

Stabilisation of abandoned salt mines in North West England

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Abstract: This paper presents a case history of the stabilisation of abandoned salt mines in the Cheshire Basin. Long-term stabilisation of four mines lying at approximately 90 m depth is an essential component of the ongoing regeneration programme for the town of Northwich, since their stability could not be guaranteed in their untreated condition.

The paper presents a summary of the geology and history of salt mining in Northwich, and describes the condition assessment of the mines, including shape, size, and stability. The stabilisation works comprised pumping a cement and PFA grout mix into the mines, overcoming restraints associated with the built-up nature of the site area. The design and testing of the grout mix are described.

The risks associated with movement of the mines, before, during and after the stabilisation works, are described in the context of the exposed buildings and infrastructure above the mines. Indigenous risks associated with an upper salt layer above the mines are discussed in the context of the stabilisation works. It is shown that the monitoring regime adopted, and its interpretation, including the definition of amber and red movement thresholds, was fundamentally important to the success of the works.

Finally, the key lessons learnt during the technical development of this unusual project are presented.

Résumé: Cet exposé présente l'étude de cas de la stabilisation de mines de sel désaffectées dans le bassin du Cheshire. La stabilisation à long terme de quatre mines situées à environ 90m de profondeur était une composante essentielle du programme de régénération pour la ville de Northwich, puisque leur stabilité ne pouvait être garantie autrement.

L'exposé contient un résumé de la géologie et du passé minier à Northwich. L'article décrit la méthode de diagnostic et d'évaluation de l'état des mines selon des critères comme la forme, la taille et la stabilité. Les travaux de stabilisation comprenaient le comblement des mines par pompage d'un coulis de ciment et de cendres volantes, en prenant en compte les contraintes posées par les structures en surface. L'étude et les tests effectués sur le coulis sont décrits.

Les risques associés avec les mouvements des mines, avant, pendant et après les travaux de stabilisation sont décrits par rapport aux bâtiments et infrastructures affectés à la surface. Les risques intrinsèques associés à un horizon de sel au-dessus des mines sont traités dans le contexte des travaux de stabilisation. On montre que le programme des observations et leur interprétation, qui comprend la définition des seuils d'alerte pour les mouvements, est essentiel pour le succès des travaux.

Enfin, les leçons clés retenues durant le développement technique de ce projet sont présentées.

Keywords: abandoned mines, case studies, grouting, mining geology, risk assessment, underground mining.

INTRODUCTION

Situated in the heart of the Cheshire Plain, Northwich is the largest town within the Borough of Vale Royal. The town sits at the confluence of the rivers Weaver and Dane at a focal point of the Weaver Valley Regional Park. The town plays an important sub-regional role and serves an extensive rural hinterland as a centre for retail, employment and local services.

A regeneration framework has been developed to set out a clear, ambitious yet achievable strategy for the renaissance of Northwich town centre. The strategy builds upon the analysis, research and community engagement, which has been undertaken in recent years. The Northwich Vision identifies a comprehensive retail led, mixed-use development in the Barons Quay Development Area as the most important area in which to focus development in Northwich Town Centre.

The promotion of retail led, mixed-use development focused on Barons Quay is a planning initiative. To achieve the objectives set out in the Northwich Vision Regeneration Framework, the Council has identified a "comprehensive retail led mixed-use development in Barons Quay as the primary driver to deliver the step change improvements necessary to strengthen and enhance Northwich's position as an important market town, retail and visitor destination securing its long term vitality and viability as a key town identified in regional planning guidance".

The proposals will need to ensure a comprehensive approach, proper integration into the existing 'high street' town centre, public access, permeability and a high quality design. These allow for adjacent sites and areas outside of Barons Quay to be considered if a more comprehensive and superior solution could be delivered, which maximises the quality, integration and function of the town centre. Such comprehensive development in Barons Quay has been made

possible by English Partnerships' £32 million grant funding to stabilise the abandoned rock salt mines that lie beneath the town centre.

The mines stabilisation programme comprises the stabilisation, through infilling, of four abandoned salt mines underlying the town centre. The four mines to be infilled are named Baron's Quay, Witton Bank, Penny's Lane and Neumann's Mine. The mines are at approximately 90 m below ground level and prior to the infilling works were open and flooded with brine. The adopted infilling method has comprised the injection of grout via multiple injection points into the mine with simultaneous extraction of the brine.

The town of Northwich acquired its status as a town of some economic significance within the area as a direct result of its extensive salt resources, which have been exploited since Roman times. However, as described in this paper, the intense mining activities in the 19th Century were far from sustainable. In those times the focus was on meeting the needs of the present in terms of prosperity for the mine owners, not on the plight of future generations. In Northwich, a century on from the abandonment of the mines, the ability of the present generation to meet their needs in terms of maintaining a thriving local economy and residential areas, has been severely restricted by the presence of the mines and the threat of instability associated with them. As part of a wide-reaching regeneration strategy entitled *Northwich Vision* the stabilisation of the mines is a fundamental requirement.

TOPOGRAPHICAL, GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Topography

The topography of the study area comprises the valley of the River Weaver in the west and slightly higher ground to the east, which is part of the Cheshire Plain. The River Weaver is incised into the general level of the Cheshire Plain, with the flood plain/valley bottom at an elevation of 12-15 m Ordnance Datum (OD) (this has been much modified by subsequent filling). The eastern side of the study area rises to an elevation of 20-23 m OD.

To the south the ground falls gently towards the valley of the River Dane, which joins the River Weaver just south of Northwich town centre. To the north the ground falls towards the valley of the Witton Brook. This area has been much modified by the collapse of the salt mines beneath to form an extensive 'flash' with the partly flooded surface at about 12-13 m OD.

Geology

The solid geology of the study area comprises Triassic Mercia Mudstone (British Geological Survey 2002). This consists of a sequence of mudstones and halite deposits up to 1200 m thick deposited in a fault-bounded subsiding basin known as the Cheshire Graben (Figure 1). In the Northwich area the Mercia Mudstone formations overlying the Northwich Halite have been removed by erosion. The interface between the overlying strata and the rock salt deposit, where brine from the dissolution of the salt is present, is generally known as the 'wet rockhead'. In the area of the four mines, the Northwich Halite is about 55 to 60 m thick and comprises two beds, referred to, herein, as the Top and Bottom Salt Beds. These are separated by about 9 m of mudstone (referred to as the 30-Foot Marl). The Top Salt occurs at approximately 35 to 45 m below ground level and varies in thickness from 10 to 20 m. The variations in thickness appear to be primarily due to natural solution with time. Wet rockhead occurs at the top of the Top Salt, but there is no evidence of a similar feature at the interface between the 30 Foot Marl and the Bottom Salt. The Bottom Bed salt forms a pure consistent unit of halite about 28 m thick, below which is a Saliferous Marl.

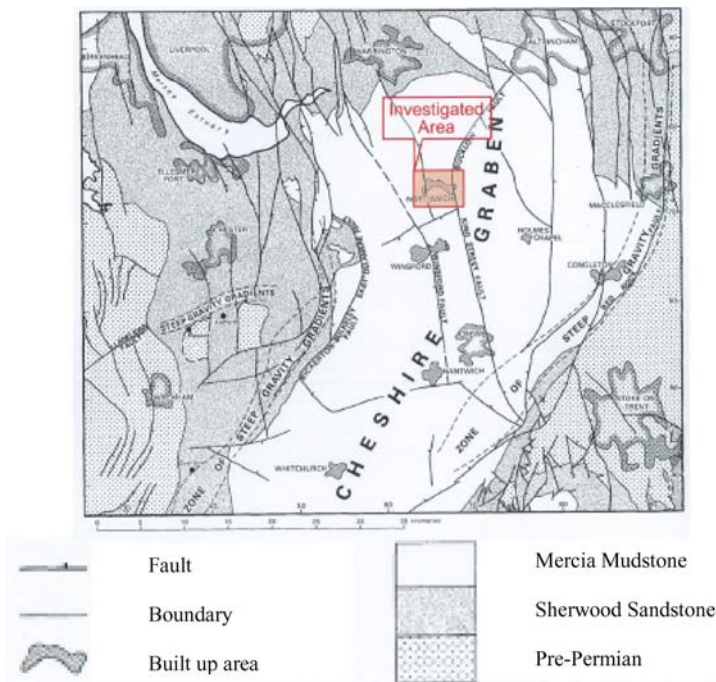


Figure 1. Regional Geological Setting (KBB 2000)

Overlying the solid geology are glacial drift deposits from the last (Devensian) glaciation, comprising mainly glacial till with minor lenses of fluvioglacial deposits. However, some deposits infill the subglacial meltwater channels (tunnel valleys) and comprise fluvioglacial and locally glaciolacustrine deposits. The locations of subglacial meltwater channels are indicated in Figure 2. An over-deepened meltwater channel is located just to the south of Northwich Town Centre and extends over 50 m into the Triassic strata, cutting through the Top Salt in the area (Figure 2).

Hydrogeology

The complex regional hydrogeology cannot be presented in detail in this paper. However, the significant features relating to the stabilisation programme are as follows:

- Fresh water in the superficial drift deposits. These deposits are of variable permeability but include pockets and lenses of sands and gravels. The glacial meltwater channel to the south of the study area (Figure 2) also provides a source of fresh water, and has a relatively high permeability. The water table is at approximately 12 m OD.
- An aquifer at wet rockhead, formed by a combination of natural solution processes and man-made processes such as brine pumping and mining. The undisturbed materials above and below this aquifer are likely to have much lower permeabilities so that water flow is confined vertically to a thin layer and is likely to take place only through semi-open disturbed zones or natural 'brine runs' or those formed in response to the brine pumping activities.
- Thirdly, a man-made aquifer existed in the four lower mines, which were flooded with brine.

The hydrogeological regime is significant with respect to the stability and infilling of the lower mines in terms of the water pressure in the flooded mines, the degree of saturation of the brine in the flooded mines, and the potential ingress of fresh water into the mines as discussed further in this paper.

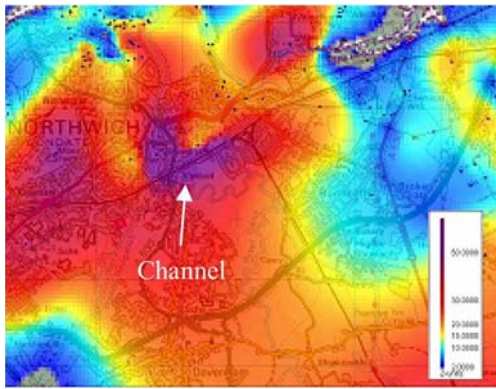


Figure 2. Drift thickness (courtesy British Geological Survey 2004)

SALT MINING IN CHESHIRE

Salt mining has been taking place in the Northwich area since Roman times. Initially, this comprised evaporation of salt from surface springs but since the 17th Century salt has been extracted from deeper layers of salt. The four mines discussed in this paper were opened during the mid- to late-19th Century and abandoned at the end of the 19th to the beginning of the 20th Centuries.

Surface extraction of brine

In pre-industrial times, the brine in the Northwich area was extracted from 'brine pits' or shallow wells in locations where brine was naturally close to the surface. Some of these wells or pits may have originally been natural brine springs, enlarged in response to increased abstraction requirements.

Mining from the Top Bed salt

When the top salt layer was discovered in 1670, many small mines were sunk into this layer and mined throughout the 18th century (Wharmby 1987).

Mining from the Bottom Bed salt

The lower salt bed was discovered in 1779 (Wharmby 1987) and this discovery resulted in the rapid phasing out of the Top Bed mining and the beginning of an extensive phase of mining in the lower bed, using the traditional 'room and pillar' method, that lasted throughout the 19th century. The Bottom Bed mines in the Northwich area were mainly excavated in the late 19th century. Mining continued into the 20th century, with the last working in the Adelaide mine to the north east of the town of Northwich in 1929. The mines were located towards the base of the Bottom Salt, and are between 4 and 6 m high.

Extraction of brine from the 'wet rockhead'

Extraction of brine through pumping from boreholes sunk into the natural reservoir of brine found at wet rockhead took place throughout the 18th century. The advent of steam engines in the early 19th century resulted in a rapid increase in brine pumping from the wet rockhead, such that natural brine was virtually exhausted by the middle of the century (Wharmby 1987). Natural brine extraction from the 'wet rockhead', now much modified by the effect of past brine extraction and past 'bastard' brine pumping (described below) continues to the present day from a location to the north east of Northwich.

'Bastard' brine pumping

The term 'bastard' brine pumping is used to describe the practice of extracting brine from flooded mine workings in an essentially uncontrollable manner. This took place from both Top and Bottom Salt mines in the Northwich area and led to spectacular collapses and widespread subsidence, as fresh water from the surface and near-surface drift deposits was able to access the salt deposits via the collapsed mine workings. Bastard brine pumping was phased out in the 1930s.

MINE LAYOUT AND GEOMETRY

The locations, shape and size of the four mines are shown in Figure 3. The information has been compiled from various historical and present sources. An abandonment plans was available for Baron's Quay mine, but not for the other three mines. Historical plans were available for all mines, but these do not allow us to interpret the actual size of the mine at the time of abandonment. Further enlargement of all of the mines may have occurred due to unofficial mining ('pillar robbing'), bastard brining causing additional solution of the mines, or erosion due to the infiltration of unsaturated salt water. Over a century has elapsed since the cessation of mining from these mines and a particular risk

is the unknown size condition of the supporting pillars and whether any local collapses may have occurred during this period. Furthermore, the exact locations and conditions of mine shafts and mine-to-mine connecting passageways are poorly documented in historical records.

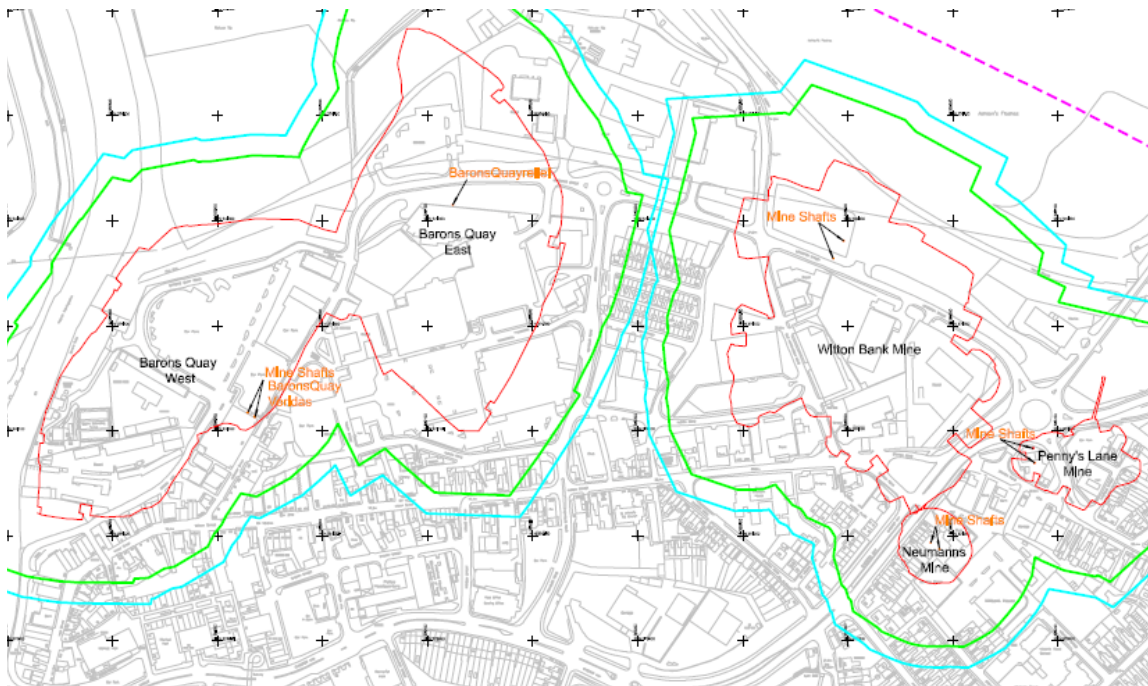


Figure 3. Mine layout. (Base plan reproduced under licence from the Ordnance Survey)

Therefore, additional surveying to ascertain the shape and size of the mines in their present condition was an essential component of the stabilisation works. This comprised the drilling of boreholes and carrying out a number of ultrasonic surveys both prior to, and during, the stabilisation programme. The undertaking of ultrasonic surveys in fully saturated brine presents additional complications in terms of calibration and interpretation of the data. However, ultimately, a very high density of surveying allowed interpretation of the data (e.g. Figure 4). Generally, it was found that the present shape and size of the mines was approximately in agreement with the historical plans but that these plans contained a number of minor errors and inaccuracies.

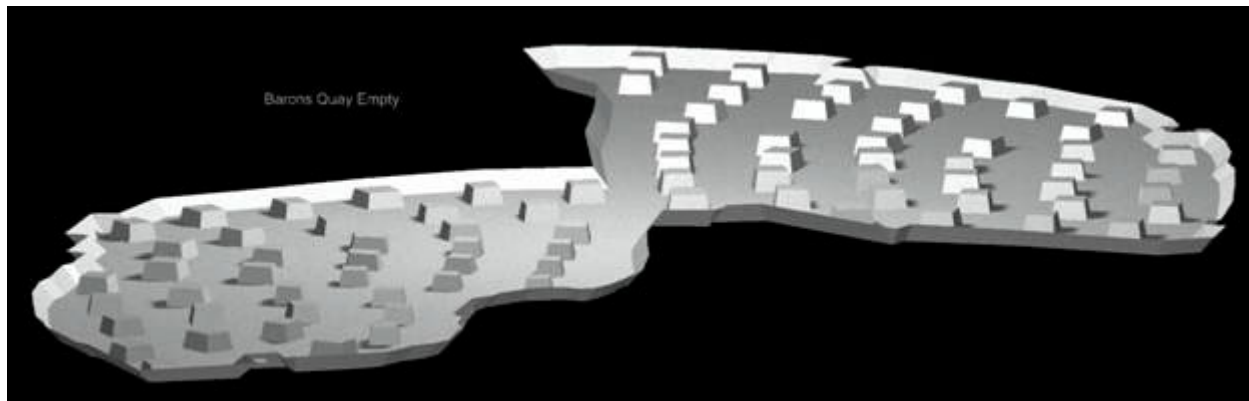


Figure 4. Barons Quay Mine survey results

The total mine volume to be infilled was of the order of 800 000 m³ of which Barons Quay Mine (Figure 4) is over 60% of the total.

LAND USE AND OWNERSHIP

The land overlying the four mines is presently of mixed-use, comprising a number of residential properties, primarily to the eastern part, a mix of small and large commercial properties, offices and public buildings. Other infrastructure includes roads, car parks and sewage works. The retail and commercial properties form the northern part of Northwich Town Centre. Services above the mines include gas, telecommunications, electricity, water and drainage. The diversity of exposed infrastructure and the multiple ownership of potentially affected properties increased the complexity of the works in terms of planning, control and monitoring. An important component in this respect was the condition surveys undertaken prior to any intrusive site works.

The surface development above the mines reflects the growth, decline and regeneration of part of Northwich town centre. During the 19th century, retail and residential properties developed in corridors along the main roads. During the late 19th and early 20th centuries much of this area was affected by subsidence, resulting in the progressive demolition of many of the residential properties. By the mid-20th century, much of the south part of the study area had been demolished and rebuilt.

CONDITION OF THE MINES

Evidence of collapse

Major collapse of any of the mines would have resulted in significant subsidence at the ground surface. Therefore, it was understood that, before the commencement of the stabilisation works, this had not occurred. However, localised collapses may have occurred at this depth without clear evidence at the surface. The ultrasonic surveys showed no evidence of either debris on the floor of the mines or non-planarity of the roofs. The roofs were found to be planar and flat throughout the majority of the mines (Figure 4). The pillars appeared to be in agreement with the size and shape indicated on the historical plans.

A number of boreholes were sunk into the mines and these indicated that the rock mass above the mine roofs was intact and of good quality. Limited geophysical logging supported this observation.

Stability of the mines

All four mines have undergone significant changes in their 'stress history' since abandonment. In particular, flooding with brine will have significantly relieved the effective overburden pressure on the pillars compared to their open state during operation, potentially increasing their factor of safety against failure. The biggest risk identified was that had under-saturated groundwater flooded the mine at some point, then erosion of the exposed surfaces would have resulted as the salt went into solution, reducing the cross sectional areas of the pillars thereby making them less stable.

Air under pressure

A number of 'blow outs' have occurred historically, resulting from the release of air pockets under pressure within the mine. These would have had the effect of temporarily increasing the pressure on the pillars and reducing the factor of safety.

Behaviour of rock salt

Apart from an initial elastic response, salt generally behaves in a visco-elastic manner with irreversible strain occurring under constant load (secondary creep – Phase II) (Figure 5). However, at very large strains plastic deformation takes place (tertiary creep – Phase III) and the salt structure loses strength leading to sudden failure. There is archive evidence that an adjacent mine, the Adelaide Mine, failed as a consequence of such tertiary creep behaviour of the pillars early last century. The onset of tertiary creep presents the biggest risk to the built-up area overlying the mines, since by this time there would be insufficient time to carry out stabilisation works.

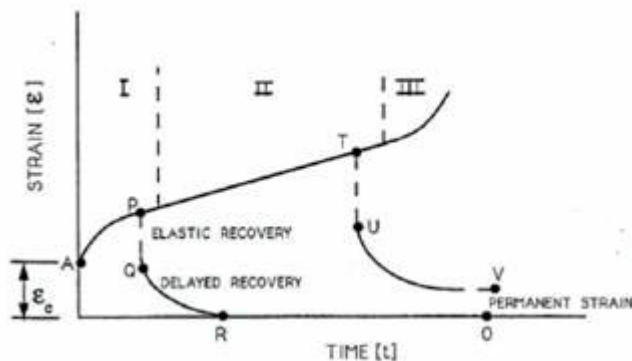


Figure 5. Time dependent behaviour of rock salt (Jeremic 1994)

Stresses in pillars

A semi-quantitative assessment of the pillar stresses and hence the factor of safety on the pillars was carried out using tributary area theory (e.g. Hoek & Brown 1980). Based upon their fully flooded condition, these assessments, which err on the conservative side, suggested that all the mine pillars have factors of safety greater than unity. Nonetheless, the stresses induced in the pillars when the mines were dry, and the stresses induced due to the occurrence of 'blow outs,' means that it cannot be guaranteed that the mines have not progressed towards their tertiary creep stage. Higher safety factors were calculated at Penny's Lane and Neumann's mines than in the two larger mines.

MONITORING REGIME

Whilst the pillar stress analysis suggested that the mine pillars had an adequate factor of safety and, therefore, were not at risk of imminent failure, settlement monitoring throughout the area indicated that significant movements were taking place at localised spots above the mines. These movements could have been associated with continued or accelerated settlement of the roof of the mines or, alternatively, with completely independent processes taking place at wet rockhead or even in the surface materials. The release of air under pressure in the mines triggered by the drilling of boreholes into the gas pockets would have temporarily imposed significantly higher stresses onto the pillars, until water was drawn down the boreholes to fill the punctured void. Therefore, it should be considered that such events would bring the state of the pillars and roof closer to 'tertiary creep' as shown in Figure 5.

Surface settlement

A dense network of surface levelling points was established for the purpose of almost continuous monitoring, through precise levelling of movement at the ground surface. Although labour intensive, both in terms of measuring and interpretation, this procedure was found to be the most reliable approach for providing the earliest possible indication of any potential change in conditions of the mines or the wet rockhead. The surface monitoring showed that settlement was occurring in certain locations above the mines, but there was no clear correlation between the observed settlement patterns and the boundaries of the mines, or particular pillar locations. The evidence and interpretation strongly suggested that surface settlement patterns are almost exclusively related to processes occurring in the strata above the mines, i.e. at wet rockhead and in superficial soils.

Sub-surface settlement

Magnetic extensometers and rod extensometers were installed above the mines. The former were installed with the intention of providing specific data regarding the relative settlement of the various strata, whereas the latter were more specifically for reliable long-term monitoring of the movement above the roof of the mines, for validation of the stabilisation works as well as for pre-stabilisation movement monitoring.

Water levels

Careful control of the water levels in each of the aquifers described previously (Bottom Salt mines, wet rockhead and surface water) was identified early on as an important issue for the stability of the mines. This was done through dipping a series of standpipes terminating in different strata and by the continual monitoring of transducers installed in the mines.

Salinity profiling

The elevation of the brine:freshwater interface is a critical variable since it affects not only the pressure within the unfilled mines but also the potential for freshwater ingress into the mines, leading to dissolution of the mine walls, pillars, roof and floor. A typical plot of the salinity profile recorded in one of the boreholes to the mine is presented in Figure 6.

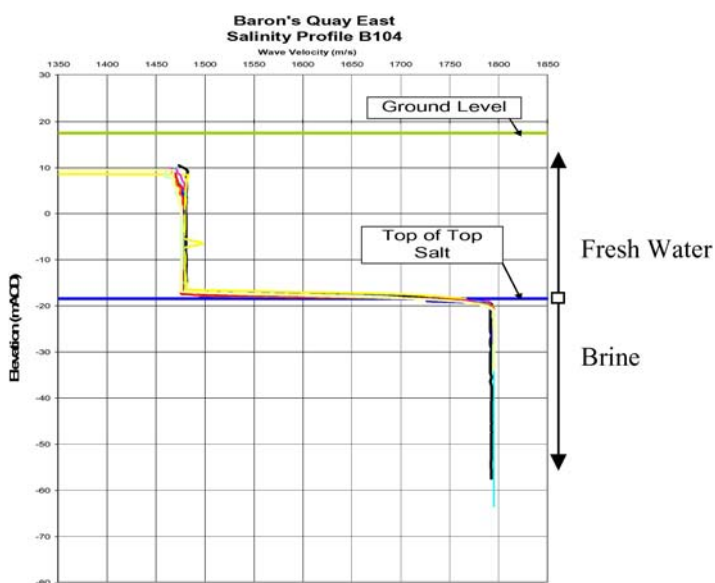


Figure 6. Sound wave velocity in standpipes/Salinity Profile

STABILISATION WORKS

Figure 7 shows the key elements of the infilling works from preparation through to post-infilling quality control.

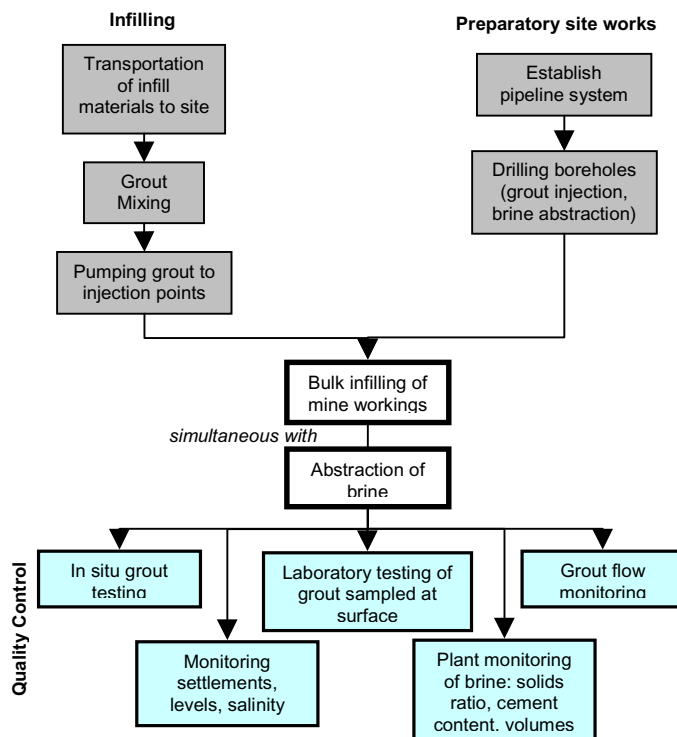


Figure 7. Key elements of infilling works

Particular challenges relating to the design of the infill material in this project included:

- The requirement for the grout mix to be made using fully saturated brine, rather than fresh water, and the significant length of pipework between the mixing plant and the injection holes required due to planning constraints.
- The grout mix, which comprised PFA, cement and brine was investigated and tested rigorously in order to understand the chemical behaviour, in particular the influence of the salt crystals, and the potential for the salt to leach out of the set grout with time, thus destroying its fabric. This investigation included X-Ray diffraction tests (Figure 8) and microscopy (Figure 9), which revealed the development of cementitious minerals.
- The performance requirement of the grout in the mines was based upon the tolerances for angular distortion at the ground surface, being the critical variable for the new and existing infrastructure.

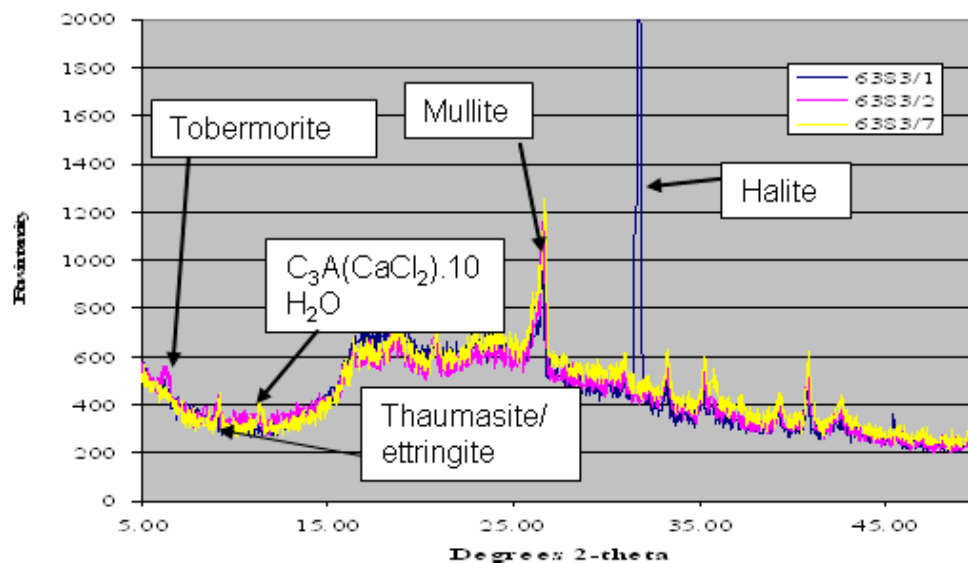


Figure 8. Results of X Ray diffraction tests

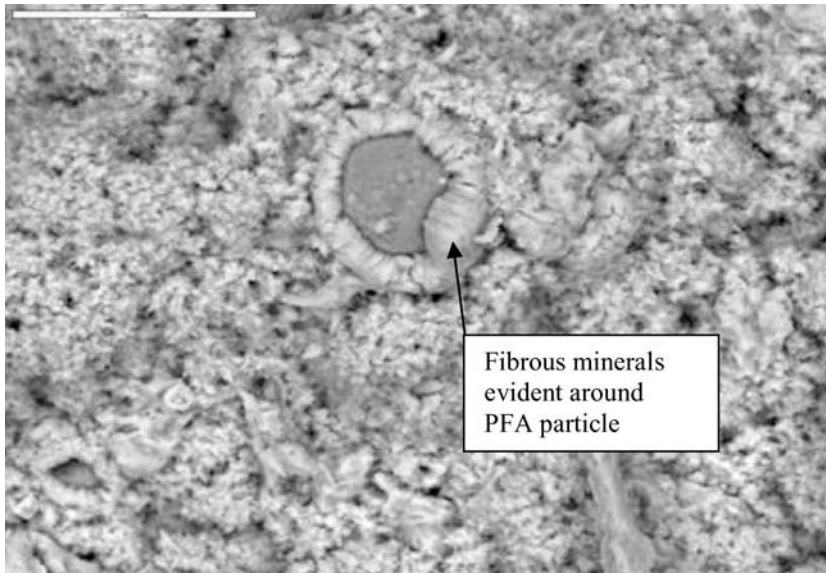


Figure 9. Results of microscopy

RISK MANAGEMENT

Civil engineering projects governed by geological materials, as in this case, are intrinsically more risky than those which are largely dependent upon man-made (and therefore quality controlled) materials. The difficulties in adequately characterising soils and rocks from limited physical investigations, combined with the inherent variability of naturally occurring materials leave significant uncertainties for engineers to deal with. In the case of the Northwich Salt Mines, the uncertainty was compounded by the mines being at 90 m depth and inaccessible due to being flooded with brine, thus creating unknowns related to the size and condition of the mines as well as the properties of the overlying geological strata. Notwithstanding these geotechnical risks, the size and unique nature of the Northwich Mines Stabilisation programme presented a number of commercial, contractual and schedule-related risks to all stakeholders, which required careful review assessment and management, as described subsequently. Table 1 summarises a number of the most significant risks and the adopted mitigation approach.

Table 1. Significant risks identified before mine infilling

| Risk Area | Risk | Example mitigation measures |
|------------------|--|---|
| Top Bed Salt | Short-term significant local and regional variations in hydrogeology. | Establishing hydrogeological precedents. Monitoring water levels and settlements. |
| | Inadequate casing seal around wet rock head during borehole drilling. | Implementation of a careful drilling protocol when drilling boreholes through the wet rockhead. |
| | Settlement caused by ongoing activities, unrelated to lower mine infilling works, such as brine extraction. | The inherent factor of safety in the casing depth. Monitoring the condition of vulnerable structures/services during infilling. Installation of appropriate monitoring devices such as rod extensometers to enable Top Bed and Bottom Bed Mine movements to be distinguished. |
| Bottom Bed Mines | Significant errors in works information or geological model, leading to the mines being in a less stable condition than previously assumed, such that the infilling works may exacerbate any existing instability. | Increase coverage from ultrasonic surveys, and accelerate rate of surveying, in order to provide advance warning of any significant errors. |
| | Natural collapse of lower mines not attributable to infilling works. | Improve monitoring of Bottom Bed Mine convergence using rod extensometers. |
| | Uncertainties relating the grout mix design, stiffness, strength and durability. | Undertake rigorous suite of trials, analyses, detailed laboratory tests and inspections in order to fully understand the expected behaviour of the grout. |
| Shafts | Damage to facilities overlying existing mine shafts, as a result of the planned shaft treatment works. | Review method of treatment and need for treatment for each individual shaft. Define a controlled works area. Shore neighbouring buildings. Monitor ground and building movement. |

The adopted risk management methodology (Figure 10) (Arup Project Management 2000) is in broad compliance with recognised guidance from Godfrey (1996), Hillson & Newland (1997), Anon. (1998), Clayton (2001) and Anon

(2004). It includes the essential elements within the ‘management systems’ approach to risk, namely identification, assessment, control, monitoring and review. Identified risks were qualified/semi-quantified in terms of their potential for causing damage, losses or delays and the magnitude of these consequences.

Collected data including property condition surveys, ultrasonic survey data, mine plans, boreholes, monitoring etc. were used to determine loss event probabilities. A probability-impact risk matrix was used to highlight the more significant risks to prioritise risks for more detailed Quantitative Risk Analysis (QRA) and, if necessary, for further control.

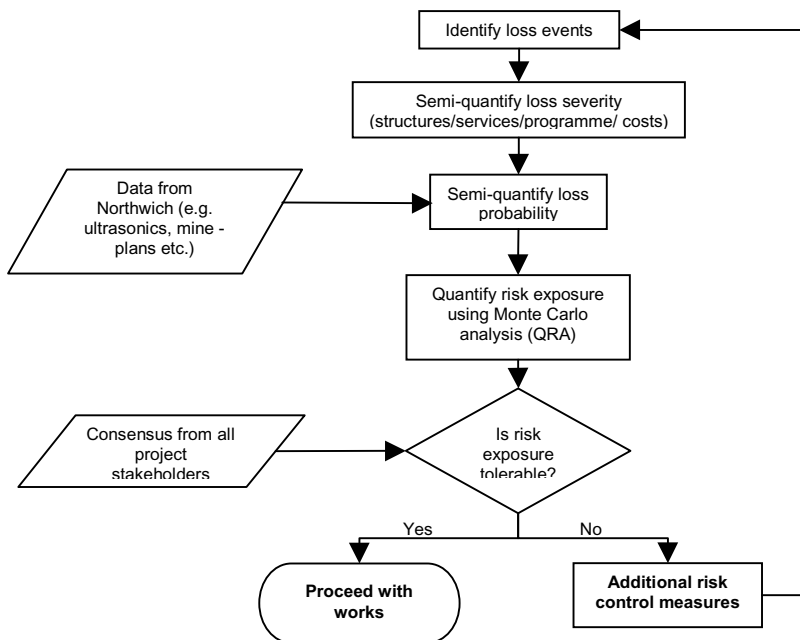
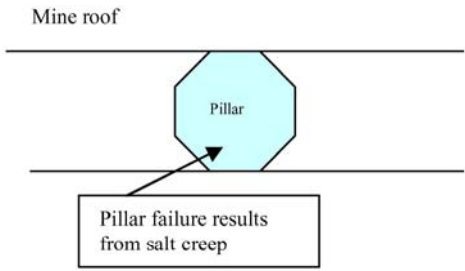
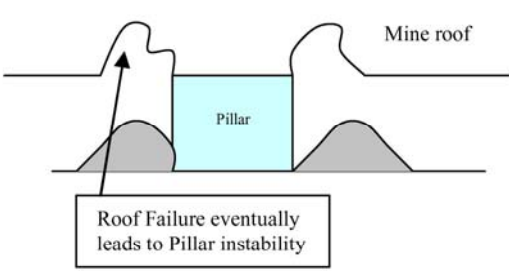


Figure 10. Overview of project risk management methodology.

COMPARISON WITH OTHER MINE INFILLING WORK

To classify the risk associated with the salt mine infilling work it was compared with the considerable experience available of infilling major limestone mines in the West Midlands (O’Riordan *et al.* 1984). This comparison indicates that the collapse mechanism of the two mine types are quite different and that, crucially, the level of knowledge regarding the design of grouts for use in a brine environment was much less (Table 2).

Table 2 Comparison between limestone and salt mine infilling

| Salt | Limestone |
|---|--|
| Strong, ‘impermeable’ roof | Weak, highly permeable roof |
| Weak pillar, soluble, prone to creep | Strong pillar, ‘insoluble’ |
| Brine-filled Highly compressed air pockets | Air- or ‘fresh water’ -filled |
|  |  |
| Grouting: zero experience | Grouting: much experience |
| Grout in/ brine out control | Straightforward pump grout in |
| Limited/no science | Much science |
| Grout stiffness and filled volume is critical | Grout required only to act as void-filler, to ‘choke’ upward roof failure |
| Mines open and free from minor collapse | Mines partly choked by minor collapse |

However, it was judged that the overall level of risk associated with the salt mine infilling is equivalent to that involved in the infilling of limestone workings.

CONCLUSIONS AND LESSONS LEARNT

The factors controlling settlement and the future stability of the Northwich Vision development area are complex and involve both the Top Bed and Bottom Bed salt. The stabilisation work currently in progress will remove the possibility of collapse of the Bottom Bed mines and Vale Royal Borough Council would hope that any cessation of brine pumping in the area will reduce the solution of the Top Bed salt.

There are important differences between salt mines and limestone mine stabilization so the established techniques for infilling mines on this scale cannot be directly applied. Risk management methodologies to identify and evaluate the risks associated with the new techniques are necessary to achieve a balance between the technical and commercial drivers.

Monitoring during the works is vitally important, due to 'impermeability' of mined stratum and the sensitivity of the mines and surrounding strata to changes in brine/ air pressure.

The aim of the project is to remove blight from the heart of Northwich and to enable development. At the time of writing infilling of the Bottom Bed mine is in progress.

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