Remedial works for the Iron Bridge

by J. A. WILLIAMS, FICE, FIStructE, Sandford Fawcett, Wilton and Bell

Introduction

The bridge which still spans the Severn Gorge in Coalbrookdale, at the township of Ironbridge, was the first cast-iron bridge ever to be built in the world. It is now almost 200 years since the structure was first opened to traffic and it remains in full use today, although for the past 40 years it has served as a footbridge only.

The purpose of this article is to describe certain remedial works currently being undertaken with the object of preserving this ancient and historic bridge, with special reference to the foundation problems encountered. Before so doing it may be of interest to describe briefly the history of the bridge, this serving as a background to the scene of the operations now in progress.

History

The Coalbrookdale area has been described as the cradle of the Industrial Revolution and it can thus easily be appreciated that, in the late 18th century, there must have been considerable disruption and frustration to the cross-river industrial traffic which, at this vital point in the Severn Gorge, had to rely on ferries. At all events, a scheme for a bridge was promoted in Parliament and an Act for this purpose was passed in 1776.

Prominent among the promoters were John Wilkinson and Abraham Darby III, both members of famous iron-founding families, also Thomas Farnolls Pritchard, who prepared a detailed design and drawings and has come to be known as "the inventor of cast-iron bridges". Pritchard, however, died in 1777 and—although his pioneer work on cast-iron structures was outstanding—he apparently had no hand in the final design of the Iron Bridge, whose actual designer has not, so far, been identified. This re-assessment of the bridge's origins follows comparatively recent research by Mr. P. Mathews and Mr. R. Maguire.

The estimated cost of the original work was £3 200-11-0d (although the actual cost proved to be appreciably greater) and it is important to note that the project was a hard commercial proposition, intended to produce a rapid return on investment by toll income. Economies were no doubt introduced and it can be speculated today that such economies were, perhaps, applied to the substructures rather than to the then novel cast-iron superstructure, where there would be an obvious reluctance to "cut unknown corners".

A description of the ground conditions at the bridge site is given later. Suffice to say in this historical note that there is important circumstantial evidence which indicates that, even before any of the cast-iron superstructure was erected, there occurred some movement of the south abutment. Subsequently over the centuries sporadic abutment slip has continued until today it is believed that the abutments have closed in by over 460 mm (18 in), although it is not known whether this closure has developed at one, or both, sides. It is reasonably sure, however, that the south abutment must have caused further trouble because in 1800, 19 years after the bridge was opened, the solid-filled south approach was replaced by two timber arch spans. These latter were, in turn, replaced in 1821 by the light iron arches still to be seen. Nothing appears to have been done in the past to the north abutment, but whether this was because those responsible for the bridge were satisfied that the northern end was stable, or because funds were not available or whether there was some other reason, remains one of the enigmas in the bridge's history. Thomas Telford, County Surveyor of Salop and the first President of the Institution of Civil Engineers probably summed up the situation accurately when he wrote in 1788, with reference to the bridge. ". . . it does not offer sufficient resistance against the pressure of earth behind the abutments, which has pushed them forward thus raising the arch in the middle."

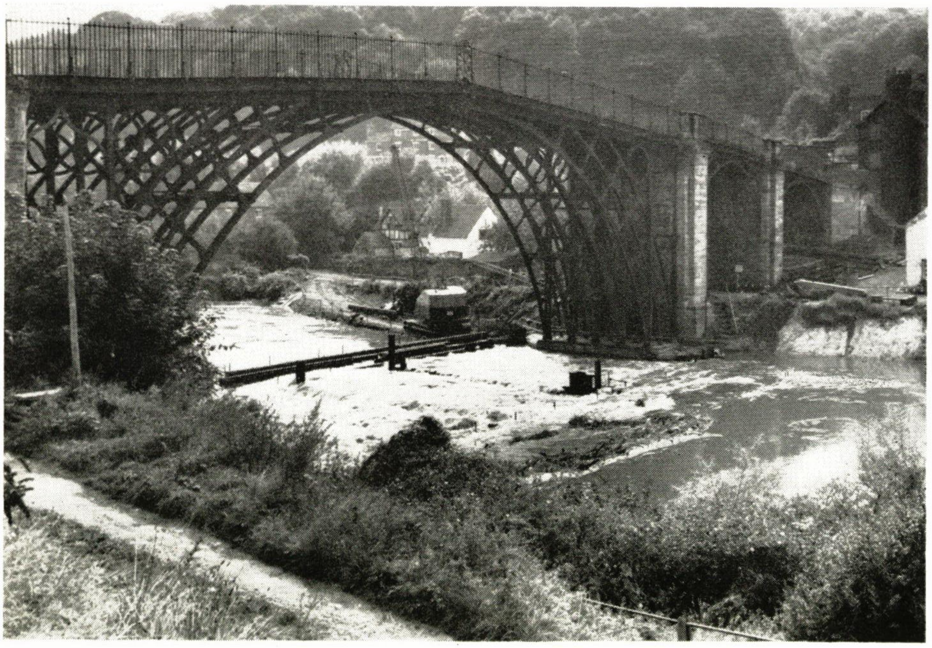
Although the abutment movements inevitably caused occasional fractures in the somewhat complex cast-iron superstructure, these were all of a minor nature and nothing sufficiently untoward occurred to raise serious concern for the overall safety of the bridge. Nevertheless, from 1950 onwards (when the bridge became the responsibility of Salop County Council) regular check measurements of the span showed that abutment movement was still occurring. Clearly this state of affairs, if allowed to continue indefinitely, must have led ultimately to the loss of the bridge. Indeed, despite the apparent absence of serious repercussions in the ironwork, fears were expressed of a major build-up of stresses in the cast iron which, in tension zones, could lead to instantaneous failure of main members.

There followed some years of intensive research and investigation into the precise nature of the earth movement and its affect on the various parts of the structure by the County Surveyor and the government departments concerned. In the meantime, maintenance work was continued at the expense of the County, using specialist labour both from County and Central Government resources. The outcome was that in 1969 consulting engineers, Sandford Fawcett, Wilton and Bell, were retained to report on the condition of the bridge and the need or otherwise for remedial works, including a review of all previous proposals for such work.

Investigations

The bridge is founded on shale/mudstone, the upper strata consisting of various clays. At the site, the north bank of the River Severn rises at about 1 in 3, being somewhat less steep to the south. Normal river level is 3.4 m (11 ft) below arch springing level, but flood flows, especially during the winter, are frequent, the maximum recorded to date being 3.7 m (12 ft) above springing level.

Shallow-seated earth slips occur fairly frequently on the valley sides, but there have been no major earth movements recorded in the immediate vicinity. Elsewhere in the valley, however, there have been more serious landslides, for example



Left—The Iron Bridge remedial works subjected to Severn River flood

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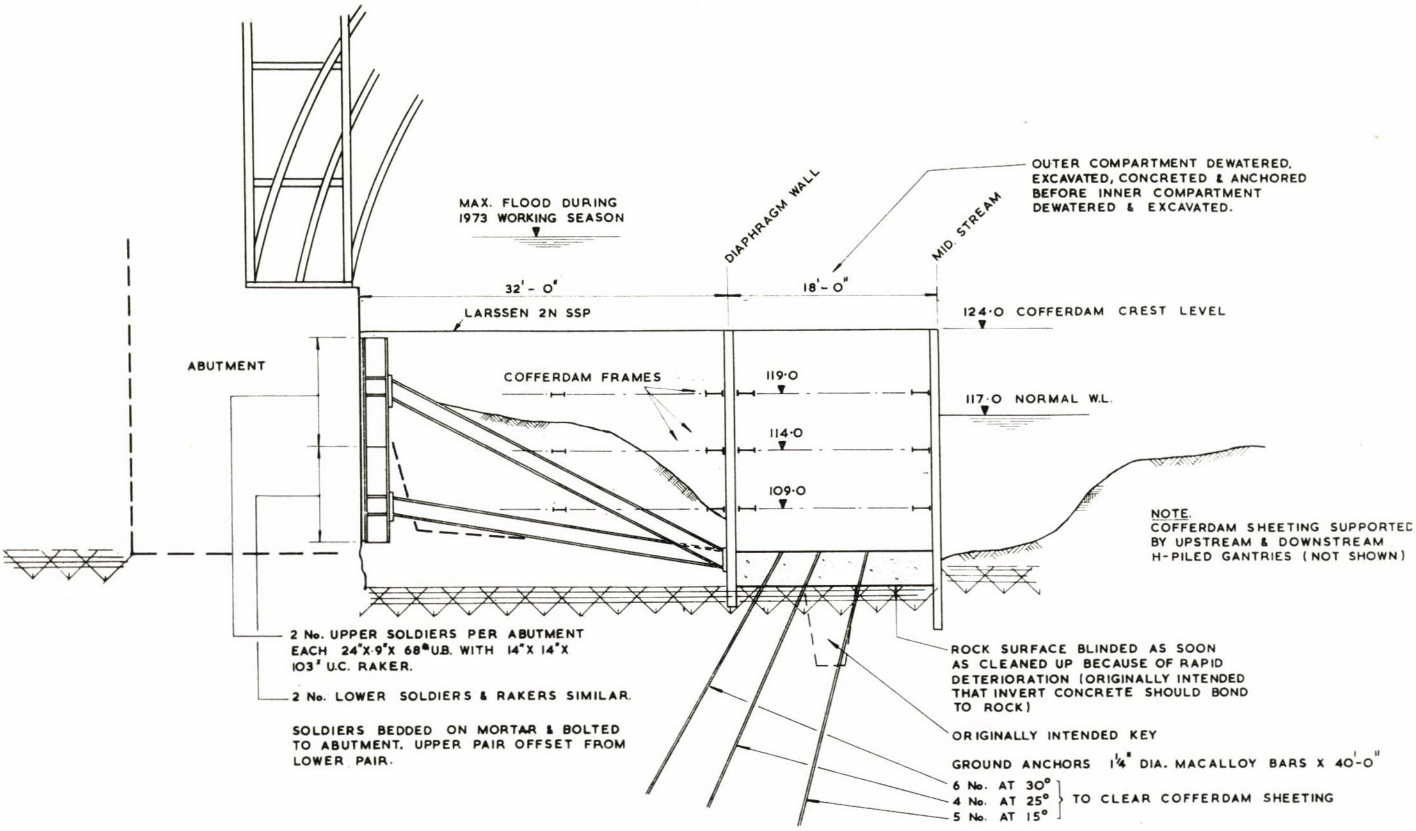
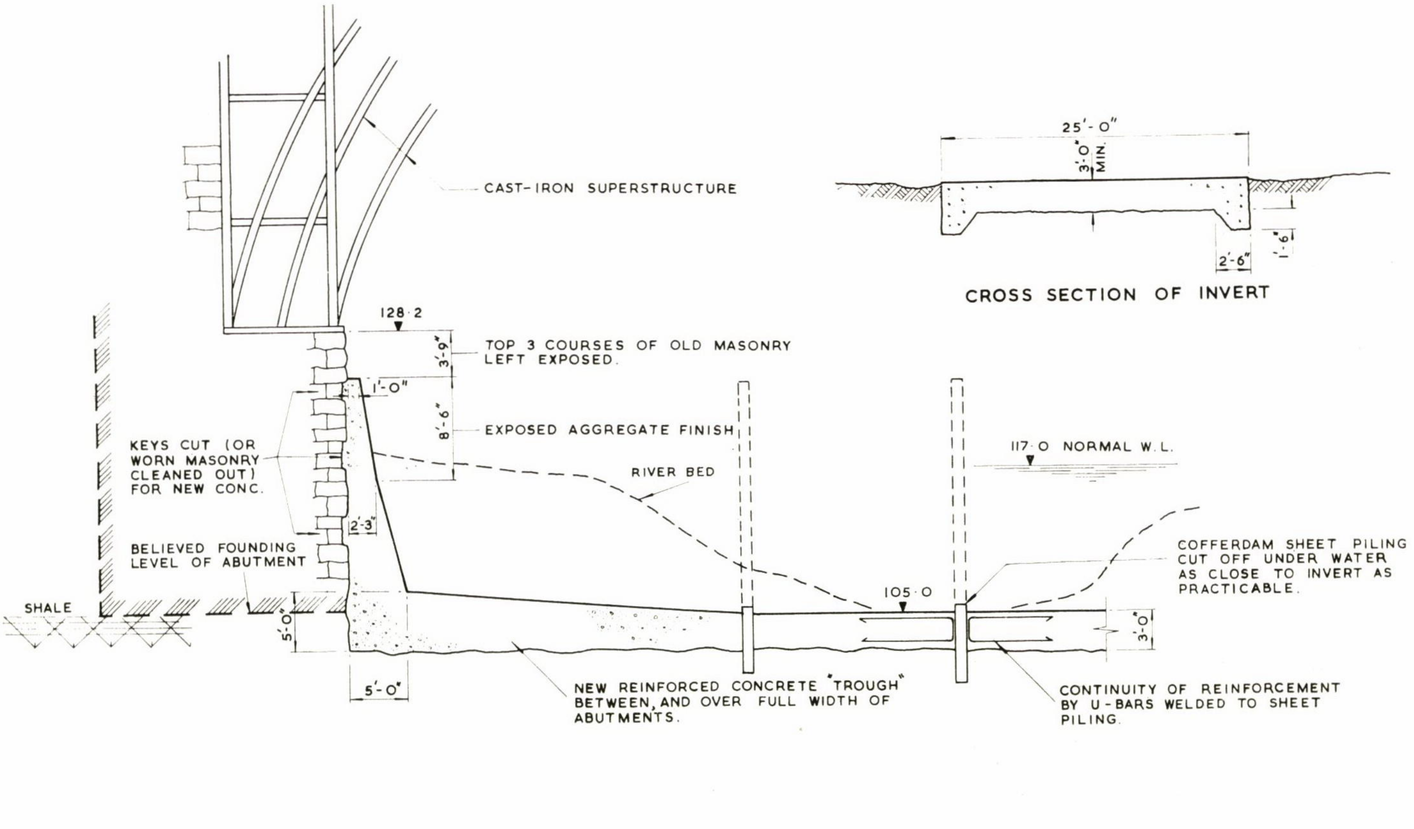
Above—Stage 2 temporary works revealing use of ground anchors

Below—Detail of Stage 2 shows the extent of the new reinforced concrete trough traversing complete width between abutments





CROSS SECTION OF INVERT

in 1773 at Buildwas, 3.2 km (2 miles) upstream of Ironbridge, and in 1951 at Jackfield, about 1.6 km (1 mile) downstream. With reference to the former, it is interesting to note that this occurred only a few years before work began on the Iron Bridge and one is tempted to deduce that the promoters selected what, possibly by repute and tradition, was the most stable area of the valley for their purpose.

The first broad conclusions reached during the 1969 investigations were as follows:—

(a) That there were no abnormal forces acting on the abutments, but that the abutments were (as surmised by Telford) either insufficiently massive and/or inadequately keyed into the rock. They apparently had a "factor of safety" against sliding in the region of 1.0 and hence from time to time small slippages occurred.

(b) That there was evidence to show that the stresses induced in the cast-iron superstructure by abutment movement might be appreciably less than had been feared; this, however, was a qualitative assessment only.

(c) That although (a) and (b) gave some reassurance against imminent danger of loss of the bridge, the time had nevertheless arrived when some remedial work should be undertaken.

(d) That such remedial work should be directed towards stabilising the abutments and/or otherwise relieving the arch frameworks of any further increase in applied thrust.

The next phase of the investigations was concerned with the examination of numerous alternative schemes for safeguarding the structure in detail.

There was no quantitive soils data available, nor any positive details of the abutment structures themselves; even if such data had existed, an estimate of the thrusts exerted by spandrel-filled approaches could not have been precise. However, if the abutment movement was to be arrested, the thrust which would then be generated would be something between the extremes of the conventionally calculated active and passive pressures. Starting from this fact it was estimated that the additional stabilising resistance which ought to be provided by any remedial works which prevented abutment movement would be between 300 and 700 tons, and this must be applied to both abutments.

Because of the imprecision of the earth pressure calculations considerable thought was given to schemes which involved the introduction of special bearings below the arch ribs. These would normally be "locked" to maintain arch action, but would be capable of being "unlocked" to relieve built-up stresses induced by abutment movement, which would be allowed to continue.

These ideas however had very serious disadvantages, not least being the extreme danger and difficulty of introducing such bearings below the existing superstructure. Consequently attention was next turned to methods of preventing further abutment movement and many alternatives were examined, the principal being:

(a) The construction of independent screen walls to relieve the abutments of load.

(b) Dowelling the abutments to the underlying rock

(c) Stressed anchorages.

(d) Strutting between the abutments.

Schemes (c) and (d) emerged as the most promising, the latter, in turn, being sub-divided into proposals for construction "in the wet" and within cofferdams.

From all the foregoing considerations a comprehensive scheme of remedial works was drawn up, implementation of which began in 1972 and is still continuing.

Remedial works

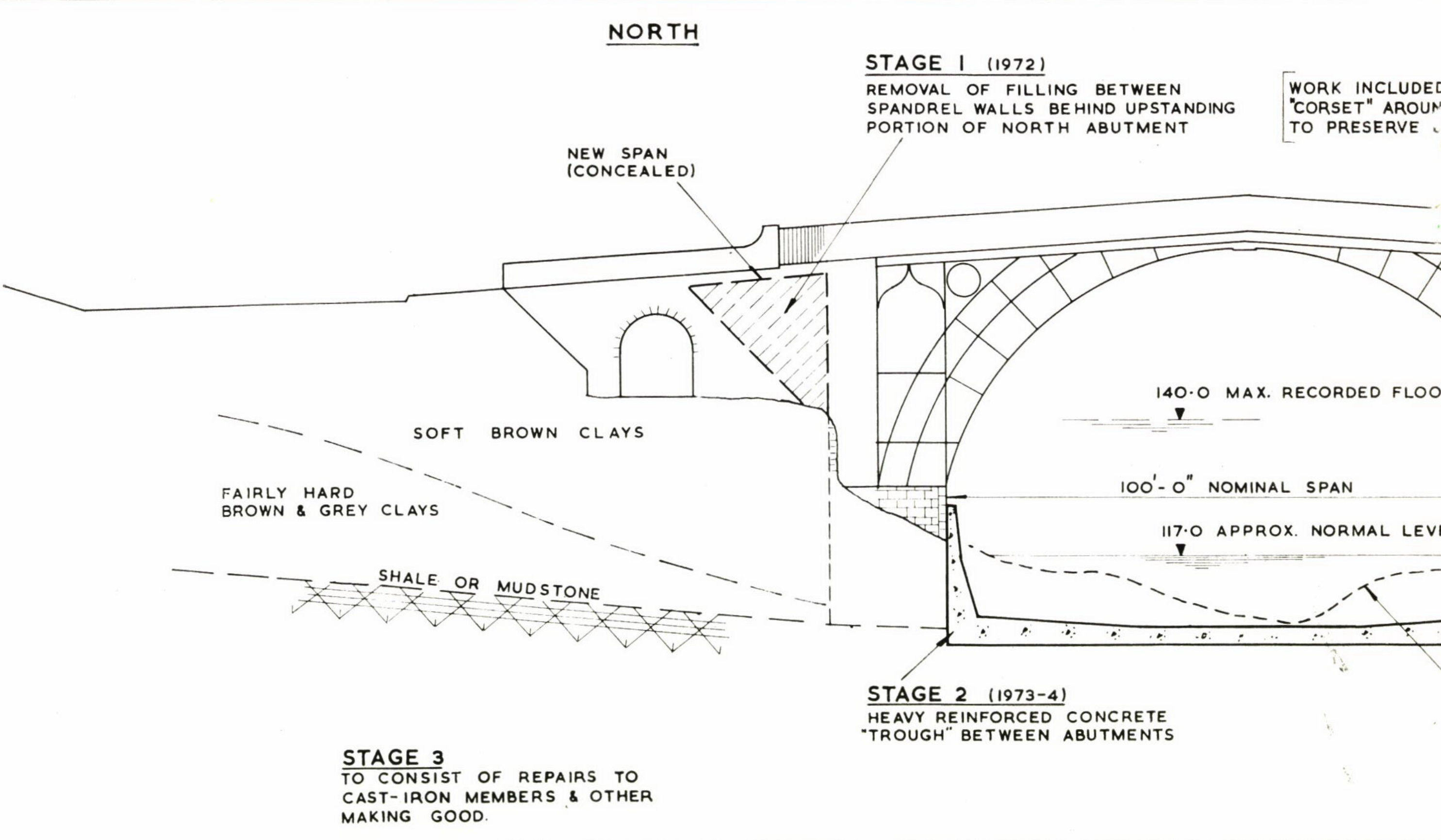
The finally agreed programme of works was planned in three stages, as follows:

Stage 1. Relief of the north abutment

This work was included as an important adjunct to the principal scheme of stabilising the structure. It consisted quite simply of removing the spandrel filling from behind the upstanding portion of the north abutment and providing a short deck span over the resulting gap, all being concealed within the existing spandrel walls, which were themselves stiffened on their newly-exposed inner faces by a reinforced concrete lining. This had the triple advantages of, (a) reducing one of the potential forces causing movement, (b) removing a suspected source of fractures in some of the northern secondary cast-iron members and, (c) achieving much more evenly balanced loading over the whole structure, compared with the previous preponderance of load on the north abutment. Construction work was undertaken by the Salop County Council Direct Labour organisation, to the consultants design, and was carried out during 1972 without any untoward difficulties.

Stage 2. Strutting between abutments

The scheme finally selected consisted of a heavy reinforced concrete invert slab at river bed level between, and over the full width of, the abutments together with heavy reinforced concrete facing walls to the abutments. The invert and facing walls together form a very substantial trough section, the function of the invert being, as a strut, to prevent further sliding at abutment toe level, while the monolithic facing walls resist any resulting tendency for the abutments to tilt forward above toe level.



Stage 3. Miscellaneous works

When Stage 2 has been completed and the bridge stabilised it is planned, in Stage 3, to carry out repairs to the cast-iron superstructure and to do other minor "making good".

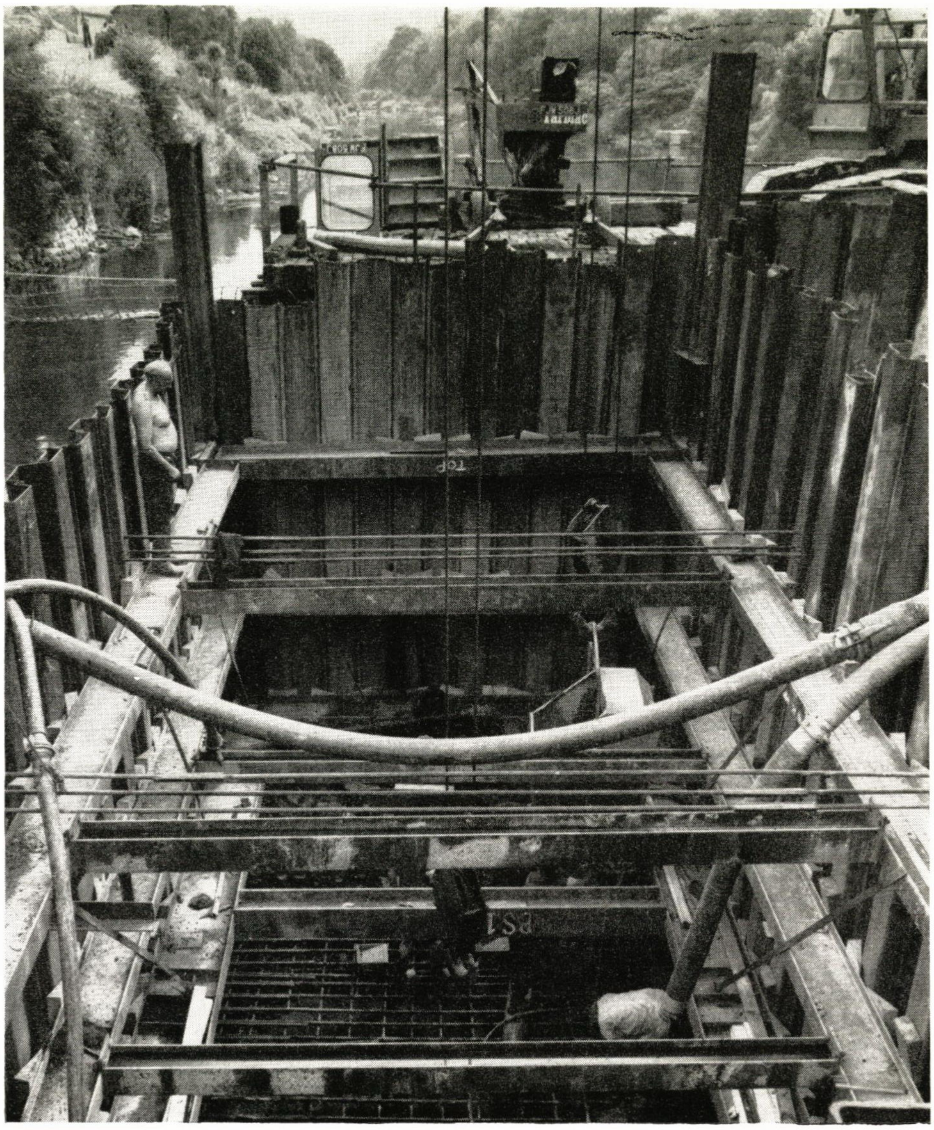
The remainder of this article is devoted to a more detailed description of the Stage 2 works, which are currently in progress.

Strutting between abutments

As described above, this part of the stabilising works consists essentially of a heavy reinforced concrete trough section between the abutments, the floor of the trough forming an invert slab at river bed level.

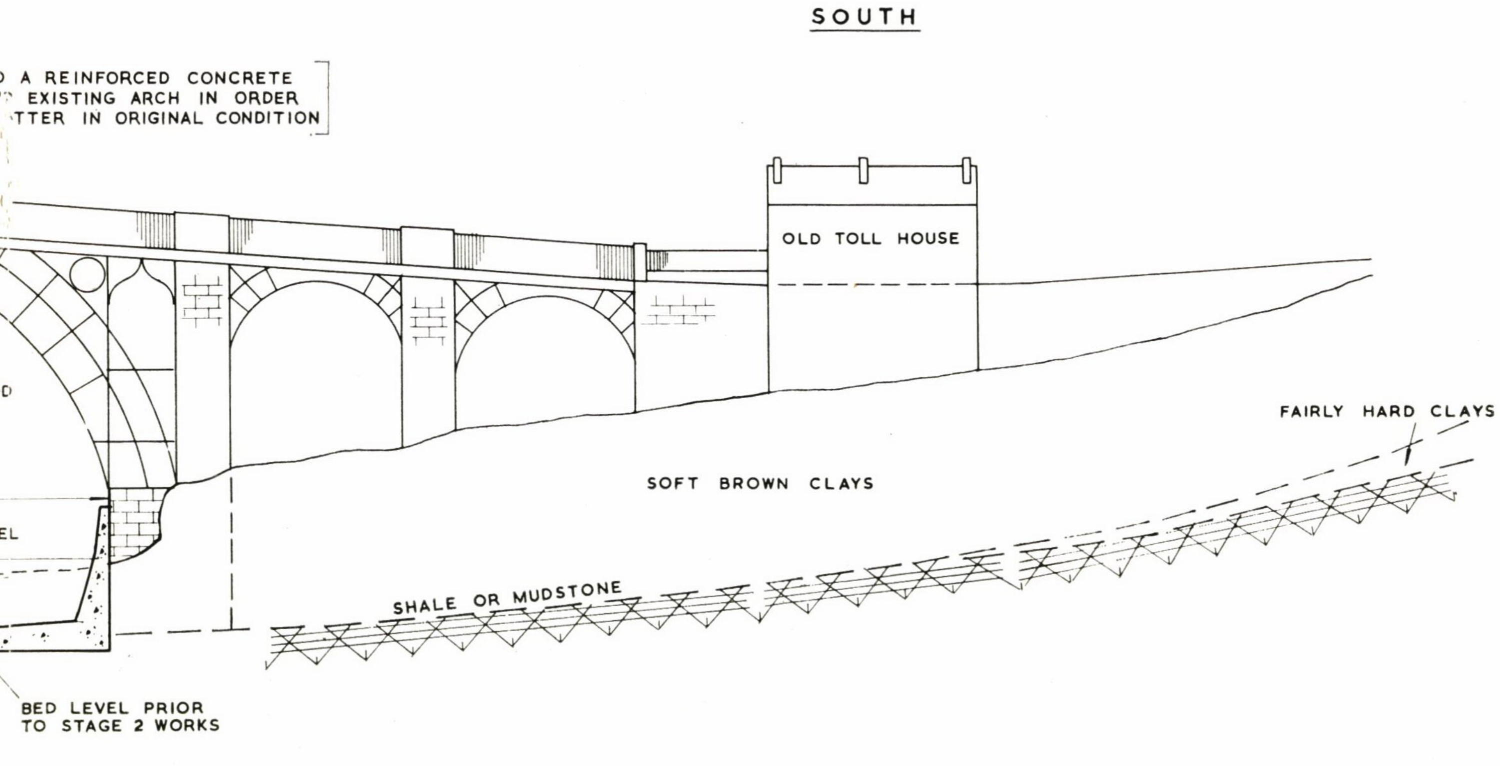
It was decided to carry out the work by contract and tender documents were prepared which stipulated that construction was to be "in the dry", single-skin sheet-piled cofferdams being envisaged, but not specified. Following discussions with the Severn River Authority, tenderers were given the alternative of doing the work within 3 separate cofferdams (i.e. closing one-third of the river at one time) or within 2 cofferdams (closing half of the waterway at one time), but with a lower crest level for the cofferdams in the latter case. Work within the river was confined to the months, April-October inclusive.

Tenders were invited from a selected list of firms and were received in January, 1973, a contract subsequently being awarded to Tarmac Construction Ltd. who opted for the two-cofferdam sys-



Above—Concreting of invert strut in small compartment of the south cofferdam

Below—General arrangement of the iron bridge remedial works showing stages of the work and the ground conditions



tem of construction. It is of interest to note that there was an approximately evenly divided choice between 2 and 3 cofferdams in the tenders submitted.

The permanent works included in the contract are in themselves relatively simple and call for no special comment. The object of the design was to provide a structure of substantial strength which could be easily and rapidly built, within one section of cofferdam at a time, once the latter were successfully dewatered and the existing abutments temporarily propped and strutted. It was considered that the contractor would have three principal problems, viz, forming watertight and stable cofferdams in a fast-flowing river with uncertain bed conditions; temporarily supporting each abutment to ensure complete stability once the head of river water had been removed and the abutment fully exposed by excavation for the new work; coping with the inevitable periodic over-topping of the cofferdams which river records indicated could be expected several times during the working season. It was therefore important that the construction of the permanent work itself should not constitute an additional problem. The foregoing is reflected in what must be a most unusual contract price, where the permanent works, including excavation, constitute less than 25 per cent of the total cost as tendered.

Although at the design and tender stage some previous borehole logs from nearby locations were available, together with the results of driving a test sheet pile, it was far from certain what penetration into the shale/mudstone stratum could be achieved for cofferdam piling. The contractor therefore prudently based the design of the Temporary Works on the premise of achieving only a few feet of penetration with single-skin sheet piling, sufficient to provide a cut-off, and obtaining overall cofferdam stability by internal framing combined with the support obtained from two H-piled working gantries across the line of the river, one upstream and the other downstream of the bridge. This design has, in the event, justified itself, although not without some "trials and tribulations".

Temporary works under stress

The second of the contractor's principal problems — temporarily propping each abutment—was clearly a vital and delicate matter. The whole object of the exercise was designed to stabilise structures which were known to be moving; hence the necessary removal of even the small amount of resistance provided by the river itself and the bed adjacent to each abutment could have proved to be "the last straw". The engineers required the temporary strutting to be capable of sustaining a horizontal load of at least 700 tons per abutment. The contractor's proposal for providing this resistance was to sub-divide each main cofferdam into 2 compartments; the smaller, outer compartment would be de-watered and excavated first and the contained portion of invert slab constructed with a deep key into the rock (see sketch). The inner compartment would then follow, excavation being taken out piecemeal to accommodate a system of soldiers pinned to the abutment face with raking struts back to the keyed slab in the outer compartment —an upper layer of soldiers and struts being placed first, followed by a lower tier as excavation progressed. How this worked out in practice is described later.

The third problem—river flooding—could only be met as and when it occurred, apart from ensuring that the Temporary Works were generously designed and that moveable items were removed or "battened down" when a flood warning came through. With reference to general safety it can be mentioned here that a safety line was provided across the river, downstream of the works, with a rescue boat on full-time stand-by duty. To date the latter has, fortunately, not been in action on account of site personnel, but early on in the contract, the alarm klaxon sounded and the rescue boat put out exceedingly promptly to pick up some overturned canoeists who otherwise would have been in serious trouble.

The intended scheme has been adhered to and has justified itself, but inevitably on a work of this nature problems have occurred.

Pile penetration resistance

The first major problem to be encountered, and one which influenced the timing of all subsequent work, was the fundamental one of sheet pile penetration. Work began from the south side and at once difficulty was experienced in getting the piles toed in to the rock stratum, the driving resistance being extremely hard. At this point, working to what was virtually a day-by-day programme, it was tempting to accept reduced penetration (knowing that stability was assured by the gantries) and to "hope for the best" when it came to de-watering. This temptation was, however, resisted and driving continued until an average of about 915 mm (3 ft) into the hard stratum was achieved. This persistence undoubtedly paid off later, although on such a tight programme it did not prove possible to regain the lost time. (Almost from the start the contractor has worked a 7-day week of extended daily hours).

The H-piles in the gantries were driven without incident, using a 600N hammer. The sheet piling was driven by a No. 6 McK.T. hammer in the early days which was later replaced by a 600N hammer. In view of the "delicate state of health" of the bridge, pile driving operations were monitored for vibrational effects. In all cases—including one or both hammers working—vibrations recorded on the bridge superstructure proved to be extremely slight, less, in fact, than those attributable to pedestrian traffic.

As work progressed across the river, the pile driving conditions changed and, during the driving of the first section of the northern cofferdam, although resistance increased when rock was reached, penetration was achieved comparatively easily and as later described it became necessary to continue driving a further few feet in order to ensure watertightness. This, in turn, involved the frustrating, exercise, from the time view-point, of lengthening the affected piles.

As noted earlier, the attention paid to achieving a reasonable cut-off penetration with the sheet piling was subsequently justified in that, apart from two specific incidents, de-watering and excavation operations were largely trouble-free. The first incident followed the pumping out of the outer compartment of the No. 1 cofferdam, when a "blow" occurred in the sheet pile diaphragm between the two compartments (where, significantly, a penetration of about 300 mm (1 ft) into rock had been adopted as it was a diaphragm wall only). This was successfully plugged without great difficulty, but inevitably lost some further time. The second incident was a more serious "blow"—actually a series of "blows"—in the first compartment of the No. 2 cofferdam. As noted above, pile driving here had been easier, and lengthening the piles and re-driving cured all but one area of ingress. This incident took place in October and was particularly frustrating as the contractor was "racing the clock" with the specified end of the working season fast approaching. Nevertheless this particular "blow" was beyond the capacity of any simple plugging and a length of sheet pile curtain wall had ultimately to be driven outside the area of "blow" and sealed by punching clay with an H-pile "hammer" into the gap. This emergency repair subsequently held good for long enough to enable the excavation, steel fixing and concreting of the slab to be pushed through at great speed, after which the compartment was flooded permanently.

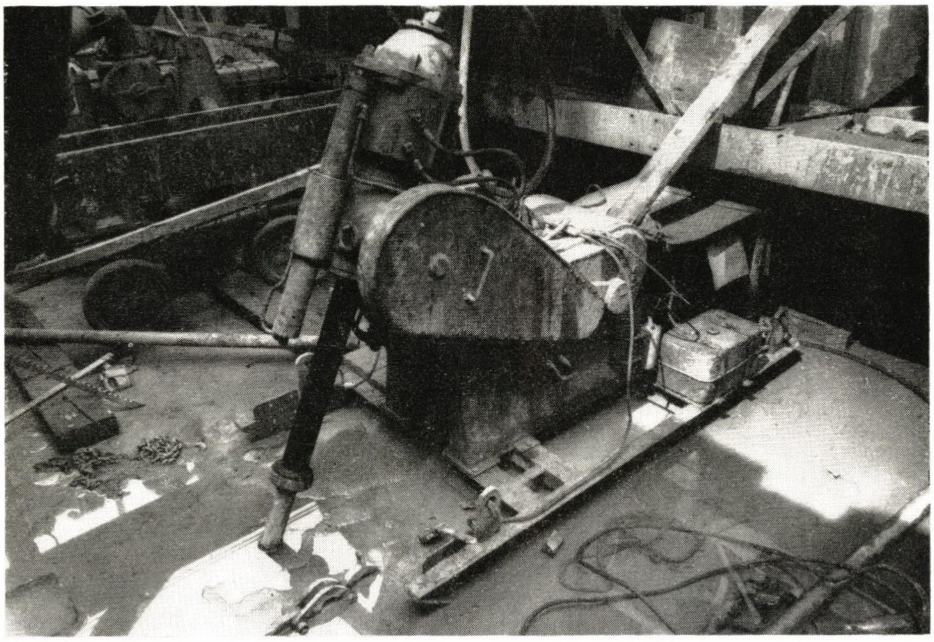
Turning now to the temporary support of the abutment, it was mentioned earlier that the intention was to take the reaction of the temporary raking struts by keying a section of permanent invert slab into the rock. In the event, despite the hard pile driving and excavation conditions, the mudstone deteriorated quickly on exposure to the atmosphere. The value of the key thus became most suspect and in view of the possibly vital role to be played by the temporary support system, the decision was made to abandon the proposed key and to substitute a system of ground anchors (see sketch). This decision was reinforced by the unwelcome fact that, at this time, it was clear that the original target—to complete the contract in one working season—was no longer practicable. Thus as virtually the whole of any remaining cofferdam, temporary strutting, etc. have to be taken out of the river during the "close season", the ground anchor installation would ensure adequate support of the south abutment through the winter, pending final "closure" of the invert slab next season.

The angle of inclination of the ground anchors was restricted by the working room available, and the actual installation had, of course, to be carried out within the limitations of the cofferdam internal framing, but otherwise this additional work went ahead smoothly.

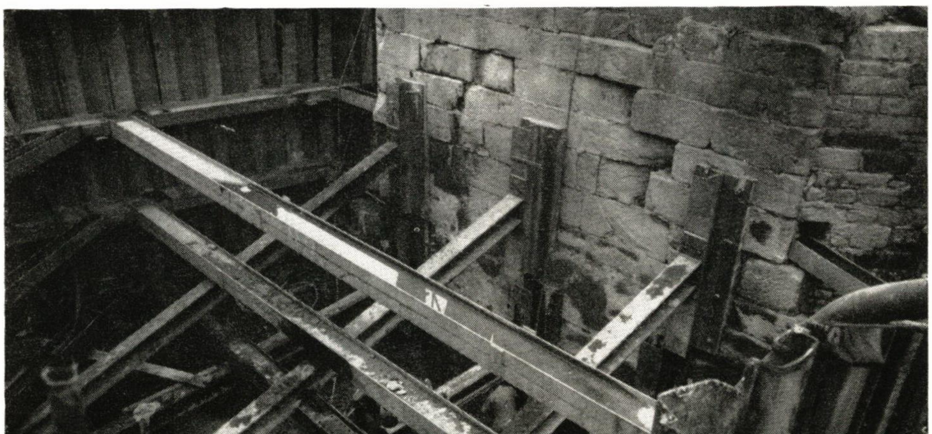
When excavation began in the main compartment of the No. 1 cofferdam, a trial shaft was put down adjacent to the face of the south abutment to determine whether, in fact, this face was vertical over its full depth to rock level, as deduced from the records, or whether it was stepped forward with a conventional toe. If the latter, it was important to ensure that any resulting modification to the design of the new works, re-bending of reinforcement, etc. was completed in advance of excavation. This trial shaft confirmed that the abutment was not stepped—but brought to light a further possible problem of some magnitude.

There was a heavy flow of water through the interface between the abutment base and the rock into the trial pit. The consequences of this lubrication on an already slipping abutment, quite apart

Looking south east, the upstream gantry and access road—May, 1973



Drilling rig for rock anchor installation in small compartment of South cofferdam—September, 1973



Final excavation in rock in front of South abutment, showing upper and lower raking struts

from the physical problems of dealing with the water during steel fixing and concreting can easily be imagined. The contractor and the engineers therefore together prepared a scheme for underpinning and plugging the toe of the abutment, but for once Fortune smiled and when the main excavation reached base level the inflow had all but ceased. Presumably the trial shaft had either released a pocket of trapped water or else had acted as a sump for a small flow, giving an exaggerated effect.

During the April-October working season the cofferdams were overtopped on six occasions involving some 25 days delay. During one of these the river rose to "the highest level for a summer flood during living memory"—some 1.5 m (5 ft) above arch springing level. On one or two of these occasions the temporary gantries suffered comparatively minor damage, but by and large, the Temporary Works proved adequate to resist both the flood flows and the inevitable pile-up of debris. The contract provided for such flooding so at least the "paper work" did not give rise to any problems.

Conclusions

So the first working season of the principal Iron Bridge remedial works ended. If there was disappointment because the target of full completion in one season had not been achieved then this was offset by a sense of satisfaction arising from "problems overcome" and the knowledge that what had been done had been well done.

Despite the experience gained this year it is known that the old bridge still has one or two new problems to present. As work finished in 1973 an underwater examination of the north abutment face revealed a hitherto unknown course of masonry protruding from the face, well above formation level. Is this an isolated string course, the first of a series of outward steps, evidence of previous north abutment movement, or something else altogether? Investigations are proceeding, but clearly this contract, small by present-day monetary standards, is going to keep all concerned "on their toes" until final completion is achieved.

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Acknowledgements

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Thanks must also be expressed to the residents of the cottages adjacent to the south abutment who have suffered long hours of pile driving, pumps and compressors without complaint.