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Brine Migration from Deep Flooded Abandoned Salt Mines and its Influence on Surface Stability

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Abstract

Historic salt mining at Carrickfergus, Northern Ireland has left a legacy of hazards including surface subsidence and land contamination through brine water discharges. Three abandoned salt mines, hydrologically connected, pose a risk to overlying infrastructure and properties and the environment. Post closure, the mines are undergoing active subsidence resulting in crown-hole development and a series of extensive brine discharges at surface contaminating the surrounding lands and watercourses. Numerous assessments and monitoring methods, conducted over decades, have been implemented to understand the processes of instability with the results indicating a cyclic direct connection between surface instability and brine discharges.

Keywords: salt mines, ground stability, brine discharge, multiphysics integration, geodetic monitoring

Introduction

The abandoned Duncrue, French Park and Maiden Mount salt mines are located directly adjacent to each other within the town of Carrickfergus, Northern Ireland. Situated on an elevated slope Maiden Mount is the upper and mostly northly mine working and Duncrue the lower mine with French Park located between the two (Fig. 1). There is an elevation difference of 50m between the three mines. Operating from 1853 to 1958, all three mines initially worked independently using conventional methods, later changing to solution mining methods. Brining operations have left a legacy of instability as a result of dissolution of the mine support pillars due to water injection. Surface monitoring data collected since 1991 shows the area overlying the mines are undergoing active subsidence and heave. A public road, public water supply intake, residential properties and the Belfast Gas Transmission Pipeline are located on the lands overlying and adjacent to the mine site

Geological setting

Carrickfergus is situated on the south-eastern edge of the Antrim Plateau on a low lying coastal plain rising in elevation to the west. The superficial geology is dominated by boulder clay till and tidal flat deposits of clay and sand (Table 1). The bedrock geology is dominated by lava flows of the Lower Basalt Formation at elevations towards the north-west and the Triassic Mercia Mudstone Group on the coastal plains. Between these two dominant features, at elevations above 100 meters, is the Cretaceous Ulster White Limestone Formation (UWLF), Waterloo Mudstone Formation (WMF) and Triassic mudstones of the Penarth Group (PNG) and Mercia Mudstone Group (MMG). A number of north-south trending faults cut across the greater Carrickfergus area (Mitchell *et al.* 2004).

Carrickfergus is predominately MMG bedrock, a fine-grained mudstone with silty horizons which, from an engineering

Table 1 Summary geology of the greater Carrickfergus area. (Mitchell, 2004)

Age	Group/Formation	Lithology
Quaternary	Till	Boulder clay, sand & gravels
Paleogene	Lower Basalt Formation	Basalt
Cretaceous	Ulster White Limestone Formation	Limestone, hard white chalk, with flints and basal glauconite-rich beds
Jurassic	Waterloo Mudstone Formation	Grey mudstone with thin limestone beds
Triassic	Penarth Group	Dark grey mudstone
Triassic	Mercia Mudstone Group	Red and green mudstone and marl with thick salt bands

perspective, has a high bearing strength (Cigna et al, 2017). Gypsum occurs in veins and anhydrite as irregular nodules. Halite beds occur in the lower sequences of the MMG ranging in thickness up to 40 m.

The Maiden Mount, French Park and Duncrue mine workings are situated on the MMG with the northern boundary containing PNG and WMF. Maximum superficial till coverage is 20 m at Maiden Mount and 15 m at French Park (Griffith *et al.* 1983).

History of mining

Mine development started in 1853 and by 1870 three salt mines operated directly adjacent to each other. Both Maiden Mount and French Park mines extracted two halite beds while Duncrue extracted one. The mines initially operated using conventional mining methods using room and pillar design. As the mines developed, French Park and Duncrue mines became hydrologically connected to facilitate a change to uncontrolled brining operations. Maiden Mount continued to operate independently, adopted solution mining however, it did not develop any engineered connection to the adjacent French Park mine.

- ***Maiden Mount mine*** operated from 1869 to 1937 using conventional room and pillar methods. In 1953 brine production started at the mine and continued until 1958. The depth to the workings is 278 m below ground level (bgl) with an extraction height of 13 m, in areas worked out, and 33 m within the brined void (Atkins, 2004). The last recorded mine plan, based on underground surveying is dated 1937. Production records show 47,270 t of salt was produced during the brine operations between 1953 and 1958, equating to a further volume of 21,000 m3 halite removed (Atkins, 2009).
- ***French Park mine*** opened in 1870. A tunnel to extract brine was constructed within the mine in 1896 to connect the adjacent, closed Duncrue mine. The tunnel stopped short of the Duncrue mine and was connected via a series of inclined boreholes. Brining operations continued until 1952. Average depth of workings is 203 m bgl with an extraction height of 10 m, in areas worked out, and 28 m within the brined void (Atkins, 2004).
- ***Duncrue mine*** opened in 1853. Instability is first recorded in 1865 with the failure of a pillar close to the shafts which then propagated to adjacent pillars. Due to concerns on the stability of the workings, underground operations ceased in 1871. From 1896, brine was pumped from the mine through connections to French Park mine. Brine operations ceased in 1938 following a collapse which destroyed the connection to French Park mine. The average depth of workings is 180 m bgl with an extraction height of 11 m (Atkins, 2004).

Monitoring and assessment methods

The assessment and monitoring of the three mines include:

- Precise levelling and sub-surface extensometer
- Ultrasonic, sonar cavity and Close Circuit Television surveys
- Groundwater level monitoring and mine water salinity
- Multi geophysics: seismic, electrical resistivity and electrical self-potential
- Interferometry Synthetic Aperture Radar (InSAR)

Data from these surveys is used to determine ground motion at various locations, ascertain the structure and

migration of the mine voids and assess the interior condition of the mines and evolution of mine water processes and pathways.

Six probe boreholes were developed into Maiden Mount (3) and French Park (3) mines. Each probe hole contained extensometers and facilitated access to collect groundwater levels, measure saline concentrations at various levels and enable ultrasonic and CCTV surveys of the mine to be carried out. Ultrasonic and CCTV show the mines to be flooded, and all support pillars completely dissolved or are in a very poor state due to dissolution as a direct result of brining. At each probe hole it is noted that limited salt is retained on the mine roof, resulting in the exposure of the MMG at various points and this is more pronounced at freshwater injections points such as old shafts and injection hole (Atkins 2009). Sonar cavity surveys carried out in the 1990's identified the Maiden Mount mine cavity had migrated towards surface (Arup and Partners 1992). This void migration led to the development of crown holes in 2001 and 2006 resulting in surface depressions exceeding 100 m in diameter and 18 m in depth.

Results

The results of precise levelling show a steady downward trend of the surface overlying Maiden Mount, while at French Park the same trend occurs at a number of monitoring points however, a number of others points record variable periods of recurrent heave and subsidence. Data from Duncrue shows relative stability across the site with one monitoring station, located at its boundary with French Park, recording significant cumulative subsidence.

Brine Seepages

Four notable large scale brine seepages occurred at French Park, two in 2001, one in 2004 and 2005 continuing for periods exceeding 18 months. Smaller scale discharges and salt patches at surface are routinely observed on a regular basis (Parker 2023). In the months prior to crown holes developing at Maiden Mount, salt patches were reported on lands adjacent to the shafts at French Park and following collapse saline springs developed at the same areas (Atkins 2003). At the same time, there was an increased rate of heave at monitoring stations across French Park (Atkins 2004). There is no direct evidence of any interconnections between the two mines, however, the data indicates an apparent relationship between the crown hole appearing and the emergence of brine springs downslope. At the time of the 2006 crown hole, water levels at Maiden Mount decreased by more than 9 m while at the same time, at French Park it rose by almost 8 m.

The crown hole at Maiden Mount is primarily fed by surface water. Salinity levels within the crown hole are stratified with saline concentrations greater with depth, however, concentrations are vastly lower than those measured at the saline springs down slope. This rules out the possibility of water within the crown hole infiltrating pathways within

Table 2 *Laboratory results of water analysis of samples taken at various points within the three probe holes (FP1, FP2 & FP3) at French Park.*

Sample	Depth (m bgl)	Temp (°C)	pH	Na (g l^{-1})	Cl (g l^{-1})
FP1-A	192.65	15.7	7.14	54.4	82.2
FP1-B	189.50	14.8	7.06	58.2	27.5
FP1-C	186.50	14.8	7.02	74.8	35.3
FP1-D	183.50	15.7	7.08	82.7	38.9
FP1-E	180.50	14.2	7.05	61.0	28.5
FP2-A	197.90	14.9	7.04	80.1	43.4
FP2-B	192.00	14.6	7.02	76.7	35.4
FP2-C	188.00	14.8	7.00	89.9	39.3
FP3-A	227.00	15.3	7.29	85.3	37.6
FP3-B	122.96	13.1	7.36	12.4	52.9

the shallow quaternary till and springing out downslope to create the saline springs. Salinity measurements taken from within the French Park mine indicate a near saturation brine within the flooded sections (Table 2).

Structure and groundwater pathways

The borehole records for the monitoring wells note heavy fluid loss during drilling suggesting some form of mining induced fracturing of the mudstones has occurred. It is proposed migrating voids that have reached surface has resulted in the overlying MMG to be severely brecciated above the mine. This is supported by the borehole logs which details heavily fractured rock. The MMG, recorded within the area, is of low permeability and does not act as a good pathway for fluid movement (Mitchell *et al.* 2004) however brecciation and fracturing as a result of void migration will have developed additional groundwater pathways to surface. Regular monitoring also shows old mine shafts and probe holes act as good pathways to surface for groundwater.

Multi-geophysical techniques using seismic and electrical resistivity surveys combined with electrical self-potential (SP) surveys were conducted to characterize the geological and hydrological processes driving the mining hazards. Resistivity and seismic refraction were acquired to characterise the subsurface structures while patterns within SP profiles and resistivity-velocity images of the subsurface were used to identify brine plumes, groundwater flow and underground cavities. Results from the geophysical surveys identified compositional changes and deformation altering the geochemistry of the groundwater. Water ingress to the underlying strata from crown holes has led to gravitational slumps as a result of dissolution of the halite bearing strata. This has resulted in deformation and stepped thrusts coincident with brine migration to surface. The occurrence of brine migration to surface at French Park is more prevalent following Maiden Mount surface subsidence as a hydraulic head in the deep mine induced by freshwater injection to the crown hole at surface promotes the movement of saline waters through pathways created by weaknesses within the strata, boreholes and shafts leading to extensive land contamination events (Meju *et al.* 2023).

Interferometry Synthetic Aperture Radar (InSAR)

Surface levelling data combined with subsurface extensometer and mine water levels have shown to provide an indicator of brine transport to surface. Decreasing surface and water levels at Maiden Mount in combination with uplift in surface and water levels act as a precursor to large brine seepages at surface. To better understand how monitoring surface motion can be utilised to maximum effect and provide a near-real time early warning of both subsidence and brine discharge events, satellite InSAR data was evaluated using historic data from three European Space Agency satellites spanning the four decades: ERS (1992-2000), ENVISAT (2002-2010) and Sentinel 1 (2014-2022). InSAR provides regular ground deformation measurements with millimetric accuracy that allow users to reconstruct the kinematics of the motion and correlate it to environmental factors such as mining. One of the main drawbacks of InSAR is its reliance on stable targets to provide reliable measurement points (Parker *et al.* 2024), and it generally does not provide reliable deformation data over areas of vegetation (Garthwaite 2017).

InSAR provides regular ground motion data and wide coverage to millimeter scale without the requirement to visit the site, providing a cost-efficient technique. The results returned from the three satellites showed relative stability however target coverage is poor (figure 2) so we cannot exclude the possibility of the area moving. The results however did identify those areas of land where no acquisitions are being recorded due to the absence of stable ground reflector targets and were InSAR artificial targets might be placed in the future to improve coverage.

Conclusions and future work

The mine site at Carrickfergus poses a risk to infrastructure through instability while also posing an environmental risk to the overlying lands due to contamination. Research and

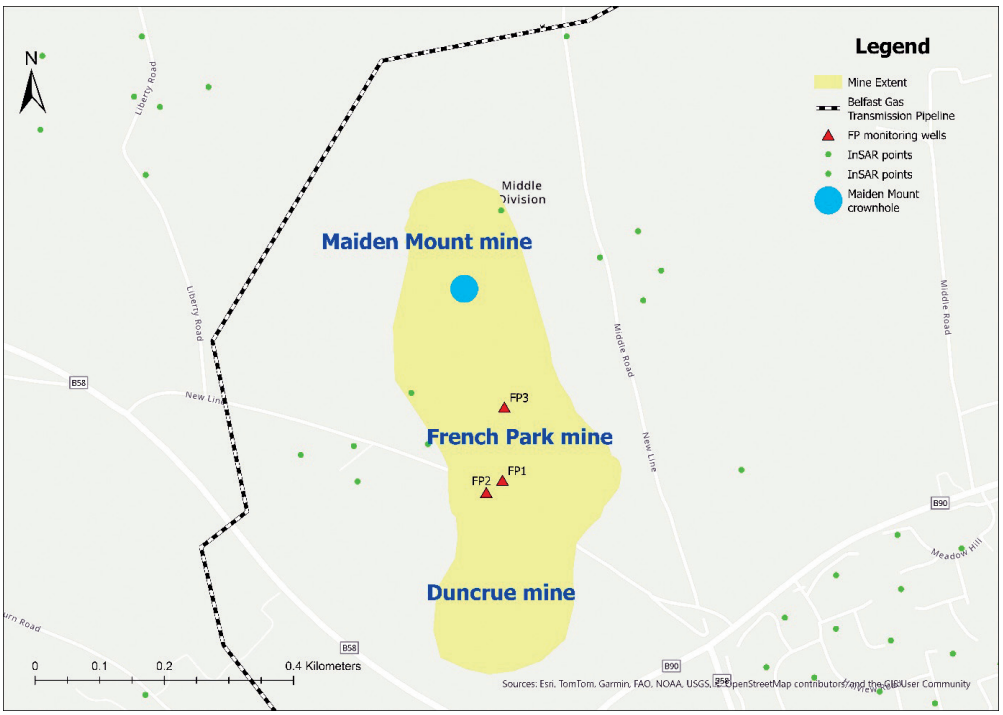

Figure 1 *Layout of the mine complex at Carrickfergus showing the location of the mines extent and proximity to the BGTP. Monitoring wells at French Park are lie downslope from the crownhole at Maiden Mount mine. InSAR results for the Carrickfergus area show the low reflector response for the area of interest with very limited return acquisitions over the mine extent and area extending across the BGTP.*

investigations have shown processes at the mine site to be complex and inter-connected. The major factor leading to instability is considered to be infiltration of freshwater via mine shafts, fractures and areas of crown holes at Maiden Mount. These hydraulic processes occurring at Maiden Mount may then be influencing those at French Park which is impacted by active ground motion, fluctuating water levels and contamination of the overlying lands through large scale brine seepages. The hydraulic head driven by freshwater injection is entering the Maiden Mount mine at depth, transporting through pathways, the nature of which is not clear, to the French Park mine, and is then driven up through the fractured mudstones to the surface. These discharges create space within the mine voids leading to surface subsidence, infiltration of freshwater, creating further dissolution within the mine, and the process continues in a cycle of subsidence, water injection, discharges, subsidence. Trends are identified within the results from surface stability monitoring and water levels which indicates a source of information that can be used to predict seepages at surface, future evolution of ground deformation and impact to the overlying infrastructure.

To investigate further and gain a better understanding of the interconnecting relationship between surface stability and groundwater processes, a newly developed monitoring network, designed on this and other previous work, is at present being implemented. This will include a high-density network of twenty-five monitoring stations across the site. Each station will be equipped with permanent GNSS stations, InSAR reflector target and precise levelling point. These stations will investigate the reliability and comparability of each geodetic method which will be important, given the varying costs and constraints with each method. Flow meters are installed up slope and down slope of the site to monitor changes

in surface water flow which could indicate freshwater injection from surface to the mine site. Further flow meters will be installed at various points across the two streams directly over the site. Water levels will continue to be monitored at a number of points using the monitoring wells. Further analysis of mine water geochemistry will be undertaken at regular intervals to assess stratification, brine levels and the evolution of mine water, particularly following brine seepages and following freshwater injection. Sub-surface monitoring using the extensometer monitoring boreholes are to be continued to assess stability and void migration. Combined with regular topographic, aerial LiDAR, aerial photogrammetry surveys, the network will provide an important research observatory to understand processes within flooded abandoned salt mines.

The greater Carrickfergus area contains a further five abandoned salt mines as well as an extensive active salt mine which has been in operation since 1965. The knowledge gained from the work at Maiden Mount-French Park will have implications for the management of these assets while also providing critical knowledge for the management of salt mines globally.

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References

Arup and Partners (1992) Report on the site investigation (Phase 2) of the Duncrue, Maiden Mount, Burleigh Hill and Black Pit salt mines, Carrickfergus, County Antrim, Northern Ireland. Department for Commerce.

Atkins, 2003. Maiden Mount mine, Infilling crown hole with PFA: Hydrogeological risk assessment. Department for Enterprise, Trade and Investment.

Atkins, 2004. Potential subsidence for BMAP plan, 2004/17. Department for Enterprise, Trade and Investment.

Atkins, 2009. Maiden Mount mine settlement prediction. Department for Enterprise, Trade and Investment.

Cigna F, Banks VJ, Donald AW, Donohue S, Graham C, Hughes D, McKinley JM, Parker K, 2017. Mapping Ground Instability in Areas of Geotechnical Infrastructure Using Satellite InSAR and Small UAV Surveying: A Case Study in Northern Ireland. Geosciences. 2017; 7(3):51.

Garthwaite, M.C., 2017. On the design of radar corner reflectors for deformation monitoring in multi-frequency InSAR. Remote Sensing, 9(7), p.648.

Griffith, A.E., Wilson, H.E., Bennett, J.R.P., 1983. Geology of the country around Carrickfegus and Bangor: Sheet 29. Memoirs of the Geological Survey of Northern Ireland.

Meju, M. A., Kulessa, B., Gallardo, L., Thompson, S., Ruffell, A., Parker, K. 2023. Improved imaging of ground deformation and brine seepage around abandoned flooded salt mines by joint inversion of multiphysics data, Journal of Applied Geophysics, Volume 219, 2023, 105217.

Mitchell, W. I. (ed), 2004. The geology of Northern Ireland – Our natural foundation, Geological Survey of Northern Ireland, Belfast.

Parker, K. 2023. Ground stability analysis review of Carrickfergus abandoned mines potential impact on the Belfast Gas Transmission Pipeline: Monitoring network proposal. Geological Survey of Northern Ireland.

Parker, K., Novellino, A., McAllister, E., Bateson, L., Lemon, K. 2024. Carrickfergus abandoned salt mines: Assessment of ground stability and implications to the Belfast Gas Transmission Pipeline, British Geological Survey