction comes strongly out, for the impingence of an eddy is so much more effective than the friction of its parent current, that when marked scour has been observed where there was a noticeable eddy, it has sometimes been attributed simply to the eddy, and the inference drawn that eddies scour much more than direct currents.

The reality appears to be that the distinction between the frictional and impinging modes of action not hitherto drawn applies equally to both direct currents and to eddies or backward currents, and that, with the same mode in each case, the eddies have the less scouring force.

Where scour, apparently from an eddy, has been marked on a canal side below a fall, it has probably been from the impingence of the outplay as already described.

It will be seen that the analysis controverts no observed facts, but when applied to them, furnishes a connected and connecting explanation not otherwise supplied.

Fifth:—*Indications on practical matters afforded by the Analysis.*

The chief practical indications suggested by the analysis seem as follow.

As the pier scour proper is not a general action across the whole channel, protective works, like continuous floorings across its entire breadth, are seen to be unnecessary for the purpose, at least, of pier protection.

Experiment shows that, with certain dimensions and form of piers, the scour effect is less than with others, elongated and comparatively narrow piers, with pointed cut-waters, producing less than thick, bluff, or circular piers.

Of course, a medium is requisite, because a very narrow pier might be too weak in cross-section, and if too long would be exposed to dangerous impingement scour from an oblique current, which latter can never take a round pier at a greater disadvantage than the direct stream.

The stem in the cylindrical form comprises the up-stream semi-circumference, which, with some farther part, is *deeply* scoured; while at an elongated pier, with a cut-water, less than a fourth of the periphery is exposed to the *worst* scour. The latter also is stronger in the stream-line to resist the current thrust, and, if under-scoured at its stem or cut-water, may stand, through the short period of the flood, on the rest of its base, while a cylinder undermined at its stem, i. e., half-section, can scarcely stand at all.

The object of a protective work is by the present analysis seen to be to receive, check, and deflect off horizontally the down-sweep, before it penetrates the bed material deep enough to endanger the stability of the pier foundation or other primary work.

Provided this object be attained, it is of no consequence of what construction the protective work be—whether of masonry, of boulders, or other material, and whether made with the original work or subsequently applied.

Piles and brushwood or bamboo framework and matting are used to protect the face of spurs, &c. Instances are known of such matted framework, on being scoured at the base, sliding down or falling forward, and of *farther deepening scour thereon ceasing*. The analysis suggests this to have been from their falling over the place where the down-sweep was impinging, and so preventing it from excavating deeper.

For complete protection a certain *width* is needed at each pier, abutment, wing-wall or other work, this width being the utmost breadth of the down-sweep, measured radially from the opposing surface, which the greatest flood can, at the particular obstacle, produce.

The outer zone of in-fall is of no consequence.

If less width be given to the protecting surface, some of the radially outer layers of down-sweep may impinge beyond it; although as the inner layers in more immediate contact or proximity to the opposing surface seem to have the strongest scouring force, even a narrow projection like a *footing* will do good.

There is a certain *depth* above which the upper surface of the protective arrangement should not be, if it is an isolated work, the flank of which the current can turn, *namely*, the lowest level to which the stream can lower its bed by ordinary scour.

If the protective work be not so low as this, the lower layers of the current will catch on the exposed up-stream face of this work itself, and be deflected downwards and possibly work mischief beneath, even though the down-sweep from the bottom of the current may be weaker than that from the mid-depth or other layers excepting those which turn upwards at the pier stem.

If, however, the protective work is a continuous flooring, then, *provided it be broad enough up-stream* beyond the pier cut-waters, &c., to receive the down-sweep from the piers, &c., it may, so far as strictly down-sweep action is concerned, be raised like an ancient with a bridge on the top. But in that case the extra action on the down-side will need to be guarded against. And though the general tendency of a raised continuous bar across a channel is to check the ordinary on-scour for a little way above it, yet a strong current on scouring its bed from above may carry on that scour to the up-stream edge of a raised flooring, there lifting up and carrying over the on-swept material. Or, if approaching a weir obliquely, it tends to down-sweep at one part, turning farther on into a strong uprise from the bottom.

With every foot it descends below the bed-level, the down-sweep appears, the more expended in ejecting material and opposing the in-fall from the outer zone, rapidly extending as the latter does in area with increasing depth, so that, at a certain depth, a down-sweep of a certain power cannot, beyond counterbalancing the in-fall, excavate a farther grain of bottom sand.

This limit will be sooner reached with coarse, heavy material than with fine and light. It would hence appear that material in large pieces, such as stones, &c., will resist ejection at a less depth than fine sand, and so on progressively upwards with heavier masses. Thus, with equal down-sweep force, stones, &c., of a weight in each piece which could not resist expulsion at 2 or 3 feet below the bed level, may withstand it if 15 or 20 feet lower, as it is reasonable to suppose that it really requires a greater force to eject a stone from the deep than from the shallow cavity.

The general point, however, is clear that, where stones are used for protection, they must, if not enormously massive, be placed much lower than solid masonry work, and that the lighter the fragments, the deeper they must be deposited. Roughly speaking, their cubic increase will indicate their increased resistance to movement by water, while the power of the latter over them will increase only as the square, i. e., the opposed surface.

Though the special scour on the down-stream side of a bridge is of a more general nature than the pier-scour on the up-stream side, yet, if the protective work against the latter be continued around the piers, it will guard against the former also; one general indication being to keep the surface *as low as possible*, and probably also sloping downwards from the pier or abutment side.

The down-stream scour also appears a more diffused and less intense action, so that boulders and stones of a size which would be expelled from the up-stream aspect of a pier may resist removal in the other locality. I have seen coloured stones placed for experiment at a pier cut-water, appear afterwards, some of them in and some beyond, the scour hollow below the bridge.

A fringing of boulders is, in fact, a common adjunct to masonry floorings on the down-stream side.

The greater safety against scour of a sloping as compared with a vertical obstacle is intelligible, when it is observed that, while the face of the latter may be attacked perpendicularly by a current setting against it, and the down-sweep will next act at its base, *a slope cannot be attacked by running water perpendicularly in all directions*; for, if so as regards the horizontal line, there is obliquity in the vertical.

This obliquity tends also to deflect the current upwards, and thus to increase the harmless up-swell at the expense of the dangerous down-sweep; and this latter, from the upper part of the slope, is received first on the lower part, so that if a slope be long enough in proportion to depth, there may be no active scour on the bed beyond its lower extremity.

The Indian Ghât, or slopingly stepped form of water-wall, is thus seen to possess an advantage over a vertical wall where a current sets against it, as each horizontal step surface takes the down-sweep from the vertical step-face above; but it can scarcely help the deflection upwards as a simple slope does.

It is believed that the foregoing analysis, by elucidating the nature and scope of the scour action at obstructions, and by thus defining the danger that is to be encountered, will afford aid in practically dealing with it.

Abstract of Observations and Experiments during 1872 on the movements of water after impingence, and on the scour action occurring at Bridges and other Obstructions in Rivers and Canals, by SURGEON-MAJOR J. P. STRATTON, M. D., Member, Bombay Branch, R. A. S., Political Agent, Bundelkhand, with an Introduction and Notes by T. LOGIN, Esq., C. E., F. R. S. E., and M. I. C. E., Superintending Engineer, Umballa, Punjab.

INTRODUCTION.

The motion of fluids is one of those subjects about which, perhaps, less is known in the present day than of almost any other branch of science; for the Select Committee of the British Association of 1869, in their memorial to Government speaking of it, say, "they found the present state of scientific knowledge to be so vague and imperfect, that it is in their judgment necessary to obtain, in the first instance, a complete series of experimental data;" and this was the opinion given by such men as Hawksley and Rankine.

Being a Member of this Committee, Dr. Stratton sent me the accompanying papers for perusal and remarks. The extended notes I have made will show the interest I have taken in the questions that gentleman has, I believe, been the first to raise.

What, perhaps, adds most to the value of these papers is that, at the time of Dr. Stratton writing them, he was not aware of the exact nature of the accidents which happened to the bridges over the Beas, Sutlej and Gaggur Rivers on the Line of the Sindhi, Punjab and Delhi Railway, when describing the action which takes place at cylindrical piers, and as his deductions so exactly coincide with what actually happened at the Beas Bridge, it gives additional force to his deductions.

Though I cannot say that I agree with him in all of them, yet it will be seen by my notes that my personal observations go far to support them, and by future experiments it is hoped that any little differences of opinion that may exist now will, before long, be set to rest.

The subject of impact of water on obstructions, treated as Dr. Stratton has done, is worthy the study of both the professional engineer and natural philosopher, and I have little doubt, if it be properly followed up, will lead to the solution of many vexed questions in hydraulics, whether they be in the construction of our artificial rivers, or spanning those of nature; therefore, the result cannot but be of vital importance in the present day to India.

T. LOGIN, F. R. S. E.,
Supdg. Engr., 2nd Circle, Punjab.

SECTION A.

SCOUR AT PIERS, AND OTHER OBSTRUCTIONS.

I.—Occasion of observations being noted.—The following paper contains an abstract of more extended notes of observation and experiment during the last monsoon [1872], which notes I have found it impossible, at present, to get fairly arranged and transcribed *in extenso* under my own supervision, during the constant movement and occupation of District work in the cold season.

The subject of *scour* came before me quite unexpectedly while superintending some works of particular construction.

The experiments I was able to make were merely of a rough-and-ready kind, and my leisure for observing and experimenting was limited to the morning and evening, when the growing interest of the matter gave an object to the ordinary walk or ride.

The results are here noted, subject, of course, to sufficient further investigation, while the inferences ventured on practical matters are submitted suggestively, rather than in any way conclusively, to the consideration of those better qualified than myself to judge.

In summarising, I have necessarily had to omit various details of observation and experiment, and of inference and suggestion, as well as of connected matters already on published record, the insertion of which would have farther illustrated the subject.

II.—Scour in unobstructed channels.—Running water is described to sweep or roll along with it sand or other fine material forming its bed, and when, at any place, it takes more onwards than it has brought there from up-stream, a *scour* or lowering of the bed at that place is produced.

With high velocity, some of the finer material is lifted from the bed, diffused through the water, rendering it turbid, and is, in this manner, transported by the current.

The action is greater the higher the velocity, and the finer and less cohesive the material.

The scouring and transporting force is farther described to be greater when the water is not already laden and turbid with material, and when it is moderately shallow, as compared [that is] with a very deep stream.

The above is in general terms the ordinary form of scour in a free channel, without obstructions necessitating the stream to pass around the side or beneath them.

III.—Scour at obstructions.—A continuous obstruction, like a weir right across a channel, presents no side passage to the current, but only an up-stream and a down-stream aspect, at the former of which there is not [*vide* Part XX] a tendency to the special scour action now to be considered, while at the latter, the effects of an over-fall in scooping out the bed at the foot are familiar.

Where local obstructions, either directly transverse, or oblique, exist to a direct movement of the current, which has then to pass them otherwise than by rising and running over them, special local scour is developed.

Thus, at bridges, embankments, &c., scoured-out hollows caused by floods have been observed of any depth down to 10, 20, 30 or 40 feet, or perhaps even more, below the ordinary bed-level in the immediate neighbourhood.

This has usually been referred to increased velocity; but occasionally also to eddies at the place.

The increased velocity is thus explained—

The bridge piers, &c., occupy part of the channel, and thus reduce the water-way at the spot; the water consequently is partially dammed up on the up-stream side; and, from this heading up or afflux, there is increased velocity between the piers or abutments.

The higher speed is accompanied by greater scour, and hence the extra depth scoured at such places.

The above explanation from increased velocity at bridge piers is not, however, quite free from difficulty.

Velocity is usually greatest about the middle of a stream, but it is found that the deepest scour is close to the piers, and not in the middle of the arch water-ways, in which line the unobstructed current naturally runs faster than the portions obstructed by the piers can manage to get round the cut-waters and along the sides.

Increased also as the velocity is by the "heading-up," and increased as the ordinary scour must be where that higher velocity operates, very high velocities are found in other places where the stream is unobstructed without such tremendous local effects as are produced at obstructions.

The greatest depth is moreover at the very cut-water stem, where the general current receives its first and principal check, and before it recovers its own, or gains from the afflux, an increased velocity, which it does between the piers, *i. e.*, a little way ahead of the point of deepest scour.

Farther, while the suggested causes are general across the channel, the worst scour effects are localised close to the piers, abutments and wing-walls.

I have seen no explanation of the action of *eddies*, to which scour is occasionally attributed, nor, taking the word in its ordinary sense, either of a whirl or of a backward flow, such as may be seen at the side of a rapid current, have I seen the special scour now under consideration produced by merely such movement of the water as distinguished from onward flow.

On the point of scour at bridges being, in general, referred simply to high velocity, ordinarily produced by contraction of water-way and afflux, I may here give the following extracts:—

[1].—From *Roorkee Treatise on Civil Engineering*, 2nd Edition, Volume II, 1871, pages 77 and 78—

"Now, as water flows by reason of the slope in a river's bed, if we know the velocities caused by certain slopes, we can calculate what amount of opening would allow the whole of the water of the above section to pass under a bridge at its mean velocity, and so avoid that heading-up of the stream which, if carried too far, causes a velocity destructive to the bed of the river, and so to the foundations of the piers of a bridge placed across it."

[2].—Also in page 79—

"If, therefore, the section of the river and its velocities can be accurately measured, the amount of water-way required for the bridge, so as not to cause too great an afflux whereby the normal velocity would be dangerously increased, can be easily ascertained."

[3].—From *Roorkee Professional Papers on Indian Engineering*, 2nd Series, Volume I, No. 4, April 1872—

Report of the Committee assembled at Simla in September 1871, on the design for the foundations of Punjab (State) Railway bridges.

Page 338 "***** while, in the event of the bed of the river getting scoured, the obstruction opposed to the current, when flowing in a direction paralld to the piers by the smaller cylinders, would be very greatly diminished."

[4]. Further on in same page—

"The design* is based on the necessity of arresting the onward motion of the material of which the beds of these rivers is composed, and which in times of flood partakes of a semi-fluid nature."

* For a flooring and curtain-walls to protect the pier foundations.

[5]. In page 330—

"The great obstruction which the unprotected cylinders create when laid bare by the scouring of the bed around them, is thus avoided"***** &c.

[6]. And again in same page—

"The larger the diameter of such cylinders, the greater the obstruction they present, and the greater the obstruction, the higher velocity of current will they create, and consequently, the greater scour will result; and thus the forces at work to undermine the pier are being generated in a continually increasing ratio."

Of the foregoing extracts, Nos. 3, 4 and 5 refer to the piers as respects liability to be denuded by independent scour of the river, while No. 6 deals with their own effect in increasing the scour.

As an instance of scour at bridges being occasionally referred to *eddies*, I may give the following extract:—

[7]. From *Professional Papers*, 1st Series, Vol. IV, No. 14,—February 1867.

Report on floods on the East Indian Railway.

Page 76 "*****it was formerly observed that the eddies by which the foundations of the bridges are generally damaged have been usually produced close to the upper faces of the bridges."

Occasional references of erosion in canals also to a like cause [eddies] might be similarly quoted, as, e. g., from *Professional Papers*, 1st Series, Vol. II, page 195.

IV.—Form of scour hollow at piers.—*Inner zone*.—*Outer zone*.—In large rivers, turbid from being laden with earthy matter, the form of the scour hollow cannot be seen during floods, and still less can the action be observed in progress.

Observation and experiment on a smaller scale, but in a clear current, with a bed of clean, coarse sand or small gravel has, however, thrown light on the subject.

The first point which unexpectedly attracted, and, indeed, compelled, my attention was the form of the scour excavation around the up-stream cut-water of a pier, which, in shape, resembled a rather bluntly pointed arch.

The scour hollow around this was in *two zones* of distinctly separate slope, the outer and upper slope being the gentler,† while the inner and deeper was abrupt and almost vertical. This arrangement gave a stepped appearance to the excavation, and the whole following the contour of the cut-water, irresistibly suggested the form and moulding of the wall around a Gothic window opening.

† In the observed instance with coarse bed material, the angle of the upper slope was about 30° from the horizontal.

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A section of the scour hollow, starting from the level of the bed up-stream, and traced downwards, would give, *firstly*, an incline as already described, which sometimes extended at the same angle to the brink of the next, and sometimes merged into a flatter step-like slope at the foot. The foregoing constituted the outer zone; *secondly*, the steep scarp-like slope, and the nearly level bottom of the inner zone; *finally*, the vertical surface of the pier.

Horizontally, the outline has already been mentioned, but, for piers generally, it may be described as resembling the letter U reversed, i. e., with the curve up-stream, embracing the cut-water, and the limbs applied to the pier sides, shallowing as they tail off, and sometimes broadening out so as to join on the down-stream aspect of the pier.

The deepest scour, and the most distinct midstep between the two slopes, are at the curve, and specially in the middle, or wherever the current impinges most directly.

After the curve, the midstep, or distinct margin of separation between the two zones or slopes, gradually fades out, although, as far as the scour hollow extends along the pier side, its inclination is greater the nearer it approaches to the pier, except at the very last, where it is flattened off just before it comes into actual contact with its surface.

V.—Visible scour action in inner zone.—The Gothic arch appearance of the excavation was first noticed after a flood without the producing action at the bottom being at once observed.

The water was still partially turbid, when, one day in looking at the curious outline, a few wreaths [as it were] of sand were seen to be repeatedly whisked up.

Natives, who then observed what I was watching, suggested that there must be some water-animal burrowing and throwing up the sand.

Subsequently, at a still clearer stage of the current, the ejective action was seen to be regular along the whole outer margin of the inner and deeper zone at the foot of the upper, outer and gentler slope.

The sand thus ejected upwards fell partly on the latter, and was partly whisked onwards by the current.

The natural circumstances favorable for observation were that the bed material was a clean, coarse sand, or small gravel, which permitted a considerable velocity without turbidity. It might be actively moved at the bottom, or even whisked up and carried along, but it had little tendency to remain suspended in the water.

Derived from disintegrated red granite or syenite, its variously coloured particles could often be individually followed with the eye for a little as they were swept along or otherwise moved at the bottom.

The artificial condition also of a contracted water-way helped to make scour well marked.

It is not supposed that the *result on the bottom* will be the same when that is composed of fine sand or other minutely divided material, but it is evident that the *movements of the current* from impinging on a pier, or other obstruction, must be similar whatever the bottom may be.

The difference of effect on the latter will probably be more one of degree than of kind.

The finer, lighter and less cohesive the particles of material, the more it will be disturbed and scoured out by an equal velocity of current, and the sooner will the uplifting, suspending and transporting stage supervene on that of mere sweeping along at the bottom.

Probably, too, separate zones and slopes will be the less defined and distinct.

The sooner also will the stage be reached in which the current, beyond ordinary sweeping and transporting, disturbs the bottom more, and hurries along still larger quantities of its bed material in a semi-liquid mass.

VI.—*Rationale of action in inner zone. Deflection and impingement*.—I here introduce the explanation which, after lengthened observation and experiment, gradually suggested itself, and was found applicable to the phenomena of scour at piers and in many other situations.

Water, on impinging on another body, acts, so far as its own physical constitution as a liquid permits, just as any other soft substance does. For example, when a leaden bullet strikes a hard object, its head spreads or splay out in all directions, and tends to turn back and re-curve upon itself, especially if the opposing surface is broader than its out-splay.

Similarly, moving water on coming against an obstacle spreads out.

At an obstruction, such as a pier cut-water, for instance, it swells up on the surface, pushes out to each side, and presses down to the bottom. [Mr. Login's Note, 1 L.]

The superficial uproll and swell are visible enough immediately around the cut-water, and are quite distinct from the general afflux, but they are soon checked by gravity and the onward flow of the stream, and are of little moment except as an indication of the existence, breadth and intensity of the down-sweep below, *which movement it is that works the scour mischief on the bottom at the pier base*. But if the bottom is too hard to yield to the down-sweep, the uprise and out-splay may appear intensified.

The lateral out-sweep may not be of much consequence between piers and abutments, but in some situations, as will afterwards appear, it is of importance.

The down-sweep working on the bed around the cut-water insinuates itself a little way at first between the latter and the sand, turns back or off from the pier surface, and finally curves up at the bottom of the current.

In this course it stirs about, sweeps back, and throws up the sand, which is then caught in the onward current overhead and carried on. Gaining thus a hollow below the onward stream, the down-sweep is less hampered by the latter than the up-swell is on the surface.

By this mode of operation, the down-sweep scours out or excavates the inner zone around the pier head, which hollow then shallows off along the sides.

As there are the three movements in it, viz., downwards, backwards and upwards, this scour action might be described by any of these terms, but probably *back-scour* would be as convenient a name as any to roughly distinguish this recoil action of a current on meeting an obstruction from ordinary scour, i. e., the simple *on-scour* of an unobstructed stream.

But as action identical therewith in nature is not always precisely backwards as regards the general direction of the main current, that name would not be so generally, and indeed, it would not be so scientifically, correct, as the term "*Impingement Scour*." This will appear more clearly further on.

VII. *Movements of water in inner zone*.—A float or a weed sub-merged somewhat below the surface, a little up-stream from the scour zones, may be seen on reaching the stem to be carried down to the bottom, swept back, and then thrown up at the ejection edge of the inner zone. If it has kept straight in the stem line, or rather the part-water*

* The part-water here meant is coincident with the cut-water stem line only when the current comes fair on; for, when it approaches obliquely from one side, the part-water is a little on that [same] side.

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line, it will come on again, and the movements will be repeated.

There is, however, a tendency to one side or other, and, if not thrown too much up, or laterally, to escape the inner zone action, it may sometimes be seen running the gauntlet of the movements in it all round the cut-water shoulder; the circular movement at the stem or part-water line where the recoil is direct gradually opening out* into an increasing spiral or cork-screw form, as it becomes more and more oblique, and finally ceases somewhere on the pier side, leaving then only the onward motion. [Note 2 L].

It is intelligible that, when the extremity of a body re-curves on itself without the outer circumference of the roll increasing, movement cannot continue without tending to issue laterally more or less in the line of the axis, turning first into an increasingly opening spiral.

As also the water in the inner zone is constantly changing and direct, onward progress is obstructed by the pier, a movement round the side is the necessary result.

I may mention some other experiments:—

A bulky body, slightly heavier than water, was attached by a fine line to a float just able to swim with the drag hanging suspended below at any desired depth as regulated by the length of line.

This was thrown in a little up-stream, and when close to the pier stem, and in the part-water line, the float was pulled down to the bottom by the drag, even when the suspending line was very short, showing that the down-sweep close to the pier-head acting on the submerged drag began *here* very shortly below the surface. In saying "very shortly," I should add the scale was small, but it means nearer the surface than the mid-depth of the current.

Further out from the pier, the connecting line required to be longer before the float was pulled below, indicating that *there* the down-sweep movement began only from a deeper level.

When tried at the *side*, a little distance from the part-water, the down-sweep was weaker and more modified by the onward movement of the current than in the medial line.

The difference of the commencing level of down-sweep in its inner and outer portions might be illustrated by a diagram showing the out-splay of a soft rod on impingement.

If lines were drawn to indicate the direction of its fibres before impingement, and then curved so as to show their course in the out-splay, it would be found that the out-splaying fibres, measured at a line on which, in their new or deflected direction, they impinged perpendicularly, were longest on the impinging surface itself, and were shortest a little behind this where the first out-swell began to appear on the previously straight outline of the rod.

This may help to explain what appears to be the fact, *viz.*, that the down-sweep is strongest close to the surface impinged on, and grows weaker in impinging force towards its outer border, at which the action of the whole breadth combines to eject what it has, perhaps, separately stirred up and swept back.

VIII.—*Production of outer zone.*—But sand will not of itself remain stable to form the side of a nearly perpendicular excavation. It will tumble in till it rests at its angle of repose.

This is precisely what occurs at the margin of the true scour excavation.

The sand falls in all around, forming an outer and upper slope of its own, distinct from, and gentler than, the inner and deeper ejection slope, and constituting thus an outer and shallower zone of depression around the inner and deeper zone of excavation.

Even after the down-sweep has scoured out as deeply and widely as it can, ejection is still brisk so long as the current is active. The ejection from the inner zone is fed by the in-fall of sand from the outer, and the latter zone again is being constantly replenished with sand swept by the stream along its general bed, and sliding down the outer slope on reaching its upper margin.

One might, perhaps, expect the sand to continue the in-fall slope at its angle of repose down to the very bottom of the scour excavation, but so long as the current is at all active, the sweep downwards, backwards, and then upwards, is sufficiently strong to maintain a steep side around a certain portion of the depth at bottom.

One can imagine that a powerful blast or jet directed perpendicularly from a pipe on sand, would make an excavation, the deepest part of which would be steep-sided, while the upper would spread out in a slope proportioned to the depth and to the particular character of the sand as to fineness, &c.

So it is in pier-scour, with coarse sand at all events, in which, indeed, the difference between the two slopes is so marked during activity of current, as strongly to distinguish the two zones, and to produce the midway stepped or terraced appearance in the general hollow.

While the current is brisk, the deep inner zone may represent a steep-sided excavation, cutting off with a sudden dip the lower part of the upper slope; but when the current and down-sweep grow feeble, the distinction between the two becomes less marked, the in-fall and on-sweep gradually overpower the out-throw and slowly fill up the deeper excavation, at first to a nearly uniform slope, and finally altogether to the level of the general bed.

IX.—*Movements of water in outer zone.*—To complete this brief outline of the movements in both zones, it may be noted that, in the outer zone, besides the impulse upwards and outwards from the inner and deeper hollow, and the dip from above of the onward stream, there is, close to the foot of the slope, and closely up its face, a feeble back movement, by which, although sand or other heavy material is not prevented sliding down, a light sunken weed may actually be slowly swept up the face of the slope.

There is also a lateral tendency in the outer zone, due partly to causes similar to those which induce a like movement in the inner zone.

The up-rush of water from the ejection edge of the latter, and the dip of the stream over head, have to be got rid of, and a course obliquely to the side and onward affords the only issue to the ever-incoming supply.

It is of practical import to notice that the onward current of the stream, although it may dip a little below the upper surface of the outer zone, does not rule within the scour hollow, in which an entirely different set of movements prevail, produced by that current impinging on, and being deflected by, the pier or other obstruction.

Again, in the different zones also, the movements differ as now described.

X.—*Progressive sand terraces.*—The feeble back movement, creeping up the outer slope, does not depend altogether on the up-rush from the inner zone, for where, in other parts of the bed, the sand lies in a terraced or rippled form, a similar faint movement can be detected on the down-stream slope.

This latter, even in sand ripples, is the more abrupt of the two slopes, and in the terraced form, it is the only decided slope observable, as the up-stream aspect is broad, flat and often so nearly horizontal, that an upward slope in the down-stream direction can scarcely be noticed on the terrace back or plateau.

There is not space within the limits of this summary to discuss the original formation and final obliteration of these sand terraces, which formed a very interesting subject of observation and for record in my extended notes.

These sand terraces are in constant progression down-stream, the front border or slope growing at the expense of the back or plateau, along which the sand is swept by the current till it reaches the brink of the slope, down which it slides to the bottom and there rests, being then speedily covered up by the next succeeding particles, the whole maintaining on the front border a particular slope or angle of repose. Terrace equally succeeds terrace while the stream is of uniform activity, and thus the general bed-level is maintained.

Excess of onward sweep at any part, as compared with the sand coming in from up-stream, would evidently lead to a lowering or scour-depression of the bed, and *vice versa*, an incoming excess over the onward outgoing would constitute a raising of the bed at that place, of which process a marked example will presently be given.

It is when the front slope of one of these advancing sand terraces reaches and takes the place of the upper margin of the outer zone that, for the time, this edge is most sharply defined, while the remains of the previous slope form the flatter step-like part mentioned as occasionally presented at the bottom of the outer zone slope.

When the slope of an advancing terrace reaches and merges into that of the outer zone, it cannot farther advance, as its lower part is being constantly eroded and falling in at the ejection brink of the inner zone.

The lateral extensions of such terraces may, however, pass on under the bridge.

XI.—*Scour pool filled up by advancing terrace.*—I have noticed a large scour-pool, 4 feet or more, deeper than the rest of the bed, and some 60 or 70 feet long, slowly filled up by a huge terrace, advancing at an average rate of about 3 feet a day, and levelling it up with the rest of the bed. [Note 3 L].

There was here no filling up by successive horizontal layers of silt deposited from suspension in the water.

Whatever was thus deposited while the stream was turbid, was a mere sprinkling.

The deep pool took three weeks thus to fill up. The terrace advanced, from the first, at the level it was to maintain throughout. It began in the shallowest part of the scour depression up-stream, where the hard bottom had prevented deeper erosion, and went steadily on till it was 4 feet in vertical thickness in the deepest part of the pool. Its plateau was being continually swept to add to its onward slope. But small terraces were as constantly advancing along its back, keeping up its level, and maintaining its brink clear and defined. The slope was an angle of about 30 degrees with the horizontal.

This arrangement might give a plane of fracture corresponding with the slope if material so deposited should become consolidated into stone.

In all the matters of observation or experiment, whether with regard to these sand-terrace movements, or to scour action, mentioned in these paras., it will be understood that the coarse gravelly sand already described was the bed material.

With a very high velocity of current, these terraces may be more or less obliterated in a confused hurrying along of a semi-liquid mass of sand and water at the bottom.

This result will doubtless be arrived at with a lower velocity when the sand is finer.

And when the bottom is composed of clay and mud, such terraces are probably not formed at all, or, at the utmost, are not with any approach to such distinctness.

XII.—*Inner zone of scour out-throw—Outer zone of in-fall.*—It will have been seen that the inner zone is the primary and real zone of scour excavation, containing the active down-sweep, the back turn, and the up-throw.

The outer zone is merely a secondary one of depression, tending to fill in the real zone of excavation by the in-fall of sand around the steep ejection edge, and being itself replenished by the on-sweep of sand from the general bed up-stream.

The distinction is of practical importance as will afterwards appear.

XIII.—*Scour at oblique obstructions.*—So far the action has been spoken of as more or less directly backward, but when a current impinges obliquely, as on the shoulder of a cut-water or abutment, or on a wing-wall leading to the contracted water-way of a bridge, or on the concavity of a bend in the bank of a winding stream, the action does not cease, though blended with, and modified by, the onward current and its on-scour.

When the impingement of the current is oblique, so also are its subsequent movements, and while it loses thus in intensity, the loss seems to be partly compensated by the greater co-operation of the onward flow.

At the part-water line of a stream against a pier, the action is most directly backward and intense, but unless the ejection of sand is high enough, or sufficiently to one side to be caught by the onward current, the same particles fall in again, only to be again ejected, until, on some occasion, they are thrown high enough, or gradually get sufficient siding to enable them to be carried on.

When the action is oblique, the ejected material is thus much more readily carried on at once, and the sharp ejection edge between the two zones is often not apparent, being scoured or planed off by the onward movement of the current sweeping through the excavation, which extends more or less longitudinally, though obliquely, in the stream-line. Into this the current dips more than into the short, abrupt, transverse hollow, which is formed at a pier stem or other direct obstacle. The movements in oblique impingement scour are those already detailed as occurring at the shoulders of a pier head, and may be described as down-sweep, off-turn, and up-sweep, all more or less obliquely blended with an onward motion, giving the whole a spiral character. There is also surface up-roll.

As the sharp ejection brink is often scoured off in oblique action, so also the distinct and almost vertical up-throw of the sand is liable, in it, to be replaced by an oblique sweeping or brushing motion, onwards and upwards.

XIV.—*Effect on concavity of bend in bank of winding river.*—The changes in position of the heads of a tortuous stream have, I believe, been explained by Mr. T. Logan in a paper read at Home, though whether as the result of actual investigation, or as a suggested elucidation, I am not sure, in the following way:—That each bend, meandering freely through a wide expanse of sandy channel, tends to progress as a whole in the down-stream direction of the general channel.

The foregoing analysis of impingement scour shows how the stream works, deepening and undermining along all the concave curves of its bank.

This would tend to cause each bend to extend more and more laterally, as well as to progress down-stream as regards the line of the general channel; but in the former direction, the tendency is checked, after a certain time, by the current finding inclines less favourable for its progress, while in the latter there is no such check.

SECTION B.

DISTINCTIVE CHARACTER AND FARTHER ILLUSTRATIONS OF SCOUR AT OBSTRUCTIONS.

XV.—*Distinction between impingement and friction.*—In seeking the characters most distinctive respectively

* *Impingement* suggests rather the movement up to impact, which latter again implies the actual touch, without taking in the consequent movements with which the present subject is largely concerned.
The word *impaction*, similar in formation to friction, would, perhaps, best include the sequence, and correspond distinctively with friction.

of ordinary free scour, and of scour at obstructions, they seem to be *friction and impingement*, or *impaction*.*

Friction may be mere impingement of the roughnesses of the side of a moving body, against those of the body along which it slides, rolls or moves rubbingly.

Friction may thus be impingement of particles, or particulate impingement laterally of a moving body; but practically it differs from impingement of the whole thickness of the moving body, or corporate impingement capitally, *i. e.*, head-first, or "end-on."

In friction it is merely the side surface of the moving body which directly receives the check, especially in the case of a liquid, the upper layers of which will run ahead of the lower ones when these are retarded by friction [Note 4 L], whereas, in impingement, the whole moving body is directly checked.

In friction the check is, as regards the entire body, merely partial, and is parallel with its line of movement; while in direct impingement it is complete and transversely opposed, and in oblique impingement it is more or less so.

In the first the current is merely chafed or chafes on the side as it proceeds; in the other it goes end-on and is brought to a stand unless it can overcome the obstacle, or change its own direction.

Friction is a more diffused, and impingement a more concentrated, action.

There is something of the difference between the side graze of a shot and its effect when it strikes a surface at right angles.

A river may run for years for a number of miles with a fall of several feet in that distance without its friction sensibly altering its general bed level on the whole, though at times and places the current may scour a little, or deposit a little.—[Note 5 L.]

But if a fall of some feet were introduced at any one point, the impingement of the falling water would speedily scoop out a deep pool, even though the bottom were of hard material.

A certain amount of the force of the moving body is doubtless lost in impingement, or is taken by the body impinged on; and, under these circumstances, when movement continues in a different direction, it is only the balance of the original force which is available.

But the effects of moving water after impingement show that this balance may still be considerable, and that, *where acting in its new direction again impingently, and not frictionally*, it still exhibits some degree of the concentrated character described.

Now, the down-sweep from obstruction at a pier acts impingently on the bed, and hence seemingly the strong local effect completed by the back-sweep and up-rush into which the downward movement turns.—[Note 6 L.]

The lateral out-sweep from an obstruction also acts impingently on any opposing body within reach, as will elsewhere be noticed.

There is often a difference in some practical respects between a momentary impulse or application of force of great intensity, and a long-continued impulse of more moderate character, though at times they lead to similar results: as for instance, when a heavy body is lifted at once by direct force, or when the same mass is raised more slowly by a gentler force acting longer, or through a greater space, by means of a lever or a pulley.

For illustration of practical difference, the communication between the forcing pump and the interior of a hydraulic press may be supposed to be a long tortuous pipe, instead of a short straight one.

A slowly-forced column of water from the pump may be rendered something less effective by friction and change of direction, but it will, in the main, still communicate the force finally to the interior of the press.

If it were possible, however, to concentrate in one momentary impulse the force of many strokes of the pump, the result of the length and changes of direction of the communicating pipe would be that it would almost certainly be burst by the sudden impulse ere the latter could reach the water in the interior of the press.

With a short, straight pipe the impulse might reach the interior of the press and be relieved by the yielding of the piston without fracture occurring.

A momentary impulse of concentrated energy may thus expend itself violently but speedily on the first obstructions, while a quieter, but more sustained impulse, especially in so flexibly mobile an element as water, pressing equally in all directions, may reach more distant objects in spite of diversions of direction by the way.

As will appear in a subsequent Part [XXVII], a good deal of the persistent penetration or boring effect of current water, once diverted in a down-sweep at an obstruction, or simply descending without such deflection as at a fall, and gaining entrance under floorings, &c., appears to be due to the continuousness of the push by the current from behind, and is not produced solely by the vertical head of water immediately above, or the mere velocity or force of the first impact.

XVI.—*Varieties and combinations of impingement.*—Impingement may be traced out under various conditions. Thus, it may be described as primary, secondary or even tertiary, perpendicular or horizontal, or with degrees of obliquity as regards either main direction, immediate or mediate, and either rectangular or oblique to the plane of impingement.

Primary impingement is that in which a current meets with an obstruction to continuing in the direction which, under the influence of gravitation, it is pursuing, as when a stream comes against a pier, or water from a height falls on the ground.

Secondary is when, after being deflected once, the diverted current meets an obstruction in its new line of movement,—as when the already deflected down-sweep at a pier impinges on the bottom,—or the similarly diverted out-sweep from a bulky obstruction in a narrow channel plays on the banks.

A *tertiary* form may be when that secondary and lateral impingement strikes the bank with sufficient force to be again deflected and to produce a third impingement on the bottom at the base of the bank. It is, of course, not here implied that the water, in being thus successively deflected, takes the several turns angularly. It moves rather in curves. It will be intelligible that primary impingement is the strongest, and tertiary the weakest in its effects.

Perpendicular and horizontal impingement are respectively illustrated at the foot of a water-fall and the pier of a bridge, though the horizontal direction is, of course, only approximately attained, as water must have some fall or incline to make it run.

Perpendicular is naturally stronger than horizontal action, from the greater "head" from which the descent takes place.

Immediate is when the moving water itself impinges directly on the obstacle, as on a rock at the foot of a fall, off which the water flows away at once.

Mediate is when the impact is softened by a cushion of water, not partaking of the same movement, as for example, when retained in a depressed basin at the foot of a fall.

Obviously, immediate is stronger than mediate action.

Impingement at right angles to the surface impinged on occurs in the horizontal plane when a stream comes "fair on" a transverse obstruction as at the very stem line of a pier head, while it is *oblique* at the cut-water *shoulder*; or rather, at the stem, as also at a square-headed obstruction, the impingement of a direct stream is *fully* rectangular, being so as regards a line drawn across the direction of the stream both in the vertical and horizontal planes, while at the pier shoulder it is oblique to the horizontal cross-line though rectangular still to the vertical.

In a vertical plane, a difference as to directness or obliquity similarly occurs at the foot, respectively, of a perpendicular fall, and of a sloping rapid.

Naturally, impingence at a right angle is more active than when oblique, and more so when rectangular in all directions than when so only in the one plane and oblique in the other.

There may be various combinations of the above forms.

The difference in direction between full impingement and mere friction of a body being an angle of 90 degrees, any mixture or combination of the two may be found within that limit. At 45 degrees both actions might be thought equally blended. Practically, as will afterwards appear, it is of some importance to regulate this point as to whether, under the circumstances of each case, it is better to let water reach a particular spot impingently or frictionally.

In an instance of the most effective action of all, *viz.*, that at the foot of a cascade, [high enough for the water to fall perpendicularly at the foot, but not too high in relation to its volume] where there is a horizontal surface, but no hollow at the bottom retaining a cushion of water, the impingement is primary, perpendicular in descent, immediate, and at right angles to the surface impinged on.

But generally it soon scoops out, even in rock, a hollow which retains water, and the latter somewhat breaks the fall, diffuses its effect, and thus dulls the impingement.

On reaching the bottom it first wears it away by direct impingement.

The water splays out on all four sides, and as a hollow is formed by the first action, the out-sweep acts with a secondary impingement on the sides of that hollow, wearing them away and widening it.

Backwards, this effect of the out-sweep tends to undermine the cliff over which the stream falls, and it gradually tumbles down in fragments, so that water-falls tend to retrograde.

Laterally, the out-sweep becomes weaker as it proceeds farther, and the hollow thus shallows off in those directions, as it does similarly also in front.

Under the conditions then produced, the impingement would become mediate from falling on a cushion or buffer of water.

There may be obliquely falling impingement, either immediate or mediate, as where the water has not fallen from a sufficient height to become perpendicular, but is still affected by the curve given by its velocity before reaching the brink, or at the foot of a steep incline not sufficiently near the perpendicular for the water to fall clear of it.

The scouring action at such places is strong at the foot, though, as is quite intelligible without separate discussion, it is, in proportion to its obliquity, less violent and more diffused onwards than in impingement at a fully perpendicular fall.

On a rock or pier-head horizontal impingement may be said practically to produce no effect, this being a great difference from the result of the perpendicular movement, which latter force is well illustrated by the Latin phrase that "a drop often falling hollows out a stone."

Water thus falling freely through the accelerating attraction of gravity is naturally more effective than a deflected current descending merely because checked in front and pushed on by the stream behind, but able to progress in its downward course below the bed level only by pushing on, displacing and forcing to rise again elsewhere the other water and material ahead of it.

Horizontal impingement, when it occurs on a soft friable body like an earthen bank, &c. does, however, produce marked effects, which, with equal character of bank material, are greater or less according as the impingement is immediate or mediate, and rectangular or oblique.

The current of an inlet entering a canal at right angles is known to erode the bank opposite its entrance.

If the canal be otherwise empty, the action will be immediate and stronger, while if the canal be already fairly full of water, it will be mediate and weaker.

Similarly, a feeder stream entering a river at a considerable angle tends to communicate its own motion and thrust the main current against the opposite bank, and thus erode it.

And in a concave curve of a river bank, the set of the single current against it erodes by primary [horizontal, immediate, and oblique] impingement, besides the farther effects of secondary action on the bottom at the base of the bank.

Taking the scale already outlined, the strongest action would thus be that from a free fall, and which is primary and truly perpendicular or vertical in itself, and is immediate and fully rectangular or perpendicular to the plane of impingement in all four directions.

The weakest—that which derived from a current horizontal and oblique to the plane of primary impingement—is secondary and also oblique to the plane of its own incidence, and is mediate, or deadened and diffused by a cushion of comparatively quiet water.

But practically, a large proportion of engineering difficulties is connected with *secondary* impingement, the nature and mode of action of which being less apparent, have remained longer obscure than in the case of primary impingement, as at the foot of a water-fall, the effects of which, even though the action may not have been analysed or distinguished from friction, are evident, and are, therefore, the more easily foreseen and guarded against.

XVII.—Impingement of water on water.—When observation first suggested to the writer a recoil or deflection of water through impinging on water [and more especially even when the latter body is moving in the same direction, though more slowly than the impinging current], he hesitated at entertaining the idea.

Yet farther observation and experiment, and the collation of separately recorded facts regarding water action in canals and rivers, lead to the conclusion that such really takes place, and that few actions are more important to be understood in canal works than this recoil or deflection of water from water.

The writer first noticed it on the down-stream aspect of a small-bridge with contracted water-way, the rushing current from which dashed into the wider and slower moving mass of water a little after leaving the openings. There it curled up and back in a foaming, roaring breaker. At the sides there was on the surface a distinct, though more gentle, back-flow or eddy. Underneath a deep pool was scoured out, the filling up of which by an advancing terrace has already been described.

There were thus visible on the surface in three directions the splaying-out movements of impingement, and the effect on the bottom afforded evidence of the action in the fourth.

As on the surface, the water in the up-swell and re-curving breaker at any moment is in the next merging into the onward current farther ahead, being replaced in the same breaker-form by the succeeding current water; so, doubtless also at the bottom, the down-sweep may first curve back a little, but the water in it has similarly soon to turn to an onward under-sweep or bottom scour, which carries on the sand stirred up by the down-sweep and farther on scours the bed by direct action.

The whole of this takes place at a deeper level than that of the general bed around, or, possibly, than the original current would have reached in the way of ordinary scour had its velocity been maintained, and if part of its volume and force had not been diverted to a lower level by the obstruction of the slower moving water into which it dashed impingently.

Just at the issue from the bridge, the archway current could not scour beyond a certain shallow depth, as it presently encountered rock. Over this it carried its own high velocity, and the point of collision where the breaker rose was a little farther on where the rock had sunk away. At the farther end of the scour pool the rock was out of reach, and the rising slope of that end of the pool was of the ordinary sand and gravel.

While watching the current, an apparent alternation of activity and lull in the noise of the rushing foaming water caught my ear.

So regular was it that, for a time, I could not be sure but that it was only imaginary and due really to the pulsation of the arteries in one's own head become perceptible while attention was being strained.

But the eye showed that the quasi pulsating alternations of energy and comparative rest were real. They could be seen distinctly and steadily in the form and position of the upcurling breaker. Subsequently, in almost every kind of water movement or action observed, the same curious alternation could more or less be traced.

XVIII.—*Impingement action in canals.*—The present analysis of impingement action may be tested by applying it to known facts in canal and bridge experience.

One may pass over briefly the evident results of primary impingement on the bottom of falls, and the *immediate* foot of rapids.

At natural [*i. e.*, artificially unprotected] falls the most noticeable result is deepening of the bed at the foot and retrogression of the fall through the cliff being eroded and undermined at its base.

It may be said that the difference between falls, rapids, and inclines scarcely amounting to rapids, is not one of kind, but rather of degree, in receding more and more from vertical impingement.

It is interesting to observe that similarly, the results differ only in degree and not in kind.

Early experience on the Eastern Jumna Canal before its levels were regulated showed in portions with excessive slope in relation to the nature of the bed, that scour began at the lower extremity of such inclines, and retrograded, deepening the bed and eventually creating actual rapids, which increased in power as they cut backwards and became more abrupt.

As regards primary falling or vertical impingement of the current on the more level bed at the foot of the slope, it must in such cases be so oblique as to be insignificant.

Most of the scour is probably due to the secondary impingement of the more rapid incline current, deflected in its primary impingement on the slower water at the foot.

The down-sweep erodes the *toe* or extremity of the slope, and reduces it more or less nearly to the flatter level ahead. The *toe* is thus constantly retrograding, while naturally also the slope is becoming more abrupt as it is thus shortened, and so this retrogression of level tends to continue with increasing rapidity till brought up by some bar of rock where an actual fall may be constituted.

It is, I believe, stated that the *regimen* of a river is affected mostly by the conditions existing at its mouth, or at the lower extremity of any portion of its channel having a distinctly independent character, and that it thence extends up-stream. I have no detailed authority at hand to refer to at present, but I notice the point from its seeming connection with the action just mentioned and presently to be farther described.

Retrogression of bed-level may naturally be expected rather when the extra rapidity of the upper part of the current is originated by extra slope in that part of the channel, *i. e.*, by difference of channel-bed incline. The ultimate dependence of water motion on surface incline is not here questioned.

When the superior velocity of the upper portion is due simply to heading-up, or to extra flood entry up-stream, *i. e.*, to difference of stream-surface incline, there may be a pool scoured out, but I apprehend there will be less tendency for that pool to work backwards.

It might, indeed, do so if the current were to prolong the pool down-stream far enough to make it open into the channel without an ascending slope, and thus to constitute it practically a deeper part of the proper current channel, and not a mere local pool which does not really increase the effective water-way any more than is done by the wedge-shaped space on the up-stream side of a weir, and below its crest.

Cutting through the forward slope of a pool would resemble breaking down a submerged weir; the space then would become available for flow down to the level opened out, a difference of bed incline would be established at the upper end of the quondam pool, and retrogression might go on as in the other case.

It is known from experience that water *not* falling into a canal, but entering in horizontally, or at least on the canal's own plane of inclination, as when delivered onward from the foot of an ogee fall, or from the foot of a rapid, produces a special scour on the bed and sides of the canal *for some way beyond the foot*.

The water, though not falling *on* the canal bed, comes *into* the channel with some portion of the velocity or "way on it" which its previous descent had imparted.

Its velocity is thus in excess of that which can be maintained on the gentler slope of the canal bed.

The more rapid current dashes into the slower moving water ahead.

Impingement action and its consequences are established.

There is a down-sweep which impinges secondarily on the bed and cuts it up, and a lateral out-sweep which similarly works on the sides; while on the surface, there is an up-rising wave, or even a breaker, if the difference of velocity be great enough.

The action proceeds with lessening force far enough along the canal for the extra velocity of the entering current to be dissipated, after which the canal flow continues at the rate due to its own inclination, &c.

It is evident that [as has been practically observed at canals] the *previous* velocity is much more effectually got rid of by a fall than by a rapid, though, doubtless, greater strength of work is needed, concentrated in a small space at the fall foot than what has to be spread out over a larger area at a rapid.

The known use of a hollow basin or cistern at the foot of a fall, below the level of the canal bed ahead, is now more fully explained by this analysis.

Without this hollow retaining a cushion of water, the cascade would practically act with *immediate* impingement, needing a much stronger floor to withstand its fall. This point was, of course, well known before.

Then the out-splay would act, not only on the sides and rear of the fall all of which would, doubtless, be of masonry, *but it would act also freely onward into the canal channel*.

This onward splay would have immense velocity, and would impinge with corresponding force on the slower water in the canal. Down-sweep and lateral out-sweep would thus be established in the canal itself with such force as to destroy the bed and sides, unless strongly protected by masonry for a considerable distance onwards.

But with a sunken basin, provided it be large enough, while the bottom receives the primary impingement mediate, the sides below the canal bed-level receive the secondary impingement, not only in rear and laterally, *but also in the onward or canal direction*. Thus the water may enter the canal with little remains of its previous velocity, and more nearly at the rate due simply to the height in the basin over the height of the water in the canal in front.

The perfection of the plan would be, if by the form or arrangements of a mouth-channel [which could not be discussed within the limits of this summary], the water could be delivered into the ordinary bed of the canal simply at the velocity which would there be uniformly continued.

The larger the sunken reservoir or chamber, the better it would facilitate that result, and act somewhat also as a *moderator* in the way a lake entered by a flooded river moderates the flood for the issuing river below.

Increasing the size of the basin would necessarily have its practical limits in expense and use, &c., but to some extent there would be a counterbalancing economy in floorings and side-walls beyond it, as a large basin would dispose of nearly the whole of the secondary, as well as the primary impingement, the former of which action necessitates these protective works to be continued further on when the basin is smaller.

A fall, unless of considerable height, can scarcely impinge quite perpendicularly. There is a slight onward obliquity, and in the recoil there is a corresponding onward deflection.

The recoil wave or breaker, which would rise equally around the whole circuit of a truly vertical fall, rises therefore chiefly *ahead* of the point of incidence, and it would seem advisable to have the receiving basin large enough in the onward direction for that wave to be well within its area.

Otherwise, almost equally expensive works may be needed in flooring of reverse slope, and in side-walls, &c., further on. For, as I have frequently noticed, where surface agitation is seen, bottom disturbance may be inferred. If the whole depth of water partakes of the movement of which the surface agitation is a result, then [more or less] equal violence below may be supposed. If, however, the movement is only in the more superficial layers of water, with a mass of comparatively quiet water beneath, then disturbance at the bottom, though some may still be expected, will naturally be much weaker, the movements on the surface affecting the bottom only mediate through the cushion of quieter water below. [Note 7 L.]

XIX.—*Impingement of water on air. Gratings at canal falls.*—In relation to impingent action, the beneficial effect of gratings at canal falls may be examined by aid of the present analysis.

Thus, it is said, they firstly check the impulse from above and give the water a new and lower starting-point from which to begin gaining velocity.

Also that they serve to break up the massive body of falling water into many smaller streaks intermingled with air, and that in this way the water is more spread out and falls, therefore, with less concentrated intensity of force on each equal area at bottom.

That second effect merits study.

A falling body tends, under the influence of gravity, to accelerate its pace during every second of its fall.

In vacuum it might do so without check. But in air it has to overcome the resistance of that fluid, which is in proportion to the impinging surface, but increases as the square of the velocity.

A bulky body, like a sphere or cube, which has considerable mass or weight in proportion to its surface exposed to resistance, has such momentum in falling that it is *comparatively* little retarded by the resistance of the air.

But if the thick massive body be beaten out into a broad thin plate, and be made to descend, not edgewise, but on the flat, it will encounter on its increased surface such increased resistance from the air in proportion to its own mass or weight [which will be merely the same as before] that practically it will fall at a much slower rate.

The slowness of descent of a parachute, and even ascent in the case of a paper kite, catching the wind obliquely, are known facts.

But a liquid like water is liable to have its body, as it were, beaten out, and thus horizontally extended by its own impingement on air.

It is a familiar fact that a small body of a water falling over a cliff, high in proportion to the volume of the stream, is apt to be dissipated *as a body* before arriving at the bottom, which it then reaches merely in the form of a widely-spread shower.

Here, then, is a marked result on water, even from impingement merely on air, so that deflection or other movement and its consequences from impingement on other water, need be no matter of surprise.

The falling sheet or column first grows taperingly thinner as the central parts fall more rapidly than the surface layers exposed to the resistance of the air. Finally, the falling water loses continuity and breaks into drops which do not reach the bottom at a narrow point, but descend in a widely dispersed shower.

Gratings at a canal fall seem thus to produce some of the effects which air would cause if the fall were from an extreme height. [Note 8 L.]

XX.—*Conditions at continuous obstructions, weirs, &c.*—A gap in the subject would be left if the effects of continuous obstructions like weirs right across a channel, were not adverted to.

The action at the down-stream side will be noticed farther on.

On the up-stream aspect, under what seem to be the most common circumstances, silt is deposited in the channel, while under others it is not.

The silting effect is what I have chiefly seen, and this part was first written from that observation, and from finding mention of silt at Madras anicuts.

Thus, at the Koomrari and Bhurur streams near Nowgong, a causeway raised about two feet above the ordinary bed-level has caused silting on the up-stream side flush with the roadway, except in the deep-stream line, where there are small culvert openings at the piers and abutments of which the scour is strong.

The floods which rise 6 or 8 feet over the causeways appear to have, or at any rate they leave, no scouring effect against the up-stream border when they come *fair on*; the only action of that kind being where a side drain or nullah enters the channel close above the causeway, and its oblique or cross current tends to scour along the edge. Troublesome results therefrom are, however, easily prevented by a rough stone slope or step being sunk in the sand below the edge-level. The side current then scours down on this, and no more.

Whatever the condition *during* floods, the silting up as just described is found on their subsidence, and as the causeways are made of loose boulders resting in one case merely on sand, and set only a few feet deep, it would appear that any disturbance of the sand below the causeway level cannot exceed a few inches, for, if there was deeper action, the causeways could scarcely escape injury as they do. Yet the velocity is not small, for at times when the current has been low enough to go wholly through the culvert openings, I have measured a rate of six feet per second, while in floods it is much higher.

At the Morar River near Gwalior, a weir 19 feet high caused a silting of 14 feet in depth before certain sluices that had been kept closed for two or three years were opened again. These now keep open a narrow channel to them scoured through the silt, and seem to prevent further accumulation in the general width of the channel.

But experience on canals shows that a weir or bar a few feet high, placed on the crest of a fall, *does not cause silting up*.

Such bars were placed at certain falls on the Ganges Canal to check the velocity of approach, which tended to cut up the channel a little above the falls; and they succeeded in preventing or remedying this scour without inducing silt above the canal bed proper. [See *Roorkee Professional Papers*, 1st Series, Vol. I, page 38.]

The movement of the deep water on the up-stream aspect of a weir may be traced by a body just heavy enough to sink.

It is swept slowly along the bottom till near the weir, and then it rises and goes over in the fall.

Under certain circumstances, this movement of the water below the weir-level is active enough to raise and carry over it all the material brought on by the current, thus preventing silt, while under other circumstances it is not strong enough to do so, and silt accumulates.

Coarse sand and gravel which, in the free channel are merely swept along the bottom by velocities which raise and carry fine sand and clay in suspension, will doubtless tend

more to silt at weirs than the latter material, especially as the deep water in taking its upward turn at the weir face, whatever substance it may lift that is enveloped in it, from such body being on or above the general surface of the bottom, has not the same tendency to cut into, scoop out and throw up material from below that general surface, which the down-sweep at piers has.

It may be supposed that, with greater head and velocity above a weir-level, as compared with its height, the stronger will be the movement below it; and that the non-silting at a bar 4 or 5 feet high, above an *un*-widened canal fall, may be accounted for by the proportionate relations between the bar height, the current and the bed material.

At the Morar Weir, on the other hand, the channel is about double the width it has a little higher up; and the current being thus spread out, is slower and shallower above the weir-level than if the channel were not thus expanded. With this gentler current the movement at bottom seems to be so much reduced as to allow silt to accumulate up to within some 5 feet of the weir crest, above which level again the floods may rise as much more.

But at the Koomrari and Bhurur Causeways, there is no widening out of the channel, and yet the floods leave the bed silted up as described, the material being coarse gravelly sand.

As regards the object of this paper, however, it suffices to notice that, seemingly from the want of lateral or inferior issue, there does not appear to be at the up-stream base of continuous obstructions a tendency to the peculiar down-digging scour found at obstacles, such as piers, &c., which, after impeding a current, next allow it to pass by their side.

But if, from imperfect construction, or want of repair, a weir lets water continuously pass in any considerable quantity beneath or through it, there seem, from experiments on a small scale, to be movements set up in the water at the up-stream face which do maintain a hollow along it, even though silt is in progress immediately higher up. [Note 9 L.]

If also a current does not come *fair-on* at a weir, whether from obliquity in part of the stream, or in the bank, or from side contraction of channel just before or at the weir, or from other cause,—oblique down-sweep seems to be favored, ending farther on in a strong rise from the very bottom up to the overfall. If the obliquity proceeds from both sides, the uprise at the meeting may be of boiling-up intensity.

SECTION C.

PRODUCING CONDITIONS AND THEIR EFFECTS.

XXI.—*Producing conditions of scour at piers.*—The producing conditions on which the depth and breadth of the scour hollow at piers, &c., depend, appear to be several in number, such as [1] the velocity, and [2] depth of current; the form of pier as to [3] the obtuseness of its cut-water, and [4] its transverse width; [5], the fineness and looseness of the bed material; and possibly also on [6] the comparative freedom of the stream from being previously laden with earthy matter.

With increase of these conditions, the scour excavation may, under certain limits and reservations of mutual proportion in the case of some of them, be expected to increase, and *vice versa*.

Perhaps one might say that, while the two first, *viz.*, velocity and depth of current proper, supply the intensity and amount of the original moving force, the two next, *viz.*, the bluntness of cut-water and transverse width of pier, affect the character and amount of the deflection of that force which causes the peculiar scour; and that of the two last, the fineness and looseness of bed material, regulate the effect which that diverted force can produce thereon, and that, finally, the comparative freedom from previous admixture of this material with the current influences its power of acting on the fresh material it encounters at the pier base.

It is not possible to discuss separately and completely within the limits of this abstract the share of each of these conditions in the final result, or the modifications thereof by variations in the mutual proportions of the several producing elements.

In fact, precision on these points has yet to be experimentally attained, whatever general approximations may now be possible.

There are probably certain mutual proportions which are the most effective for scour, and any departure from these may lessen the effect. Thus an increase of one of the elements beyond its best proportion implies a disproportionate deficiency of some of the others, and the result may possibly be impairment of joint result, notwithstanding increase of one of them.

It is not probable that all these have an equal share in the conjoint effect, or that each acts with indiscriminate equality on the several parts or proportions of pier scour, such as the depth and breadth of its separate zones; or that variation in one producing condition, such as doubling or halving it, even within the limits of its best proportion, will affect to the same extent [*i. e.*, double or halve] that result which is the joint product of several.

Regarding the general effect of [1] *velocity*, and [5] *fineness and incohesion of bed material*, there can be no doubt.

Of the effect of the [4] *transverse width of pier*, and the [3] *bluntness of cut-water* form, within certain proportionate relations to current, there probably will be none, when,

after a few experiments, this scour is recognised to be a purely topical action from impingement, strictly confined to the immediate border of the pier* or obstruction, not produced simply or directly by the high velocity of the current, and not, therefore, operating in other places where that, though equally at work, is so alone, as in the rest of the channel width, or arch water-way.

* Of course there is usually a shallowing prolongation of the scour hollow for some little way beyond the piers on the down-stream side, but the special scouring work is done at the up-stream border, and to a lessening extent along the shoulders and sides of the pier.

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Being, in fact, generated jointly by the current, and by the obstruction thereto, it cannot be produced by the current alone, although the velocity of the latter may be high, and being so, will cause correspondingly active on-scour of the ordinary kind such as occurs where there is no obstruction.

The subject will, however, sufficiently occupy a separate Part. I have here spoken only of piers, &c., of ordinary dimensions, and not of elongated obstructions, such as spurs with a channel at one end, or detached break-waters with channels at both; the proportions of current to which usually suffice only to scour at and near the free extremities, and may even permit accumulation of silt at the landward end and middle, respectively.

Though [6] *clearness*, or *freedom from earthy admixture*, may possibly have less influence in this than it is described to have in ordinary on-scour, yet it seems probable that, to some extent, turbidity, or an already laden condition of the water, will operate similarly here also in dulling or hampering the intensity of action.

There remains one condition, *viz.*, [2] *depth of current*, which I have classed from all I have been able to observe as increasing pier-scour within at least the limits of the small scale that has come under my own notice, and, if I do not judge incorrectly, within those also of the most common proportions of masonry piers and ordinary rivers.

Within the ordinary or average conditions in view are not meant to be included the cases of such exceptionally narrow piers as the iron screw-piles on the Bombay and Baroda Railway, or such excessively deep streams as the Jumna when in flood at Allahabad.

The above view as to depth appears to differ from what has been already mentioned from the experience† of a practical observer, as to increased depth of a current diminishing its scouring and transporting energy.

† See pamphlet by Mr. T. Login, C. E., F. R. S. E., on a method of protecting foundations, Umballa, 1872.

There is not room here to discuss the difference in all its details, but it may be remarked that the opinion quoted has been based chiefly on observation of, and refers primarily to, simple onward scour and transporting capacity from unobstructed high velocity; and has been applied to scour at piers under the original view of the action at them being of the same nature.

My impression at present is that [increasing] depth of current primarily and more directly affects [in the way of increase] the *breadth* of the down-sweep and the inner zone; while velocity has more immediate influence on the depth of this excavation zone.

But, with so quaquaversally pressing a substance as water, and so mobile a material as sand, the several producing conditions work together and help each other as will be attempted to be illustrated in next Part.

So far as I have yet been able to judge, the impinging [and scouring] power of the down-sweep from a current 20 feet deep at a pier of ordinary dimensions may, even with merely equal velocity, be expected to be greater than that from a current only half the above depth, and though the depth of scour would not be doubled, its breadth, I think, would be increased, as also to some extent its depth.

One practical inference drawn from the experience quoted as to the ordinary onward scouring or transporting power of currents of equal velocity decreasing in some degree as the depth increases, is stated to be that stones or other material of a lightness in each piece, which would be swept away in a current of a certain shallowness, will remain unmoved in a current of greater depth, though of equal velocity.

The impression I derived from observation on a small scale here appears counter to the above experience on a larger scale.

But though, according to that impression, heavy material, *immediately at the bottom level of the current proper*, would more easily be moved by down-sweep impingement from a current vertically tall above it, than by the same down-movement from a shallower stream of equal velocity, yet if, for the simple term *depth of current* as employed in the opinion already quoted, in which, indeed, a distinction between the proper current depth, and the scour already quoted, is not made, there be substituted the expression *total or aggregate depth, both of current proper and of scour excavation*, then the present writer arrives at the same practical conclusion as that in the quoted opinion, *viz.*, as to material being more able to resist transportation at a greater depth, *i. e.*, *joint depth*, than at a less.

The force of the down-sweep is derived from the current proper, which, in its onward and undeflected direction, dips only a little into the upper zone level.

Supposing, then, that the deeper the current is down to *that point*, the more it helps the velocity in producing scour, provided certain proportions of obstacle to current are maintained; still, with every foot that the down-sweep descends below the bottom of the current proper from which it is derived, it, with its sequence of other movements, is expended more and more in scouring out the sand and opposing the in-fall, which latter rapidly increases by the spread of the outer slope, increasing with greater depth of the scour excavation.

At a certain depth the down-sweep ceases to have power of operating further, and the up-rush can just maintain the scour hollow against the in-fall. This limit is naturally reached sooner with heavy material to be thrown out than with light. That is to say, heavier material will resist movement and ejection by the down-sweep and subsequent up-rush at a smaller *joint* depth than light material; and the heavier it is, it will be able to remain stationary at a smaller joint depth; *vice versa*, the lighter it is, the further down it must be in the joint depth before it can resist movement.

Thus, when the scour depth is coupled with the depth of the current proper, and the depth is described jointly from the current surface downward to the bottom of the scour hollow, the same practical conclusion as already quoted is reached, as to similar material being less transportable at a greater [joint] depth than at a less. [Note 10 L.]

I must add that, in the foregoing remarks I am not questioning the conclusion of an experienced professional observer as to the ordinary onward scouring and transporting power of water diminishing in some degree with increase of depth, the velocity being the same.

Several points, indeed, suggest themselves that might help to explain such result. But these points, so far as they have yet occurred to me, do not seem equally to explain why the effects of two down-sweep columns of different vertical measures down to the bottom of the current proper, having the same velocities, but *other proportions according to the respective lengths*, should differ in this way that the longer should have the smaller scouring power.

However, beyond the greater risk of inaccuracy of conclusions from a small scale, there is in observing at merely one locality the difficulty of distinguishing and eliminating the effects of increased velocity from those of increased depth, as at the same place, in a natural channel, there is, of course, always higher velocity with the greater depth.

Where the proportion of pier width to current depth is not adequately maintained, the existence of an interfering element, presently to be discussed, is intelligible, which may account for a reduction of scour after a certain depth of current proportionate to pier width is exceeded. But apart from this, I am, from limited observation on a small scale merely at one place, not entitled to speak with confidence that there may not be other interfering elements hitherto undetected, which, even in this special scour, may, with increasing current depth, grow so rapidly as finally to turn the balance and lessen the effect.

XXII.—*Form of pier as the artificial element in the producing conditions.*—Of the producing conditions mentioned in the last Part, four, *viz.*, the velocity and depth of current, the nature of the bed material and the admixture of particles thereof in the stream, are natural elements of the impingement action, little under our control in natural streams, though in canals some of them can be more or less regulated.

But the *form of pier* [or other obstruction] is an artificial condition more or less within our control, and thus merits more detailed consideration than was given in the preceding Part.

A fixed pier in a current may be compared with a vessel moving through still water, the difference consisting in the interchange of position of the force and resistance in solid and liquid, respectively.

That horizontal outline with which a deep vessel of a certain general size would require least power to propel it at a certain speed, *i. e.*, the form which would encounter least resistance in passing through the water at that rate, might theoretically be the best for a pier of the same general dimensions to offer least resistance to a current of similar velocity. A ship, however, needs buoyancy, and a pier stability. In the *vertical* line, a cut-water sloping forwards above would not be so good as the "*Ram*" form of bow, which causes a great up-roll of water. See Part XXXII regarding slopes.

A tub is the very synonym for a bad sailing ship, like an old-fashioned dumpy Dutch sloop, or Newcastle collier brig, as compared with the performance of a clipper ship built on well designed lines. (Note 11 L.)

The ship form exactly followed in a pier might, however, be weak in the cross-stream direction, and the cut-water might be too sharp and thin to resist injury from floating timber or drifting boats. And the side length might offer too great obstruction to an oblique current.

(With two bodies of equal cross-section and stem-outline, one of them merely as long as it is broad, while the other is, within certain limits, longer, resistance to movement in water is less in the case of the latter.)

Of two cut-waters, the one semi-circular, and the other sloping to an angle of ninety degrees, the former, I have seen stated, encounters something less than two-thirds, and the latter rather more than one-half of the resistance which their directly transverse basal section would meet.)

Still the general principle of having greater length in the stream line than thickness across stream, from which also results greater stability of base in the direction of the ordinary stream force to be encountered, and of having the up-stream extremity sloped off in a more or less sharp cut-water outline, has been followed in bridges generally, though of late there have been some exceptions. (Note 12 L).

Experiments by the writer (on a small scale, it is true), have indicated that, with other conditions equal, great difference in back-scour effect is caused by variations in the size and form of pier, the effect increasing by a progressive rapidity, with increase in the cross-stream breadth of pier and bluntness of its cut-water.

Simple experiment will show, and easy calculation will explain, that downward columns of force of equal intensity will, with their subsequent up-rush, succeed in making and maintaining excavations in sand or other fine, loose and moveable material in some degree deeper, as the columns have larger transverse sectional areas, so as to act on a larger space, while doing so with equal intensity of force on each point or area unit.

Though the quality or intensity of force in each equal area is the same, yet, as the aggregate area is increased in one case, so also the quantity or amount of force is greater in it than in another which has not been increased, and hence the total of the scour effect is greater.

Even if the depth of current primarily and chiefly affect the breadth of the inner zone, it will, I apprehend, within the limits elsewhere adverted to, still aid the velocity in increasing the zone depth, for, with increasing depth of excavation, the outer zone of in-fall is constantly extending its periphery, and the in-fall of sand thus increases so rapidly, that it will much sooner overpower a narrow excavating force [*i. e.*, of small sectional area] and so prevent further deepening than it can overcome a broad one of equal intensity per equal area.

In a rough, mechanical way one might say that, at a pier of given breadth, the column of down-sweep force has to operate in four directions while scouring out, *viz.*, on the bottom, on each of the two sides of the hollow scoured in the first direction, and in front or up-stream.

In rear it rests against the pier, and has no work to do.

But in the first direction, it has originally to stir up and push aside the bottom material and, in the other three, to eject by its final up-rush that disturbed material, and oppose the constant in-fall of sand from those three sides into the excavation.

The work to be done, or resistance to be overcome by the single column of down-sweep, may thus be represented by the number 4.

But let the pier be doubled in breadth; the down-sweep will now be of double sectional area, or, say, consisting of two columns; these together will have to work on two areas at bottom, on one at each side of the duplicate column, and on two in front. That is resistance represented by 6, as compared with a force of 2.

The apposed sides of the parallel columns have no work to do directly, but whatever amount of force each could separately have exercised, cannot be lost. Doubtless it strengthens the action in those directions in which sand is encountered, and this may explain how the scour hollow at a pier obstruction of double breadth is not merely doubly broad across stream, as it must be, but is wider also in the up-stream direction, and is likewise deeper than at an obstruction of single breadth.*

* Let a man dig a hole one yard square in sand at the foot of a rock. He has to excavate the bottom, and to throw back the in-fall on three sides.

Next let two men side by side dig an oblong hole of two square yards.

Each man has no in-fall from the side of his neighbour to contend with, but only on two sides, so that with equal labor he can work more on the bottom, or on those sides, and thus deepen and broaden the space more than the single man could do in the single yard.

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Were the breadth increased to 4, the numbers would be 10 to 4.

These rough proportions successively of 4, 3 and 2½ to 1 may, perhaps, serve to illustrate, though not, of course, exactly to define, the fact, that increase in the breadth of an obstruction within proportionate limits as aforesaid leads to increase in depth and up-stream width as well as in cross-stream breadth of the consequent scour excavation.

But after the obvious direct result on the cross-stream measure of the scour, it seems to me that the next most marked effect from increase of pier width will be on the depth.

It is a simple, yet striking, experiment to take a plank and place it on one end in a stream active enough to be sweeping its bed sand along.

When holding it with the edge to the stream, there is hardly any action, but on gradually turning it round, the down-sweep and scour are rapidly developed, until finally, when the flat width is fairly opposed to the current, the action is greatest. Laid lengthways, edge down and broadside to stream, a plank, very long in relation to current velocity and depth, is scoured merely at and near the free ends, while sand may accumulate at the middle.

Yet if this disproportionately long cross-stream obstruction be placed with a certain obliquity to the stream, it will be scoured to a moderate extent throughout, just as the opposing, *i. e.*, the concave, bank of a winding stream is scoured.

The two first cases illustrate the point that, within certain limits of proportion between obstacle and stream, equal velocities of current, &c., produce greater depth, as well as more expanse of scour against a broad obstruction or pier, than against a narrow one, and

also that, with a given proportionate breadth, it is more intense when that breadth receives the current directly on a square headed or almost directly on a bluff-headed, cut-water, than when the breadth is fined off into a sharp cut-water, so as to receive the impingence obliquely.

The two next cases show that when the obstacle is disproportionately broad to the current, the latter is unable to scour its middle portion when directly opposed, but that in this case, scouring is facilitated by obliquity. These latter points are not devoid of practical bearings on some works.

An actually square-headed pier might, theoretically, seem much the worst of all, but practically, the scouring action at a circular pier [a weighted hogshead having been used for experiment] has appeared little inferior.

At a square-headed pier, as the impingement is more direct or perpendicular over a greater breadth than at any other form of pier, the down-sweep is most active, and the depth continuously great along the up-stream face. Hence the inference that impingement scour will be much worse with this form of pier than with any other. And so it probably would be but for some modifying circumstances.

The lateral out-sweep of the current proper from a square-headed pier, and the finally lateral movements from both zones set considerably across the current, and with comparatively little down-stream obliquity. The on-sweep of sand by the current tends thus to fill up speedily the lateral prolongation of the scour from a square-headed pier.

With a cylindrical pier, however, the lateral sweep of the current and issue from both zones while still powerful, set much less decidedly out from the pier, and across the stream. There is a greater tendency in the scour trough to hug the side of the pier so as to carry its main depth with but little diminution beyond the up-stream semi-circumference, and thus to continue it in a horse-shoe shape around a greater proportion of the circuit than occurs at a square or any other shape of pier.

In all the forms the down-stream extremity of a pier is less exposed than the upper, or even than the sides.

But, so far as I have been able to observe, the cylindrical form appears, in proportion to its peripheral measure, more liable to be denuded by scour than, perhaps, any other shape of pier that has been tried.

A circular pier may thus be said to be deeply scoured to one-half of its circumference, and to be considerably denuded for a still farther portion.

Of an elongated pier, on the other hand, probably not one-fourth, and, perhaps, much less, is exposed to the worst scour.

The circular form, however, is at no greater disadvantage when attacked by an oblique current, while an elongated pier is more endangered when attacked on the side.

The analysis of this scour showing that it is a strictly topical, or *immediately* local action at the up-stream base of piers, abutments and wing-walls, and not a general scour action across the whole channel* that is to be feared, attention may be more directed to reducing this local action by form of pier and adjuncts with less apprehension than formerly, from simple high velocity of unimpeded current elsewhere in the general channel or the arch water-ways.

* Unless there is a flooring or apron across it, imperfect in some of the conditions presently to be described as essential to the safety of such protective works themselves.

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The plank-edge experiment first suggested the existence of some interfering influence.

There seemed nothing to imply that the down-sweep deflection at it was not as strong per equal cross-stream measure as at the plank-face. But it not only did not produce a corresponding scour effect on its own narrower area, but it produced scarcely any effect at all. What was the cause? The explanation which suggested itself was that the down-sweep water is in contact laterally with the onward current rushing at right angles to the former, and with greater force as being undeflected.

The two currents when in contact must rub on and interfere with each other, but the stronger will have most effect. This will be to entangle, drag and carry on with it the outer side layers of down-sweep. The latter being thus, as it were, peeled, becomes narrower from side to side as it descends, so that in the case of a tall narrow obstacle, when finally it reaches the bottom, it plays merely on an almost linear space in the stream line, on which its effect is instantly overpowered by the general on-sweep of sand.

At the plank-face again, the down-sweep was similarly interfered with, but, from its greater cross-stream measure, it could better afford it. A sufficiency of the medial parts of the down-sweep reached the bottom to have a fair working area, the necessity for which, in relation to other conditions, I have already attempted to elucidate.

If, now, the plank-edge and stream depth be equally multiplied till the former is of the thickness of an ordinary masonry pier, the latter will be an *extraordinarily* deep river, but the relative proportions being the same, there is nothing to indicate that the result

would differ from the former beyond the proportion due to different magnitude, or that the effect, which is small at the plank-edge, would be otherwise than small in similar proportion to the depth on the great scale.

I had seen the iron screw-piles used on the Bombay and Baroda Railway, and had read newspaper accounts of flood disasters to its bridges, and while working out the above subject I felt that, if the ideas which had suggested themselves were correct, it would not be scour which worked the mischief at those piles, tall thin columns as they are, in relation to the deep-flooded Nerbudda. Subsequently I found that the damage there was really not from scour.

But the masonry piers of the Jumna Bridge at Allahabad present a more difficult case. The river in flood may be 60 feet deep, but the piers being about 25 feet in cross-stream measure, cannot be considered disproportionately thin as compared with the depth.

The bed is of sand, in which the foundations are sunk about 43 feet. No scour damage has occurred at them that I have heard of.

Yet, if other things are equal, why has much worse scour not occurred at these larger piers in a deeper stream than at the circular piers of the Delhi and Punjab Railway?

There are certain differences at the Allahabad piers, *viz.*, cut-water form, footing projections of foundation, especially beyond cut-water, and greater length of base in the stream line, the beneficial effects of which will be elucidated farther on; but still the point remains for investigation, whether there is in excessive depth, without disproportionate narrowness of pier, a hampering effect on pier scour as described in relation to ordinary unobstructed scour. Is there another element in the matter not yet detected, or is it some farther proportionate relation between those already considered, as, *e. g.*, one between velocity and depth, that requires to be ascertained?

XXIII.—*Amount and proportions of scour at piers*—The absolute amount of impingement scour mentioned in a previous para. to be sometimes very great, depends on the combined result of the several producing conditions already detailed.

The proportionate measure of the different parts varies with variations in these several producing conditions, but with a brisk current, a bulky pier, contraction of water-way and afflux, and with coarse sand, the following proportions have been observed:—

Taking the depth of the current proper as one, the depth of the outer zone below the former may be one more, and that of the inner zone one again below that of the outer, giving the depths thus, as 1, 2 and 3, respectively. The cross-stream measure of the pier itself in these cases was represented by 3. [Note 13 L.]

It is to be noticed that back-scour depth is always in addition to, and below the depth caused by the ordinary on-scour of, the unimpeded current.

By current is meant here the *current proper*, as, although it dips somewhat into the scour hollow, yet, on the whole, an entirely different set of movements as summarised in preceding Parts exist in it.

Those movements have been detailed as fully as I could trace them in the longer notes, of which the present description is an outline.

The limit to the possible depth of the current proper at any place is practically an important point to be known.

The usual bed may be lowered by the ordinary on-scour of the onward stream, and such extra depth must be reckoned in that of the current proper, as it is from and below that level, *viz.*, the bottom of the real onward and impinging current, that back-scour operates.

Like the depth, the breadth also of back-scour varies with differences of the producing conditions.

Under circumstances similar to those already mentioned in illustrating the proportions of depth, the breadth has often been observed about equal to the depth.

Thus a total depth of three in the inner zone, close to the pier stem, might be accompanied by an aggregate breadth of both zones, similarly of three from the cut-water surface to the circumference of the outer zone, and this might be pretty fairly divided between the two.

At other times the outer zone would have the greater width.

The extreme width of inner zone which may be scoured out at any pier, or other work, is a second point of great practical importance.

The greater the velocity of current, the more strongly is the inner zone developed.

With diminishing velocity, the relative proportions of the outer predominate; and finally, as ejective energy in the inner dies out, the in-fall from the outer zone and the on-sweep of sand from the general bed by the current fill up the excavation.

While a current after a flood is diminishing in rapidity, and especially when it has become comparatively feeble, experiments are apt to be complicated by the scour excavation being partly due to the previous greater activity of current through the on-sweep [in coarse sand, at any rate] not filling it up so rapidly as the diminishing force of the down-sweep would really permit.

In fact, in a current of *diminishing* rapidity, both simple on-sweep and impingement down-sweep are weakened.

Till the above was detected, some experiments yielded very puzzling results, which there is not room to detail here.

In such case the safest way was found to be to fill up the excavation artificially with sand, and let the current scour it out again to the extent of its power under its velocity at the time, after which the experiments could be tried again.

As to greater depth of current causing probably greater width of down-sweep and true impingement scour, this may be intelligible from the mechanical illustration of a soft rod beaten on the end. A thick rod will give a thicker out-curl than a thin one.

Or a simple diagram would illustrate it, as if one supposed the half of a current depth to curl downwards, the down-curl would have a thickness equal to half the depth of the current.

The deeper current would thus give a broader down-sweep, and this would necessarily produce a broader impingement scour.

The above illustrative proportion might imply that half the current depth joins in the down-sweep, and that, consequently, the breadth of the inner zone will not exceed half the current depth. But from my experiments it would seem that more than half the current depth at the pier surface is often or generally engaged in down-sweep, though possibly at times there may be less.

The internal proportions and external relations of the two zones, and the several modifications thereof by alterations of the several producing conditions, could, however, only be correctly ascertained by an immense number of carefully repeated and varied experiments.

The breadth of the inner zone in coarse gravelly sand, at any rate, appears to exceed that of the down-sweep merely by the narrow base of the steep ejection slope, or a very little more.

The breadth of the down-sweep seems to coincide below with the breadth of the up-roll and up-swell on the surface around the pier head. These are quite distinct from and above the general damming up or afflux, the *head* from which, however, doubtless adds to the power of the down-sweep.

The up-roll, meaning thereby the water which curls or wells up in immediate contact with the cut-water surface, is the most easily distinguished, because the up-swell just outside it rises less highly and actively, and is often masked by ripples from the onward surface current running up over it till near the cut-water.

The real breadth of the up-swell can thus be seen best when the current is comparatively gentle, and in certain lights which are not too strong.

Both up-roll and up-swell, however, are merely parts of the same thing, *viz.*, the upward portion of the general out-spread of the water on impingement.

In the up-roll there was very observable that alternation of comparative activity and lull which first struck me in connection with the noise and form of the breaker wave, where a contracted bridge stream dashed into a body of quieter water, and which alternation appeared to exist in every form of water action observed.

At first, before I noticed the broader up-swell, I thought the up-curl alone might indicate the entire thickness of the down-sweep from the pier surface outwards, as doubtless it does correspond with its most active portion.

As the up-curl is scarcely one-quarter as broad as the inner scour zone, protective measures as will afterwards appear would have been comparatively easy had that supposition proved correct.

In the preceding Part it was mentioned that it is within certain limits of proportion between obstacle and stream that the scour increases with increase in the cross-stream measure of the obstruction.

A spur thrown out from a river bank is scoured at its free end, and most strongly at the corner of its up-stream side with the stream-line edge of the extremity.

From it towards the bank the scour grows less,—and finally silt is favoured.

Should the junction with the bank be cut through, that extremity will also be scoured, but if the cross-stream measure be sufficiently great in proportion to the water passing onwards, the scour may not reach its centre, where even silt may remain.

A weir across a wide part of a channel, and broken through at one or both extremities, would be similarly circumstanced.

But with all ordinary proportions of piers to current, the scour round the cut-water appears aggravated by increased thickness of pier.

XXIV.—Two points of importance—Depth of current proper, width of impingent deflection.—The two points mentioned in the preceding Part [XXIII], as being of practical importance may be here brought together, viz. :—

- (1).—The lowest bottom level of current proper which may be encountered at any place.
- (2).—The extreme width of the inner zone of back-scour which may be there excited at any particular pier, wing-wall, &c.

I have already remarked that the current proper does not, especially at the central point of impact, predominate in, or even occupy the scour excavation, and that, indeed, it only dips partially into the plane of the upper zone, i. e., it strikes on the pier with any effective impinging force, very little below the level of the bed, immediately up-stream from the margin of the outer zone.

Also that the level of the bed may itself be lowered during a flood by ordinary on-scour, and that whatever depth it has, or thus acquires, contributes for the time to down-sweep action, and that at this depth-level the bottom of the effective current proper has to be reckoned.

In the tailing off prolongations of pier scour, which are more or less in the line of the stream, and also in originally oblique impingement scour, the current dips farther into the excavation, and blends more in the scouring action.

Of course, in the simple shallowing prolongations after the pier is fairly passed, it is on-scour which is at work.

If, as I have supposed, the depth of current has, among the other producing conditions, more than an average share in contributing to the breadth of the down-sweep and inner zone, it will presently appear that the depth of current proper in the two respects of absolute depth, and of the lowest point to which that depth has at any time and place to be reckoned, is an element in impingement scour deserving of careful consideration.

The practical bearings of these two points will be discussed in a subsequent Part.

SECTION D.

FLOOD INJURIES AND SAFEGUARDS.

XXV.—Different structures differently attacked by floods.—Different structures are differently attacked by floods.

* We already use the word "apron" to signify the covering or flooring of masonry to protect the part now in view; so the term "skirt" may be allowable to indicate the part itself, though the expression "outskirt" or "train" would be more precisely accurate.

However, there can be no serious objection, while there is some convenience in designating that part the skirt the covering for which we already call the apron.

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Thus, an *ancient weir or dam* is chiefly attacked at its down-stream skirt* by the impingement of the falling water of the overflow.

The conditions existing on the up-stream side have been discussed in Part XX, and it is sufficient here to notice that there is not a tendency to the particular down-sweep scour at the up-stream skirt [Note 14 L]. That is more particularly if the stream comes fair-on. Obliquity of approach favours oblique down-sweep, turning finally into an uprise to escape by the overfall.

Raised bridge floorings, if not extended up-stream as far as the down-sweep from the piers, are differently circumstanced, as will be noticed further on. At them there will be scour.

Although the ordinary tendency of a continuous bar or weir is to check scour above it, or even to cause silt, yet, under some circumstances, especially when the channel is narrowed as it approaches the bar, and the velocity and volume of the current are high in relation to the height thereof, a current, strong enough to be lowering its bed up-stream by ordinary on-scour, may carry this process on to the upper edge of the bar, or raised flooring itself. This will more readily be the case when the bed material is fine and light so as to be easily lifted and carried by the stream, in place of being merely swept along its bed.

If the foundation of a weir be not carried deep enough, or the soil below it be not impervious enough, there may, from the "head" pressure of the water on the up-stream side, be leakage beneath it, appearing at the down-stream skirt; but I am here discussing more particularly dangers from flood currents. To some of these dangers, however, such leakage under pressure may, when continued and excessive, assimilate. *Vide* Part XXVII, &c.

The down-stream skirt has to be protected by an apron of masonry tailed off with

* *Tringe* from following out the idea of an a broad fringing* of boulder work, or by a sloping apron already familiar. J. P. S. ing talus of massive boulders.

Bridge piers, &c., on the other hand, are attacked specially at the up-stream skirt, and to a less extent along the side skirt. On the down-stream side, though involved in a continuation of the scour hollow from the upper aspect they are comparatively little attacked close at the skirt, though, where the water-way is much contracted, or the flooring raised at the bridge, a particular scour is established a very little below it, which may more or less affect the down-stream skirts.

That scour is the scour produced by impingement of more rapid on less rapid water as already explained; the archway currents having a greater velocity, from their contraction and the afflux above the bridge, than the general and wider current below. The scour pool thus produced slopes first downwards to its full depth, and then upwards, and is more or less elongated in the stream line, instead of the short, abrupt, transverse hollow at the up-stream skirt of a solid obstruction.

Around the latter, however, the scour will also pass for some way completing the outline of the letter U reversed, i. e., the curve being up-stream.

The scour at the down-stream side may reach back to the very skirt of the piers, &c., but usually the greatest depth is a little farther on, the chief intensity of action appearing to be at that place where, on the surface, the archway stream forms an up-curling wave or breaker on the general body of water ahead.

The higher the velocity of the impinging stream, the further down-stream that wave appears, as if the quicker current carried its own acquired velocity, and pushed every thing in front of it for a greater way before the slower water below is able to check it.

There is lateral out-sweep also below a contracted bridge waterway, though its effect is more easy to be seen in a canal, with capacity strictly limited to the quantity of water it has to convey than in a natural channel.

That lateral out-sweep, if it impinge on a bank, may erode this by a horizontal secondary impingement. If that movement be strong enough, a down-sweep may be established from the bank, giving rise to a tertiary vertical impingement on the bed at the bank skirt.

The wing-walls below a bridge, of course, resist the horizontal secondary impingement, but they may thus be scoured at the skirt by the tertiary.

In a very narrow channel the out-sweep from a thick pier might perhaps cause lateral action on the up-stream side, but from the tendency onwards, it would probably be received on the abutment side, and as the wing-walls and abutments on the up-stream aspect are themselves directly attacked by the current, any deflected action from a pier need scarcely be considered there.

So far, piers of the ordinary massive form and elongated in the stream-line have been considered.

But bridges have been built with piers formed of simple cylinders of iron, screwed or otherwise forced into the bed, and of such comparatively small transverse section (2½ feet) as to offer little resistance to the current, and to afford, therefore, a comparatively small basis for the establishment of deep back-scour.

On the Bombay, Baroda and Central India Railway, the Nerbudda and other bridges have been thus constructed.

But a new danger is developed with this form, viz., that from the onward rushing push of the floods, acting on tall cylindrical columns, each of which has singly no greater basis of stability in the stream line in which it is exposed to the thrusting force, than in the cross direction in which it is exposed to little or none, except from an oblique current.

Single, tall, cylindrical columns, vibrate, oscillate and sway about under the rush of floods, so that they are speedily destroyed from loosening of the bolts and joints at the junction of the several length-pieces of which they are built up, or even from actual fracture of the pillar.

Even when several such columns are braced together in the stream line to constitute one pier, there is still great difficulty in entirely preventing those effects during flood currents of 20, 30, or 40 feet in depth. Increasing the number of pillars from 3 to 5 in the stream line of each pier, and bracing them together throughout almost their entire height, instead of to a less extent, have been found necessary additions to strengthen and rigidify the original design.

The tall chimney stalk of a factory can, I have heard, be seen slightly to oscillate in a gale, when observed against the sky, close to the clear cut-edge of some more massive building.

A factory stalk is much taller than a bridge pier, but the latter has a much weightier element to content with than the former.

When a pier composed together with its foundation of a single brick cylinder, like some of those on the Delhi and Punjab Railway, is exposed to a flood 20, 30, or more feet in depth, and rushing at the rate of 8 or 10 miles an hour, it seems open to consideration whether such pillar, having no increased base of stability in the stream line, can stand such thrust without undergoing, to some extent, vibration, oscillation and swaying, which may injure or crack the brick jointing at some part below, even although it be 12½ feet in diameter as those cylindrical piers are.

Water being about 800 times heavier than air, the latter would require a velocity some 28 times [i. e., the square root] greater than water to act with equal momentum.

Water running 10 miles an hour, or about 15 feet a second, would be a raging torrent and wind at 80 miles an hour would be a terrific hurricane, but this is scarcely one-third of 28 fold.

The above velocity of water is a very high one, but it has sometimes to be encountered by bridges, and it is not higher comparatively than that supposed for the wind.

It would seem, therefore, that piers have to resist double or treble the *momentum* which the tallest chimneys have to withstand, and which makes them oscillate—or sometimes even overturn them.

Such chimneys are, however, taller than piers, and the effect of the wind, or other moving body, is in proportion to the length of lever on which it operates; but if a pier be exposed to a current of water 20, 30, or 40 feet deep, this would [taking the above supposed proportion of the *momenta*] be equivalent to double or treble these heights in a chimney acted on by wind.

The foregoing figures are mentioned, not as being exact, but only in the way of rough illustration. [Note 15 L.]

It would scarcely matter how much of the whole exposed depth encountered the current, and how much was in the scour hollow, for the current would be in the upper part and acting on the extremity of the lever.

The chimney-stalk is at one disadvantage compared with a pier as regards resistance to oscillation, *viz.*, that it is hollow, while the pier cylinder is finally filled in solid with concrete.

But on the other hand, the pier cylinder is at a disadvantage in regard to basal stability, as it is merely of a diameter from foundation base upwards [on the Delhi Railway] of 12½ feet, while a tall factory chimney has at base a much larger diameter, though it thence tapers upwards. [Note 16 L.]

Nor is the shaking, racking, and fracturing tendency the sole danger in simple cylindrical pillars.

A tall pier, in relation to the stream-power on it, may be regarded as a lever in two ways. In one of these the material in which it is imbedded furnishes both the fulcrum and the resistance; and in the other, the material on which the foundation rests affords the fulcrum, while the pier's own weight supplies the resistance.

In both ways the power is the current pressing on the up-stream side of the exposed portion.

Under one view, the pier is a straight lever of the first order,* having as the fulcrum the bed material from the bed-surface downwards applied to the down-stream aspect of the foundation, while the resistance is the bed material similarly applied to the up-stream side of the foundation, and traced from the foundation base upwards to the bed-surface.

But if the bed material be scoured out, as at times it is, for 20 or 30 feet, or even more on the up-stream side, and almost as much at the sides, and to some extent also on the lower side, the resistance on the up-stream side is diminished; the measure of the lever between the bed-surface fulcrum on the down-stream side and the upper limit of power at the surface of the stream is lengthened, and the force correspondingly increased.

Hence it is conceivable that such pillar, under increased lever-power and diminished resistance, might be somewhat tilted over even without actual fracture occurring.

Whether there was fracture or not, the tilting from mere thrust would be in the down-stream direction. [Note 17 L.]

In this light the prevention of deep scour at a pier especially of simple cylindrical form, is seen to be of high importance.

Under the other view, a pier is a rectangular lever and of the second order†

In it the fulcrum is the material on which the foundation rests, and more particularly that part which is beneath the down-stream toe or margin of the foundation.

The resistance is the weight of the pier itself, which may be viewed as concentrated at the up-stream toe of the foundation.

It is evident that the resistance to being tilted by the stream rush will, with equal weight of pillar, be in proportion to the length of the foundation in the stream-line, *i. e.*, between the fulcrum and the resistance.

Double the length of base in the stream-line will imply double resistance, not merely to being tilted over unbroken, but probably also to oscillation and fracture.

In this way the piers of the Jumna and Soane Bridges on the East Indian Railway, which have respectively 10 and 12 circular wells [of almost the same size as those singly used on the Delhi Line] in their foundation, arranged in double rows, excepting one at each end, will [under the rectangular lever view of the matter] have respectively about 6 and 7 times the base resistance to being tilted over by the stream, which the single cylindrical foundations and piers at the Beas and Sutlej, on the Delhi and Punjab Railway, have. And this will be in addition to the greater stability from the greater weight.

If simple back-scour reached and undermined a pier, without sufficient force of current to tilt it onwards, the inclination would be up-stream, as may easily be seen by the simple experiment of placing in a channel some obstruction which the stream cannot tilt over or carry away.

It is under-scoured and undermined at the up-stream toe, and gradually sinks in the sand, head [*i. e.*, up-stream extremity], deepest. [Note 18 L.]

The simple cylindrical form is at the same disadvantage for resisting thrust in any direction as a man standing on one foot is to resist a push on the shoulder, as compared with the same man standing on both feet, with legs planted widely apart in the direction of the coming thrust.

The foregoing points appear suggested to consideration if risks of debiting scour at cylindrical masonry piers with more than its due, is to be avoided. Though the reply may possibly be in the negative, the question, whether such masonry pillars are liable to those racking and tilting dangers, can scarcely be passed by without being noted.

The principal dangers from flood currents at different structures may be thus recapitulated:—

[1.]—At *anicut*s, weirs, or dams, scour on the down-stream skirt from primary vertical impingement;

[2.]—At *bridge piers*, wing-walls, &c., of the ordinary construction, of masonry, with the piers elongated in stream-line, and having a sloping cut-water. Scour on the up-stream skirt, *i. e.*, of cut-waters, &c., and to a less extent at the side skirts of the piers, &c., from secondary vertical impingement [the primary being on these structures themselves];

[3.]—At *bridges* with a contracted water-way and afflux up-stream, or with floorings not low enough, scour on the border of the down-stream skirt of the piers, &c., from secondary vertical impingement [the primary being on the slower water below];

[4.]—At *piers composed of iron-cylinders* of very small diameter in proportion to height;

Racking vibration, oscillation and sway, loosening of bolts, screws, rivets and joints, and perhaps actual fracture, caused by the swaying on-push of the flood torrent.

Several of such pillars have to be planted in the stream-line and braced together to form a single pier of the requisite stability.

[5.]—At *piers composed* [as well as their foundations] of single masonry cylinders, tall as regards their thickness, as for example, although about 12½ feet in diameter, they may be imbedded 50 feet in the sand, much of which depth may be scoured, and they may stand half as much more above the ordinary unscoured bed level of the sand;

Scour at the up-stream skirt and sides from the secondary vertical impingement, as with piers of ordinary form—see [2.] above.

But at the simple cylinder form, the deep scour embraces and extends even somewhat beyond the half circumference.

Query also, is this form wholly exempt from the dangers found to attack tall iron cylinders, such as the racking vibration, and tendency to be tilted over or fractured by the pushing thrust of a flood acting with great lever advantage on a tall pillar denuded by scour, and having no increased base for stability in the direction of the thrust?

XXVI.—*Bengal method of securing foundations*.—The *Bengal* or Northern India method of securing foundations in sandy river beds is to carry them to such a depth that the scour cannot reach so far down as to undermine the basis on which they rest, or to denude their whole surface down to that basis.

Yet cylindrical piers, 12½ feet in diameter, resting on foundations of similar shape and dimensions, at the Sutlej and Beas Rivers on the Delhi and Punjab Railway, sunk to the depth of about 45 feet below the bed-level, have failed, from what particular cause, however, I have no details before me to show.

But as piers are now being sunk on the Punjab State Railway, at the Ravee and Chenab Rivers, to a depth of some 20 feet more, it would appear that it has been found advisable to exceed the depth sunk on the Delhi Railway.

The *special* liability of simple cylindrical piers and foundations to dangerous attack by impingement scour has already been indicated.

Still, the extreme depth latterly stated might be expected to be beyond the reach of down-sweep scour.

Having no particulars to show whether the failure of cylindrical piers with foundations 45 feet deep, was simply from scour, or from the other causes found operative on tall circular pillars, or from these aided by scour, I may note the reasonable expectation that, if the damage was purely and solely from scour denudation or undermining, then the extra depth now being given in other instances may afford sufficient security.

But the matter seems to merit the further consideration that, if the failure was caused partly also by the racking on-push of the flood producing cracks or fracture of the pillar, or tilting it over down-stream, then mere extra depth given to foundations may perhaps not suffice to avert danger. [Since writing this abstract I have learnt that the piers on the Punjab State Railway are being constructed, not of single cylinders, but of elongated form, resting on three well cylinders placed in the stream line].

The mechanically moderating principle, that a scouring force of a certain intensity cannot scour so deeply against a narrow obstacle as against a broader one* would doubtless tend to stop the scour at some point short of the base of a pier foundation carried to an extreme depth without its transverse breadth being increased.

* By reason of the area of in-fall from the top, so rapidly increasing with greater depth, and its filling-up action sooner balancing the scour force when the latter affects only a small area.

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Increase of diameter in a cylindrical pier and foundation would give increased stability against the racking and thrusting of a flood, but, supposing other circumstances the same, the increased width of obstacle to the current would generate with it such increased scour, that this would probably more than counterbalance whatever advantage accrued from otherwise increased stability.

If any danger exist at cylindrical masonry piers from the racking vibration and tilting on-push of the flood, it can only be fully obviated by greater base length in the stream-line; just as the depth of the back-scour may, even in the natural bed, be lessened by a good cut-water outline being given to the pier.

Each measure would help the other, for a shallower scour would check the decrease of resistance, and increase of lever length afforded to the tilting power of the current.

Even if the cut-water or toe of an elongated foundation, such as is used on the Jumna Railway Bridge at Allahabad, were undermined, the mass would probably still stand on, as it were, the flat of the pier foot and heel, for the few hours such scour might last, unsilted up again.

But, in a circular foundation, the cut-water or toe forms a full half of the whole basis, and if this were under-scoured, the mass could scarcely stand on the heel-half with no intervening foot-sole. [Notes 19 L and 20 L.]

XXVII.—*Madras system of guarding foundations.*—By the *Madras* system, foundations are carried down to a comparatively small depth below the bed surface, but they are protected between the piers by floorings of masonry extended apparently, in instances, for some little way in the up-stream and down-stream directions from the piers, in the form of an apron, and finished off in both directions with marginal drop-walls, which latter may in some cases have on the down-stream side, the additional safeguard of a fringe of boulder-work.

The *Madras* system of foundations has been most notable, perhaps, in its application to anicuts, the scour attack on which is at the down-stream skirt, where the apron and fringe, or the sloping talus, have usually given satisfactory protection.

When applied to bridges in the way it is sometimes described, as I have seen even in a *Madras* work, as giving merely a flooring between piers from cut-water point to point, it is accompanied by the danger of the protecting work itself incurring danger; for, unless the flooring extend in an apron sufficiently up-stream to clear the limit of down-sweep from the cut-waters and wing-walls, it may itself need protection; and in that condition, if not well sunk below the on-scour level of the bed, as is recommended in *Madras* works, the danger may be increased by impingement scour being generated on itself. [Note 21 L.]

Other danger exists when, on the up-stream side, the border drop-walls are carried down too short a depth, or when there is any interstice, flaw, or crack in the perfect continuity of the masonry, especially of the drop-walls.

The danger referred to comes into operation when, from the surface of such flooring not being placed low enough, the current catches on an exposed portion of the drop-wall or flooring edge, and a down-sweep is established, reaching the weak point in the armour. If the action still continue beyond this it merits study.

One hears occasionally of floorings being undermined and blown up; of the material filled in between wells, drop-walls and other foundations, being washed out; and of foundations at bridges and at canal rapids and falls being thus destroyed through water penetrating and acting under a considerable head or pressure, &c.

It does not seem clear that there can, in most instances, be any such pressure from mere height or head of water as to produce these results; for, except in the case of a foundation below a fall being affected by underground percolation or leakage from above the fall, or the nearly similar circumstances of the down-stream apron of an overfall weir, when the water is higher above than below the weir, the water immediately over the disintegrating floor or other foundation is directly continuous with the water below which is working the mischief. The latter water is therefore not pressed on by any superior head to that which overlies the structure itself, and can therefore exercise no lifting effect on a flooring, or, indeed, active effect of any kind, as it might do on the principle of the hydrostatic bellows, if the water below were distinct from that above the foundation and connected by a separate tubular channel with water standing elsewhere at a higher level.

Here, again, the analysis of impingement action seems to facilitate an explanation.

The pressure exercised by the velocity of the original impinging current is comparable with that of a certain head of water.

In the down-sweep after impingement, though some of the original velocity and force have been expended on the obstruction and in the change of direction, yet there is still considerable current pressure, which seems to act almost with concentrated energy when rushing down into a comparatively confined and narrowing scour cavity.

Each part goes down with its own speed, and when checked, it is constantly pushed on by the succeeding water.

The leading portions of the down-sweep, acting with this continuous force, are ready, under its pressure, to penetrate any where they can find an opening, quite as readily onwards in an under-sweep as in any other direction, and perhaps even more so.

On finding an opening, however small, the stream bores its way in and soon enlarges it by washing away fragments of lime, sand, &c.

But if it once gain admission into the closed chamber formed by the flooring, drop-walls, pier foundations and bottom material, no matter how small the channel of entry may be, it presently begins to act with hydraulic force as in the hydraulic press, the current force, diverted by impingement into down-sweep, acting in lieu of the pump force. Or at a fall, it may be some thread of the descending current which gains admittance through a flaw in the masonry, and acting in continuation of, rather than by deflection from, the down-pour.

In either case this may at length loosen and burst up the flooring, though scarcely "blow it up," unless there were air, i. e., an elastic fluid, also confined below the flooring.

If openings can be found or forced in the down-stream drop-walls, or in the flooring, without bursting it, the pressure may be relieved without actual disruption, but probably some degree will remain, and there will be movement of water under pressure through the foundation works, which will loosen and remove lime, sand, &c., and finally may hollow out and practically destroy the foundation. [Note 22 L.]

XXVIII.—*Mr. Login's plan for protecting cylindrical piers and foundations.*—The

* *Vide* pamphlet before quoted.
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plan* recommended by Mr. Login, for protecting cylindrical pier foundations from scour, is by attaching a hollow shoot to the up-stream side [and, if need be, on the down-stream aspect also] and carrying this a considerable number of feet below the bed-level, say half-way down to the foundation base.

Into the shoot after its being cleared out, stone or other heavy material is to be thrown at the top. This will sink farther of itself, as scour penetrates below the open shoot bottom.

The subsidence will be visible, and more can then be thrown in even during a flood.

The shoot being made in cut-water form, is intended also to receive the current better than the bluff circular pier, and so to help in directing it more to the centre of the archway, so as to scour deeper there; while the immediate skirt of the pier is protected by the stone or other material lying in a slope around it.

This material may be partly moved by the current from the stem to the side, and will slide to its own angle of repose from the heap first formed immediately below the shoot.

Mr. Login remarks that deep streams have less power of transporting heavy material than shallower currents, and that, therefore, material of a weight in each fragment, which would be swept along at, say, the depth of the ordinary bed-level, may be able to resist transportation by the same velocity of current if previously deposited 10 or 20 feet deeper, and the current should scour so deep.

In Part XXI I have noted the steps by which, starting from a different point of view as to the action in pier scour, and travelling by a different route; the analysis I have attempted to make arrives at the same practical conclusion, viz., that comparatively light material will, if deposited at a greater depth [meaning here joint depth of current and scour] be as able to resist transportation by the current as heavier material when placed at a less [joint] depth from the surface.

Observation and experiment [on a small scale, it is true] tend to show that the onward current does not extend to the depth of the scour hollow, but only dips a little below its own proper bottom in the bed above, that a good part of the lower layers of the current itself close to the pier-head constitute a down-sweep, and that, even in the superficial layers, there is in the part-water line close to the cut-water surface a checked and uncertain condition of current.

From these points it would seem that sounding explorations, and the deposit of heavy material, if attempted, at the part-water line, with a good vertical fall given before reaching the surface of the water, would, even in a moderate flood, not be so hopeless in respect to the lead or heavy material reaching the bottom without being carried far onwards by the current, as they must appear to be from the surface rush of the water, and from the impression that they have to encounter an equal onward rush of the current all the way down to the bottom of the scour crater.

This last word used by Mr. Login is very felicitously descriptive of the form of excavation, especially at circular or bluff-headed piers.

Or, if protection to the descending lead or material were needed, and given by a tube fixed to the stem till the down-sweep layers are reached, perhaps this much might suffice, if at the part-water line, as the down-sweep there would itself aid direct descent, though the weight or material would need to be heavy enough to resist expulsion when it reached the bottom of the scour hollow.

SECTION E.

EXPLANATIONS AND PRACTICAL INDICATIONS AFFORDED BY PRESENT ANALYSIS.

XXIX.—Resumé of matters explained by present analysis.—The present analysis of the impingement action of moving water appears to explain and bring together a number of facts now separately known.

Sundry of the facts alluded to are here re-capitulated:—

1.—Scour immediately at the up-stream skirts of cut-waters and sides of piers and wing-walls, &c.

2.—This scour, if it reach down to the very base of an obstruction, and find loose material beneath it, turning forward in an undersweep, scouring out and undermining first at the up-stream toe, so that the obstruction, if able to resist the onward thrust of the current, then tends to tilt over in the up-stream direction.

3.—Scour along the concavity of banks in a winding stream on their face and skirt.

Scour in this situation supplying an explanation for any tendency in each bend to progress, as a whole, downwards as regards the general direction of the main channel.

4.—Scour a little on the down-stream side of a bridge at which the water-way is contracted, but tending to reach back to the bridge.

5.—Similar scour-pools formed elsewhere in the general bed, where a more rapid current dashes into a slower one, or into quiet water, or into water moving in a different direction.

6.—In channels of just sufficient capacity for the stream, scour similarly produced, not only on the bed by the down-sweep, but on the sides also by the lateral out-sweep, as, e. g., in front of the foot of canal rapids and ogee falls, &c.

7.—Besides the more patent deepening at foot of a water-fall and the retrogression of the fall itself, a similar deepening and retrogressive lowering of levels from the lower termination of portions of a canal having excess of slope (and hence of velocity) in relation to nature of bed material and inclination further on.

8.—Regimen of rivers being affected chiefly by conditions in lower portion, and thence extending backwards up-stream.

9.—The boring penetration of the down-sweep, whether with or without an onward or other turn, or of any current, deflected or not, if it gains entrance by an interstice or crack in drop-walls, floorings, &c., into any interior space within foundations, such as that beneath floorings, &c., and its tendency there to hollow out, disintegrate, or even burst them.

10.—Scour strongly developed beneath an obstruction, between which and the bed a passage exists, by the down-sweep impinging on the bed and deepening it, while it presently turns ahead as an onward under-sweep and scour.

11.—The extra scour under a floating break-water in a stream by the down-sweep from it, though at the same time the break-water may help to divert the surface current by the lateral out-sweep also induced.

12.—Probably the action* on the bed and sides of a canal, produced by a boat of considerable size in relation to the canal section, and moving at high speed, is similar to that in the two last instances; the only difference being the interchange of power and resistance, the solid body in this case representing the moving force, and the water the resistance.

13.—The fact that the violent action of descending water in canals is got rid of sooner and more easily with vertical falls and sunken basins at foot to receive the falling water than by rapids.

14.—The farther benefit derived from gratings at a canal fall.

15.—Possibly also some part of the destructive action of waves in shallow water, driven bodily onwards (and not merely undulating progressively) by the wind, when they strike a vertical sea-wall, is due not only to the battering force of the primary impingement, but also to the consequent down-sweep scouring and undermining at the skirt of the wall, if not protected by a sloping approach of masonry or of rocks.

If my memory serves me right, the destructive effect is less in deep water, and possibly the explanation is as follows:—

When the depth is such that the *onward* movement does not extend to the bottom water, the latter, though somewhat disturbed, acts as a cushion to break the force of the down-sweep from the wind-impelled surface waves as they impinge on the wall.

At sea-walls, &c., during a storm, it is a familiar fact that the brisk up-curl and quieter up-swell of an ordinary current on meeting an obstruction are intensified into an up-dash of water and spray many feet high.

There is, indeed, no lateral issue except at the free ends of moles or break-waters, but the movement is not a continuous or current push, in which case, if the wall withstood it, the water, if unable to pass, must be brought to rest. It is rather a series of separate blows, each like the first impact of a flood torrent "coming down like a wall" on an obstruction, which is more immediately dangerous than the subsequent push of the current.

16.—Active scour has been observed in some places where there are eddies, as on the sides of a canal below falls and rapids; and hence eddies have sometimes been credited with peculiar scouring powers beyond those of a direct current.

They are, however, generally the result of a prior impingement and deflection of the latter, and are naturally therefore weaker, if anything.

At any spot an eddy passes laterally or frictionally its scouring power may thus be less than that of the more rapid stream from whence it has been derived.

But when it meets an obstruction more or less *transverse to the line of its movement at the time of meeting it*, and thus *impinges* on it, then it will scour more than the friction of its parent current, though, being of a secondary nature, it will do so less than the latter would, through its greater velocity, have effected by a primary impingement on the same obstruction.

In the situation given as an example, the action on the sides of the canal appears to be from the lateral out-sweep, as that on the bottom is from the down-sweep.

The analysis, by *distinguishing the two modes of action*, thus seems to bring direct, and backward or whirling, flow under the same general principles.

XXX.—Indications from analysis on practical points.—Form of pier.—Besides its aid in explaining or defining various matters, the analysis appears, as already more or less noticed, to offer sundry practical suggestions regarding bridge works which will be further discussed in this and the succeeding Parts.

The point found most strongly marked has been the difference in local intensity of force on equal areas between impingement and friction.

Between perpendicular impingement and parallel friction there is a wide range at any angle within which a mixed action may take place, having more of friction the greater the angle of incidence [with the perpendicular] and the more of impingement the less.

As the special scour now under consideration is caused by a diversion of the current force, or part of it from its original nearly parallel direction, in which it acted only frictionally on its bed, to a direction more or less perpendicular to some part of the channel so as to act impingently on that part, rather than by any increase of mere velocity and consequent extra frictional on-scur, the advisability naturally suggests itself of bridge works being so outlined that the angle, whether horizontal or vertical, of current incidence, may be as far as practicable from being perpendicular to the plane impinged on.

The distinction may be noticed that at bridges of the two modes of action, the more of friction there is, to the exclusion of impingement, the better, while, at drops of level in canals, impingement falls are found to be practically the best. Also, that at bridges the more oblique any unavoidable impingement is, the better; whereas at changes of canal level, vertical falls are found to be under better control than oblique ogee falls and rapids.

In canal works, however, the change of level is unavoidable, and there must [practically speaking] be impingement somewhere, and of some kind or other in effecting it. And it happens that it can, in most places, be best dealt with by receiving and disposing of it at once by a vertical fall into a depressed basin containing a cushion of water, the sides of which basin take the secondary as the cushion softens the primary impingement. [Note 23 L.]

At a bridge the impingement is in some degree optional. If abutments are built flush with the bank, and the channel can be crossed in a single span, no impingement action will be caused by the bridge at all.

And where it is necessary, owing to the great breadth of a channel, to narrow the water-way by abutments and piers, it is still possible to give them that form which will excite least of the particular action which in that situation will be least under our control. It happens that at all ordinary bridges this action is impingement, and hence the more that friction can be substituted for it in such situations so as to have as little impingement as possible, and the more we can make that little oblique, the better.

As greater width and bluntness of pier seriously increase impingement scour, a comparatively narrow and elongated form with sharp cut-water seems preferable to a simple cylinder

at which friction is almost reduced to the two points where the cross-stream diameter touches the circumference, and impingement acts on half the periphery around, more indeed than which half very deep scour extends; while at an elongated pier, with a current coming fair on, the deepest scour may not embrace more than a quarter of the pier circuit, if even so much. If, however, the current attack it obliquely on the side, the scour will be greater in some proportion to the greater opposing measure, and this necessarily imposes a restriction on length.

The increased base in the stream line will give greater stability to resist the push and shaking of the current as occurs with a cylindrical column of great height; and if under-scoured at the cut-water toe, an elongated pier might have enough foot sole and heel to rest on for the short time the worst floods usually last, while a circular pier similarly under-scoured at its cut-water, *i. e.*, its up-stream half section, could scarcely stand on the down-stream half alone.

The narrower a pier is in cross-stream section, the less obstruction there is of water-way, and the less afflux above and increase of velocity past them, and consequently less of the scour on the down-stream side of the bridge from the contracted span-way streams dashing impingently into the slower water ahead.

A circular well is found the easiest to sink, but where funds will not permit the cost of a group of 10 or 12 wells forming an elongated foundation—as at the Jumna and Soane Bridges of the East Indian Railway—to support an elongated pier resting thereon, it would seem worth considering whether 6 or 4 such wells, or even a couple, could not be allowed; or whether, if absolutely only one can be afforded, that single well might not be built somewhat elongated, or oval, with its long diameter in the stream line, instead of being simply circular [Note 24 L].

Since writing this Abstract last month, I have, while it is being copied out fair, had an opportunity of seeing the issue for April last, No. 4 of Vol. I of the 2nd Series of the *Roorkee Professional Papers on Indian Engineering*, from an Article in which I have, since then, inserted extracts in Part III of this paper.

The Report therein published, of the Committee assembled at Simla in September and October 1871, to decide on the form of piers for the Punjab State Railway bridges, shows that there were two proposals before it, *viz.*—

(1).—A single cylinder, 18 feet in diameter.

(2).—A pier to be composed of two cylinders, each 12½ feet; the depth to which, in either case, the foundation should be sunk being 60 feet.

The Committee decided by a majority against the single enlarged cylinder, and recommended, even in place of two wells of more moderate size, that *three* such should be built in line, and an oblong pier with a cut-water should be raised on that foundation.

Government thereupon so decided.

If the rationale of scour action at piers now outlined be correct, it supplies a very strong reason in support of the recommendation of the Committee, additional to the reasons given in the Report, when it is perceived that whatever increase of velocity the obstruction of the piers may cause past them, the dangerous and special scour is not due to that velocity alone, or to its ordinary unimpeded operation, but that the obstructing pier is itself, in proportion to its transverse width and bluffness, an essential co-efficient with the current in generating the dangerous mischief.

It would seem also that, through the above procedure of the Committee and Government, the Punjab (State) Railway may be congratulated on escaping for its bridges the still more formidable scour which would thus have been generated by cylinders of 18 feet diameter than that produced by those of 12½ feet on the Delhi Railway, whatever increase of strength and stability might otherwise have been derived from the greater measure and depth of foundation.

XXXI.—*Indications continued—Depth for the upper surface of protective arrangements. Width of protective arrangements.*

The importance attributed in the beginning of Part XXIV to a knowledge of two points, *viz.*—

Bottom of current proper, and width of down-sweep, is connected with what appears to be their bearing on protective measures against scour, if induction from observation and experiment on a small scale be correct.

Their bearing may be thus *generally* stated :—

There is a certain *depth*, namely, that of, or rather just below the lowest bottom level of the current proper, or in other words, the lowest level to which the current can lower its bed by ordinary on-scour higher than which the upper surface of the protecting work or material should not be, otherwise the current will catch on it and establish down-sweep on the latter itself.

If the upper surface of the protective arrangement be placed fairly below this point, no theoretical advantage is gained by placing it deeper; but there is this practical difference, that the down-sweep, though presumably greater with greater depth of current producing it, becomes expended and weaker every foot it scours out below the depth of that current pro-

per; and therefore if loose material, stones, &c., be used for protection, lighter blocks will be more secure from expulsion at a greater, than at a less, depth below the general bed level around.

Hence, if material be procurable only in comparatively small and light pieces, these will need to be deposited deeper than would be safe enough for heavier blocks. Their resistance to removal may be supposed to increase with augmented size as the cube, while their exposure to the water-power increases rather as the square.

With a current just sufficient to maintain a slight scour hollow and show the action on the sand, I threw in, as an experiment, a number of small pebbles taken for sake of recognition from a different river, and of a particular sort and colour.

One morning they were not apparent.

The stream was a little more turbid and higher than the previous day, and I thought the stones had, from the disturbance of the sand, buried themselves in it. But it was not so. The stream had risen in the night 2 or 3 feet, thereby doubling its then depth and increasing its velocity. This temporary rise had scoured out the stones, some of which were seen in, and others just beyond, the scour-pool below the bridge. Though they were small, ranging only up to 12 ounces, they were dense and heavy for their size. It was intelligible that such rounded pebbles might easily be rolled along by the current when once they were on the bed-level; but that they should have first been thrown up out of an abrupt hollow, and afterwards some of them carried through another more gradually sloping pool, gave a vivid impression of the intensity of action at the cut-water, and to a less extent in the pool below the bridge.

Similarly, there is a certain *width*, namely, that of the down-sweep at the skirt of pier and other obstructions, varying with variations in the conditions producing down-sweep, which is liable to this scour, and if that width be fully protected [with a slight additional margin] further extension of protective floorings, &c., appears unnecessary; unless, indeed, it be desired at any place permanently to fix the bed surface, or lowest passage level, at a certain exact level, as may, perhaps, sometimes be requisite. Such fixed level, however, if it check velocity and natural scour, and hold up the water up-stream, increases the fall and scour below it. [Note 25 L.]

If the required width of protection be not given at the skirt, the outer part of the down-sweep will attack the bed beyond the margin of protection.

These matters merit, however, more detailed examination.

As regards the *width*, there appears to be no option if *complete* protection be desired.

Subject to the above reservation as to reasoning from experiments on a small scale, it would seem requisite in every case that the protective arrangements should extend up-stream from the main work needing protection, fully to the width of the inner zone of down-sweep scour, which the particular current at its highest would establish against the particular work if unprotected; and, to ensure safety, they should somewhat exceed that limit.

I have spoken above of *complete* protection, because possibly there might be sufficient practical protection with a little less width, as although in that case an outer ring of the down-sweep would reach the bed beyond the margin of protection, and scour it to some degree, there is reason to believe that the outer portion of the down-sweep is comparatively much weaker than the inner portion close to the pier surface on which it is generated.

One might expect also that the back-turn of the inner portion of down-sweep when arrested and deflected outwards by the protective work, would strike upon and interfere with the down-sweep farther out, though my experiments have not yet demonstrated this satisfactorily.

But for completeness and safety, it would be better to exceed somewhat than fall short of the strict limit.

In respect to the *depth* at which protective measures should be placed, there is, under a certain condition, an option. That condition is, that the current shall not be able to turn the flank of the protective arrangement and pass it laterally, but can pass it only by rising above and flowing over it, as over a weir or dam.

Except under this condition, it is essential for complete protection that the upper surface of the protective arrangement, and more especially the upper edge of its up-stream margin, should not rise above the lowest possible bottom level of the current proper.

For entire security, a margin of slightly greater depth would be advisable, although, *perhaps*, practically sufficient safety might be obtained somewhat short of it.

For instance, a protective platform or footing, entirely solid might *possibly* be safe, though projecting a foot or so above the bottom of the current proper.

That height [supposing, of course, there was the indispensable width to receive and dispose of the down-sweep from the upper work] would be impinged on only by the lower foot

of the current, and perhaps that foot might not generate enough scour to be dangerous, although the usually greater breadth of such lower works would cause greater scour than a similar height of the narrower pier above, and the action might, therefore, be formidable.

But if the protecting or protected work had any crevices and looser material in its interior, as under a flooring with curtain-walls, &c., the down-sweep from even a foot height of obstruction might penetrate and work mischief. [Note 26 L.]

This boring interstitial damage is independent of whether the current passes the protective work laterally, or only by surmounting it.

To run over details according to the nature of the protective arrangements:—If these are applied separately to each pier, &c., so that the stream, if it could get low enough by ordinary scour, might pass them laterally as well as go over them, they must be kept below the indicated depth-level.

If not as low as, or lower than, the bottom of the current proper, then, even if wide enough to check the downward deflection from the protected work, a down-sweep scour is established on and against themselves. This refers more particularly to protective works of masonry. If composed of loose stones, these, if massive enough to resist removal, would, if under-scoured, simply fall lower and into a better place; while, if not sufficiently heavy, they would themselves be scoured away, unless at a depth below the general bed-level proportionate to their lightness. [Note 27 L.]

But if the protection be applied across the whole channel in the manner of a continuous flooring, so that the water cannot pass the protective works laterally, then, provided the conditions of width from the piers in the up-stream direction and impermeability are complied with, the flooring may, so far as this special down-sweep scour is concerned, be raised like a weir or anicut with a bridge constructed on the top of it. The tendency of oblique culverts at weirs has already been noticed.

Of course, sufficient strength and closeness of construction is here supposed, together with the protective measures at the down-stream skirt needed for weirs.

If the continuous flooring do not stretch as far on the up-stream side, clear of the piers, abutments, or oblique wing-walls, against which the stream impinges as the down-stream or inner zone of scour from them extends, the flooring, even if low enough, is itself partially endangered by the outer margin of the down-sweep from the piers, &c., playing on the natural bed material beyond the curtain-wall border of the flooring.

A flooring with up-stream border simply stretching from pier stem to stem, or even with its drop-wall margin fairly clear of the cut-waters, but without the above breadth being attained, does not suffice.

On the experimental scale I have seen a curious propagation of the down-sweep at a too prominent pier carried along the face of the adjoining continuous flooring, where, but for the pier down-sweep reaching the bed beyond the flooring and starting the movement, such action was not to have been expected.

In the Resolution of 20th December 1871, on the Report of the Committee on the Pier design of the Punjab (State) Railway Bridges, quoted in the preceding Part [XXX], Government directed that "for the further protection of the abutments of the Ravee and Chenab * * * a brick flooring, 3 feet thick, be laid round each abutment, and one pier nearest to it protected by a curtain of deep blocks all round: the line of curtain blocks being 40 feet from the wells of the piers and abutment on the up-stream side, and 75 feet from the wells on the down-stream side, and extending 40 feet beyond the piers on the one side, and 40 feet beyond the abutment on the other side. The line of curtain blocks should be 20 feet deep on the sides parallel to the stream and on the down-stream side, and 10 feet deep on the up-stream side. All round the flooring outside the curtain blocks, there should be thrown in boulders or brick-rubbish, at 200 cubic feet to the foot run where they are 10 feet deep, and 100 cubic feet to the foot run where they are 20 feet deep."

If the indications of the present analysis have been rightly understood, they would imply that, unless the rivers named have some extraordinary depth in floods, the up-stream extension of the flooring will be amply wide to receive all the down-sweep from the pier thus protected.

The level at which the flooring will be placed is not stated. The analysis suggests that it should be as low as possible, more especially as regards all its exposed margins; and that if the up-stream margin be not as low as the stream can deepen its bed by on-scour past it, there will be impingement scour established on it and the curtain-wall, working round to the stream face, and that this scour may be expected to be strongest as in all such cases, and at spurs, &c., it is at the angle between these two sides.

Of course, all the grounds on which the design and proportions of the flooring were decided are not detailed in the Resolution, and thus as regards the smaller width of flooring and smaller depth of its curtain-wall blocks on the up-stream than on the down-stream side, I can only note the general suggestions of the analysis as to the greater measure in those respects being usually needed on the up-stream side, unless when the flooring is so raised

or the water-way so contracted as to produce a fall, rapid, or rush on the down-stream aspect of the bridge, in which case, as the arrangements possible in a canal are not practicable in a large natural channel, the best plan is to carry the apron in a slope as far and to as low a level as possible.

In a comparatively small work I have found a rough block and boulder slope carried * Coarse and gravelly, below the dry-season water-level in the sand* and then flattened out beneath it stand floods of 6 or 8 feet in height without injury. The floods, however sudden, thus never could find bare sand or stone to impinge on at the foot of the slope, but encountered a cushion of water. More stone was thrown in or placed in that rough sunken flooring or apron as found to be required till matters seemed to arrive at an equilibrium.

The action at the foot appeared to be strongest when the stream was only deep enough to form a violent rapid down the slope, and to be weaker when the water was so deep that the obstruction was, as it were, drowned, and there was a uniform flood surface with little or no mark of obstruction below. [Note 28 L.]

The object of protection being by this analysis defined to be to receive check and deflect horizontally outwards the impingement down-sweep, and prevent its penetrating deeper, or to the very base of the foundation, it is,—provided this object be attained,—obviously no matter by what means it is so—whether by loose boulders and stones, or by masonry footings, platforms or floorings, or any other material or substance; or whether the protective be constructed with the original work, or added thereafter.

Spurs and embankments are often protected by bamboo screens and mats, or by piles and brushwood, and when these slide down or fall forward, they are still found useful in their lower or advanced position.

The analysis explains this.

In the first position, of course, they protect the face of the work from the direct primary impingement of the current; while, in the second, they slide or fall over the skirt, and so protect it from further excavation by the down-sweep.

With this knowledge they might now be designedly placed in both positions from the beginning.

XXXII.—Effects of a slope.—It is well known that a gently sloping bank will resist erosion under conditions which would scour away a steeper bank.

A covering of turf in either case helps to protect the surface, but still there is a decided difference of effect due to slope.

A sudden flood occasionally "comes down like a wall" in Indian torrent beds. An obstruction across the channel will be far less able to withstand this if it opposes thereto a vertical face, instead of a sloping surface up-stream.

The former will be exposed to a battering blow at first impact, then to a continued thrust, until the momentum of the water up to the top level of the obstruction, and in the up-stream direction somewhat towards the point where the bed coincides with that level, has been checked; and until this has been effected, there will be strong downward pressure at the up-stream skirt of the obstruction, though it will be hampered by want of free lateral issue.

After that wedge-shaped mass of water has received a check, the force below the obstruction level will become gentler, and the tendency will be to rise and flow over the obstacle rather than to dig down at its base.

But before this stage, which is the usual condition of anicuts and weirs, has been reached a vertical obstruction may have yielded to the sudden violence of the triple attack.

Yet an obstruction, though not made of stronger material, may withstand the assault without injury if it presents a slope up which the flood may rush, acting with more of friction than of impingement.

Sand-banks usually exhibit this slope naturally on the up-stream side. It may on them be coated and partly protected by pebbles, kunkur, or coarser gravel than in the rest of the bed, or some such difference of bed material, original or transported, may have led to the formation at the place of a shoal or bank.

But, without the gentleness also of the slope, such material could not remain even for the period a sand-bank may retain its position.

If the sand-bank received the current with a steep front, such material would be quickly scoured and undermined by the impingement and down-sweep.

The plank experiment mentioned in Part XXII illustrated the result of lateral or horizontal obliquity; but a similar result was obtained by varying it so as to see the effect of a deviation from the vertical.

When the upper end of the plank was gradually tilted over down-stream, it was found in the writer's experiments that, at an angle of about 45 degrees with the perpendicular, the down-sweep at the up-stream skirt of the plank, though still feebly at work on a narrow line, produced little or no deepening effect, and that, at an inclination of about 22 degrees

further, the play of the down-sweep, as judged by the cessation of all movement in the sand particles at the skirt, had ceased to reach beyond the plank slope to the bed itself. Sufficient inclination down-stream, in fact, favored the detention of the bottom on-sweep material and its accumulation into a sand bank.

The angle of 45 degrees gives a slope of one to one, *i. e.*, the base of the slope was of the same measure as the vertical depth of the current.

This angle may be considered as midway between the lines of full impingement and mere friction.

If it were safe to draw any inference from a few small experiments, it would be that the breadth of the down-sweep and inner zone of impingement scour does not exceed the depth of the current, even when a square-headed pier is opposed to it.

The whole of the down-sweep of any force was evidently received on the slope itself, and not on the skirt.

Indeed, the scour was not of great note until the sloping plank was raised to be only one-quarter of a right angle from the perpendicular.

It was greatest in the actually vertical position, except, indeed, when the plank was tilted a little up-stream, on which the scour became worse by an admixture of under-sweep.

Although the foregoing proportions might imply that the breadth of the true scour-zone equals the depth of the current, it is to be noted that they were roughly estimated, taking full and whole numbers, and were observed against a square-headed obstruction.

Practically, therefore, I apprehend that down-sweep impingement scour of *any dangerous force* has not, under ordinary circumstances, a breadth equal to the depth of the stream, and probably it is very much less.

A little of the down-sweep from the upper part of the current impinging on the plank doubtless flowed down the slope, and thus reached the bed at the foot, so as to make the sand move sufficiently to keep the on-sweep from actually beginning a sand-bank there, which would extend up-stream; and even such action I reckoned.

But this movement, though of similar or allied nature, was very different practically from that which is strong enough to scour at a hollow.

As the current impinging on the slope is checked first in its onward progress, and the down-sweep from this check is next received on a lower part of the slope, the slope thus takes both the primary and secondary impingement, so that any impinging impulse which reaches the skirt of a sufficiently long slope, can only be of a tertiary nature and weak and oblique. The deflection from the very lowest part of the slope may, doubtless, impinge secondarily on the inner border of the skirt, but it will be narrow and insignificant.

And when, in place of a sloping bank being directly or transversely opposed to a current, it presents obliquity thereto, also laterally, or in the horizontal plane, the down-sweep, as already described, is reduced in intensity while being spread along a line longer than the measure of its actual obstructive capacity by so much the more as it departs from being directly transverse to the stream.

It will be observed that a sloping bank cannot be attacked by running water with full rectangular impingement in every direction, because, even if the current impinges perpendicularly to the horizontal line of the bank, yet, in the vertical direction, the slope presents an obliquity on whose plane obliquely falling water alone can strike at right angles.

A slope further has this important quality, that it tends to increase the proportion of the harmless upward deflection at the expense of the danger-working down-sweep.

From the experiment with a float and drag mentioned in Part VII, it will be intelligible that, even if a slope be not gentle and long enough in base line, in relation to the depth of the current, to receive the whole down-sweep, still, in receiving that from the upper layers of current, it will dispose of the most active and inner belts thereof, leaving only the weaker outer belts to play on the bed material beyond its margin.

XXXIII.—*Indian water-ghât, or stepped form of masonry slope.*—Possibly there is no great difference, except in the matter of deflection upwards, between an even slope and an uneven or stepped slope.

The former might be compared with a stair having a great number of very minute steps.

The effect of a stepped slope is, in one respect, however, most easily analysed.

For this purpose it is better to consider each step as consisting of a vertical face up-most, and a horizontal surface or footing below it, than as composed of a plateau and a perpendicular scarp below.

In this way the upper surface of the topmost step is not reckoned at all, and the lowest step would end with a horizontal surface level with the river bed.

Supposing now ten steps, each a foot high and a foot broad, and the stream to be 10 feet in depth, the upper step would take and mostly dispose of the impingement of the upper foot of the current.

The primary impingement would be on the vertical face, and the secondary impingement of the down-sweep from it would be received on the horizontal surface at the skirt of the scarp.

The second downward step would similarly receive the impingement of the second foot layer of the current, and so on downward to the last.

Farther into the stream than the horizontal surface of the lowest step, there would probably be no down-sweep, or any that did occur might be a comparatively weak and oblique deflection from the lower steps.

Instead thus of each of the 10 feet of current depth contributing to the down-sweep in immediate contact with the wall surface, as might have been the case had the latter been a simple vertical wall, the upper and most land-ward step receives only that of one foot of current depth. And though there may be a little impulse from each upper step affecting the next lower, yet, in the main, each step has merely to encounter the impingement of one foot depth of current.

In this way the current, instead of being able to attack the skirt of a vertical wall, close in at the base, with the deflected force supplied by 10 feet depth of running water, is broken up and received in detail.

On the foregoing understanding of the effect of a slope, the ghât, or stepped form of water-wall so much used by the natives of India, has an advantage over a bare vertical wall at river sides against which a current sets. The vertical form would need deep foundations, or a broad apron over its skirt, or both, to prevent down-sweep scour.

But in the ghât form, if the slope be great enough, the steps themselves will receive all the violent down-sweep, and the skirt beyond the lowest step will almost wholly escape.

If, indeed, under some circumstances, the current become deadened near the ghât face, and the stream behind be deflected by impinging on that quieter water in front, then possibly scour may be developed clear of the slope foot.

In the above respect this form may not differ from a smooth slope, but the stepped ghât probably does not aid upward deflection as a smooth sloping ramp does.

XXXIV.—Footings, or out-spread of foundations beyond the surface of the pier above, act, if they are below the lowest bottom level of the current proper, beneficially in checking down-sweep so far as their width extends, and it is to be noticed that the strongest down-sweep is close to the pier where the footings are. [Note 29 L.]

The footings thus given to the piers of the Jumna and Soane Bridges of the East Indian Railway, especially at the cut-water, must, so far, check down-sweep.

Probably it is of little practical consequence whether such footings project at once like a border terrace around the base of the pier at its junction with the foundation structure, or are sloped in an even batter, or in a number of little off-set steps, provided that the whole footing of whatever shape is below the lowest bottom level of the current proper.

But this and many other questions could only be settled by experiment or experience.

The slope carries the outer edge farther down, and therefore more out of the reach of attack by primary impingement from the direct current.

I imagine therefore a slope, whether even or stepped, would be safer than a flat out-footing if the highest part of the slope were on the level which would be given to a flat footing, but that the latter might be the best if it were at the level which would otherwise be given to the outer and low edge of the slope.

Footings, if low enough down, thus help to act at pier skirts as aprons elsewhere; and, as in the case of masonry aprons, there might be substituted, so far as that function is concerned, either an apron or a sloping talus of boulders, or other heavy material, or, in fact, anything which would check and deflect out-wards the down-sweep so as to prevent it excavating deeper.

The primary object, however, of the footing extension of the foundation is, of course, to give greater base and stability to the pier; but if this broader part of the foundation be not below the lowest level to which the current on-scour may lower the bed, its extra width in the cross-stream direction will contribute to scour by generating a down-sweep from itself when impinged on by the stream.

XXXV.—*Summary of indications regarding bridge works.*—The chief practical points in connection with bridge works which the foregoing analysis of impingement action appears to indicate may be thus recapitulated—

1.—Of the several elements conducing to scour at piers, the effect of the artificial condition, *viz.*, the pier itself, is in some degree under control.

A pier with a sharp, sloping cut-water, and of a comparatively narrow and elongated form, possesses several advantages over a thick, bluff or circular pier, though there are certain restrictions against excess of narrowness and of length.

2.—If pier foundations are to be farther protected from this special scour, otherwise than by being carried down below its lowest possible limit, and being made of that form which will generate with the current least scour action, there is a certain depth below which the upper surface of any protective arrangement should be, *viz.*, the lowest bottom level

of the current proper, excluding the special scour excavation itself, but including any increased depth which the current can make for itself by simple and unobstructed onward scour immediately before reaching the pier.

3.—Similarly, there is a certain *width* around a pier greatest at the cut-water, less at the sides, and least at the down-stream border, which requires such protection; this width being that of the down-sweep from the primary impingement of the current on the pier-head, the hollow scoured out by the secondary impingement of which down-sweep is prolonged some way onwards from the up-stream aspect of the pier, or abutment, or wing-wall.

4.—The action is so strictly local and confined to the skirts of the piers or other obstructions, that if the width and depth proper at each place, with a fair additional margin, be given to the protective arrangements, there appears no necessity, as regards protection of the primary works, to extend the former still farther, or altogether across the channel, as in a continuous flooring, unless there be some other and independent reason for doing so.

5.—If the requisite breadth and depth be not given to the protective works, they will themselves be attacked and may need protection. Thus, they may be penetrated, under-scoured and disintegrated by the tendency of the down-sweep to bore in whatever direction it can progress, acting in any enclosed space below, to which it gains admittance (as under a flooring) with a degree of hydraulic pressure or force derived from the continuous onward push of the current converted on obstruction into the down-sweep.

6.—Scour, occurring on the down-stream side of a bridge, implies greater velocity of the current from the bridge openings, than in the free current below—arising from *relatively contracted water-way in the former*—or from its having a flooring higher than the lowest level to which the current can lower its bed by ordinary on-scour.

The contraction was above styled *relative*, as the water-way may be ample for the fullest flood discharge, and as large as in the channel on the up-stream side of the bridge.

But if the channel suddenly widens immediately below the bridge, the velocity of current will be less in the widened part, and the archway streams will dash impingently into it, producing down-sweep and scour.

Such scour from impingement of water on water at the down side of a bridge is, however, ordinarily more diffused and less concentrated and dangerous than the scour from impingement on the bridge works themselves at the up-stream skirt.

The protective arrangements on the up-stream and side-skirts of the piers, &c., will, if continued around the down-stream aspect, usually suffice against the action here also, a general indication being to keep their surface, and especially its outer margin, as low as possible.

If further protection be required, it can be had from boulders, which may resist movement here when of a size and at a depth that would not be safe against the more intensified down-sweep at the pier cut-water.

7.—When a point merely below the lowest level of the bed, however lowered by ordinary on-scour, was above indicated for the upper surface of the protective works, solid footings, platforms or floorings were in view.

Where loose stone is employed, it must, unless in enormously massive blocks, be placed much deeper, especially at the pier cut-waters, and the up-stream aspect of other works; and it needs to be lower in proportion as the pieces of material used are lighter.

XXXVI.—*Conclusion*.—Though the physical facts observed as to the movements of water on impingement were such as to be patent even to an uninstructed eye, and could not be intelligently observed by any one without sundry inferences suggesting themselves, yet, of course, the accuracy or practical value of these can only be tested by engineering experience.

As the subject grew and unfolded itself, earlier observations and impressions were often corrected by further examination and experiment.

At the present stage, therefore, I cannot but feel that in the *matter* of this paper many points must need correction, as I know that, in its *manner and arrangement*, there is ample room for revision.

There has, in hurriedly writing a general description, been a difficulty in avoiding the use of various terms in accordance rather with their looser popular mode of employment, than in the more exact or technical meaning to which science has restricted them. I have also been obliged to make some new combinations of words, such as *part-water*, *down-sweep*, &c., &c., to express clearly and briefly the action observed.

Another difficulty has been that, beyond references of the nature quoted in Part III, to scour effects found scattered throughout Engineering writings in connection with particular works, I have come across no treatise, article, or, indeed, anything treating directly and explanatorily of scour action itself; and thus, when endeavouring to trace out the precise *modus operandi*, I have mostly had to feel my way merely by the light which nature herself threw before me on her own proceeding.

But I have absolutely no time or opportunity at present for further enquiry or revision.

This paper must either be submitted, imperfect as it is, to the perusal of those competent to judge, if there is anything useful in it, or it must be thrown aside.

Hoping that there is something elucidatory of scour action which may lead to useful practical results, I venture on the former course.

Indeed, if the principles of the analysis of impingement action now hurriedly attempted should be proved correct, they may possibly be found to furnish a key for opening up various intricate and otherwise obscure matters in water action.

Although I have, for rough and ready convenience of practical distinction, spoken of ordinary scour in free channels, and of special scour at obstructions as, respectively, on-scour and back-scour, or as frictional and impactional, the intention is not thereby minutely to define the points of difference, or to exclude the elements of similarity or connection.

If the supposed sequence of secondary impingement, after a primary impingement on water itself be found fully correct, it would seem, indeed, that this may further encroach on the sphere even here spoken of as that of ordinary on-scour.

But the present paper having originated in observation of scour at obstructions, and having already attained excessive dimensions, cannot, though sundry points connected with unimpeded action also came under notice, attempt to discuss the *entire* subject of scour of which that at impediments, solid or liquid, is but a portion.

BUNDELKHUND;

December, 1872.

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XXXVII. *Postscript*.—Before giving the foregoing papers finally to the public, I was desirous of the opinion thereon of a professional Engineer of experience in the Province, *viz.*, the Punjab, from which news of damage by floods to Railway bridges had, during the last two or three years, most frequently appeared in the public journals.

With this view I transmitted it first to the Superintending Engineer, Umballa, Mr. Login, F. R. S. E., who has been good enough to write an introduction and several notes now attached.

From these it will be seen he does not consider I was wrong in believing the subject of importance.

Though not concurring in all my deductions, yet he supports many of the observations from his own experience; and, in regard to the central fact of the analysis as to the movements of water on impingement, and the mode of scour action at obstructions, which I have described from *ocular observation*, he has, by employing this in his notes, considered it to commend itself to acceptance in lieu of the explanation from theory hitherto employed from [at least] the time of Colonel Abbott's Treatise on Indian Bridges, to that of the latest authorities as already quoted.

I have also jotted down a separate *resumé* of the chief points arrived at, divested of the detail of experiment and inference here necessarily given to afford the means of judging in a new and intricate matter of this kind.

March 1873.

J. P. S.

Notes by MR. T. LOGIN on DR. STRATTON'S Paper on the scour action of water at obstructions.

NOTE 1 L.

SECTION A, PART VI, PAGE 9.

This up-swell on the surface of the stream above the cut-water of a bridge pier, if it could be accurately measured, will, I believe, accurately indicate the power of the down-sweep below the bed of the river, be the depth of the river what it may. This up-swell is checked by gravity, while the opposite and equal force of down-flow is resisted by friction on the pier face and the bed.

The depth to which this down-flow extends will therefore depend on the shape of the surface of the pier, and the nature of the materials of which the bed consists.

If this matter can sink rapidly in water, the scooping action will be proportionately less, and still more so if the stream has been already highly loaded with this heavy matter, as for example, a mountain torrent carrying down boulders and shingle. The tenacity of the particles to each other, such as stiff clay, will also retard this action, but it is only a work of time, for the stiffest clay can be eroded with very small velocities; so it is owing to the short duration of high floods that gives stiff clay so great an advantage, from there being no sufficient time for dangerous scour.

Moreover, during floods the water is more or less already loaded with solid matter, which, it is believed, also reduces the action.

Where the action is greatest is where the material of the bed has little or no tenacity such as *very* fine sand with an admixture of mud. Such a soil only sinks very slowly in water; thus the stream can pick up such materials, and by its ascending currents raise them from below with much greater facility than if they were heavier. Hence the great scour in rivers whose beds consist of such soil, and if the conclusion here arrived at be correct, there is all the more necessity to study shape of the surface of the piers, so as to resist by artificial means this down-flow.

NOTE 2 L.

SECTION A, PART VII, PAGE 10.

The motions here described as circular and cork-screw are, I believe, identical, whether caused by the friction of a pier, or by the bed of river, and are caused by the obstruction being not in the direct line of the force where they are, that is, the *part-water line* can only exist in one vertical plane, and it is in the line of this vertical plane that the up-swell and down-flow is greatest. The broader or bluffer the obstruction is within certain limits, the greater will be the up-swell and down-flow, and the more these circular cork-screw motions; and so with a rock or any obstruction in the bed of a river.

Where the bed is regular, the less will be the friction on the bed, and the fewer of these cork-screws; yet, for all that, as the friction is on the bottom chiefly, there the circles will have a horizontal axis, though at the sides of the stream they become more vertical and thus disturb the flow. In the same manner, obstructions such as piers have the same effect by the introduction of another variety of these circles.

NOTE 3 L.

SECTION A, PART XI, PAGE 11.

A somewhat similar action may be observed at the mouth of a small turbid stream which discharges itself into a deep pool. The heavy matter appears as if pushed out into the deep water, and the outer face of this deposit is exceedingly steep, should the water in the lake not be disturbed by the wind.

Where it is not, the heavier matter rolls down the outer face of this slope, and so encroaches on the deep water, while the lighter particles, by the *momentum* of the stream, are carried farther out into the lake and are deposited in the deep water in extended strata, to be afterwards overlaid by the heavier matter. Thus we have the finer particles of mud or clay deposited in fine thin strata like slate, with the heavier and coarser grains of sand, deposited in a thick mass above, having its stratification at a steep incline compared to the horizontal beds of fine clay underneath, and all done by the same stream; both actions being in progress at the same time.

This action I have often watched on a small scale while carrying on extensive drainage operations on the Ganges Canal north of Roorkee. And I believe the very same process is now at work at the head of the Bay of Bengal on the large scale, where the sand heads are being pushed out in the Bay; but here we have great disturbing elements at work, the south-west monsoon and tidal influences, both of which tend to flatten out the outer slopes of the sand banks as they advance on the deep water.

What this goes to show is, that we may find a slaty deposit underlying an enormous mass of sand-stone, both formed by the same stream; the former, speaking in geological terms as to time, of the same age as the latter.

NOTE 4 L.

SECTION B, PART XV, PAGE 12.

Or, in other words, roll over each other, and hence the ascending and descending current in a stream.

NOTE 5 L.

SECTION B, PART XV, PAGE 13.

Because the river is in train, and has already got its proper load of solid matter held in suspension, so cannot scour or deposit.

NOTE 6 L.

SECTION B, PART XV, PAGE 13.

Is it not rather the lateral out-sweep, or, speaking more correctly, the ascending current as described at Parts IV and V, particularly in the first five paras. of Part V, where the natives suggested that "some water animal was throwing up the sand," that causes this strong local effect?

I believe that wherever this ascending current is greater than the rate at which the material of the bed can sink in the water, scour will take place at that point, and will go on till such time that the work that can be done by this ascending current is balanced by the masses of heavy material which fall in from the sides of the cavity scooped out; for the larger the proportion of earthy matter, the greater the work to be done.

The lighter, therefore, the material, the deeper will be the cavity, but the velocity of this ascending current must decrease as the hole gets deepened. So for all rivers this scouring power must depend on the velocity and the material of the bed, hence the advantage of heavy stone, &c., placed at a certain depth below the bed where it can withstand this action.

NOTE 7 L.

SECTION B, PARTS, XVII AND XVIII, PAGES 15 AND 16.

In these two Sub-divisions of Section B, Dr. Stratton has very clearly described the action which takes place in running canals at falls; and I could, if space would permit, verify his statements by what I have frequently observed on the Ganges Canal, as well as to this back-wave below a bridge of which he speaks.

At the Markundah Bridge, 12 miles from Umballa, this back-wave is about 35 feet beyond the piers, where fortunately the work is protected by an apron and deep curtain wall; but, nevertheless, this deep pool spoken of exists to a considerable depth beyond this curtain wall during high floods. This I have seen measured to a depth of 13 feet below the river bed close up to the curtain wall, but it has since been protected by a mass of heavy material thrown in. In the same manner I protected several of the bridges on the Ganges Canal in 1861-62 and the beginning of 1863. At some bridges these holes were scooped out to a depth of from 5 to 10 feet below the foundations; and a similar scooping out took place at several of the falls, as above described, in other Sub-divisions of the canal. As much of the works as possible were similarly protected while the canal was dry, but a large quantity of heavy material was thrown in from boats with a flowing canal.

In the case of rivers like the Markundah, the danger is of *not* observing this scooping out action, for these holes get silted up after the flood passes off, and cannot be seen in the dry season of the year.

The remedy also must be applied at the time of flood, or as it subsides, a work of no little difficulty, owing to the rush of water over the flooring.

The causes of this action in both cases are the same, *viz.*, the floorings of the bridges cause an obstruction to the natural flow, by being, in the case of the Markundah Bridge, a foot or two too high, and not the contraction of water-way which is more than sufficient. On the Ganges Canal, on the other hand, the general level of the canal bed had got depressed, owing to the excessive velocity with which the water was at that time (prior to November 1861), permitted to flow. So these bridge floorings became nothing more or less than submerged weirs, disturbing the natural flow, causing an ascent above the bridge, and a descent below, and thus scooping out the bed to a dangerous state. Speaking of them in my Report dated 8th November 1861, after saying that nearly one hundred million cubic feet of earth had been scooped out of the first 50 miles of canal channel, I went on to say "bars thrown across the channel are in my opinion nuisances that only disturb the flow of the water, causing greater abrasion both on the bed and banks in their vicinity. We have them at every bridge flooring," &c., &c. I continue further on—"taking all things into consideration, I have come to the conclusion that we must concentrate all our difficulties to one point, and that point is at the falls." Rather more than a year afterwards I carried out my suggestions which have had a most beneficial effect:—the velocity of the water was reduced from 4½ feet a second to 3½, and the slope of the surface from nearly 18 inches to rather less than 15 inches in the mile, so that these holes, which were at that time dangerous, have almost, if not altogether, disappeared, while the bed has gradually been sifting up ever since, and this was simply effected by raising the lip of the over-falls some 5 feet.

I should not pass over in silence the preference given to perpendicular over the ogee form of fall.

Sir Proby Cautley perfectly understood the advantage of a perpendicular over an ogee form of fall; but what he feared was, that the concussion of so vast a body of water falling 8 and 9 feet would cause such a vibration as to shake the falls in time.

The tremor exists at all the falls to a most sensible degree even now, though the total fall is broken up into three steps as suggested by me in this same Report of November 1861, and carried out a year after by me, first at the Mahmudpoor Falls, and subsequently adopted at several others, so now the system recommended by Dr. Stratton exists.

I should not close this extensive Note without confirming what is said about the intermittent action referred to, for I have been often struck with the same fact in the Ganges Canal. Where I first observed it, and on a much larger scale, was, when a young lad, watching the breakers roll in after a continued Atlantic gale. These waves appear to go in multiples of three, and can be distinctly seen breaking on a large submerged rock.

First, there are three waves whose crests just break, then come three larger waves, to be followed by three more enormous rollers, after which there is a long interval of unbroken water.

The bore of the Sittang in Burmah, I observed also consisted of three lines of breakers, the last the highest of the three.

NOTE 8 L.

SECTION B, PART XIX, PAGE 18.

The action here described is fully borne out on the Ganges Canal Falls, where I introduced bars of open wood-work, so that some of the water should pass through the bar, and some over it, and thus reduce the concussion.

They acted very well for several years, but have since been superseded by dead walls, which, in my opinion, are no improvement, as these tend to concentrate the action. In my paper read before the Civil Engineers' Institution in 1868, the nature of these bars is fully shown, and in that same paper, with a view to reduce the action, I have suggested extending the lip of the fall.

NOTE 9 L.

SECTION B, PART XX, PAGE 19.

Where the slope of the country is very great, and the flood waters contain a very large proportion of earthy matter, continuous masonry bars do hold up the beds of rivers; and this was done by Sir Proby Cautley with great success after he opened the Eastern Jumna Canal, for by these bars he was able to prevent a dangerous scour in the beds of the torrents which cross the canal.

This scour was caused by the comparatively pure canal water escaping through the canal dams during floods; so when the velocity was thus increased by its passing down the bed of the torrent, the water had more power to carry a heavier load, and hence scour.

The effect of these bars or weirs was to partially reduce the slope. So a silting-up took place, and the dangerous cutting was stopped.

NOTE 10 L.

SECTION C, PART XXI, PAGE 21.

It is necessary here for me to make a few remarks, as I hold the opinion that the scouring power of water in rivers is in some inverse ratio to the depth.

The main difference between the opinion of the author and myself, I believe, when it comes to be worked out, is rather of a local than of a general nature, and the question is effected by so many collateral contingencies that it would be difficult to discuss them all here at length. Our objects are somewhat different. The author goes to consider rather the effect of depth at any particular point on a natural stream where it meets with an obstruction; whereas I take up the question more as to the varied aspects in which we find a river at different points of its course, with the view to study its probable effect on artificial rivers under various conditions.

To take the matter as applied to one particular point, it is self-evident that the scour must increase with the depth, for increase of depth of a river at that point must imply a proportional increase of velocity, the fall per mile being constant; so, under such circumstances, increase of depth simply means increase of power.

If, however, we take the same river at different points of its course, where not only the depths differ, but the fall per mile also, though the velocity may be the same, we shall not find the scouring power increase with the depth in anything like a direct proportion. But here comes in another element, namely, that having the velocities the same, but the depths differing, the load of solid matter a certain volume can hold in suspension will greatly differ also. At starting, the more pure the water is the better it can scour, and judging thus, the deeper the river the greater the facility for scouring, as the water is purer, but in reality this is not the case. We may take the velocity of our rivers at 10 feet a second when in very high flood, or 7 miles an hour as a near approximation. The Sutlej has had its velocity often measured, and the maximum is, I believe, 9 feet a second, and I found it the same on the Markundah torrent with a 10 feet flood. The velocity will be nearly the same on such a river as the Jumna where the Railway crosses it near Saharanpoor, Delhi, Agra and Allahabad. Under such circumstances, if the scouring power increased with the depth in anything like the same proportions, it would latterly be enormous, for the scour has been observed 40 feet deep high up the course of the stream. Thus a hole 38 feet deep has been measured on the Sutlej; and on the Beas it must have been much greater, for the scour appears to have extended below the pier on the upper face of it, as the pier fell up stream. The up-country rivers in highest flood only rise a little over 10 feet, and are merely about the same depth in the cold season, or in all about 20 feet deep. So to what depth should the scour be at Allahabad where the river is often more than 20 feet deep in the dry season, and the floods rise four times as high as they do up-country?

Instead of such being the case in reality, we find the scour at the Allahabad Railway bridge has been less than at the up-country Railway bridges. This may in some measure be accounted for by the peculiar shape of the piers, but, nevertheless, in the former case, from near the natural bed-level downwards, the obstruction is greater to the water passing than in the latter; so the only conclusion I can arrive at from such data is, that somehow or other the scour does not increase with the depth to any great extent, even at places where the flow is diverted by artificial obstructions, such as bridge piers. To attempt to explain why, would occupy too much space, and after all would probably be a waste of time, as up to the present it is only a matter of theory, for having no facts to guide us as yet to solve this important problem, I will simply state my general opinion is, that though a large high volume of water may aid the passage of a stream in its vertical downward direction, it quite as much obstructs its ascent afterwards, and the scouring power depends on this upward velocity as to what load of solid matter it can raise.

Holding this view of the case, it does not so much matter what the depth may be, but all depends on the velocity with which the water impinges on an obstruction, and the facility with which that obstruction can glance off this impinging force. As stated in foot-note 1 L at page 41, I believe the up-swell at the cut-water simply indicates the down-sweep, and that the latter is greatest where the up-swell is highest. Thus the down-sweep may hereafter be found by measuring the shape of the up-swell.

NOTE 11 L.

SECTION C, PART XXII, PAGE 21.

The author of this paper has happily illustrated the case by the instance of a Dutch sloop, or a Newcastle collier brig, compared with a "clipper" ship of the present day.

To this I would add that, in the two former examples, the effect is that the old bluff bows rose to the sea, while in too many cases the "clippers" cut through the waves, and thus are looked on by sailors as very uncomfortable "watery" ships. It may not be out of place here to state that, in the Thames it was found the deepest part of the river at London was along the line these Newcastle colliers moored, showing that their bluff bows caused a descending current under their bottom, and thus produced a scour on the bed of the river.

NOTE 12 L.

SECTION C, PART XXII, PAGE 22.

The object of the cylindrical piers, I believe, was to expose a uniform obstruction to the stream, let it come down on the bridge in whatever direction it may.

This was done so as not to interfere with numerous changes that may be taken by such rivers as the Sutlej, which I have seen pass down through the Sutlej Bridge, then flow for a short distance parallel to it, and again pass up-stream under the bridge near its centre. The stream for a short distance more continued its course again parallel to the bridge, and for a third time this cold-weather deep-water channel re-crossed it near its right abutment, having first crossed the line near the left abutment.

NOTE 13 L.

SECTION C, PART XXIII, PAGE 24.

It would be premature at this stage to attempt to lay down any law as to the increase of the down-scour. This power of the down-sweep, as affected either by depth of stream or breadth of obstruction, has yet to be discovered to arrive at practical conclusions. Probably, within certain limits, the down-sweep increases considerably with the depth of the stream and the breadth of the obstruction, but I believe these limits are soon reached.

Particularly as to depth, so that in practice very much stress on this question need not be insisted on. In the case of a river 20 feet deep and one 40 feet, the danger from scour, I think, may be taken as about the same so far as depth is concerned, but it is quite a different matter doubling the thickness of a pier, say, from 7 to 14 feet. A 7-foot pier might cause, comparatively speaking, little scour, and at the same time and place a 14-foot pier might be most dangerous, while a 140-foot obstruction might be even more stable with the same depth of foundations than the one of 14 feet broad.

The relations which each bear to each other have yet to be discovered. Suffice to say this "down-sweep" action has now been discovered, which in itself is a great step in the right direction.

I think this remark can only be taken in a comparative sense, for where the flooring of a bridge is higher than the natural bed of a river, there is a tendency to scour on the up as well as the down-stream side of the flooring, but not to so great a degree on the up-stream side. This I observed at the Markunda Bridge on the Grand Trunk Road to a small degree, and also on all the bridges of the Ganges Canal, though not to such an extent as to cause anxiety and danger, where the breadth of water-way is ample; but contract the breadth of water-way, and the scooping out on the up-stream side becomes dangerous.

As to weirs, however, they are either thrown across a river where the channel is wide, or are carried in an oblique direction to the general course of the stream, and thus gain length of lip, under which condition there is not this tendency to scour below the natural bed of the river on the up-stream side. The great point with a weir appears to be, that, during the highest floods, there should be no holding up of the surface level, and if this be attended to, the action on these works during very high floods is but little, while also the regimen of the river bed up-stream is not interfered with so long as the general level of the surface of the water in the river during high floods is not raised.

The floods in the rivers which are crossed by the Delhi and Punjab line only rise a little over 10 feet, seldom or ever 12 feet, and the observed velocity is about 7 miles an hour.

The total depth of the river, however, may exceed 20 feet in flood in its natural state without any obstruction.

On the other hand, the Jumna at Allahabad rises above its cold-weather level nearly 40 feet when in high flood, at which time it is probably in all 60 feet deep in some parts of the channel.

At the head of the Delta of the Irrawaddy in Burmah, the rise of the river was 38 feet, and I found it to be for a short distance of its course over 50 feet deep in the dry season, or in all 90 feet deep when in high flood.

Wells, with sloping sides or funnel-shaped, might meet this difficulty. As far back as 1849, I introduced this system of sloping sides to foundation blocks, and it was found that not only was there a broader base given to the foundations, but also there was a great saving in sinking those sloping-sided blocks compared with those having perpendicular sides.

The pier on the Beas Bridge fell *up-stream*, showing that the excessive scour was on the up-stream side, while on the Sutlej, the piers fell down-stream, showing that the force of the stream pushed them over.

This simple experiment, I think, exactly explains what happened on the Beas Railway bridge, and led to the falling of the pier up-stream. What makes this paper all the more valuable in my estimation is, that the author does not appear to be aware of the fact of this pier falling *up-stream*. The reason why the pier should fall up-stream is contrary to what most people would have expected (myself among the number), but these observations of Dr. Stratton to my mind now throw a great and most important light on the whole question, and do away with the necessity of the lengthy argument used about leverage in the case of the Beas Bridge, by simply proving that the scour extended below the bottom of the cylinder on the up-stream side and undermined the pier.

This, I say, throws an altogether new light on this most important question when comparing the Jumna and Soane Bridges on the East Indian Railway with those on the Punjab Line. On the latter, we have one perpendicular straight line, extending to the bottom of the foundation, *with nothing to impede or deflect the descending current* formed by the impact of the stream on the cut-water.

In the case of the East Indian Railway bridges, the foundation wells cover a large area compared to the pier they support, so that in this case there is a *step all round the pier* sufficiently low down as not to obstruct the discharge of the river, *while this step stops this descending current in its progress downwards, forcing it to glance off* in a radiating form from the pier as the centre.

If this be the solution of the question, or any approach to it, we have at once a most important practical addition to our engineering knowledge which it is difficult to over-estimate.

Dr. Stratton has here shown that the failure of the piers on the Beas and the Sutlej is owing either to excessive scour, or to the thrust, or to a combination of both. To meet the latter, an increase of diameter of the cylinders increases the scour, and to add to the depth in no way reduces the thrust or leverage at which the stream acts on the pier.

Again, when the stream comes obliquely to the line of bridge, and not at right angles, even the addition of a second cylinder does not appear to meet the difficulty altogether, for *breadth* as well as length of base is necessary. Under such circumstances, some of the piers on the Baroda Railway were pushed over sideways.

This brings me back to 1849, when I introduced sloping sides to the foundations on the Ganges Canal, and I think they can, with advantage, be adopted here also. What I would suggest, therefore, is to make the bottom of the cylinders 18 or 20 feet in diameter, and to slope the sides to 10 feet in breadth a little before reaching the river bed, at, say, 5 feet below the cold-weather water-level, when the sides of the piers may be run up perpendicularly 8 feet thick.

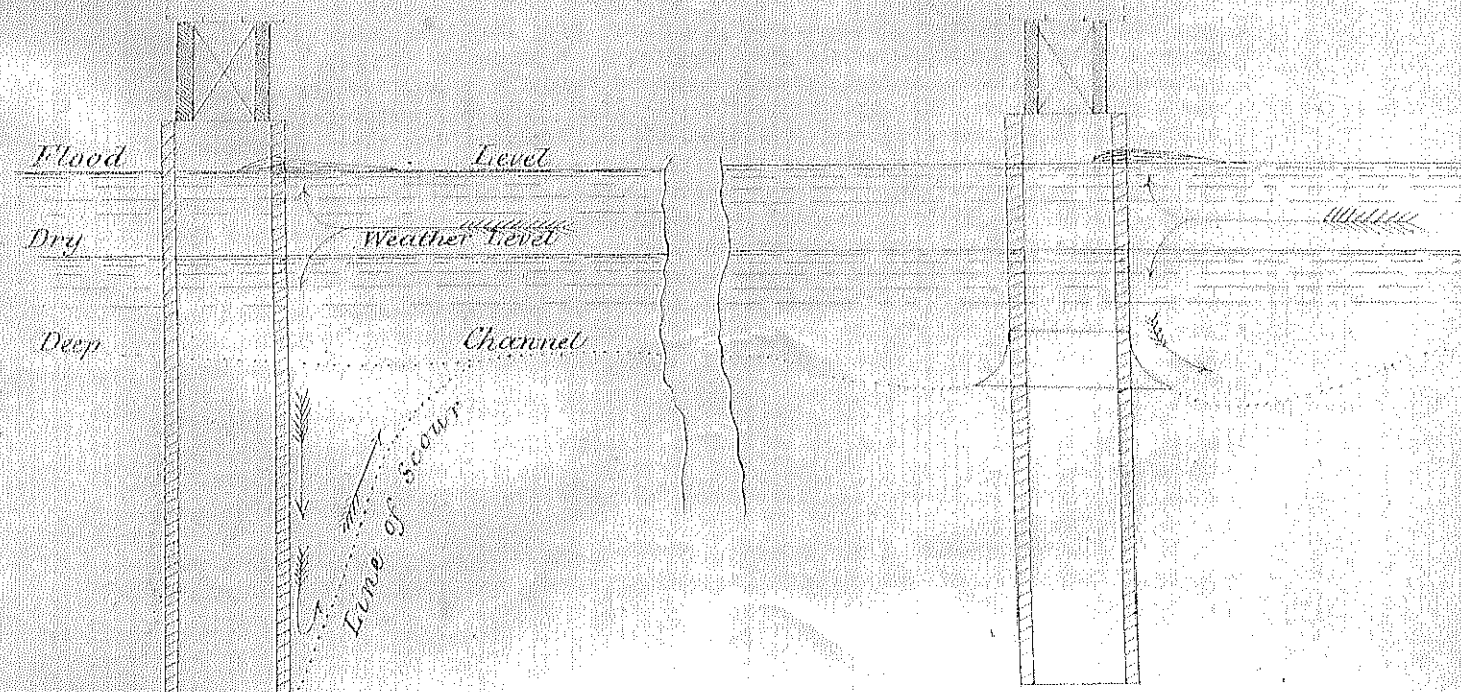
The up and down-stream walls of the wells, I think, should not have so much batter, and they may be 15 feet long,—thus at 5 feet below the surface of the water in the dry season the foundations can be completed, so that the length (measuring at right angles to the line of bridge) will be $1\frac{1}{2}$ times the thickness of the piers nearly. From this level the piers may be run up, say 8 feet thick or broad, and of double that length including cut-water, by bricking out 6 inches at the ends. Thus the plan of the foundations would be represented by the letter O, the base being circular and the top *elliptical*; while in the channel of the river the obstruction would be reduced, when the stream passes down at right angles to the bridge, to only 8 feet with cut-waters; while, if the flow is oblique to the pier, say at an angle of 45° , the actual obstruction at right angles to such a stream would only be 11 feet 4 inches, or more than 1 foot less than the present $12\frac{1}{2}$ feet cylinders; while the base is increased to 18 or 20 feet. Such an arrangement, I think, would meet the difficulties Dr. Stratton has so clearly pointed out. But what would add to the security would be to keep the cut-waters hollow, as suggested by me a year ago, so as to have the power of depositing heavy material *below* the deep-water bed of the river in its natural state, and thus not obstruct the discharge of the river, which the throwing down of stone round the piers *above* that level most certainly does, as shown by the fact that they have again been scoured out to a depth of 20 feet close to the piers of the Sutlej Bridge, the stone having been scooped out round these piers in a very similar manner to that described by Dr. Stratton, where sand is the substance scoured.

What would still further add to the security of the foundations would be to surround the pier by an iron-collar or shield, say 5 feet broad. The section of this shield would be very similar to the present iron-curbs or neemchuks, but inverted with greatest depth at the inner instead of the outer rim.

The object of such a shield would be that when the downward stream Dr. Stratton speaks of impinged on it, the oblique surface on which it descended would divert it off horizontally, and thus stop this dangerous descending current, as shown in Fig. A compared with Fig. B.

FIG. A.

FIG. B.



NOTE 20 L.

SECTION D, PART XXVI, PAGE 30.

Since reading these Notes, I have given the subject a good deal of thought, and perhaps the accompanying diagram may aid in explaining why there should be so much scour on the cylindrical form of pier compared with other shapes, for Dr. Stratton found the down-sweep scour greater when he used a round barrel than at any other shape.

Let a, b, c, d, e and f represent six equal forces, all exerted in the same direction, and striking a body which presents different surfaces as to obliquity.

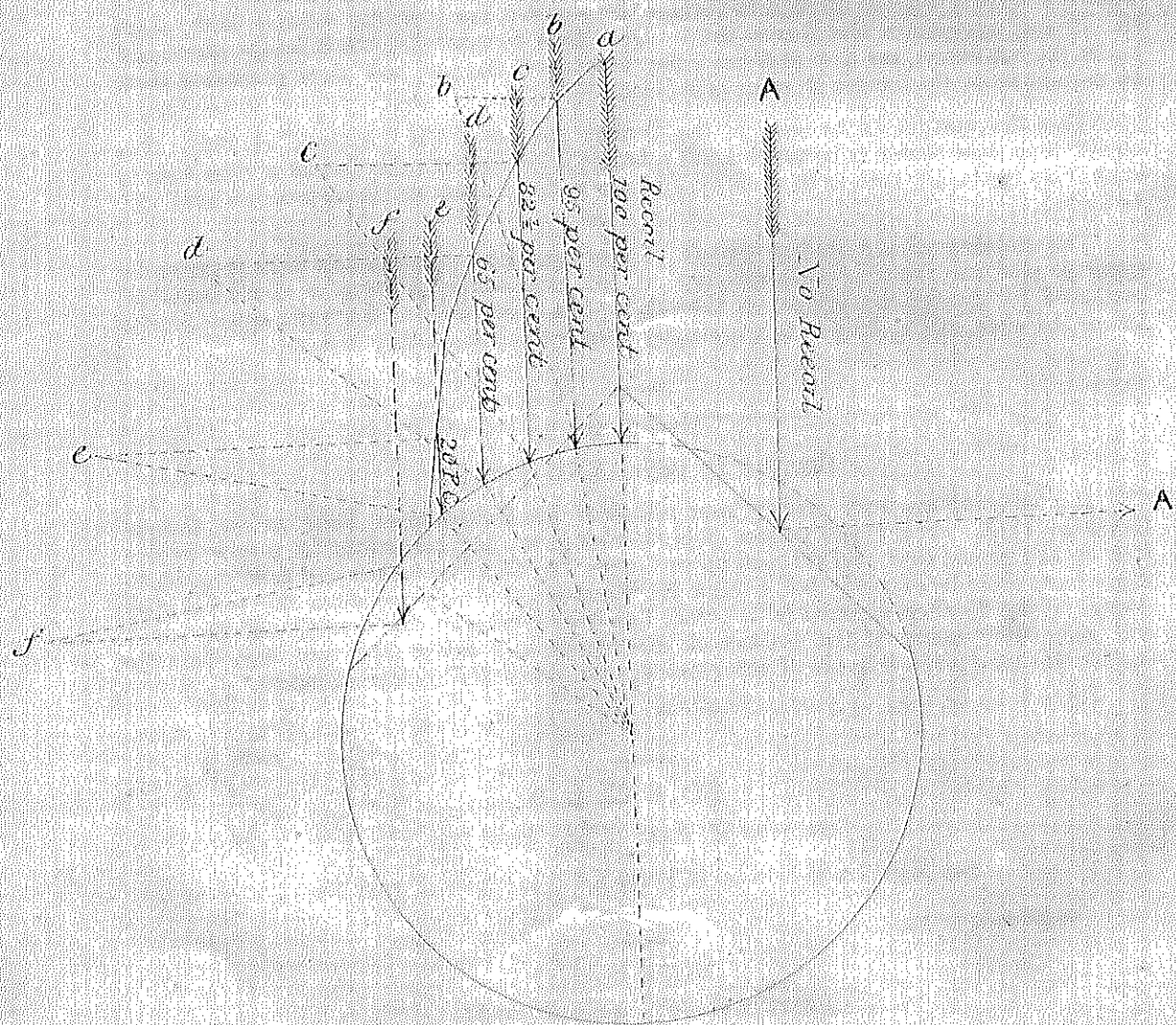
It is evident that the force *a* striking a body at right angles, would, if rigid, receive back the whole force on itself; the force *b* nearly 95 per cent. of it; the force *c* about 82½ per cent.; again *d* would only have a little over 65 per cent.; and *e* merely some 20 per cent; while with *f* the force would glance off altogether.

Such would be the case if we had perfectly rigid bodies to deal with, if it be true that the angle of incidence is equal to the angle of reflection. On the other side of the drawing where the impinging force strikes the obstruction at the angle of 45 degrees, the direction would be changed to right angles to that of the first force as shown by A and A'.

Instead of a rigid body, we have a fluid, which, if poured down in a small stream from a considerable height on to a flat substance, throws back water in all directions.

This in a river it cannot do, so the force is expended on the surrounding particles of water forcing them in all directions which they, in like manner, resist, they all having the same force exerted on themselves.

These forces being bound up laterally must give a resultant vertically, hence the "up-swell" and "down-sweep," the former showing itself on the surface of the water, and the latter by scooping out the bed of the river at the obstruction.



Should the above diagram in any way represent the actual forces acting on a circular pier compared to the action which takes place where the stream strikes an angular cut-water in an oblique direction, we have at once an explanation why a cylindrical pier should not stand, while the thick massive Mahomedan ones do, for they present an oblique surface to the stream, and rest on broad steps, or on a number of wells which extend out beyond the pier, and form a step on which the water impinges, and the down-sweep thus is checked.

NOTE 21 L.

SECTION D, PART XXVII, PAGE 30.

This has been very well exemplified in the case of the Markundah bridge flooring, where the river set on the right abutment of the bridge. There the deep channel scooped out a deep hole on the up-stream side of the curtain wall, and was only stopped by extending the apron up-stream at this right flank.

On the Ganges Canal also in 1861 a similar action was threatened, and but for the crib-work on the up-stream side of the up-stream curtain walls this scouring out above bridges would most certainly have happened. The injury done to some bridges on the East Indian Railway clearly exemplifies this, for there the action was so violent that in one or two instances the bridge cracked longitudinally, and the upper portion of the bridge fell bodily up-stream into the hole scooped above the bridge, leaving the lower half standing.

With my paper read before the British Association at Exeter in 1869, one of the diagrams represented a bridge, showing that the flooring should be depressed level with the foundations, and extend some distance both up and down-stream with deep curtain walls.

The object of this diagram was to show the extra water-way that could be thus gained by lowering the flooring without any danger to the foundations, as they were protected by these curtain walls, and at the same time that, should the water-way be contracted, this can be done with safety, even if the flood rose to level with the crown of the arches, for it is not what the velocity may be through the bridge that signifies, but it is the velocity with which the stream approaches and leaves the bridge. Thus, by extending the floorings above and below the cut-waters, say 3, 4 or 5 times the thickness of the pier, and there protecting them by curtain walls, the danger of scour is avoided.

This diagram is to be seen in the October number of the "Artisan" of 1869. The object is to show that it is better to lower a bridge a few feet into the bed of a river than to stick it up in the air, both as to stability, and also as to economy for the approaches need not be raised.

The stability of the Madras system of floorings is that these curtain walls being so far from the pier, and the wing-walls splaying out, the cross-section of area is much increased, compared to that of the bridge, so the velocity is not increased as the water approaches or leaves the work, and so long as this is strictly attended to the stability is secured.

NOTE 22 L.

SECTION D, PART XXVII, PAGE 81.

The foregoing was very clearly exemplified at the Mahmudpoor Falls on the Ganges Canal in 1862, when I saw masses of brick-work in one bay, measuring $12 \times 8 \times 1\frac{1}{2}$ feet torn up and turned over, and till reading this paper I could never understand how this enormous force could be exerted; but I think Dr. Stratton has clearly explained the action that goes on at the floorings of canal falls. Once find a weak point in the flooring, and the water will soon work below if the brick-work be inferior, as it was in this case; but where the surface was good, even 6 inches of brick-on-edge has saved the brick-work below.

There is no blowing up process whatever.

NOTE 23 L.

SECTION E, PART XXX, PAGE 33.

See Note 7 L in Section B, Parts XVII and XVIII, page 43.

NOTE 24 J.

SECTION E, PART XXX, PAGE 34.

See Notes 19 L and 20 L, Section D, Part XXVI, pages 47 & 48.

NOTE 25 L.

SECTION E, PART XXXI, PAGE 35.

Bridge floorings do not fix the bed surface. See Note 21 L, page 49.

NOTE 26 L.

SECTION E, PART XXXI, PAGE 36.

See Note 22 L, Section D, Part XXVII, page 49.

NOTE 27 L.

SECTION E, PART XXXI, PAGE 36.

From the best information I can obtain, it appears that the action here described has actually taken place with the stones thrown in around the piers of the bridges on the Punjab Railway, for the soundings show that they have been washed out to a depth of 20 feet at 5 feet from these circular piers, and in some cases to only 4 feet below the bed at 20 feet off showing that on such rivers as the Punjab Railway has to cross the stone used can afford little or no protection for all depths less than 20 feet. All stones, therefore, which do not reach a greater depth than 20 feet below what is called the bed in the cold season, that is, the spring level of the water at the pier in the dry weather, cannot, under such circumstances, be of much practical good, so the question is how to get them to the required depth where they can be of service.

NOTE 28 L.

SECTION E, PART XXX, PAGE 37.

A similar action as here described was observed on the Ganges Canal Falls.

The violent action on the apron floorings appeared to be greater when there was a small rather than a full supply, as the height of the back-water below the falls was greater, and the return wave thus approached nearer the bottom of the "Ogee Fall," and so saved the apron flooring and the work on beyond. The same is observed on the Madras anicuts. The injury is not done during very high floods, but rather by small ones, for once the river rises to its full flood level, and there is no heading up of the water at the site of the weir or anicut, there is only a slight ripple. A rather amusing case of the kind once happened under me on the Ganges Canal. I had put up a bar or weir 3½ feet high in one of the chambers of the Bahadurabad Falls (8 miles below the head works). While the supply was very small in the canal, it acted admirably in protecting the apron below the Ogee. A young Assistant, who had only lately joined, was much struck with the capital way this weir worked; but a few days afterwards on his next visit, the supply had been increased and the weir drowned. The apparent effect on the surface of the water so totally disappeared that the Assistant wrote to me saying that this temporary weir had been carried away, but though on the surface it did not indicate its presence, yet there it was all right. It is when the surface of the flood-water is held up above its natural level, either by the water being contracted, or the lip of the weir being too high, that there is this violent action below the works, and probable raising of the bed of the river up-stream. And in designing weirs, particularly in sandy beds of rivers, this I think is a most important matter to look to, for the less we interfere with nature and her laws the better.

NOTE 29 L.

SECTION E, PART XXXIV, PAGE 39.

See Note 18 L, Section D, Part XXV, page 46.

No. 133 A, dated 1st March, 1873.

From—T. LOGIN, Esq., *Offg. Suptg. Engr., 2nd Circle, Punjab,*To—*Secretary to the Government of the Punjab, in the P. W. Dept.*

In continuation of this Office No. 2 A of the 4th ultimo, and in the spirit of the last para. of that letter, where I say "my great aim all along has been to arrive at facts," even should they go to show that my pre-conceived views "may be open to doubt, and in some cases incorrect," I now venture to lay before you Notes by Dr. Stratton on the flow of water as affected by its impact on obstructions; and the conclusions that gentleman has arrived at are so remarkable and so striking, that I consider them well worthy of study by all who take an interest in such matters, be they professional Engineers or Natural Philosophers.

2. I cannot say that my book learning is very extended in these matters, though the interest I have taken in the flow of water has been considerable; so it is not much to say that I have never met with any book treating the subject in the manner Dr. Stratton has done. But for this last quarter of a century I have had ample opportunities to study the book of nature, and it is from the lessons thus read that I now venture to lay these Notes before you on purpose that they be published by Government and circulated, for it is by ventilating such questions as Dr. Stratton has raised that we can ever hope to arrive at any correct conclusions as to the laws which regulate the flow of water.

3. The author sent these papers to me for perusal and for my opinion. I have read them with peculiar interest, as the manner in which Dr. Stratton treats the subject, throws, in my opinion, quite a new and important light on the question of hydraulics.

4. In my foot-notes which accompany these papers, I have tried to give practical examples bearing on the matter that have come within my own personal knowledge, and I think they go far to support Dr. Stratton's observations, which, if correct, will lead to very important changes in hydraulic engineering, whether it be in bridging large rivers, or constructing canals, so the questions raised in these papers are of most vital importance to India in the present day.

No 2486/M.D.

Per Mr Madras Govt.

Read the following
from the Govt of India (H.E. No 370-98 & 19 June/3)

P.W. 5122/73.

Ordered that the
spare copies of the papers
on 'water movements on
impingence' &c to circu-
lated to District Engi-
neers who will, when
the subject shall have receiv-
ed due consideration,
submit to the Chief
Engineer for Irrigation
any observations they
may

may wish to offer.

May 23/9/73

4/11/73

N^o 158-59

1 Copy of lines drawn
to the fair engineer for
Review 9/11/74

Note to Adams 11/11/73

The Chief Engineer for
the District Engineer
S.C. with two copies of lines
drawn to each - 17/10/73

Migration

Dated

Recd.

Encl. /

G. O. No. 2486

Nov. 1887

Notes movements are
impinging. Copies of
papers, submitted by
the Govt of India, on
water movements are
impinging, and should
be circulated to
the Govt for the
purpose of observation
on the subject.