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An Example of the Use of Jet Grouting to Permit Tunneling in Chemically Weathered Limestone

by

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AN EXAMPLE OF THE USE OF JET GROUTING TO PERMIT TUNNELING IN CHEMICALLY WEATHERED LIMESTONE

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ABSTRACT

The paper describes the use of an insitu ground modification technique, jet grouting, to consolidate glacial and alluvial overburden overlying highly fractured limestone bedrock to permit mining by a rock tunneling boring machine of a mixed face condition. A unique case history in that special measures and modifications had to be made to the technique to overcome the challenge of some very difficult site soils.

INTRODUCTION

At present the Upper Scioto West Interceptor Sewer (USWIS) is under construction in the northwestern section of Franklin County, Ohio. The sewer is being built using rock tunneling methods with the excavated diameter of the tunnel varying between 9.5 and 13.5 feet.

The tunnel was designed for excavation by tunnel boring machine (TMB) and a Lovat soft ground machine with Boretech rock head, 129 in. in diameter was selected by the Contractor to drill the bedrock limestone and install 24,000 linear feet of pipe. In addition ten shafts are to be built along the tunnel alignment.

REGIONAL/SITE GEOLOGY

The subsurface exploration for the project revealed that the tunnel would be built generally within the rocks of Middle Devonian formations representing the Paleozoic Era. The bedrock is generally covered by glacial and alluvial soils deposited by Illinois and Wisconsin glaciers during the Pleistocene and by streams during recent times. Importantly valleys were cut deeply into the bedrock prior to glaciation. These tributary valleys were subsequently in-filled with glacially-derived sediments along the tunnel corridor. It was therefore anticipated that limited reaches of the tunnel alignment would have a mixed face. In these areas hand mining was specified at a larger diameter to allow the TBM to pass through the area.

There are two distinct aquifer systems at the site. Discontinuing unconsolidated soils and gravels interbedded with glacial till, primarily confined to the deep buried valleys and the limestone aquifer. In general depths to water in wells along the tunnel alignment generally range from 25 to 50 feet below grade.

One such possible area was identified in the Geotechnical Design Summary Report (GDSR) when a borehole revealed bedrock at 77 ft., close to the tunnel invert elevation, with twelve feet of gravel over the bedrock. This depth of overburden was thirty feet deeper than that found in adjacent boreholes.

It was therefore decided to undertake an additional investigation program in the vicinity consisting of six borings on approximately thirty feet centers, using hollow stem augers with split spoon sampling below 50 ft. Grain size analysis were carried out.

Most zones immediately above the bedrock were classified as silty or clayey sands, or as gravels with sand and silt or clay. Gravels were described as angular to subangular. The cohesive deposits were stiff to very stiff with varying amounts of rock fragments and the coarse grained soils were dense.

The zone where gravel was found previously at great depth was reinterpreted as a localized feature, a crevice, possibly a solution feature in the limestone bedrock which had been filled with detrital material during subsequent geological processes, as opposed to a buried valley filled with alluvial material. An additional boring at the same location did not encounter rock at 8 ft. below tunnel invert while borings 10 ft. and 20 ft. away in plan identified rock above the tunnel crown.

Furthermore, the gravel was angular to subangular, suggesting this was not from a typical alluvial streambed where more rounded gravel would be expected.

The new rock profile indicated at least 180 ft. of mixed face mining which the TBM could not mine unless modified to a Earth Pressure Balance (EPB) mode. The other alternate, as envisaged by the Contract, was to hand mine at a larger diameter to allow the TBM to pass. This was a slow, high risk operation and other options were sought.

The use of permeation grouting techniques where cement-based or chemical grouts are injected under controlled pressure into the soil pores to provide consolidation was discounted given the fine grained nature of the soils immediately above bedrock. With fines contents in general over 20 percent this placed them in the marginal to ungroutable category.

Nicholson Construction Company of Bridgeville, PA were contacted, as a specialist Geotechnical Contractor, for advice and proposed the use of jet grouting to consolidate the overburden deposits to sufficient strength to allow the TBM to mine through the area. This technique is not dependent on the pore size of the deposits as it breaks down the soil fabric and mixes the soil and grout insitu.

THE JET GROUT TECHNIQUE

The A.S.C.E. (American Society of Civil Engineers) has defined jet grouting as a "technique utilizing a special drill bit with horizontal and vertical high speed water jets to excavate alluvial soils and produce hard impervious columns by pumping grout through the horizontal nozzles that jets and mixes with foundation material as the drill bit is withdrawn".

While jet grouting is not familiar to many practicing Geotechnical Engineers and impressive list of successfully completed projects now exists in the U.S.A., going back as far as 1986 (Andromalos and Pettit, 1986) with many impressive recent case histories (Bruce and Pellegrino). It is the intent that this paper adds to the body of technical information currently available on the technique, as a case history in very difficult soils never previously documented.

At present there exists three basic jet grout methods used by Nicholson Construction, all developed by the sister company Giovanni Rodio & C. of Milan, Italy.

Rodinjet 1 - Single Fluid System : The fluid is grout which injected at high nozzles pressures (>20mpa) cuts and mixes the soil in situ.

Rodinjet 2 - Double-Fluid System : This system utilizes on air shroud around the grout to produce greater cutting efficiency and to improve spoil removal.

Rodinjet 3 - Triple-Fluid System : In this system, which is the most complex, the cutting medium is a high pressure water jet with an air shroud with a low pressure separate grout nozzle for replacing the cut material.

For all systems the sequence of operation is very similar in that:

a) A drill string is advanced to the desired depth by rotary drilling with the jetting tool (monitor) fitted to the end, using direct circulation of water or bentonite mud at low pressure.

b) Grout jetting through radial nozzles located on the monitor as the tool is rotated and extracted. In order to prevent high pressurization of the ground the annulus must be maintained at all times with excess spoil and grout returning to the surface, thus ensuring pressure release.

The size and properties of the jet grout columns formed depends upon the nozzle geometry, lift rate and rotational speed of the monitor, the type, density and strength of the soil, and the grout mix.

TEST PROGRAM

In order to determine the most appropriate jet grout parameter to achieve the ground improvement required it is always advisable to construct test columns and, wherever possible, to excavate, visually examine and survey the resulting product.

To permit satisfactory tunneling it was established that a target compressive strength after treatment of 6N/mm^2 (800 psi) was needed for the overburden soils and that the block of consolidated soil would extend six feet above the crown and six feet below the invert, or to rock, with a width of 6.9 m and a length of 92 m. (See Figure 1.) The jet grout was not required to provide water cutoff as the flows expected from perched water in the overburden were low.

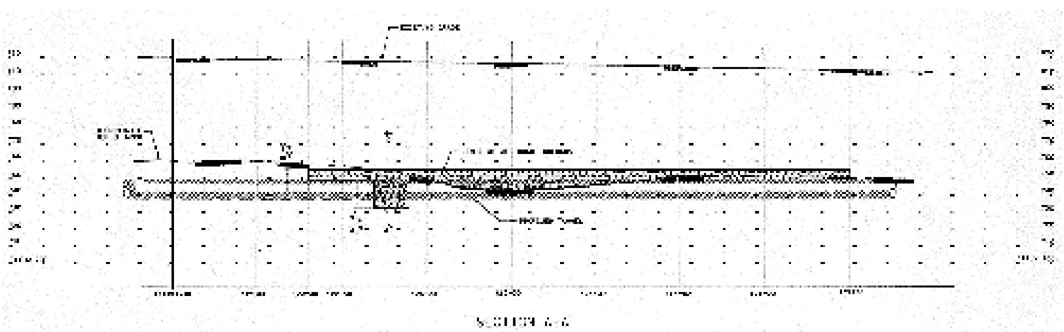

Figure 1: Design Section - Jet Grout

Since it was impractical to excavate test columns in the production area due to the overburden depth the test section was located adjacent to shaft #7 where rock was at 6 m (20 ft.) and the soils were stiff to very stiff silts with some gravel and medium dense fine to coarse sand, typical of the soils anticipated for the production phase.

A total of 4 test columns were built using the RJ2 System and subsequently excavated and cores taken of the jetted material. All columns formed were over 1.8 m (6 ft.) in diameter with the more cementitious grout producing the higher strengths. Test results are provided in Figure 2.

Column No.	**Pressure Cement (bars)**	**Pressure Air (bars)**	**Withdrawal Rate (sec/step)**	**Grout Flow (l/min.)**	**c/w Ratio**	**Diameter (m)**	**U.C.S. (N/mm^2)**	**Age (dys)**
A1	400	11	8.9	10	0.93	1.5	3.2 5.6	7 28
A2	400	11	8.9	10	1.10	1.5	4.7 4.0	7 28
B1	400	11	12.9	10	1.10	1.8	3.2 5.2	7 28
B2	400	11	12.9	10	1.10	1.8	4.2 7.3	7 28

Figure 2: Test Program Results

The parameters adopted were as for the 'B' series of columns allowing the use of a grid on 1.5 m c/c with a total of 258 columns to provide the block dimensions required. (See Figure 3) It was anticipated that the hole depths would vary from 19.5 m (64 ft.) to 26 m (87 ft.).

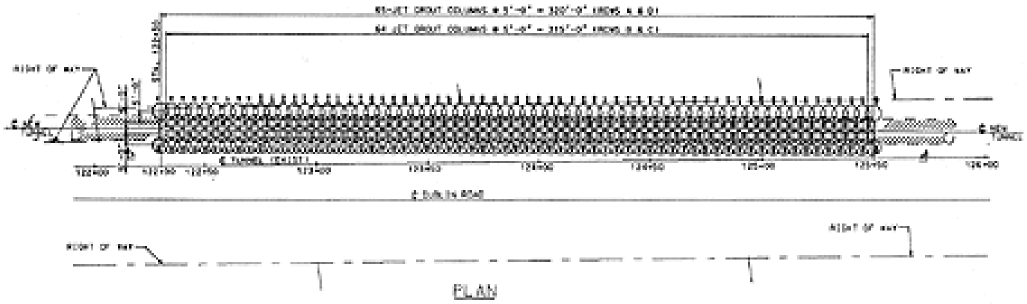

Figure 3: Jet Grout Plan

CONSTRUCTION

Even though the site was restricted within the tunnel right of way good progress was made with an equipment spread consisting of a Casagrande C8 Jet Grout rig, a Rodio IM20 Batch Plant and a GeoAstra Jet Grout Pump.

Of some concern was the very variable depth to rock experienced with depths varying across the block over 6.1 m (20 ft.) and with major differences from column to column. This suggested possible extensive vertical fissures and cracks in the rock which the drill string was following. It was clear though that two separate, district valley features did exist. (See Figure 4.)

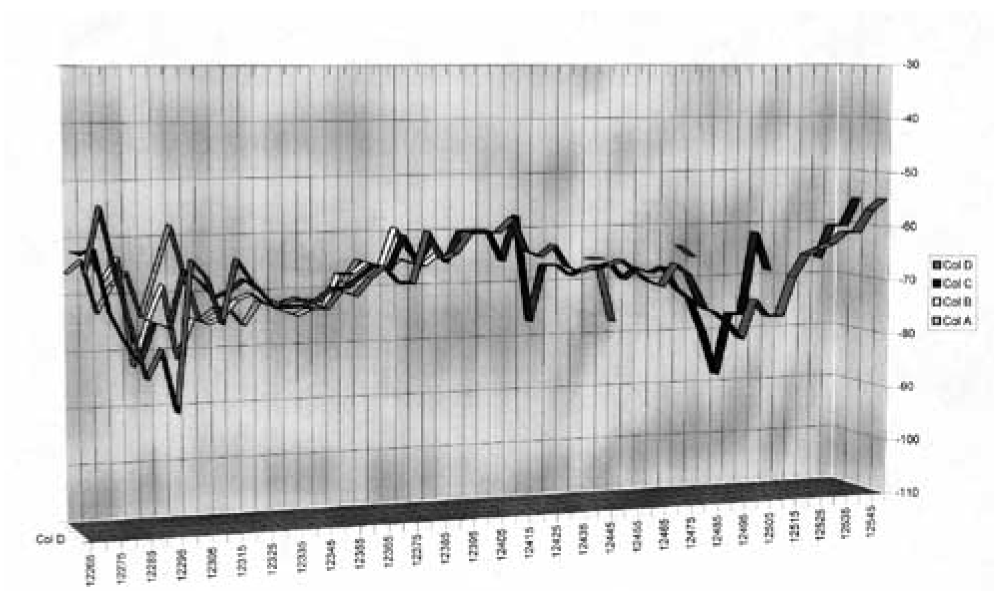

Figure 4: Actual Rock Elevations

Figure 5: Test Column B2

Unfortunately when the initial cored holes were sunk to retrieve samples of jet grouted soil areas of untreated clean gravels were found within the cores. This indicated loss of grout during jet grout operations. Work was suspended until the cause of the problem was identified. Three wells were sunk adjacent to the block with the well screens set in the suspected high permeability material. A KVA Model 40 Horizontal Meter was used to evaluate static groundwater velocities which were found to be low at an average of 1.7 ft. per day, and were consistent with static groundwater gradient data.

Interestingly when a pump well in the bedrock which was located 45 m from the nearest monitoring well was activated 5 ft. of drawdown was observed after 45 mins. and flow velocities were higher than could be measured by the instrument (> 50 feet per day). Furthermore drawdown was also observed in the other wells confirming that the gravel layers were hydraulically connected and of high permeability.

Subsequent coring also revealed the presence of some small (> 150 mm thick) solution cavities within a few feet of the top of rock.

It was decided to attack the problem in two ways. Firstly, to test a tremie grout method where a stable cement grout is injected under pressure within ungrouted columns from the rock/soil interface upwards as a drill casing is slowly withdrawn. This could provide two benefits, grout solid the open gravels and seal possible shallow solution cavities.

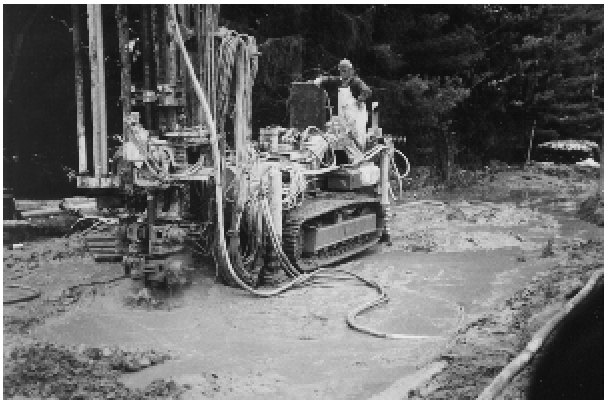

Figure 6: Jet Grouting in Progress

Secondly to look to use additives to accelerate the initial set of the grout during jetting and to vary the jet grout parameters previously employed.

A total of sixteen tremie grout holes were carried out within the deeper valley feature using cement bentonite grout mixes (Figure 7).

Mix	Water (l)	Cement (Kg)	Bentonite (Kg)	Marsh Cone (sec)	Specific Gravity	Bleed
						<5%
1	84	84	3.2	Not passing	1.54	<5%
2	84	84	1.4	50	1.50	<5%
3	84	84	0.9	43	1.50	<5%

Figure 7: Tremie Grout Mix Properties

Grout takes very variable, and it was found that the more viscous mixes were needed to produce a seal which then provided sufficient pressure to free grout into the ground. This suggested that the gravels contained varying amounts of fines or were interbedded with cohesive deposits.

Follow on coring revealed that the tremie operation was only partially successful in that well grouted solution features were cored, but the overburden, critically within the tunnel face was predominately cohesive and very stiff, impossible to permeate, and had not responded well to the earlier jet grouting.

Much better success was achieved in the second valley feature in unjetted areas after the jet grout parameters were changed. The air pressure and flow were reduced to try and reduce the amount of disturbance of the rock/soil interface and a sodium silicate accelerator was introduced to the air/grout stream in order to produce a ‘flash’ set of the cement as it left the nozzle. This would then prevent the grout leaving the targeted location.

After trials to determine the optimum silicate quantity good return of highly viscous spoil and setting grout were observed during column formation. Cored samples recovered the following day from a gravel and sand zone had average compressive strengths of 14.5 N/mm^2 and a max value of 23.7 N/mm^2, with core recovery exceeding 98%. This was far in excess of the performance requirements of the contract.

It was decided in the areas of the very stiff clay that precutting would be necessary where on the first pass water at high pressure is used instead of grout and then a second pass is carried out with the conventional Rodinjet 2 system. This produced excellent results with total or near total replacement of the clay with grout.

Production work then recommenced with all jetting using silicate and precutting being implemented if the driller identified stiff clay from his drill cuttings during penetration, prior to grouting.

CONCLUSIONS

At the time of writing jet grout production continues, but all indications are that the results will be positive.

This project has proved very challenging because of the geological conditions encountered with heterogeneous overburden deposits ranging from very stiff clays to clean gravels overlying a highly fractured limestone bedrock that had experienced the dissolving action of groundwater to open and infill these crevices and to form solution cavities.

The jet grout technique has proven flexible in meeting these unique demands and to provide ground improvement to enable a rock tunneling machine to be used, thus removing the risk of hand mining and reducing the overall cost of the project for the City of Columbus.

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