Relationships between grout takes and drilling parameters for compaction grouting

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ABSTRACT: Ground improvement in the form of compaction grouting was used to remediate a sinkhole and strengthen the foundation of the highway in close proximity to the sinkhole in the province of Gauteng, South Africa. This paper presents an analysis on the data from the first phase of compaction grouting for the project which was conducted over a section of the highway covering an area of approximately 3 000 m^2. The relationship between drilling parameters and grout take is explored in this paper for primary, secondary and tertiary boreholes. The characteristics of boreholes which took very high and very low volumes of grout are also studied in an attempt to find indications from drilling data that allude to either high or low grout takes.

1 INTRODUCTION

Compaction grouting is a form of ground improvement in which grout is injected into the ground in stages to displace and compact weak soils. In dolomitic areas it is often used for purposes of void filling. Compaction grouting can be completed in a downstage manner (grouting performed from the top down) or an upstage (grouting performed from the bottom up) manner. Upstage grouting involves installation of a casing or grout pipe to a desired depth, followed by injection of grout under pressure in stages as the grout pipe is lifted (Bell & Kirsch 2013). Grout injection continues until set pressure or grout volume cut-offs are reached. Once these are reached, the casing is moved upwards, and the next stage commences.

Compaction grouting is usually conducted in a specific sequence, with initial holes grouted on a primary grid. Secondary holes are then completed in between the primary holes in areas where the primary grout takes were high. Tertiary holes can be completed if necessary.

In South Africa, compaction grouting is a common form of ground improvement used to treat poor ground in dolomitic areas. Examples include ground improvement for the rehabilitation of sinkholes on the N14 highway near Carletonville, Gauteng. For the N14 sinkhole rehabilitation, grouting started on a primary grid with a 3.4 m by 3.4 m spacing. Secondary boreholes were completed in areas where primary grout take was high. The percentage of ground volume replacement or improvement (i.e., percentage of the treated volume of ground replaced with grout) for the N14 project was reported to be 3 %. The majority of boreholes on the N14 project had a grout take of less than 5 m^3 per borehole. Two boreholes had a higher grout take of more than 20 m^3 (Roux et al. 2013).

Compaction grouting was also used for foundation solution of some of the viaducts of South Africa's Gautrain which traverses dolomitic geology in certain areas.

In terms of ratios of volume replacement achieved using compaction grouting, different estimates are present in literature. Han (2015) reports that typical volume replacement is in the order of 5-15 %. Bell and Kirsch (2013) report grout injection volumes of 8-12 %.

Dolomitic geology is characterised by highly variable conditions; thus, the estimation of grout take is a challenge and has implications on the duration and cost of the project. Studying the relationship between the grout takes and the drilling parameters of compaction grouting boreholes could possibly provide more insight into when high grout takes are expected.

2 BACKGROUND

2.1 *Geology of the site*

The site area studied in this paper is underlain by the dolomitic geology of the Eccles Formation of the Malmani Subgroup. Brink (1985) characterises this formation as chert-rich dolomite, with chert content decreasing with depth. The ground profile observed on site comprised dolomitic bedrock at varying depths, overlain by a chert-rich dolomite residuum and an upper colluvial layer. Fill material was placed above the residual and colluvial materials to construct the highway.

2.2 *Ground improvement on the site*

Compaction grouting took place within an excavation at the sinkhole area, and beneath the road pavement in close proximity to the sinkhole. Section 3 of this paper focuses on data from compaction grouting conducted on a section of the roadway itself in which consistent grouting criteria, described in Section 2.3, were applied. This data is from compaction grouting completed on three outer lanes of the highway with a total treatment area of approximately 3 000 m^2. Additional lanes of the carriageway that were grouted at a later stage of the project and compaction grouting completed within the excavation had slightly different grouting criteria. The study in Section 4 of this paper makes use of all the compaction grouting data, as the focus in this section is only on boreholes with abnormally large or small grout takes.

2.3 *Project specific grouting criteria*

The project made use of upstage compaction grouting. Each stage length was 1 m. The grid spacing for primary grouting boreholes was 6 m by 6 m. A 6 m by 6 m grid was selected as this distance was deemed sufficient to prevent interaction between boreholes when two adjacent holes were being grouted simultaneously. Secondary boreholes were completed where necessary at a split spacing within the primary grid (i.e., 3 m by 3 m grid.) If secondary grouting boreholes showed no pressure buildup for consecutive stages or were not successful in treating the full depth of profile due to factors such as poor ground conditions, tertiary boreholes would then be specified. An indication of the grid layout is provided in Figure 1.

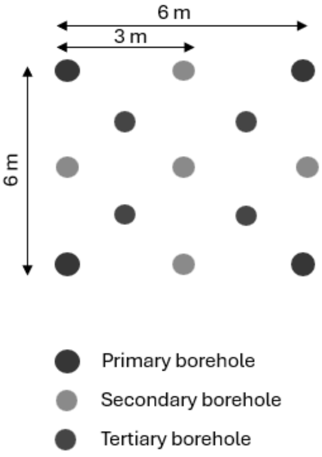

Figure 1. Grouting grid layout

The compaction grouting criteria specific to the project, such as drilling and grouting cut-offs are summarised in Table 1 for reference.

Table 1. Project specific compaction grouting criteria

Criteria	Value
Maximum drill depth (m)	40
Drill socket into rock – Primary holes (m)	4
Drill socket into rock – Secondary holes (m)	3
Grouting hole diameter (m)	0.114
Volume cutoff per meter (m^3)	5
Pressure cutoff per meter	1.5* Overburden

3 DRILLING PARAMETRS AND GROUT TAKES

This section presents an analysis on the drilling parameters for the grouting boreholes and the grout takes of the boreholes to quantify relationships between the borehole profile and the grout takes.

3.1 *Background on drilling parameters*

During the project duration, hard rock dolomite was considered to have been encountered at drill rates of 120 seconds per meter or more. Very soft, highly compressible wad, or possible cavities, were considered to be present when drill rates less than 10 seconds per meter were recorded.

The general guidelines presented in Table 2 relating drilling rates to the material consistency were considered in this paper.

These guidelines were based on correlating the drilling rates to visual geotechnical chip logging of sample retrieved during this project. The assumption for the low-density wad/cavity material is based on the fact that air losses and sample losses were prevalent for these drill rates less than 10 s/m.

Table 2. Drilling rates and the corresponding material consistency assumed.

Drilling rate (/m)	Material Type
≤ 10 s	Low density, highly compressible wad
11 s – 30 s	Soft material – dolomite residuum
31 – 90 s	Medium density material – dolomite residuum
91 s – 120 s	Soft to medium hard rock dolomite
> 120 s	Hard rock dolomite

3.2 *Data to be excluded from the analysis*

During compaction grouting, grouting of a borehole is terminated prematurely if complications arise. These boreholes were excluded from the data set. Causes for early termination of grouting were as follows:

- Ground heave: Ground heave in the trafficked roadway needed to be limited. Grouting of boreholes was terminated as soon as signs of heave (such as cracking and changes in the road level) became apparent.
- Blocked casing: When the grouting casing became blocked, and grouting could not proceed, the borehole was terminated.

- Grout breaching another borehole: Generally, the boreholes were grouted far enough apart for breaching of other open boreholes not to occur. However, on the rare occasion that grout breached another borehole, grouting was terminated.

3.3 *Overview of grouting operations*

Table 3 summarises some of the key results from the grouting completed on the section of highway with treatment area of approximately 3 000 m^2 as described in Section 2.2.

The reduction in grout take per meter from the primary to the secondary and tertiary boreholes indicates the effectiveness of the ground improvement. The increase in average drill rate per meter from the primary to the secondary and tertiary boreholes also alludes to the fact that the ground profile has become "denser" on average as the ground improvement exercise progressed.

Table 3. Borehole types and their project data.

Borehole	Primary	Secondary	Tertiary
Number of boreholes	83	188	69
Avg. hole depth (m)	35	32	33
Avg. grout take (m^3)	38	20	21
Avg. take/m (m^3)	1.1	0.63	0.65
Avg. drill rate (s/m)	46	54	57

Figure 2 below provides more detail on the different grout takes for the studied grouting phase. This indicates that the majority of excessive grout takes, greater than 50 m^3, occurred during grouting of the primary boreholes. The majority of secondary and tertiary boreholes had grout takes ranging from 0 – 30 m^3 and exhibited much fewer grout takes in excess of 50 m^3 in comparison to the primary grouting boreholes.

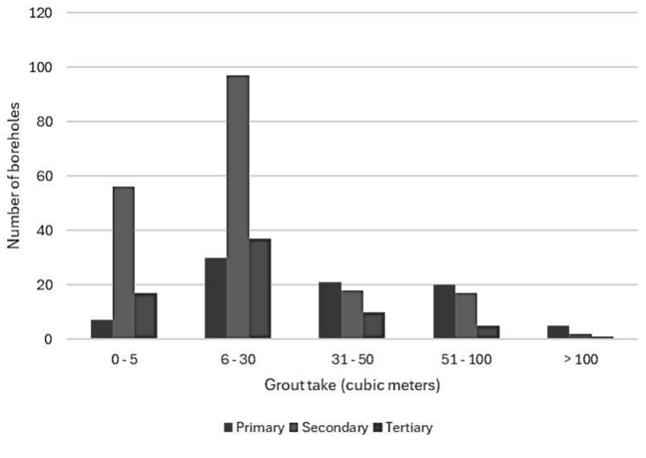

Figure 2. Summary of primary, secondary and tertiary grout takes.

3.4 *Correlations between drilling penetration rates and grout takes*

A borehole with a poorer drilling profile, and so a higher quantity of rapid penetration rates per meter, would be expected to have a larger grout take. If strong correlation is found between the drilling penetration rates and the grout take, penetration rates recorded during drilling of compaction grouting boreholes can provide an indication of expected grout quantities to be used, which can improve cost and program predictions for a project. To investigate this correlation and determine whether any reliable relationship between the drilling penetration rates and grout takes exist, the grout takes of primary, secondary and tertiary holes were compared to different groups of penetration rates. Data was split into data for primary, secondary and tertiary boreholes, as the improvement that already occurs during primary grouting affects the secondary and tertiary grouting results.

As an initial step in investigating the relationship between drilling penetration rates and grout takes, the number of meters of the drilling profile found to comprise material of various consistencies as per Table 2 was plotted against the grout take for primary, secondary and tertiary boreholes.

The coefficient of determination (R^2) of the linear relationship between the quantity of the profile comprising each material type (indicated by the number of meters of the associated drilling rate) versus the grout take, was taken as an indicator of the strength of correlation between the drilling penetration rates and grout volumes.

For drill rates up to 30 seconds per metre (s/m), weak positive correlations were seen. For drill rates between 30 and 120 s/m, no clear correlation was present and for drill rates greater than 120 s/m, a weak negative correlation was apparent.

Table 4. Coefficients of determination (R^2) for the number of meters of the drilling profile with certain penetration rates per meter vs grout takes.

Criteria	≤10s	11-30s	31-90s	91-120s	>120s
Primary	0.264	6E-05	0.0004	0.0064	0.057
Secondary	0.059	0.1103	0.0004	0.0002	0.0007
Tertiary	0.123	0.203	0.0012	0.0923	0.042

The highest coefficients of determination (R^2) (indicating the strongest linear correlations) in Table 4 were found in boreholes where rapid penetration rates occurred. Less clear relationships were present when studying slower penetration rates. Therefore, studying the relationship between the more rapid penetration rates and grout takes in more detail was deemed to be beneficial. Therefore, grouping the more rapid penetration rates into different categories was done for the primary, secondary and tertiary boreholes to determine which of these variables provided the most insight (highest correlation) to grout takes experienced.

Table 5 summarises the coefficients of determination for these groups of poorer drill rates studied. For the primary grouting holes, the number of meters of drilling in which rates were less than 4 s/m had the strongest correlation to the grout take. While for secondary and tertiary holes, the number of meters of the profile with drilling rates less than 30 seconds had better correlation to the grouting volumes. However, the correlation between the independent and dependent variable was still considered to be weak. Figures 3, 4 and 5 present the trend lines for the strongest relationship between drilling and grouting parameters for each category of borehole.

Table 5. Coefficients of determination (R^2) for groupings of the less dense drill rates vs grout takes.

Criteria	Primary	Secondary	Tertiary
≤ 3 s	0.270	0.082	0.166
≤ 4 s	***0.277***	0.063	0.162
≤ 5 s	0.268	0.05	0.130
≤ 10 s	0.264	0.059	0.123
≤ 20 s	0.215	0.110	0.251
≤ 30 s	0.177	***0.149***	***0.259***
≤ 40 s	0.159	0.124	0.242

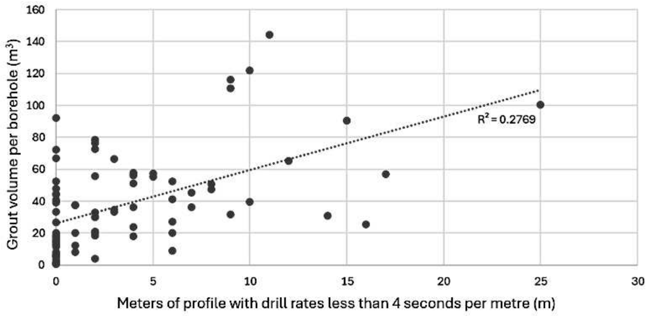

Figure 3. Relationship between meters of profile with rates less than 4 seconds per meter and the grout take for primary boreholes.

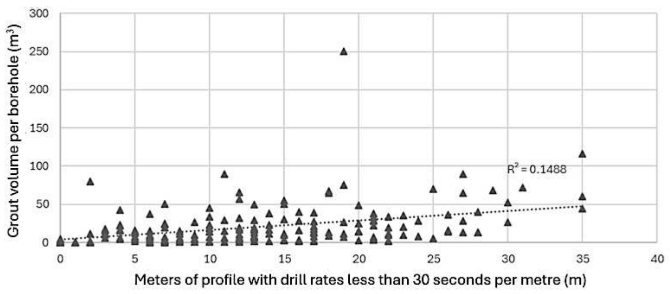

Figure 4. Relationship between meters of profile with rates less than 30 seconds per meter and the grout take for secondary boreholes.

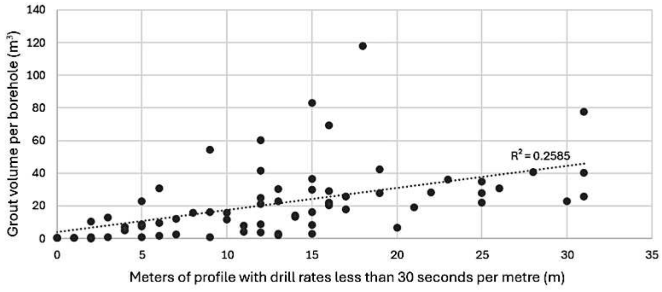

Figure 5. Relationship between meters of profile with rates less than 30 seconds per meter and the grout take for tertiary boreholes.

3.5 *Studying the average drill rate per meter*

In this section, to obtain an indication of the consistency of the ground profile per borehole, the sum of the penetration rates over the entire depth of the borehole was divided by the borehole depth to obtain an average penetration rate per borehole. The correlation between this variable and the grout volumes injected was studied.

Profiles with more rapid average penetration rates, i.e., "less dense", did indicate greater grout volumes, however, as Table 6 shows, the correlations were not as strong as when using the individually studied drill rates as in Figures 3, 4 and 5. Figure 6 summarises the correlations between the grout takes and the average drill rates per borehole.

Table 6. Coefficients of determination (R^2) for the average penetration rate of each borehole profile and the grout take.

Criteria	Primary	Secondary	Tertiary
Coefficient of determination (R^2)	0.176	0.059	0.191

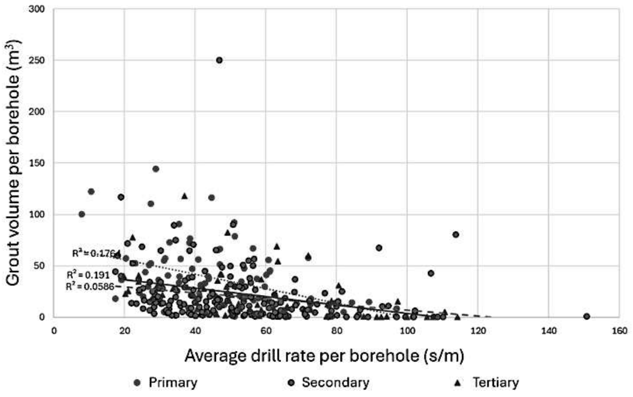

Figure 6. Grout take versus average penetration rate per borehole profile.

3.6 *Correlation between grout volumes and multiple independent variables*

Multivariate linear regression was used to determine whether a stronger correlation could be found between drilling variables and grout take when a combination of independent variables is considered.

Variables considered were the total borehole depth, as well as the number of meters of the drill rates that were considered to have the strongest correlation to the grout take for primary, secondary and tertiary boreholes respectively as determined in Table 5. Tables 7, 8 and 9 indicate the variables used in various multivariate linear regression models that were tested for the primary, secondary and tertiary data respectively. The parameters considered in each model are indicated with a tick mark (✓). An asterisk appearing adjacent to the tick mark indicates independent variables whose p-value was too large, indicating that the relationship to that variable was not statistically significant. The coefficients of determination (R^2) and standard error (SE) of the resulting models are provided.

Table 7. R^2 and standard error for various multivariate linear regression models on primary grouting data.

	Independent variables			R^2	SE
Model	Depth	≤ 4 s	Avg. drill rate		
1	✓	✓		***0.349***	***24.8***
2	✓	✓	✓*	0.341	25

Table 8. R^2 and standard error for various multivariate linear regression models on secondary grouting data.

	Independent variables			R^2	SE
Model	Depth	≤ 30 s	Avg. drill rate		
1	✓	✓		0.153	24.6
2	✓	✓	✓	***0.193***	***24***

Table 9. R^2 and standard error for various multivariate linear regression models on tertiary grouting data.

	Independent variables			R^2	SE
Model	Depth	≤ 30 s	Avg. drill rate		
1	✓*	✓	✓*	0.225	19.3
2	✓*	✓		0.237	19.2
3		✓	✓*	0.236	19.2

The models for primary borehole data indicated an improved prediction of primary grout take when the total borehole depth and meters of profile in which penetration rates were less than 4 seconds per meter were considered.

The models for secondary borehole data indicated an improved prediction of secondary grout take when the total borehole depth, meters of profile in which drill rates were less than 30 seconds per meter and the average drill rate per borehole were considered.

For the tertiary borehole data in Table 9, the highest R^2 from the multivariable analysis was 0.237, whereas for the single variable analysis it was 0.259 as per Table 5. Therefore, the models for the tertiary borehole data in Table 9 did not improve the prediction of grout take beyond what the single variable relationship as shown previously in Figure 5 could do.

Although the multivariate models improved the prediction of grout take, the correlation is still rather weak and the standard error too large for there being much merit in attempting to use the models to accurately predict grout takes.

4 STUDY OF BOREHOLES WITH ABNORMAL GROUT TAKES

4.1 *Study of boreholes with excessive grout takes versus those with very low grout takes*

This section presents a study of the characteristics of boreholes with very high versus very low grout takes. In this section a “high” grout take is considered one in which the borehole took a volume greater than 100 m^3. A “low” grout take was considered less than 5 m^3. Data for all phases of grouting during the project was used in this section to increase the sample size as mentioned in Section 2.2.

Table 10 presents a summary of data for these high and low grout-take boreholes. The data indicates that the profiles of the poor boreholes were generally much less dense with plenty of wad horizon.

The number of meters of a continual horizon where drill rates were less than 10 s/m was investigated. In the boreholes with grout takes greater than 100 m^3, a continuous horizon of wad and cavity of up to 30 m was found. Whereas, out of the 178 boreholes with low grout takes the maximum continuous horizon of wad and cavity was 8 m. Very few of the boreholes with high grout take had no presence of wad at all. However, more than half of the low-take boreholes did not exhibit the poor drilling rates attributed to wad. The average depth of boreholes with low grout take was also more than 10 m less than those of the high grout take, which average at 39 m. This indicates that the majority of the low grout take boreholes would have hit the cutoff depth criterion into hard rock dolomite.

Another feature investigated was the average percentage of the borehole profile that showed extremely poor penetration rates of 3 s/m. These drilling rate possibly indicate the presence of cavities. On average, 8% of the borehole profile of the high grout take boreholes had “cavity” in the profile, while only 1 % on average of the low grout take boreholes exhibited this “cavity” profile.

The average drill rate per meter for the high grout take boreholes was 36 seconds, while for the low grout take boreholes it was much higher at 73 seconds, indicating a much denser profile.

Table 10. Characteristics of boreholes with extremely high versus extremely low grout takes

Criteria	> 100 m^3	<5 m^3
No. of boreholes	30	178
Maximum “continuous wad”	30 m	8 m
No. (%) BHs with no wad	2 (7 %)	103 (58 %)
Average BH depth	39	26
Average drill rate per profile	36 s	73 s
% drill rates ≤3 s (“cavity”)	8 %	1 %

Figure 7 indicates box and whisker plots for the number of meters of profile per borehole with drill rates that fell within the categories of less than 3 seconds, 5 seconds and 10 seconds for the boreholes in which the grouting volumes were either very high (greater than 100 m^3) or low (less than 5 m^3). The average percentage of the ground profile in boreholes with the large grout volumes that had drill rates less than 10 s/m was 24 % while for the boreholes with the small takes it was 5 %.

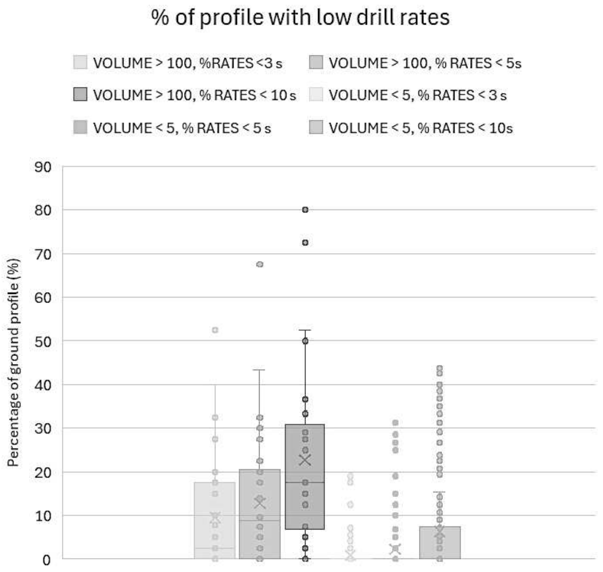

Figure 7. Summary of the presence of low drilling rates in boreholes with high and low grout takes.

4.1.1 *Characteristics of boreholes with "better" drill profiles in which grout takes were still high*

As per Table 10, there were two boreholes in which no rates less than 10 seconds were present, and yet their grout takes were still greater than 100 m^3. These two boreholes as well as another two that exhibited a generally "better" profile in terms of drill rates were studied to determine features that possibly led to their higher grout takes.

The profiles of these boreholes are indicated in Figure 8. Profiles C and D in Figure 8 are terminated in areas comprised of poor, possibly cavity or wad material. They both exhibited large grout takes near the bottom of the holes. Therefore, one could assume that grout possibly flowed downwards past the cut-off depth since they were terminated in poor material.

In the case of profiles B and C, it is noted that there are intermittent bands of harder (indicated by grey and black colours) and softer material. This could indicate chert bands interspersed by wad zones or cavities. During excavations on the site, it was seen that the more resistant chert bands were often interspersed with weathered zones. This could provide conduits for grout to flow elsewhere, possibly to a larger cavity further afield.

Profiles A, C and D were also on the edge of the grouting strip and so grout possibly flowed outside of the treatment zone, as they weren't confined on the edge by ground improvement that had already taken place in other primary holes.

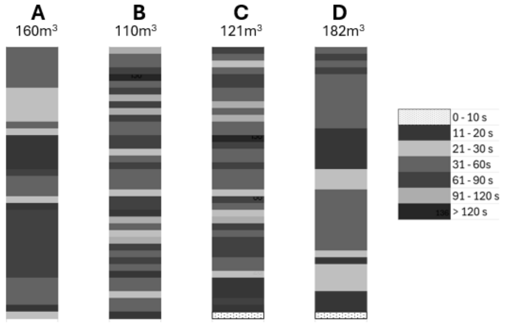

Figure 8. "Better" drilling profiles of boreholes that took a large volume of grout.

4.2 *Comparison of ground improvement volume replacement to literature for the grouting phase presented*

Han (2015) and Bell and Kirsch (2013) reported replacement volumes ranging from 5 – 15 %. The estimated volume replacement for the section of highway discussed in this section was 8.5 %, which falls within the ranges reported by the literature, yet is higher than the quantity of volume replacement reported by Roux (2013).

5 RECOMMENDATIONS AND CONCLUSIONS

The variability in ground conditions associated with the karst environment comes across clearly in the data, as the data generally exhibited a large amount of scatter. The low coefficients of determination in the relationships between drilling penetration rates and grout takes that were studied indicated that it may not be possible to create an accurate model that can predict grout take from drilling penetration rates. Drilling rates do, however, provide an indication of when a high or low grout take can be expected.

It is recommended that further data from other compaction grouting projects also be studied to provide additional insight into the problem.

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