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Advances in the Construction and Design of Jet Grouting Methods in South America

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SYNOPSIS: This paper presents a brief historical development of the two most popular jet grouting methods used in South America, namely, the chemical churning pile method (CCP) and jumbo jet grouting. Advantages and limitations of each procedure are cited. A brief discussion follows covering the history of CCP jet grouting in South America. Field trials performed to improve the design methodology and construction of CCP and jumbo jet grouted columns are presented. Finally, three case histories are presented to illustrate the use of jumbo jet grouting where limited head room exists, jet grouting in close proximity to pile supported structures, formation of a diaphragm wall in gravelly soil with boulders. The paper closes with a short discussion of a recent tunnel project in which horizontal jet grouting is used as the temporary tunnel support.

INTRODUCTION:

Jet grouting is a general term describing a construction method which utilizes a high speed fluid to cut, replace, and then mix the native soil with a cementing material. The high velocity jet stream is developed by using high pressure pumps, which eject the fluid through relatively large nozzles or injectors, 2 to 4 mm in diameter. The most important feature of jet grouting, when compared to injection or permeation grouting, is that jetting allows the cementing medium to be uniformly mixed with a wide range of soils, i.e. sands and gravel or even hard clayey soils. Other general advantages of jet grouting include: little ground heave when compared to the volume of soil stabilized; relatively high compressive soilcrete strengths; treatment can begin at most practical depths and can be terminated below the ground surface (Yahiro, 1973; Miki 1984).

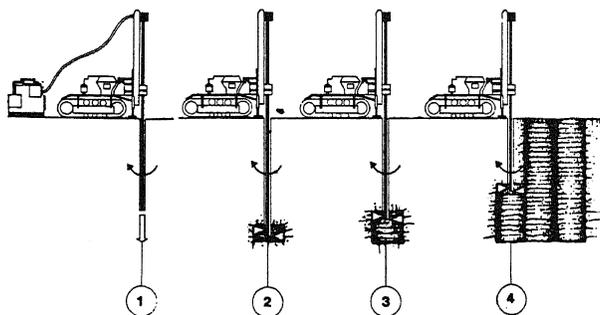


Figure 1 Sequence to Construct a CCP Column
1 - Drilling Guide Hole
2 - CCP Jet Grouting
3 - Lifting and Rotation
4 - Completion and Repetition

At present there are about eight different construction techniques which can be classified as jet grouting methods, with about four or five predominate ones (Miki 1984; Yahiro 1982; Bruce 1987). The diversity in the number of jet grouting methods arises because of the many factors which go into the jet grouting process. Each method has its own advantages and limitations and each should be considered for use in light of their individual characteristics. The two jet grouting methods primarily used in South America, chemical churning pile (CCP) and jumbo grout are discussed more fully in this paper.

EARLY DEVELOPMENTS OF JET GROUTING:

The chemical churning pile (CCP) method of jet grouting was one of the first forms of jet grouting developed in Japan during the early 1970's by Nakanishi (Miki 1984). The technique utilizes a water-cement grout as the jetting medium which is injected into the soil at high velocities through an injector located at the bottom of a single drill rod. The installation sequence is schematically represented in Figure 1, where it can be seen that: first a guide hole is drilled or jetted; followed by jet grouting which involves both lifting and rotating the single rod while injecting grout. A pile-like, soil-cement (soilcrete) column is formed, which may be interconnected to form a wall.

Most of the early work conducted using CCP jet grouting was performed using chemicals, thus arose the tradename, chemical churning pile (CCP). However, due to environmental concerns, most CCP work today is conducted using a water-cement grout as the cutting and cementing fluid. In 1973, an Italian contractor, Romano Colla, was the first to form CCP columns using ultra-high pressures (5000 psi.) and high flow rates (100 to 250 l./min.) through two rather

large injectors (1.8 to 2.4 mm diameter). The CCP technique originally proposed by Nakanishi and later modified by Colla is the CCP jet grouting method presently used in South America by Novatecna.

Experiments conducted in Japan (Yahiro 1973, 1974) indicated that the soil cutting efficiency of a high velocity jet stream could be improved by encapsulating the jet stream within a cone of compressed air, travelling at the speed of sound. Nakanishi modified the CCP method to take advantage of compressed air, and developed jumbo special grout (JSG), which involves simultaneous injection of high speed water-cement grout and compressed air. Injecting two fluids separately into the soil requires a more complex double rod system when compared to CCP jet grouting. In South America JSG is called jumbo jet grouting.

CCP's major advantage over jumbo grout and other jet grouting methods is the simplicity of the single rod system used to jet grout, and therefore, ease with which the single rods can be uncoupled when jet grouting in limited headroom situations. The compressive strength of the soilcrete formed during CCP jet grouting is usually greater than the soilcrete formed during jumbo grouting. The reason is primarily related to the compressed air being trapped within the soilcrete mass formed during jumbo grouting. However, the typical size of a jumbo column is very large, up to 1.9 meters in sands and 1.3 meters in clay, which are at least twice the size of CCP column formed under comparable conditions. Furthermore, the increase in size of the jumbo soilcrete body can be achieved by using lower jetting pressures (3500 - 4500 psi), thus reducing wear to the high pressure pumps. Finally, the cost per unit volume of stabilized soil is generally less expensive when using jumbo jet grouting. The jumbo jet grout method is very popular today in South America and used by Novatecna for a wide range of applications.

JET GROUTING DEVELOPMENTS IN SOUTH AMERICA:

CCP jet grouting was first introduced in South America in 1980 by Novatecna Construction Ltd. of Sao Paulo, Brasil. Jet grouting was rapidly accepted in Brasil because this technique was better suited to grouting the silty and clayey soils of coastal Brasil than conventional methods. Furthermore, the CCP method was initially utilized in Brasil because of the relative simplicity of the rod system used to jet grout.

The first CCP jet grouting job performed in South America was in July 1980 for the Sao Paulo water and sanitation department, (SABESP), and involved the repair of a collapsed tunnel crown for the Sanegran Interceptor Tunnel. The stratigraphy at the site is depicted in Figure 2, and is essentially silty clay in the upper 10 meters, underlain by 4 meters of fine to medium sand with some clay, and then 1.5 meters of fractured gneiss, underlain by sound gneiss. The water table was

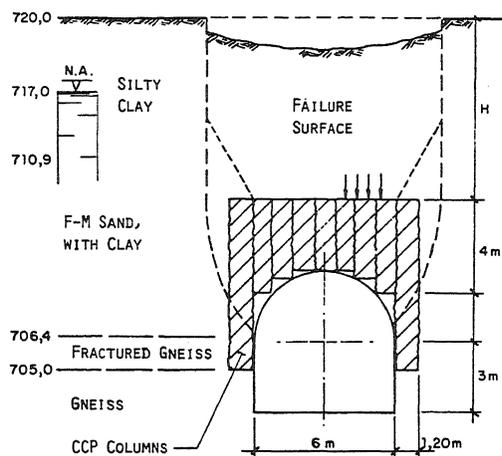


Figure 2 Profile of Sanegran Tunnel Collapse and Typical CCP Repair

about 3 meters below the ground surface. The failure surface depicted in this figure developed while blasting rock in a mixed face section (rock/soil) of the tunnel, leading to collapse of the tunnel crown, which caused a 10 meter diameter dish shape depression to form at the surface (Guatterri, et.al. 1986).

The depression was filled with sand and jet grouting initiated. Problems developed when the columns were formed because the loose sand and fill began to slide into the unhardened jet grout columns leading to further loss of soil at the surface and sinking of the jet grout drill rig. A steel support system was erected across the hole and work progressed smoothly. The jetting parameters used to form the 0.75 meter diameter CCP columns listed in Table I, are typical of the jetting parameters used for CCP jet grouting in South America. It took about 60 days to form the 4.5 meter thick soilcrete arch pictured in Figure 2, which consisted of 490 CCP columns.

Pressure	(psi)	5300
Rotation Rate	(rpm)	18
Injectors		
diameter	(mm)	1.8
number		2
Lifting Speed	(min/m)	4.2
Grout		
injection rate	(l/min)	63
water : cement ratio		1 to 1
cement consumption	(kg/m)	200
Average Column Size	(m)	0.75

The soil along the 12 km Sanegran Tunnel was variable and susceptible to future collapses. Therefore, SABESP decided to performed additional jet grouting work. During the two years of jet grouting for the Sanegran Tunnel, jet grouting was utilized at 10 problem sections: to repair a second tunnel collapse due to lose

of compressed air, and to consolidate soft silty clay fill by forming a soilcrete vault prior to advancing the tunnel shield. Tunneling progressed smoothly mostly due to using about 70,000 meter of CCP columns to stabilize soft ground prior to advance of the tunnel.

Other early CCP projects performed in South America (Novatecna 1987; Guatteri 1984; Nicolls 1985) include: construction of diaphragm walls and floors for unbraced retaining structures (Mercedes Benz, Dalmine Siderca); deep shafts for a pump station at Capivari reservoir; cutoffs for earth dams (Porto Primavera and Edgard de Souza Dams); underpinning (Sao Paulo iron works); slope stabilization (San Clemente, California). Since the introduction of CCP jet grouting in South America, Novatecna has formed about 130,000 meters of CCP columns.

CCP FIELD TRIALS:

One of the drawbacks of jet grouting is related to the lack of information about the variation of the column diameter while jetting. Now there are no practical methods for measuring the change in the column's diameter with depth. The size of a jet grout column is usually estimated by reliance upon past experience or field trials. In 1982 Novatecna undertook extensive CCP field trials to examine how various drilling parameters interact with different soil types to produce a certain sized column.

The drilling parameters which have the greatest influence upon the formation of CCP columns, include:

- outlet pressure at the nozzle
- size and efficiency of the injector
- number and spacing of injectors
- flow rate of cement grout
- lifting speed of the drill rods
- lifting increment per step
- rpm's of the drill rods

With the exception of soil type, the most important parameter influencing the formation of jet grouted columns is the outlet pressure. If the pressure is not large enough the jet stream will not develop sufficient velocity to cut the soil. Data from the literature (Miki 1984) indicates that for most soils a pump pressure of about 40 MPa (5800 psi) is needed for effective cutting. The size and number of the injectors used is dictated by the capacity of the pump and horsepower of the engine. The injector size, and therefore grout flow rate, are selected so that enough fluid mass is injected to cut the soil and also provide enough cement to satisfy the design compressive strength. It was not the intent of the CCP field study to obtain the optimum combination of the above list of drilling parameters, but rather, understand how a single drilling parameter could be used to control the size and economy of forming CCP columns. Therefore, it was decided to examine what influence the lifting speed had upon the size of CCP columns formed in three soil types. However, since the

lifting speed is only an indicator of the amount of time which the jet stream cuts the soil, it was decided for discussion purposes to also use the terms jet impact time and rod revolutions per step. The jet impact time is equal to the product of the lifting speed, lift increment per step, and number of nozzles. The jet impact time has units of time/step. The rod revolutions per step is the product of lifting speed, lift increment per step, and rod revolution rate.

The three soils selected for the CCP field tests were sedimentary soils commonly found in the Sao Paulo area, and included: sands, silty clay, and an organic clay obtained from the Sanegran Tunnel excavation. Three pits 10 X 10 X 5 meters deep were excavated into the bank of the Tiete River above the tide line. All materials were end dumped from a truck into their respective pit and compacted using either a D6 dozer or Cat 966 rubber wheeled front end loader. The highly plastic (LL = 60, PI = 40), soft organic clay was placed at its natural water content in 30 cm. lifts and compacted. The silty clay and sand were compacted in a wet state. The in-place unit weights of the silty clay and sand were 102 and 113 pcf, respectively.

Twenty CCP columns were formed in each pit. All sixty columns were made using the same nozzle pressure, rotation rate, size and number of injectors, water-cement ratio and grout injection rate as specified below in Table II. Within each pit 10 columns were drilled using a lifting speed of 2.9 min./m. and then another 10 were formed using twice that lifting speed, and twice the amount of cement.

Table II Drilling Parameters Used During CCP Field Trials in Sao Paulo

A). Constant Parameters		
Pressure	(psi)	4200
Rotation Rate	(rpm)	18
Injectors		
diameter	(mm)	2.2
number		2
Grout		
water:cement ratio		1 to 1
injection rate	(l/min)	91
B). Variable Parameters		
Lift speed #1	(min/m)	2.9
Rod revolutions/step		2
Jet impact time/step	(sec/step)	14
Cement Consumption	(kg/m)	200
Lift speed #2	(min/m)	5.8
Rod revolutions/step		4
Jet impact time/step	(sec/step)	26
Cement Consumption	(kg/m)	400

The measured size of the CCP columns and average compressive strengths of the soilcrete are summarized below in Table III. The sand compressive strengths reported in Table III are based upon past experience with this

material, and were not measured from columns formed during the CCP field trials. However, all other strengths recorded were obtained from soilcrete specimens formed during the field trials.

Soil Type	Lifting Speed min/meter	Column Diameter cm	Average Compressive Strength kg/cm ²
clay	2.9	55 to 60	20
clay	5.8	65 to 70	40
silty clay	2.9	65 to 70	50
silty clay	5.8	75 to 80	70
sand	2.9	75 to 80	80
sand	5.8	85 to 90	120

The data obtained during the CCP field trials supports the following observations:

1). Doubling the jet impact time from 14 to 26 seconds does not have a significant influence upon the size of any CCP column formed. Doubling the jetting time resulted in 15% to 25% increase in the diameter of CCP columns. It appears that most of the cutting action of the water-cement jet is expended during the first two revolutions of the drill pipe.

2). The compressive strength for all soils was significantly increased by doubling the jet impact time, allowing double the weight of cement to be injected per meter of column. The increase in strength was double for the organic clay and about a 50% increase for the silty clay and sand.

3). The soil type played a significant role in determining the size of CCP column formed, and could account for up to 50% of the difference in the sizes of columns. As the amount of clay in the soil increases the columns decrease in size. As shown in Table III, the smallest columns when formed in the organic clay (0.55 to 0.60 m.), intermediate sized in silty clay (0.65 to 70 m.), and largest in sand (0.85 to 0.90 m.).

4). Finally, soilcrete made by mixing 1 to 1 water:cement grout with sand results in compressive strengths (80 kg/cm²) about four times greater than comparable grout mixes in clay, with the lowest clay strength being about 20 kg/cm².

JUMBO GROUT FIELD TRIALS

The diversity of applications of jet grouting produced a need for larger diameter columns than those produced using the CCP process. When constructing a continuous wall a large part of the cost is associated with drilling

guide holes prior to jetting. With CCP columns the interaxes spacing between columns is rather close, about 0.50 m, which results in many guide holes to create a wall. Interaxes spacing for jumbo columns is about 1.2 to 1.4 meters, which requires about half the guide holes needed for a comparable CCP wall.

The jumbo grout field trials were conducted in four phases over a period of 9 months, between April to December 1984. The first two phases were performed to understand the role lifting speed played in the formation of jumbo columns in cohesive soils. Phase three consisted of forming jumbo columns in sands, and in the last phase jumbo grout panels were made. At present panel walls represent a provisional method of wall construction, and only the results from the column studies will be discussed in the following sections.

The jumbo grout field trials were conducted in large pits (30 X 6 X 5 meters deep), excavated in the banks of the Tiete River in the vicinity of the original CCP field trials. During phase I and II the same soil type was used, and was typically silty clay, with about 20 to 30% fine sand. The top 1.5 meters of the fill was medium to stiff in consistency and was soft below 1.5 m to the bottom of the pit. The sand used during phase III tests was a fine uniform sand which was placed moist and in a loose state.

All jumbo grout columns were formed using a nozzle pressure of 3000 psi and a single 3.0 mm injector, as listed in Table IV. The double drill rods were rotated at about 18 rpm's, and the air cone was delivered at 4 m³/min at 100 psi. The 1:1 water:cement grout was injected at about 70 l/min.

Twenty-two jumbo columns were formed during phase I. The only variable changed was the lifting speed, and as indicated in Table IV, the speeds varied between 1.6 and 3 min./m. The fastest lifting speed was selected to insure that at least one full revolution of the drill pipe occurred before moving the jet to a higher elevation. Excavation of all 22 columns revealed nonhomogeneous, poorly cemented cylindrical bodies, with measured diameters between 1.8 and 2.0 meters.

The solution to the nonhomogeneity of the soilcrete body was to either use more than one jet, or jet longer. It was decided to investigate how extremely long jetting times, using one injector, influence the size and strength of jumbo columns. Therefore, during phase II 6 columns were formed using two very long lifting times, 12 and 18 min/m.

The results from the phase II studies showed that no significant size increase resulted in jetting 4 to 6 times longer at a particular elevation; phase II columns were still about the same size as the phase I columns. However, the phase II soilcrete bodies were much stronger and more homogeneous than phase I.

Table IV Drilling Parameters Used During Jumbo Field Trials in Sao Paulo		
A). Constant Parameters		
Pressure (psi)		3000
Rotation Rate (rpm)		18
Injectors diameter (mm)		3.0
number		1
Grout water:cement ratio		1 to 1
injection rate (l/min)		70
Compressed Air pressure (psi)		100
flow rate (m ³ /min)		4
B) Phase I Clayey Silt 22 columns		
Lift speed #1 (min/m)		1.6
Rod revolutions/step		1.1
Jet impact time/step (sec/step)		3.8
Cement Consumption (kg/m)		90
Lift speed #2 (min/m)		1.8
Rod revolutions/step		1.3
Jet impact time/step (sec/step)		4.2
Cement Consumption (kg/m)		100
Lift speed #3 (min/m)		2.0
Rod revolutions/step		1.4
Jet impact time/step (sec/step)		4.8
Cement Consumption (kg/m)		115
Lift speed #4 (min/m)		3.0
Rod revolutions/step		2.2
Jet impact time/step (sec/step)		7.2
Cement Consumption (kg/m)		175
C). Phase II: Clayey Silt 6 columns		
Lift speed #1 (min/m)		12
Rod revolutions/step		8.6
Jet impact time/step (sec/step)		28.8
Cement Consumption (kg/m)		600
Lift speed #2 (min/m)		18.0
Rod revolutions/step		13.0
Jet impact time/step (sec/step)		43.2
Cement Consumption (kg/m)		900
D) Phase III Sand 2 columns		
Lift speed #1 (min/m)		12
Rod revolutions/step		8.6
Jet impact time/step (sec/step)		28.8
Cement Consumption (kg/m)		600

A total of 122 six inch high specimens were cut from the Phase II columns formed using 12 min/meter lifting speed. Samples were cut from the upper, middle, and lower third of the soil-concrete body and were allowed to cure for 30 and 60 days. Both unconfined compressive and Brazilian tensile tests were performed. The results are summarized in Table V, where it can be observed that the 30 day compressive strengths vary between 25 kg/cm² at the top of the column and decrease to 14.2 kg/cm² near

the bottom of the column. After 60 days of curing the column tends to have a more uniform strength over its length, whereby the lower portion of the column has experienced a 40% increase in compressive strength between 30 and 60 days. The results from the tensile strength tests are inconsistent. The tensile strength in the upper and middle portion of the columns tend to decrease with age, while the tensile strength in the lower third of the columns increase with age. This inconsistency is believed to be due to testing a small number (6 samples) of specimens from each location at 30 days.

Table V Average Compressive and Brazilian Strengths Obtained From Phase II Jumbo Columns								
Column Portion Tested	Average Compressive Strength kg/cm ²				Average Brazilian Strength kg/cm ²			
	N*	30 Day	N*	60 Day	N*	30 Day	N*	60 Day
Upper	7	25.0	12	30.9	6	5.6	9	4.5
Middle	12	19.4	8	22.8	6	7.2	20	3.8
Lower	12	14.2	9	20.3	6	3.0	15	4.1

*: N represents number of samples tested

A more comprehensive set of strength data has been reported by Guatterri and Teixeira (1987). The results from their study indicates that the average tensile strength of a jumbo column, formed in a wide variety of soils, increases with time and is about 10 to 15% of the average compressive strength.

Two jumbo columns were made in a loose sand during phase III, as a reference to compare to columns made in cohesive soils. Both columns were drilled using lifting times of 12 min/m. and resulted in extremely uniform (1.9 to 2.0 meter), and slightly larger columns than formed in cohesive soil. However, the sand soil-concrete strength was significantly higher than in clay, which is consistent with the results from the CCP field trials.

The results from phase I and II tests indicate that the high speed water-cement jet quickly cuts the soil at a particular elevation, and only takes about 2 revolutions (5 to 7 seconds jet impact time) of the drill pipe to form the column. However, this amount of time does not allow enough cement to be injected, nor is it sufficient time for the jet stream to properly mix the cut soil with the injected cement.

JUMBO GROUT CASE HISTORIES:

One criticism leveled against jet grouting is that due to the relatively low tensile strength of soilcrete, jet grouting is not a cost effective nor technically viable scheme for constructing unbraced earth retaining structures. Although this statement may be true for very deep walls, the use of jumbo grout to form retaining structures for depths up to about 6 meters is not only technically viable, but cost competitive with other construction methods. To illustrate this viability and robustness of jet grouting, three case histories are presented, where jumbo grout was used to construct diaphragm walls for both temporary support of the soil during construction and also as the final wall. Typically, a 15 cm. thick, lightly reinforced concrete wall is placed over the soilcrete wall for protection against the elements and also to create an architecturally pleasing surface. Other important aspects of jet grouting illustrated by the selected case studies included: importance of pre-jetting to eliminate possible high pressures from developing during jetting, applicability of using jumbo grout in limited head room situations, and lastly feasibility of using jumbo grout in soils containing cobbles and large boulders.

RINCAO CHANNEL, SAO PAULO CITY

Sao Paulo City wanted to construct a trapezoidal water channel to convey runoff to the Rio Tiete. A 40 meter long section of the concrete channel had to go beneath a 19 meter wide viaduct at Rincao. The soil beneath the overpass consisted of about 5 meters of soft silty clay, 15 meters of fine to medium sand with some clay, and then a second clay layer. The soil profile for the first 10 meters is shown in Figure 3c, which is about the depth of the jumbo columns used to form the wall, shown in cross section in Figure 3b. The water table was located about 1.5 meters down from the surface. Due to hydraulic considerations for open channel flow, the bottom of the channel had to be one meter within the fine to medium sand layer. Due to the limited overhead clearance under the viaduct and the flexibility of using jet grouting to make both the walls and bottom plug of the channel, city engineers decided to use jet grouting to construct a U shaped channel. The transition between the trapezoidal and U shaped channels was done with a traditional soil bentonite slurry trench which was keyed into the second clay layer located 15 meters below the surface, which was the primary reason for not using a conventional diaphragm wall to construct the walls of the channel.

The jet grouted channel was 40 meters long by 9.50 meters wide, by about 5 meters deep, as illustrated in the general plan view and channel cross section A - A drawn in Figure 3a and 3b. There were a total of 60 columns, each 9 meters long, jet grouted in a single row to make the two walls of the channel. All jumbo columns were about 1.6 meters in diameter and spaced about 1.3 meters apart. The 2 meter thick bottom plug consisted of 207 columns. About 80% of the channel was constructed

beneath the 19 meter wide viaduct, shown in the general cross section B - B of Figure 3d, with only 3 meters of headroom.

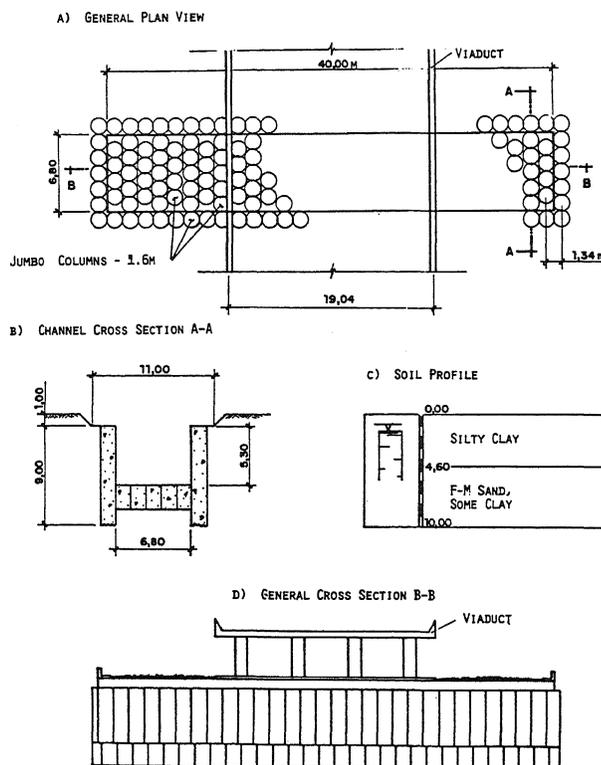


Figure 3 General Cross Section and Profile of Rincao Channel, Sao Paulo City

All columns at Rincao were jetted using 3000 psi pressure with a 1 to 1 water:cement grout, injected through a single 3.0 mm injector, as indicated in Table VI. Half of the wall columns were in sand and half in clay. Two different lifting speeds were used with the slower speed being in the clay so that the wall columns would be able to achieve the design strength of 30 kg/cm² in the clay portion of the columns. The plug was located only in sand, and the design strength of 100 kg/cm² could be achieved using a lifting speed of 5.5 min/meter.

There were three major concerns expressed by city engineers during construction of the Rincao channel. The first was related to the possibility of causing distress to the viaduct when jetting with high pressures within two meters of the pile foundation supporting the viaduct. Secondly, if the jet grouted wall had windows in the vicinity of the piles, water and sand could flow into the channel, thus undermining the viaduct's foundation. Finally, because the jet grouting work progressed rapidly, the city wanted to excavate the soil from the interior of the channel only after 30 days and not wait for the soilcrete to cure the originally planned 60 days. A low strength jet grout wall near the piles might cause excessive deflection of the viaduct. Due to time constraints it was decided to excavate the soil from inside the jet grout wall after

30 days. Visual observations showed that there were no distressful movements of the viaduct when either jet grouting with high pressures, or wall movements when removing the soil.

Pressure	(psi)	3000
Rotation Rate	(rpm)	18
Injectors diameter	(mm)	3.0
number		1
Grout injection rate	(l/min)	120
water : cement ratio		1 to 1
Compressed Air pressure	(psi)	100
injection rate	(m ³ /min)	4
Lifting Speed clay	(min/m)	8.8
sand	(min/m)	5.5
Cement Consumption clay	(kg/m)	800
sand	(kg/m)	500
Average Column Size	(m)	1.6

The Rincao jet grout wall was not internally reinforced nor was bracing used to support the excavation. For approximately one week the wall was standing free for a height of 5 meters. Furthermore, excavation of the interior soil from the channel revealed a tight, water-proof barrier formed by the jumbo grout columns in the wall and plug of the channel. The channel was then lined with a 15 cm. thick, lightly reinforced concrete covering for erosion protection. The project finished one month ahead of schedule.

GENERAL MOTORS STAMPING MILL PIT:

General Motor of Brasil wanted to expand their manufacturing capabilities by building ten new auto body stamping mills. The mills were to be placed at the bottom of a long, narrow pit (68 X 9.7 X 6.5 meters deep). GM also required that the steel plate stock for the stamped parts be stockpiled along side the pit, which would induce a surcharge loading of about 20 tons/m². The lateral force induced by the surcharge would be about twice that imposed by the soil forces. The soil profile at the site is shown in Figure 4c, and consisted of fill in the top 2.5 meters, underlain by alternating layers of silty clay and sand, with the water table about 2 meters below the bottom of the jet grout columns. A diaphragm wall with tie backs was rejected as a solution primarily because the tie backs would have to infringe upon land which GM wanted to conserve for future expansion. Therefore, a single row of unreinforced and unbraced jumbo grout columns was used as the earth retention system. However, toe support of the wall was supplied by

3 meter thick soilcrete struts spaced about 4 meters apart, which are shown in the general plan view of Figure 4a and pit cross section of Figure 4b. The general plan view of the jet grout wall was symmetric about the center line shown in Figure 4a, and only half the general plan view is shown in this figure. The surcharge loads were supported by clusters of columns formed around the perimeter of the pit and arranged as shown in Figure 4a and b.

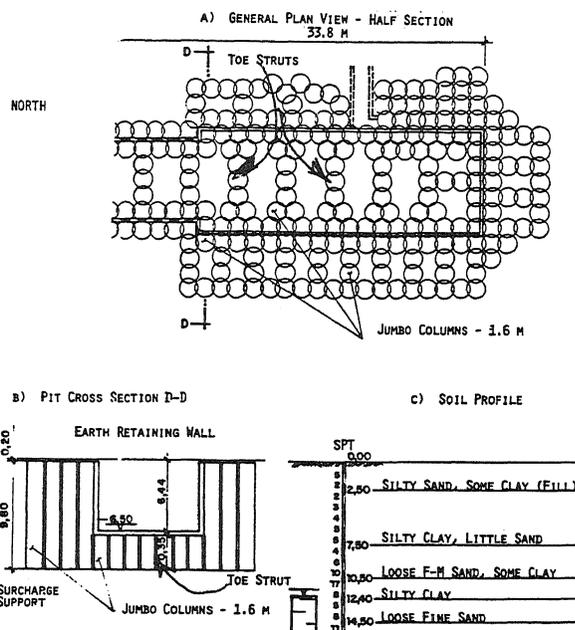


Figure 4 General Plan and Profile of General Motors Stamping Mill Pit

A major concern expressed by GM engineers was related to the effect which the high jetting pressures would have upon the foundation of an existing building, which was only two meters away from the jumbo columns used to support the surcharge along the north side of the pit, upper portion of wall shown in Figure 4a. If sufficient grout flow was not communicated to the surface, then there existed the possibility of building-up very high pore pressures in the sub-soil. The pore pressure build-up could cause distress to the foundation of the adjacent building. Therefore, during this project all the jumbo columns used to support the surcharge along the north side of the excavation were pre-jetted with a special bit so that a 10 inch diameter hole would be created, which would assure pressure relief in the borehole. Furthermore, all surcharge support columns were jetted using relatively low pressures (3500 psi), and rapid lifting speeds (2.2 min/m). Due to the silty nature of the subsoils at the site and need to create large (1.6 meters), strong, soilcrete columns pre-jetting only water was used to form all columns at the GM pit, as listed in Table VII.

There were three different sets of jetting parameters used to construct the jumbo grout columns in the GM pit. The single row of wall

columns were made using the highest nozzle pressures (5200 psi) and slowest lifting speeds during pre-jetting and jetting, 4.4 and 7.2 min/meter, respectively. About 600 kg/meter of cement were injected through the 3.4 mm injector, using a 1:1 water-cement grout. As expected the wall columns were the largest formed, averaging 1.8 meters in diameter. The drilling parameters used for the surcharge support columns and soilcrete struts at the bottom of the excavation were selected to insure a minimum column diameter of 1.6 meters. There were a total of 509 jumbo columns made, totaling 3566 meters. Jetting of all columns was discontinued 0.2 meters below the surface.

TABLE VII Jet Grouting Parameters Used For General Motors Stamping Mill Pit

Pressure	(psi)	
wall		5200
toe struts		4000
surcharge support		3500
Rotation Rate		18
Injector		
diameter	(mm)	3.4
number		1
Grout		
injection rate	(l/min)	
wall		111
toe & surcharge support		103
water : cement ratio		
wall & surcharge support		1 to 1
toe struts		0.8 to 1
Compressed Air		
pressure	(psi)	100
injection rate	(m ³ /min)	4
Cement Consumption	(kg/m)	
wall		600
toe struts		400
surcharge support		600
Lifting Speed	(min/m)	
wall		
pre-jet water		4.4
jet grout		7.2
toe struts		
pre-jet water		3.3
jet grout		4.4
surcharge support		
pre-jet water		2.2
jet grout		7.7
Average Column Size	(m)	
wall columns		1.8
toe & surcharge support		1.6

After the GM pit was excavated down to its full depth of 6.5 meters, a 75 ton Linkbelt crane was used to place a steel frame for the building which housed the pit. A photograph of the fully excavated pit and crane, shown in the background, are pictured in Figure 5. Although the crane moved around the entire excavation, typically only one meter from the edge of the wall, no visual movements of the wall

occurred. The jet grout wall system has functioned well, and in July 1987 GM was placing a 15 cm. concrete covering over the wall.



Figure 5 Photograph Showing General View of Excavation For General Motors Pit

PETROBRAS WASTE DISPOSAL PITS

In early 1986, Petrobras, the Brazilian national oil company, wanted to improve their re-cycling and disposal of waste products created during crude oil refinement at their Cubatao installation. The project required soil stabilization beneath a large oil storage silo, along with the excavation for two large waste storage pits (P-3915 and P-3921) and a smaller service pit. Jet grouting was selected because soil stabilization beneath the oil silo and the earth retention system for the pits could be constructed using the same equipment. Furthermore, the site was strewn with boulders and it would have been very difficult to form a diaphragm panel wall. Also the bottom of the excavation needed to be sealed to prevent groundwater intrusion, which was also accomplished using jet grouting.

The soil profile for the largest pit (P-3921) is shown in Figure 6c, and consisted of about 5 meters of silty clay fill, containing several large boulders in the top one meter. Under the fill was three meters of loose, fine gray sand, which formed the bearing stratum for pit P-3921. Beneath the fine gray sand was another sand layer and then over 7 meters of soft, dark organic clay. The ground water table was about 3 meters down from the surface. The soil stratigraphy for the second pit, P-3915, was essentially the same as that just described for pit P-3921. However, in the case of pit P-3915 there were many more boulders in the top 3 meters of fill. The rocks ranged in size from 15 cm. cobbles to 3 meter boulders up to half a meter thick, which can be seen in the close-up photograph contained in Figure 7. The wall shown in this photograph is about 3.5 meter deep, and had to be excavated by hand.

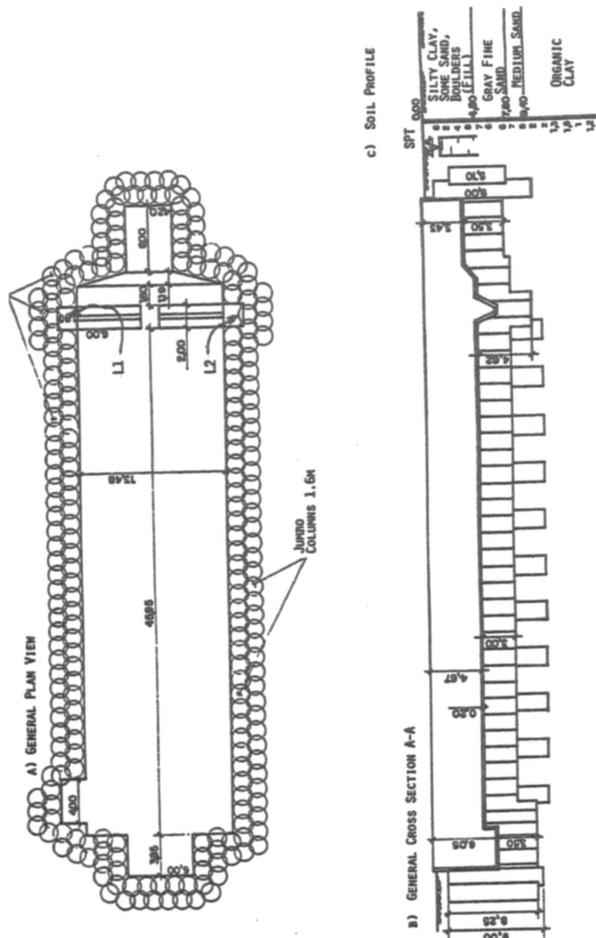


Figure 6 General Plan View and Profile of Petrobras Waste Pit P-3921



Figure 7 Photograph of Large Boulder Jet Grouted into Wall of Pit P-3915

Jet grouting work commenced in November 1986, utilizing a single Haliburton T10 pump and a Novatecna rotator-extractor drill rig. A large single injector (3.8 mm diameter) was used to create the jumbo grout columns. This is about the largest injector that can be used with a T10 pump and still deliver 140 l/min of grout at 4000 psi, which were the highest flow rates and pressures utilized during the formation of the diaphragm wall for pit P-3921, as listed in Table VIII. Pit P-3921 had the longest free cantilevered length of unreinforced wall (6.1 meters), and therefore, required the greatest compressive and tensile strength. It was decided to inject a relatively large volume of cement (800 kg/meter of column) by injecting grout at 140 l/min and lifting the jet grouting monitor slowly (7.4 min/meter).

Pressure	(psi)	
Pit P-3915		3500
Pit P-3921		4000
Bottom Plugs		3500
Rotation Rate		18
Injector		
diameter	(mm)	3.8
number		1
Grout		
injection rate	(l/min)	
P-3915		130
P-3921 & Bottom Plug		140
water : cement ratio		
P-3915		0.8 to 1
P-3921		1 to 1
Bottom Plug		1.2 to 1
Compressed Air		
pressure	(psi)	100
injection rate	(m ³ /min)	4
Cement Consumption	(kg/m)	
P-3915		700
P-3921		800
Bottom Plugs		550
Lifting Speed	(min/m)	
P-3915		
pre-jet water		3.3
jet grout		6.0
P-3921		
jet grout		7.4
Bottom Plugs		
jet grout		6.0
Average Column Size	(m)	1.6

The bottom plugs for the two pits and walls for pit P-3915 were jetted using the same nozzle pressure (3500 psi) and lifting speed (6 min/m). However, the amount of cement injected for each structure was varied by changing the grout injection rate, with the lowest for the bottom plugs, 130 l/min, which resulted in 550 kg cement per meter of column being injected for a 1.2:1 water cement ratio.

The Petrobras waste pits were the most difficult jet grouting job done by Novatecna up to now because of the relatively high water table and long unsupported length of unreinforced wall. The section modulus of the wall needed to produce an acceptably low tensile stress along the backside of the wall required the formation of a double row of jumbo grout columns, which produced walls about 3 meters in thickness. The largest pit P-3921 was about 46 meters long by 13.5 meters wide, as illustrated in the plan view contained in Figure 6a. The wall for this pit required about 170 jumbo columns, each over 1.6 meters in diameter and spaced 1.3 meters center-to-center. A total of about 330 jumbo columns were used to form the 3 meter thick plug at the bottom of the excavation for pit P-3921, shown in the profile of Figure 6b.

When the soil was excavated from inside pit P-3921 two small leaks developed carrying fine gray sand into the excavation at points L1 and L2 marked on Figure 6a. The relatively high velocity of water inflow made it impossible to seal the leaks using jet grouting. The inflow of water was stopped by building two small brick walls around each leak and then allowing the water to rise inside of the well, thus equalizing the water level inside and outside the excavation. Thereafter, conventional tube-a-machette grouting was used to seal the leak. Several factors could have lead to the leak developing through the plug of pit P-3921. First, the interax spacing of 1.3 meters could have been too large, causing small or no overlap of the columns in this area. Secondly, during excavation of the soil inside the pit, the backhoe could have jarred the columns and caused them to separate. Most likely it was a combination of the two effects

The 2198 meters of columns for pit P-3915 were constructed in 41 days, using one rig working 10 hours per day, six days per week. The construction of the largest pit, P-3921, took 50 days working a similar shift. The entire jet grouting project was completed in May 1987, about six months after the start of the project.

CURRENT JET GROUTING WORK IN SOUTH AMERICA

The town of Campinas, approximately 50 km North of Sao Paulo, is presently constructing a twin 16 meter diameter tunnel. The support system for the twin tunnels are being constructed using vertical jumbo columns near the portal of the tunnel for about 50 meters. From 50 meters up to the other end of the tunnel, an additional 200 meters, tunnel support consists of an arch created by horizontal jet grout columns. These horizontal columns are formed using the CCP system. The tunnel is scheduled for completion during Fall 1988.

Access to the portal of the tunnel is permitted by two unbraced, unreinforced, jumbo grout diaphragm walls. The north wall was formed by jetting 5 rows of jumbo columns. Through October 1987, the 17 meter high north wall has not experienced any distressful movements.

CLOSING REMARKS:

We are still in the early stages of the learning curve for understanding jet grouting. Difficulties now exist in measuring in-situ the diameter of the column as it is formed. When jetting very deep columns the problems associated with maintaining verticality becomes critical. However, these technical difficulties can be overcome, and permit improved field quality control. Novatecna is now working on solutions for the above problems.

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