Underpinning Considerations for Design Unit A-140, Metro Rail Transit Project

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The proposed rail transit system, Section A-140 of the Southern California Rapid Transit District, consists of two cut-and-cover stations and approximately 1.5 mi of twin bore tunnel. Along the proposed alignment are numerous structures many of whose foundations rest above the invert of the proposed tunnels or adjacent to the proposed station excavations. Consideration is given to protection of structures along the proposed route. The influence zones for tunnel mining and station excavation, based on design criteria, available literature, and past experience, are established. Next, settlements of the buildings within the influence zone are predicted and compared with the estimated allowable settlements. Those buildings whose predicted settlements exceed allowable settlements are thereby identified. Technically sound and economically feasible underpinning methods are considered for protection of those structures whose predicted settlement exceeds the allowable settlement, and the most effective underpinning scheme is proposed for each structure. Finally, the current project status is briefly outlined.

The Southern California Rapid Transit District (SCRTD) is in the process of building a rail transit system to serve the people of metropolitan Los Angeles. The initial line (see Figure 1) will begin at Union Station, travel west, pass the Civic Center and the Jewelry Mart and then travel north, approximately parallel to Wilshire Boulevard, to the San Fernando Valley, a distance of approximately 18.5 mi.

Section A-140, of the proposed rail transit system, the subject of this paper, consists of two cut-and-cover stations and almost 1.5 mi of twin bore tunnel. It begins at approximately Station AR 112+30 in the Union Station parking area and extends to approximately Station AR 199+47 in the vicinity of the intersection of 7th and Hope Streets. The approximate locations of each major type of construction are given in Table 1.

Along the proposed alignment are numerous structures many of whose foundations rest above the invert of the proposed tunnels or within the zone of influence of the proposed station excavations. Therefore, consideration has to be given to protection of structures along the route. The purpose of this paper is to discuss the options considered for protecting these structures.

SUBSURFACE CONDITIONS

In general terms, the subsurface conditions along Design Unit A-140 consist of alluvium over weak claystones and siltstones (1, 2). The general subsurface conditions are shown in Figure 2. The alluvium largely consists of clean sands and gravels, but may also contain some silt, clay, and boulders. The thickness of

the alluvium ranges from less than 10 ft to more than 100 ft within the limits of Section A-140. The variation in thickness of alluvium is related to the alignment within the margin of the Los Angeles basin. In general, the regional groundwater occurs within the bedrock. However, local areas of perched water can occur within the alluvium. These areas can include a substantial thickness of saturated soil.

The soil and bedrock materials have been categorized by name. The named units include:

1. The young alluvium, or granular alluvium, which consists primarily of clean sands and gravels with numerous layers of sandy silt, sandy clay, and silt. It also contains boulders up to 4 ft in diameter. The compactness ranges from loose to very dense.

2. The old alluvium, or fine-grained alluvium, which consists primarily of silts and clayey silts. The consistency varies from soft to stiff.

3. Bedrock, of the Fernando and Puente Formations, which consists of claystone and siltstone. The bedrock possesses a strength that would characterize it not as a rock but as a stiff to hard soil.

Two channels, tributaries of the Los Angeles River, will be traversed by the tunnel line. These channels contain both young and old alluvium, but at the depth of the tunnels only the young alluvium will be encountered. The first is between Stations 113 and 125, and the other is between Stations 177 and 200. Weak bedrock of the Puente and Fernando Formations will be encountered in the tunnel line from approximately Stations 125 to 177. Mixed-face conditions, that is, alluvium and weak bedrock contacts, should be anticipated in the vicinity of Stations 125 and 177.
TABLE 1 OUTLINE OF APPROXIMATE LOCATIONS OF MAJOR TYPES OF CONSTRUCTION

<table>
<thead>
<tr>
<th>FROM</th>
<th>TO</th>
<th>TYPE OF CONSTRUCTION</th>
<th>LENGTH (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>112 +30</td>
<td>146 +53</td>
<td>TWIN-BORE TUNNEL</td>
<td>3,423</td>
</tr>
<tr>
<td>146+53</td>
<td>152 +48</td>
<td>CUT-AND-COVER STATION (CIVIC CENTER)</td>
<td>595</td>
</tr>
<tr>
<td>152 +48</td>
<td>170 +00</td>
<td>TWIN-BORE TUNNEL</td>
<td>1,752</td>
</tr>
<tr>
<td>170 +00</td>
<td>178 +21</td>
<td>CUT-AND-COVER STATION (5th/HILL)</td>
<td>821</td>
</tr>
<tr>
<td>178 +21</td>
<td>199 +47</td>
<td>TWIN-BORE TUNNEL</td>
<td>2,126</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>8,717</td>
</tr>
</tbody>
</table>

At the two station sites, the alluvium is generally less than 30 ft thick. Within the northern two-thirds of the Civic Center Station, artificial fill, 2 to 3 ft thick, directly overlies fresh bedrock. At the south end of the station, the bedrock surface drops off steeply and a zone of weathered bedrock thickens to the southeast. In this area, the weathered bedrock varies in thickness from about 8 to 17 ft and is overlain by young alluvium and fill. At the extreme southeast corner of the station, the fill is approximately 18 ft thick and the old alluvium is about 5 ft thick.

The 5th and Hill Street Station is located on the edge of the alluvial basin with the surface of the bedrock forming a subsurface ridge dropping off sharply toward the southeast. The depth of bedrock ranges from approximately 20 ft under the northern two-thirds of the station to as much as 50 ft south of 5th Street. There may also be as much as a 10-ft drop in the bedrock surface across the width of the station excavation. Overlying the bedrock is the young alluvium with a thin veneer of fill.

The young alluvium is the material that will be most problematical for tunneling, particularly where the tunnels pass beneath, or alongside, foundations of buildings. The ground here is expected to be slow ravelling, with fast ravelling to running ground to be found in lenses of cohesionless sand.

EFFECT ON ADJACENT STRUCTURES

Underpinning Guidelines

The basic criteria to determine the zone of influence as a result of station construction are proposed in Figure 3. Fifteen buildings were found to be located within the defined influence zone (Table 2).

Underpinning guidelines for tunnel construction are shown in Figures 4 and 5. Application of these guidelines resulted in more than 30 buildings deemed to be within the zone of influence of tunneling and, therefore, considered to be at risk from ground movement. The most economically important buildings located within the defined influence zone are given in Table 3. The necessity of protective measures for these struc-

FIGURE 2 General subsurface conditions.
Allowable Settlement of Buildings

The allowable building settlement criteria contained herein are based on work performed by Skempton and MacDonald (3) and by Polshin and Tokar (4). Skempton and MacDonald summarized settlement and damage observations on 98 buildings, 40 of which exhibited signs of damage. The study included both steel and reinforced concrete frame structures and structures with load-bearing walls. Buildings supported on spread footings, mats, and piles were included in the study. Skempton and MacDonald used angular distortion as their criterion for damage, as most of the damage appeared to be related to distortional deformations. Angular distortion was defined as the ratio of the differential settlement between two points (B) to the distance separating the two points (L). It was concluded that cracking of load-bearing walls or panel walls in frame structures will occur when B/L exceeds 1/300 (0.33 percent) and that structural damage is probable when B/L exceeds 1/150 (0.67 percent). Skempton and MacDonald recommended B/L = 1/500 (0.2 percent) as a design criterion to provide an adequate factor of safety against damage due to settlement in buildings. The Skempton and MacDonald criteria were subsequently incorporated into recommendations that relate the magnitude of B/L to various types of damage by Bjerrum (5).

In a more recent study, Grant et al. (6) reviewed the settlement and damage data reported by Skempton and MacDonald in conjunction with data on an additional 95 buildings, 56 of which reportedly suffered some damage. This study supports the Skempton and MacDonald conclusion that cracking of walls can be anticipated when B/L exceeds 1/300 (0.33 percent). Furthermore, Grant et al. recommended criteria for architectural damage based on the deflection ratio. The deflection ratio is defined as the maximum displacement, $\Delta$, relative to a straight line between two points to the distance, L, separating the two points. According to the Grant et al. study, cracks in panel walls of frame buildings and load-bearing walls are likely to occur if the deflection ratio exceeds 1/100 (1.0 percent). Note that this ratio is equivalent to an angular distortion of 1/500.

### Table 2: Structures Located within the Influence Zone of Station Construction

<table>
<thead>
<tr>
<th>Approximate Station No.</th>
<th>Ground Type</th>
<th>Construction Type</th>
<th>Number of Stories</th>
<th>Relative Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR 146 + 75</td>
<td>Rock</td>
<td>Flexible</td>
<td>3</td>
<td>M</td>
<td>Court of Flags</td>
</tr>
<tr>
<td>AR 146 + 75</td>
<td>Rock</td>
<td>Flexible</td>
<td>2</td>
<td>M</td>
<td>County Mall Parking</td>
</tr>
<tr>
<td>AR 150 + 00</td>
<td>Rock</td>
<td>Rigid</td>
<td>6</td>
<td>H</td>
<td>County Courthouse</td>
</tr>
<tr>
<td>AR 150 + 00</td>
<td>Rock</td>
<td>Flexible</td>
<td>2</td>
<td>M</td>
<td>County Law Library Parking</td>
</tr>
<tr>
<td>AR 173 + 25</td>
<td>Rock</td>
<td>Rigid</td>
<td>12</td>
<td>H a</td>
<td>Clark Hotel</td>
</tr>
<tr>
<td>AR 174 + 50</td>
<td>Soil</td>
<td>Rigid</td>
<td>2</td>
<td>L</td>
<td>Abandoned Commercial</td>
</tr>
<tr>
<td>AR 175 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>10</td>
<td>M</td>
<td>Commercial/Warehouse</td>
</tr>
<tr>
<td>AR 175 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>3</td>
<td>L</td>
<td>Zody's</td>
</tr>
<tr>
<td>AR 175 + 50</td>
<td>Soil</td>
<td>Rigid</td>
<td>2</td>
<td>L</td>
<td>American Barber College</td>
</tr>
<tr>
<td>AR 175 + 75</td>
<td>Soil</td>
<td>Rigid</td>
<td>2</td>
<td>L</td>
<td>Persisct Theater</td>
</tr>
<tr>
<td>AR 176 + 25</td>
<td>Soil</td>
<td>Flexible</td>
<td>1</td>
<td>L</td>
<td>Koi's Burger</td>
</tr>
<tr>
<td>AR 176 + 50</td>
<td>Soil</td>
<td>Rigid</td>
<td>3</td>
<td>H</td>
<td>Pershing Square Bldg.</td>
</tr>
<tr>
<td>AR 176 + 75</td>
<td>Soil</td>
<td>Rigid</td>
<td>12</td>
<td>H</td>
<td>Thrifty Drug</td>
</tr>
<tr>
<td>AR 178 + 00</td>
<td>Soil</td>
<td>Flexible</td>
<td>3</td>
<td>M</td>
<td>Pershing Square Parking</td>
</tr>
</tbody>
</table>

Note: H = high, M = medium, and L = low.

aHigh value due to status as historic landmark building, only.
Polshin and Tokar (4) discussed allowable deformations and settlements and defined criteria similar to those of Skempton and MacDonald. In this study, Polshin and Tokar treated frame structures and load-bearing walls separately. However, their limiting values of angular distortion for frame structures ranged from 1/500 to 1/200 and are approximately the same as those of Skempton and MacDonald.

Polshin and Tokar’s treatment of load-bearing walls introduced the concept of allowable settlement defined in terms of the deflection ratio, and assured a relationship between maximum allowable deflection ratio and a critical level of tensile strain in the wall. Using this concept, the deflection ratio at which cracking occurs in a (brick) wall is related theoretically to the length-to-height ratio of the wall. A larger deflection ratio is allowed for structures on plastic clay than on sand or stiff clay. It is presumed that the slower rate of settlement allows time for creep within the structure, thus increasing the level of tensile strain, and therefore increasing the deflection ratio at which cracking begins. It should be noted that the critical tensile strain applies only to visible damage and not to structural damage.

In summary, the essential criteria used to define allowable settlement of buildings are based on the works of Skempton and MacDonald, and Polshin and Tokar. Extensions of these works were provided by Grant et al., and Burland and Wroth (7). From these works, general conclusions on allowable settlements may be drawn as follows:

1. For frame structures with panel walls,
   (a) An angular distortion of 1/500 is allowable for buildings in which cracking is not acceptable,
   (b) An angular distortion of 1/300 is allowable in buildings in which some cracking is acceptable, and
   (c) An angular distortion of 1/150 is allowable in buildings in which severe cracking is acceptable but structural damage is not acceptable.
2. For load-bearing walls, the allowable differential settlement is reduced to 75 percent of that for frame structures.
3. The allowable differential settlement is reduced to 75 percent of the values in Items 1 and 2 when the settlement pattern is concave downward.

SETTLEMENT ESTIMATES

Estimates of settlements of foundations within the zone of influence were made. These estimates were based principally on the 1975 paper by Cording and Handsmire (8), which relied heavily on a paper by Peck (9). Settlements for existing conditions were made assuming 3 percent ground loss as the best estimate, based on a review of available literature of reported case histories for similar ground conditions, the estimated settlement trough, and the geometric position of each particular foundation within the zone of influence of the settlement trough.
METHOD FOR CONTROL OF SETTLEMENT

Buildings Adjacent to Station Excavation

Techniques Available

Four methods feasible for underpinning structures adjacent to station construction are (a) jacked piles, (b) slant-drilled piles, (c) hand-dug pit, and (d) column pickup. Other methods that may be considered feasible for protecting such structures are compaction and consolidation grouting.

In the column pickup method, foundation loads are not transferred below the influence zone to a lower stratum; rather specific structural elements are relevelled in the event that excessive settlements occur.

In the hand-dug pit method, a pit is excavated below the influence zone to an alternative bearing stratum. Because the distance from footings to the bottom of the influence zone is approximately 40 ft for most buildings near stations, this method is not considered feasible for the situations under consideration.

Both jacked piles and slant-drilled piles are considered feasible for underpinning structures adjacent to station construction. As both methods will carry the column loads to a lower stratum, their effectiveness is practically independent of the performance of the excavation support system. Also, both jacked piles and drilled piles can be preloaded to minimize potential settlements. The cost of these two techniques is relatively high, and accessibility to the bottom of the foundation that needs underpinning may be questionable.

Compaction and consolidation grouting techniques have been used in subway station construction in Baltimore and in Pittsburgh to underpin adjacent buildings. These techniques are relatively economical and direct access to the bottom of the foundation is not required. They are not positive structural underpinning methods and should be used in conjunction with a conservative soldier pile wall. Also, quality control of the grouting operation, as well as an adequate instrumentation program, are required to ensure the effectiveness of this technique.

Predicted Settlement of Buildings

The need to underpin, and the selection of the appropriate type of underpinning for specific buildings located adjacent to station excavations, depend on many factors. Each structure must be evaluated independently. However, the basic approach was to select a relatively rigid excavation support system that would minimize ground movement to such a low value that the need to underpin adjacent buildings would be reduced or eliminated.

If a conservative soldier pile wall is constructed as proposed, the maximum lateral and vertical movements should be limited to approximately 0.1 percent of the excavation depth; the a

<table>
<thead>
<tr>
<th>APPROXIMATE STATION NO.</th>
<th>GROUND TYPE</th>
<th>CONSTRUCTION TYPE</th>
<th>NUMBER OF STORIES</th>
<th>RELATIVE VALUE</th>
<th>TUNNEL LOCATION</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR 167 + 25</td>
<td>Rock</td>
<td>Rigid</td>
<td>4</td>
<td>H</td>
<td>Adjacent</td>
<td>Myrick Hotel</td>
</tr>
<tr>
<td>AR 181 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>14</td>
<td>H</td>
<td>Adjacent</td>
<td>International Jewelry Ctr.</td>
</tr>
<tr>
<td>AR 182 + 00</td>
<td>Soil</td>
<td>Flexible</td>
<td>3</td>
<td>M</td>
<td>Under</td>
<td>Pershing Square Garage</td>
</tr>
<tr>
<td>AR 185 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>9</td>
<td>M</td>
<td>Under</td>
<td>Jewelry Mart</td>
</tr>
<tr>
<td>AR 186 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>14</td>
<td>H</td>
<td>Under</td>
<td>Park Center Bldg.</td>
</tr>
<tr>
<td>AR 187 + 50</td>
<td>Soil</td>
<td>Rigid</td>
<td>12</td>
<td>H</td>
<td>Adjacent</td>
<td>L.A. Jewelry Center</td>
</tr>
<tr>
<td>AR 189 + 00</td>
<td>Soil</td>
<td>Flexible</td>
<td>5</td>
<td>M</td>
<td>Under</td>
<td>Athletic Club Parking</td>
</tr>
<tr>
<td>AR 189 + 75</td>
<td>Soil</td>
<td>Rigid</td>
<td>10</td>
<td>H</td>
<td>Adjacent</td>
<td>L.A. Athletic Club</td>
</tr>
<tr>
<td>AR 190 + 50</td>
<td>Soil</td>
<td>Rigid</td>
<td>9</td>
<td>H</td>
<td>Under</td>
<td>Olive Center Bldg.</td>
</tr>
<tr>
<td>AR 191 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>14</td>
<td>H</td>
<td>Under</td>
<td>Bank of America Bldg.</td>
</tr>
<tr>
<td>AR 192 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>4</td>
<td>M</td>
<td>Under</td>
<td>Clifton's</td>
</tr>
<tr>
<td>AR 192 + 25</td>
<td>Soil</td>
<td>Rigid</td>
<td>4</td>
<td>M</td>
<td>Under</td>
<td>Okada Restaurant</td>
</tr>
<tr>
<td>AR 193 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>13</td>
<td>H</td>
<td>Under</td>
<td>Brack Shop Bldg.</td>
</tr>
<tr>
<td>AR 193 + 75</td>
<td>Soil</td>
<td>Rigid</td>
<td>13</td>
<td>H</td>
<td>Under</td>
<td>Quindy Bldg.</td>
</tr>
<tr>
<td>AR 195 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>21</td>
<td>H</td>
<td>Adjacent</td>
<td>Wilshire Grand Bldg.</td>
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<tr>
<td>AR 196 + 50</td>
<td>Soil</td>
<td>Rigid</td>
<td>11</td>
<td>H</td>
<td>Adjacent</td>
<td>Robinson Dept. Store</td>
</tr>
<tr>
<td>AR 197 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>12</td>
<td>H</td>
<td>Adjacent</td>
<td>Ryowa Bank</td>
</tr>
<tr>
<td>AR 199 + 00</td>
<td>Soil</td>
<td>Rigid</td>
<td>8</td>
<td>H</td>
<td>Adjacent</td>
<td>Central Bank</td>
</tr>
</tbody>
</table>

Note: H = high and M = medium.
lar rotation of adjacent buildings caused by ground movements should be approximately 1 to 1,000. Thus, a 60-ft excavation would result in approximately 0.75 in. of settlement over a distance of approximately 60 ft. However, the adjacent buildings are approximately 25 to 50 ft away from the excavation. The angular rotation of adjacent buildings may be greater than 1 to 1,000 when these buildings are located approximately 10 ft from the face of excavation. There are four high-rise buildings (Subway Terminal Building, Clark Hotel, Thrifty Drug, and Pershing Square Building) in the conditions previously described, along the 5th and Hill Street Station excavation.

Installation of a properly designed and adequately constructed slurry wall would also likely eliminate the need for underpinning of existing buildings close to the station excavation. Therefore, the installation of a slurry wall is considered to be equivalent to the conservative soldier pile wall as a method for control of settlement.

Buildings Along Tunnel Line

Techniques Available

There are four classes of techniques available for reduction of settlements caused by nearby tunneling:

1. Control of tunneling practices,
2. Consolidation grouting,
3. Compaction grouting, and
4. Underpinning.

Control of Tunneling Practices Refers to the limitation of loss of ground during tunneling; this is somewhat analogous to providing a conservative soldier pile or slurry wall in open cuts. It may be accomplished by exercise of a combination of controls including

1. Careful metering of spoil to assure that its volume corresponds to the advance of the bore,
2. Installation of a noncompressible lining, and
3. Rapid backfilling and grouting of the space between the lining and excavated surface.

All of these operations would normally be executed and controlled to a certain extent regardless of whether the tunnel lies adjacent to or beneath a structure subject to settlement. The additional effort required to exercise careful control is considered to have a negligible effect on the cost and progress of the work. Therefore, it is taken for granted that these controls will be adopted in the construction contract and that they will be carefully enforced.

Consolidation Grouting Consists of the injection of chemical grout into the voids in the soil ahead of, above, and to the sides of the tunnel. Its purpose is to create a zone of soil with sufficient strength to distribute the load from an overlying footing to columns of grouted soil in the sidewalls of the tunnel.

It is doubtful that the grouted soil would possess sufficient strength to carry the load of an overlying column to the grouted soil columns adjacent to the tunnel. The function of the grouting is to lengthen the time for the subsidence of the soil into the annular space around the shield and lining, thus providing time for the cavity to be grouted by routine contact grouting operations.

Consolidation grouting can be executed from the ground surface (through holes inclined so as to reach underneath buildings), from basements, from a completed adjacent tunnel, or from the heading of the tunnel itself. Grouting from the tunnel heading is extremely disruptive to ongoing tunneling operations and would normally be used only when access from other locations is impossible. Because of the alternative locations from which the work can be done, consolidation grouting lends itself well to reduction of settlement under the conditions that exist in Design Unit A-140.

Another advantage of consolidation grouting is that it will cause essentially no disruption to current use of buildings whenever work can be executed from outside the building or from within an adjacent tunnel or the tunnel under construction. At other times, when the work must be done from basements, the materials are relatively clean and amenable to containment, and the equipment is small enough to be handled easily.

Compaction or Displacement Grouting Consists of the injection of a stiff grout or mortar into the ground at sufficiently high pressure to displace the soil and cause heave of overlying materials. The use of this method here would not be to initiate heave but rather to arrest the settlement or actually raise a footing or column that has started to settle.

The principal advantage of compaction grouting is that it can be called on for use when needed. It is therefore economical in the sense that costs are expended only where instrumentation has indicated that preventive or remedial work is actually needed. Its disadvantage is that it must usually be done from the basements of buildings, thereby disrupting day-to-day use.

Underpinning Consists of the installation of structural support beneath a column or footing in order to carry the load to an area below the zone of influence of the tunneling operations. Four techniques are used for installing underpinning:

1. Jack piles: costly; require that construction operations be conducted within the building; are of little practical value when the tunnel passes directly beneath the column to be supported.
2. Slant piles: must generally be driven by standard percussive techniques. This operation must often be carried out from within basements of buildings below which tunnels must pass.
3. Hand-dug pits: like jack piles, are useful only when the underpinning can be extended vertically downward from the column to be supported. This is not generally practical for tunnels passing directly beneath structures.
4. Column pickups: require no work to be performed beneath the existing footings, which is a significant advantage over the aforementioned methods of underpinning. The installation and operation of column pickups does, however,
require work to be done in basements of buildings. Although the equipment for this work is small, and would cause less disruption of other uses of the building than would be caused by pile driving or jacking, it is the opinion of the authors that the use of column pickups would have little practical application here.

CONCLUSIONS

Extensive discussions took place within and among the design teams concerning the best approach to use to protect the structures along the proposed alignment for Section A-140. In general, these discussions can be summarized as follows:

1. Good tunneling practices must be required and enforced through compliance with a well-documented tunneling specification.
2. Structural underpinning methods are economically infeasible and would cause too much disruption to building occupants.
3. It was agreed that 20 structures identified as needing protection during construction could be adequately protected using grouting techniques.
4. For six buildings (Jewelry Mart, Park Center Building, Oliver Center Building, Bank of America, Brack Shop Building and Quinby Building), where the proposed tunnel is directly under the foundation with only one- to one-and-a-half-diameter clearance, the designer and the General Engineering Consultants have not reached agreement on the technique to be used to underpin these structures.

ACKNOWLEDGMENTS

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REFERENCES