Pipe Failure Caused by Improper Groundwater Control

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A sewer collection system installed in a Middle Eastern city incorporated 11 km of fiberglass reinforced plastic mortar (RPM) sewer pipe 500 to 1100 mm in diameter. A short time after installation it was discovered that the pipelines were highly deflected and that some pipe was cracked at the crown. Subsequently a number of the cracked pipes failed, causing large craters and collapse of the roadway. Inspections showed that more than one-half of the RPM pipe system was deflected well over 5 percent, the limit imposed by the contract documents, with some portions deflected up to about 20 percent of their original diameter, and that numerous sections of pipe were cracked at the crown. Investigation of the conditions at the sites showed that the deflections and failures resulted mainly from inadequate control of the groundwater during construction and improper attention to the grading of the crushed stone pipe embedment relative to the natural sand materials against which it was placed. During construction the dewatering system did not maintain the groundwater level below the trench bottom, resulting in water washing into the trench through open sheeting joints, carrying sand with it and leaving cavities behind the sheeting. When the sheeting was pulled, the stone embedment lost support and moved into the cavities, allowing high pipe deflections. Migration of fines from the native sands into the voids in the open graded stone is also believed to have contributed to the loss of pipe support gradually after construction.

A sewer collection system designed for a Middle Eastern city was installed between 1979 and 1981. Some 11 km of fiberglass reinforced plastic mortar (RPM) sewer pipe, between 500 and 1100 mm in diameter, was incorporated into the system. Just before the lines were put into service, several leaks were discovered in the network. Investigations showed that a large portion of the RPM pipe system was deflected well over the 5 percent limit set by the contract documents, with some portions deflected up to about 20 percent of their original diameter, and that numerous pipes had cracked at the crown. Subsequently some pipes collapsed, causing failure of the roadway above the pipe. The high deflections were surprising because the pipe trenches were backfilled with crushed stone, which normally provides excellent pipe support with minimal compactive effort. Information related to geotechnical aspects of the installation that resulted in the high deflections is presented in this paper. Performance of the pipe and a detailed discussion of the failure mechanism has been presented previously (*1*).

BACKGROUND

The sewer collection system was designed as a gravity flow system. Because the city was on the coast, there was a natural upward grade of the land surface away from the coast. The system design took advantage of the natural grade by conducting flow downhill to pumping plants near the coast, where the effluent was pumped via pressure lines to a treatment plant. This resulted in a relatively constant depth of burial for the entire system of about 3 to 4 m.

The native soils were predominantly sands that allow relatively free flow of groundwater. Sieve analysis during the investigation showed the material to be nearly 100 percent between 2 mm (No. 10 sieve) and 0.075 mm (No. 200 sieve), making it a medium to fine sand. The water table was within 0.2 m of the ground surface at the coast and gradually became deeper with increasing distance from the coast, where the elevation was higher. It was below the pipe invert at the highest parts of the system. In some of the higher regions the sand was underlain by limestone, which formed the walls and bottom of the pipe trench.

RPM pipe was selected for the large-diameter portions of the system because of its good performance in corrosive environments. The ground conditions were very severe, and traditional types of pipe materials had not performed well in the past. Eleven km of pipe, between 500 and 1100 mm in diameter, was installed. The RPM had a pipe stiffness (load per unit deflection or $EI/0.149R^3$ per ASTM D2412) of about 100 kN/m/m. The contractor was to install the pipe with deflections less than 3 percent of the original diameter at the time of installation, and 5 percent long term.

The system was originally installed with no indication of problems; however, when manholes were being cleaned just before the lines were put into service, it was noted that there was water in the system, which should have been dry. An investigation made as a result of that finding showed that about one-half of the RPM pipe sections were deflected more than 5 percent and some sections more than 15 percent, and that 17 pipes were cracked in the crown. Later, pipe collapses occurred in which the top half of the pipe caved in. Since the water table was high, the groundwater would flow into the pipe and carry off the soil, in turn allowing more soil to flow into the pipe and be carried off. The final result was similar to a large sinkhole. The deflections tended to be highest nearest the coast, where the water table was highest, and lowest at the higher elevations, where the water table was deeper. The pipe failures occurred in the regions where the highest deflections were measured.

The pipe cracks and subsequent collapses were found to be the result of strain corrosion that occurred because of the excessive deflection levels. The investigation focused on the causes of the high deflection.

CONSTRUCTION METHODS

Project specifications called for the pipe to be installed in open trenches. The required trench width was 4/3 times the diameter

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plus 45 cm. This provides a backfill width of 560 mm at each side of a 500-mm pipe and a width of 960 mm at each side of an 1100-mm pipe. Pipe backfill was to be crushed stone from a minimum of 1/6 times the diameter or 15 cm below the pipe as bedding up to a height above the invert of 0.7 times the pipe diameter. The requirement for shoring was anticipated by the designer, but all shoring used below 30 cm above the top of the pipe was required to be left in place. However, because of the expense that this involved, during the construction phase the contractor requested and was granted permission to remove the sheeting from the trench during backfilling.

Method of Excavation

During investigation of the high deflections and pipe failures an opportunity was available to observe the construction procedures because repairs of failures were in progress. Methods observed were reportedly the same as those used during the original construction. The excavation steps were as follows:

1. Remove the pavement.
2. Drive the sheeting at both sides of the proposed trench location with a vibratory driver. The sheeting came in 600-mm-wide sections that simply overlap at the edges. The sheeting did not have interlocking joints.
3. Install well points for dewatering. These are placed at about 1-m intervals along the outside of the trench sheeting. The well point pipes were about 6 m long with a plastic filter over the bottom meter to permit the entry of water but not sand. The pipes were long enough so that the filter portion was well below the bottom of the trench. A ball-check valve was located on the end of each pipe to permit installation by jetting but to prevent inflow of sand during dewatering.
4. The dewatering pumps were then set up and allowed to run for several days. It was obvious during the investigation that the free flow of water through the native sands made dewatering a difficult task.
5. Excavation was with a backhoe. Cross bracing was installed at an appropriate depth.
6. If water was seeping into the trench, the contractor would dig a small sump hole and insert a hose connected to the vacuum dewatering system. Whereas this helped control the water in the trench, it undoubtedly reduced the efficiency of the dewatering system by breaking the vacuum and probably increased the overall flow of water into the trench.

The typical trench installation configuration using the preceding construction methods is shown in Figure 1. Although it was not directly observed during the investigation, a second sheeting system was reportedly used at some parts of the project. This method consisted of H-piles and timber lagging. As noted later, remnants of timber lagging were found at several locations during the investigation. No specific information is available on how this system was installed; however, typically the H-piles are driven before excavation and the timber lagging is installed as excavation proceeds.

Method of Backfill

Crushed stone backfill was placed on the bottom of the trench and compacted, followed by pipe installation. Later sieve analyses

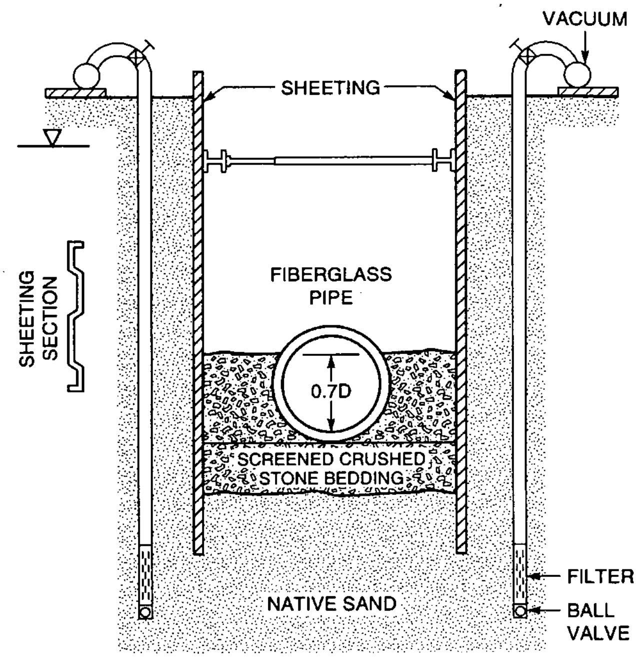

FIGURE 1 Typical braced sheeting installation.

showed the gravel to be 100 percent between 19 and 4.8 mm, giving it a classification of fine gravel. The stone backfill was then placed in layers and compacted to a height above the invert of 0.7 times the diameter of the pipe. The layer thicknesses are not known; however, the open-graded stone backfill requires only minimal compaction to provide proper support to buried pipe. Above the stone a sand backfill material was used. This material was very similar to the native sand. During backfilling the sheeting was pulled with the aid of vibration. There is no evidence that the pipe deflections were monitored during any part of the pipe installation process.

INVESTIGATION OF CAUSES OF DEFLECTION

The investigation into the causes of the failures consisted of review of available documents, interviews with personnel involved in the project, and inspection and testing of failed sections of pipe. Several failure sites were investigated during repairs. The following is a presentation of the significant findings.

Dewatering System

The dewatering system used during the replacement of failed pipe was reportedly the same as used for the original construction. It became evident as the repair excavations progressed that the system was inadequate and the water level just outside of the sheeting was well above the invert of the trench. This was confirmed by using some of the dewatering pipes as observation wells. As a result, large quantities of water flowed into the trench through the sheeting and the trench bottom. Aspects of this condition include the following:

- As noted earlier, if water collected in the trench the contractor would use a line from the dewatering system to remove the free water. This results in breaking the dewatering vacuum, reducing the effectiveness of the system substantially, and increasing the water level outside of the sheeting.

- Because the sheeting did not have interlocking joints, the sheets separated as they were driven. The gaps between sheets were observed to be up to 12 in. during the investigation. Groundwater flowing into the trench through these gaps carried native sand with it and created voids behind the sheeting. These voids were also observed before the investigation conducted by the authors. At that time some were observed to be as large as 1 m^3. Where the sand was above the phreatic surface, where pore pressures are negative, it was stable, even if the sheeting joints were open.
- Sheeting could not be driven where the lines were crossed by utilities. At these locations the contractor used lumber to support the trench walls; however, this was only partly successful, and gaps occurred at these locations as well.
- At the ends of the excavations, the gravel backfill around the adjacent existing pipe allowed water to flow even more freely than did the native sand. This provides a great deal of water to further overload the dewatering system.

During the investigation by the authors, the contractor was aware of the voids and made attempts to fill them with stone before backfilling. If this was not done, the removal of the sheeting allowed the movement of the stone backfill out into the voids and the subsequent loss of support to the pipe. This process of stone movement is accelerated when the sheeting is removed with the aid of vibration, as was the case on this project.

Migration of Fines

It is well known that when a coarse, open-graded material is placed next to a finer-grained material, a flow of water can carry the fine material into the voids of the coarse material. This mixing of the materials causes a net loss of total volume and, when it occurs next to a pipe, can cause a loss of support to the pipe. This mechanism is called migration. The major factors in migration are the gradations of the two adjacent materials and the presence of flowing groundwater to carry the particles.

Current installation specifications, such as ASTM D2321 *Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications,* provide the following guidelines for the gradation of adjacent materials to prevent this migration:

$$D_{15} < 5d_{85} \quad (1)$$

$$D_{50} < 25d_{50} \quad (2)$$

where D_n is the sieve opening size passing n percent by weight of the coarser material and d_n is the sieve opening size passing n percent by weight of the finer material.

Figure 2 shows the gradation of the trench backfill sand, the adjacent natural sand, and the pipe embedment crushed stone. Also shown in the shaded area is the required gradation of pipe embedment material that is compatible with the sand gradation based on the preceding criteria. The figure clearly shows that the crushed stone backfill is too coarse to prevent migration of fines.

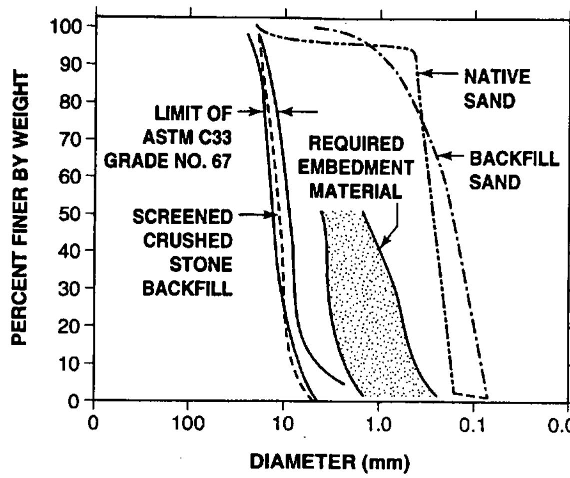

FIGURE 2 Gradations of sands and crushed stone materials.

The investigation showed that flow of water was likely to exist at the site. The groundwater level was well above the pipe crown in most areas, and there were at least three possible sources of a pressure head to cause a flow of that water:

1. Dewatering operations—During the original construction the dewatering of one section could cause substantial flow of water in the previously installed sections. Even though only a small section of trench would be open at any one time, the crushed stone around the previously installed sections can act as a French drain by conducting water toward the excavation and, as a result, cause flow from the sand into the stone for a considerable distance from the excavation. This could also occur during any subsequent excavations near the pipe, and especially during repairs of failures.
2. Termination of dewatering—Groundwater will move after termination of dewatering as the water returns to its normal elevation.
3. Natural changes in groundwater—Seasonal changes can cause the groundwater to fluctuate and in this case, because the town is on the coast, there can be daily fluctuations due to tidal changes. The variation of the natural groundwater level was not investigated in this project, but it is not believed to be as likely a source of groundwater flow as the dewatering operations.

All of these mechanisms are greatly enhanced by the lack of fines in the in situ sand, which allows free flow of water. In many cases where the preceding rules for relative gradation of adjacent materials are not met, migration would not occur because the ground conditions do not permit water velocities sufficient to move substantial amounts of material.

During investigation of the failures, cross sections of the backfill were carefully excavated, and the migration of fines could be clearly seen. This was quantified by taking successive samples across the width and depth of the stone backfill. Since the largest particles of the sand were typically smaller than the smallest particles of the crushed stone, it was a simple matter to distinguish the amount of penetration of fines by evaluating the particle gradation on the basis that any material finer than 2 mm (No. 10 sieve) was from the sand. Figures 3 and 4 show the results of such measurements taken in the stone near the sites of two sep-

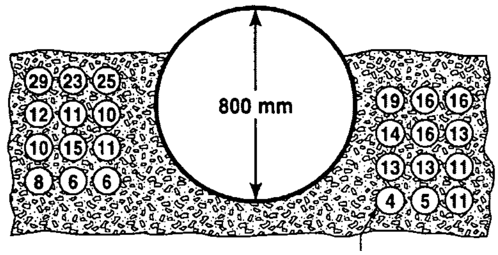

FIGURE 3 Percentage of sand in crushed stone backfill at failure site of 800-mm-diameter pipe.

arate failures. Both show the results of gradation tests taken at approximately 150-mm spacing across the stone backfill. The figures suggest that migration was occurring, although much more dramatically in the 800-mm-diameter pipe than in the 600-mm pipe. Some mixing of the sand and stone will occur during installation but would not contribute to deflection of the pipe; however, the broad distribution of the finer than 2 mm fraction and the significant percentages present suggest that migration could have been a significant contributor to the overall deflections being recorded.

The significance of migration can be calculated. On the basis of measurements of samples, the stone backfill had a bulk specific gravity of 2.47 and a rodded density of 14.9 kN/m^3. This indicates a porosity (ratio of volume of voids to total volume) of 38 percent. Because of the large particle size and the nearly complete lack of fines in the stone backfill, nearly all of the voids in the stone could be filled by the sand. Assuming that migration only takes place in the outer 150-mm portion of the stone and that only 50 percent of the voids are filled with sand at its in situ density, 29 mm of thickness is lost. If this all translates into deflection, then for 500- and 1000-mm pipes 5.8 and 2.9 percent deflections will occur. Assuming again that the in situ density of the sand is 15 kN/m^3, the foregoing migration would produce 16 percent sand content in the stone.

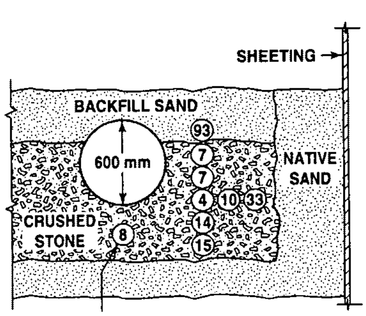

FIGURE 4 Percentage of sand in crushed stone backfill at failure site of 600-mm-diameter pipe.

DISCUSSION OF PROBLEMS

As noted, the principal causes of the deflection problems were the improper control of the groundwater during construction and the failure to address the possibility of migration of fines in the design phase of the project. These issues and their proper treatment during construction are discussed in this section.

Control of Groundwater During Construction

After installation, the embedment zone material should provide firm support for the buried pipe. This requires proper placement and compaction of the material, a process that can be completed most successfully in dry trenches and at proper backfill moisture contents. On this project the groundwater was not controlled properly, with disastrous results. Elements of the dewatering system and trench bracing contributed to the problems encountered.

Dewatering System

To be effective, a dewatering system must maintain the groundwater level below the bottom of the trench during excavation. In this project this was a demanding task because of the high water table and high permeability of the native sand material. The performance of the dewatering system was apparently never actually assessed for its effectiveness in practice. The dewatering pipes were always spaced at 1-m intervals and the same pumping equipment was always used, regardless of the performance. When water was encountered inside the trenches during excavation, the approach taken was to cope with the water by bringing a suction line into the trench rather than to consider why the water was there in the first place. The use of the suction line probably exacerbated the situation by further reducing the effectiveness of the overall dewatering system. This is a classic case of trying to cope with the symptoms of a problem rather than eliminate the cause.

In such difficult conditions, correcting the dewatering system would probably be expensive. More pumping capacity and possibly a closer spacing of the dewatering pipes would be required. Installation of two lines of sheeting, with dewatering in between, could create a barrier sufficient to reduce groundwater flow to a level that could be handled with the existing system. Drainage through the ends of the excavation also needs to be considered, especially because of the French drain effect in the backfill stone. This could be handled with waterstops installed periodically to reduce the flow.

On this project the use of sheeting with noninterlocking joints also contributed to the problem. Since the noninterlocking joints open up as the sheeting is driven, paths are created for sand to flow through the joints. Sheeting with interlocking joints may well have reduced the problem on this project. However, as observed at many locations, when the phreatic surface is maintained below the bottom of the trench, the sand is stable even when the joints are open.

The decision to remove the sheeting below the crown of the pipe was also a significant contributor to the overall problem. Not only did pulling the sheeting remove a barrier between the stone backfill and the voids, but also the vibration used caused the stone to settle into the void at a faster rate. These factors are in addition to displacement of the backfill to fill the space occupied by the sheeting.

Any one of the preceding problems may not have created the major problems encountered on the project. For example, the ineffective dewatering system may have been tolerable if the sheeting had had interlocking joints. If the sheeting were left in place, the sand may have settled and filled the voids from above and not disrupted the support to the stone backfill (although problems with street settlement could have been significant). Given all of the problems occurring simultaneously, the high deflections were likely. If there were no voids at the sides of the pipe the loss of support created by the voids might not have occurred; however, this is a procedure that has long been recognized as a potential problem because pulling the sheeting can cause serious disruption by dragging compacted fill with it. Most standard installation specifications recommend that sheeting be left in place below the crown of the pipe.

Migration of Fines

Two solutions are available to prevent the problem of migration of fines. One is to place only compatible materials, based on the foregoing gradation criteria, next to each other. The other is to use a geotextile (filter fabric) between the incompatible materials. The mixing of dissimilar materials has long been known to be a problem for many construction situations (*2*); however, its impact on pipeline behavior is often ignored by specifiers. Even though ASTM D2321 has carried a warning against migration of fines since 1974, it was not until 1990 that specific guidance in the form of Equations 1 and 2 was incorporated into the standard. One reason why the issue of migration is often ignored is that many installations do not meet the gradation criteria but perform well. The authors believe that this is often because there is insufficient flow of groundwater to mix the adjacent materials. Unfortunately, no standard criteria are available to address this aspect of migration.

SUMMARY

The investigation into the high deflections observed in a project with 11 km of RPM sewer pipe showed the problems to be the result of inadequate control of the dewatering system during the original installation and migration of fines from the in situ sand materials into the voids of the open-graded stone used for pipe embedment. The dewatering problem had many aspects, including insufficient overall pumping capacity, noninterlocking sheeting, and end drainage due to open-graded stone in previously installed pipe sections. The migration of fines resulted from the use of a coarse backfill material with no fines next to a uniform sand. The high groundwater table and high permeability of the sand created a situation in which high flows could occur to cause mixing of the adjacent materials.

These problems may not have been anticipated by the engineer or the contractor; however, if observation of the pipe deflections had been made at the end of installation, the problems should have been identified and corrected before putting the lines into service. Furthermore, the inadequacies of the dewatering should have been apparent to knowledgeable inspectors during construction.

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Publication of this paper sponsored by Committee on Subsurface Soil-Structure Interaction.