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Soft Ground Tunnel Failures in Michigan

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SYNOPSIS Three failures of non-reinforced concrete tunnels in Michigan have been investigated. Descriptions of the failures have been presented, together with geotechnical data for the sites. A probable failure mechanism has been described, as well as design concepts which need to be considered on future projects. Finally, construction procedures to be specified as part of the design process have been evaluated.

INTRODUCTION

During the period from 1977 through 1980, three separate tunnel failures occurred in the suburbs of Detroit, Michigan. All three failures occurred some time after the tunnel had been bored and lined with concrete. Although the sites of the individual projects are several miles apart (See Figure 1), all are within a common geologic setting. Since there are definite similarities among the failures, a study has been undertaken to establish common design and/or construction process which might be related to the three failures.

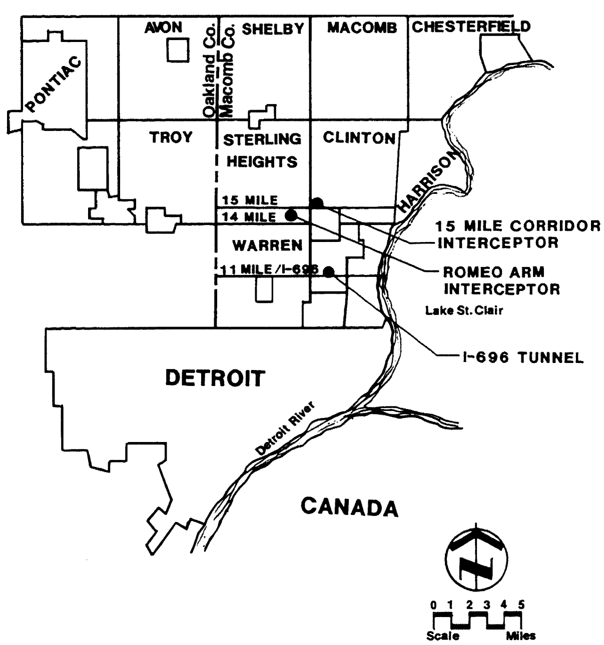

Fig. 1. Vicinity Map

The geologic setting is near the terminal moraines of the Wisconsin glaciation in this region. Bedrock is at considerable depth, probably in excess of 150 feet. Overlying the shale or limestone bedrock is glacial till or deltaic deposits associated with early Wisconsin or late Illionoian glaciation. This formation includes very compact fine sands, silty sands and sandy silts. These soils are in turn overlain by desicated glacial lake clays or more recent glacial outwash.

The regional groundwater level slopes downward to the southeast. Lake St. Clair and the St. Clair River have water surfaces in the range of Elevation 570 to 580. The groundwater level at the three sites being studied is in the range of Elevation 570 to 585. Due to the presence of the impermeable glacial lake clays above the older till and deltaic deposits, the lower aquifer is under artesian pressure.

I-696 TUNNEL

The design of Interstate Highway 696 in Roseville, Michigan required a large diameter tunnel to carry storm water from the depressed freeway to Lake St. Clair. This tunnel was constructed under several separate contracts in 1976 through 1978. The 2 mile stretch from Hayes Road to Nieman Road was to be 102 inches in diameter with the invert at approximately Elevation 550.

Soil conditions at the project location were investigated by the drilling of test borings along the alignment. Figure 2 gives a generalized profile of subsurface conditions in the area where the failure eventually occurred. The contact between the upper impermeable clays and the lower water-bearing sands varied from several feet above the crown of the tunnel to several feet below the invert.

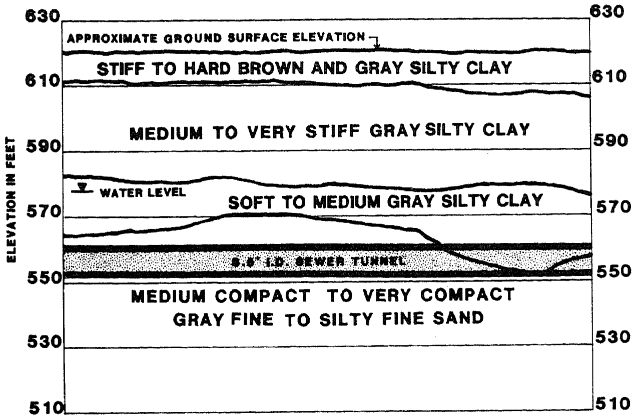

Fig. 2. I-696 Tunnel Soil Profile

During construction, dewatering wells were installed by the contractor to lower the artesian head in the aquifer. A wheel-type tunnel boring machine (TBM) was used to excavate the tunnel. Circular steel ribs and timber lagging provided the primary ground support with monolithic non-reinforced concrete used for the secondary lining. Mining was completed prior to commencement of concrete lining placement. No unusual problems were noted during the construction of the tunnel.

After a sinificant portion of the tunnel had been mined, concreted, and accepted by the project owner, ground settlement over the tunnel was noted in several places. Subsequent investigation disclosed that the tunnel had settled as much as 6 inches, had developed cracks, and was partially filled with sand.

Three sections of tunnel, each approximately 150 to 200 feet in length were replaced by deep open cut excavation techniques. In addition, many of the construction joints which were formed without waterstops were grouted to stop inflow of water and potential inflow of soil in other areas.

The cost of this remedial action is reported to have been approximately $10 million and litigation between the project owner and the contractor is continuing as of the date of this paper.

ROMEO ARM INTERCEPTOR

During the late 1960's and the 1970's, a major expansion of Detroit's regional sewerage collection and treatment system took place. This expansion included large diameter interceptor tunnels extending to the northerly suburbs. One of these tunnels, the Romeo Arm Interceptor, ran along 15 Mile Road at a depth of approximately 55 to 70 feet.

Figure 3 presents a generalized profile of subsurface conditions along the Romeo Arm Interceptor. The upper clay soils are heavily overconsolidated and the lower granular soils are in a very compact state. The contact between the impermeable upper soils and the artesian aquifer varies from below the tunnel invert to above the tunnel crown.

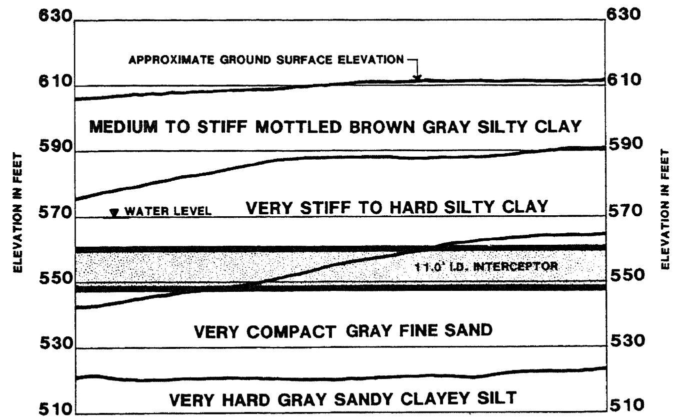

Fig. 3. Romeo Arm Soil Profile

The tunnel was constructed in 1972 and 1973 using a tunnel boring machine (TBM) equipped with an hydraulically operated digger arm. Deep well dewatering was used to lower the groundwater level in advance of the mining operation. Most of the tunnel was constructed under compressed air with pressures being in the range of 6 to 10 pounds per square inch (psi). The primary lining was constructed of steel ribs and timber lagging with a monolithic concrete lining placed as the mining progressed. Although difficult mining conditions were noted, there was no evidence of unresolved construction problems.

In 1978, a contract to connect a local sewer to the tunnel was awarded by the City of Fraser, Michigan. The contractor was required to excavate a shaft to the tunnel and to connect a drop to an eye in the existing tunnel at a depth of approximately 60 feet. A limited number of dewatering wells were installed and the excavation reportedly encountered very wet soils as it advanced into the sand layer. It is believed that the unbalanced hydrostatic head in the soil resulted in upward flow of soil into the shaft excavation. This theory is supported by the observation that the contractor removed soil for several days without the shaft getting any deeper.

On July 29, 1978, the tunnel collapsed in the immediate vicinity of the shaft. Since this sewer served an area of more than 55 square miles, its collapse presented a major threat to the environment and the health of the local residents. An emergency by-pass of the failed section was installed by contractors retained by the City of Detroit Water and Sewerage Department. As shown on Figure 4, this emergency repair required mobilization of considerable equipment and personnel.

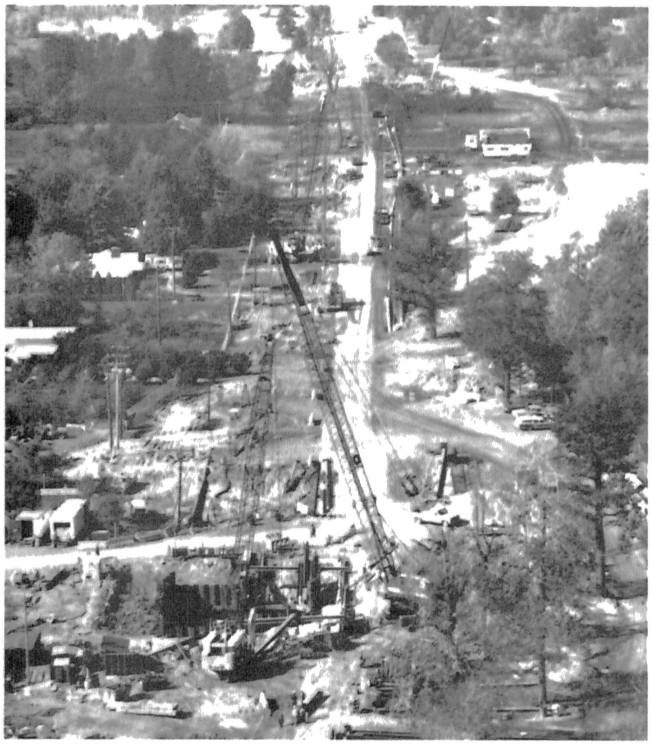

Fig. 4. Emergency Repair at Romeo Arm

In order to stop inflow of soils into the ruptured tunnel, a program of dewatering and grout injection was initiated. It was know that it would take at least several weeks to lower the level of the grounwater to a point below the tunnel. Pumping of cement-based grout, however, proved effective in halting the progressive collapse of the system within 7 days. Dewatering wells were able to eventually lower the groundwater level to below the tunnel.

The cost of the emergency repairs to the collapsed interceptor was approximately $15 million. The permanent repair of this stretch of tunnel is presently underway and is estimated to cost approximately $5 million.

CORRIDOR INTERCEPTOR

The sewage flow from the Romeo Arm Interceptor joins with flow from eastern Oakland County and is conveyed toward the Detroit Wastewater Treatment Plant through the Corridor Interceptor. This 12-foot 9-inch sewer was constructed during the period from 1970 through 1972. As shown on Figure 5, the generalized soil profile for this tunnel is geologically similar to that at the previously discussed tunnels. However, at this location, a stratum of compact silt was encountered between the upper cohesive soils and the lower granular soils.

This tunnel was constructed with a wheel-type TBM. Deep wells were drilled to lower the groundwater level during the initial construction. The dewatering was reportedly effective and the use of compressed air to prevent water inflow was not necessary. Steel ribs and timber lagging were installed for primary support. The secondary lining of monolithic-poured non-reinforced concrete was placed after most of the tunnelling had been completed.

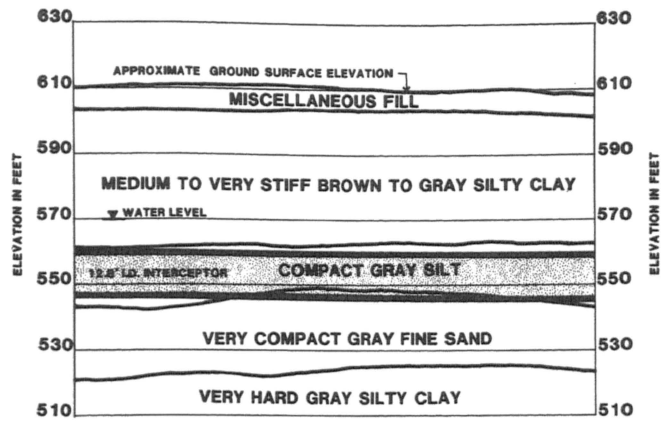

Fig. 5. Corridor Interceptor Soil Profile

After being put into service in July of 1972, no problems were reported with the tunnel until January of 1980. During a walking inspection of the tunnel on January 27, 1980, three separate areas of structural distress were found in a 2,500 foot length of tunnel. In the worst area, the tunnel had settled approximately 3 feet and the concrete secondary lining had fallen out, exposing the steel ribs and timber lagging. Total collapse of the tunnel appeared to be imminent.

The emergency procedures used to divert the flow around the distressed areas were similar to those used on the Romeo Arm project. However, in order to prevent further collapse of the tunnel during repair operations, the soil immediately above the worst distress area was frozen with a liquid nitrogen system. When the flow was finally diverted from the tunnel, the area of the worst distress appeared as shown in Figure 6.

The permanent repair of the Corridor Interceptor was accomplished by jacking a 9-foot inside diameter reinforced concrete pipe through the distressed areas. The annular space between the new pipe lining and the old concrete tunnel was filled with cement grout. In addition, an extensive program of grouting outside of the original tunnel was undertaken. Repairs in this area have now been substantially completed.

Fig. 6. Corridor Interceptor Tunnel Distress

The total cost of repairs to the Corridor Interceptor within the areas of distress was approximately $16 million. Additional funds have been spent grouting leaks in the concrete lining in other sections of the interceptor. This procedure is being undertaken to prevent similar failures in other areas of this critical tunnel.

FAILURE MECHANISM

The circumstances surrounding the collapses of these three tunnels are somewhat different. However, it is believed that the similar failure mechanisms contributed to the collapse of each of the three tunnels. A thorough investigation of the Corridor Interceptor failure was made by the U.S. Army Corps of Engineers. Their conclusions were as follows:

a. Seismic activity was not a factor.

b. Concrete composition, homogeneity, and quality were not factors and there was no evidence of deterimental chemical reactions.

c. At end of construction, the concrete liner contained open construction joints and/or cold joints at several locations.

d. The fine to medium sands, silty sands, and silts will pipe through openings as narrow as 0.01 in. under water pressures less than 2 psi.

e. After construction, the external water pressure on the tunnel invert ranged from 4 to 8 psi.

f. Soil piped into the tunnel in varying amounts depending on the location of the strata of piping soil with respect to open construction joints and/or cold joints. As material piped into the tunnel, the tunnel lost bottom and side support.

g. When loss of support occurred beneath the invert, the resulting loading caused the structure to crack circumferentially as was observed in Distressed Area No. 3.

h. When loss of support occurred at the springline, the resulting nonuniform loading caused the resistance of the structure to be exceeded and initiated and pattern of ovalling and longitudinal cracking and spalling observed in all distressed areas.

Flow of groundwater into sewer tunnels has always been considered undesirable because of the effect of this addition water flow on sewage treatment facilities.

However, if groundwater flows can carry even minute amounts of soil into the tunnel, eventual collapse of the tunnel structure should be anticipated. Such inflows of soil occur most commonly at the tunnel invert since that is the point of greatest external water pressure. As soil is removed from below the tunnel, there is a tendency for the tunnel to deflect downward at that point. This results in the tunnel "bending" as a long beam with tension on the bottom of the beam. In non-reinforced concrete, this tension results in the opening of existing cracks and the formation of new cracks. The failure then becomes progressive with larger cracks leading to greater soil inflow leading to larger cracks, until collapse occurs.

In the case of the Corridor Interceptor and the I-696 tunnels, this mechanism appears to have been the primary cause of failure. In the case of the Romeo Arm Interceptor, external forces associated with the shaft construction are believed to have initiated the cracking. However, it appears that once cracking started, the above described mechanism contributed to the rapid and progressive collapse that was observed after the initial failure was detected.

GEOTECHNICAL DESIGN CONSIDERATIONS

The design of any underground facility ought be based upon adequate data regarding soil and groundwater conditions. In the case of tunnels below the groundwater level, it is important to evaluate the possibility of soil being carried into the tunnel by groundwater inflow.

During the geotechnical investigation for a tunnel project, the design team should obtain reliable information on the vertical and horizontal extent of aquifers encountered. Accurate information on piezometric levels is also considered essential, including different piezometric levels where multiple aquifers are found.

If the geotechnical data indicates that the tunnel will be even partially within a water-bearing formation, the grain size distribution of the soils within that formation should be evaluated by laboratory tests. A significant number of tests are generally required to arrive at a realistic range of soil properties. In stratified soil formations, it may even be necessary to run laboratory tests on thin portions of individual soil samples.

As shown on Figure 7, the soils near invert elevation at all three tunnels were fine sands. Studies have indicated that granular soils will flow through an slotted opening which has a width approximately equal to D_{70} of the soil. For the soils on these sites, this relationship would result in soil flowing through cracks as small as 0.008 inches.

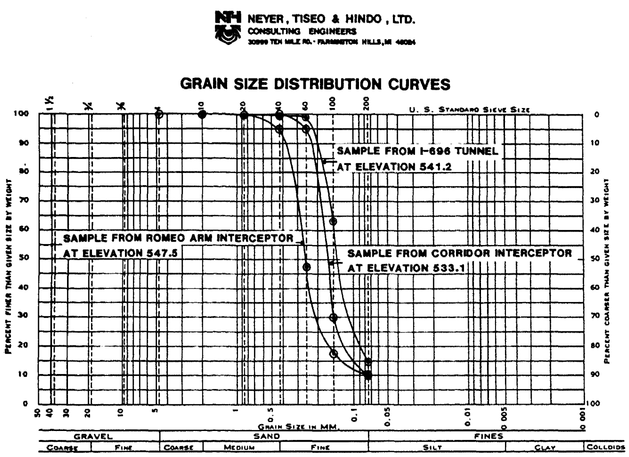

Fig. 7. Grain Size Distribution Curves

Cracks in non-reinforced concrete are not an uncommon occurrence. Wherever a concrete pour is terminated by a bulkhead, a shrinkage crack is likely to develop. For this reason, it is recommended that designers specify water stops at all construction joints where soil and groundwater conditions appear likely to permit soil inflow. Waterstops should be designed to provide a total seal against water inflow at the joint.

Shrinkage cracks can also occur in between the construction joints. These cracks are more likely to form in high strength (high cement factor) concrete. Also, the longer the distance between construction joints, the more likely it is that significant shrinkage cracks will develop. It is therefore recommended that concrete strengths be maintained in the lower range (3,000 to 4,000 psi) to minimize shrinkage associated with high cement factors. It is also recommended that the length of pour be restricted to a manageable length (not more than 120 feet between construction joints for most tunnels).

GEOTECHNICAL CONSTRUCTION CONSIDERATIONS

It is the belief of the author that tunnel design is not completed until tunnel construction is completed. More than any other structure, a tunnel must be in harmony with its surrounding environment (soil and groundwater) if it is to survive. Data from test borings and other preconstruction investigations generally gives a fair picture of what the designer ought design for. But as the construction proceeds, more is learned about subsurface conditions. This new data should be checked for compatibility with the data which formed the basis of the design.

In order for the designer of a tunnel project to do a complete job of tunnel design, it is obviously necessary that he or she be involved in the project throughout construction. It is the authors' belief that the designer, and not the contractor, must be responsible for verifying that construction procedures are consistent with design assumptions. The contractor, on the other hand, must be responsible for the actual construction of the project in accordance with the plans and specifications, as modified by the designer during the construction process.

Where tunnel cracking is anticipated due to abrupt changes in subsurface conditions, consideration should be given to installation of additional waterstopped joints or to reinforcing these field-identified areas.

Last, but not least, tunnel designers ought recall the words of many an instructor in Concrete Design I, "Concrete cracks!" For this reason, it is considered imperative that an examination be made of the completed tunnel after all dewatering systems have been shut down and the groundwater level has returned to its static condition.

If cracks are found to be leaking water, even clear water, the construction process is not complete. All cracks should be sealed with permanent grout materials. For large cracks, cement-based grout pumped outside of the concrete lining can be effective in sealing cracks. For smaller cracks, epoxy grouts have proven effective.

CONCLUSIONS

It has been said that more can be learned from one failure than from 10 successful projects. The three failures reported in this paper have given tunnel designers and constructors an opportunity to learn. The cost has been high - more than $40 million for the three projects combined. Fortunately, there was no loss of life or serious injury associated with these projects. If the lessons learned prevent future distress in tunnels in equally hostile environments, then perhaps it was worth it.

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