



Subsidence Report for the Curraghinalt Project Dalradian Gold

This is a discussion document for the potential subsidence from the proposed Curraghinalt Mine to support the 2019 Planning Application and Further Environmental Impact submission to the Northern Ireland Department for Infrastructure by Dalradian Gold.

INTRODUCTION

This report summarises the results from the investigation into the potential for subsidence as a result from underground mining at the Curraghinalt project. The mining method for the deposit is to be predominately long hole stoping with backfill. A small proportion of the cut and fill mining method is proposed to be used in flat zones of the orebody or should very poor ground conditions exist.

MGT completed an extensive data collection programme as part of a 2017 to 2019 geotechnical assessment study, building upon prior work. High quality data with defined spatial extents is the foundation of the geotechnical model. This was used for empirical assessment of ground support schemes, forecasting long hole stoping performance and rating of the rock mass for the numerical modelling. Numerical modelling focused on forecasting mine scale surface subsidence, crown pillar stability and rock mass damage to large underground excavations.

MGT engaged Itasca Australia to undertake 3D numerical modelling using data collected, and Dalradian's proposed mining method. The modelling covered multiple sensitivities to understand what factors impact the forecast. A comparison to the previous subsidence modelling was also made to the work completed by SRK, 2017.

The amount of subsidence that occurs is controlled by the

- size of the voids made by mining
- placement of fill and how stiff that fill is material
- location and extent of unmined section (pillars)
- geological and geotechnical setting of the deposit.

DATA SOURCES

Curraghinalt has an extensive drill hole database containing 45.5km of detailed geotechnical data. The 45,522.45m of data was compiled from detailed geotechnical logging across 222 drill holes and a total drill hole data base of the 153,296.19m of core.

This data was used to calculate the rock mass classifications schemes of; RQD (Deere and Deere, 1989), Q-System (NGI, 2015), RMR₈₉ (Bieniawski, 1989) and GSI (Hoek and Marinos, 2000). Statistical analysis of logged and rolling averaged core intervals was used to describe the rock mass domains. Spatial association of rock mass classification to geotechnical domains was made through the lithology model and interpretation of the weathering profile.

Structural data had been collected from previous studies. Due to the difficulties with obtaining consistent orientation on drill core, oriented core drilling for geotechnical purposes was stopped in late 2017. Downhole geophysics data was collected from 32 drill holes with a total of 10,994m of survey data, of which around 1,410m was discarded due to tool centralisation issues. The resulting data set comprises 29,248 structural measurements.

The MGT work also comprised of 72 rock strength tests. These tests demonstrated a statistically significant improvement of the rock strength parameters for the Curraghinalt deposit compared to prior work.

The in situ stress regime was assessed by the Western Australian School of Mining (WASM) AE Technique and aligns with the understood stress regime for Northern Ireland.

GEOLOGICAL DESCRIPTION

The Curraghinalt deposit is hosted within the Mullaghcarn Formation. Despite being in a regional scale recumbent fold (Sperrin nappe) ductile deformation seems to be restricted to the shear zones and syndepositional microfolds. The lithological and structural units anastomose on a large and small scale. Joint sets and vein sets over print lithological units. Three broad lithological units have been identified within the turbidite sequence; psammite, semi-pelite and pelite.

- Psammite (SPS) is a competent, fine grained, low metamorphic alteration meta-sandstone
- Semi-pelites (SSP) are mixed psammite and pelite bands that are more competent than pelite and although foliated, do not have a high biotite content
- Pelite (SPE) is altered, biotite rich and low strength. Generally, it has been attenuated into narrow anastomosing bands between psammite units with the deformation of the turbidite sequence

Review of previous geotechnical logging shows wide variation in the definition of pelite adopted by geologists which has then impacted geotechnical allocation. The geotechnically significant definition of pelitic zones developed by MGT is rock that has an RQD < 25%, is high in biotite alteration and typically low strength for more than 3m of drill core intercept. This has been given the term weak-pelite.

PROPOSED MINING CONTEXT

Orebody Geometry

The Curraghinalt deposit is an extensive series of undulating narrow quartz shear zones (D veins) within a highly deformed large turbidite sequence. The mine volume is large, >700m long by >400m wide by >500m depth comprising of 17 major shear hosted quartz veins and a large number of minor shears hosted quartz veins

The high-grade quartz veins have an average width of 0.47m and are considered as very narrow width. The quartz veins range in geotechnical competency from extremely poor to good with the host rock being similarly variable. The quartz veins crosscut the general foliation trend. The turbidite sequence foliation orientation is consistent but with a reasonable variation in orientation due to the nature of formation and deformation of the deposit.

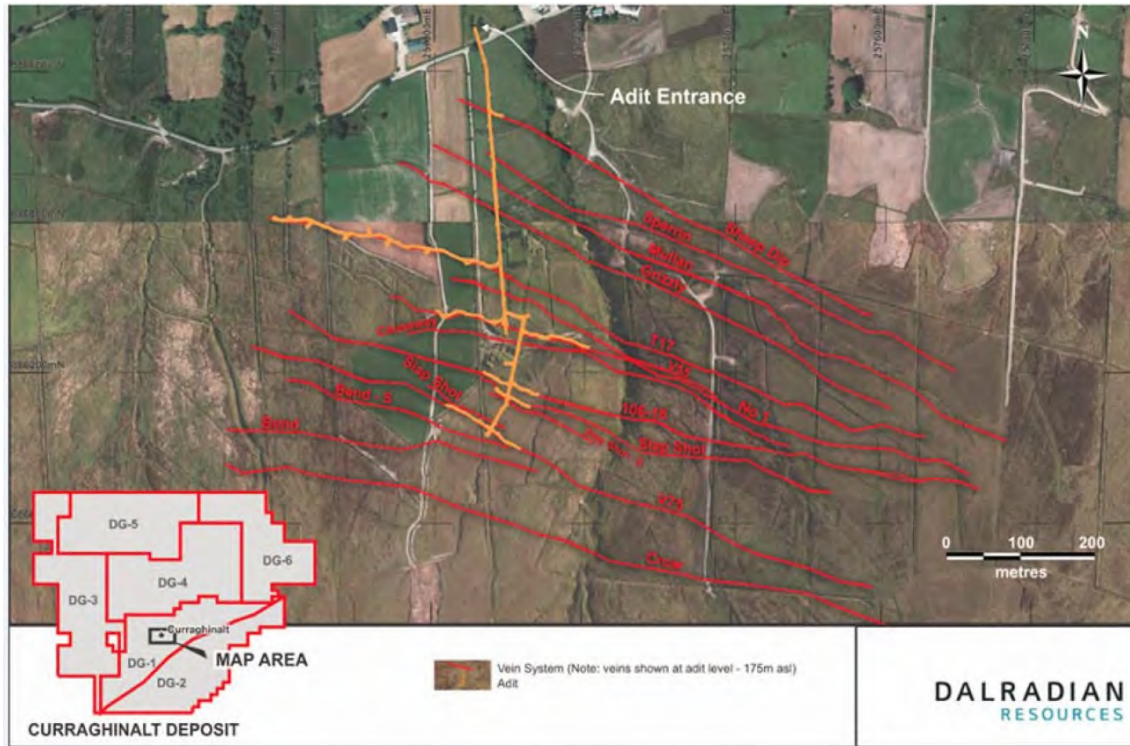


Figure 1: Location of principal veins at Curraghinalt (JDS 2017, Figure 4.2)

Rock Mass Conditions

Five lithology based geotechnical domains were identified during the assessment study and were used in the numerical model. These are:

- Alluvium
- Weak-pelite
- Strong pelite
- Semi-pelite
- Psammite

The near surface material (within 50m of the ground surface) was identified for each lithology to account for the highly fractured and weathered area near the surface. Strength properties for each of these domains are summarised in Table 1.

Table 1: Median strength properties for each rock mass domain. Highlighted cells have been assumed the same as equivalent unweathered material

Domain Name	Intact Rock					Rock Mass - Hoek-Brown GSI Downgrading Procedure							Elastic Parameters	
	Density (kg/m ³)	UCS (MPa)	mi (-)	Ei (GPa)	D (-)	GSI (-)	mb (-)	s (-)	a (-)	cc (MPa)	ctm (MPa)	Dilation Angle (Deg)	Erm (Gpa)	Poisson's ratio (-)
Pelite Weak	2700	23	12.5	40.1	0.0	19	0.7	0.0001	0.55	0.2	0.004	10.0	1.7	0.15
Pelite Weak BOX	2700	23	12.5	43.5	0.0	18	0.7	0.0001	0.55	0.2	0.004	10.0	1.8	0.22
Pelite Strong	2700	44	13.6	40.1	0.0	47	2.1	0.0029	0.51	2.3	0.061	10.0	10.5	0.15
Pelite Strong BOX	2700	39	13.6	43.5	0.0	38	1.5	0.0011	0.51	1.2	0.027	10.0	6.2	0.22
Semi Pelite	2700	70	8.4	61.9	0.0	50	1.4	0.0041	0.51	4.3	0.199	10.0	19.6	0.24
Semi Pelite BOX	2700	39	8.4	43.5	0.0	40	1.0	0.0013	0.51	1.3	0.050	10.0	6.9	0.22
Psammite	2700	106	11.3	61.9	0.0	56	2.3	0.0074	0.50	8.9	0.337	10.0	26.4	0.24
Psammite BOX	2700	57	11.3	67.7	0.0	45	1.6	0.0022	0.51	2.5	0.079	10.0	15.0	0.17

The structural environment was simulated in the numerical model and ten large-scale faults were included.

MINING METHODS

The mining method for the deposit is to be predominately long hole stoping with backfill. A small proportion of the cut and fill mining method is proposed to be used in flat zones of the orebody or should very poor ground conditions exist. This is illustrated in Figure 2 and Figure 3

All ore extraction voids are planned to be backfilled and a proportion of the associated lateral access development. The mine design will use rock fill, cemented rock fill and cemented paste backfill (paste).

The mine design comprises of crown, sill and regional pillars for global stability and mitigating the surface subsidence.

- The regional pillars are 40m around the cross cuts, with a 285m spacing (centre to centre). Three regional pillars have been defined in the model
- The sill pillars are 20m high, with a 60m spacing (centre to centre) between the first two sill pillars, and 100m thereafter. Five sill pillars have been defined in the model.

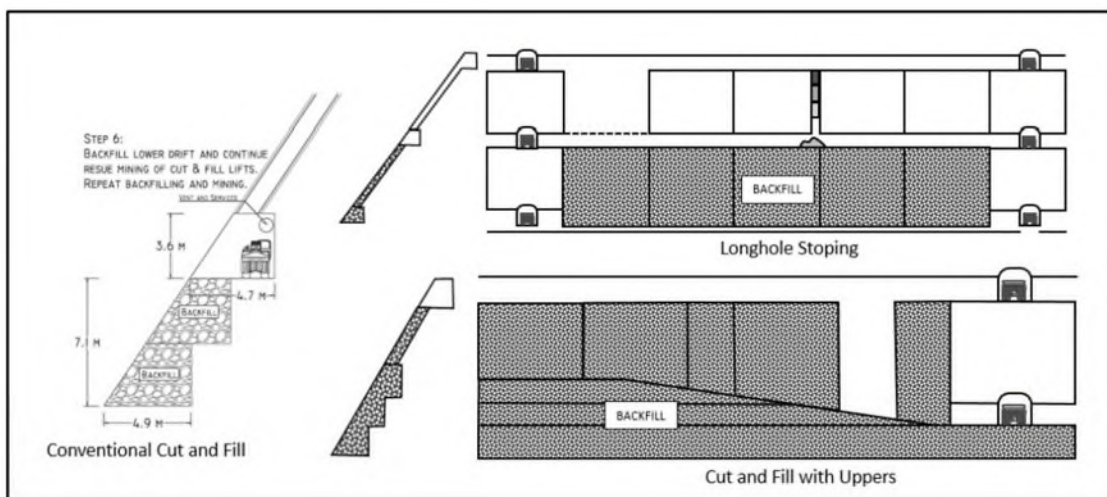


Figure 2: Illustration of proposed mining methods. Conventional cut and fill (left) and longhole open stope and backfill (right) (JDS, 2017)

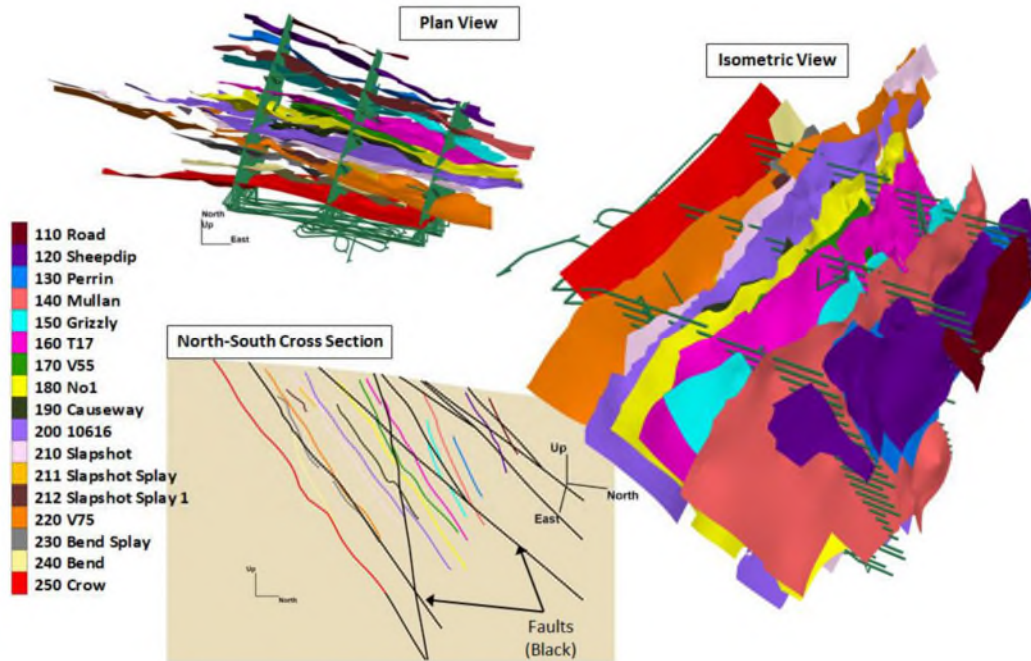


Figure 3: Isometric, plan view and vertical cross-section of the 17 veins included in mine model

Crown Pillar

The crown pillar is a term used to describe the rock cover that exists between near surface excavations and the alluvium cover. The stability of the crown pillar was assessed as part of the numerical modelling.

Based on results from the numerical modelling, it is recommended that a preliminary 50m crown pillar is established between the upper level of underground stoping and surface where there are nearby buildings.

Through geotechnical monitoring program, data obtained will be utilised in a feedback loop to correlate the numerical modelling. This increasing knowledge will result in more informed decisions regarding timing and extent of crown extraction. Veins that are remote from buildings (towards the footwall of the deposit) should be exploited to within 20m of the surface to obtain important calibration of the numerical model.

Calibration between numerical model forecast of subsidence and extraction and the actual measured subsidence following extraction will ultimately determine the extent of the pillars (crown, regional and sill)

Regional pillars

The extent and spacing of vertical regional pillars were assessed through numerical modelling. To protect underground infrastructure and to control potential subsidence, recovery of the regional pillars should only be attempted at the end of mine life following validation of subsidence modelling of the actual rock mass performance and the forecast deformations.

The detailed extraction sequence for the regional pillars will require specific modelling once the rock properties, actual versus modelled response, and fill deformation properties have been calibrated.

Sill Pillars

Horizontal sill pillars separate each mining panel. They are planned as blind up hole stopes.

The sill pillars are currently planned to be progressively extracted as they become available and the mined void will be filled with paste backfill. The removal of these pillars increases the amount of potential subsidence that can occur. The actual extraction of the sill pillars will be dependent on validation of subsidence modelling between actual rock mass performance and forecast resultant deformations.

Backfill approach

Backfill will be utilised to enable extraction of secondary stopes along strike adjacent to primary backfilled stopes, to control rock mass deformation and to allow a bottom up mining sequence working on the fill.

The mining sequence has several levels in each panel. The lowest level will be filled with high paste strength fill to allow undercutting at a latter date. The mid levels with combination fill masses of waste rock, ore sorter rejects and paste. These mid level fill mass have the potential to have significantly higher modulus depending on the placement of the fill components. The upper fill will have a paste strength and stiffness appropriate to the mining situation.

Always filling the stopes at planned intervals controls the stope dilution and also controls the amount of deformation and hence subsidence that may occur from mining. The stope filling cycle is a critical part of the mine design.

SUBSIDENCE MODELLING

Three-dimensional numerical analysis was performed using FLAC3D. Ten models were run to study the sensitivity of the assessment study mine model over a range of parameters, including backfill stiffness, rock mass strength and extraction variations.

Model Sensitivities

To assist with determining plausible maximum deformations, sensitivity analysis was undertaken by running multiple sensitivities. The results of three of the sensitivity model runs are detailed in this report. These sensitivities are:

- Case A (base case) – using the parameters in Table 1, the stress state, the assessment study annual mining stopes (including extraction of all regional and sill pillars), 200MPa paste stiffness;

- Case B – as per the base case except using a 50 MPa modulus paste backfill stiffness. This is the plausible worse case modulus value;
- Case C – the parameters understood to be in the prior work by SRK were modelled with the current extraction geometry.

The 50 MPa modulus value selected as a Case B for the analysis has been derived from 4*1D consolidations tests. One sample was tested in the full range of loading condition expected at Curraghinalt (1 to 7 MPa).

Surface Infrastructure Damage Forecast

The potential for surface infrastructure damage was undertaken by Itasca using the work from Harrison (2011) relating Angular Distortion and Horizontal Extension Strain. This is illustrated in Figure 4. The description of this damage is provided in Table 2.

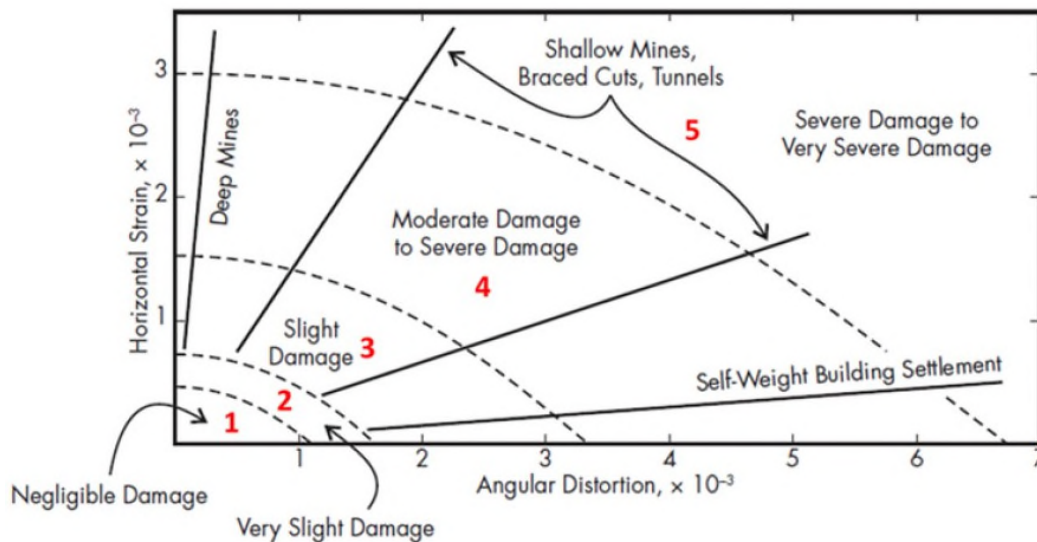


Figure 4: Relations of damage to angular distortion and horizontal extension strain (Harrison, 2011)

Table 2: Classification of building damage (Harrison, 2011)

Class of Damage	Description of Damage*	Repair	Approximate Width of Cracks, mm†
Negligible	Hairline cracks	None	<0.1
Very slight	Cracks in exterior brickwork visible upon close inspection; possible isolated slight fracture in building	Fine cracks easily treated during normal redecoration	<1
Slight	Several slight fractures inside building; visible external cracks; doors and windows may stick slightly	Cracks easily filled; redecoration probably required; some repointing may be required for weather tightness	<5
Moderate	Doors and windows sticking; weather tightness often impaired; utility service may be interrupted	Cracks may require cutting out and patching; recurrent cracks can be masked by suitable linings; repointing and possibly replacement of a small amount of exterior brickwork may be required.	5–15, or several cracks >3 mm
Severe	Windows and door frames distorted; floor slopes noticeably; walls lean or bulge noticeably; some loss of bearing in beams; utility service disrupted	Extensive work involving removal and replacement of sections of walls, especially over doors and windows	15–25, also depends on number of cracks
Very severe	Beams lose bearing, walls lean badly and require shoring; windows broken by distortion; danger of instability	Major work involving partial or complete reconstruction	Usually >25, depends on number of cracks

Source: Adapted from Wahls 1994.

*Location of damage in the building or structure affects assessment of degree of damage.

†Crack width is only one aspect of damage and should not be used solely as a measure of it.

Subsidence Sensitivity Results

A summary of maximum potential surface movement and settlement for three model sensitivity cases are provided in Table 3. These are illustrated in Figure 5 and Figure 6 in chart format to illustrate change over time.

The model deformation, shown as a transparent overlay on the project area aerial view, are shown in Figure 7 to Figure 12. The three cases are presented as two figures, before and after regional pillar extraction.

The deformation is very low considering the lateral extent of the operation due to the steep dip of the orebody, narrow stoping width and mining practices of tight filling with paste and leaving pillars. The main deformation area is up hill away from farm buildings and houses. In all cases, no potential large-scale surface cracking is predicted in the rock mass.

The vertical deformation expressed as a cross sectional view through the deposit between two of the regional pillars are shown in Figure 13 to Figure 15. The three cases are presented as paired figures showing before and after regional pillar extraction. These three figures show the proportion of orebody extraction (white), major faults (black), surface topography and total vertical displacement (coloured scale).

The forecast strains for the three cases are presented in Figure 16 to Figure 21 as pairs of figures before and after regional pillar extraction. Case A (base case) plot within the *negligible* damage category, there are a couple of instances of *very slight* damage, these areas do not plot near surface infrastructure. Case B (50MPa paste modulus) plot with *negligible* damage category, there are broad areas of *very slight* damage, particularly about faults, and several areas of *slight* damage forecast, again about fault locations. Case C plots as *negligible* damage category.

The key difference between the SRK 2017 and Itasca (2019a and 2019b) models are the input parameters, namely:

- Increase in mined stopes in 2019 model
- Lower stress state in SRK model 1.5 : 1 : 1 compared to in situ stress measurement of 2 : 1.5 : 1
- Different rock mass modulus and rock mass strength (higher and lower for the range of geotechnical domains)
- Update lithology boundaries for allocation of the geotechnical domains

The conclusions to Itasca's numerical modelling have been summarized by MGT as

- The backfill stiffness and response is the key controlling parameter for determining the subsidence. It has been modelled as single stiffness with lower and upper bounds. Testing will continue to verify the lower bound value as mining progresses.
- Verification of large scale foliation strength is important to undertake during mining to assist with model forecasts for subsidence and excavation stability. Verification will continue via detailed models that compare forecast displacement to measurable displacement from underground monitoring as mining progresses.
- Pore pressure redistribution from groundwater was considered to be non-critical for ground displacement and should be verified during mining by inclusion into the model if other factors do not resolve any error between forecast and actual displacement.
- Subsidence is influenced by stope width. Actual stoping widths should be used during smaller detailed model verification of forecast and measured subsidence and then brought into the life of mine model as an average across all stopes in a vein as mining progresses.
- Numerical models tested a range of plausible input parameters to understand the forecast deformation sensitivity to the model. These forecasts should be monitored and verified during life of the mine monitoring by precision surface measurements and improving the understanding of backfill stiffness and rock mass state and properties.

Table 3: Maximum deformation from mine scale subsidence models (Itasca 2019a)

	Maximum Potential Surface Movement (mm)		Maximum Potential Surface Settlement (mm)	
	Year 16	After extraction of Barrier Pillars	Year 16	After extraction of Barrier Pillars
Case A – Base case 200 MPa Modulus Backfill	77	104	43	60
Case B - 50MPa Modulus Backfill	141	201	85	146
Case C - SRK assumptions	63	83	41	52

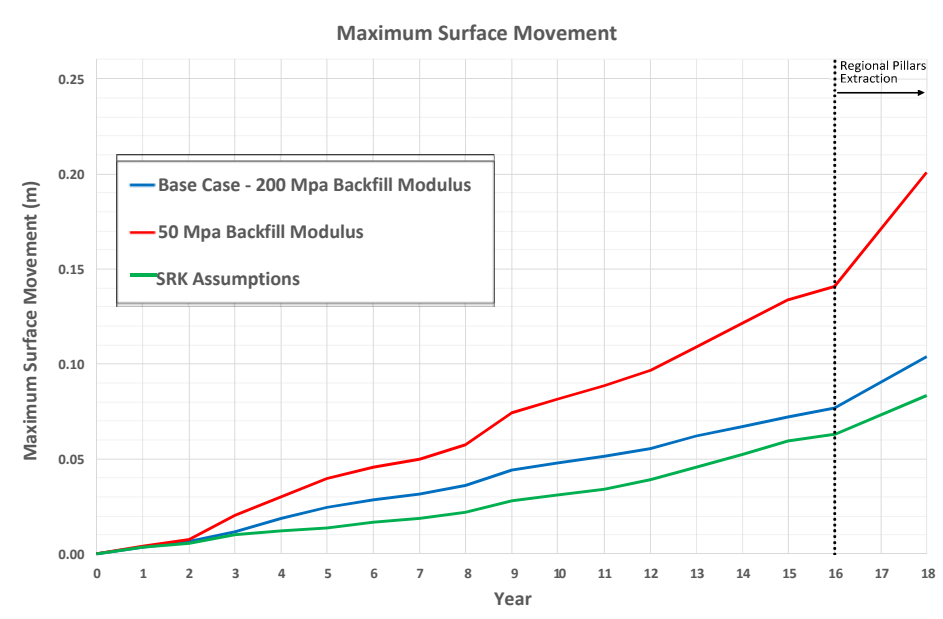


Figure 5: Surface deformation with time, showing results of three sensitivity cases

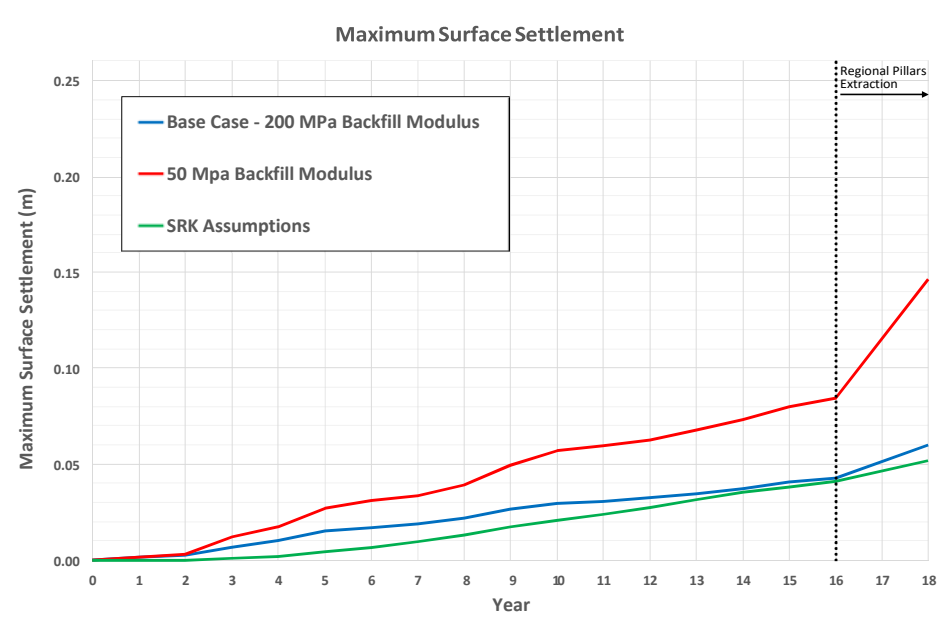


Figure 6: Surface settlement with time, showing results of three sensitivity cases

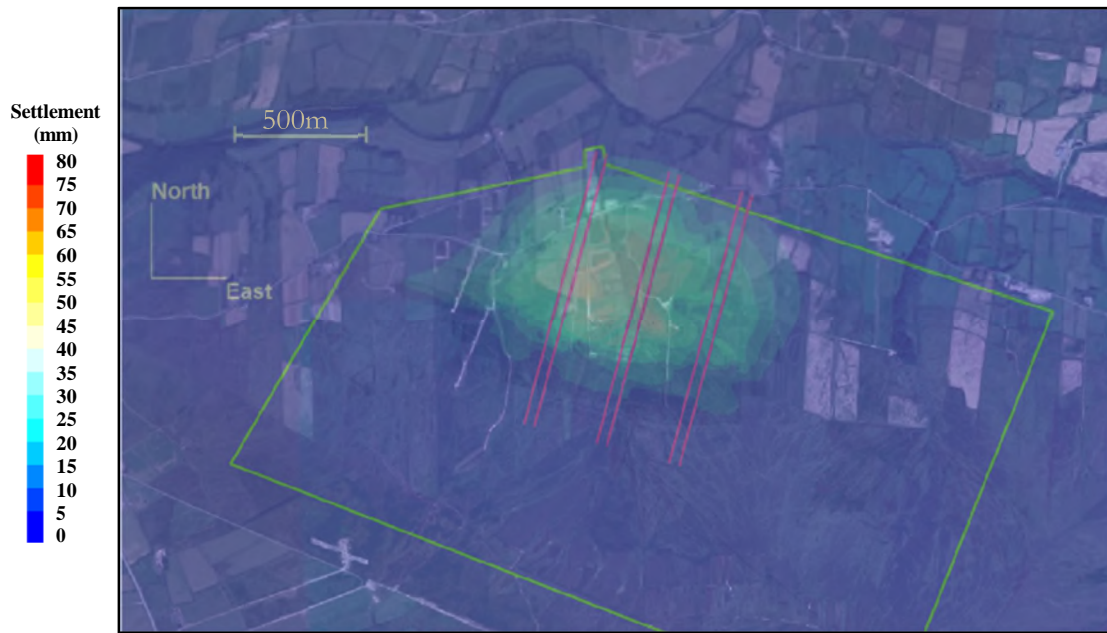


Figure 7 : Surface settlement near end of mine life – Case A results

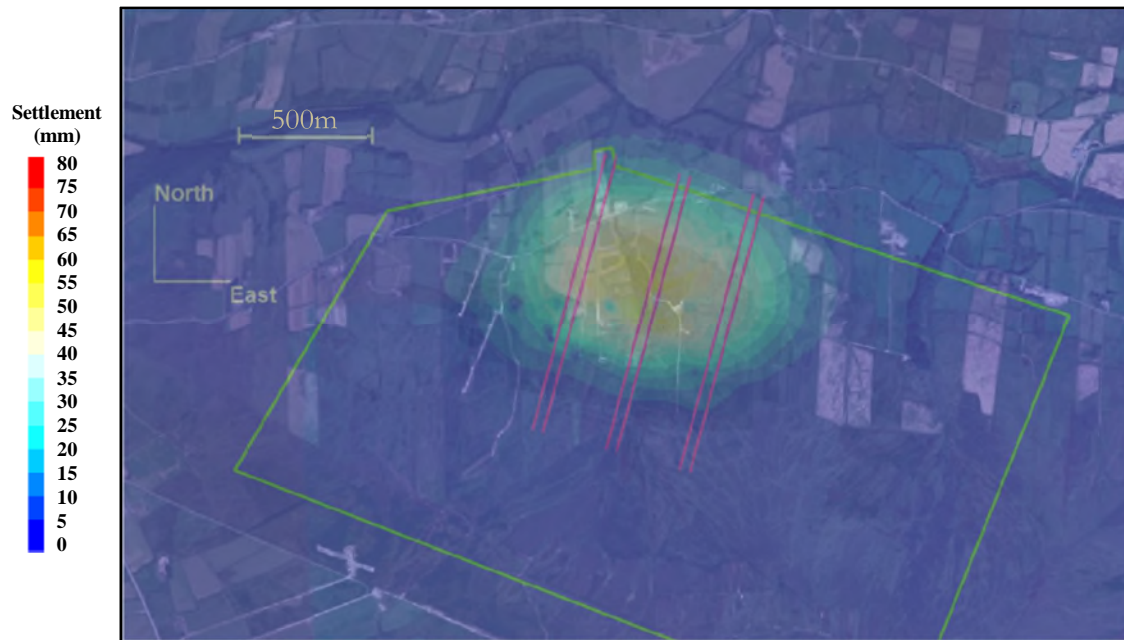


Figure 8 : Surface settlement after regional pillar extraction – Case A results

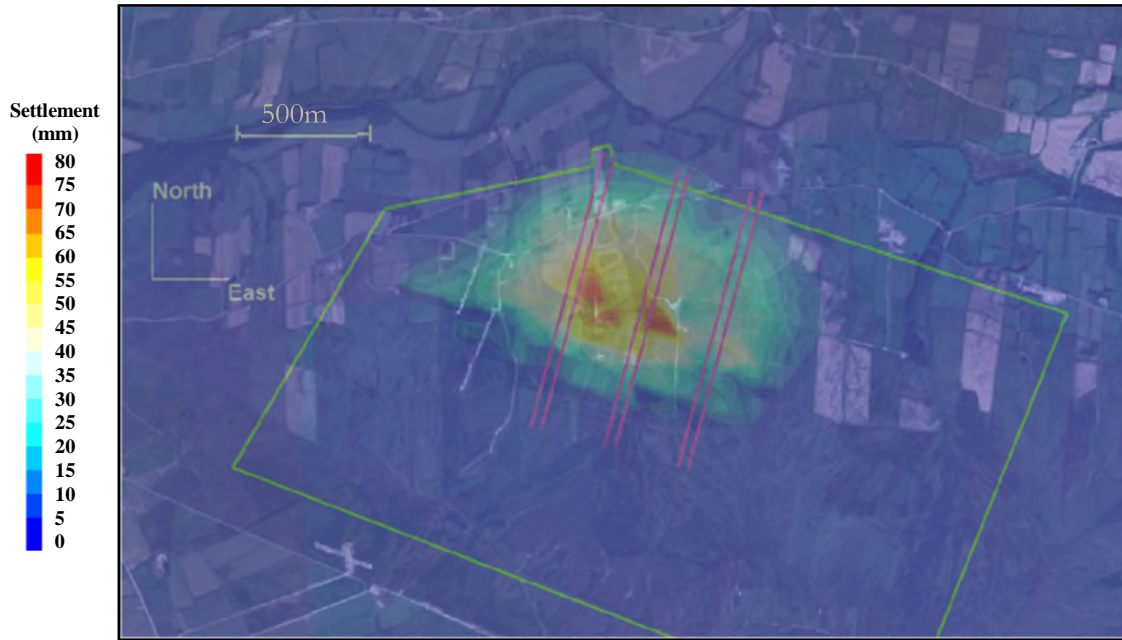


Figure 9 : Surface settlement near end of mine life – Case B results

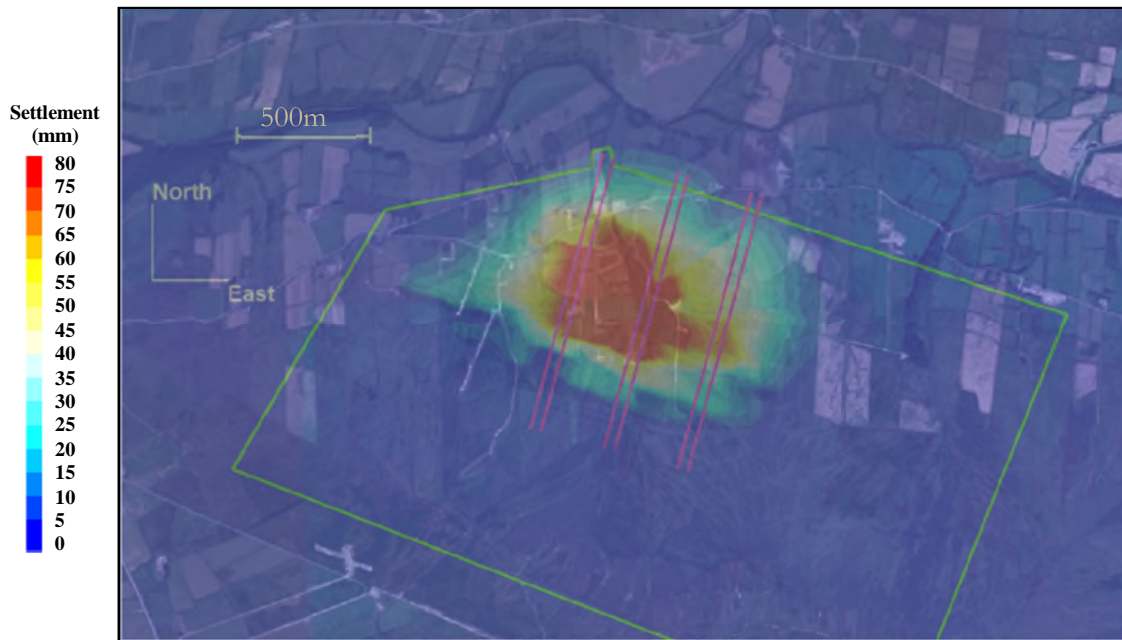


Figure 10 : Surface settlement after regional pillar extraction – Case B results

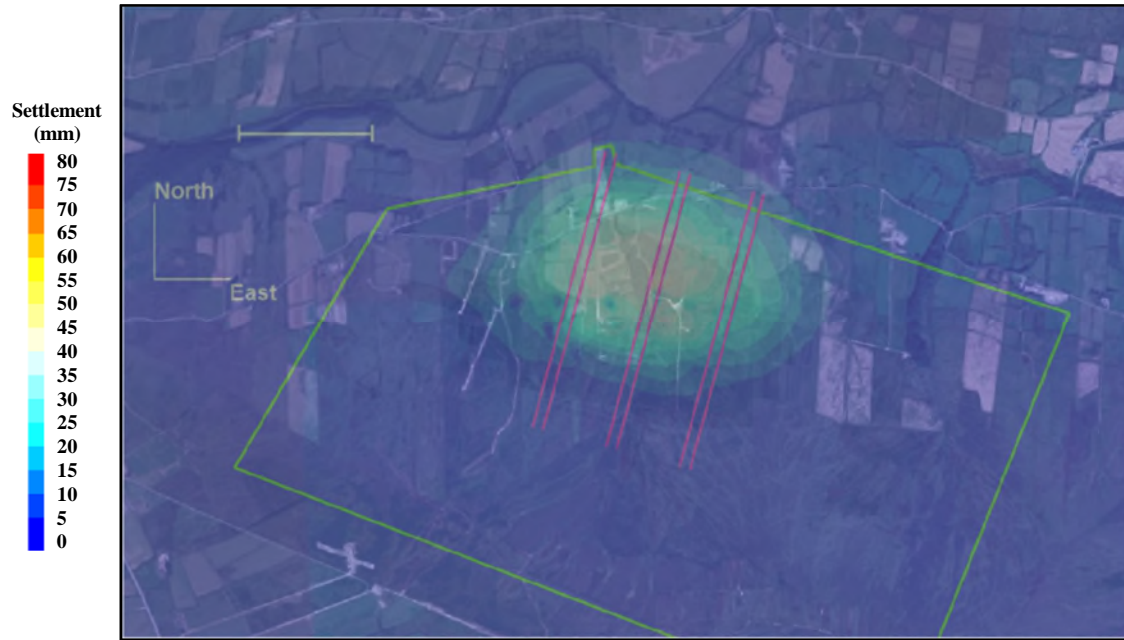


Figure 11 : Surface settlement near end of mine life – Case C results

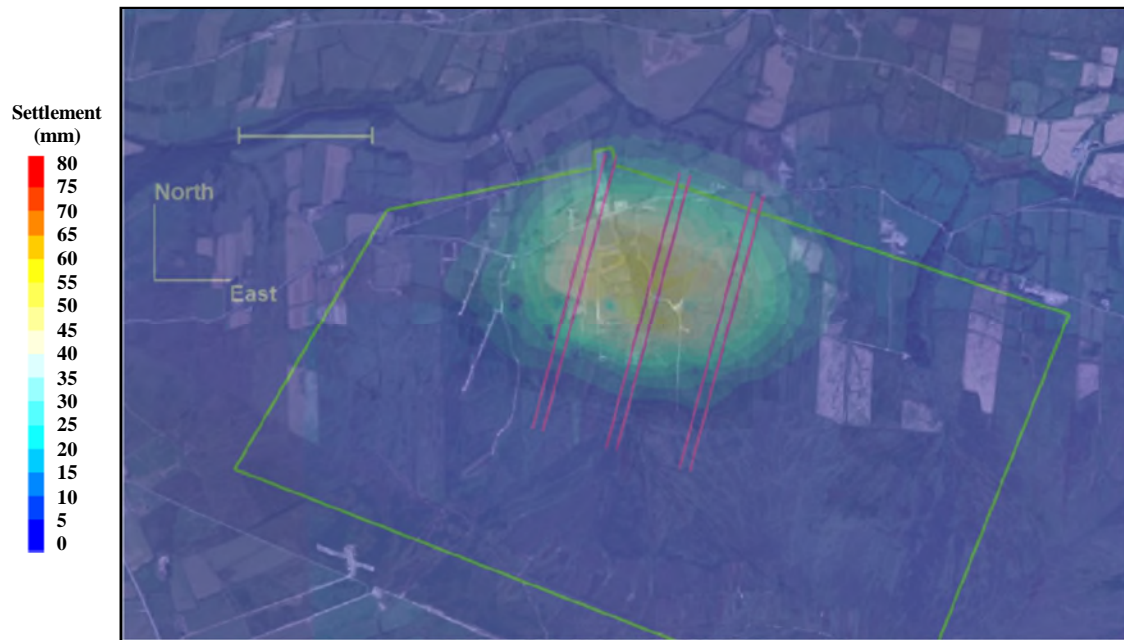


Figure 12 : Surface settlement after regional pillar extraction – Case C results

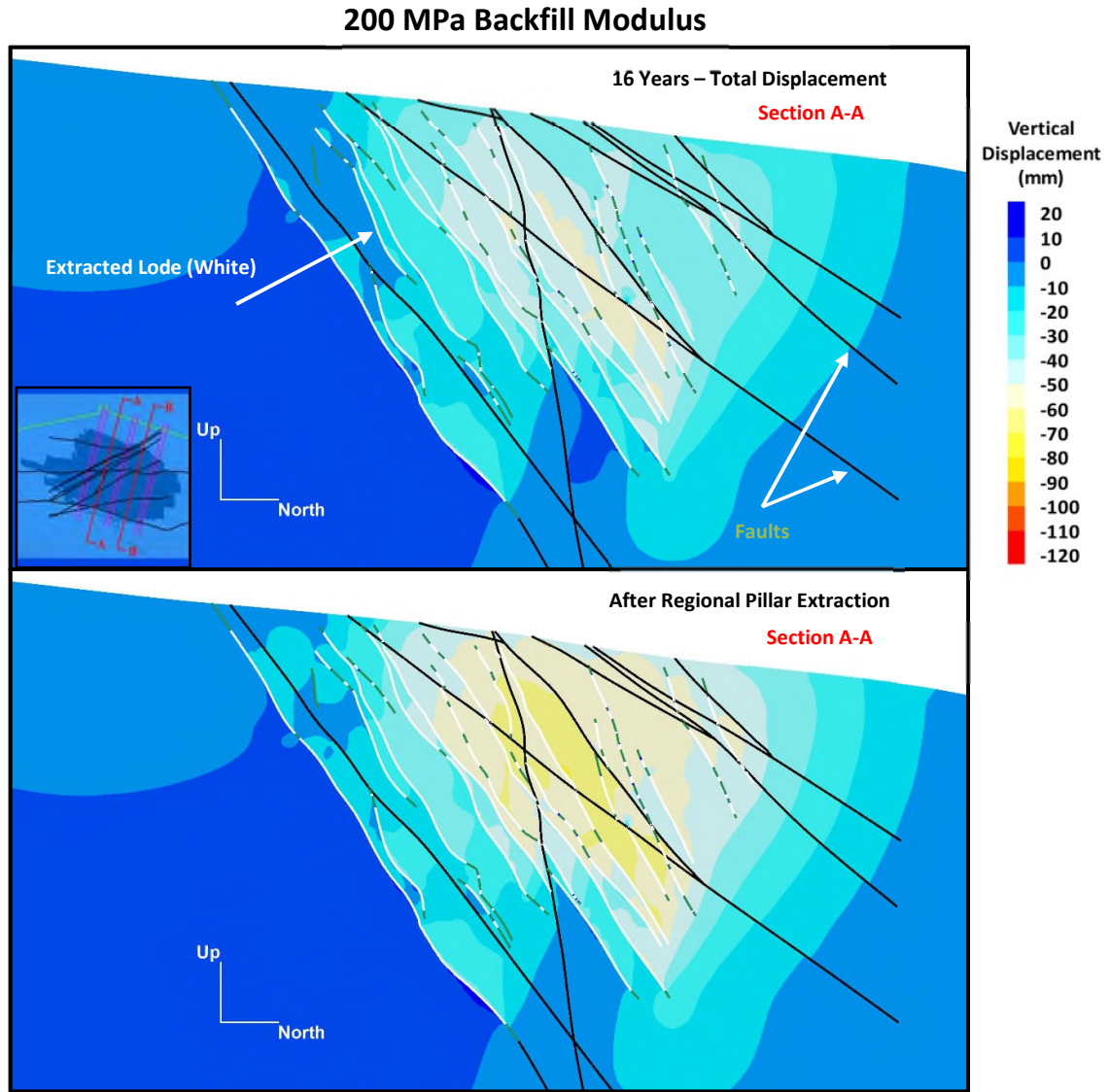


Figure 13 : Vertical settlement before and after pillar extraction – Case A

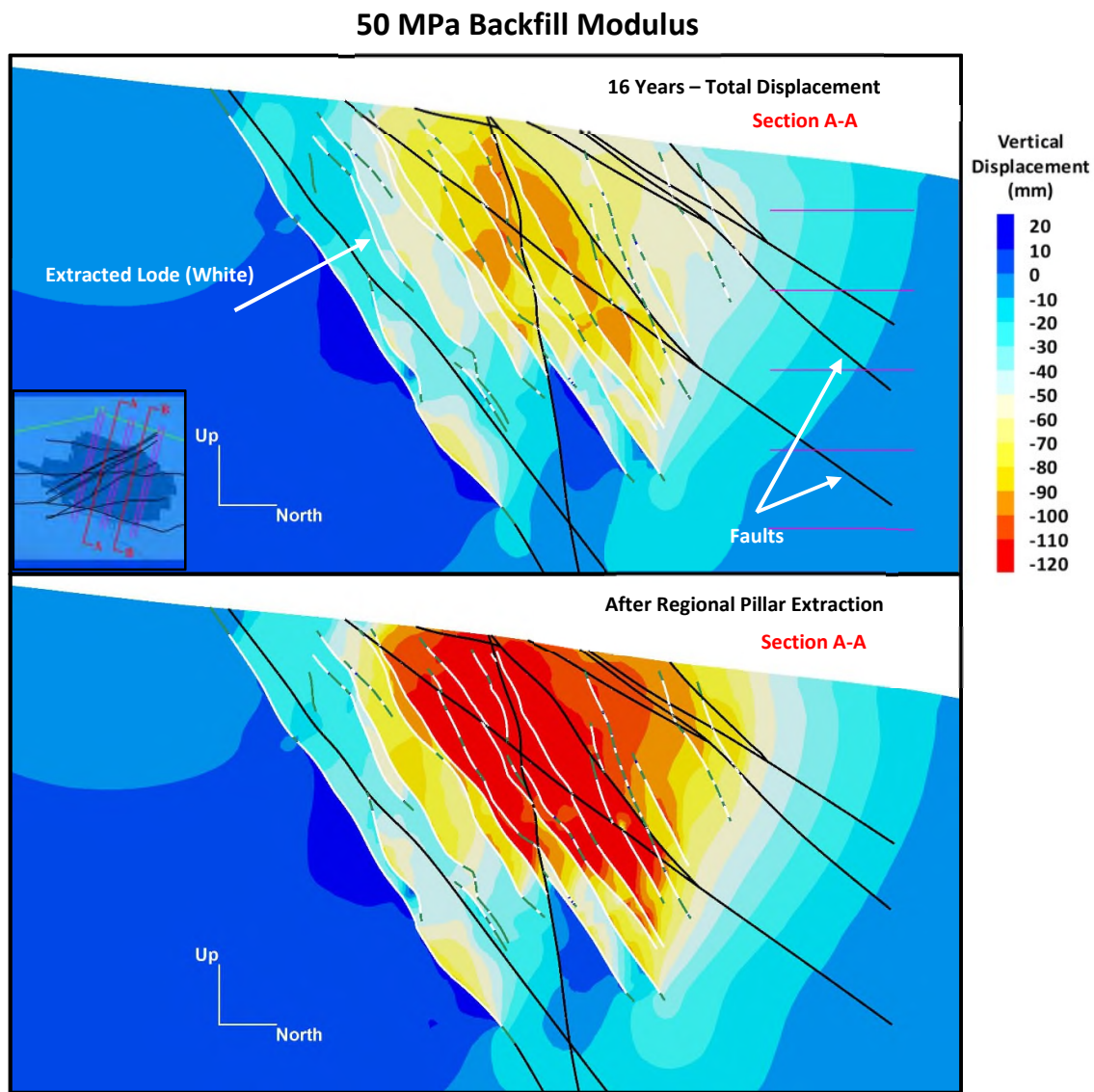


Figure 14 : Vertical settlement before and after pillar extraction – Case B

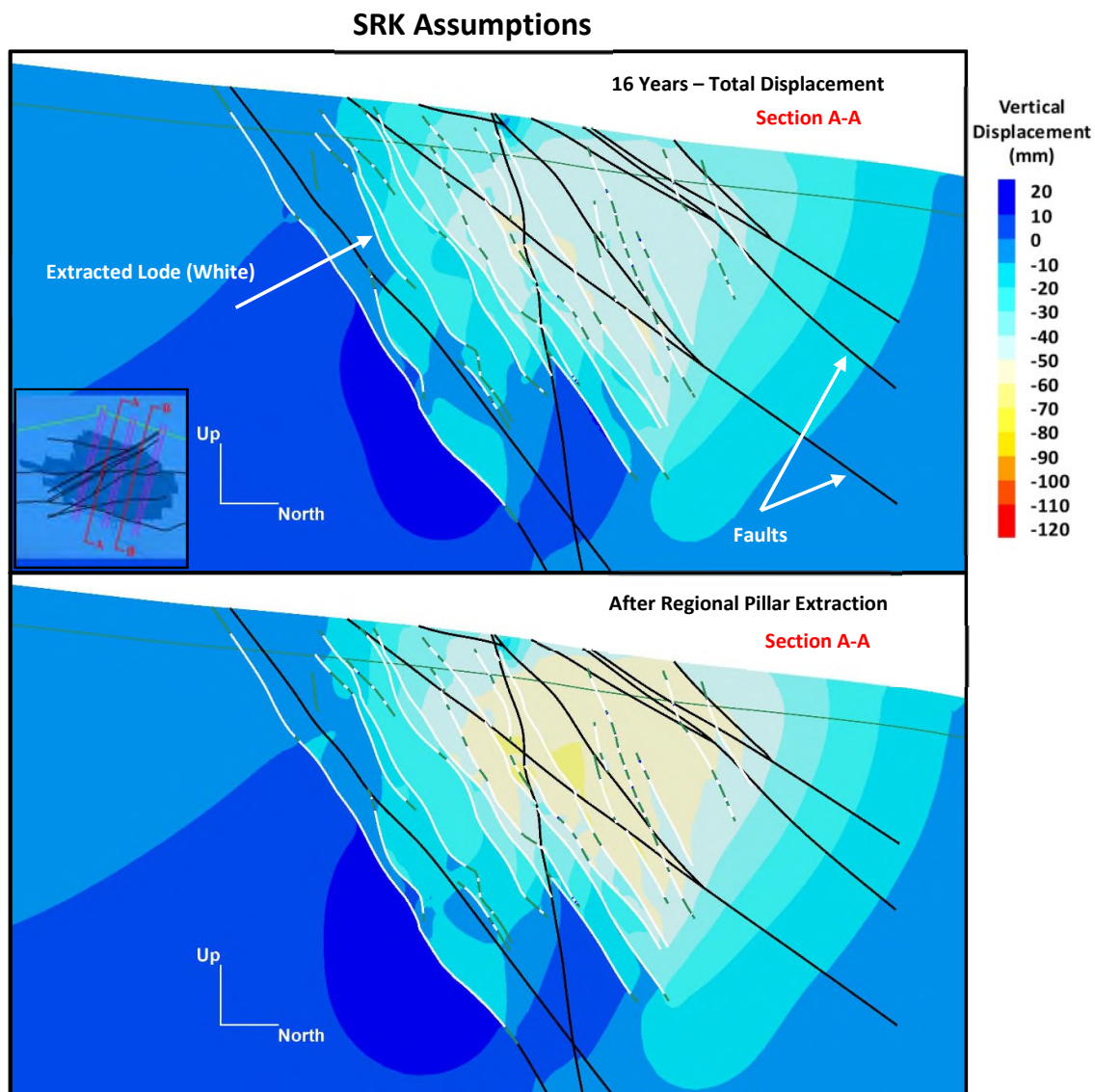


Figure 15 : Vertical settlement before and after pillar extraction – Case C

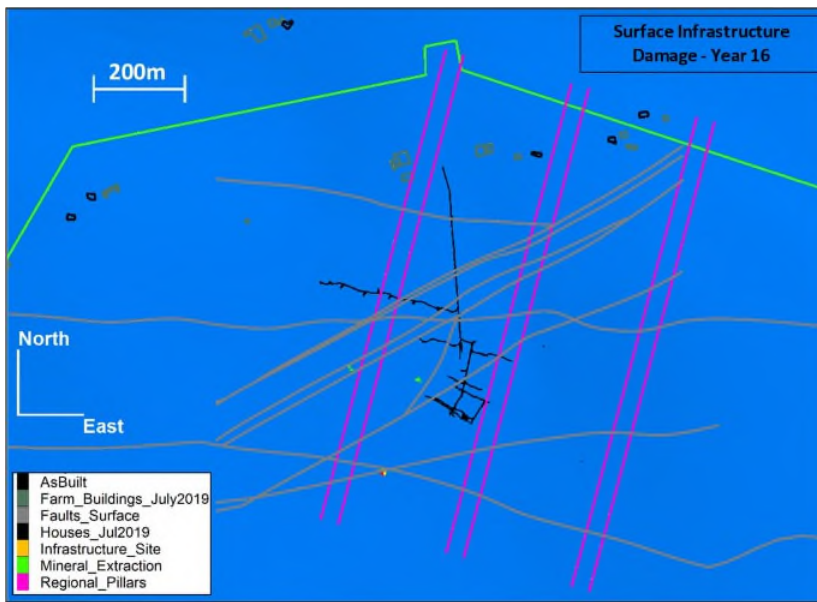
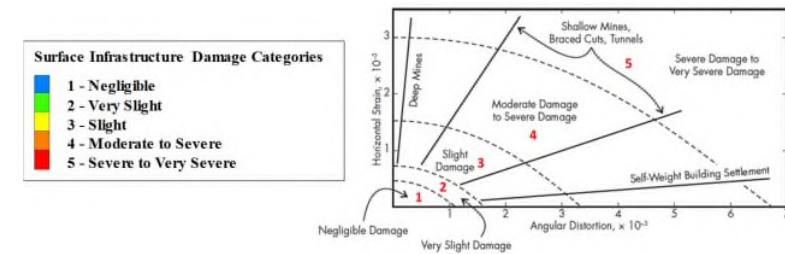


Figure 16: Surface infrastructure damage near end of mine life – Case A results, based on Harrison, 2011 (Itasca, 2019b)

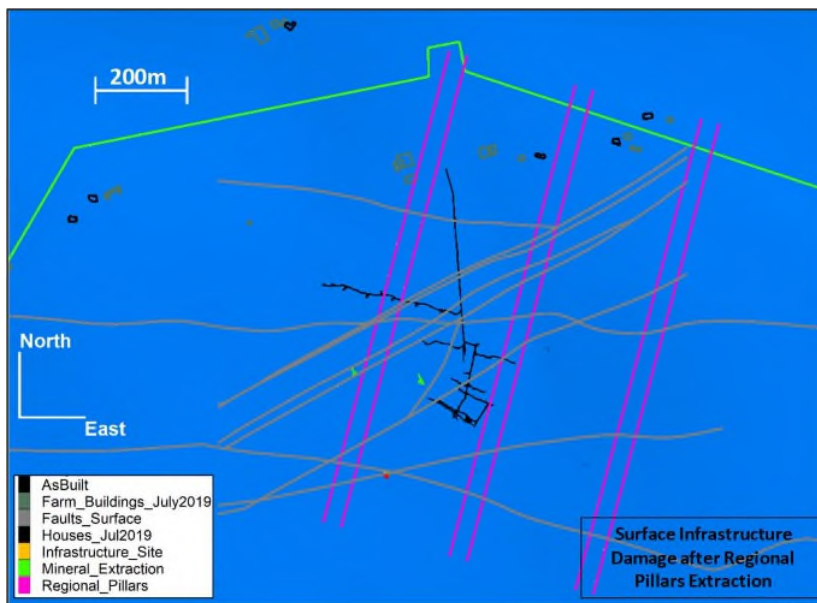


Figure 17: Surface infrastructure damage after regional pillar extraction - Case A results, based on Harrison, 2011 (Itasca, 2019b)

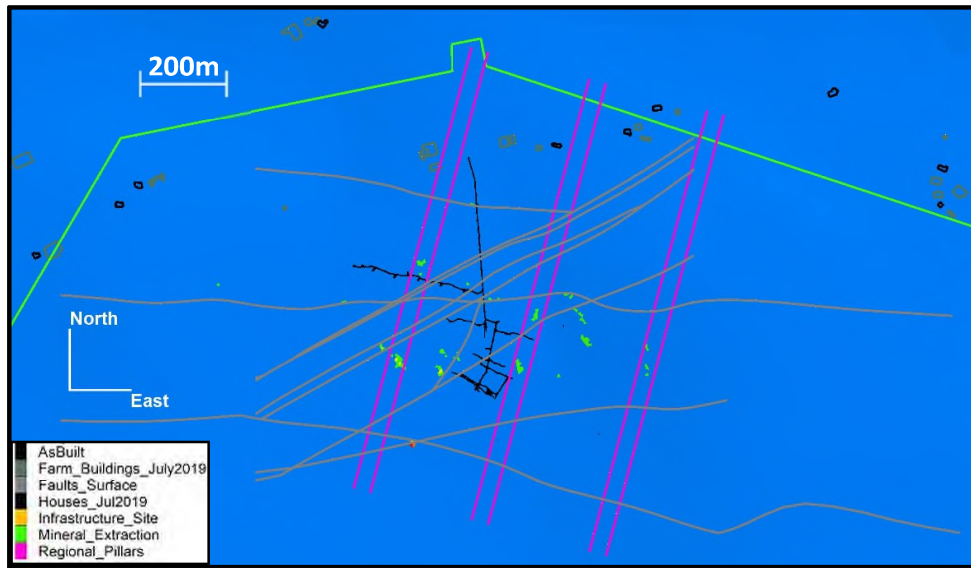


Figure 18 : Surface infrastructure damage near end of mine life – Case B results, based on Harrison, 2011 (Itasca, 2019b)

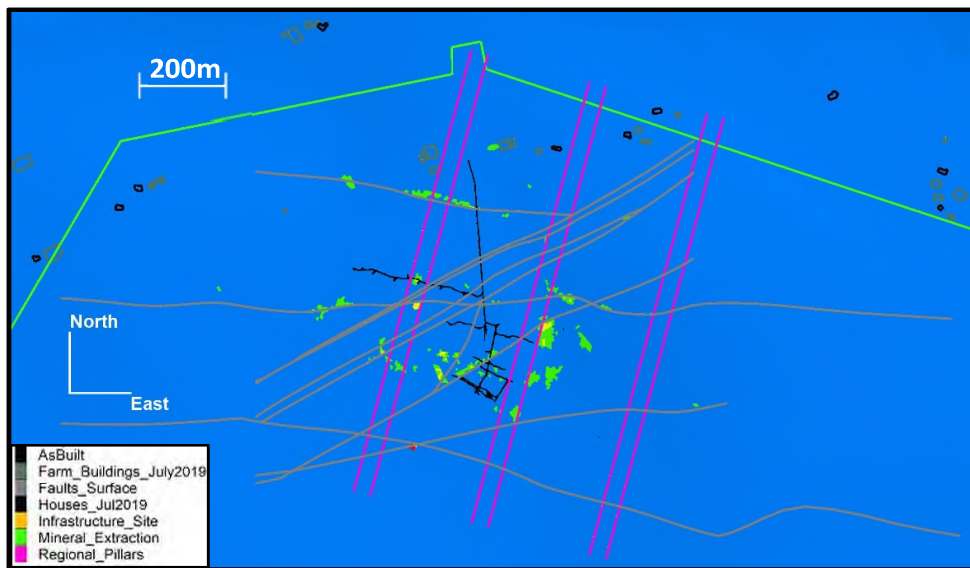


Figure 19 : Surface infrastructure damage after regional pillar extraction - Case B results, based on Harrison, 2011 (Itasca, 2019b)

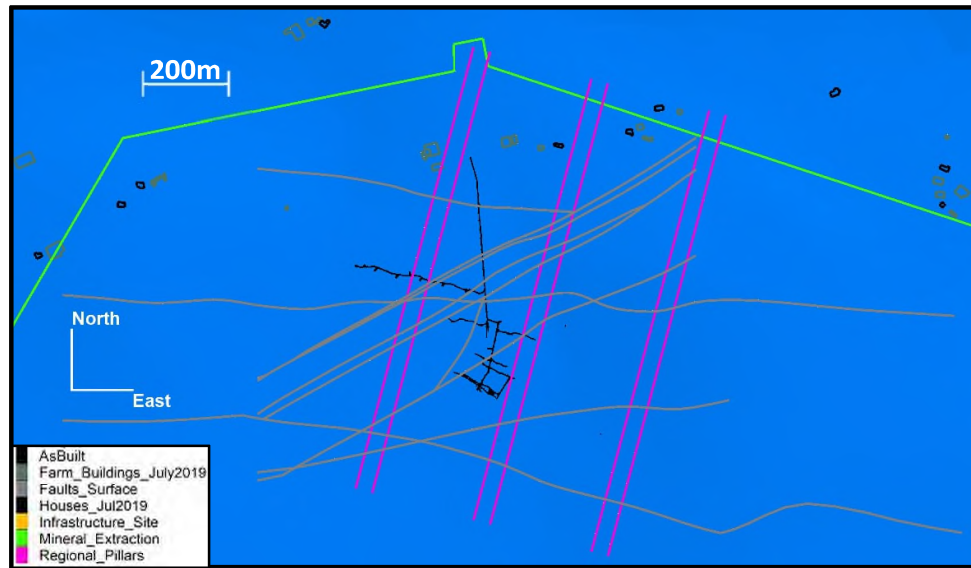


Figure 20 : Surface infrastructure damage near end of mine life – Case C results, based on Harrison, 2011 (Itasca, 2019b)

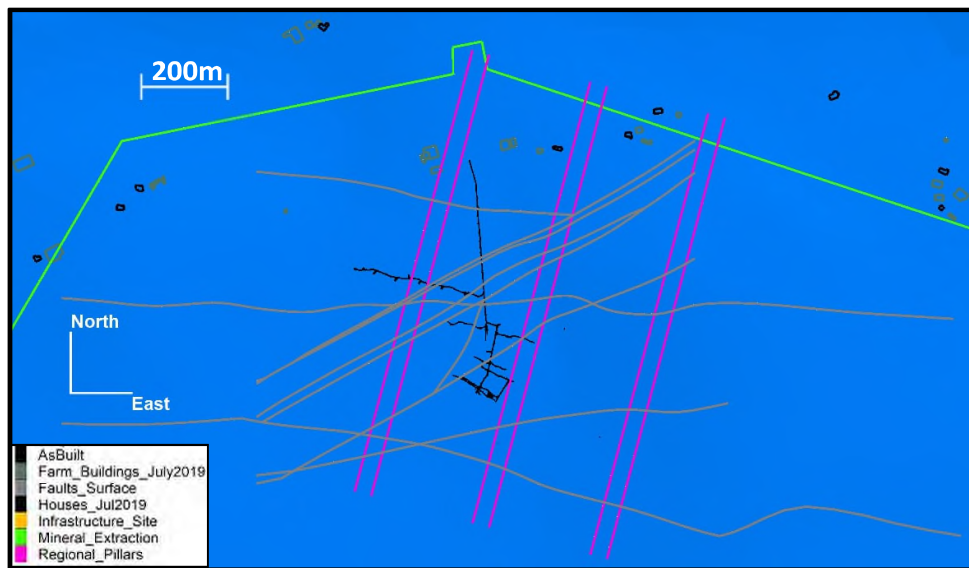


Figure 21 : Surface infrastructure damage after regional pillar extraction - Case C results, based on Harrison, 2011 (Itasca, 2019b)

MONITORING REQUIREMENTS SUMMARY

A key recommendation from the MGT assessment study and Itasca numerical modelling is the requirement of geotechnical monitoring during mining of the Curraghinalt project. The following summarises the monitoring requirements recommended specifically to calibrate the numerical model and thereby improve the accuracy of predicted subsidence:

- In situ Stress: Monitor stress changes using Hollow-Inclusion cells or USBM cells. Areas of interest would include the major excavations and abutment areas
- Seismicity: Mine scale and regional seismic monitoring system. This will be used to monitor the progression of seismicity on mine scale structures and general rock mass response. A regional system has limitations and will need to be accounted for in the design of the system
- Surface Deformation: the forecast potential deformation is so small, multiple permanent stations outside and inside the area of influence are required to be used to close the survey transects across the project area. A Light Detection and Ranging (LIDAR) and Interferometric Synthetic- Aperture Radar (InSAR) can be used to provide additional vertical movement data between the high precision transects across the project area
- Sub-surface Deformation: Monitoring closure of the filled stopes by indirect means (borehole extensometers measuring wall changes of stopes) and general rock mass deformation from in borehole extensometer and lidar can also be used to calibrate the model

CONCLUSIONS

The assessment of potential rock mass deformation and subsidence during mining of the Curraghinalt project was completed. MGT engaged Itasca Australia to undertake 3D numerical modelling on ten sensitivities to capture a range of parameters, including backfill stiffness, rock mass strength and extraction variations.

Input parameters for the numerical modelling were derived from a comprehensive and extensive geotechnical investigation program.

All mining results in some deformation to the earth's crust. The amount of deformation is dependent on the geotechnical model, the mining methodology and the scale of mining.

The Curraghinalt project modelled potential subsidence is very small because it is comprised of narrow veins and weak, jointed rock mass and the mining methodology employed utilises backfill after small stopes are extracted.

MGT have undertaken extensive scenario testing to investigate sensitivities of the potential subsidence modelling and are confident these sensitivities have covered the base case scenario and also plausible worst-case scenarios in correlation with cemented paste fill modulus.

Understanding and predicting the subsidence and deformation can be achieved over time as a feedback loop to verify model forecasts. Ongoing collection of the input rock mass data will occur with drilling and mine development. The rock mass response data to excavation from monitoring for mine subsidence, deformation and seismicity will be used to calibrate, refine and verify numerical modelling to the actual rock mass performance. This feedback loop will then be used for more accurate forward prediction of deformation. This feedback loop results in up to date subsidence expectations which can then be used in long-term planning to adjust strategies to suit the actual environment.

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Conditions regarding the site may not have been detected given the nature of the rock mass data collection be available for MineGeoTech's enquiry. Accordingly, additional investigations and reports may be required.

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Recommendations

Care should be taken when interpreting and relying on this report.

Assumptions of rock mass conditions are to be validated through actual conditions upon excavation. Should there be variance between the assumptions and that identified through excavation it is recommended to discuss this with MineGeoTech.

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Potential for Mining Induced Seismic Activity at Curraghinalt Mine

This is a discussion document for the potential for mining-induced seismic activity from the proposed Curraghinalt Mine to support the 2019 Planning Application and Further Environmental Impact submission to the Northern Ireland Department for Infrastructure by Dalradian Gold.

INTRODUCTION

This document summarises the investigation into the concerns raised by members of the public in response to Dalradian Gold application for environmental permit for mining.

The two concerns highlighted are

- Response of the rock mass and water table to mining resulting in an induced earthquake or micro-seismicity
- Placement of a dry stack tailings facility on the surface will induce an earthquake.

This report addresses these concerns.

Natural Earthquake History

The natural earthquake history for Northern Ireland is considered.

United Kingdom Historic events

The magnitude and frequency of historic events can indicate the susceptibility of natural seismicity in the area.

The first two figures show all “major events” (magnitude greater than four) since 1932. The second figure shows all the events that have been recorded since 1956. These figures reveal no events have been recorded in the Curraghinalt project area.

Significant earthquakes in the UK from 1932– present



Figure 1: All major events (magnitude > 4) since 1932 in United Kingdom (BGS website)

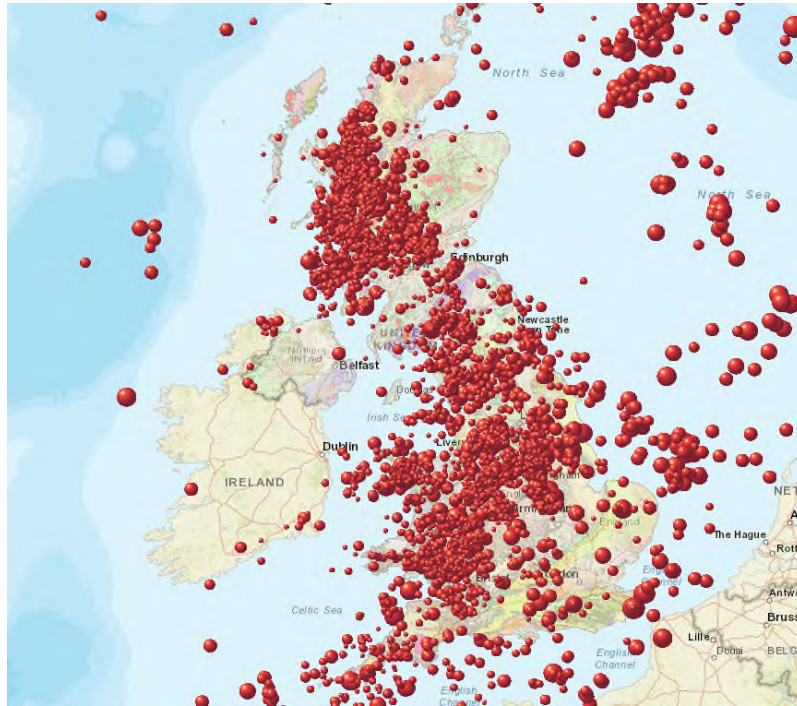


Figure 2: Earthquakes in Great Britain and Ireland since 1956 as recorded by the British Geological Survey (BGS website)

A magnitude 4.0 earthquake happens in Great Britain approximately every two years. A magnitude 5.0, approximately every 10-20 years. The earthquake activity map shows several regional variations. Most earthquakes occur on the western side of Great Britain. The North Sea is more active than Great Britain (British Geological Survey website). Earthquakes are almost completely absent from Ireland, with two local “hot spots” at Donegal and The Irish Sea (Irish National Seismic Network).

The reason for earthquakes in Great Britain and Northern Ireland is not clear. Regional compression caused by motion of the Earth’s tectonic plates and uplift resulting from the melting of the ice sheets is one reason for earthquakes. These can concentrate on regional faults, the natural weak point in the rock mass.

The cycles of for natural earthquakes is significantly longer than human lifetimes and changes in the earthquake history of Ireland (Republic of Ireland and Northern Ireland) is expected at some point in the future in that temporal context. This is the position regardless of whether or not there is mining in Northern Ireland.

United Kingdom Earthquake Hazard Map

Earthquake hazard maps have been generated by British Geological Society (BGS, 2007) for the United Kingdom. These maps use ground motion models to calculate the Peak Ground Acceleration (PGA) using data from local stations. These maps are shown in Figure 3.

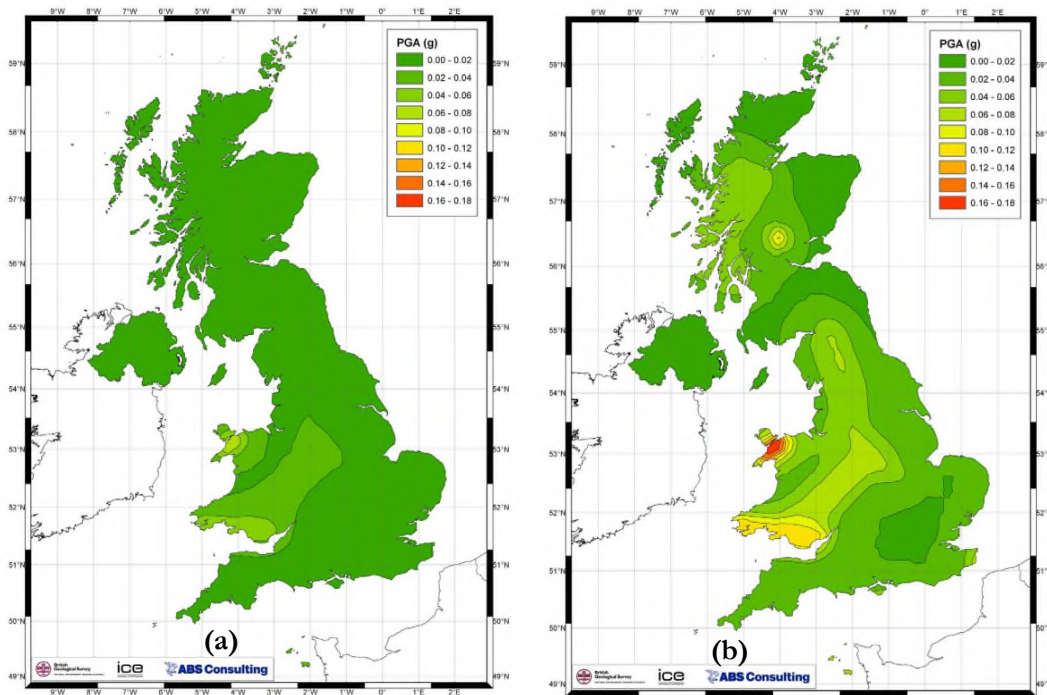


Figure 3: (a) Hazard map for 475-year return period (b) Hazard map for 2,500-year return period

Northern Ireland has been assigned a PGA between 0.00 to 0.02 for both a 475 year and 2,500-year return period. This value is shown in comparison to the rest of Europe in Figure 4 (JRC, 2008). This seismic hazard map is the ESC-SESAME European-Mediterranean for PGA with 10% probability of exceedance in 50 years. This is equivalent to a 475-year return period. The figure highlights the low hazard of Ireland (Republic of Ireland and Northern Ireland) in comparison to the rest of Europe.

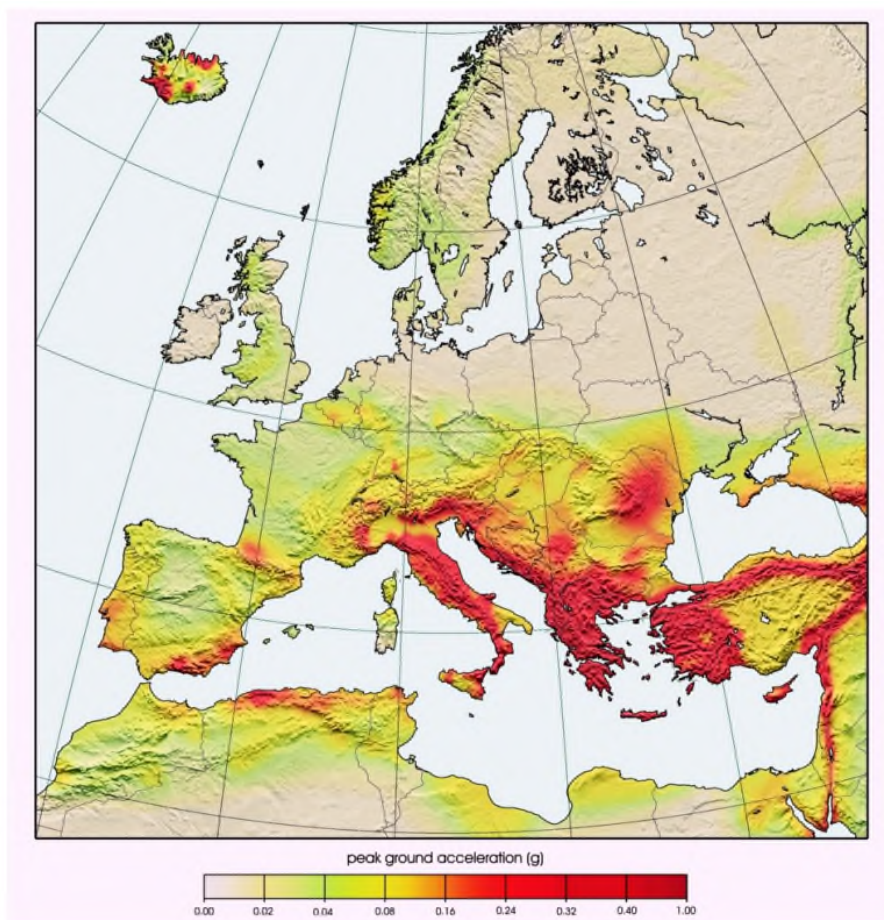


Figure 4: Hazard map for Europe (JRC, 2008)

For comparison between public perception and recorded PGA, the United States Geological Society (USGS) developed an instrumental intensity scale which maps peak ground velocity on an intensity scale. These values are used to create shake maps by seismologists around the world (USGS, 2011).

Table 1: USGS instrumental intensity scale (USGS, 2011)

Instrumental Intensity	Acceleration (g)	Velocity (cm/s)	Perceived shaking	Potential damage
I	< 0.0017	< 0.1	Not felt	None
II-III	0.0017 – 0.014	0.1 – 1.1	Weak	None
IV	0.014 – 0.039	1.1 – 3.4	Light	None
V	0.039 – 0.092	3.4 – 8.1	Moderate	Very light
VI	0.092 – 0.18	8.1 – 16	Strong	Light
VII	0.18 – 0.34	16 – 31	Very strong	Moderate
VIII	0.34 – 0.65	31 – 60	Severe	Moderate to heavy
IX	0.65 – 1.24	60 – 116	Violent	Heavy
X+	> 1.24	> 116	Extreme	Very heavy

Comparing this to the Northern Ireland hazard is an acceleration between 0 and 0.02 is at worst, lightly felt, but no potential damage.

Potential Earthquakes from Underground Mining at Curraghinalt

The potential for induced seismicity from underground mining is addressed.

Curraghinalt Location and Mining Method

The deposit is in an extensive series of undulating narrow quartz shear zones within a highly deformed large turbidite sequence. A turbidite sequence is a complex geological sedimentary setting.

Shallow rocks and especially shallow sedimentary rocks tend to be weaker than those at greater depth limiting the magnitudes of earthquakes that can occur (Gibson and Sandiford, 2013).

The mining methodology employed utilises paste (pumpable fine waste material which has cement to provide strength) to backfill the extracted narrow ore zones. To minimise instability during the ore extraction, maximum stope dimension is 20 m vertical, 25 m on strike and in general are between 1.2 m to 2.9 m wide. After extraction these are backfilled prior to the next stope in the sequence being extracted.

The objective of restricting the stopes to this size and using backfill is to provide confinement to the remaining rock mass and the lower quality of the rock mass. This reduces the potential for the remaining rock mass to deform and “build-up” a store of strain energy from the redistribution of natural earth stress. Rock masses that are brittle, strong and massive have the capability to store more strain energy than rock masses that are deformable, weak and structured.

Curraghinalt Geotechnical Environment

For the Curraghinalt sub-surface geotechnical assessment, MineGeoTech have defined the geotechnical environment through data collection and analysis. This included:

- Establishing geotechnical domains (lithological units that have different mechanical behaviours)
- Rock property testing to define the strength variance of these domains
- Establishing and defining the structural environment – defining both the minor (rock fabric) and major fault within the project area
- Define local stress conditions by undertaking stress measurements

The investigation into the geotechnical environment concluded:

- The rock mass is not massive but structured comprising of five joint sets resulting in a blocky rock mass
- A weathered zone of a high degree of fracturing exists up to 50m below the surface
- The strength of the rock mass varies from very weak to strong.
- Rock mass failure will be a result of weak rock mass and gravity block failure
- Minor and major shears have the capacity to slip due to clay infill and smooth surfaces

Numerical modelling was completed as part of the study to identify rock mass damage and potential subsidence associated with the extraction. Several sensitivities were undertaken to investigate variances (encapsulating volume and strength) that impact potential subsidence. The numerical model revealed that the rock mass can easily deform, meaning the system cannot store enough energy to induce a large earthquake on an existing regional fault.

Mining induced micro-seismicity is expected at the Curraghinalt project. However, the magnitudes are expected to be small. This is due to:

- Narrow veins
- Rock mass is dominated by weak and structured material
- Production blasts will be small
- Voids are designed to minimise dilution and will be backfilled once mined
- Backfill of voids – provides confinement reducing the rock mass response to mining.

Production blasting undertaken during the trial stoping at Curraghinalt in 2016 was not detected by the Irish National Seismic Network (<https://www.insn.ie/events/automatic-insn-detections-all/>) which covers Northern Ireland. Figure 5 shows the data set which starts in August 2014. Quarry blasts are shown on the left-hand as light green circles. The production blasts and stopes of the three trial stoping were at the same scale as what will be used during normal production.

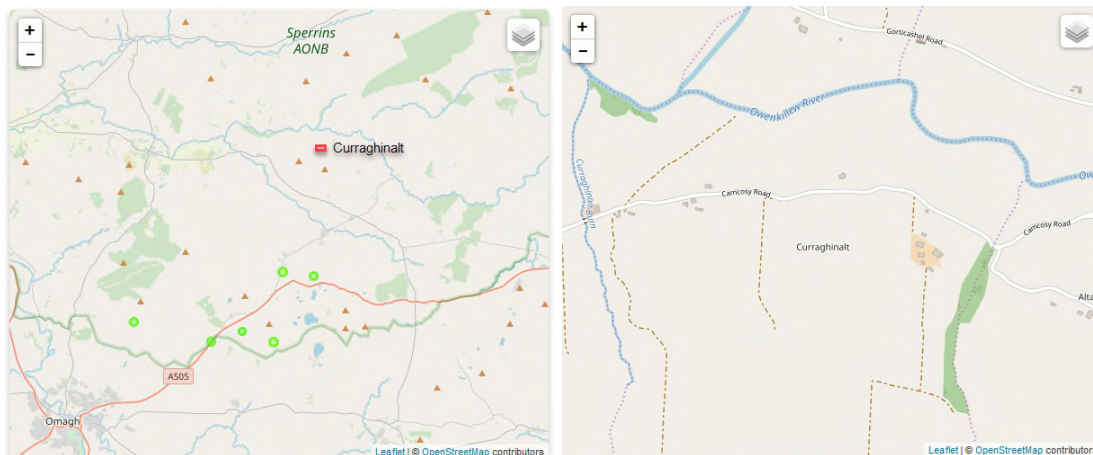


Figure 5 Seismic Events around Curraghinalt INSN.

Klerksdorp Mining Induced Seismic Event

The very large mining induced seismic event sited at Klerksdorp required a significant volume of brittle, strong and massive rock mass with widely separated significant natural faults with offsets (100's of meters) and no backfill placed following the mining of the stopes. This allowed the “build-up” of strain energy on the natural faults and a large redistribution of the natural earth stress.

The Klerksdorp mining district involved the mining of a single reef, over 260km², in extent that had been offset by multiple regional scale faults (Glazer, 2018). Multiple companies were mining the one orebody without a collective approach to the management of the strain energy “build-up” and the resultant rock mass failure. In comparison, Curraghinalt is less than 1% of the area of the

Klerksdorp district and will be mined and voids back filled. This is therefore not a reasonable comparison because of the factors set out above. The potential for mining induced seismicity will be actively monitored.

Potential Earthquakes from Surface Infrastructure

Large reservoirs and dams can induce earthquake by additional loading weight from the water and change in stress state on faults due to change in ground water pore pressure (weight and volume). This increases as the reservoir is filled and can trigger an earthquake. If a dam setting naturally has the potential for a large earthquake (and sometimes they do because these have topography's that also provide large suitable catchment areas, Appendix A) it can be activated.

This was the case for the Koyna Dam located in the mountainous area of Western India. During the 3 years the reservoir was being filled, more than 100 earthquakes between a magnitude of 1.5 to 3.5 were recorded, including two large events of 5.0 and 5.5 occurred months before the 6.5 event (Chopra and Chakrabarti, 1973).

The Koyna Dam has a significant reservoir and dam wall situated in a mountainous valley with a complex interlocking fault system. Seismic activity shows annual changes with the rising and falling of the dam levels with seasonal rain fall and water release. This cycle is related to the changes in load from the weight of the water changing the slip potential of faults, (Pandey and Chadha, 2003, Arora et al 2018). The Koyna Dam surface area is 892 km², the reservoir capacity is 105 TMC which equals 2,971.5 million cubic meters of water. This is a loading of 2,797 million tonnes (50km long x 80m average depth).

The surface infrastructure which has raised public concern at Curraghinalt project is the dry stack (filtered) tailings storage. The volume of the dry stack tailings is 4.8 million cubic meters, this is 7.7 million tonnes of material over an area of 0.28 km² (28 hectares). The loading and environment between the Koyna Dam and the Curraghinalt dry stack are substantially different. There is no excavation of the bed rock and no storage of water in the facility. This is therefore not a reasonable comparison because of the factors set out above. The construction of the all infrastructure is designed to comply with all required earthquake design parameters and regulations.

Risk Mitigation

The mitigation strategy to reduce the potential for seismicity at Curraghinalt includes:

- Backfill of voids – provides confinement reducing the rock mass response to mining.
- Data validation during mining – validate the geotechnical environment
- Correlation of numerical models – use validated data to model actual conditions and improve forecasts
- Underground seismic monitoring system –database of micro-seismicity to monitor seismic sources and for model calibration of rock mass damage
- Surface survey monitoring – measure the surface displacements to correlate and improve model forecast for adjustments to the mine plan
- Surface vibration monitoring system – monitor surface vibrations being felt from underground blasting and micro-seismicity

The objective is to validate and calibrate data (feedback loop) used in the mining study to refine mining extraction strategies that is appropriate for the project environment.

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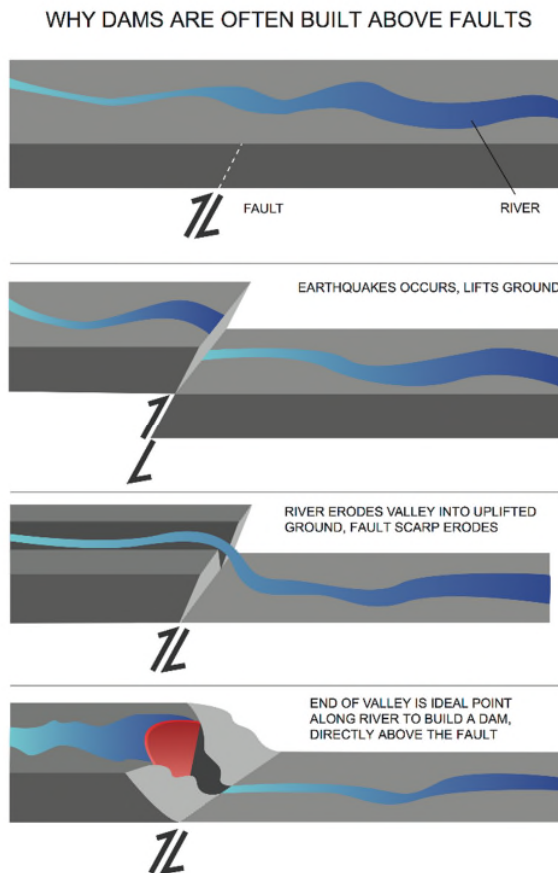
Appendix A - Dams & Earthquakes

<https://www.src.com.au/earthquakes/seismology-101/dams-earthquakes/>

People involved in the design, construction and operation of large dams are normally particularly sensitive to earthquakes.

This is because of four factors:

- Dams are often built in active earthquake areas
- Reservoirs can trigger earthquakes
- Some water supply structures are susceptible to earthquake motion.
Embankments and outlet towers respond to earthquake vibrations. Shaking an unstable slope that has been weakened after saturation by rises in ground water levels may produce a landslide into the reservoir.
- The consequence of a dam or water supply failure is high.
The effects of a dam failure on people and structures downstream are dramatic and obvious. A more likely example of earthquake damage would be loss of control of the water supply.



Why are Dams Often Built in Active Earthquake Areas?

- Dams are usually built in valleys
- Valleys exist because active erosion is taking place
- Active erosion implies there has been recent uplift
- Under compressional tectonic force, reverse or thrust faults produce uplift
- Reverse or thrust faults dip under the up thrown block
- Therefore, many dams have an active fault dipping under them

Reservoir Triggered Earthquakes

Large new reservoirs can trigger earthquakes. This is due to either:

- change in stress because of the weight of water, or more commonly by
- increased groundwater pore pressure decreasing the effective strength of the rock under the reservoir.

For triggered earthquakes to occur, both mechanisms require that the area is already under considerable tectonic stress.

Reservoir triggered earthquakes are often referred to as reservoir induced seismicity (RIS), but use of the term “induced” is now becoming unfashionable. To many people it implies that the reservoir caused the earthquake. The energy released in a reservoir triggered earthquake is normal tectonic strain energy that has been prematurely released because of the reservoir.

Water Pore Pressure

Ground water plays a large part in earthquake activity. Fluid injection into wells in USA, Japan and elsewhere has triggered small earthquakes.

Water pore pressure reduces the normal stress within a rock while not changing the shear stress. Under any circumstances, an increase in water pore pressure means that a failure is more likely. The critical value of shearing stress may be made arbitrarily low by increasing the pore pressure.

Pore pressure can increase in two ways:

- Due to the decrease in pore volume caused by compaction under the weight of the reservoir. This occurs while the reservoir is being filled.
- Due to diffusion of reservoir water through permeable rock under the reservoir. The rate of flow depends on the permeability of the rock, so this effect is not instantaneous. The increase in pore pressure takes more time depending on the distance from the reservoir. It may take years for the pore pressure to increase at depths of kilometres beneath a reservoir.

Examples of Reservoir Triggered Earthquakes

World

- Koyna, India, 1967, M 6.7
- Xinfengjiang, China, 1962, M 6.2

Australia

- Warragamba, NSW, 1973, ML 5.5
- Thomson, Victoria, 1996, ML 5.1

Duration of Reservoir Triggered Seismicity

Reservoir induced seismicity is a transitory phenomenon which will occur either immediately after filling of the reservoir, or after a delay of a few years. If there is a delay, this depends on the permeability of the rock beneath the reservoir.

Once stress and pore pressure fields have stabilised at new values, reservoir induced seismicity will cease. Earthquake hazard will then revert to similar levels that would have existed if the reservoir had not been filled.

Even for those reservoirs that show a correlation between earthquake activity and water level, reservoir induced seismicity does not continue indefinitely as it is limited by the available tectonic energy.

Depth of Reservoir Triggered Seismicity

Depths of reservoir induced earthquakes, especially those occurring immediately after filling of the reservoir, are normally very shallow. If detailed seismograph coverage is available, then depths within one to three kilometres of the surface are common.

Induced earthquakes at reservoirs that have experienced delayed triggering may be much deeper, perhaps as deep as ten to twenty kilometres. These may occur ten to twenty years after filling of the reservoir.

Prediction of Reservoir Triggered Seismicity

It is not easy to predict whether a new reservoir will experience reservoir induced seismicity, because the two most important factors – the state of stress and the rock strength at earthquake depths – cannot be measured directly.

This is the same reason why prediction of normal (non-induced) earthquakes is normally unsuccessful