New Methods For Building Protection From Settlement Due To Underground Transit Construction

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ABSTRACT

Despite the best efforts of a contractor to minimize ground movements associated with underground construction, surface settlement is a constant concern when constructing subsurface transit systems in urban environments. While methods for prediction of settlement due to tunnel and cut-and-cover construction have been well established since the early 1970s, methods for mitigating settlement or protecting buildings from settlement have changed significantly in the United States over the last two decades. Tunnel excavation methods that minimize ground movement are being used with greater frequency, such as earth pressure balance (EPB) tunnel boring machines and construction aspects of the New Austrian Tunneling Method (NATM). Underpinning, traditionally an expensive and disruptive building protection method, has been largely supplanted by ground modification methods to mitigate settlement. Examples of ground modification for building protection include permeation grouting and compaction grouting, which came into widespread use in the 1980s, as wells as compensation grouting, which was first used in the United States in the 1990s. In addition, new, sophisticated instrumentation systems have been developed to monitor building movement with great accuracy in real time, thus allowing efficient and effective grouting efforts. Two examples of compensation grouting for settlement protection are reviewed: the Tren Urbano transit system in Puerto Rico, which used compensation grouting in conjunction with an automated building monitoring system; and the Eastside Light Rail Transit project in Los Angeles, which is planning to implement compensation grouting in a phased payment approach.

INTRODUCTION

Transit guideways and stations are often constructed in dense urban environments where settlement from underground construction is almost always a key environmental issue. Frequently, these transit structures are relatively shallow, excavated in soil, and, thus, are more likely to generate surface settlement; tunnels and stations excavated in rock generally do not generate appreciable surface settlement. In addition, underground transit guideways are usually constructed as twin tunnels, which further exacerbates settlement.

To mitigate settlement due to underground construction, numerous methods have been developed, ranging from improved tunnel excavation and ground support techniques to various ground modification methods. The selection of settlement mitigation measures depends on the magnitude and extent of settlement, as well as the potential for settlement to damage adjacent structures. This paper reviews how settlement is predicted for underground transit structures, and how building damage can be predicted from such settlements. Settlement mitigation methods employed over the last 20 years are then reviewed. Finally, the authors' experience is discussed in two case histories for tunnel settlement building protection.

PREDICTION OF SETTLEMENT

Methods for predicting two types of settlement are discussed in the sections that follow: settlement due to tunnel construction and settlement due to open-cut construction.

Settlement Due to Tunnel Construction

The method commonly used for calculation of tunnel settlements is primarily based on one first put into widespread engineering practice by Peck (1), and more recently summarized in the Tunnel Engineering Handbook (2). This method assumes that the tunnel settlement trough is bell-shaped. The volume of the settlement trough is assumed to be equal to the total volume of "lost ground" during tunneling, which is usually given as a percentage of the excavated diameter. Lost ground is defined as the volume of all ground movement taking place around a tunnel. The estimation of ground loss is dependent on many factors, including tunnel excavation method, workmanship exhibited by the contractor, and geotechnical conditions. In the end, the engineer's experience with the same tunnel excavation methods in similar geologic settings will yield the best estimate of ground loss for a particular project.

The maximum settlement and width of the settlement trough at the surface are a function of the volume of lost ground, depth of the tunnel, and geotechnical characteristics of the soils. The calculated settlement troughs for two adjacent tunnels (common to transit systems) are assumed to be additive (see Figure 1).

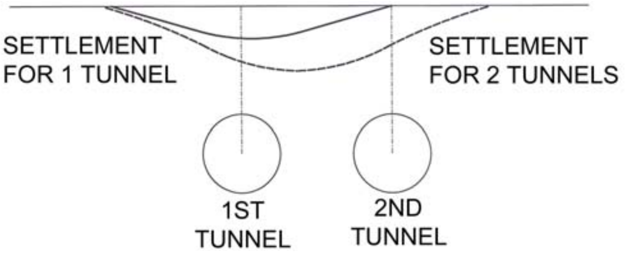

Figure 1. Settlement Troughs Due to Twin Tunnels.

Settlement Due to Open-Cut Construction

Peck (1) also developed early fundamental approaches for calculating ground movement associated with open-cut construction. Subsequent field performance monitoring has refined methods for estimating ground movement, which consider not only the excavation depth, but also the geologic conditions and structural stiffness of the excavation support system. This more refined approach is given by Clough and O'Rourke (3).

Ground surface settlement adjacent to open-cut excavations is usually calculated using empirical surface settlement envelopes. Depending on the geotechnical conditions, maximum settlement is based on a percentage of wall height, and the distribution of the settlement follows a trapezoidal envelope.

PREDICTION OF BUILDING DAMAGE

The state of practice for predicting building damage due to tunnel settlement is summarized by Boscardin and Cording (4). This method takes into account the overall magnitude of ground movement, building location within the settlement trough, and horizontal strains in the ground associated with settlement. Buildings are assumed to behave as deep beams, which has historically been the simplest way to establish a framework for relating settlement, building movement, and structural performance of the building. Calculated maximum values of angular distortion and horizontal strain for each building (as a beam) are correlated to a strain diagram with defined damage categories, which are easily confirmed by field observation (see Table 1).

Class of damage	Description of damage
Negligible	Hairline cracks.
Very Slight	Fine cracks easily treated during normal re-decoration. Perhaps isolated slight fracture in building. Cracks in exterior brickwork visible upon close inspection.
Slight	Cracks easily filled. Re-decoration probably required. Several slight fractures inside building. Exterior cracks visible, some re-pointing may be required for weathertightness. Doors and windows may stick slightly.
Moderate	Cracks may require cutting out and patching. Recurrent cracks can be masked by suitable linings. Tuck-pointing and possibly replacement of a small amount of exterior brickwork may be required. Doors and windows sticking. Utility service may be interrupted. Weathertightness often impaired.
Severe	Extensive repair involving removal and replacement of sections of walls, especially over doors and windows required. Windows and door frames distorted, floor slopes noticeably. Walls lean or bulge noticeably, some loss of bearing in beams. Utility service disrupted.
Very Severe	Major repair required involving partial or complete re-construction. Beams lose bearing, walls lean badly and require shoring. Windows broken by distortion. Danger of instability.

Table 1. Building Damage Correlations, After Boscardin and Cording.

Boscardin and Cording's approach was developed for unreinforced masonry buildings, since these building types comprise a large number of older buildings affected by modern-day urban tunnel construction in the Midwest and eastern U.S. This method, however, is also considered applicable to other types of buildings. For example, although a timber frame building has substantial redundancy and could be expected to sustain higher strains than an unreinforced masonry building, interior finishes, such as plaster walls and ceilings, would be expected to exhibit more brittle behavior, and hence sustain architectural damage at lower levels of distortion. This assumption would also apply to steel frame buildings with veneers susceptible to cracking, such as stone.

METHODS OF BUILDING PROTECTION IN THE 1980S

three methods of building protection are discussed below: underpinning, permeation grouting, and compaction grouting.

Underpinning

Underpinning is a general term for installation of a new foundation under an existing building foundation for the purpose of supporting building loads on a soil stratum that is not subject to settlement. Methods of underpinning vary, and some methods may not be feasible for structures situated directly over a tunnel. The method used for underpinning is dependent on geotechnical conditions, access to foundations (from the ground surface or within building basements), type of existing building foundation, type of building structure, and magnitude of the building loads.

Traditional underpinning involves hand excavation of pits underneath existing foundations, followed by backfill with mass concrete. This type of underpinning is still used today, but is typically costly, labor intensive, and disruptive. For any type of underpinning, there is the risk of settlement and damage to the structure in the process of attempting to protect the structure.

For buildings that lie mostly within the predicted settlement trough, it is likely that underpinning will not be technically feasible for building protection, since underpinning elements would have to “bridge” over tunnel structures.

Permeation Grouting

Permeation grouting is a ground modification technique that fills pore spaces in soil (see Figure 2). Performed at relatively low injection pressures, permeation grouting is most often used to decrease permeability and limit ground loss/settlement by increasing the strength and stiffness of the soil. Various materials are used for this type of grouting, including ordinary Portland cement, microfine cement, bentonite, epoxy resins, and, most commonly, sodium silicate. The types of soil in which permeation grouting is usually effective include clean gravels and sands, i.e., soils with a silt and clay content less than 20 percent.

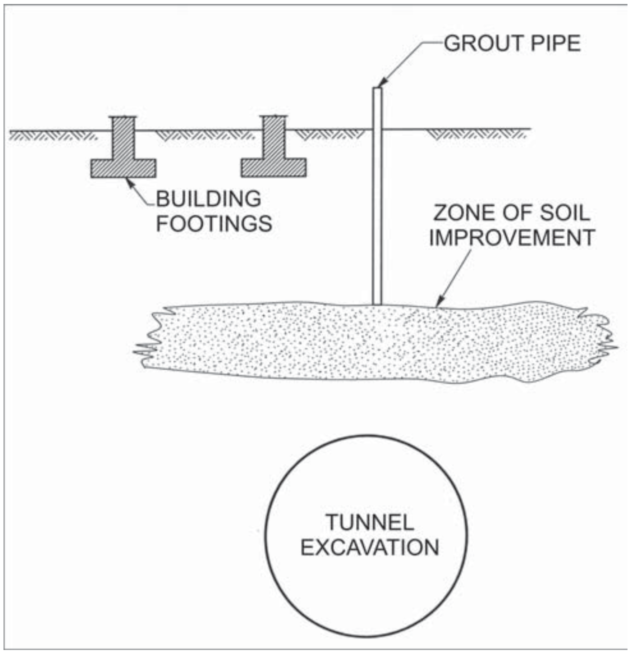

Figure 2. Permeation Grouting.

Permeation grouting has been used successfully on many underground projects by injecting grout through pipes installed from the ground surface.

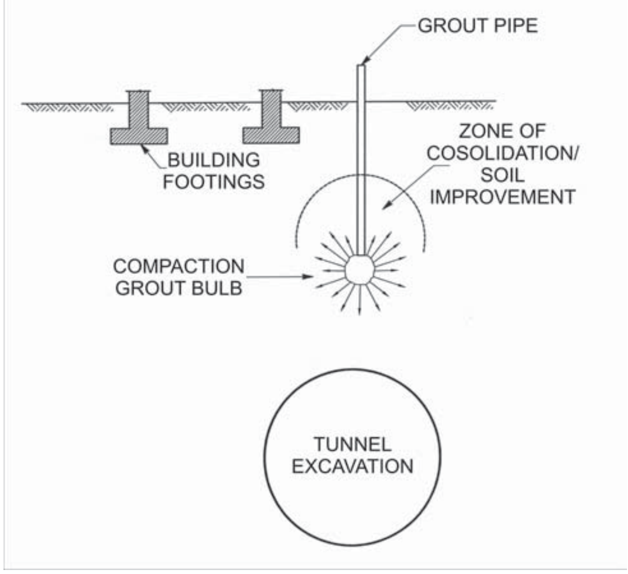

Figure 3. Compaction Grouting.

Compaction Grouting

Compaction grouting involves injection of a very stiff mortar-like grout into subsurface soils in a closely controlled manner. The objective is not to fill inter-particle voids, as is done with permeation grouting, but rather to displace and compact soil in place. During compaction grouting, the soil is densified through compaction (see Figure 3). The shape of the grout mass is usually spherical (a bulb) or cylindrical. The primary uses of compaction grouting are to improve soil properties and/or compensate for voids, usually as a preventive or remedial measure for structure movement in response to settlement.

Compaction grout is injected under high pressure through a steel pipe, which can be installed from the surface or from within subsurface excavations, such as a shaft or tunnel (5). Pipes installed from the surface are usually set up in advance of underground excavation. When used to reduce settlement under buildings, it is best to inject grout below footings that are directly under load-bearing members of the building. In addition, it is usually more economical to install grout pipes from the surface, access permitting. Although compaction grout can be installed from within a tunnel under construction, the grouting process interrupts the normal cycle of tunneling, which can lengthen the construction schedule.

When the diameter of the grouting bulb is relatively small, the pressures are essentially radial and, therefore, horizontal. As the size of the grout mass increases, considerable uplift forces develop. This uplift force can be used to raise structures that have settled; however, careful control of grouting pressures is necessary so as not to damage structures by excessive heave.

One of the principal advantages of compaction grouting is that it has maximum benefit in the weakest soils. It is frequently used in fine-grained soils, but has limited application in fine-grained soils with low permeabilities that develop high pore pressures when subjected to induced stresses (6). In these cases, grouting must take place in a series of injections.

METHODS OF BUILDING PROTECTION SINCE THE 1990S

Four relatively new methods of building protection are discussed in the sections below: pressurized-face tunnel boring machines, Sequential Excavation Method (or New Austrian Tunneling Method), jet grouting, and compensation grouting.

Pressurized-Face Tunnel Boring Machines

Large-diameter steel cylinders, or tunnel shields, have long been used to protect workers when excavating soft-ground tunnels. When a tunnel shield is fitted with a rotating cutterhead, it is usually referred to as a tunnel boring machine (TBM). Cutterheads on a TBM can be open or closed to the atmosphere. Closed cutterheads, with the proper seals, can maintain pressure on the soil in front of the TBM and permit construction in soil conditions that would be unstable with an open cutterhead. Currently, there are two basic types of pressurized-face TBMs: (1) slurry shields, and (2) earth pressure balance (EPB) machines.

Slurry shields rely on a slurry to apply pressure to the tunnel face in the plenum (pressure chamber), which counterbalances earth and hydrostatic pressures. Pressure is maintained on the excavation face by a mud cake, which forms on the tunnel face spontaneously as excavation proceeds. Excavated soil is carried away from the cutterhead by the slurry, which is separated from the soil at a plant on the surface. Separated slurry is re-circulated to the cutterhead.

EPB machines rely on the excavated soils, under confinement in a cutterhead chamber, to balance earth and hydrostatic pressures. The pressure is maintained by a screw conveyor in which a soil plug provides the seal (see Figure 4). Excavated soil is removed through the screw onto a conveyor or into muck cars.

The choice between slurry shield and EPB excavation methods is influenced by several geotechnical factors, including grain size distribution, cohesiveness, occurrence of boulders or obstructions, occurrence of gas, soil contamination, feasibility of soil separation and muck disposal, and settlement considerations.

The advantage of pressurized-face TBMs is that ground losses can be minimized, even in unstable ground conditions. When used properly, pressurized-face TBMs can yield smaller surface settlements than open-face tunnel shields.

Sequential Excavation Method (or New Austrian Tunneling Method)

As defined by the Austrian Society of Engineers and Architects, the New Austrian Tunneling Method (NATM) "…constitutes a method where the surrounding rock or soil formations of a tunnel are integrated into an overall ring-like support structure. Thus the supporting formations will themselves be part of this supporting structure." Fundamental principals of the NATM include maintaining strength of the surrounding ground; rounded tunnel shapes; a flexible, thin lining; and in situ geotechnical instrumentation and monitoring during excavation. In worldwide practice, however, when shotcrete is proposed for initial ground support of an open-face tunnel that is excavated and supported sequentially, it is often referred to as NATM. As

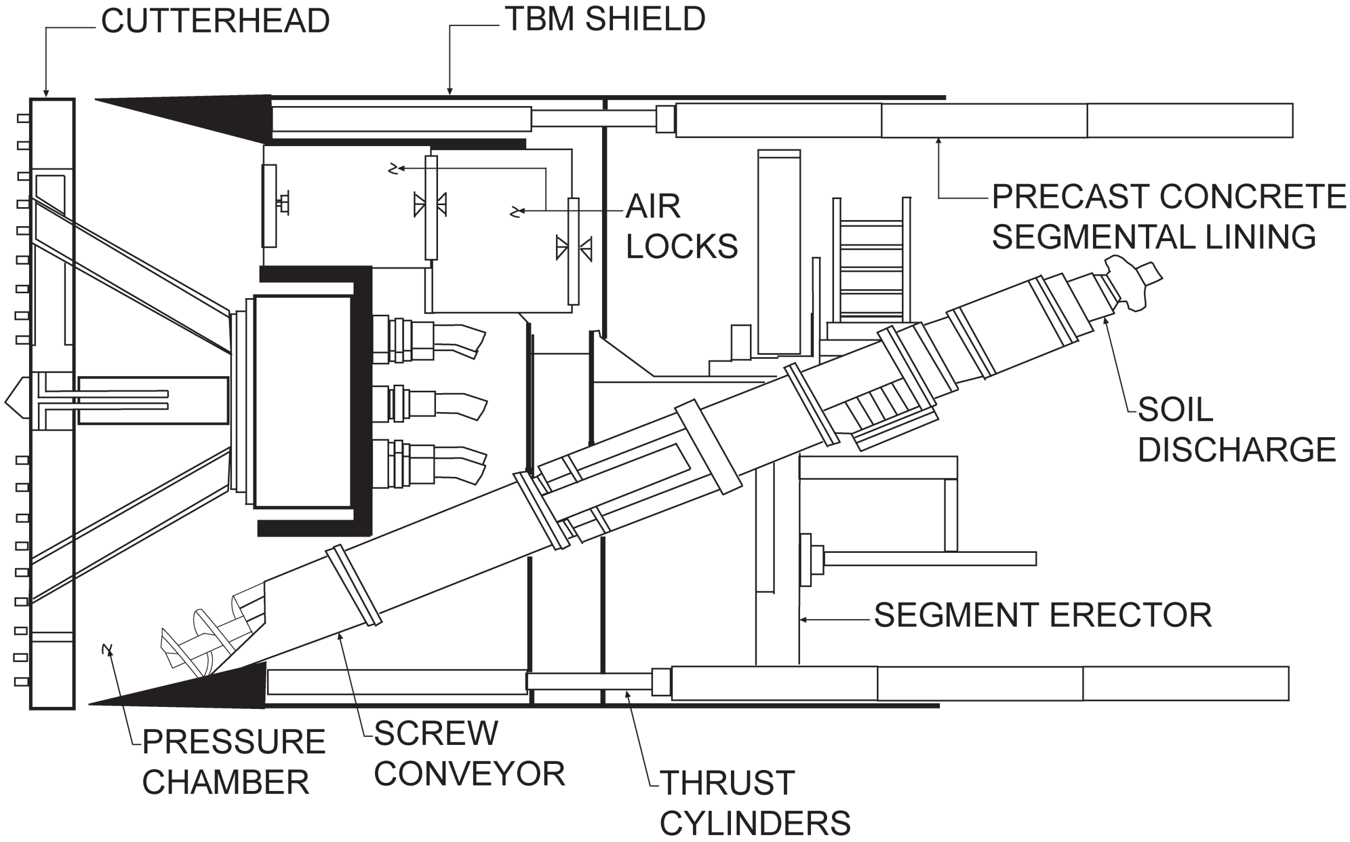

Figure 4. Earth Pressure Balance Tunnel Boring Machine.

a result, tunnels constructed by this method are often referred to as either NATM or SEM (for Sequential Excavation Method). The NATM/SEM does not use tunnel shields for worker protection, since the application of shotcrete is not amenable to excavation with TBMs.

In order to limit settlement and ensure worker safety, most soil tunnels constructed by the NATM/SEM employ the following measures: (1) excavation stages must be sufficiently short, both in terms of dimensions and duration, and (2) erection of the "full ring" of initial ground support must be completed immediately after the full face is excavated. When these measures are carefully employed by an experienced contractor, the resulting settlement can be less than occurs when using open-face or pressurized-face TBMs.

Jet Grouting

Jet grouting is a ground modification technique based on the erosional action of very high-velocity fluids, acting under high nozzle pressures. The fluids (generally water and/or grout) are injected via a special drill tool called a "monitor," which is attached to the end of a steel drill string (see Figure 5). As the monitor is rotated and withdrawn at controlled rates, the pressurized fluids fracture, erode, mix, and partially replace the surrounding soils with a cementitious grout. The high velocity and pressures are obtained by pumping the water and/or grout with heavy-duty pumps through small-diameter nozzles located on the monitor. The soil structure is obliterated by the jets, and the original subsurface material is ultimately mixed with grout to form soil-cement columns. Since the grout being injected only partially replaces in situ soils, eroded soils and excess grout are returned to the surface as spoil with the consistency of slurry. The dimensions and mechanical properties of the jet grout columns depend on the type of soil, composition of the grout, grout pressure and flow, and monitor rotational and withdrawal speed (7).

Jet grouting for tunnel construction is usually used as an underpinning element for building foundations adjacent to tunnel construction, or as a ground improvement technique for soils to be excavated by tunneling, as described by Romero and Pellegrino (7). For either application, there must be reasonable access from the surface for jet grouting. In urban environments, the large volumes of slurry spoil generated during jet grouting must be adequately handled and disposed. In addition, due to the high pressures employed during jet grouting, care must be taken to prevent heave of adjacent structures. Despite these limitations, jet grouting has considerable advantages for use in tunnel construction, particularly in the most challenging ground conditions.

Compensation Grouting

The principle of compensation grouting involves carefully controlled injection of grout between an underground excavation and structures requiring protection. For tunnel applications, the pipes for grouting are installed above the intended tunnel position, in advance of tunneling (see Figure 6). A key component in controlling compensation grouting is careful monitoring of both structure and ground movement in order to optimize the timing and quantities of grout injected. Grout can be injected repeatedly via sleeve-port-pipes (also known as tube-a-manchettes), with the injected volumes being controlled to limit the lateral spread of the grout. Grout injection can take place before, during, and after tunneling activity by reusing the sleeve-port-pipes. Often a "preconditioning" phase of grouting is carried out before tunneling to stiffen the ground and produce a slight heave in structures above.

Compensation grout tends to fracture rather than permeate soil (as with permeation grouting) or form a bulb (as with compaction grouting). Grout mixes used for compensation grouting vary, but usually a low viscosity cement and bentonite grout is injected. Grout fractures in the clay tend to propagate more or less horizontally with occasional subvertical interconnections, while grout fractures in sand tend to propagate more or less equally in all directions. Grout lenses usually vary in thickness from fractions of an inch up to 1 inch where multiple injections produced a cumulative thickening. A significant advantage of compensation grouting is the wide range of soil conditions in which it can be applied, from hard clays and very dense sands to very soft clays and very loose sands. (8, 9, 10).

CASE STUDY: TREN URBANO - RIO PIEDRAS CONTRACT, PUERTO RICO

The new Tren Urbano heavy rail transit project in San Juan, Puerto Rico includes one very significant portion, the Río Piedras Contract, which is being constructed underground. The Tren Urbano system is 10.7 miles long and has 16 stations. All construction is being completed under design-build contracts as a demonstration project funded by the Commonwealth of Puerto Rico and the U.S. Federal Transit Administration.

The Río Piedras Contract is completely underground and involves several types of tunnel construction in poor soil conditions (weathered alluvium). One portion has twin tunnels that were driven with an EPB TBM and lined with one-pass precast concrete segments. Another section has four short tunnel drives at a turnout, which was constructed

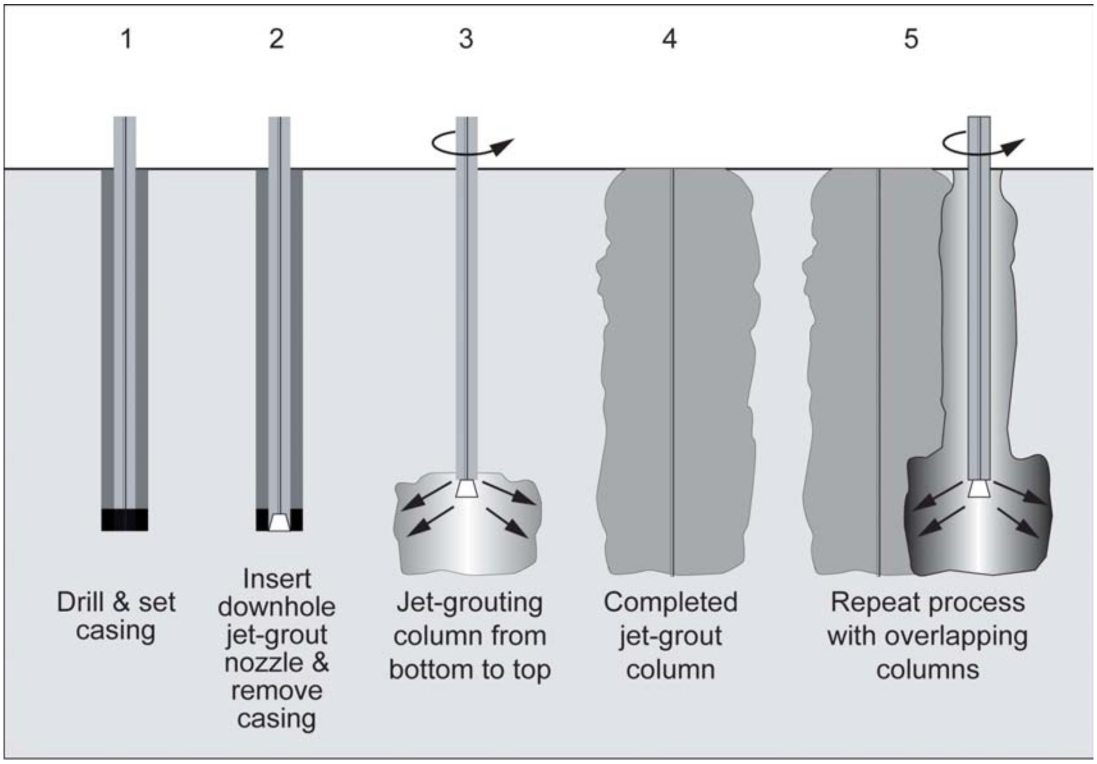

Figure 5. Jet Grouting.

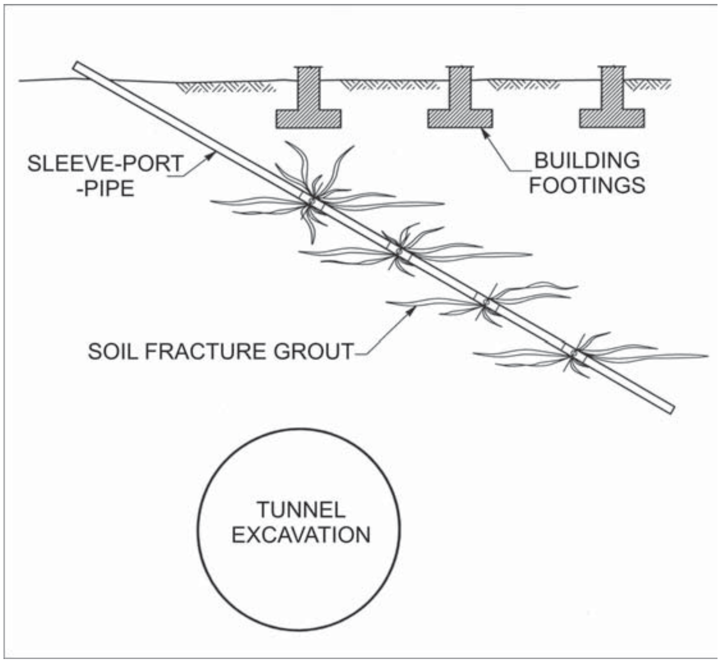

Figure 6. Compensation Grouting.

with an initial support of shotcrete and lattice girders (i.e., NATM/SEM). The most complex construction was the Río Piedras Station, which was built as a stacked drift tunnel with a total of 15 individual tunnel drifts. After being sequentially excavated and concreted, the drifts form a structural arch for the 62-foot-wide by 53-foot-high station. This structure was excavated in soil with less than 16 feet of cover, immediately below historic buildings.

In the design-build contract documents, the owner specified threshold limits and specific actions for various levels of settlement. Compensation grouting was selected by the contractor as the building protection method since it was considered the most appropriate and flexible procedure to mitigate settlements caused by excavation of the various tunnels on the project (10, 11).

For the NATM/SEM and EPB tunnels, sleeve-port-pipes for compensation grouting were installed from the ground surface or from 14-foot-diameter grout shafts. For the Río Piedras Station stacked drift tunnel, sleeve-port-pipes were installed from within an 8.5-foot-high by 9.5-foot-wide grout gallery. Grout pipes were spaced 5 to 10 feet apart, with injection ports on 1- to 1.6-foot centers. The phases of the compensation grouting program were as follows:

1. Identification of the areas to be protected, based on a simple 45-degree angle projected from the base of each tunnel structure.
2. Drilling and installation of sleeve port pipes in an array beneath areas anticipated to be influenced by excavation settlement. The sleeve port pipes make it possible to inject compensation grout precisely beneath a particular zone, using an inflatable double packer.
3. Performance of preconditioning grouting to recover relaxation due to drilling, and to pre-compact the ground so that subsequent injections are more immediately effective in compensating for settlement. Grouting is interactive with geotechnical monitoring.
4. Compensation grouting is undertaken as required during the excavation work to compensate for ground loss and limit settlement to an acceptable amount. Grouting is interactive with geotechnical monitoring.

A key aspect of this compensation grouting program was the use of an automated building monitoring system, which consisted of a computer-controlled theodolite that automatically recorded movement of target prisms mounted to surrounding buildings. This enabled an accurate survey (+/- 1 mm) of structures every 10 minutes. The pressure, volume, and location for grout injection was based on the real-time data obtained from the building monitoring system.

Control of settlement by compensation grouting on the Río Piedras Contract was very successful, despite considerable ground losses experienced during tunneling. Although settlement was difficult to predict and was influenced by many factors, such as complex structure geometries, complex soil profile, and leaking utilities, the compensation grouting program was flexible in accommodating non-uniform settlements along the project alignment.

CASE STUDY: EASTSIDE LRT, LOS ANGELES

The proposed Eastside LRT Project consists of a light rail mass transit system, approximately 31,600 feet long, extending from Union Station in Central Los Angeles east along 1st and 3rd Streets through various East Los Angeles communities. While most of the project is at grade, a twin bore 1.8-mile-long tunnel under 1st Street, with two cut-and-cover stations at Soto Street and Boyle Street, are proposed. The tunnel portion of the project will be delivered by design-bid-build, and at the time of this writing the tunnel contract is in the bid stage.

Along the 1.8-mile tunnel route, commercial buildings consist mainly of offices, clinics, and retail stores. Residential buildings are primarily single-family homes. Two major highways cross the alignment, namely U.S. Highway 101 and Interstate Highway 5. Based on predictions of tunnel and station construction settlements, numerous buildings were identified as lying within the horizontal extent of potential surface settlement. Each of these buildings was surveyed by external inspection for structure type and general condition. Data from this survey and the settlement predictions were used to select a number of structures for further study, which included interior inspections and prediction of building damage using the Boscardin and Cording approach.

Based on the building damage predictions, a smaller number of buildings was specified as being potentially threatened by tunnel settlement. These buildings were then divided into two groups. The first group (Group I) consists of buildings located at the start of two tunnel drives, where the contractor is likely to be on a “learning curve” and settlements could be most severe. The remaining buildings (Group II) are farther along in the tunnel drives. Compensation grouting was deemed the most flexible building protection method for the anticipated geotechnical conditions (alluvium). For Group I buildings, compensation grouting will be performed as required based on the settlements observed during tunneling. If it is determined that tunnel settlements are so small that the grouting is not required, then the Group II buildings will not be protected by compensation grouting. By requiring different pay items for Group I versus Group II buildings, the reduction of grouting for Group II can be equitably negotiated.

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