MINE SUBSIDENCE ASSESSMENTS AND REVIEW OF SELECTED GROUTING REMEDIATION PROJECTS IN THE NEWCASTLE AREA

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ABSTRACT

Widespread mining has been undertaken beneath developed areas of Newcastle and it's surrounds since the early 1800s, and continues to the present day.

Local geotechnical consultants are regularly asked to assess the risk of mine subsidence for proposed developments, and to provide 'worst credible case' subsidence parameters in the event of a future subsidence event. Where the risk of subsidence is considered too high for the proposed structure, ground improvement is usually adopted which includes remedial grouting works, in order to limit the risk of future subsidence to acceptable levels.

The uncertainties associated with grouting of the old mine workings beneath sites in and around Newcastle has in the past been seen as a big risk for prospective developers, with the potential for expensive overruns associated with grout volumes making them reluctant to commit to developments underlain by mine workings. The introduction of a Government backed Newcastle Mines Grouting Fund has now provided a safety net to developers in the event that grout costs are more than anticipated. This safety net has provided developers and financiers more confidence to proceed with developments, but the need to understand the likely quantities of grout required to remediate sites continues to be an important consideration for both Government and developers alike.

This paper presents data for numerous local projects where remedial grouting works have been undertaken for large developments. Common methods of investigation and assessment of the condition of the mine workings are discussed. The focus of the paper, however, was to compare the volume of grout required to remediate selected projects with knowledge of the mine conditions to develop an empirical approach to evaluate the quantities of grout for future projects in the Newcastle Coalfields.

1 INTRODUCTION

1.1 LOCAL MINING HISTORY AND GEOLOGY

Underground coal mining began in Newcastle in the early 1800s when coal was taken from workings in the Dudley Seam in the vicinity of Fort Scratchley, where coal was exposed in the nearby sea cliffs. Further coal mining development rapidly ensued; in the early to mid-1800s the Australian Agricultural Company (AA Co.) began exploration and shaft sinking in the inner Newcastle area, and mining also propagated to surrounding areas of the coalfield (Gregson, 1907). Mining in the Newcastle Coalfield continues to the present day.

The old mine workings in the Newcastle area are commonly of 'bord and pillar' methods. Parallel roadways (bords) were mined through the seam at regular intervals, and coal was left in place between the bords to support the overlying soil and rock. The bords are generally connected via 'cut-throughs' or 'headings', forming the remaining coal supports into a series of pillars.

The stratigraphy of the Newcastle Coalfield consists of three Permian aged coal measures sequences; the Greta Coal Measures, Tomago Coal Measures, and the overlying Newcastle Coal Measures. Within each of these three coal measures there are numerous coal seams which have been subject to mining. The thickness of the mined seams ranges from less than one metre, to over 10 metres (Hawley and Brunton, 1995).

1.2 REMEDIATION OF OLD MINES AROUND NEWCASTLE

As more development takes place in the Newcastle region, including high rise development in the CBD area, and residential and infrastructure projects on previously undeveloped land, there is a need to understand the risk that previous mining operations beneath these sites pose to the proposed developments. Where the level of risk is assessed to be too high, remedial options are required to reduce the risks to acceptable levels such that development can proceed.

Options to manage mine subsidence risks for developments can include structural design to accommodate the effects of future subsidence and / or ground improvement of the site to reduce the risk and effects of future subsidence. The adopted approach in the Newcastle area is commonly a combination of the two.

The two commonly adopted approaches to remediate sites which are affected by mining are:

- Earthworks – where shallow mining is present (typically less than 10 m), earthworks can be an economical option to reduce the mine subsidence risk. Overburden material is removed down to mine level (refer Figure 1), and material is then re-placed and compacted in layers back to the design level;
- Grouting – where the mine workings are too deep, or site conditions (such as adjacent developments) make it impractical to undertake earthworks, grouting of the old mine workings is commonly undertaken (refer Figure 2). This option is the focus of this paper.

Figure 1: Earthworks remediation of shallow mining to the west of Newcastle. Note the undulations in upper seams in cut batters due to subsidence, and remnant coal pillars exposed in the floor of the excavation

Figure 2: Grout plant set up in Newcastle CBD, with downhole camera being deployed in to a bore to assess the grouting operations

1.3 GROUT FUND

The Newcastle Mines Grouting Fund was established by the NSW Government in 2015 as a means to improve the confidence of developers who are proposing to build over areas which have previously been undermined. The fund was set up as a way of capping the amount that developers pay to grout their sites. The NSW Government provides the funding while the Hunter Development Corporation administers the Fund.

Developers pay the full cost of grouting up to a capped cost, which varies depending on the location of their site within the Newcastle inner city. If the actual cost of grouting exceeds the specified cap, then the Grout Fund pays for any extra approved costs.

It is therefore important for both the developer and the administrators of the Grout Fund to understand the likely grout volumes which will be required to remediate a site, in order to understand their potential costs.

2 RISK ASSESSMENT AND SITE CHARACTERISATION

Assessment of mine subsidence risk is usually undertaken as a staged approach, which generally includes a desktop assessment, followed by intrusive investigation.

2.1 DESKTOP ASSESSMENT

The desktop assessment will usually involve:

- A review of the plans of the historical mine workings (called Record Traces or RTs), other historical documents, as well as data from relevant previous projects;
- Pillar stability analysis for mapped coal pillars beneath the site and within the 'angle of draw' of the proposed development site boundaries. In the Newcastle Coalfields the angle of draw, which is the zone which could theoretically be affected by subsidence from a failed pillar, is typically taken as 2V:1H, extending upwards from the old mine workings;
- Comment on the pillar stability and the likelihood of mine subsidence affecting the site; and
- Comment on the subsidence parameters (strains, tilts and curvatures) which could occur from a hypothetical 'credible worst case' subsidence event.

RTs which were prepared by mine surveyors provide the only record of the position of the mine workings. These records have at times proven to be incomplete or may not represent the actual conditions of the workings. Furthermore, depending on the mining era, survey techniques may not have been as accurate as present day methods, and plan locations of mining can be inaccurate. Experience in the Newcastle CBD is that the RTs are generally a reasonable representation of the conditions at mine level, however there are local anomalies. An example is shown in Figure 3(ii), where it can be seen that the measured location of the mine workings (which were measured by downhole sonar profiling) were found to actually be about one mined roadway (bord) width towards the south east compared to the historical mapping.

Pillar stability analysis is typically undertaken based on methods developed by UNSW (Galvin et al, 1998). The formulae are founded primarily on an empirical approach based on broad databases of previous mining experience both locally and overseas. The method is a standard approach to assess the factors of safety (and probability of failure) of pillars in the Newcastle area.

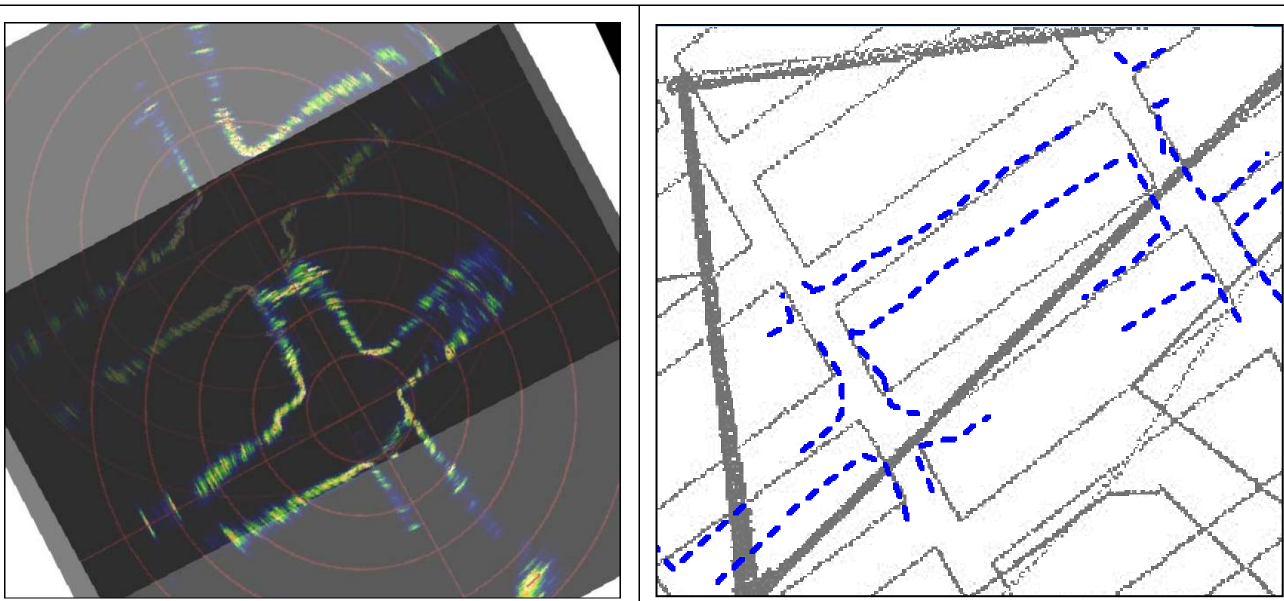
2.2 SITE INVESTIGATION AND REMEDIATION

Depending on the outcome of the desktop assessment, site investigation is often needed in order to characterise the site conditions, to better assess the level of risk. Investigation is also very useful to inform the design of any subsequent remedial grouting works, if it is likely to be required.

There are various downhole tools that are adopted in order to assess the geotechnical conditions, and the properties of the mine workings. These include:

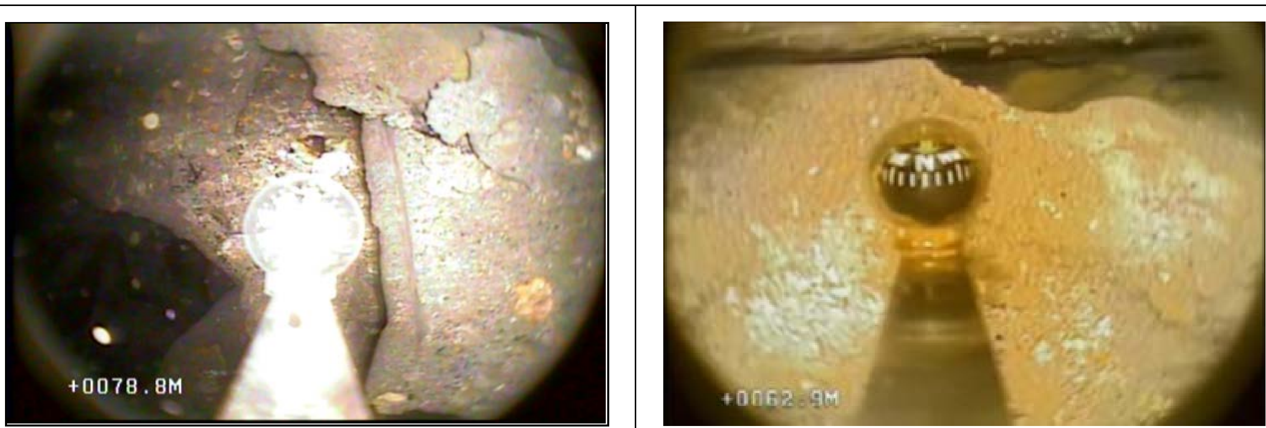
- Investigation drilling, to assess overburden and mine conditions, including depth of mining, presence of voids and rubble, and mining induced fracturing within the overlying rock mass;
- Downhole geophysics;
- Downhole CCTV camera with tilt up and pan capabilities;
- Downhole sonar and laser range finder; and
- In recent times, 3D scanning of the remnant void is also being employed as indicated by Johnson et al. (2018).

Some examples of the output of these techniques are shown in Figures 3 and 4 below.



(i) (ii)

Figure 3: (i) Superimposed sonar images of mined roadways (bords) within Borehole seam workings beneath Newcastle (ii) Inferred mining layout from georeferenced sonar images (blue lines) compared to historical mapping



(i) (ii)

Figure 4: Downhole CCTV camera images showing (i) rubble (collapsed mine roof) on the floor of abandoned mine workings, and (ii) grout in contact with the roof of mine workings

3 CASE STUDIES OF GROUTING PROJECTS

As discussed above, a realistic estimate of likely grout volumes that will be required to remediate a site is needed in the early planning stages of projects, in order for developers (as well as the administrators of the Grout Fund for projects in the Newcastle CBD) to understand their likely costs and risks. There is often little known about the specific mining conditions beneath a site in the early project stages, apart from a desktop assessment and a limited geotechnical investigation, which may not have extended to the depth of mining. For this reason, reliance is often placed on the previous experience of consultants and contractors in terms of knowledge of the likely mine conditions, and grout takes for previous similar sites.

A review of numerous previous grouting remediation projects in the Newcastle area has been undertaken, in order to compare the various site and mining conditions in relation to the volumes of grout required to remediate the sites.

For the purposes of comparison, sites were split in to two categories:

- ‘Mass Filled’ sites: these are sites where grouting has been undertaken on a systematic grid, with bores typically filled with grout to refusal. Generally this technique has been used on sites around Newcastle where workings are at depths of less than about 40 m;
- ‘Targeted Grouting’ sites: on these sites, grouting has been undertaken in targeted bords only, in order to increase the strength of existing pillars and reduce subsidence to acceptable levels. The vast majority of targeted grouting in the Newcastle area has been undertaken in the Borehole seam.

3.1 MASS FILLED SITES

Five separate projects, comprising a total of 2177 bores, were reviewed where mass filling grouting works have been undertaken. The sites were separated based on the assessed conditions within the mined seams, as follows:

- “Goafed”: either the mine has collapsed due to removal of the majority of pillars that supported the mine, or alternatively pillar failure or roof collapse has occurred, causing the mined coal seam to become filled with soil and / or rock; i.e. no evidence of significant voids encountered during drilling;
- “Partially Goafed”: conditions include predominantly open rubble within the mined coal seam with <50% of bores encountering standing voids during drilling;
- “Open”: more than 50% of bores encountered standing voids. Note that no such “open” conditions were present within the mass filling projects that were reviewed.

A summary of this data is presented in Table 1.

Table 1: Summary of Mass Filled Site Data

Site	Seam	Estimated Working Section (m)	Condition of workings	Grid spacing (m)	No. of bores	No. of bores that intersected mine / void	Approx Area to be Grouted (m^2)	Avg. Depth of Bores (m)	Total Grout Volume (m^3)	Avg. Grout Take (m^3/ bore)	Avg. Grout across Target Area (m^3/m^2)
1A	Tomago	2	Fully Goafed	3	420	184	3316	10.7	311.6	0.74	0.09
1B	Tomago	2	Fully Goafed	3	111	43	853	10.9	52.5	0.47	0.06
1C	Tomago	2	Fully Goafed	3	115	76	967	14.7	324.8	2.82	0.34
1D	Tomago	2	Fully Goafed	3	53	36	504	14	107.4	2.03	0.21
1E	Tomago	2	Fully Goafed	3	25	5	263	14.6	9.8	0.39	0.04
2A	Tomago	2	Fully Goafed	3	68	2	532	9.4	30.9	0.45	0.06
2B	Tomago	2	Fully Goafed	3	69	40	520	13.5	49.4	0.72	0.09
2C	Tomago	2	Fully Goafed	3	45	0	315	10.7	4.2	0.09	0.01
2D	Tomago	2	Fully Goafed	3	59	19	421	14	30.1	0.51	0.07
3	Borehole	2.2	Fully Goafed	4	63	63	1200	13.0	30.0	0.48	0.03
Totals – Fully Goafed Workings					**1752**	**812**	**14794**		**1756.8**	**1.0**	**0.12**
4A	Australasian	2	Partially Goafed	2.5-12	89	89	3460	37	1893	21.27	0.55
4B	Australasian	2	Partially Goafed	3.0-6.0	59	59	1512	33	1152	19.53	0.76
5	Greta Top Seam	4	Partially Goafed	3	129	74	2000	12	882	6.84	0.44
Totals - Partially Goafed Workings					**425**	**370**	**11944**		**6972**	**16.4**	**0.58**

Figure 4 shows a frequency distribution of grout takes per bore, for the 930 bores for which this data was available (comprising 786 "fully goafed" site bores and 144 "partially goafed" site bores). The data is divided into "fully goafed" and "partially goafed" sites for comparison purposes.

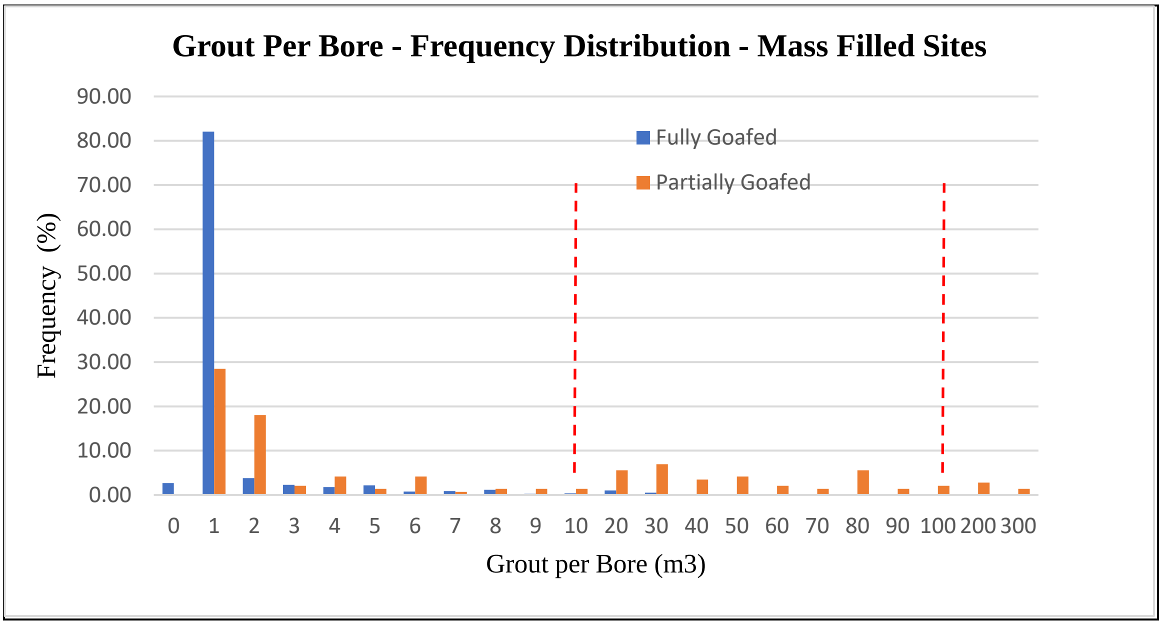


Figure 4: Frequencies of grout take per bore as a percentage of the total number of bores – mass filled sites

Figure 4 shows that the frequency of certain ranges of grout takes varies significantly between "fully goafed" and "partially goafed" sites. For "fully goafed" sites, over 80% of the grout takes are in the range of 1 m^3 to 2 m^3, compared to less than 30% for the "partially goafed" sites, however grout takes of greater than 20 m^3 can be seen to be much more prevalent within bores on the "partially goafed" sites.

From Table 1 it can be seen that, on average, the grout take across sites that were assessed to be "fully goafed" was less than 25% of the average grout take on the "partially goafed" sites.

Figure 5 shows the total grout take per site, plotted against site area.

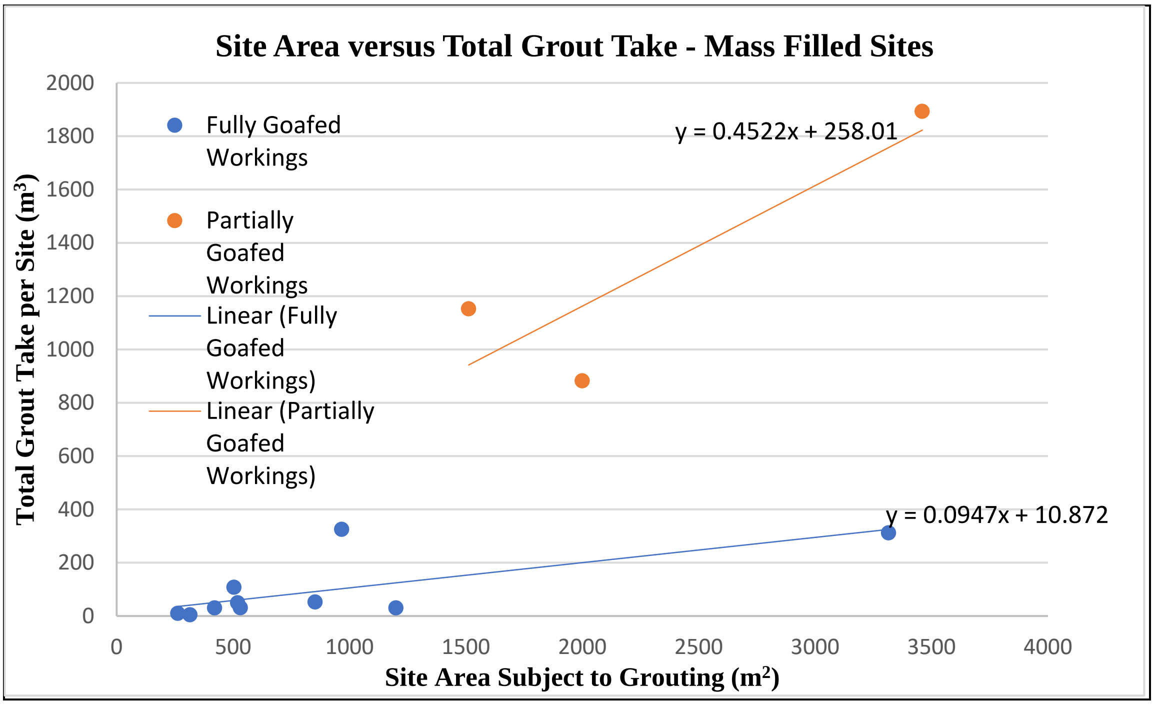


Figure 5: Site area subject to grouting versus total grout take – mass filled sites

From Figure 5, it can be seen that a rough linear relationship exists between the site area and total grout take for both "fully goafed" and "partially goafed" sites, for the data reviewed.

3.2 TARGETED GROUTING SITES - BOREHOLE SEAM

Seven projects were reviewed where targeted grouting has been undertaken in the Borehole Seam mine workings, in Newcastle's inner city area.

It is noted that the remediation grouting design 'intent' did vary between some of the sites reviewed. For example, at some sites the intent was to grout to the top of the Borehole Seam, and for others it was to grout to the top of the observed void (which could extend some distance above the coal seam, due to collapse of the roof of the mine).

During the review, it was apparent that, regardless of the original design intent, projects which were only required to fill to the top of the coal seam generally exceeded this height. The main reason for this is that grout will slope away at a certain angle from the injection point with typical recorded angles in the range of about 4H:1V to 6H:1V subject to the grout mix. Therefore, in order to satisfy the design intent (e.g. filling to the top of the coal seam), it is necessary to over-fill at the injection points, to ensure that the design intent is still satisfied at the limits of the target area which is being grouted. This is illustrated in Figure 6 below.

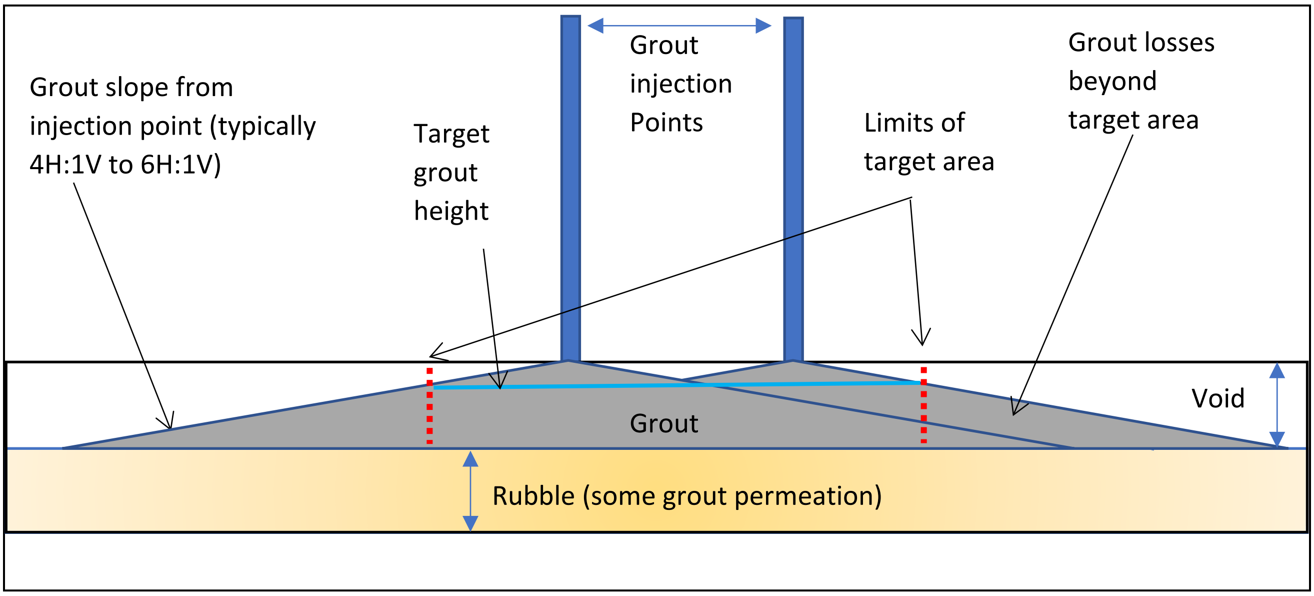


Figure 6: Schematic of typical grout delivery to a target area

For simplicity of comparison, it was assumed that the majority of the remnant void was filled by grout, which represents the majority of targeted grout areas on the projects reviewed.

3.2.1 Borehole Seam - Background

Extensive workings are present in the Borehole Seam across a large part of Newcastle. The depth to the workings is typically in the range of about 50 m to 80 m in the eastern parts of the city (near the coast), and the seam generally rises towards the west, being present at less than 20 m depth over large areas of Newcastle's western suburbs (note that Site 3 in Table 1 above relates to mass filling of Borehole Seam workings at less than 20 m depth).

Targeted grouting of Borehole Seam workings has to date been focused in and around the eastern parts of Newcastle, where high rise developments are constructed, and the workings are greater than 50 m below the surface.

Beneath the Newcastle CBD, where the vast majority of grouting projects have been completed, mining was undertaken by the Australian Agricultural Company (AA Co.) throughout the 19th and early 20th centuries. Reference to historical Record Trace documents for the AA Co. workings indicates that the Borehole seam thickness is typically about 6.2 m to 6.4 m in this area. Workings were typically undertaken in three stages (To, 1998). This is presented in Figure 7 below on a seam section taken from the historical RT.

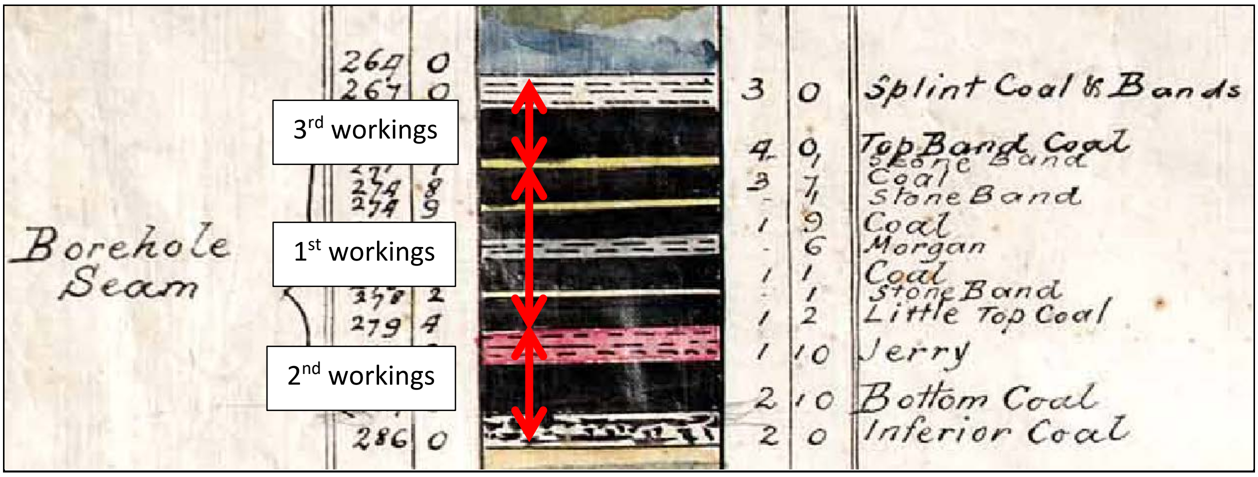


Figure 7: Section of Borehole seam from AA Co. workings (RT566), with typical stages of workings shown

Therefore the total working section ranged up to about 5.4 m, however in places only the 1st or 1st and 2nd workings were undertaken in which case the working section would be approximately 2.6 m or 4.2 m.

There is a history of instability in the Borehole Seam mine workings in The Hill area, which is situated immediately south of the Newcastle CBD. The previous instability is referred to as the First, Second and Third Creep events, and occurred between May 1906 and January 1908. Surface subsidence of up to 825 mm was reported during these events, with surface cracks of up to 75 mm width. Thrust from the hill and earth movement were also reported, and roads, pavements and buildings were damaged.

Information gained from the creep events described above have been used by engineers to better understand the risks presented by the Borehole Seam workings in Newcastle, as well as for estimating the effects of possible future subsidence if a similar event was to occur.

3.1.2 Data Review

A summary of the project data which was reviewed is presented in Table 2. The projects are identified as B1 to B7.

Table 2: Summary of Targeted Grouting Data by Project – Borehole Seam

Site ID	Mined Seam	Mined Thickness (Working Section) - best estimate (m)	Observed Rubble Thickness (m)	Observed Void Height (m)	Total Grout Take (m^3)	Total Target Area (m^2)	Grout Take / Target Area* (m^3/m^2)
B1	Borehole	5.4	3.3-6.3	2.3-3.1	4473	450	9.9
B2		5.4	4.4-5.6	2.0-3.3	3907	445	8.8
B3		3.2	1.0-3.9	0.35-2.0	1907	780	2.4
B4		5	1.0-5.0	1.0-3.0	4343	1132	3.8
B5		5.3	3.0-5.2	1.95-3.25	8740	1215	7.2
B6		5.4	0.7-6.6	0.3-3.9	10821	1476	7.3
B7		5.4	3.0-6.6	1.0-3.5	8414	1941	4.3
Totals					42605	7439	5.7

Notes to Table 2: *Based on total quantity used for the project

From Table 2 it can be seen that the observed rubble thickness and void height within all of the bores for which data had been recorded was highly variable, even for individual project sites. Accordingly, it is expected that empirical estimations of grout take based on assumed rubble and corresponding void heights is difficult, given this data is often not known in any detail until well into the grouting process (i.e. when drilling and downhole CCTV / sonar / geophysics has all been completed).

The overall grout take divided by the target area, per project, was found to range from approximately 2.4 m^3/m^2 to 9.9 m^3/m^2. The variability was found to be reduced when it was normalised based on a best estimate of the mined height (working section) of the seam at the site location. This is explored in some more detail below.

Figure 8 shows a frequency distribution of grout take per bore, for the 156 bores drilled and grouted across the seven Borehole Seam project sites.

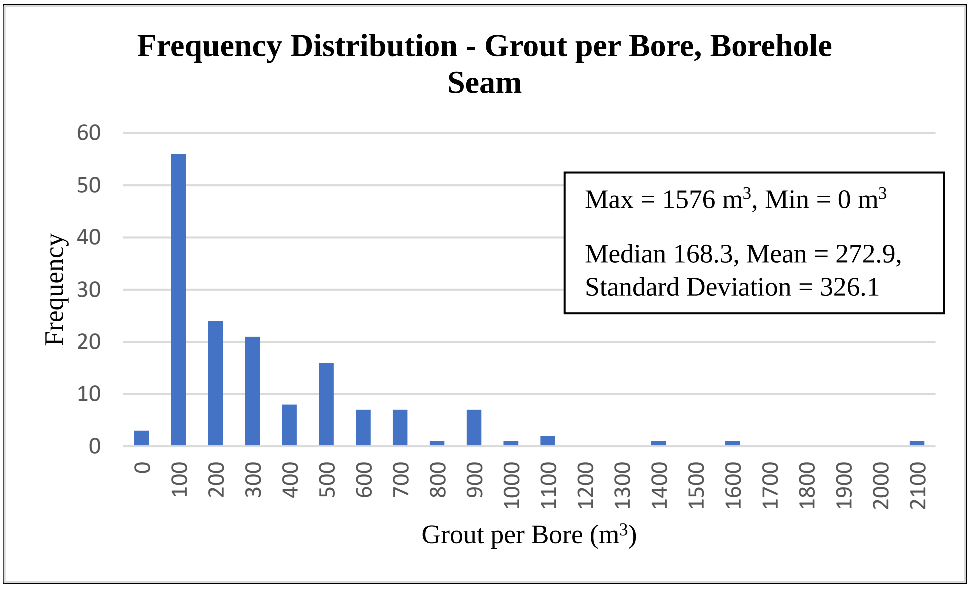


Figure 8: Site area subject to grouting versus total grout take – targeted grouting sites

From Figure 8 it can be seen that there is a large range of recorded grout takes from bores drilled to the Borehole seam workings, ranging from 0 m^3 to 2100 m^3. Of the 156 bores reviewed, 59 (38%) had grout takes of less than 100 m^3, and 82% had grout takes of less than 500 m^3.

It is noted that the grout take in a bore is highly dependent on the stage that the bore is grouted within a project. Because grout can flow within the old mine workings, some areas of the mine may be filled at a significant distance from the injection point.

Figure 9 presents the total grout take per site, normalised by the estimated working section, plotted against the total plan area of the target grout zones for each project.

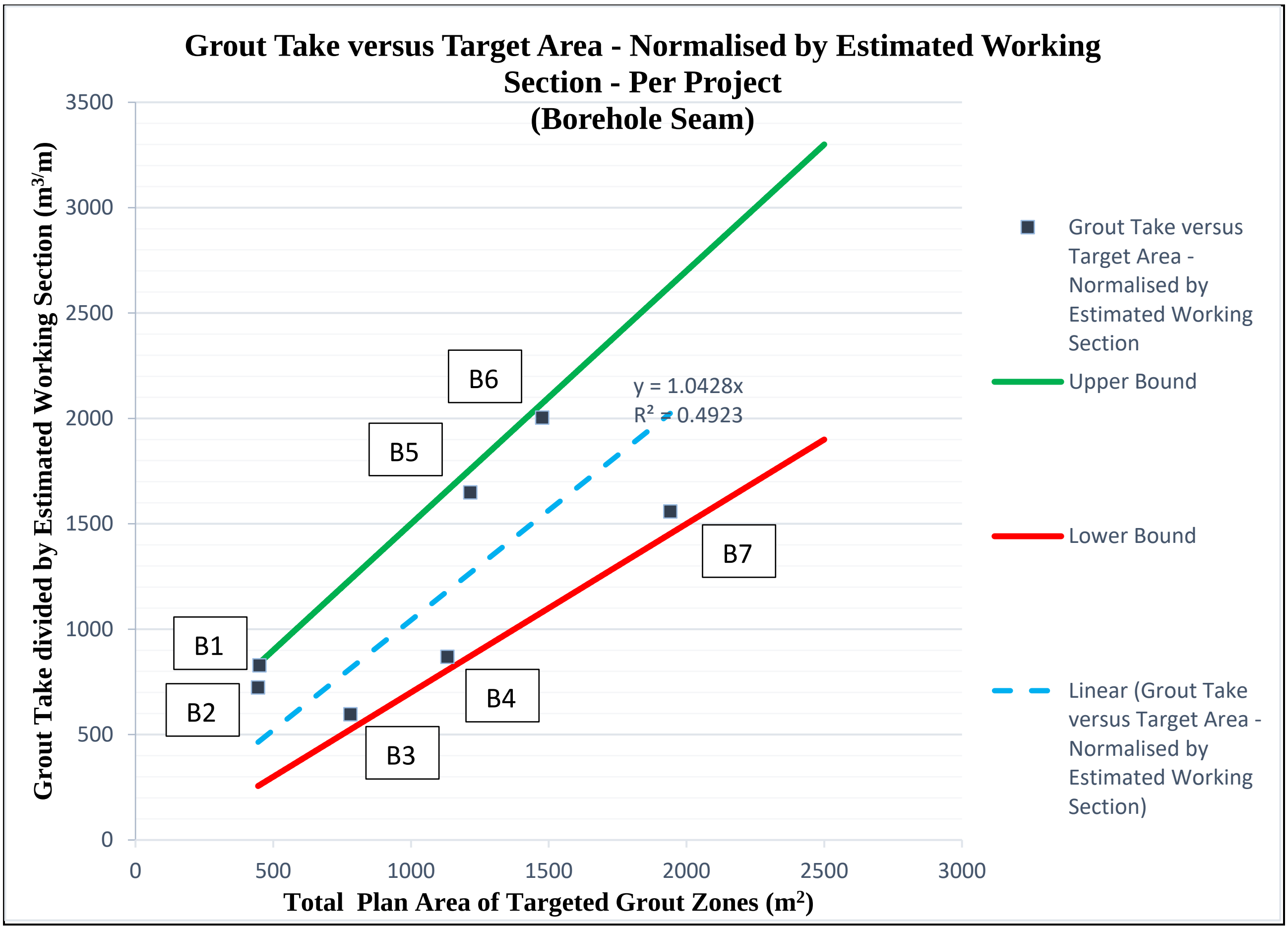


Figure 9: Target area verses grout take, normalised by estimated working section – Borehole seam

Figure 9 presents a reasonable relationship between the target plan area of the zones to be grouted, and the actual grout take, when it is normalised by the working section. The data also shows the typical upper bound and lower bound grout take values for a given target area.

From above, it can be seen that the average grout take for the Borehole Seam workings can be approximated by estimating the actual mined volume within the target grout zones (i.e. the target plan area multiplied by the mined height).

The variance between the actual grout take, and that which is approximated by estimating the mined volume within the target areas as described above, is largest for sites B1 and B2. At these sites, the target grout zones were located immediately adjacent to large intersections in the mine, which is expected to have resulted in large overall grout losses beyond the target area relative to the small site areas. Similarly, site B6 is expected to have lost large quantities of grout in to adjacent intersections – one bore alone at this site took 2100 m^3 of grout adjacent to a mapped intersection.

Based on the information presented above, it is suggested that a practical method to estimate the likely grout take in Borehole Seam workings would be as follows:

- Use Figure 9 as an initial guide as to a likely ‘average’ value of grout take per plan area of the target zone;
- If the target grout areas are in close proximity to large mine intersections, or the site is known to contain large open voids, the upper bound limit could be adopted; alternatively
- Where less voids / more rubble is present, or the target areas are away from mine intersections, or the site is in close proximity to other grout areas where grouting zones may interact, the lower bound could be adopted.

While it would be theoretically possible to incorporate more variables into the estimation of likely grout takes, and losses beyond the target areas, including quantifying the number / size of adjacent intersections, void thicknesses etc., the results of this data review indicate that there is too much uncertainty in the input parameters to be of any practical value in providing a more accurate estimation of grout take.

4 CONCLUSIONS

A review of numerous mine grouting remediation projects has been undertaken for sites in the Newcastle area. The sites were split in to ‘mass filled’ sites, where grouting had been undertaken on a systematic grid, and ‘targeted grouting’ sites in Borehole Seam workings, where grouting had been undertaken in targeted locations only.

For ‘mass filled’ sites, the results of the data review indicate that while there was a large range of grout takes per bore, on average, the grout take across sites that were assessed to be “fully goafed” was less than 25% of the average grout take on the “partially goafed” sites. The data highlights the importance of having quality geotechnical investigation data in the early planning stages, in order to be able to provide more accurate estimates of likely grout volumes, based on the observed ground conditions.

For the ‘targeted grouting’ sites reviewed, it was found that when the estimated mining height (i.e. working section) was taken into account, there was reasonable relationship between the area of the target grout zones, and grout take, although there is significant variability between the upper and lower bound values.

From the reviewed ‘targeted grouting’ data, it appears that calculating the ‘mined volume’ within the areas which are targeted for grouting (i.e. how much total volume was removed from the ground at the target location) provides a reasonable estimate of the likely ‘average’ grout take for Borehole Seam workings. It is suggested that the ‘average’ value could be used as a basis for grout estimates, and the likelihood of a specific site being biased towards the upper or lower bound estimates could be based on additional site specific data such as proximity of target zones to mine intersections, the presence of larger / open voids, and proximity to other grout areas.

5 ACKNOWLEDGEMENTS

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