Backfill Placement Methods Lead to Flexible Pipe Distortion

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Achieving good results in compacting fill around flexible culverts requires a proper matching of pipe, backfill type, and backfill placement and compaction methods. In the construction of a nuclear power plant, the circulating water lines were designed as 3600-mm-diameter, filament-wound glass-fiber reinforced plastic pipe of low stiffness. Because of a high groundwater table and concern that liquefaction might occur during a seismic event, the specifications called for compaction of all site backfill, including backfill for the circulating water pipe, to 85 percent relative density. After construction, the pipe was found to be deflected upward beyond project limits. The pipe shape was distorted, and the joints were delaminated. Investigation showed that the backfill was compacted with large self-propelled vibratory rollers operated to achieve the required density with insufficient monitoring of the pipe condition. The emphasis on meeting the compaction requirement was demonstrated by the fact that 171 density tests were conducted at the sides of the pipe and within one diameter width of the pipe, yet observations of the condition of the pipe, which indicated the presence of a problem early in the project, were not given sufficient weight. Observations during construction indicated that the compaction equipment was operated too close to the pipe, and analysis confirmed that this could result in the observed deformations. The investigative team concluded that the pipe could have been properly installed with proper selection of compaction equipment and procedures.

A nuclear power plant was to be built on a site with a high groundwater table, and there was concern that a seismic event could cause liquefaction. Compaction requirements for all site backfill were set at 85 percent relative density to minimize this risk. To ensure that this requirement was achieved, and because of the large nature of the overall project, the contractor used large compaction equipment, and the engineer required extensive compaction testing. This approach resulted in serious problems during installation of the circulating water pipe 3600 mm (12 ft) in diameter. Unfortunately, the site personnel failed to observe what was happening to the pipe even though there was ample evidence early in the project that the pipe was in distress.

This paper describes the project specifications, features of the pipe design, construction methods, and resulting problems. The paper concludes with a discussion of lessons learned from the project. All of the problems discussed in this paper were discovered before the end of construction and before the lines were put into service. Thus operating conditions such as internal pressure and temperature are not factors in assessing the causes of the problems.

PROJECT DESCRIPTION

The plant was designed with cooling towers to chill the circulating water for the two power generating units at the plant. There were four principal runs of pipe, a supply and return line for each unit, each between 170 and 250 m (550 and 750 ft) long. The supply lines brought water from the cooling towers to the turbines, and the return lines brought heated water back to the cooling towers.

The upper 7.5 m (25 ft) of the natural soil deposit excavated for pipe installation consisted of lacustrine sediments of stratified silty and clayey fine sands (SM, SC), silts (ML), and silty clay (CL). Underlying these sediments was fine, sandy, silty, clay till (CL). The natural groundwater level was near the surface at times.

Specifications called for the circulating water pipe to be 3600 mm (12 ft) in diameter. It was to be filament-wound, glass-fiber reinforced thermoset plastic (fiberglass). Pipe burial depths ranged from 1.5 to 6.1 m (5 to 20 ft). All pipe was to be designed for an H-20 surface loading [a 71-kN (16,000-lb) wheel load] and, under a haul road where the fill height was 3.4 m (11 ft), the pipe was to be designed for a 515-kPa (75-psi) surface load applied over an area of 3 by 12 m (10 by 40 ft). The supply and return lines were to be designed for internal pressures of 700 and 350 kPa (100 and 50 psi), respectively, although the actual operating pressures were expected to be 350 and 180 kPa (50 and 26 psi). At numerous locations the lines were crossed by other piping systems.

The pipe wall was designed by the manufacturer to be approximately 28 mm (1.1 in.) thick, resulting in a pipe stiffness ($EI/0.149R^3$) of about 35 kN/m/m (5 lb/in./in.). The pipe was manufactured in typical 15.2-m (50-ft) lengths with double-gasketed bell and spigot joints. Joints at bends were constructed in the field as overlay joints. The four pipe lengths designed for service under the haul road were designed with stiffening ribs, producing a pipe stiffness of about 170 kN/m/m (25 lb/in./in.). The bells of the pipe were up to 125 mm (5 in.) thick, resulting in a pipe stiffness of about 2750 kN/m/m (400 lb/in./in.).

PROJECT SPECIFICATIONS

For this project the owner elected to purchase the circulating water pipe directly from the manufacturer and contract separately for it to be installed. This was done to allow the pipe to be purchased and ready for installation when the installation contract was signed. In the following paragraphs the two contracts are only distinguished where relevant to the problems encountered.

Specifications called for the pipe to be installed in open trenches. Backfill was to be a granular material compacted to a minimum of 85 percent relative density per ASTM D2049 (this standard has since been replaced with ASTM D4253 and D4254). Lift thicknesses were restricted to 225 mm (9 in.) before compaction. Trench backfill was to be compacted out to the trench walls or for two pipe diameters on each side of the pipe, whichever was less.

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Although impact compaction tests (often referred to as the Proctor test) were not performed on the backfill samples, experience from other projects suggests that the 85 percent relative density requirement may be equivalent to 95 to 100 percent maximum dry density per ASTM D698 and could be higher than 100 percent maximum dry density. The use of a relative density type specification rather than a percent maximum dry density specification probably came from the concern for liquefaction during a seismic event. It is a reasonable specification for the type of backfill used.

The controls on the use of compaction equipment near the pipe included the following:

- "The compaction within 150 mm to 450 mm (6 in. to 18 in.) of the pipe shall be done with hand tampers . . ."
- "Wheel type earth moving equipment or track mounted equipment of less than 34.5 kPa (5 psi) earth pressure is permitted 600 mm (24 in.) away from the pipe and not across the pipe until 1.2 m (4 ft) of overburden is compacted."
- "Care shall be taken when compacting sidefill to avoid shifting the pipe."

The specifications restricted upward deflection of the pipe during compaction operations to 3 percent of the pipe diameter and downward deflection, after placement of all backfill, to 5 percent of the pipe diameter. If the 3 percent upward deflection limit was exceeded, the compaction density was to be decreased to 75 percent relative density. The pipe manufacturer's installation guidelines further expanded on this by stating that deflection measurements should only be taken at the center of the pipe. This is where the largest deflections are expected because the thick joints make the pipe ends much stiffer.

Requirements for the presence of the pipe manufacturer's personnel during pipe assembly and backfilling operations were inconsistent. The pipe manufacturer's contract stated that the pipe manufacturer shall provide a "field service technician for 5 days to advise and instruct the contractor's personnel." However, the pipe installation contract stated that "the pipe manufacturer will provide technical assistance for all field fabrication, installation and backfilling operations" and further stated that "a field service technician will be present during the entire period of actual pipe installation to ensure that the pipe work is installed and jointed correctly and in accordance with the manufacturer's recommendations." This conflict sets up the situation that the pipe manufacturer is only required to be on site for 5 days, whereas the contractor could fairly expect full-time assistance.

INSTALLATION

Records show that the pipe installation started and stopped a number of times, and the entire process took approximately 18 months. The principal reason for the delays was other construction activities at the site. Tests on samples taken during construction showed that the backfill was poorly graded sand (SP). Most of the backfill was compacted with large self-propelled vibratory rollers, which applied dynamic compaction forces of up to 93 kN (21,000 lb). Many roller passes (8 to 12) were made. Observers reported the use of this method within 600 mm (24 in.) of the pipe.

During backfilling there were a number of reports from the contractor that the compactive effort was causing excessive upward deflection in the pipe. In one instance the construction monitors noted that the backfill compaction tests were 70.1 and 80.9 percent relative density, even though the requirement was for 85 percent. The contractor responded that this was in accordance with the specifications, which allowed the reduction in compaction if the pipe is being deflected upward more than 3 percent. The site personnel in turn noted that the final deflection limit was 5 percent and that the 85 percent relative density requirement should be complied with. In this exchange the site personnel did not appreciate that the 3 percent upward deflection limit was the controlling factor and that the 5 percent limit only applied to downward deflection, nor did they institute a review of the compaction procedures. The pipe manufacturer was not contacted for guidance during the backfilling.

Overall, records of 910 laboratory determinations of maximum and minimum relative density and 624 determinations of in situ density were available. Of these tests, 171 were conducted within one diameter of the pipe springline, at elevations between the crown and invert. The mean relative density from these tests near the pipe was 86.7 percent, and the standard deviation was 13.2 percent. Of the 171 tests, 26 test results were greater than 100 percent relative density, and 47 test results were between 90 and 100 percent. Figure 1 shows the maximum, minimum, and in situ density for the entire data base of test results. Figure 2 shows the results of tests conducted close to the pipe in terms of percent relative density as reported by the testing agency. In analyzing the data it was not possible to reliably separate the tests that were considered failed by the testing agency from those that were considered acceptable. Thus the in situ test results in Figures 1 and

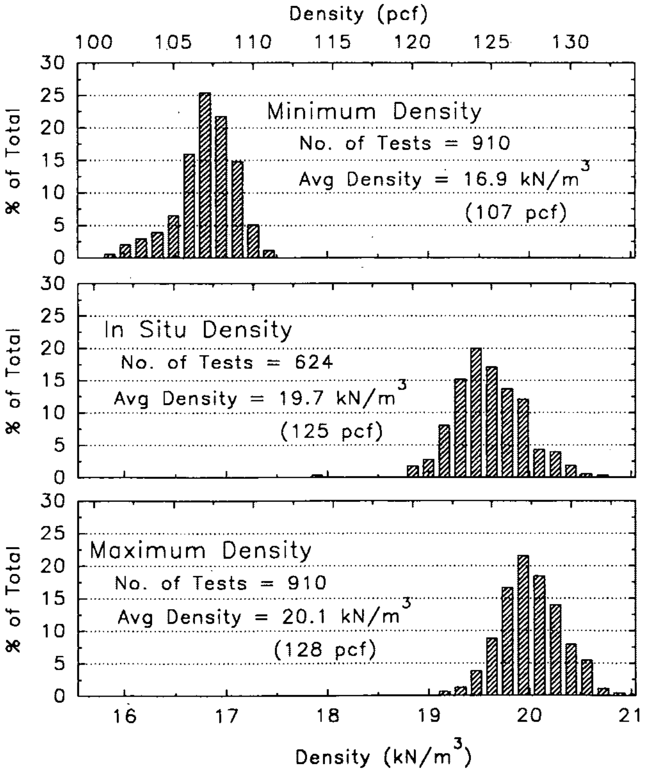

FIGURE 1 Results of all available reference and in situ density test results.

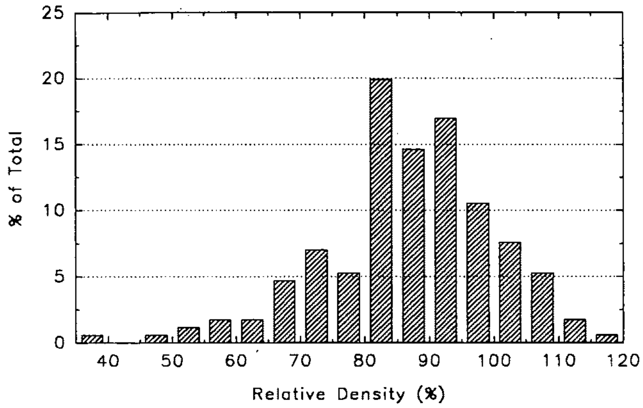

FIGURE 2 Results of relative density determinations near pipe.

2 include both. Because of this, the final, mean, in situ density is most likely higher than suggested by the figures.

The pipelines were crossed numerous times by heavy equipment involved in other aspects of the plant construction. Some of these crossings were planned and attempts were made to protect the pipe, whereas others were made without authorization. Equipment crossing the lines included a special Lampson crane brought on site to place the reactor domes and weighing 8.9 GN (2,000,000 lb) and a Manitowoc 4600 weighing 1.7 GN (390,000 lb).

PROBLEMS ENCOUNTERED

Problems with the condition of the circulating water pipe were not discovered until construction of the lines was nearly completed, even though the construction took 18 months and there was ample evidence that problems existed. Conditions that were found included the following:

- Almost all of the circulating water pipe was deflected upward at the time of the investigation, which was well after the completion of construction. Of 39 straight pipe lengths, 31 were deflected upward more than the 3 percent limit allowed by the specifications. The maximum upward deflection at the time of the investigation (backfilling complete) was 5.3 percent. The very first pipe installed on the project was deflected upward 4.6 percent. The peak upward deflections should have occurred during construction, when the backfill was near the level of the crown of the pipe. The fill above the crown should have decreased the upward deflection caused by the backfilling operations up to that level. Thus the deflections measured during the investigation were not the peak values.
- The deflected pipe shapes were distorted from the ideal elliptical shape, and the major axis of the deflected shape was frequently off-line from vertical. The pipe barrels were distorted more than anticipated by design standards for fiberglass pipe. Strains in the pipe, estimated from sagitta measurements, were commonly 0.4 to 0.6 percent at deflection levels between 3 and 5 percent. The design flexural strains at 5 percent deflection, based on American Water Works Association Standard C950, were 0.23 percent (on the basis of a shape factor, $D_f = 6$).
- The bells of the pipe deflected significantly less than the barrels because of the higher stiffness. However, of the above 39 pipe lengths, 12 joints were deflected upward more than 3 percent and 14 were deflected upward between 2 and 3 percent.
- Many of the pipe joints were delaminated and cracked.
- At two locations of known crane crossings, the pipe barrels developed helical cracks in the fiberglass laminate.

FACTORS RELATED TO DISTRESS PROBLEMS

The principal distress problems of the pipelines in this project were the upward deflection, distorted shapes of the pipe barrels, and the delaminated pipe joints.

Upward Deflection

The contractor complained repeatedly that it was difficult to compact at the sides of the pipe without distorting the pipe upward beyond the 3 percent limit. The very first full length of pipe installed was deflected upward 4.6 percent even after 7 ft of fill was placed over the top of the pipe. In spite of this condition there is no record that anyone considered changing compaction procedures or using lighter compaction equipment. Unfortunately, construction continued, and the excessive upward deflection continued for the remainder of the project. It should be a fundamental rule of installation to carefully monitor construction methods early in a project so that any problems can be corrected before their effects multiply over an entire pipeline. In this case the problem was acknowledged by the contractor but not the site monitors, and, surprisingly, the manufacturer was not consulted on the matter. The cause of the excessive upward deflection, as discussed in subsequent paragraphs, was the combination of the heavy equipment used to achieve the required density and the low pipe stiffness. The records do not show that any attempt was made to evaluate or modify the compaction procedures around the pipe to control the upward deflection.

Relative Density Compaction Requirement

The use of a relative density specification requires three measurements: a maximum reference density, a minimum reference density, and an in situ density. Each of these has considerable variability [see Figure 1 and Selig and Ladd (*1*)]. The percent variability in relative density is much greater than the percent variability in percent compaction (based on the Proctor test) because a 1 percent change in percent compaction represents a 6 to 7 percent change in relative density. As is usually the case, compaction specifications for this project did not consider this variability. They only required compaction to exceed the specified value, making no allowance for the fact that a certain percent of the backfill must fall below the specification because of normal variability. Thus, the more rigorously the specification is enforced, the higher will be the average compaction, because when test values fall below the specification more compaction is usually required, assuming that the tests are considered good (*2*).

The maximum, minimum, and in situ densities for all backfill tests during overall project construction were presented in Figure 1. The resulting variability for relative density for tests taken around the pipe was presented in Figure 2. Figure 2 shows an average density of 87 percent, with 58 percent of the tests greater than the required 85 percent relative density specified, even when failed and acceptable test results are considered. The final in situ density would likely be higher than 90 percent relative density if the failed tests could be discounted.

The figures show that the 85 percent relative compaction requirement was clearly achievable, although it was perceived by many to be the source of the upward deflection problem. The problem was actually the result of the large compaction equipment operating too close to the pipe. It is frequently thought that to obtain a high amount of compaction large equipment must be used; however, analysis shows that this is not the case (*3*). Size and weight of compaction equipment relate to the productivity of the compaction process far more than to level of compaction achieved. In this case the required density could have been achieved by the use of small equipment near the pipe to reduce the forces applied to the pipe during compaction. This issue is discussed further in the following section.

Compaction-Induced Deformation

The upward deflection was clearly the result of the compaction of backfill at the sides of the pipe. The fact that the major axis of the deflected pipe was not vertical further suggests that the backfill was not brought up evenly on both sides of the pipe. The upward deflection during construction was limited to 3 percent because compaction forces tend to be relatively concentrated and can result in local distortions. Downward deflections are caused by earth pressures, which tend to be more evenly distributed, allowing a higher limit.

The compaction was achieved by the use of large, self-propelled vibratory rollers, providing dynamic compaction force of up to 93 kN (21,000 lb) and dynamic soil pressures under the roller of 255 kPa (37 psi). This is far more than the specifications intended if the equipment is allowed closer than 450 mm (18 in.) to the pipe.

Flexible pipe can be deformed by compaction forces; however, the high stresses caused by compaction equipment dissipate very rapidly with increasing space between the pipe and the equipment. On this project there were reports that the compaction equipment was being operated very close to the pipe. To investigate the effect of this, the authors developed a simple computer model to represent compaction effects. The model used a ring to represent the pipe and springs to represent the surrounding soil, as shown in Figure 3. The pressures applied to the pipe were based on the Boussinesq distribution shown in Figure 4. Figure 4 shows two curves representing the pipe at 150 and 600 mm (6 and 24 in.) from the compaction equipment. The figure shows that the vertical soil stresses at the pipe-soil interface, when the compaction equipment is 150 mm (6 in.) from the pipe, are 5 to 10 times the pressures resulting when the equipment is held 600 mm (24 in.) from the pipe. Horizontal pressures were computed by applying a factor of 0.4 to the vertical pressures. The principal assumptions of the model were that the backfill layer currently being compacted would undergo significant lateral strains that could deform the pipe, whereas prior lifts, having already been compacted, provide a reduced lateral force on the pipe.

On the basis of a paper by Duncan and Seed (*4*), 55 percent of the lateral pressures produced under peak compaction loads were assumed to remain in the layer being compacted. In previous layers the residual lateral pressures are assumed to vary gradually from 27 to 0 percent of peak over the several previous lifts. This model had to be run iteratively for each backfill layer to be certain that springs resisting outward motion were only acting in compression. The resulting deformations were then accumulated for each layer. The deformed shape of the pipe resulting from the two conditions, 150 and 600 mm (6 and 24 in.) between pipe and compactor, are shown in Figure 5. The upward deformation when the compactor was 150 mm (6 in.) from the pipe was 6.9 percent of the pipe diameter, or almost three times the 2.5 percent deflection resulting from a 600-mm (24-in.) separation. Although it is not a rigorous treatment of the complex pipe-soil interactions taking place during backfill compaction around buried pipe, this computer model clearly demonstrates the sensitivity to deformations when large equipment is operated too close to the pipe.

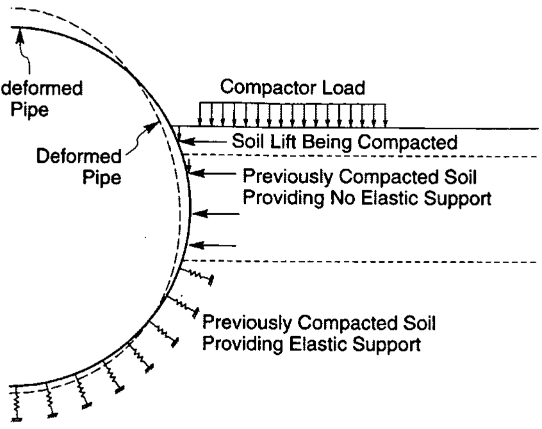

FIGURE 3 Computer model used to analyze compaction effects.

The preceding analysis can be further evaluated by analyzing the behavior of the pipe due strictly to the weight of the soil, as

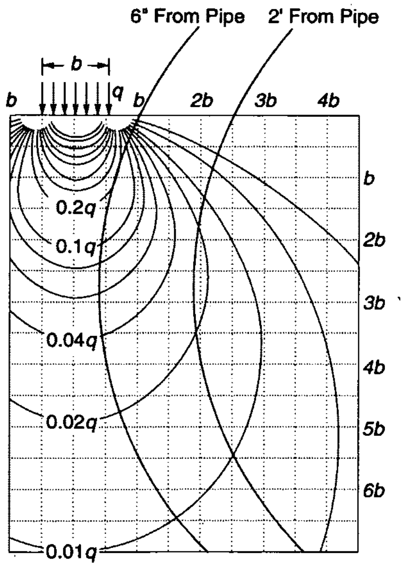

FIGURE 4 Soil stresses due to compaction near pipe.

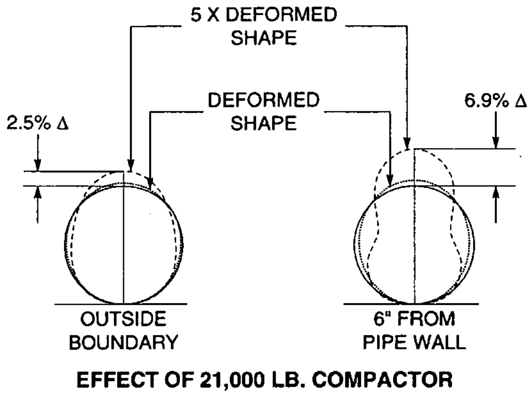

FIGURE 5 Computer model results for deformed pipe shape due to compaction effects.

is the analysis made with most currently available finite element soil structure interaction computer models. Using the program SOILCON (*5*), the pipe installation was modeled as shown in Figure 6. This models a 3600-mm pipe with 4.6 m of cover over the crown. Using this model and considering three types of backfill (SW at 85, 90, or 95 percent maximum dry density, ASTM D698) the pipe deflections were monitored as fill was placed beside and over the pipe. The results are shown in Figure 7. When only the weight of soil is considered, upward deflection occurs only for the densest soil (95 percent maximum dry density), and even in that case the upward displacement is less than 0.5 percent.

Differential Stiffness of Pipe Joint and Pipe Barrel

When a pipe barrel and pipe joint have significantly different ring stiffness, the deflection levels will vary. This is in part because of typical soil-structure interaction, as predicted by the Iowa formula (*6*), and partly because flexible sections tend to deform more than stiffer sections as a consequence of installation procedures and compaction effects, called installation deflection (*7*). The principal problem with differential stiffness between the pipe joint and the barrel is that the stiff element tends to resist a greater portion of the load and restrains the deflection of the flexible element. Thus the stiffer element will deflect more than it would if the entire pipe were stiff, and it will be subject to longitudinal stresses that can be high enough to cause failure. The differential stiffness in this project was significant, the joint being about 100 times stiffer than the barrel. Because of the excessive deflections, the pipe joints delaminated and circumferential cracks occurred. However, stress analysis of the joints using the NASTRAN finite element program showed that the pipe would have performed satisfactorily if the deflection limits had been adhered to. The results of this analysis are consistent with experiences on other projects, where the only time such failures are observed is when deflection limits are exceeded. This is logical since the effects of differential stiffness will be more pronounced as deflection levels increase. In current practice, pipe manufacturers generally avoid differential stiffness in pipe and barrels, thus avoiding the problem altogether.

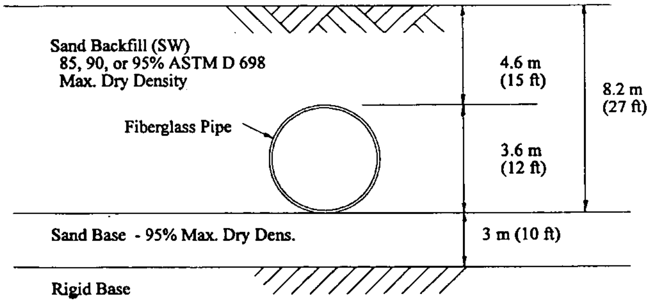

FIGURE 6 Configuration of pipe installation for SOILCON analysis.

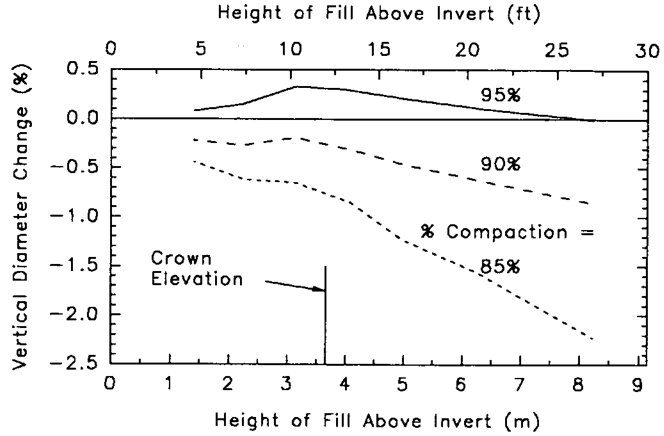

FIGURE 7 Predicted vertical diameter change with fill height for compacted sand backfill.

Use of Spiders To Prevent Pipe Deformation

An alternative method of controlling pipe deformation from compaction would have been the use of spiders to temporarily increase the effective pipe stiffness during compaction. Whereas this is certainly feasible, it is an added complexity in the construction procedure and is not required if compaction equipment is properly selected and controlled. The use of spiders can also introduce a new source of differential stiffness that results in longitudinal stresses due to nonuniform deflection. This is especially true if the spiders give the installer the false idea that spiders provide complete protection from damage.

Manufacturer's Field Assistance During Backfilling

As noted earlier, the specifications are inconsistent on the requirements of the manufacturer to assist in monitoring the pipe-laying operations. On the basis of a review of project records, the actual interpretation of the specifications at the time of construction appeared to be that the manufacturer was required on site to train the contractor's personnel in making the layup joints required at the bends in the lines, but not during backfilling operations.

CONCLUSIONS

A circulating water pipe 3600 mm (12 ft) in diameter was deflected upward beyond specification limits and distorted beyond its strength limits. The main axis of the deflected shape was not vertical. Pipe joints were delaminated. The principal reason for these problems was a failure to control compaction methods exacerbated by extensive compaction testing. Large compaction equipment was used too close to the pipe, and the resulting deflections were up to about 5 percent.

Perhaps the most important lesson from this project is to pay careful attention to the results of construction methods at the very beginning of a project and prevent any problems that are present from repeating. A careful review of construction methods after the first few pipe lengths were installed may have prevented the major financial disaster that resulted on this project.

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