Chapter 26

GROUND CONTROL PROGRAM FOR THE RIO PIEDRAS PROJECT, TREN URBANO PROGRAM, SAN JUAN, PUERTO RICO

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ABSTRACT

The Rio Piedras Alignment Section 7 of the Tren Urbano is currently being constructed beneath a historic commercial section of San Juan. Different portions of the section are being constructed using open cut, cut-and-cover, New Austrian Tunneling Method (NATM), Earth Pressure Balance Machine (EPBM), and a stacked drift mined support system. The combination of complex geology, low ground cover, and several innovative construction methods present many challenges to the ground control program. Mining and construction sequences were first developed to minimize ground movements and risk of damage to structures. A unique compensation-grouting program was developed to improve the ground, limit settlement, and recover settlements incurred due to mining.

OVERVIEW OF PROJECT

The Rio Piedras Contract Alignment Section 7 is one of seven contracts currently under construction as part of Phase 1 of the Tren Urbano in San Juan, Puerto Rico. The Rio Piedras section comprises approximately 1500 metres of the Bayamon line of the Tren Urbano, and is the only contract to be constructed entirely underground. The alignment begins near the intersection of Puerto Rico Highway PR-1 and PR-3, and proceeds north, parallel to Ponce de Leone Avenue through the town center of Rio Piedras, and then continues along the west side of the University of Puerto Rico (UPR). The alignment terminates near the intersection of Ponce de Leone and Jose T. Pinero Avenues (**Figure 1**).

The Rio Piedras Alignment Section 7 includes construction of two underground stations (the Rio Piedras Station and the University of Puerto Rico (UPR) Station), the running tunnels between the stations, and the underground tunnels and portals that connect to the aerial alignment sections to the north and south. Also included with the contract is the turn-outs for a future Carolina line, which intercept the Bayamon line just south of the Rio Piedras Station.

The alignment was selected by Tren Urbano to provide service to the University of Puerto Rico, and to provide an economic development incentive to the historic commercial district of Rio Piedras.

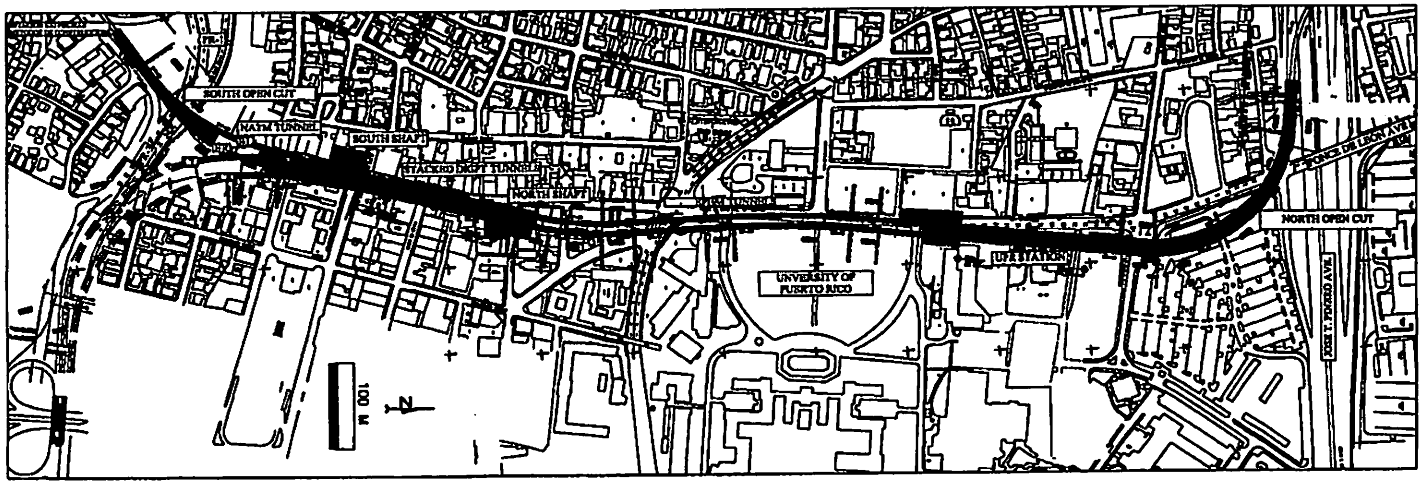

Figure 1. Plan View of Rio Piedras Section Alignment

Neither the UPR Station nor the Rio Piedras station could be constructed entirely within the right-of-way of Ponce de Leone Avenue because of geometric limitations, and the narrow right-of-way limits in the vicinity of the Rio Piedras station. This resulted in the Rio Piedras station being constructed predominantly beneath historic commercial structures, and the UPR station being constructed partially beneath the roadway and partially on University property immediately adjacent to historic university buildings.

Five different construction methods were selected for different components of the Rio Piedras alignment. The construction method for each section was developed as a balance between minimizing impact to the Rio Piedras community, and maintaining efficiency and safety in construction. In summary, the construction methods used are listed below and shown on **Figure 2.**

Section	Method	Area
North and South Portals	Open Cut	
Running Twin Tunnels	Cut-and-Cover	In areas of open access
	EPBM	Adjacent to UPR and under the Rio Piedras historic district
	NATM	Beneath historic structures
Carolina Line Turn-out	NATM	Beneath historic structures
UPR Station	Cut-and-Cover	
Rio Piedras Station	Open Cut	North and south access structures
	Stacked Drift Tunnel	Platform section

The Design-Build Team

The joint venture of Kiewit Construction Company, Kenny Construction Company, and H.B. Zachary Company (KKZ) along with CMA Architects and Engineers of San Juan Puerto Rico was awarded the contract by Tren Urbano in April 1997 as the design-build team for the Rio Piedras Alignment Section 7. Supporting CMA in the design effort are Sverdrup, Jacobs Associates, and Woodward Clyde. A key member of the ground control team was Soletanche-Bachy, a subcontractor to the KKZ team to design and perform the ground improvement, grouting operations, and settlement compensation grouting.

The design team mobilized in San Juan in May 1997. Utility relocation and surface works commenced in August 1997. Open cut excavation began in October 1997, and the first mining operations were operating by December 1997. The Rio Piedras Alignment Section 7 is scheduled for substantial completion by early 2001.

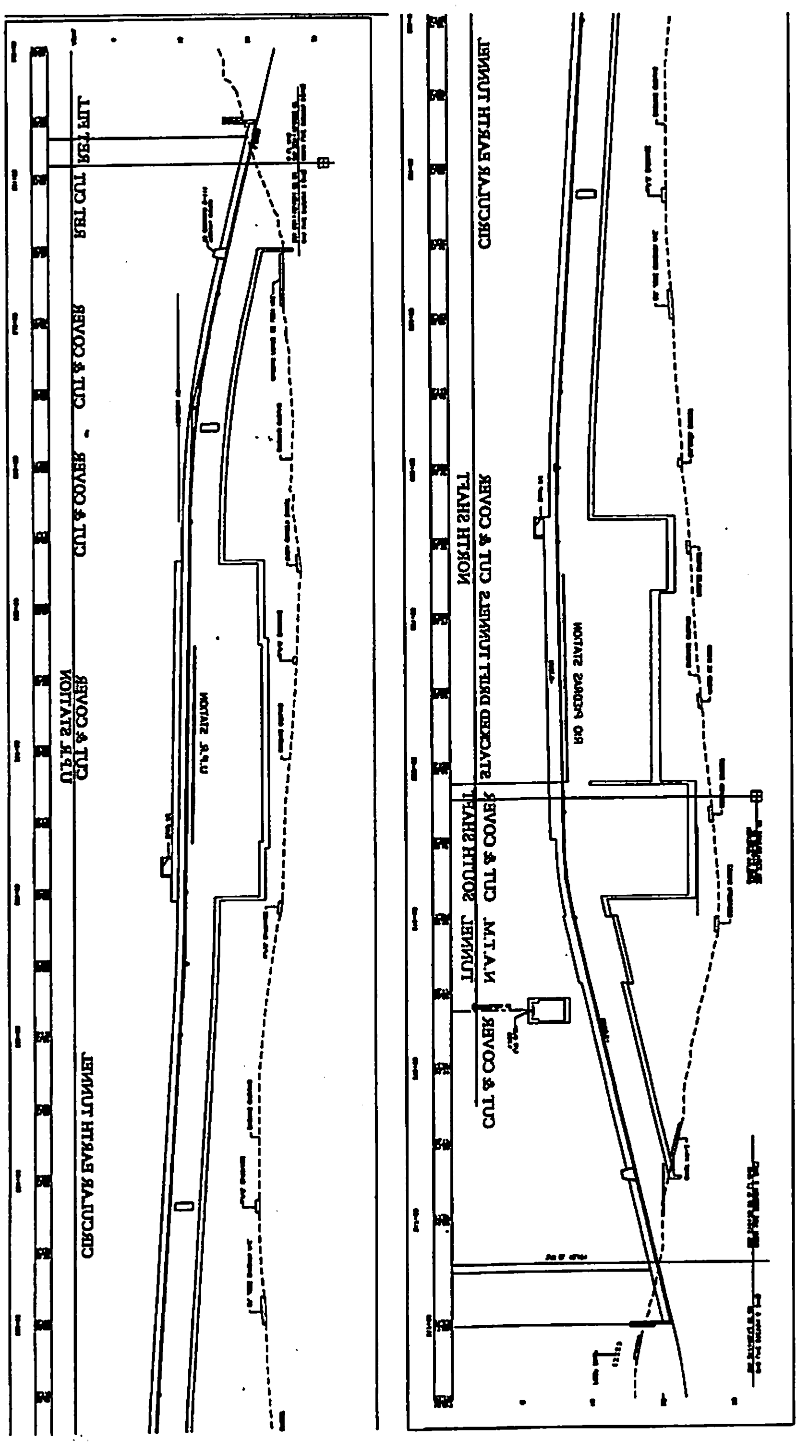

Figure 2. Profile of Allignment and Construction Methods

Contract Specifications

The Rio Piedras project has provided many challenges in terms of complexity of design, schedule, and logistics of construction in a dense urban environment. The focus of this paper is the challenges relating to the control of ground movement and the protection of historic structures along the alignment.

The contract specifications established the following limiting criteria for settlement of buildings and structures during construction:

• Minor ground movement	less than 6 mm
• Major ground movement	more than 12 mm
• Unacceptable settlement	more than 25 mm

The above contract limits for settlement includes the accumulative movement from all phases of construction including dewatering, excavation, unforeseen construction impacts, and load application to the structures. All of the above sources have proven to impact the ground control for the project to some degree.

The buildings of Rio Piedras are typically one to three stories in height, of masonry or concrete construction, and founded on shallow spread footings or rubble footings. The ground floors typically house commercial businesses, while the upper floors are used as residential apartments or small offices. Most buildings show signs of past movement such as cracks in plaster walls and slabs-on-grade, but in general are structurally sound.

SITE GEOLOGY

The Rio Piedras section of San Juan is situated in the Northern Coastal Lowland physiographic province, consisting of a broad coastal plain sloping from the foothills of the islands interior volcanic mountains to the Atlantic Ocean. The surficial soils are of alluvial origin, consisting of interbedded layers of sand and clay. In the vicinity of Rio Piedras, the alluvial soils are typically greater than 30 metres (100 feet) thick, and overlay karst limestone and ancient reef bedrock.

Density of the alluvium deposits is generally high, and increases with depth. A characteristic feature of the alluvium is the extensive conversion of non-quartz constituents to clay, although the original sand and gravel texture of the deposit is still visible.

Prior to awarding the Rio Piedras contract, Tren Urbano prepared a geotechnical data report based on the results of 22 soil borings and two groundwater pumping tests. The KKZ team further refined the subsurface profile and engineering properties of the soil with more than 15 additional borings that included pressuremeter testing and 75-mm (3-inch) continuous sample borings.

For design purposes, the subsurface profile was divided into four general stratigraphic units as shown on **Figure 3**. **Table 1** presents a summary of the engineering properties of each stratigraphic unit.

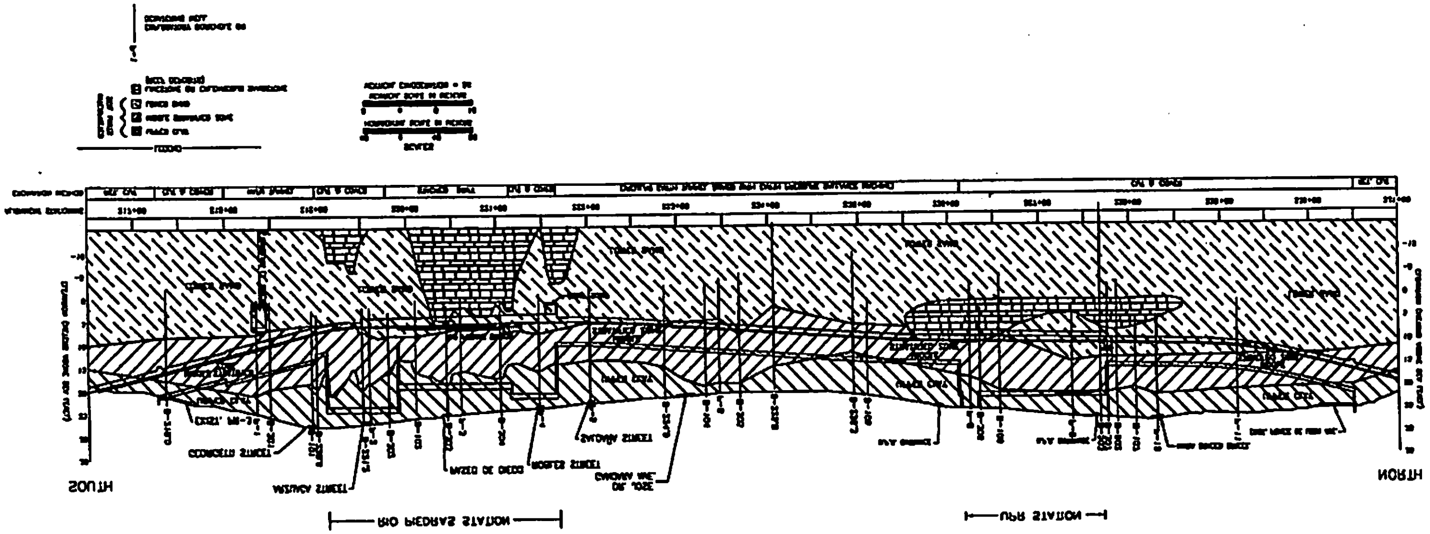

Figure 3. Geotechnical Design Profile, Rio Piedras Project

Table 1.

Stratigraphic Unit	Physical Description	Total Unit Weight (kN/m3)	Shear Strength (undrained) kPa	Shear Strength (drained) kPa	Average SPT (blows per foot)
Upper Clay	Very stiff, fissured plastic clay CH, CL	16	1.0 $\sigma'v$	$\phi' = 35^\circ$ $c' = 0$	20
Middle Stratified Zone	Interbedded clay and sand layers CL, ML, SM, SP	19.5	0.7 $\sigma'v$	$\phi' = 37^\circ$ $c' = 0$	25
Lower Sand	Interbedded, cemented silt and sand ML, SM, SP	19.5	1.4 $\sigma'v$	$\phi' = 37^\circ$ $c' = 96$ kPa	>100

$\sigma'v$ = effective overburden stress
ϕ' = effective angle of friction
c' = effective cohesion

Groundwater Conditions

Static groundwater levels generally reflect the ground surface topography at a depth of 5 to 10 metres (16 to 33 ft) below grade. Up to 3 metres of fluctuation in groundwater levels was observed between 1996 and 1998, reflecting periods of high and low precipitation.

The stratified nature of the Middle Stratified Zone and the Lower Sand strongly influences the behavior of the site hydrology. The groundwater pumping tests suggest that the groundwater regime behave like a series of aquifers, with some vertical leakage between them. Variable response of piezometers between strata and within single strata suggests the permeable layers are lenticular and locally continuous, but discontinuous over great areas. In general, the Middle Stratified Zone exhibits an average permeability on the order of 10-5 cm/sec, while the Lower Sand deposits show permeabilities as high as 10-2 cm/sec. The net effect of the stratified nature of the deposits is that deep well pumping drains the lower sand deposits very quickly, and substantial perched water remains in the sand layers of the middle stratified zone.

CONSTRUCTION METHODS AND ANTICIPATED GROUND BEHAVIOR

Controlling ground movement and protecting historic structures has been paramount in the development of the project specifications by Tren Urbano, which in turn drove the development of construction methods and settlement compensation method. The following paragraphs describe the construction methods and anticipated ground behavior of the underground components of the Rio Piedras Project.

Rio Piedras Station - Stacked Drift Tunnel

The platform section of the Rio Piedras Station is being constructed beneath the historic buildings of the Rio Piedras commercial center. Station configuration and vertical alignment restrictions result in a mined opening measuring approximately 17 meters (62 ft) wide by 16 meters (53 ft) high, with between 3 and 5 meters (10 to 16 ft) of ground cover between the roof of the station and the foundations of the overlaying buildings. A design and construction approach was developed by the KKZ/CMA team where a stiff concrete arch would be constructed around the perimeter of the station opening and then excavating the station platform area out from under the concrete arch. The arch will then function as the final structural support for the station. The arch is constructed as a series of 15 interconnected longitudinal drifts as shown on **Figure 4.**

The sequence for hand mining each individual drift consists of:

- Advancing poling plates in the crown of the tunnel using hydraulic jacks
- Excavating top heading using spaders and installing poling plates off the bench
- Excavating the bench and installing the permanent support steel and lagging
- Grouting behind lagging

Several variations to the basic concept above, such as channel spieling, mini excavators and square shields, have been tried to ease the advancement of the headings.

The primary method of controlling ground stability is dewatering. Several months prior to excavation, deep wells were installed and operated. Groundwater within the Lower Sand deposits was rapidly drawn down and maintained below the level of excavation. Even with sustained pumping, a substantial amount of perched water remained trapped in the Middle Stratified Zone. Localized wells and vacuum lances at the excavation face have provided little benefit in removing trapped water. A supplemental program of grouting ahead of the excavation was implemented to provide stability in saturated sand lenses within the Middle Stratified Zone.

Settlement and ground deformation will occur as each drift is constructed. Settlement estimates due to mining of the drifts were developed both by finite difference methods (FLAC model) and empirical methods by equating a settlement trough to a percentage of the excavated volume of the drift. **Figure 5** presents the results of the estimated total settlement based on the empirical method.

Once the arch is complete and the interior of the station mined, overburden soil loads will be transferred to the lowest drifts. This condition was determined to be most critical to the overall stability of the excavated station and total settlement, in that bearing contact pressure at the base of the foundation drifts could be as high as 900kPa (20,000 psf). However, settlement of the station structure at this stage of construction is estimated at less than 10 mm, due to the high stiffness of the cemented Lower Sand.

NATM Tunnels

South of the Rio Piedras Station, the Bayamon lines and the intersecting Carolina line extensions were constructed using NATM mining methods. NATM

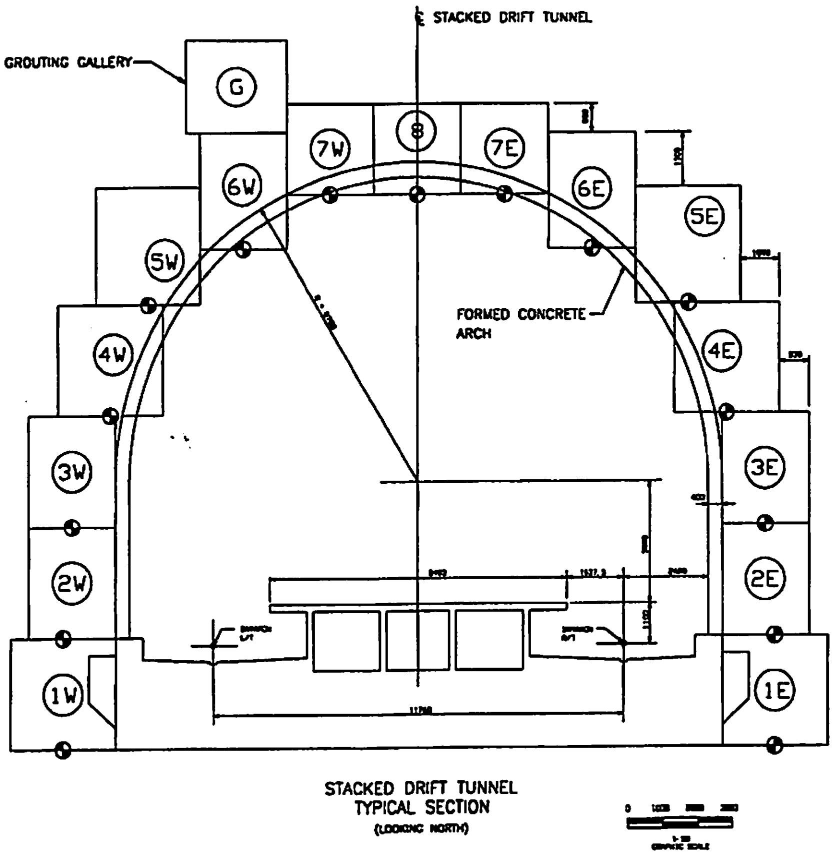

Figure 4. Stacked Drift Tunnel

was selected because each drive was relatively short (110 metres), the two Carolina drives terminates blind, and it was determined that this method provided the best control of ground movement beneath historic buildings. Complicating the design and construction of the NATM tunnels is that four adjacent tunnels would be constructed from the same shaft (**Figure 6**) and that the Carolina Left line drops and crosses below the Bayamon Right line (**Figure 7**).

The NATM tunnels are being excavated with a top heading and bench, each round being 1.2 meters (4 ft) and the top heading advanced three to four rounds ahead of the bench. Pre support for each round consists of steel forepoling pipes over 120 degrees of the crown. The primary lining consists of steel lattice girders and either a 240mm (9.4 in) or 325mm (12.8 in) shotcrete with welded wire fabric (WWF). A final 300mm (12 in) concrete lining will be placed after excavation and installation of a PVC water proofing barrier.

Figure 8 presents the predicted total settlement over the NATM tunnels.

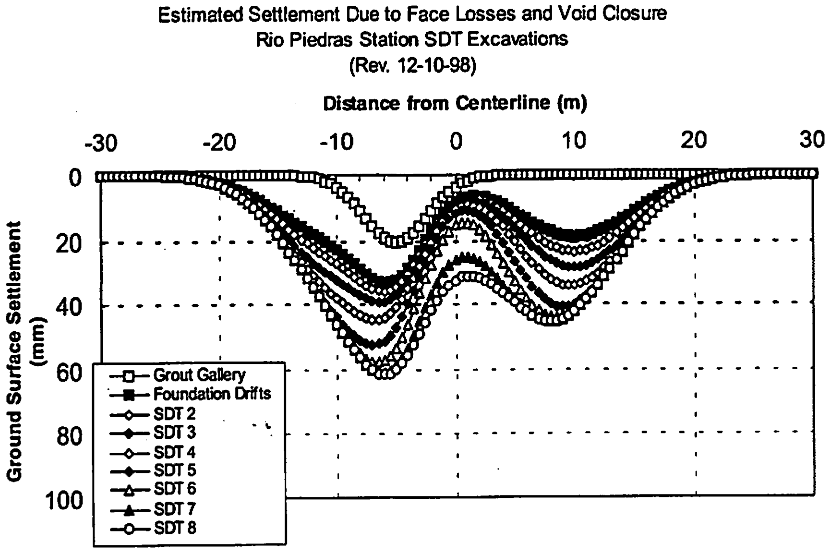
Estimated Settlement Due to Face Losses and Void Closure
Rio Piedras Station SDT Excavations
(Rev. 12-10-98)

Figure 5. Estimated Settlement Over Stacked Drift Tunnel Without Compensation Grouting

EPBM Tunnels

The UPR station and the Rio Piedras station will be connected with twin tunnels constructed using a 6.47-meter (21.2 feet) outside diameter EPBM. The segmental concrete tunnel lining will be completed as a one-pass system. The annular space between the segmental lining and the ground is continuously grouted during the advance of the EPBM.

The alignment of the twin tunnels passes beneath a historic fence structure for the University of Puerto Rico, a 7-story commercial and apartment building, and several 2 to 3-story commercial buildings. Also within the zone of influence of the tunnels are several large and sensitive utility lines within Ponce de Leone Avenue and the UPR Science building where several very sensitive physics experiments are in progress.

The twin tunnels are located within the Middle Stratified Zone geologic deposits. Several locations along the twin tunnel alignment were found to contain higher percentages of clean sand (SP) than have typically been found elsewhere. Soil cover over the tunnels ranges from 10 meters (33 ft) to 15 meters (50 ft), with the deeper cover occurring beneath the historic buildings. Dewatering wells were installed along the alignment and have been made operational for 6 months prior to beginning mining. As observed elsewhere on the project, some trapped and perched water is likely to remain within the Middle Stratified Zone, and should be encountered by the EPBM.

Settlement estimates above the twin tunnels were developed from empirical data. An allowance was made for settlements from the second tunnel to be double that of the first tunnel, due to ground relaxation. Typical predicted settlement for the twin tunnels is presented in **Figure 9**.

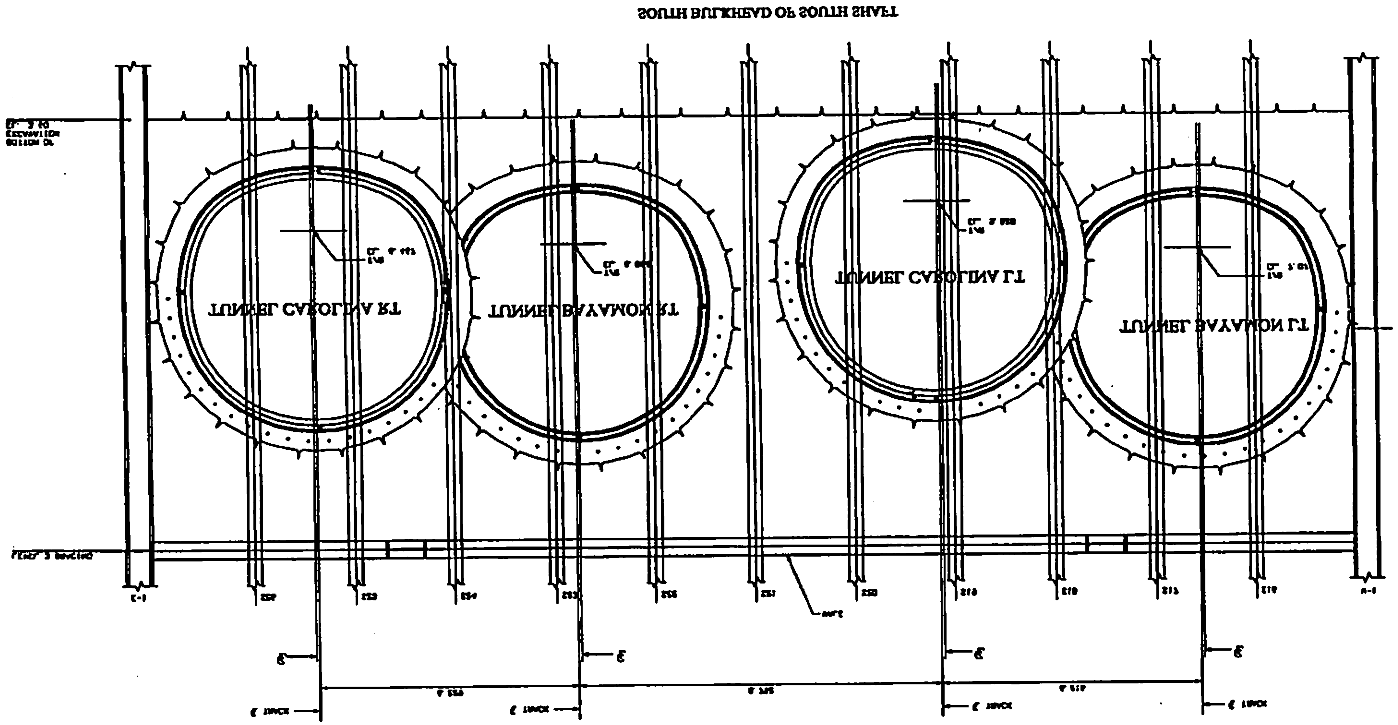

Figure 6. NATM Tunnel Excavation Sequence

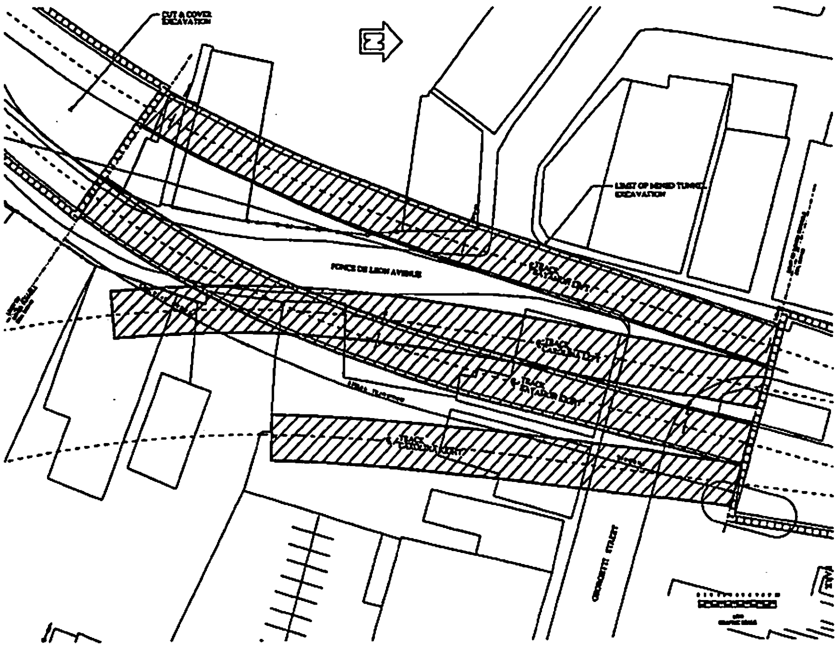

Figure 7. Plan view of NATM Tunnels

BUILDING PROTECTION METHOD

Without a supplemental method of control, the excavation of the mined portions of the Rio Piedras Project was predicted to settle beyond the contract limits set by Tren Urbano. The KKZ team subcontracted Soletanche-Bachy to develop and implement a program of compensation grouting beneath buildings and structures using a technique successfully used for the construction of the Jubilee line in London.

Compensation Grouting

Compensation grouting is a method of mitigating the effects of soil volume losses experienced during underground excavation by the controlled injection of grouts. The injection can occur before, during and after the excavation activity because the grout is pumped through reusable manchette pipes (TAM's). The grout injection sequences are designed to intercept the ground movements as they develop at the specific excavation location.

Compensation grouting for the Rio Piedras project involves a complex grout injection procedure linked to a real time computer-based analysis of information, which generates the appropriate grouting sequence and quantities. Optical survey measurements and computer motorized theodolite data are both being used on the Rio Piedras project as the primary source of ground movement information.

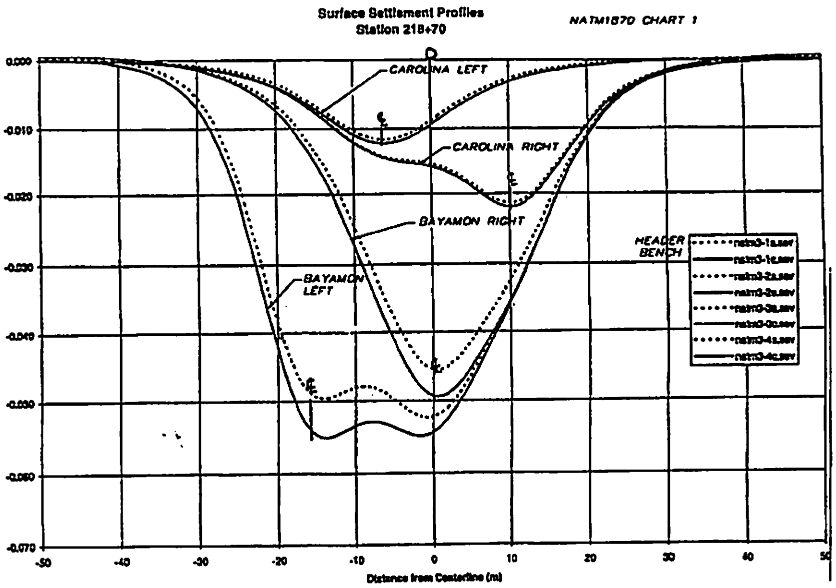

Figure 8. Estimated Total Settlement Over NATM Tunnels

Soletanche Bachy has designed software to process the large volumes of data recorded by the survey instruments, and to initiate the appropriate grouting volumes and sequences. Quantities of grout to be used in each injection phase are first based on initial settlement predictions derived from theoretical computations and the in-situ experience gained during the early stages of the work. These estimates are then compared actual ground response readings, and adjusted accordingly.

Development of the grouting program. The first step in developing the grouting program is to determine the buildings and structures that will requre protection from settlement. This is determined by theoretical calculations made during the design phase of the project. The area to be protected is then delineated with arrays of grout pipes in such a pattern as to obtain an ideal spacing between injection points, typically varying from of 1.5 to 3 meter (5 to 10 ft) in spacing. The selection of the grout pipe spacing depends both on the depth of the underground excavation and the magnitude of predicted settlements. The grout injection port sleeves on the 50-mm (2 in) diameter grout pipe are typically spaced at 0.3 to 0.5 meter (1 to 1.6 ft) centers. The multiple grout injection programs required during the course of excavation makes the use of steel pipe a mandatory requirement on the Rio Piedras project.

Once the pipes are sealed in place, compensation grouting can proceed. Grouting generally takes place in four phases:

1. *Preconditioning.* The purpose of the preconditioning phase is to stiffen the ground by compressing the soils and filling any loose areas before excavation starts. This operation pre-stresses the ground in order to ensure a quick reaction of the ground when actual compensation grouting is to start. For the Rio Piedras project, a talc-cement mix as was used to precondition the upper clay soils.

2. *Pre-lifting grouting.* The objective of the pre-lift grouting is to produce a slight heave of the structures within a specific area before settlement from the underground excavation influences them. During this phase, grouting proceeds until a slight heave of 2 to 3 mm is recorded by the geotechnical instrumentation. This movement is proof that the ground is pre consolidated, and ready to react quickly if subsequent compensation grouting is required. The pre-lifting phase may be extended if more initial heave is desirable, such as in areas where it is impossible to compensate at the same time as the excavation is ongoing.

3. *Real-time compensation grouting.* Grout injection programs were specifically developed for each excavation case such as NATM, stacked drifts, and EPBM. Grout is injected through specific ports at specific locations beneath buildings to counteract observed settlement. The grout is injected in measured increments until either the required volume has been injected or the building movement readings have reached predetermined threshold levels. Pumps used for grouting are computer controlled and can be stopped when pre selected volumes of grout or pressure thresholds are reached. The grouting program is modified during the excavation advance in accordance with the observed ground response. For the Rio Piedras project, the programmed grout volume typically corresponds to 2 to 3 times the estimated volume of surface settlements.

4. *Post grouting phase.* This last phase would be carried out in the event that post compensation grouting settlement of a building is still considered excessive, or if pre conditioning of the ground is required prior to mining of future tunnels. The grout injection process is similar to that described above.

Automated building monitoring and grout system. One of the key features of the overall monitoring system is the CYCLOPS (cyclic optical survey). The CYCLOPS system consists of an automatic computer controlled TCA-1800 theodolite. The system automatically records the position and movements of target prisms located on the surrounding buildings on a predefined cycle. It enables survey in real time of twenty two buildings located within the area that may possibly be affected by settlements due to the 148 meter (488 ft) long Rio Piedras Station. The position of the each target has been selected to take into account such problems as visibility, radius of action of the theodolite, location with regard to settlement influence area etc.

The unit, installed on the roof of the highest building in the area, is monitoring fifty target prisms installed on the surrounding buildings, and provides readings

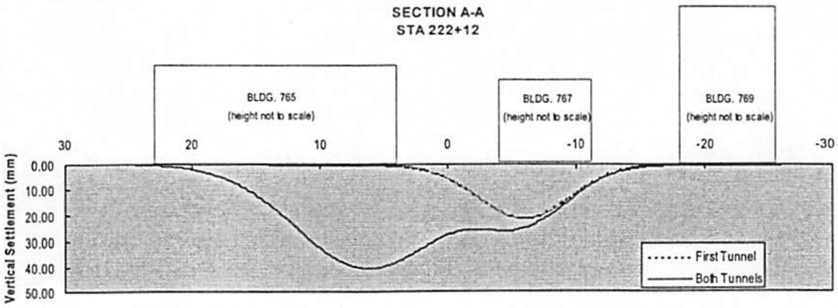

Figure 9. Typical Estimated Settlement Due to EPBM Mining

every 10 minutes. Additional target prisms are located outside of the zone of influence and allow the system to instantaneously calculate its own position, before starting the survey cycle.

The theodolite is connected to a computer in the project field office, which translates the data into three-dimensional movement of each prism in real time. The reading precision of the CYCLOPS system is +/- 1 mm at a 120-meter distance. The recorded data is stored in a database and processed to display in real time graphics showing movements versus time of each target prism.

In a second step, the theoretical and empirical settlement estimates allowed to define parameters in the Soletanche Bachy developed software COGNAC (compensation grouting assisted by computer), which integrates settlement models, and automatically defines grouting programs.

Stacked Drift Tunnels

Settlement due to excavation of the platform section of the Rio Piedras Station is predicted to impact 22 buildings. Initial estimated of total settlement range from 35 to 55 mm. These estimates were based on an assumed settlement volume equal to approximately one percent of the drift volume. Total settlement was presented previously in Figure 5. At the time this article was prepared, only drifts 1E and 1W have been excavated. Based on actual measurements during construction, settlement volumes from Drift 1E and 1W appear to have been underpredicted. Actual settlement volumes for these drifts have been in excess of 5 percent of the drift volume. Total settlements have been impacted by several events during construction that were unrelated to drift excavation. Typical results of total settlement are shown on **Figure 11**.

Final results of the total settlement will be presented in future technical publications.

The compensation grouting scheme was developed with grout pipes extending over the roof of the station, and extending across the entire zone of

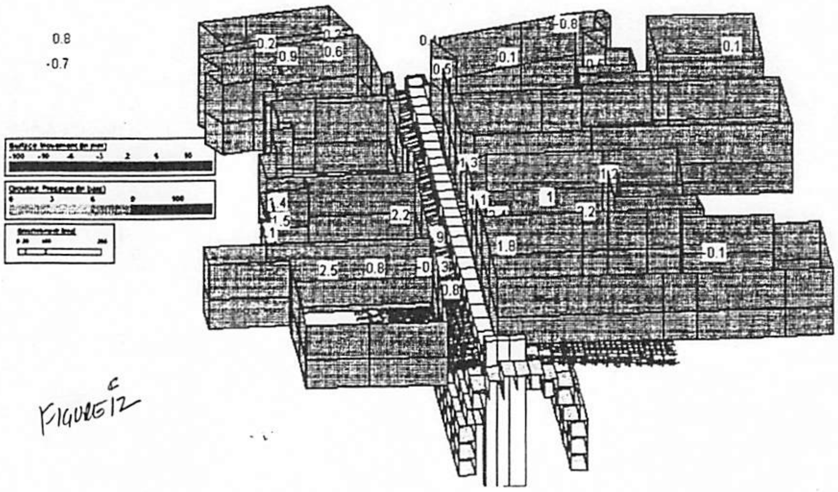

FIGURE 12

Figure 10. Location of Cyclops Measuring Points

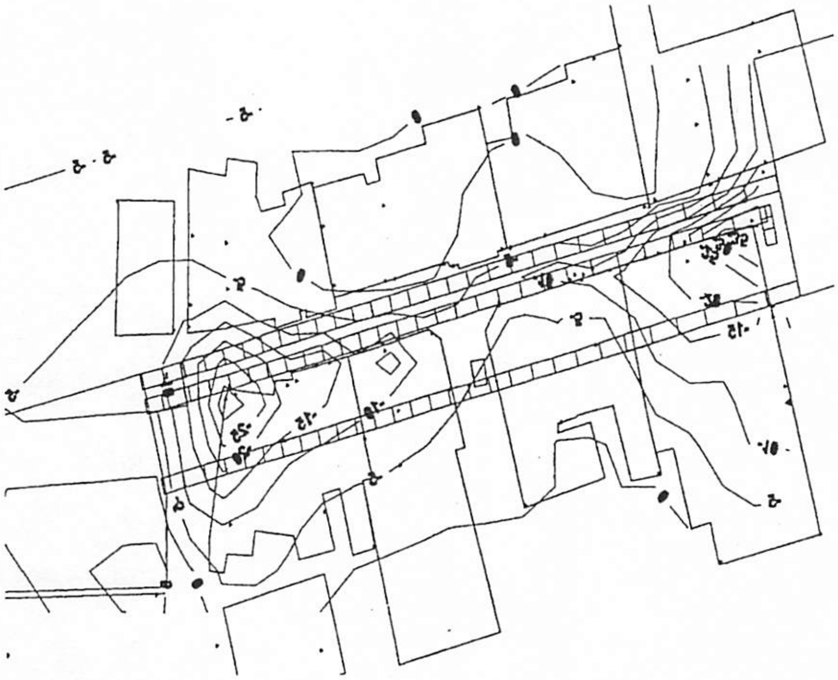

Figure 11. Actual Ground Surface Settlement During Excavation of Drifts 1E and 1W

influence. **Figure 12** presents a schematic of the grout pipe locations in relation to the stacked drifts of the Rio Piedras station.

Access for grouting operations on the site is limited. Grouting from the ground surface was not considered feasible due to space limitations. The KKZ design team determined that grouting would be performed horizontally from a drift that extended above the station structure. Location of the grout gallery drift was presented in Figure 4. The grout gallery was established as a sixteenth drift above drift no.6W. To the west of the station, the grout pipes were angled downward to inject grout lower in the formation. This has proven to be more efficient, in that higher grout pressures can be used resulting in more ground lift per unit volume of grout. Grout pipes were installed in a parallel arrangement at spacing of 1.5-meter (5 feet). Drilling for the pipes was made through the upper clay soil strata, and did not require casing. Standard drilling with a tri-cone bit and bentonite drilling fluid was sufficient to obtain hole stability.

NATM Tunnels

The four NATM tunnels pass beneath historic buildings along Georgetti Street. Predictions from the NATM excavation indicate maximum settlement on the order of 55 mm would be experienced in the Georgetti Street buildings without compensation grouting. Maximum settlement would not be realized until the Bayamon Right tunnel is excavated beside and above the Carolina Left tunnel. (Refer to: Tunneling on the Tren Urbano Project, Gay, et.al. in these proceedings for further information on the NATM excavation sequence). The compensation grouting program developed for these buildings is similar to that described or the Rio Piedras Station. The difference being that the TAM pipes could be installed in a radial manner from a single shaft location. All grouting operations will also be conducted from the single grout shaft.

The 4.3-meter diameter (14 ft) grout shaft was constructed to a depth of approximately 6 meters (20 ft). The shaft location was selected in a low area behind the buildings to minimize its depth, and so that grouting operations could be conducted with minimum impact to the community. From this shaft, 29 TAM pipes were installed in a radial pattern beneath the buildings.

Because they are placed in a radial pattern, spacing between the pipes varies from 1.5 metres (5 ft) to 3 meters (10 ft) beneath the buildings.

At the time of this writing, the Carolina Left tunnel has been successfully excavated, and work is beginning on the Bayamon Left tunnel. Maximum settlement experienced to date has been approximately 16 mm. Preconditioning grouting has been successfully completed in all grout pipes, and compensation grouting has not yet been required.

EPBM Tunnels

The twins EPBM tunnels parallel Ponce deLeone Avenue between the UPR station and the Rio Piedras station. The tunnels pass adjacent to buildings and structures on the University of Puerto Rico campus that are sensitive to settlement, and pass beneath 10 commercial and residential buildings before entering the north shaft of the Rio Piedras station. One building that was considered particularly

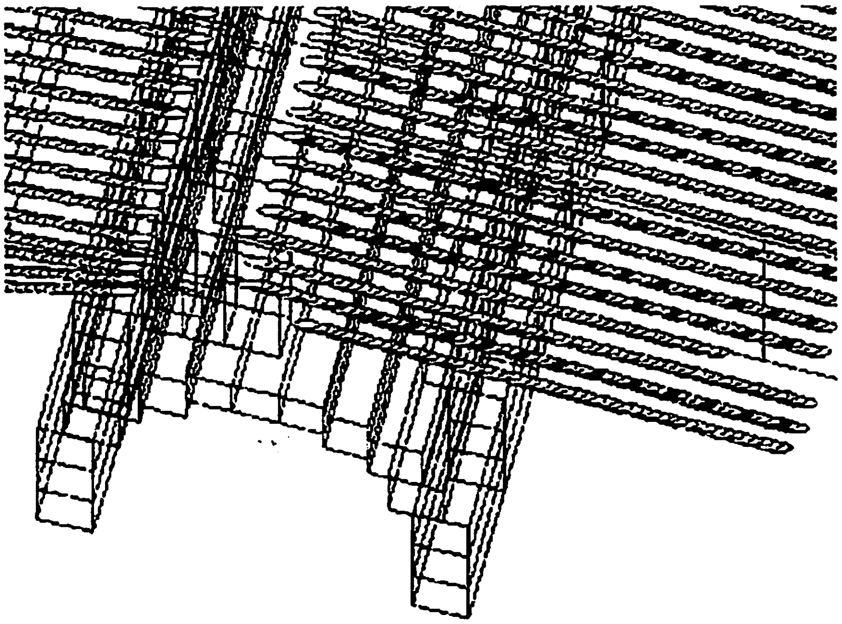

Figure 12. Scematic Location of Grout Pipes Over the Rio Piedras Station

sensitive to settlement is a 7-story commercial and apartment building located on the corner of Ponce deLeone Avenue and Dr. Jose Gandara Avenue. A compensation grouting program was developed for protection of this building.

The project settlement control plan allows for the development of supplemental building protection measures beneath other structures if the actual settlement above the twin tunnels warrants that action.

Like the NATM tunnels, adequate surface area was available to install a single shaft for the installation of TAM pipes and to conduct grouting operations. Also like that described for the NATM tunnels, a 4.3-meter diameter (14 ft) grout shaft was constructed to a depth of approximately 6 meters (20 ft). From this shaft, 18 TAM pipes were installed beneath the apartment building.

At the time of this writing, the EPBM tunnels were being prepared for mining. Preconditioning grouting has been successfully completed beneath the apartment building.

SUMMARY AND CONCLUSIONS

This paper has presented an overview of the settlement control and compensation grouting program for the Rio Piedras alignment of the Tren Urbano, currently under construction in San Juan, Puerto Rico. Based on the installation and proof-grouting operations, and the early stages of compensation grouting, we offer the following general conclusions:

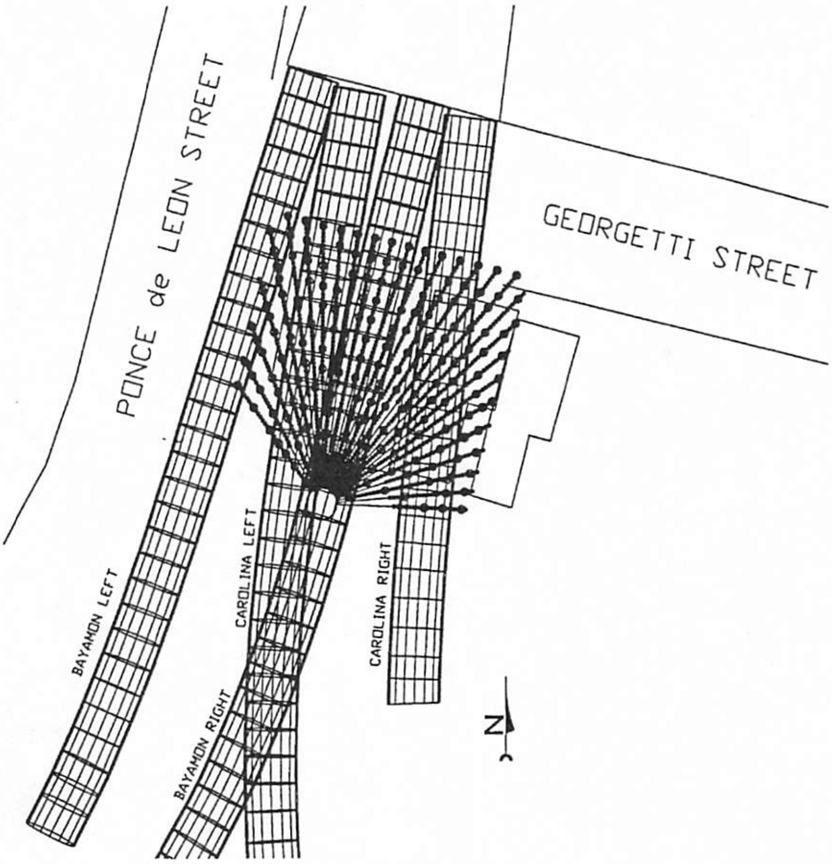

Figure 13. TAM Pipe Arrangement From a Single Shaft Location - NATM Tunnels

1. The compensation grouting method is based on an iterative process where daily grouting programs are developed from a combination of calculated settlement predictions and actual measured settlements from on-going excavation. An efficient reliable and continuous survey of the buildings and ground movements is consequently a key part in the success of this technique. The compensation grouting program established by Soletanche Bachy for the Rio Piedras project allows KKZ to monitor and control excessive settlements in real time.

2. The use of the CYCLOPS settlement monitoring system is an improvement over traditional optical survey measurements for use in compensation grouting programs. The primary improvement is in the time required to compile and evaluate settlement data, and incorporate that data into a specific grouting program.

3. Ground settlement associated with the Rio Piedras project have been difficult to predict, and have been influenced by many factors including:

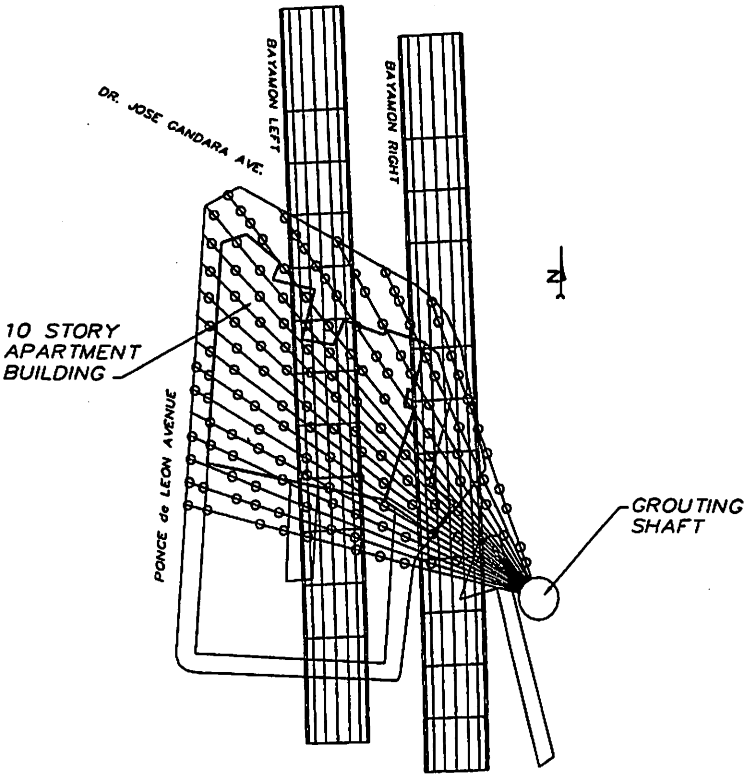

Figure 14. TAM Pipe Arrangement From a Single Shaft, 10-Story Apartment Building Above Twin EPBM Tunnels

complex geometry of the excavations, a complex soil profile, and unanticipated events such as utility line breakage. The net result has been a general underprediction of total settlement above some portions of the mining operations, and settlement patterns that are not uniform along the alignment. The compensation grouting program has been flexible in accommodating the settlements experienced to date.

4. The geometry of the stacked drift support for the Rio Piedras station presents several challenges to the KKZ team; including limited site access and shallow cover. The shallow cover above the Rio Piedras station resulted in a program that was not as efficient as one that would have been established at greater depth. The system has, however, proven adequate to control the settlement that has been experienced to date.