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SYNOPSIS: Ground runs during mining of the Papago Freeway Drain Tunnels posed significant potential risk to utilities, street pavement, and buildings located above and adjacent to one of the three tunnel alignments. Ground response to the larger ground runs resulted in open chimneys and settlement of the ground surface of up to several feet. Modifications to the tunneling machine included addition of poling plates and breasting boards. Further modification to the tunneling method included use of compaction grouting in conjunction with mining for the entire length of one tunnel alignment, and use of chemical grouting to prestabilize the ground surrounding the tunnel opening in areas of high risk utilities and in areas where subsurface conditions suggested that running ground would be encountered during mining.

This paper presents a summary of the ground behavior with and without the compaction and chemical grouting and describes the grouting methods.

INTRODUCTION

This paper presents a case history of soft ground tunneling for the Papago Freeway Drainage Tunnels in Phoenix, Arizona constructed from the spring of 1984 through mid-1987. Specific objectives are to describe the subsurface conditions, tunneling methods, the ground behavior in response to tunneling. The case history includes a description of compaction and chemical grouting methods that were used in conjunction with tunnel excavation over part of the project. The grouting allowed for rapid tunnel excavation while minimizing surface settlements above the tunnel thereby reducing the risk to overlying utilities, pavements, streets and adjacent buildings.

The Papago Freeway Drainage Tunnels are part of a drainage system for the highway expansion and improvements undertaken by the Arizona Department of Transportation in the greater Phoenix metropolitan area. Large sections of the highway system are depressed below existing ground elevations to minimize visual and noise impacts. The tunnels are part of an inverted siphon designed to carry surface runoff from intense rainfall. The system carries water to the Salt River and provides drainage for an approximately 40 square mile area. Tunnels were selected because of the disruption that cut and cover construction of alternatives would have caused to the utilities, traffic, streets, and adjacent business located along or near the system alignment.

The entire highway project is managed by the Arizona Department of Transportation (ADOT). The drainage tunnels were designed by Howard Needles Tammen and Bergendoff (HNTB), construction was done by the consortium of Shank-Artukovich-Ohbayashi (S-A-O) and construction management was provided by CRS Sirrine (CRSS).

The tunnel project consisted of three tunnels, the North, East and West Tunnels, shown in Figure 1. The total length of the three tunnels is approximately 6.5 miles making this one of the largest soft-ground tunneling projects in North America. The North Tunnel runs east and west, is 6,700 ft long, has a finished diameter of 14 ft and an excavated diameter of 17 ft. The East and West Tunnels run north and south, are 13,550 and 13,970 ft long respectively, have a finished diameter of 21 ft, and an excavated diameter of 25 ft. The North Tunnel slopes gently toward the center where it intersects with the West Tunnel. The East and West Tunnels slope gently from north to south. The depth of cover of the North Tunnel was between 25 and 40 ft. The depth of cover at the East and West Tunnels was between 33 and 45 ft. Each tunnel is connected to a concrete inlet or outlet structure at each end

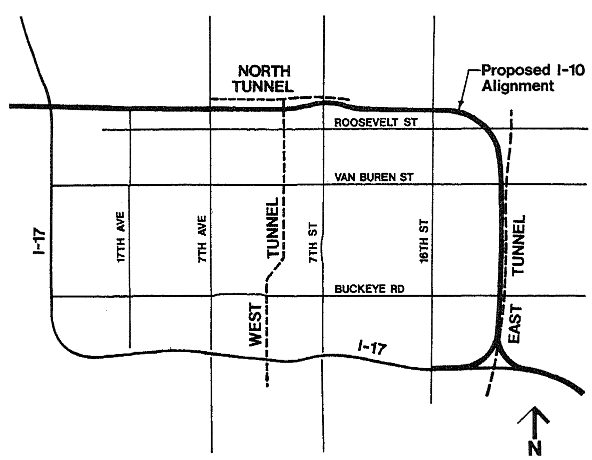

FIGURE 1 - PROJECT LOCATION

and to a number of concrete drop structures located along each tunnel alignment. The North Tunnel alignment includes several 800 to 1,000 ft radius curves and the West Tunnel is straight except for a reverse curve section with two 1,200 ft radius curves.

The remainder of this discussion deals exclusively with construction of the East and West Tunnels. No further considerations of the North Tunnel are included.

The tunnels were excavated using a shield with digger manufactured by Hitachi Zosen of Japan. The East Tunnel was driven first and was excavated from south to north. Upon completion of East Tunnel excavation, the shield was disassembled, moved and reassembled at the south shaft of the West Tunnel, and used to excavate the West Tunnel.

Almost immediately after the shield mined out of the south shaft at the East Tunnel, a series of large ground runs occurred. The runs resulted in large surface settlements of the order of 6 to 10 ft and in large open chimneys to the ground surface.

As a result of these ground runs, modifications were made to the shield. These modifications included addition of poling plates to the upper half of the shield and breasting boards inside the upper half of the shield. The poling plates were installed from springline to springline and were capable of extending 8 ft beyond the leading edge of the shield. The breasting boards extended from upper quarter arch to quarter arch and could also be extended beyond the face of the shield.

After these shield modifications, excavation of the East Tunnel was completed within a period of eight months. During excavation however, approximately five percent of the tunnel experienced significant ground runs. Individual losses associated with these runs ranged from approximately 5 to 250 cubic yards. These ground losses occurred at the top of the face and above the forward edge of the shield. Surface settlement above the tunnel of up to 10 ft and open chimneys from 3 to 10 ft in maximum dimension resulted from these ground losses.

The surface expression of the ground losses had little impact at the East Tunnel which was constructed primarily below cleared highway right-of-way. However, surface settlement and open chimneys at the West Tunnel represented unacceptable risk to overlying utilities, streets, pavements and adjacent buildings. Consequently, further modifications were added to the tunneling method including 1) compaction grouting to redensify soils loosened by ground losses during mining and to fill voids from ground runs at the face, and 2) chemical grouting to prestabilize the ground surrounding the tunnel.

Compaction grouting was used in conjunction with excavation of the entire length of the West Tunnel. The grouting was integrated with the tunnel excavation and implemented continuously and concurrently with tunnel excavation. Chemical grouting was used in section totalling 1,441 ft of the 13,970 ft of the West Tunnel. A total of 41 ft of this chemical grouting was done to prestabilize the ground, to reduce risk to utilities or adjacent buildings, and 1,400 ft was done in areas where subsurface information indicated a high probability that running ground conditions would be encountered during tunnel excavation.

GEOLOGIC INVESTIGATIONS AND SUBSURFACE CONDITIONS

The subsurface conditions along the tunnel alignments were determined by existing rotary borings, percussion borings, and four large diameter borings (LDB's) and by additional LDB's and tunnel face-mapping performed during tunnel construction. These methods allowed for a characterization of ground conditions during design and bidding for project construction, and for further detailed characterization of subsurface conditions during construction.

Rotary borings are difficult to advance to depth because of the coarse alluvial deposits characteristic of the area. Therefore, no subsurface data at tunnel depth were available from these borings. Percussion borings using reverse-circulation drills were used to investigate subsurface conditions. These borings advanced well through the coarse alluvial deposits but the results were difficult to interpret as little or no sampling is typically conducted with this boring method. Careful observation of the diesel hammer blows required to advance these borings in one foot increments allowed for some useful interpretation of subsurface conditions. Several existing borings drilled using this method extended to tunnel invert and were used to interpret subsurface conditions within the tunnel horizon. A total of four LDB's were drilled at selected locations along the tunnel alignments during site inspections for prospective contractors. Down-hole inspections were available for representatives of each prospective contractor from within casing lowered to full depth of each boring.

A total of 27 LDB's were drilled on 500-ft centers along the West Tunnel alignment and five LDB's were drilled at selected locations along the East Tunnel alignment. These borings consisted of drilling three foot diameter holes to the elevation of tunnel springline, setting a steel casing to the bottom of each boring, and inspecting and sampling from tunnel springline to a point 10-ft above tunnel crown.

The five LDB's drilled at the East Tunnel were located to determine, 1) the conditions at areas where significant ground losses had occurred in the completed portion of the tunnel and 2) to determine ground conditions at an instrumented section of the tunnel. The 27 LDB's at the West Tunnel were drilled to determine detailed subsurface conditions along that alignment and to compare and contrast those conditions to those encountered at the East Tunnel.

The project lies within the Basin and Range physiographic province. The Phoenix Basin consists of between 500 and 1,200 ft of variably consolidated alluvial sediments. These sediments are generally coarse and are the result of rapid infilling of the broad graben-like basin characteristic of the Basin and Range.

The general subsurface conditions at the East and West Tunnels are as follows:

UNIT A - Thin surface layer of fine-grained soils consisting of silty-clay, sandy clay, silt and silty sand with small amounts of gravel. Variable lime cementation (caliche) varying from strong to none was observed. The thickness of this unit varied from 0 to 20 ft with an average thickness of 15 ft.

UNIT B - Transitional sand and gravel underlying Unit A and consisting primarily of relatively clean sands, sand and gravel mixtures, and occasional silty sands. This unit occurred erratically and was not present in many areas.

UNIT C - Lower sand, gravel, cobble (SGC) underlying Unit B. All tunnels were constructed in this unit. This unit was distinguished from Unit B soils by the presence of cobbles. The unit includes highly variable alluvial deposits of gravelly coarse to fine sand, silty gravel, gravelly cobbles, sandy gravel, cobbly gravel, sand, some clay lenses, and sand and cobbles. All deposits vary in fines content from clean to trace silt or clay. Manganese oxide staining was often observed on loose gravel lenses. Variable cementation was observed in some SGC caused by calcium carbonate and clay-fraction. Clay content generally increased below a depth of 35 ft.

Groundwater generally occurred below the tunnel invert except in the southern third of the East and West Tunnel alignments. Groundwater levels followed regional trends and occurred approximately 10-ft above tunnel crown at the south shaft of the East and West Tunnels. Groundwater levels were drawn-down to below tunnel invert using several large diameter, high-capacity wells.

GROUND RESPONSE TO TUNNELING WITHOUT GROUTING

Ground response to tunneling without grouting was measured at 14 sites located along the East Tunnel alignment. Thirteen of the 14 sites were located in "normal" ground, where significant ground losses did not occur. One site was located in a zone of "running" ground. No grouting was used during construction of this tunnel.

In general, instrumentation at the East Tunnel consisted of subsurface settlement markers, multiple point borehole extensometers, and surface settlement points. In addition, inclinometers were installed at three of the fourteen instrumentation sites to measure horizontal movements.

Figure 2 presents the general ground behavior based on data from the 13 "normal" ground sites. This figure illustrates typical instrument locations relative to the excavated tunnel, the zone of influence of the tunnel, and the Generalized Surface Settlement Profile.

Vertical soil displacements shown by this figure for "normal" ground conditions indicate that displacements occur within a limited zone directly above the tunnel, that displacement is generally symmetrical about the tunnel centerline, and that maximum displacement varies from 12 inches at a point 5 ft above tunnel crown to 1.2 inches at ground surface. Most significant vertical displacements (greater than one-quarter inch) are confined within a zone equal to the width of the tunnel and all movement occurs within a zone extending from tunnel springline upward to ground surface at an angle of 20 degrees from vertical.

Instrumentation data from the only running ground site and observation of settlement troughs and open chimneys indicated the settlement was limited to the width of the tunnel, the larger depression or chimneys were generally symmetrical about tunnel centerline, and the width of the open chimneys was less in the uppermost fine grained soils than in the SGC below.

When large settlement troughs or open chimneys developed to the ground surface, the following conditions were noted:

1. Loose soils above the shield ran into the heading creating a void above and slightly behind the leading edge of the shield.
2. The loss of soil from above the shield occurred when uniform or gap graded, loose native soils were encountered at the tunnel crown.
3. In general, soils ahead of the tunnel face did not run into the face.
4. Significant settlement troughs or open chimneys developed at the ground surface and generally occurred within minutes or up to several hours after the run in the tunnel heading.
5. The surface width of settlement troughs and/or open chimneys is less than the width of the tunnel.
6. The size of the surface settlement trough and/or open chimney is directly related to the total volume of running ground removed from within the tunnel.
7. The surface expression of open chimneys or surface settlement troughs is symmetrical about tunnel centerline.

Settlement was studied as a function of distance from the instrument to the tunnel face; this indicated that the total settlement can be divided into four categories based on

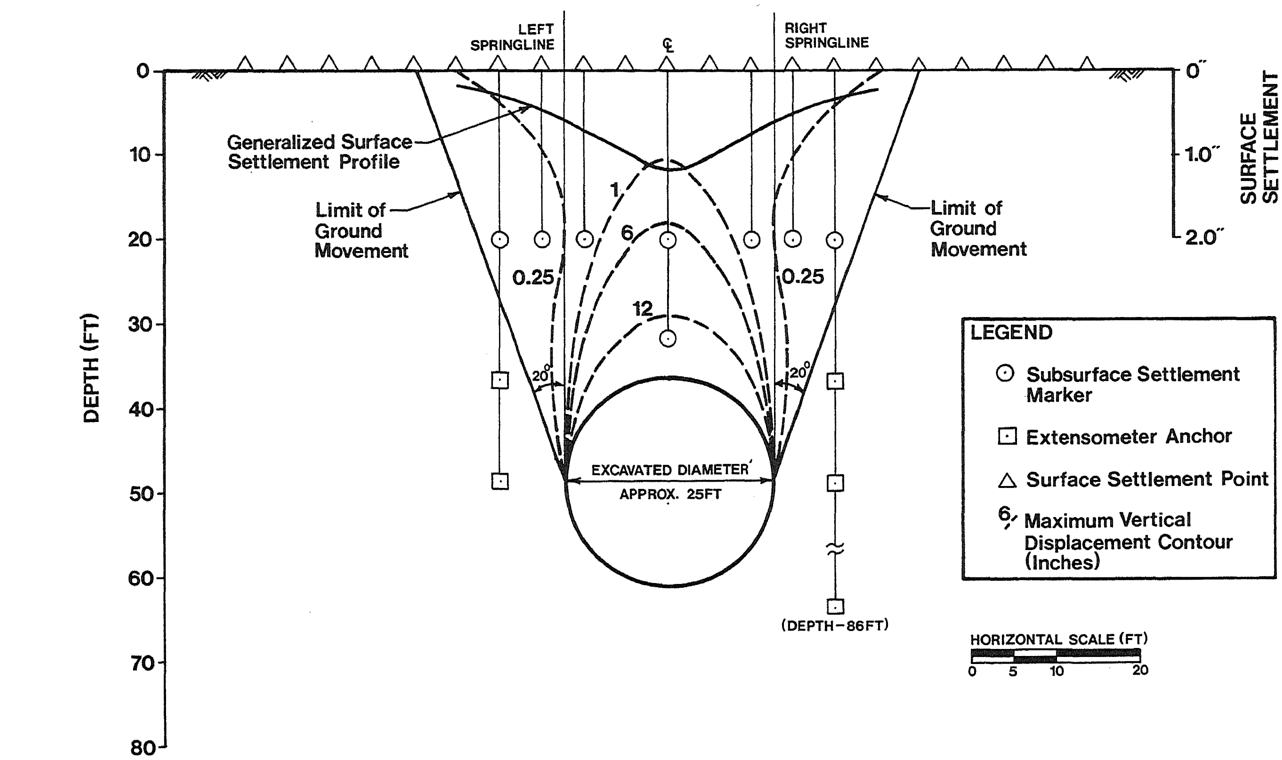

FIGURE 2 - EAST TUNNEL - GENERALIZED GROUND BEHAVIOR PROFILE

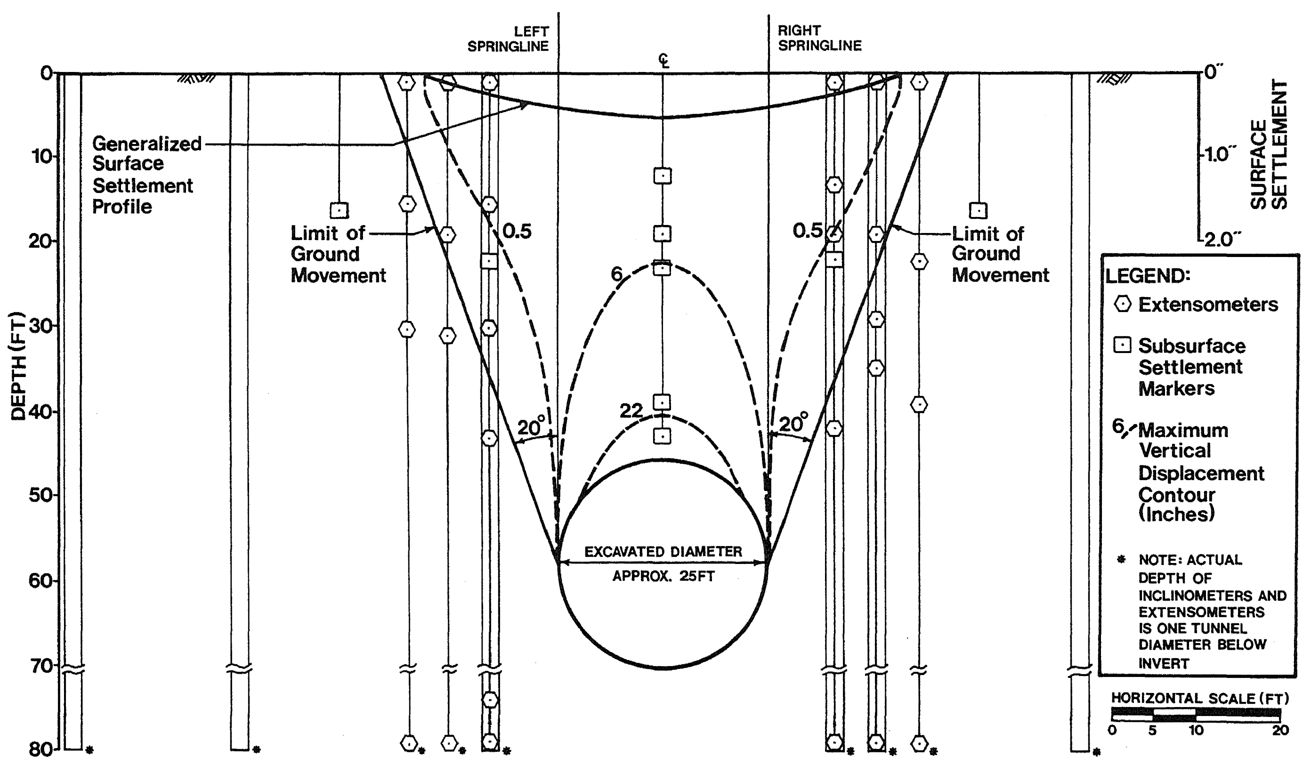

FIGURE 3 - WEST TUNNEL - GENERALIZED GROUND BEHAVIOR PROFILE

loss mechanisms within the tunnel, as follows:

- o Face losses - losses ahead of the tunnel face.
- o Shield losses - losses above the shield.
- o Tail losses - losses as soils load the initial lining.
- o Long term losses - losses due to compaction of the ground after mining is complete.

The majority of settlement is tail loss and some settlement also occurs as shield loss. Settlements from both face loss, and long term loss are negligible.

Based upon field observations, ground losses in general occurred vertically above and behind the shield, and did not extend laterally beyond springline nor ahead into the face.

GROUND MODIFICATION PROGRAM

Introduction

Potential ground losses during mining presented considerable risk to utilities, streets, pavements, and possibly buildings located above and adjacent to the West Tunnel alignment. Based upon an analysis of this risk, a ground modification program consisting of compaction grouting and chemical grouting was recommended for mining the West Tunnel. This section describes the risk analysis and presents details of the ground modification program.

Risk Analysis

The risk analysis was made with considerable input from the owner. The utilities, buildings and streets/pavements in the vicinity of the tunnel were grouped into four levels of risk, designated Low, Moderate, High or Very High, depending upon the anticipated consequences of settlement, ground loss or failure of the utility.

The Low Risk category included:

1. Service gas lines, less than 2 psi.
2. Small water lines, less than 12 inch diameter.
3. Small sanitary sewer lines, less than 18 inch diameter.
4. Small storm sewers, less than 30 inch diameter.
5. Service electric lines.
6. Low volume telephone lines.
7. Irrigation lines for residences.
8. Residential buildings and one story commercial buildings.
9. Streets/pavements with low traffic volumes.
10. Sidewalks.

The Moderate Risk category included:

1. Irrigation lines for farms.
2. Two to three story commercial buildings.

The High Risk category included:

1. Gas distribution lines, 2 to 60 psi.
2. Large water lines, 12 to 30 inch diameter.
3. Sanitary sewers, 18 to 30 inch diameter.
4. Large storm sewers, equal to or greater than 30 inch diameter.
5. Electric distribution lines, 7 to 12.5 KV.
6. Multi-story commercial buildings and municipal buildings.
7. Buildings containing machinery sensitive to settlement.
8. Streets/pavements with high traffic volumes.
9. Interstate highways.
10. Railroad lines.

The Very High Risk category was assigned to utilities which, if severed, could result in loss of life or significant repair costs. The Very High Risk category included:

1. High pressure gas lines, greater than 60 psi.
2. Large water lines, greater than 30 inch diameter.
3. Large sanitary sewers, greater than 30 inch diameter.
4. High voltage electric lines, 230 KV.
5. High volume telephone lines.

In order to determine the risk areas along the West Tunnel alignment, the utilities, buildings and streets/ pavements located within the tunneling zone of influence were reviewed. Utility locations were determined through a review of the Utility Plans and Profiles in the Contract Drawings and through discussions with utility companies. Eight Very High Risk utilities were identified, as follows:

1. One 66 inch sanitary sewer
2. Two 30 inch sanitary sewers
3. One 10 inch, 300 psi gas line
4. One 230 KV electric line
5. One 42 inch water line
6. One Transcontinental Light Guide (fiber-optic) telecommunication cable
7. One jet fuel line.

Engineering recommendations were presented to minimize the potential for significant ground surface settlement, ground loss and open chimneys to the ground surface based upon the soil conditions, the anticipated ground behavior, and the level of risk assigned to utilities, buildings and streets/pavements within the tunneling zone of influence. These recommendations are summarized in the following paragraphs.

Good tunneling techniques were recommended during mining. Good tunneling techniques included control of the shield alignment to minimize the pitch, yaw and roll of the machine. Good tunneling also included careful excavation techniques to minimize ground losses during tunneling.

To supplement good tunneling techniques, a ground modification program was recommended consisting of compaction grouting and chemical grouting. Compaction grouting was recommended along the entire length of the West Tunnel to minimize ground settlement by re-densifying loosened soil behind the tail shield and replacing lost ground during tunneling.

Chemical grouting was recommended at specific areas of active, very high risk utilities crossing the West Tunnel. Chemical grouting was considered necessary to minimize risk to these active utilities by pre-stabilizing the soil around the tunnel below these utilities. Pre-stabilizing the soil further reduced settlement potential by reducing the likelihood of significant ground losses at utility locations. Where a very high risk utility could be deactivated during tunnel mining below, chemical grouting was not recommended.

Compaction Grouting

Purpose

Compaction grouting consisted of injecting low slump soil or soil/cement grout to form a bulb above the crown of the tunnel. Compaction grouting was used along the entire length of the West Tunnel, due to the risk associated with settlement of moderate to high-traffic volume streets, and overlying buildings. The purpose of the compaction grouting program was to minimize potential ground settlement by densifying loosened soil behind the tail shield, and replacing ground lost at the tunnel face.

Procedures

Compaction grouting was accomplished by drilling holes from ground surface at 10 ft centers along tunnel centerline to within approximately 10 ft above the tunnel crown, and inserting a 3 inch pipe into each hole. After the tail shield passed, a low slump, soil grout was injected to form a bulb, which densified any loosened soil above the initial precast lining. During grout injection, lining deflection was monitored and used as a criterion for termination of grouting. When large ground runs occurred, the grouting operation was moved directly over the shield, cement was added to the soil grout, and a large volume of grout was injected to rapidly replace lost ground.

During compaction grouting, voice communication was maintained between the grout technician on the surface and the tunnel technician underground. Constant communication was necessary to monitor grouting progress, to stop grout injection when temporary lining deflections reached tolerable limits, and to adjust grouting operations to events in the tunnel.

Initially the grout consisted of well graded silty sand having at least 20 percent but not more than 50 percent passing the U.S. NO. 200 sieve, flyash, and water with a slump of approximately 2 inches. Due to the availability of a native sandy silt, vandalism of the flyash silo, and problems with sand blockage during grouting, the grout mix was changed to silt with greater than 50 percent passing the U.S. No. 200 sieve, and use of flyash was discontinued.

When grouting in areas of ground losses in excess of 100 cubic yards, one bag of portland cement was added to every 2 yards of grout mix to strengthen the grout and reduce the chances of grout flowing into the heading around the face of the shield.

Compaction grouting was performed using two shifts in conjunction with mining of the West Tunnel. The grout was pumped until one of the following grouting termination criteria was met:

1. For initial precast concrete lining segments located approximately 40 ft behind the tail of the shield that were loose (i.e., tolerate 0.08 feet of deflection and still meet final lining specifications), grout was injected until 0.08 feet of deflection occurred in one of the segments. The grout pipe was raised several feet and pumped again until additional deflection occurred.

2. For initial precast concrete lining segments located approximately 40 ft behind the tail of the shield that were tight (i.e., tolerate less than 0.08 feet of deflection and still meet final lining specifications), grout was injected until all tolerable deflection occurred. The grout pipe was raised several feet and pumped again until additional deflection occurred.

3. Segments and/or keyblocks below the active grout pipe began to crack.

4. Heave of the ground or street surface near the active grout pipe was observed.

5. Pressures in excess of 500 psi developed at the top of the active grout pipe.

When large ground runs occurred, the tunnel technician radioed the grout technician to report the volume of the ground run and its location. The grout crew responded by halting normal grouting behind the shield, identifying the grout pipe closest to the run, and moving the grouting equipment forward. Pumping of compaction grout continued until one of the following grouting termination criteria was met:

1. Grout was observed at the face or tail of the shield.

2. Segments and/or keyblocks at the tail of the shield cracked.

3. Pumping pressure exceeded 300 psi or back pressures exceed 150 psi.

4. Surface heave was observed.

5. 100 percent of the reported ground run volume was injected.

Once a run had been filled, a normal grouting sequence resumed.

On several occasions, a ground run surfaced, which resulted in collapse of the street pavement. When this occurred the void was backfilled with either pea gravel, aggregate base course (ABC), tunnel muck or a combination of these materials.

Results

Compaction grouting of the sand-gravel-cobble alluvium encountered was effective. Compaction grouting densified the loosened soils over the crown of the tunnel, minimized surface settlements, and rapidly backfilled voids, thereby minimizing tunnel excavation downtime.

Compaction grouting during normal tunneling generally resulted in placement of between 0.1 and 0.5 cubic yards of compaction grout per linear foot of tunnel. During normal tunneling and normal ground behavior, the compaction grout densified the soil above the tunnel resulting in deflection of the precast concrete segment. In most cases, segment deflection resulted in grout termination under normal tunneling conditions.

When compaction grout was used to fill large voids from ground losses due to running ground, grout volume placed was between 50 and 90 percent of the ground loss. In most cases ground heave occurred prior to deflection of the precast concrete segments and determined when grout injection was stopped.

The total cost for the compaction grouting, including hole drilling, grouting, backfilling and placing a cold patch at street level was $2,191,680 or about $160 per linear foot of tunnel. Additional project costs not included in this figure were costs for tunnel crew standby time during grouting, repair of the asphalt surface, and repair of utilities damaged during grout hole drilling.

Chemical Grouting

Purpose

The chemical grouting program consisted of the injection of sodium silicate grout using "flood grouting" methods prior to tunnel excavation. Chemical grouting was used in areas of active, very high risk utilities and in areas of anticipated running ground. The purpose of the chemical grout was to strengthen the alluvial soils by increasing their cohesion, in order to minimize the potential for large ground losses and associated surface settlement.

Chemical grouting to stabilize the loose, cohesionless soil conditions was accomplished through the injection of a sodium silicate solution from the ground surface prior to tunnel excavation through the particular zone of concern. The ground was saturated with the low viscosity solution, which set-up to form a stiff gelatinous solid. This gel provided cohesive strength to the loose sand, gravel, and cobble soils.

Procedure

In general, chemical grouting was performed using the grout pipes installed for compaction grouting. In some instances, additional holes were drilled. For combination compaction and chemical grouting, the grout pipes consisted of 3 inch I.D., schedule 40, open end steel pipe. The annulus at the upper 10 ft of the pipe was backfilled with portland cement grout to provide a seal. Additional chemical grout holes were cased with 1-1/2 inch I.D., schedule 40, closed end PVC pipe with four 1/4 inch perforations on 1 ft centers along the lower 10 to 15 ft of pipe. The pipes were drilled to within 5 to 7 ft of tunnel crown, and the annulus backfilled with pea gravel to cover perforations and then filled to the street surface with portland cement grout.

Liquid sodium silicate was clear Grade 40, with a silica to soda ratio of 3.22 and a specific gravity of 41.5 degrees Baume. Initially, the grout mixture consisted of a 30 percent sodium silicate solution. This was modified to 40 percent to reduce grout set time. A number of different activators were used including glyceryl diacetate and sodium bicarbonate. When glyceryl diacetate was used as the activator, calcium chloride was added as an accelerator. With each chemical grout mixture, a series of tests were performed, to identify the mixture which would give the desired 30 to 45 minute gel time.

Chemical grouting was performed using flood grouting procedures and batch mixing methods. Grouting was accomplished by flooding three holes simultaneously with predetermined quantities of chemical grout. Flow rates and pressure to each hole was adjusted by valves until injection was approximately equal. Generally the following grouting procedure was used:

- A concentrated activator solution (50 lbs of sodium bicarbonate in 100 gallons of water) was injected into each hole to cause quick gel of subsequent grout in areas of open gravels.
- 1,000 gallons of sodium bicarbonate/sodium silicate grout was injected into each hole as quickly as possible to saturate the soil mass in the target zone.
- 100 gallons of concentrated activator was injected into each hole.
- Another 1,000 gallons of grout was injected into each hole.
- A final 200 gallons of concentrated activator was injected into each hole.

Grout samples were taken periodically during the above process to check gel time of the grout. The process was crude in terms of mixing and delivering grout solutions to the ground and relied on alternately flooding a target zone in the ground with sodium silicate/sodium bicarbonate grout and accelerator. The process allowed for rapid placement of chemical grout in the general area desired.

Results

Chemical grouting of the sand-gravel-cobble alluvium by injecting sodium silicate grouts was effective. The grouting process was continually adapted as information was obtained after the tunnel was mined through each grouted section. The design objective, strengthening the alluvial soils to prevent large ground runs into the tunnel heading and unacceptable surface subsidence, was accomplished.

No ground losses were observed at any of the sewer crossings that received treatment with chemical grout. A total of 1,400 linear feet of West Tunnel alignment was grouted in 11 zones that had been identified as having potentially unstable, cohesionless ground and high probability of ground runs. Significant ground runs, greater than 5 cubic yards lost during one "push" of the shield, occurred in only two of these 11 zones. The first area was at Second Street and Polk Street, in front of the Arizona Republic and Gazette Building. At this location, a total of 55 cubic yards of ground was lost over a 50 ft interval within a chemically grouted zone. Extensive, very porous, gravel lenses existed in this area. The second area was between Filmore and Pierce on Second Street. At this location, a total of approximately 500 cubic yards of ground were lost over a 30 ft interval within a chemically grouted zone. Ground conditions within this zone included a 3 to 4 ft thick lens of dry, loose sand at the tunnel crown. Tunnel progress was halted, additional holes were drilled in front of the excavated face and more chemical grout was injected. Upon resumption of tunneling, the sand lens was stable and was excavated in large cemented chunks. No large losses of ground occurred after tunneling was resumed following injection of the additional chemical grout.

Small ground runs, less than 5 cubic yards lost during one "push" of the shield, occurred over approximately one third of the chemical grout zones. Grout pipes terminated 10 ft above the tunnel crown and these losses appeared to consist of material located between the tunnel crown and the grouted soil.

In many instances along the West Tunnel alignment ground runs occurred immediately before and/or after a chemical grout zone. This suggested that the ground was loose and prone to running, that the grout prevented runs, and that the ground would probably have run if the chemical grouting had not been performed.

The effectiveness of grouting to permeate the soil within the tunnel face was tested as the tunnel was mined using phenolphthalein to indicate the presence of high pH grout in the soil. This testing revealed that the soils at the tunnel face were generally well saturated with grout solution where grout pipes extended below tunnel crown. No grout saturation was found within the tunnel face in areas where grouting was done through compaction grout holes which terminated 10 ft above tunnel crown. These observations suggest that the chemical grout did effectively saturate a soil zone near the base of the grout pipes.

The total cost for chemical grouting was $410,000 or about $250 per foot of tunnel that was grouted. In most cases, chemical grouting was done through existing holes drilled and cased for compaction grouting, therefore, this cost does not include the cost of drilling grout holes from the ground surface.

GROUND RESPONSE TO TUNNELING WITH GROUTING

Ground response to tunneling with grouting was measured at 14 sites along the West Tunnel alignment. All of the sites were located in "normal" ground and no ground runs occurred within 20 ft of any instruments along the West Tunnel alignment.

In general, instrumentation used at the West Tunnel was simpler than that used at the East Tunnel. West Tunnel instrumentation had two purposes, to determine ground movements in soils surrounding the tunnel during mining, and to provide documentation of ground behavior in the vicinity of critical structures. Because of the magnitude of movements observed at the East Tunnel, subsurface settlement markers were primarily used to measure subsurface ground movements. Extensometers and inclinometers were generally used to provide information only at critical structures.

Based on the data obtained from the 14 sites a Generalized Ground Behavior Profile was developed as shown in Figure 3. This figure illustrates typical instrument locations relative to the tunnel excavation. The figure also contains approximate vertical displacement contours to illustrate the soil movements observed. Vertical soil displacements shown by this figure for "normal" ground conditions indicate that displacement occurs within a limited zone directly above the tunnel, that displacement is generally symmetrical about the tunnel centerline, and that the magnitude of maximum displacement ranges from 22 inches, 5 ft above tunnel centerline to less than one-half inch at ground surface. No measurable horizontal movements were indicated by inclinometers installed between 20 and 60 ft from tunnel centerline.

Comparing the vertical ground movements at the West Tunnel with those observed in normal ground at the East Tunnel indicates the following:

- The magnitude of displacement at 5 ft above tunnel crown is almost one foot larger at the West Tunnel, yet displacement at 20 to 25 ft above tunnel crown and at ground surface is generally less at the West Tunnel. Larger movement close to tunnel crown resulted from larger teeth installed on the shield and from other tunneling procedures. Compaction grouting limited the upward limit of these larger displacements and reduced the amount of vertical displacement observed at ground surface.
- The limit of vertical ground displacements is defined by a line extending from tunnel springline upwards to intersect the ground surface at an angle of 20 degrees from vertical.
- No horizontal soil movements were observed in any instrument within 8.5 ft of tunnel springline. This was consistent at both the East and West Tunnels.

Several areas of the West Tunnel experienced significant ground runs during excavation. These runs involved between 20 and 500 yards of material. Generally, ground runs were backfilled with compaction grout before surface subsidence or open chimneys developed. In a few areas at the northern end of the tunnel and at the beginning of the reverse curve, ground losses in the tunnel resulted in surface settlement and/or development of open chimneys. As at the East Tunnel, these were limited to the width of the tunnel.

SUMMARY AND CONCLUSIONS

A total of approximately 27,000 ft of 25 ft diameter tunnels were excavated at depths of about 45 ft in coarse alluvial sand-gravel-cobble deposits in downtown Phoenix.

Ground movements resulting from running ground conditions encountered during mining posed unacceptable risk of damage to utilities and streets overlying the West Tunnel alignment. In order to reduce these risks, chemical and compaction grouting techniques were amended to the contract provisions during construction and were utilized during mining of the West Tunnel. Chemical grouting was performed prior to mining, by placing sodium silicate/sodium bicarbonate grout using flood grouting methods to place grout at or above the tunnel crown. Chemical grout was used to prestabilize the ground at the location of two active utilities which could not be effectively shut-off or re-routed if they were disrupted by ground movements around the tunnel. Chemical grouting was also used at areas of the alignment where subsurface information suggested that running ground would occur during tunnel excavation. The chemical grouting was successfully applied and no significant ground losses occurred within areas treated by chemical grouting prior to tunnel excavation.

Compaction grouting was performed concurrently with tunnel excavation along the entire length of the West Tunnel. Grout was injected along tunnel centerline using soil or soil/cement grout to redensify soil loosened around the tunnel during mining or to fill voids above the tunnel shield immediately after ground runs occurred at the tunnel face. Compaction grouting successfully reduced soil movements around the tunnel and minimized potential damage to utilities, street pavement and nearby buildings.

Comparison of generalized ground movements above the East Tunnel where no grouting was performed and the West Tunnel where both chemical grouting and compaction grouting was performed shows that:

- Several large ground runs occurred along the West Tunnel with little or no corresponding near-surface ground movement. Ground runs of similar magnitude at the East Tunnel resulted in large surface settlement or open chimneys.

- The average surface settlement at tunnel centerline along the West Tunnel under "normal" ground conditions was 0.75 inches and 1.20 inches at the East Tunnel. Both settlement profiles were symmetrical about the tunnel centerline. No surface settlement was generally observed beyond 20 to 25 ft from tunnel centerline.

Generally, the grouting performed in conjunction with excavation of the West Tunnel was effective in limiting near surface ground movements. This effectively minimized the risk of damage to utilities, street pavement, and nearby building throughout most of the West Tunnel alignment.

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