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Project

Strengthening of the charging ramp to the Darby Furnace, Coalbrookdale

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Paper

Strengthening of the charging ramp to the Darby furnace, Coalbrookdale

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Synopsis
Sometime over the weekend of 7 and 8 March 1987, part of the charging ramp to the famous Darby furnace at Coalbrookdale collapsed. Subsequent investigations revealed that other parts of the structure were also very unstable, and they were temporarily shored.

It was decided that the collapsed section should be rebuilt and a solution to the long-term stability devised. The listed structure was to be strengthened to give an increase in the reduced margins of stability that had resulted over the years due to manmade and natural effects.

This paper describes the design and execution of the remediation scheme which was based on a combination of well-established principles and unconventional techniques, and was sufficiently adaptable to allow modification as work proceeded on site, revealing unforseen circumstances.

Introduction

All old structures under crisis have their own historical equilibrium, their weaknesses, strengths and unknowns which even the most detailed of surveys may not reveal. This means that the strengthening of an ancient structure cannot be the subject of very theoretical analysis and that there has to be a close relationship between the design and execution of the remediation works.

The following describes the evolution of a scheme to strengthen and stabilise a scheduled Ancient Monument[1] included on the World Heritage list, a small part of which had already collapsed and the remainder of which may have had a factor of safety close to unity.

The Darby furnace site at Coalbrookdale, Shropshire, is one of the most important industrial archaeological sites in the world, considered by many to be the very birthplace of the Industrial Revolution. The furnace itself, by far the most important monument on the site, was restored some years ago and now resides under a modern protective building in the Museum of Iron that has been created there. It is the charging ramp to the furnace and associated adjoining structure that was to be the subject of restoration on this occasion.

A brief history of the site is included so that the importance of the structure may be put into context.

Historical background

In an area of Shropshire renowned for many famous historical events and innovations it is, perhaps, the construction of the Iron Bridge over the River Severn in 1779 which is best known. However, about 1km to the north of the Iron Bridge, in Coalbrookdale, is the Darby furnace. This old iron furnace is where, 70 years before the construction of the bridge, the grandfather of its builder, Abraham Darby[1] had experimented with the production of iron using coke, rather than charcoal, as a smelting fuel. This was to have a profound influence on the way in which iron was produced and consequently, in the 1750s, upon the course of the Industrial Revolution. It is also the furnace where the iron for the Iron Bridge was produced.

The industrial history of this area is not clear, although it is known that a furnace had existed on the site before Darby came to this attractive gorge in 1708. He undoubtedly found an already busy, industrialised landscape[2], although the old furnace was almost certainly derelict at this time.

The upper furnace pool dam held back the water (now extensively silted up) that would have been needed to drive the waterwheel(s) that powered the site and was probably constructed in the mid- to late-17th century. It is likely that a charging ramp had always led out from the south face of the dam so that charging materials could easily be loaded into the top of the furnace. This is contrary to the normal practice with Shropshire furnaces of building them into a sloping bank for this purpose. The structure of this ramp at its northern end may have been continuous with that of the dam, although later additions and alterations have obscured all traces of this relationship. The south-facing elevation of the dam has probably always been vertical or near vertical, which would place considerable strain on its (unknown) internal construction.

It is likely that substantial repairs and rebuilding took place in 1706 after a breach in the dam. The dam was further breached in 1801, apparently causing considerable damage to the surrounding structures. At some time the top of the dam was raised to its present level. This could have taken place at the same time as the east end of the south wall of the dam was realigned, possibly as a result of the 1801 collapse. By 1805 there is clear evidence of buildings being sited against the south elevation of the dam and adjacent to the east of the charging ramp, though they certainly existed in the vicinity since, at least, the mid-18th century.

By 1827 the general line of the pool dam and the charging ramp area appear very similar to their present-day shape (Fig 1). The raised area to the east of the charging ramp proper is a late addition to the ramp itself which may have been present by the mid-18th century.

The furnace itself went out of blast in 1815, but when a parapet wall was built across the south face of the dam ca 1840 access was still provided onto the ramp, presumably for access to adjacent buildings, some of which were at least one storey higher than the dam. The area continued to be used for moulding and pattern shops well into this century.

It is apparent from recent investigations that the building that ad[illegible] the east of the charging ramp (hereafter included in all references to the ramp as part of that structure) was backfilled at some time during the 19th century. The reason for this being done is not known, but it is possible that it became

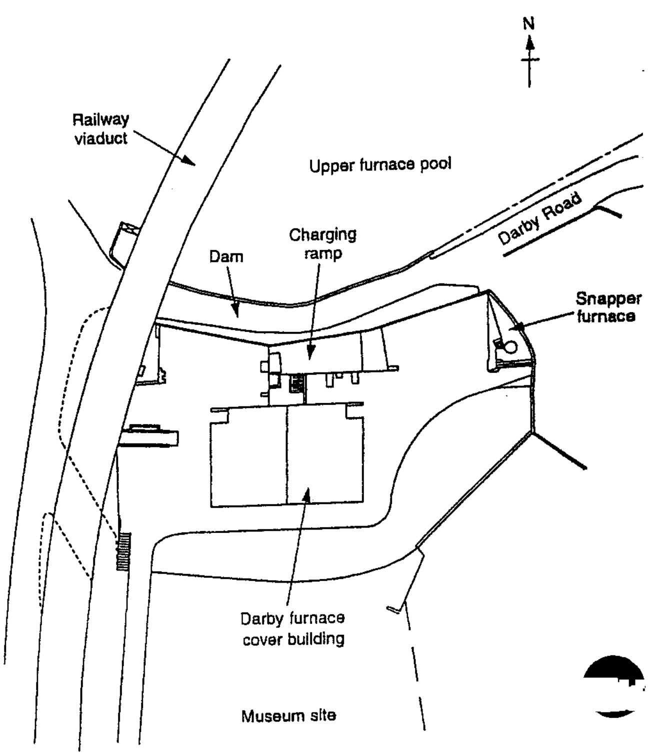


Fig 1. Present-day site plan

Fig 2. Condition of the charging ramp prior to restoration

necessary to provide a buttress to the dam after it had been increased in height. What is clear is that the filled shell must soon have shown signs of major distress. Several attempts were made to stabilise it, with only partial success. A large cast-iron cross is still in existence on the face of the south wall of the charging ramp, forming a terminal to a wrought-iron tie that penetrated and, probably, passed through the dam. Other ties, now completely corroded through, and pattress plates are also in evidence. Two large brick buttresses were added to the same wall about 100 years ago.

The moulding shops in the vicinity of the furnace were closed in 1930 and demolished ca 1950. Restoration works carried out prior to the site being opened to the public in October 1959 may have included adding a concrete capping slab to the ramp structure.

Recent history

On Monday 9 March 1987, the Director of the Museum advised that the upper part of the southeast corner of the charging ramp had collapsed over the weekend and required urgent inspection. The structure was already under investigation and being monitored to try to identify the reason for extensive cracking, following checks carried out on its safety. The walls each side of the collapsed corner were clearly distressed, particularly the south wall, which was leaning out precariously, so these were shored up while the long-term proposals for the structure and its relationship with the furnace and dam were considered.

Scott Wilson Kirkpatrick (SWK) reviewed the condition of the structure, and was asked to make recommendations for its long-term stability. The repairs were to form part of a project to refurbish several historic properties throughout the gorge.

In October 1988 a photogrammetric survey of the dam wall and charging ramp was carried out.

The structure

The structure at this time was much as illustrated in Fig 2 – a filled masonry shell, approximately 22m in length × 8m wide × 6-8m high, returning into the Darby furnace cover building, abutting and possibly buttressing the dam, with unknown internal construction and foundations. The external walls are built (or faced) with a mixture of random coursed sandstone blocks and brickwork.

The south wall consists of stone blocks up to a level 1.5-2.0m above ground where there is a clear delineation to brickwork. This entire length of the brickwork leans out at a maximum of 1 in 15 and some two-thirds of the length of the wall bulges noticeably vertically and horizontally. The reason for this characteristic deformation was to become clearer later on during the execution of the remedial work. The two large brick buttresses, 1.8m wide × 2.6m deep at the base, occur at approximately third points.

The east wall, which consists entirely of stone blocks, was reasonably plumb, though slight bulging was apparent towards the bottom. Bedding mortar had been extensively washed out from a large area at the top left-hand corner of this wall adjacent to the section that had failed. This was probably a contributory factor to the collapse, but the reason this area of masonry should have been affected in this way was not apparent at this time.

When the upper part of the southeast corner collapsed, two short lengths of wall were exposed at high level. As these were mutually buttressed and roughly vertical, they were probably in their original position. They certainly limited the extent of the collapse by continuing to retain the fill in the bulk of the structure. The rubble from the collapse had been sorted and put to one side.

The west wall and east return from the south wall were both in good condition, requiring only cosmetic repair. A narrow vaulted passageway accessed from the west face had been blocked off approximately 6m into the structure. Its position, line and length to blocking, suggested that this had probably been an access passage through the ramp.

The concrete slab at the top of the walls was on two levels, being lower towards the failed corner. The remaining brick buttressed wall therefore retained about 1.5m more material than the failed section. Preliminary calculations, assuming typical parameters, indicated that this section had a factor of safety against overturning of 0.65. Since the wall was actually standing, this was obviously on the pessimistic side, though it may have been indicative of possible impending disaster. It may also provide an indication that extra stability was being provided by hidden walls inside the block.

Scheme development

Several years of correspondence and discussion ensued with all the parties concerned, in particular Ironbridge Gorge Museum Trust (IGMT), its Archaeological Unit (AU), and English Heritage, as to the best approach to the problem. A number of ideas were sketched, but were ruled out early on as schemes considered to be too visually intrusive.

In October 1990, Wheatley Taylor Stainburn Lines (WTSL), an architectural practice whose specialisations include the restoration of ancient property, was appointed as lead consultant for the works. It was decided that the collapsed section would be rebuilt as part of a restoration package, and this should be allowed for in any scheme for strengthening.

Before a solution could be devised it was clearly necessary to investigate the internal make-up of the structure and fill material in more detail. As the structure is an Ancient Monument, scheduled monument consent (SMC) was required even before an investigation could be carried out.

Site investigation

The investigation, carried out in September 1992, included two boreholes positioned on the raised area to the east of the charging ramp and a series of 25mm diameter core holes drilled horizontally through joints in the masonry to determine wall thicknesses.

Archaeologists worked alongside the contractor, logging boreholes and coring.

The results from the investigation[3] indicated that the fill, up to the level of delineation between the stone and brickwork, was soft clay, probably an extension of a puddle clay cut-off behind the dam. The top 6m or so, the bulk of the fill, consisted of waste material such as foundry sand, ash and brick rubble.

Groundwater had stabilised at a level between 7.2m and 7.5m below the top of the structure, depending on season. This is perched 0.5-0.8m above external ground level, maybe as a result of ingress from the pool and rainwater draining through the flat top. There was evidence of seepage under and through the dam wall along the section to the east of the charging ramp.

Core holes indicated that the brickwork was generally of the order of 400-450mm thick, though these appeared, at least in parts, to be made up from three separate, mortared, but unbonded leaves. In one area, near the collapsed corner this reduced to 250mm, again probably a factor in the collapse. Thickness of sandstone walls varied between 400-800mm.

Selected option

In the light of this information, the options were reviewed.

- Gravity buttresses had already been dismissed as visually unacceptable.
- Flexural buttresses on gravity bases, although less massive and visually obtrusive, had been ruled out on archaeological grounds.
- The soil infill could have been consolidated into a single stable mass, using a pumped cement grout, on to which the walls were tied back. Also unacceptable for archaeological reasons.

In principle, a scheme using drilled and grouted ground anchors was identified as an option that was acceptable to all parties, and this was developed in more detail.

It was proposed that the ramp should not be anchored into the dam,

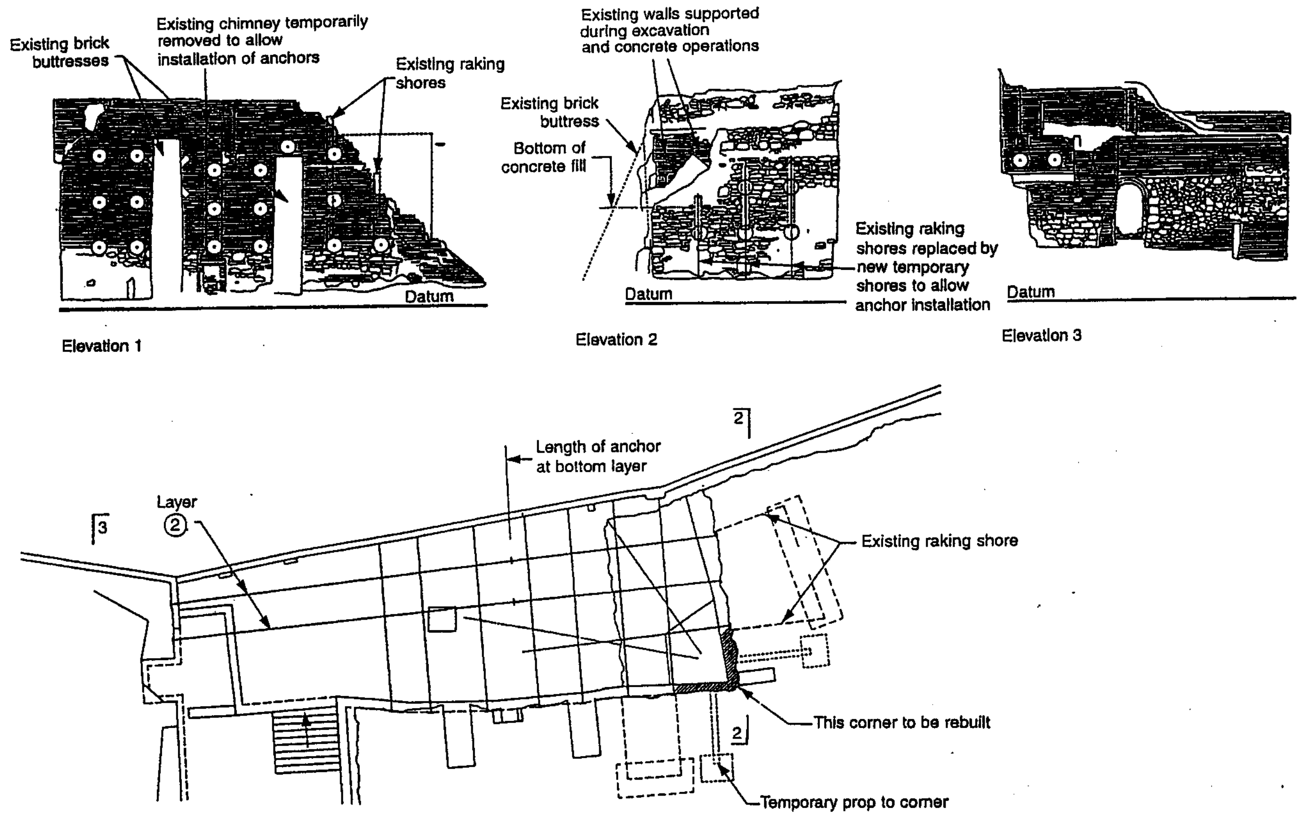


Fig 3. Proposed scheme

whose ownership was unclear, but must be stable as a filled masonry block in its own right. Ground anchors would not be preloaded as this may have had an adverse affect on the delicate equilibrium within the structure. In effect, the walls were to be 'nailed' back to the mass of fill using a matrix of anchors and, if possible, through ties (Fig 3).

The collapsed section to be rebuilt would be stabilised by excavating the remaining fill in the corner to a suitable depth and replacing it with lightweight concrete. The new masonry would be tied to this block which would, in turn, be anchored back into the mass of fill.

After installation of anchors and satisfactory load-testing, strengthening and cosmetic repairs of masonry, as specified by the architect, would be carried out. Finally, a new reinforced concrete slab would be added, tied to the top of the walls and the concrete corner block, to act as a diaphragm. This slab was to be waterproofed, laid to falls, and positively drained to prevent further the ingress of rainwater. Weep holes would be included at the delineation level between stone and brickwork on the south wall.

It was decided to adopt the Cintec MC Systems[4] anchor, since the basic principle of the system allows great flexibility of use and the anchors could be designed to cope with any unknown voids or walls within the structure. This turned out to be a prophetic choice.

The anchor designed for the particular requirements of the charging ramp is shown in Fig 4.

Detail design

The anchors were designed in accordance with the recommendations of BS 8081[5] and BS 8110[6], assuming anchorage type B with regard to the rul estimating pull-out capacity. Free and fixed anchor lengths were base the assumption of a failure mechanism using wedge theory.

Vertical spacing of the anchors was dependent upon the limiting distance that the walls could reasonably be expected to arch, taking into account the size of spreader plates and wall thicknesses and assuming a simple geometric distribution of pressure. The existing brick buttresses were assumed to be still effective in their locality.

Final positioning of anchors was determined by archaeological and constructional constraints as well as the structural requirements.

Because the design philosophy restricted anchors passing into or through the dam, ties could not be positioned in the south wall. However, two through-ties were included between the east wall and the apparently stable west wall requiring bores of approximately 22m for their installation. Tendons were high yield ribbed reinforcing bars of austenitic stainless steel to BS 970[7], and small diameter stainless steel resin anchors were used to stitch the top of the walls to the edge of the reinforced concrete top slabs and to tie the rebuilt corner brickwork back to the concrete block.

A check was made on the stability of the corner block as a gravity structure. Two ground anchors then integrated the block into the fill mass and anchor matrix.

As there was evidence that the watertightness of the dam was unreliable and the dam/ramp interface detail was unknown, the whole strengthened block was checked for stability under full external hydrostatic pressure. Finally, an independent review was carried out[8].

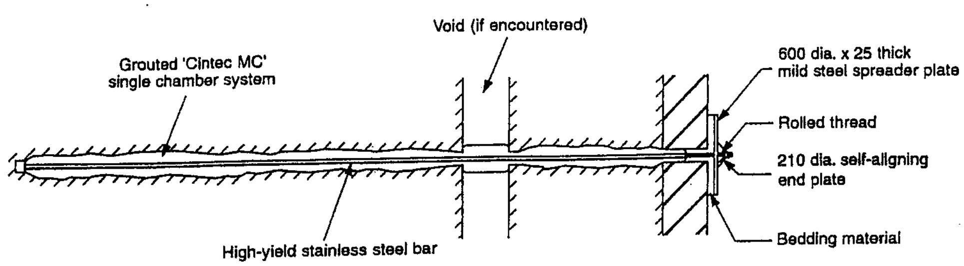


Fig 4. Proposed grouted anchor design

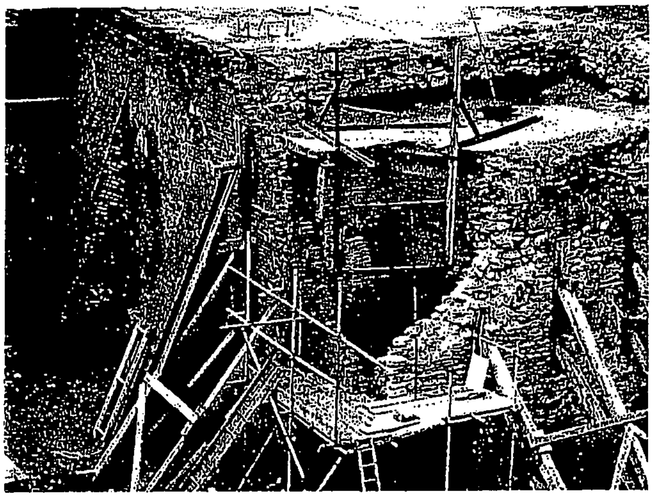


Fig 5. Southeast corner excavated prior to rebuilding

Execution of the works

On 27 July 1993, the Secretary of State for National Heritage granted SMC for remedial works to the charging ramp.

Work of this type requires extreme care, on the part of the contractor, not to disturb the already fragile structure and sensitivity in repairing ancient masonry which is seldom plumb or level. It was felt that a contractor with a proven track record in this type of work was essential.

A local contractor[9] had already shown such qualities on the site, stabilising walls and restoring masonry, including to the south wall of the dam. It was considered appropriate for the same craftsmen to complete work on the site. They had also demonstrated the ability to cooperate and act in parallel with the archaeologists, a specified requirement for this contract. To this end a contract was negotiated on the basis of previous rates and experience, although there was no precedent for this type of anchor work.

Because of the unusual nature of the anchor work it was necessary to nominate a subcontractor[10] who had experience in installing long Cintec anchors accurately into buildings, including listed structures.

Work began on site early in April 1994, on a 6-month programme, initially removing vegetation and stitching cracks. Supervision of the work

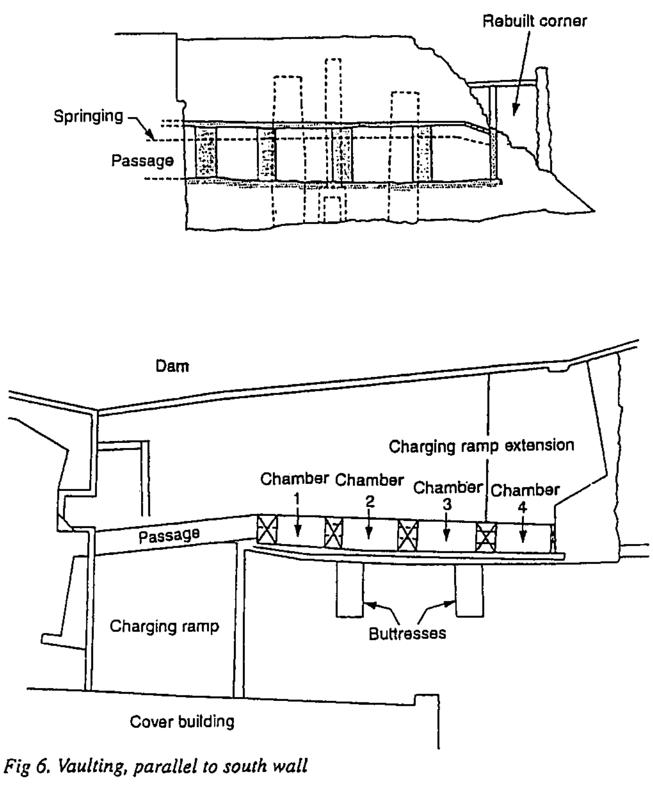


Fig 6. Vaulting, parallel to south wall

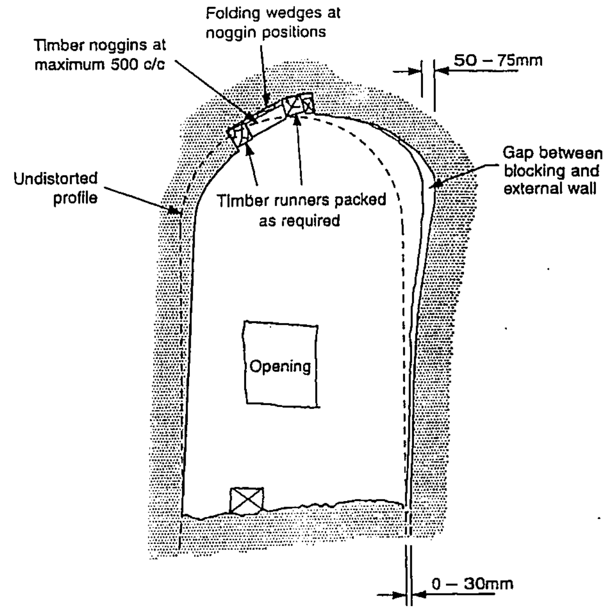


Fig 7. Typical profile of blockings and temporary stabilisation to crown withi vaults

was on a part-time basis, with frequent visits from English Heritage' Ancient Monument Inspector and the almost permanent presence of th archaeologists.

It was specified that the collapsed southeast corner had to be stabilise before ground anchors could be installed. The emptying of the remainin fill, carefully carried out by a combined team of contractors and archaeological staff, revealed the first unforseen circumstance (Fig 5). An ill-fittin brickwork blocking low down in the eastern face of the excavation indicated a large vaulted chamber behind.

Vaulting (south wall)

In fact a series of chambers, formally a vaulted passageway, had been discovered running along the edge of the structure, parallel to the south wall (Fig 6). The bottom of these chambers was level with the stone/brickwork delineation. They were of similar profile to the existing passageway visible in the west wall, of which they were obviously a continuation. A small square opening was discovered in the blocking at the end of this passage which, when slightly enlarged, allowed tight access into the first of four chambers. The original passageway had three 550-850mm-thick brick diaphragms, symmetrically positioned relative to the external buttresses, and therefore almost certainly added at the same time (ca 1880). The profile of these blockings (Fig 7) showed the considerable deformation that the vaults had already undergone at the time of their construction. The diaphragms had not been bonded or tied into the original walls, and the horizontal and rotational movement of the structure subsequent to their installation was evident from the tapering gap between them and the external wall. A small opening in each blocking provided access to the next chamber.

The centre of the horizontal bulge apparent on the outside of the south wall approximated to the springing of the (originally) semi-circular vaulting.

Upon inspection the vaults were found to be in a poor condition, with the inner of two rings progressively collapsing at the crown, indicating that a hinge had formed and that rotation had taken place due to spreading at the springings. Because the second vault ring was complete the vaults were relatively stable, but loss of bricks from this ring would almost certainly have initiated partial or complete collapse of the vaults.

Restoration work was undoubtedly required to the roof but, because this would be subject to a separate SMC, could not be carried out before installation of the ground anchors. Temporary stabilisation was therefore achieved by replacing the missing masonry at crown with timber runners, noggins and folding wedges (Fig 7). Hand force only was specified for this work so as to minimise the effects on a delicate equilibrium.

A new collapse mechanism was reviewed, allowing for the presence of these vaults and the original anchors found to be still adequate.

A slight adjustment was all that was required to move the middle row of anchors on the south wall to the vault springing line. This seemed a sensible move since the thrust from the distorted arch could be picked up directly and

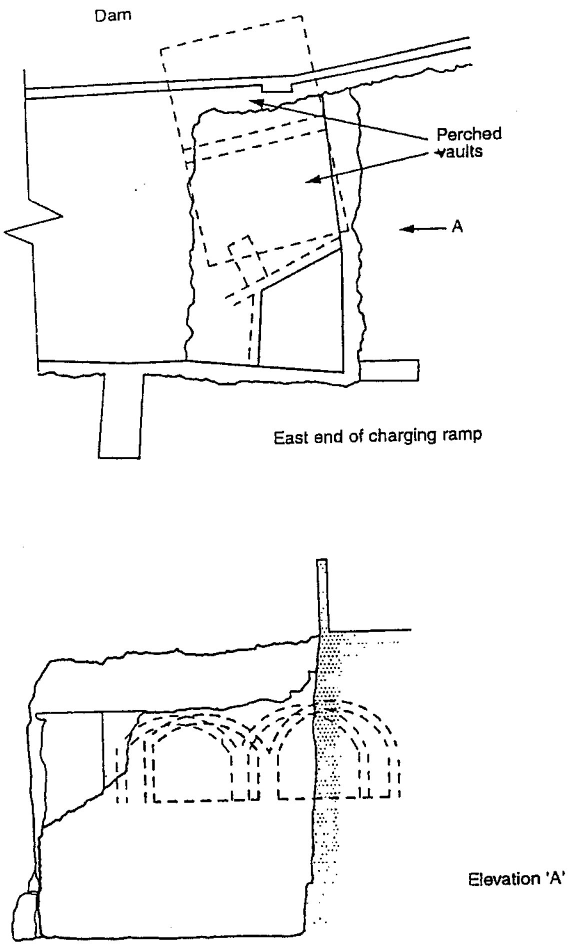


Fig 8. Vaulting, high level at east end

springing positions could be geometrically locked, preventing further spreading. By good fortune the bottom row of anchors was already at the same level as the bottom of the vaults.

The rebuilding of the southeast corner continued uneventfully, with brickwork skilfully constructed to lean outwards and twisting in-plane to tie in with the existing. Bricks were reused to obtain as good a match as possible, and many trials carried out varying constituents, to blend new and ancient mortars.

Removal of lower slab

During the operation of removing the lower slab at the east end of the structure it became clear that the stonework between the two levels required underpinning, as did the parapet wall to the dam. An underpinning detail that would not be visible in the completed works was devised to be tied into the new slab.

Break out of this slab gave the opportunity to monitor vibrations on parts of the structure, and most importantly, on the Darby furnace, prior to anchor installation. Monitoring was carried out at various points on the furnace and in the vaults, using a portable digital seismograph. At no time during the break out or subsequent drilling operations did the peak particle velocity approach that specified.

Removal of this slab also revealed a second set of vaults.

Vaulting (east end)

Two large brick vaults had been discovered perched at high level at the extreme east end of the structure (Fig 8). These were skewed, had been truncated and faced with the upper section of stonework to the east wall. Part of the north vault projected into the south face of the dam. They were clearly from an earlier, unrecorded structure.

At their southern end the springing was partly buttressed by the previously unexplained walls 'hanging' at high level in the southeast corner. This arrangement had been channelling rainwater to the top left-hand corner of the east wall, causing the area of washed-out mortar that had been observed and contributing to the collapse.

Limited inspection of both vaults, achieved using an endoscope through holes drilled in the mortar joints, revealed that the brickwork appeared to be complete and in good condition. Later, good visual access was obtained to the southern vault confirming this to be the case.

No remedial work was required to these vaults and, after recording by the archaeologists, they were simply left void and covered by the new slab.

Again it became necessary to modify ground anchor positions, this time to the east wall.

Anchor installation and testing

By early July the structure was considered stable enough for the 6-week programme of anchor installation to proceed, using a hydraulic rotary drill with a mining barrel crown.

Installation to the south wall was completed without incident. The east-west ties were to be inserted next, with drilling operations carried out from the west end, since positional tolerance was tighter at this end.

Some 13m into the first bore the drill clipped the edge of what appeared to be a hard substrate, probably a block of iron. The consequence of this was two-fold. The mining barrel crown disintegrated, causing a 1 week delay in drilling operations and, more seriously, the bore was deflected from its original course. Although only slight overboring was necessary to allow insertion of the tie, the second tie was replaced by another anchor in a revised position rather than risk a similar occurrence.

Anchor installation was completed without further problems. Representative anchors in the proximity of the existing buttresses were selected for load testing. Loading was carried out hydraulically using a 30t capacity hollow ram reacting against the buttresses, and anchor capacity comfortably exceeded that required.

Completion of the scheme

The addition of pattress plates completed the anchors. Reinforced concrete capping slabs were cast, waterproofed and drained to new downpipes. During the first week of November all shoring and temporary propping was unceremoniously removed to leave the structure standing unaided for the first time in 8 years.

Weep holes were installed in the originally proposed positions which, fortuitously, were correctly placed for draining the vaults.

By this time the stabilising work to the vaults had been granted SMC work on site was complete by the end of December 1994 (Fig 9).

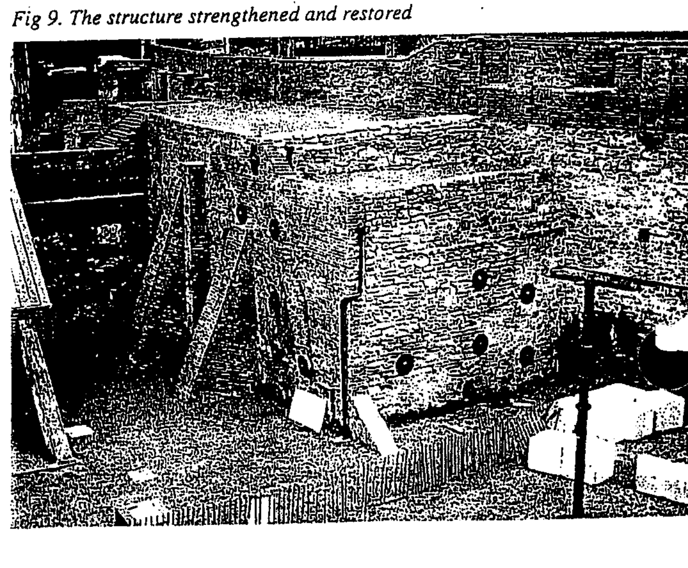
Concluding remarks

Strengthening of the charging ramp was very much a 'one-off' project. It developed over a long period, partly because the historic and archaeological significance of the Scheduled Ancient Monument Consent required careful consideration by all and an agreed scheme for repair from the outset, and partly because of administrative changes within the Ironbridge Gorge.

As with any ancient monument the solution executed had to be right first time since misjudgments cannot be rectified and the consequences have to be lived with for generations to come. The very act of preservation necessarily alters the historical precedent that is to be preserved.

The remediation scheme attempted to unify the structure and increase lost margins of safety without introducing, as far as possible, new stresses and strains, as the existing may already have been near a limiting condition. The

Fig 9. The structure strengthened and restored



general principle adopted was to reinforce the soil and masonry and tie them together whilst modifying, as little as possible, their equilibrium.

A detailed field study had been made along with investigating the history of the structure, but it was still necessary to incorporate unknowns into the works at a very late stage. This illustrates how important it is that such a scheme is flexible and allows for the closest possible relationship between design and execution of the works.

Acknowledgements

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