Comparison of Compaction Methods in Narrow Subsurface Drainage Trenches

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Field investigation results of narrow-trench compaction methods with granular materials are presented. To determine what levels of compaction energy would produce target densities of at least 95 percent of standard Proctor, thus minimizing shoulder settlement above pavement edge drain trenches, a 200-mm (8-in.)-wide trench was excavated to four different depths: 300, 600, 900, and 1200 mm (12, 24, 36, and 48 in.). Fine filter aggregate was backfilled above a 75-mm (3-in.) inside diameter corrugated polyethylene pipe. Four compaction methods were evaluated: (a) one and two passes with a relatively low-energy modified plate compactor, (b) one and two passes with a high-energy vibratory wheel compactor, (c) one pass with a front-end loader tire, and (d) flooding with water. Sand cone densities and dynamic cone penetrometer tests were taken in each test section to determine how well the backfill was compacted. The high-energy wheel performed the best, producing satisfactory compaction to 300 mm (12 in.) with one pass and to 600 mm (24 in.) with two passes. It was the only method that actually achieved the desired target density. Slight pipe distortion was noted after two vibratory wheel passes at 300 mm (12 in.) deep, but no crushing was found. The vibratory ski performed poorly; in fact, one pass of the front-end loader tire gave generally better results than two passes with the vibratory ski. Water densification in the narrow trench was only slightly better than no compaction at all. Dynamic cone penetrometer testing generally correlated well with percent of Proctor compaction data, thus showing promise for evaluating compaction in narrow, granular-backfilled trenches.

The Minnesota Department of Transportation (Mn/DOT) typically installs 600,000 to 900,000 m (2 million to 3 million ft) of pavement edge drain per year and specifies the method in which these drains shall be backfilled and compacted (Figure 1 shows a typical drain section). Until research and on the basis of consultation with several compactor manufacturers, it was assumed that if the contractor followed a specified method for compacting these drains, satisfactory density and stability would be achieved. Current Mn/DOT specifications for backfill of these narrow trenches, defined here as up to 250 mm (10 in.) wide, state that the fill shall be a moist (approximately 3 to 5 percent moisture) fine filter aggregate (equivalent to a clean washed concrete sand). It shall be compacted with a vibratory plate compactor to which a shoe or "ski" has been attached that extends below the plate and down into the trench. The fabricated ski shall be narrower than the trench by 50 mm (2 in.), shall be 500 mm (20 in.) long, and shall vibrate at a minimum of 2,000 revolutions (blows) per minute (rpm). The impact force of the compactor shall be a minimum of 1815 to 2725 kg (4,000 to 6,000 lb) depending on the depth of the lift being compacted. Individual lift depths must not exceed 600 mm (24 in.).

Use of this method specification has resulted in Mn/DOT having occasional problems with settlement above the narrow trenches (Figure 2). The question arose as to whether satisfactory densities were being achieved with this method specification. Satisfactory density is defined here as 95 percent of standard Proctor density. Skok (*1*) states in his report on trench compaction, and Mn/DOT (along with most construction agencies) believes, that to minimize settlement, it is very important to compact trench backfill to at least 95 percent of standard Proctor. Conceivably, densities down to 90 to 92 percent of Proctor may minimize settlement in narrow trenches, but no attempt was made in this research to verify any particular minimum value.

To minimize potential safety hazards for vehicles due to shoulder settlement and to diminish the need for long-term maintenance, Mn/DOT undertook this study of compaction methods using fine filter aggregate (FFA) in narrow trenches. The goal was to determine the actual densities achieved at various depths with different compaction energies and methods and ultimately specify either a compaction method or a density that would minimize the potential for settlement in future trenching contracts.

Trench compaction has been studied in the past using wider trenches or more cohesive soils, but the authors are unaware of other research that duplicates the goals of this study. ASCE (*2*) studied the compaction of clay backfill in trenches. Farrar (*3*) researched settlement of road surfaces above reinstated sewer trenches approximately 1 m (3 ft) wide. Kersten and Skok (*4*) and Skok (*1*) studied backfill densities with various soils, equipment, and trench geometries in trenches generally wider than 0.6 m (2 ft). The authors contacted several manufacturers of compaction equipment in the search for other research of this nature, but without success.

FIELD RESEARCH

The soil in which the research trench was excavated was predominantly clay with an approximate near-surface density of 1410 kg/m^3 (87 lb/ft^3) at 20 percent moisture, against a standard Proctor density (ASTM T99) of 1640 kg/m^3 (101 lb/ft^3) at 18 percent optimum moisture and a modified Proctor (ASTM T180) of 1830 kg/m^3 (113 lb/ft^3) at 15 percent optimum moisture. The research trench was constructed in an agricultural field instead of along a roadway for safety reasons. The lower densities of the clay trench walls may lead to slightly lower compacted backfill densities than would have been found if

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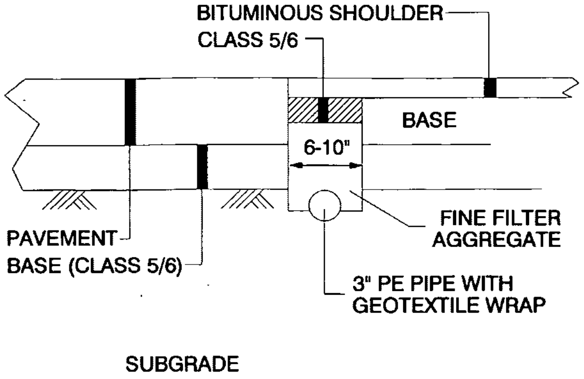

FIGURE 1 Typical drain section for Mn/DOT subsurface pavement edge drains.

the trench had been excavated into more typical higher density roadway grading materials.

A 75-mm (3-in.) inside diameter × 100-mm (4-in.) outside diameter polyethylene pipe (AASHTO M252) was mechanically laid in the bottom of the trench. The backfill material was a relatively clean sand, unprocessed, from a local pit (Belle Plaine sand). It had a standard Proctor density of 1950 kg/m^3 (120 lb/ft^3) at 11 percent optimum moisture and modified Proctor density of 2100 kg/m^3 (129 lb/ft^3) at 11 percent optimum moisture. The mechanical analysis of these two materials (Belle Plaine sand and native soil) as well as the Mn/DOT specified gradation band for FFA are shown in Figure 3. The Belle Plaine sand does not fully comply with Mn/DOT specifications for a FFA but was readily available at the research site. A short laboratory experiment was performed to correlate the field results of the "dirty" Belle Plaine sand to a more typical and cleaner (relative to the percentage minus 200) FFA. The results of that research are discussed in later sections.

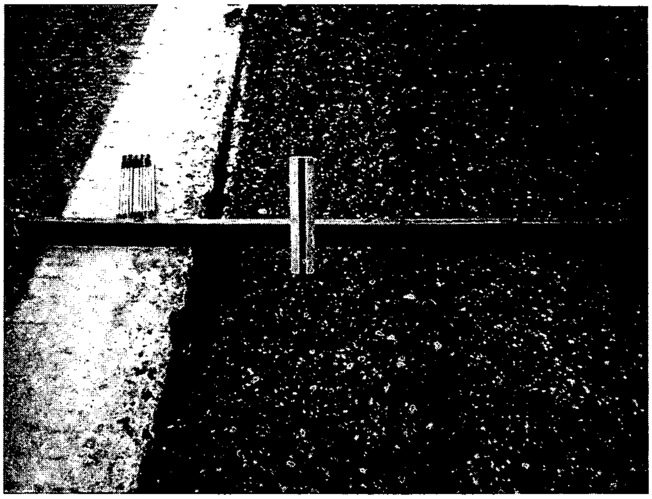

FIGURE 2 Settlement of approximately 30 mm (1.2 in.) that occurs when trench backfill is not compacted sufficiently.

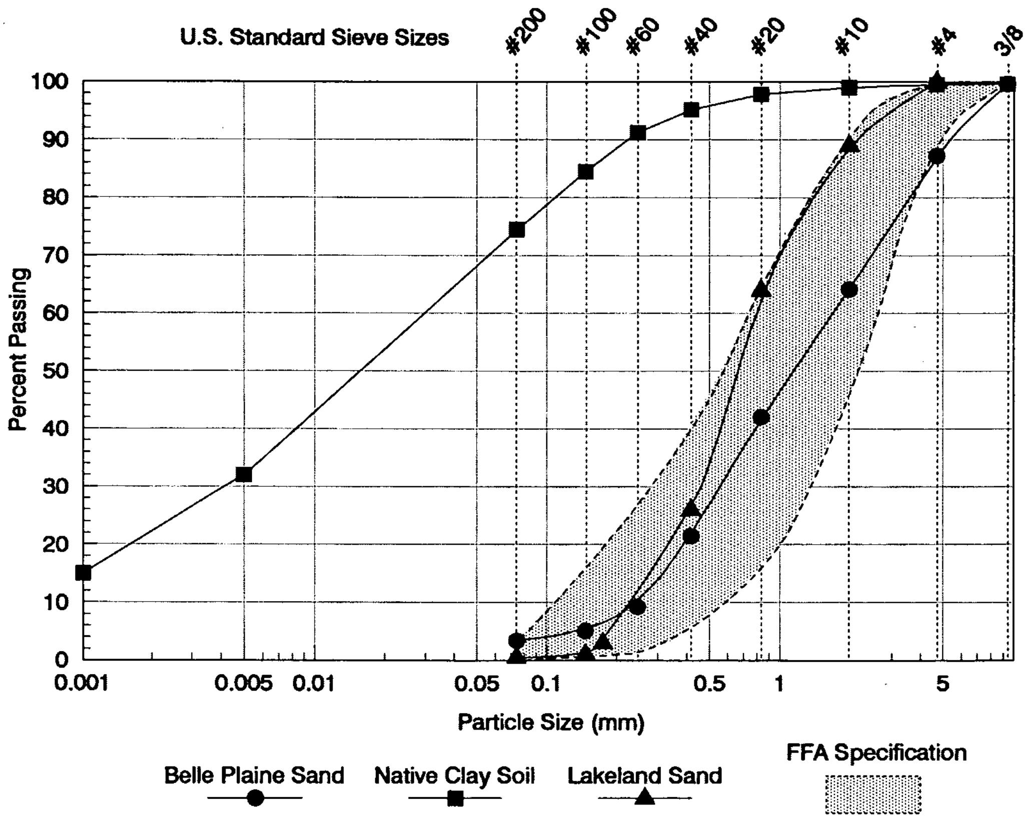

FIGURE 3 Mechanical sieve analysis of soils used and specification band for FFA.

Field Procedure

The research trench was constructed in an agricultural field just outside of Belle Plaine, Minnesota (65 km south of Minneapolis). The research was performed in fall 1991 and spring 1992. A standard Dynapac trenching machine with shield attachment was used to excavate a trench 105 m (343 ft) long by 200 mm (8 in.) wide. FFA was placed and compacted with an approximate moisture content of 5.5 percent. Figure 4 shows the trencher and backfilling equipment employed. The trench is continuous with four test cells, each 23 m long (75 ft), each of a different depth—300, 600, 900, 1200 mm (12, 24, 36, 48 in.)—and a transition zone between each cell (Figure 5). The transition zones received no compaction.

Each of the four test cells is divided into five test sections 4.6 m (15 ft) long and compacted with a different method or repetition of a method. The first test section in each cell was compacted with one pass of the low-energy vibratory ski, the second with two passes of the vibratory ski, the third with one pass of the higher-energy vibratory wheel, the fourth with two passes of the vibratory wheel, and the fifth with one pass of a front-end loader tire. All compactors traveled at an approximate speed of 15 to 18 m/min (50 to 60 ft/min), which is typical of trenching rates for Minnesota contractors.

The vibratory ski is a modified standard plate compactor with a "ski" attachment (Figure 6). The version used in this research was the Sakai plate compactor, Model PC8S with a 2633-kg (5,800-lb) rated force (per blow) operated at 3,400 rpm. The ski attachment extended 150 mm (5.75 in.) below the bottom of the plate, which was sufficient to prevent dissipation of energy onto each side of the trench. This was true even with the deepest trenches because minimal density change (compaction) was noted in the lower portions of the trench. Vibratory ski compaction was studied because it is currently the required method of compaction in Mn/DOT specifications.

FIGURE 4 Dynapac trenching machine, truck delivering filter aggregate, and shouldering attachment on front-end loader, which places filter aggregate into trench.

The wheel is a vibratory compactor made by the Vermeer Manufacturing Company, under the model name Ditcher Stitcher. It has a gross weight of 1170 kg (2580 lb) and has a rated force of 3629 to 7257 kg (8,000 to 16,000 lb) operating at 1600 rpm (Figure 7). The trench was compacted using the Vermeer wheel's maximum force. The compaction wheel itself has the ability to drop below ground level to a depth of 660 mm (26 in.). The Vermeer compactor was chosen for the research because a local contractor was using it and it was

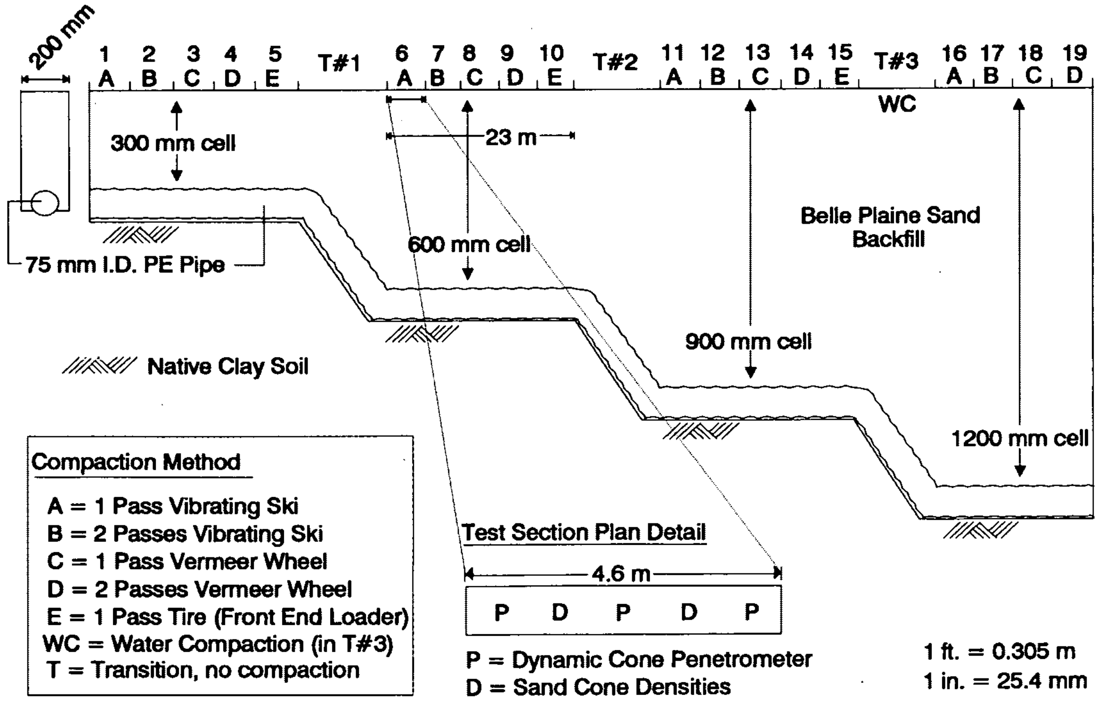

FIGURE 5 Testing layout of research trench.

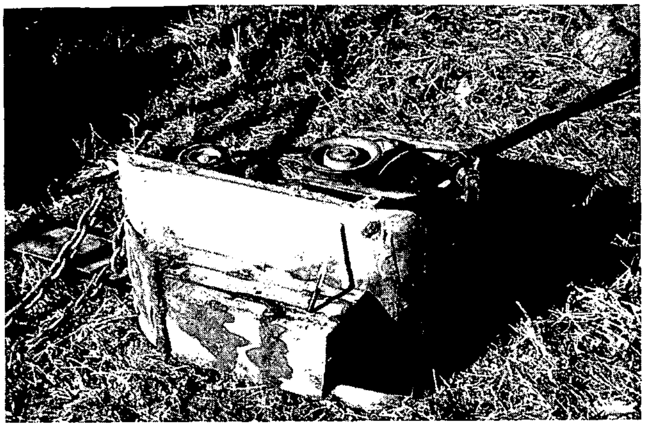

FIGURE 6 Sakai plate compactor modified into vibratory ski.

believed it represented the high end of the compaction equipment available locally. The following table presents the manufacturers' specifications for the various compactors discussed:

	Sakai PC8S "Ski"	*Vermeer*	*Stone S-52 "Ski"*
Rated force (kg)*	2633	3628–7257	2315
Frequency (rpm)	3400	1600	5400

* 1 lb = 0.454 kg

It was also decided to verify the compaction achieved by simply running a piece of heavy construction equipment, in this case the tire of a large front-end loader, over sand heaped 100 to 150 mm (4 to 6 in.) above the trench. This method of compaction was studied because of claims by contractors that densities as high as the vibratory ski could be achieved this simply.

The final method of compaction evaluated was the flooding of an area of the already backfilled trench with water. This phase was done because it is broadly speculated that flooding will give adequate densities in granular material. Transition 3 was chosen for this work because it was a deep section of undisturbed, uncompacted trench. To provide a reservoir to contain the water, the upper 350 mm (14 in.) of sand was removed, thus creating a trough 3.7 m (12 ft) long and 200 mm (8 in.) wide. The trough was flooded in two steps. The first time, 380 L (100 gal) were poured into the trough. The water was poured onto a piece of plastic at one end of the trough to avoid disturbing the surface soil and thus changing the water infiltration rate due to surface siltation. A half hour later an additional 190 L (50 gal) were applied for a total of 155 liters/m (12.5 gal/ft) of trench length. The water in the trough reached a maximum head of 180 mm (7 in.) each time water was added and percolation rates through the sand were relatively fast. Two quantities of water were used because no increase in density was noted using dynamic cone penetrometer (DCP) equipment after the first flooding. Before testing the water-densified section, it was verified that all excess water had passed through the backfill and drained out of the underlying perforated pipe, thus no further compaction would be expected.

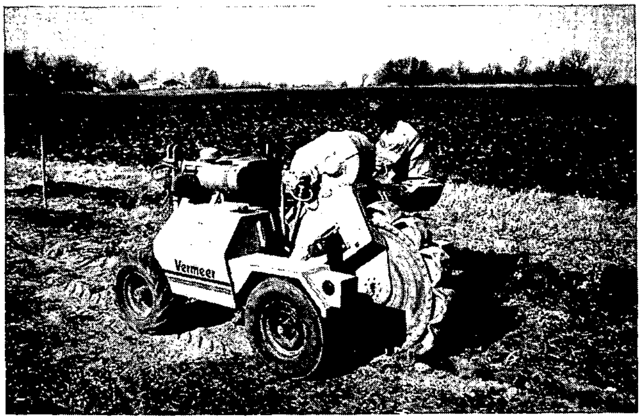

FIGURE 7 Vermeer ditcher stitcher.

Testing Procedure

The consolidation of the soil after compaction was determined by two methods. The first was by sand cone density, AASHTO T191. These were run at roughly 150-mm (6-in.) vertical intervals to the top of the pipe and at either one or two location in each test section (Figure 5).

The second method used the DCP (5). It is a semidestructive testing device used to evaluate subgrade soil strengths. It consists of a scaled steel rod 1120 mm (44 in.) long with a penetrating cone at the tip (Figure 8). A sliding 8-kg (17.6-lb) weight with a drop distance of 575 mm (22.6 in.) is attached and provides the force to drive the rod into the soil. Gross weight of the DCP is 13 kg (29 lb). After each blow, the depth to which the rod has penetrated is read. Two or three DCP tests were taken in each test section (Figure 5). For purposes of this investigation, the DCP has not been actually calibrated to give soil strength and density, but rather to provide a relative indication of the compaction in the backfill sand. The moisture content of the trench backfill sand ranged from about 4 to 7 percent during testing (8 to 9 percent in the water compacted section). The authors are unaware of any research that has been done with the DCP to determine whether, for the same density, moisture changes in granular soils significantly alter the DCP test values.

To determine whether the polyethylene pipe laid in the bottom of the trench had been damaged by compaction, the end of the pipe from Test Section 4 was exposed and the diameter measured. In addition, a 65-mm (2.5-in.) probe was pushed through the length of pipe in the same section to check for crushing. Test Section 4 was chosen as representing the worst case condition because it was only 300 mm (12 in.) deep and had received two passes with the Vermeer wheel.

Results

The results of the sand cone densities and the DCP tests have been compiled by test cell depth and shown in Figures 9–12. The sand cone densities are listed to the left of the DCP values and represent percent of standard Proctor density. These numbers are plotted at the midpoint of each tested interval, usually 150 mm (6 in.). In Figures 9–12 an ^{A} next to a Proctor percentage indicates an average of two values for the same

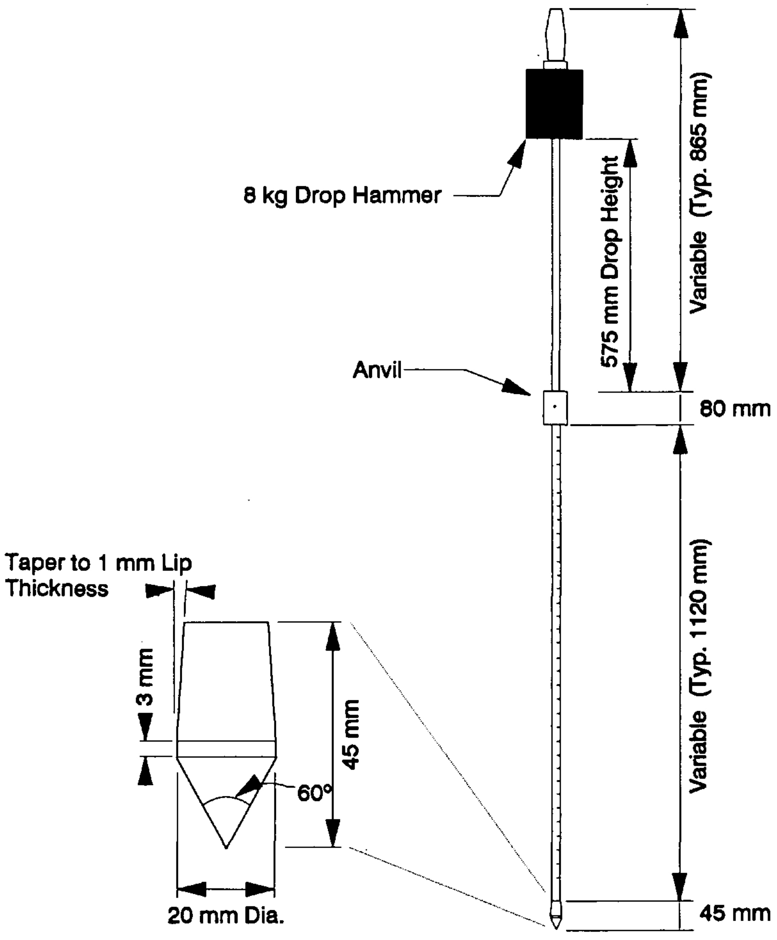

FIGURE 8 Diagram of DCP, standard South African design.

depth but in different locations in the test section. Where average values are shown for Proctor percentages, 60 percent are within ±1 Proctor percent of the values averaged, 80 percent within 2 percent, and 90 percent within 3 percent. Areas that have densities at or above the 95 percent Proctor target have been shaded.

The average density of the backfill placed in the trench without any compaction (labeled "none" on the graphs) is approximately 82 percent of standard Proctor. Higher densities were generally seen at depth due to the weight of the overlying sand. As expected, all compaction methods produced higher densities than no compaction at all.

Surprisingly, the low energy vibratory ski, which is the method currently specified by Mn/DOT for use in its narrow trenches, only gave one density reading greater than 95 percent standard Proctor—even after two passes—throughout the entire research trench. This indicates that Mn/DOT sees settlement of paved shoulders above some of the trenches because of the use of insufficient compaction energy and not as a result of inadequate construction procedures or inspections. The higher energy Vermeer wheel performed significantly better, producing densities around 95 percent of standard Proctor up to a depth of 300 mm (12 in.) with one pass and about 600 mm (24 in.) with two passes. Below 600 mm (24 in.), even with the Vermeer, compaction effectiveness dropped off significantly, as seen both by percent of Proctor and DCP blow count. That the Vermeer provided superior results with respect to the "ski" should not be unexpected because the rated force for the Vermeer is almost three times that of the Sakai compactor. Each also had different vibration frequencies (blows per minute), the possible effect of which was not evaluated here. It was also a surprise that one pass with the front-end loader tire generally outperformed the ski compactor.

After flooding a 3.7-m (12-ft) long and previously noncompacted section of the trench—Transition zone 3—with a total of 570 L (150 gal) of water—155 L/m (12.5 gal/ft)—the average density of the backfill was greater than the uncompacted sand but was still only 87 percent of standard Proctor (Figure 11). The volume of water used is greater than would or could typically be used during normal edge drain construction.

DCP blows are given in the bars on Figures 9 through 12. A line is drawn across the bars at the depth at which the DCP cone stopped. The number above the line indicates the number of hammer blows to that depth; a zero indicates penetration achieved due solely to the gross weight of the DCP because it was carefully set into the backfill. Zero penetration

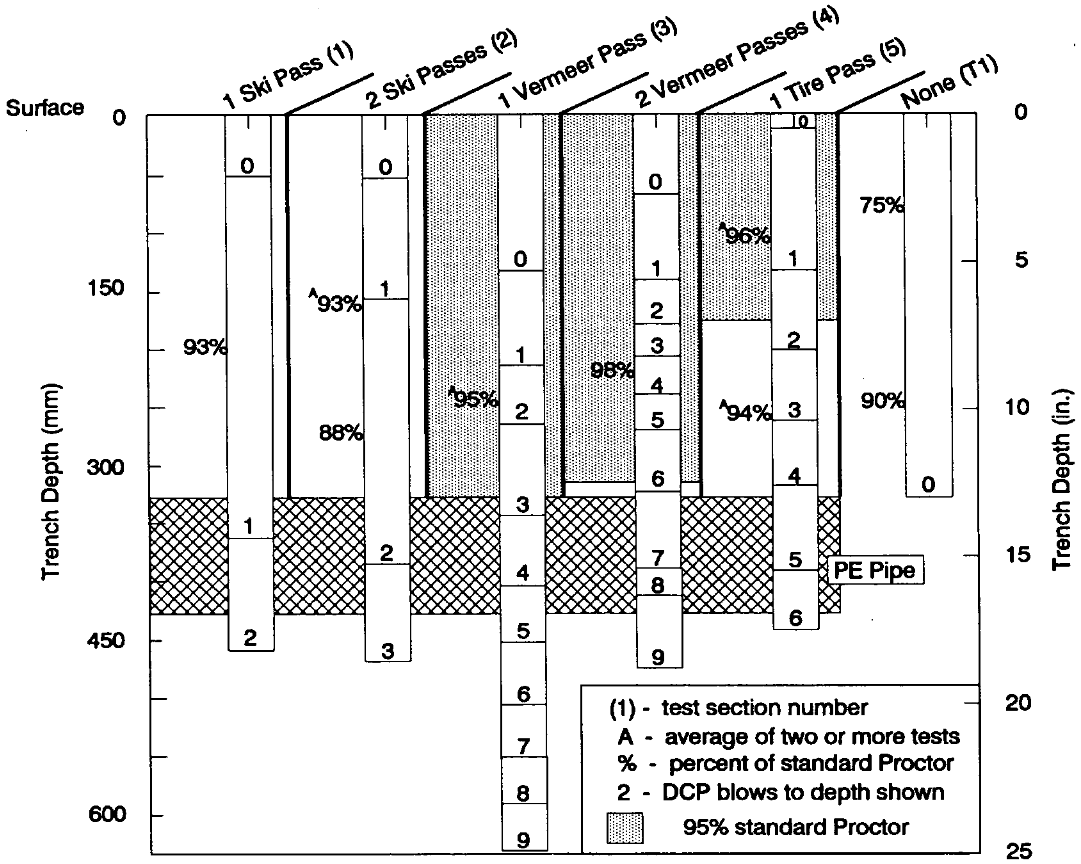

FIGURE 9 Field compaction results in 300-mm trench depth.

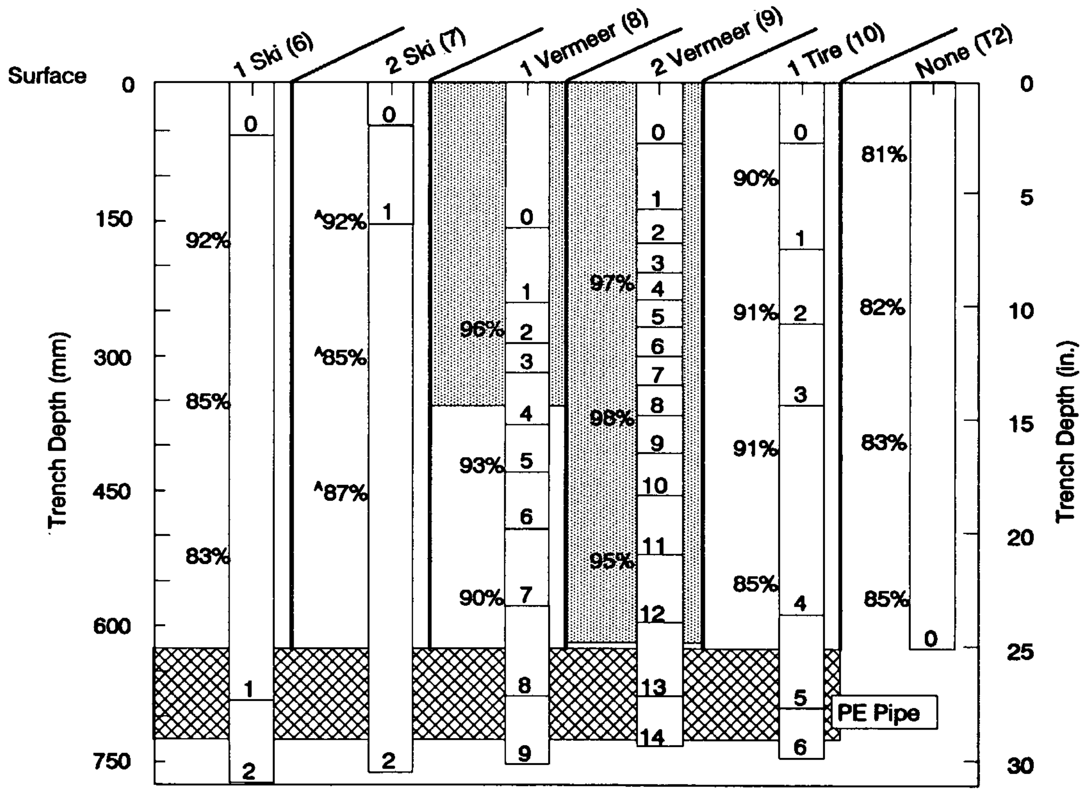

FIGURE 10 Field compaction results in 600-mm trench depth.

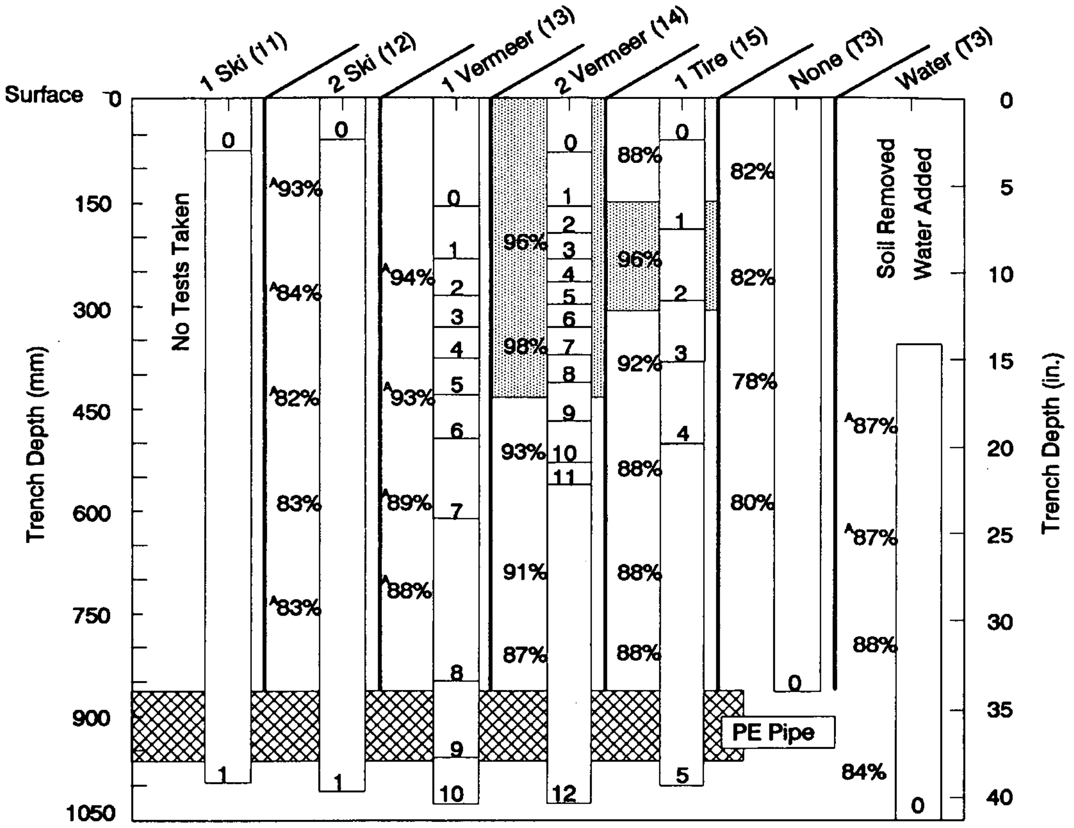

FIGURE 11 Field compaction results in 900-mm trench depth.

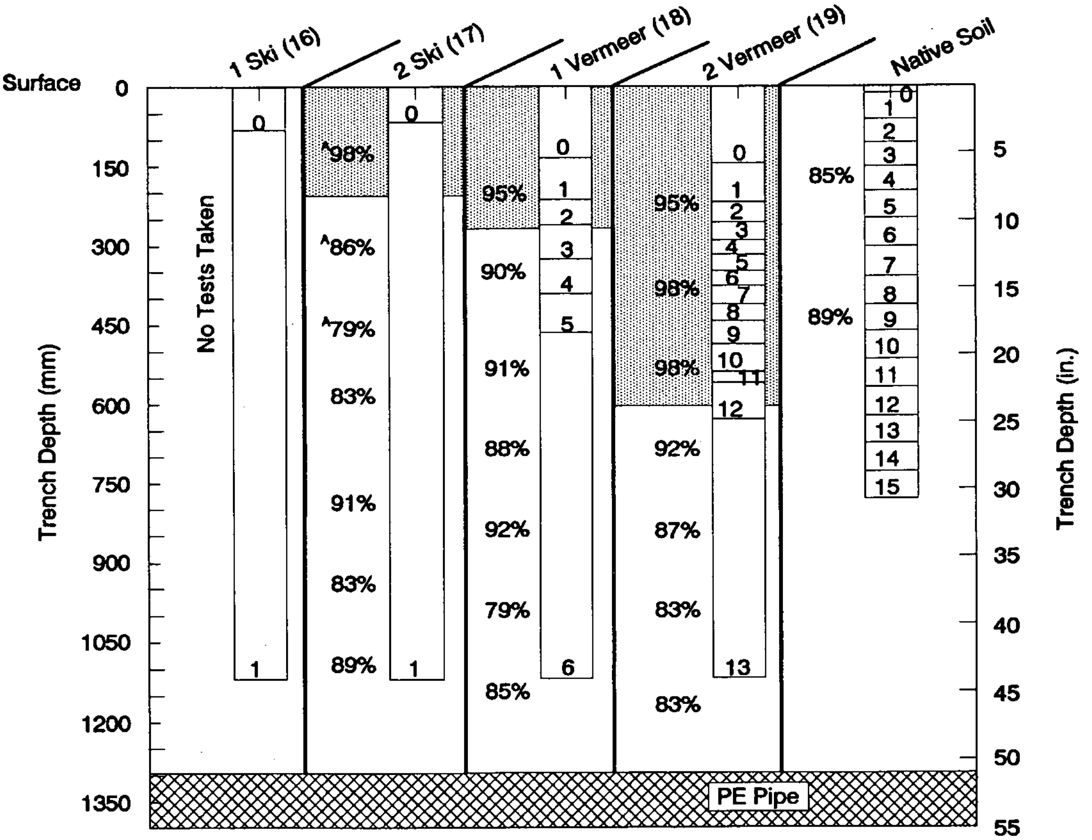

FIGURE 12 Field compaction results in 1200-mm trench depth.

points, which are shallower for two-pass test sections than one-pass test sections, are because before the second compaction passes, these sections were refilled with sand to the ground surface.

In the vicinity of the pipe, the DCP tip was driven through the pipe (with no apparent resistance) or in some instances possibly through the sand immediately next to the pipe without penetrating the pipe. Some of the plots show the DCP cone as stopping within the pipe itself, which did not actually occur in the field. This apparent anomaly is because two or three DCP tests are averaged within each test cell (some above the pipe and some at or below the bottom). Because the DCP can read a maximum 1120 mm (44 in.) below the ground surface, no data exist below this depth.

DCP penetration depths for equal blow counts were found to be quite consistent within each test section. For any blow count, roughly 70 percent of the two or three depths averaged are within ±25 mm (1 in.) of the average plotted and an additional 25 percent are within 50 mm (2 in.) of the average.

As would be expected, DCP values reflect compaction effectiveness, showing less penetration per blow the more compacted is the sand. Although a graphical method of showing the DCP data was chosen for this paper instead of the more conventional penetration per blow, the penetration index can be roughly calculated from the figures.

The polyethylene pipe was found to be distorted less than 2 mm (.0625 in.) when a 150-mm (6-in.) length of the pipe was carefully removed and the inside diameter of the pipe remaining in the ground was measured. Using a 65-mm (2.5-in.) probe, no resistance was encountered anywhere in the 4.6 m (15 ft) of pipe probed except in one isolated spot, yet the probe would still pass through. Therefore, although a maximum distortion of approximately 13 mm (0.5 in.) occurred, for the most part the pipe remained undamaged after two passes with the Vermeer wheel in the 300-mm (12-in.) test cell. Sand cone densities and DCP data for the in-place agricultural field clay are shown in the last column of Figure 12.

LABORATORY RESEARCH

As can be seen in Figure 3, the backfill that was used in the field research trench was not as "clean" as that normally specified by Mn/DOT for use in narrow trenches (about 4 percent minus 200 versus typically 2 percent minus 200). To give the results taken from the field more credibility, the slightly "dirty" Belle Plaine backfill was compared with a "cleaner" sand in the laboratory. The "cleaner" sand is identified as Lakeland sand. It had a standard Proctor density of 1800 kg/m^3 (111 lb/ft^3) at 13 percent optimum moisture and a modified Proctor density of 1880 kg/m^3 (116 lb/ft^3) at 12 percent optimum moisture. Its gradation is shown in Figure 3.

The Lakeland sand, with approximately 3 percent moisture content, was placed in 150-mm (6-in.) lifts into a plywood box measuring 200 mm wide × 600 mm long × 900 mm high (7.5 × 24 × 36 in.). The box was built to replicate a section of trench 900 mm (36 in.) deep. Each of the six lifts was compacted using a pipe-handled steel-plate hand tamper 75 × 150 mm (3 × 6 in.). The compaction effectiveness was determined by taking sand cone densities in the middle of the box and DCP tests on both sides. This procedure was then repeated using the Belle Plaine sand.

The results of this research (including Proctor densities) are shown in Figure 13. Although the gradations and sand cone density values differ, the DCP results and the percentage of standard Proctor for the two sands are quite similar.

CONCLUSIONS

The results of the research show that a relatively low-energy (force) vibratory ski, as currently specified by Mn/DOT, is not effective in achieving the 95 percent of standard Proctor density that Mn/DOT wants in the backfill of narrow trenches. One pass with a front-end loader tire over heaped sand gave generally better compaction than the vibratory ski, and compaction with water was only slightly better than no compaction at all. Two passes with the high-energy Vermeer vibratory wheel achieved the target 95 percent standard Proctor density without damage to the pipe and is thus the most effective method evaluated. The use of compaction equipment that will achieve densities of roughly 95 percent of standard Proctor should replace the vibratory ski method specification currently used by Mn/DOT.

It should be kept in mind that the energy imparted by the Vermeer wheel achieves the target density to a depth of 300 mm (12 in.) with one pass and 600 mm (24 in.) with two passes. Therefore, these lift heights should likely not be exceeded for this or similar energy equipment. Because the Vermeer wheel maximum reach is 660 mm (26 in.) below ground surface, this particular compactor, at the maximum energy level, appears to be suitable for satisfactorily compacting narrow highway trenches up to 1200 mm (48 in.) deep if the backfill is placed and compacted in two lifts.

The widely accepted concept of achieving satisfactory density with water may be true if the sand is placed under water or in a wider trench or larger area, but water appears to provide minimal benefit in narrow trenches of the type investigated. Even if flooding provided a satisfactory density increase, experience suggests that under field construction conditions the use of water is not realistic for several reasons: (a) drain outlets must be in place before water densification can be accomplished, (b) the water liberates and spreads fines over the surface of the sand, which seals and prevents rapid water infiltration into the trench, and (c) water runs downgrade along the trench and saturates discharge locations, making density difficult to achieve in the backfill soils.

Research in both the field and laboratory leads to the conclusion that granular materials anywhere in the FFA gradation band (Figure 3), even though they may differ slightly in gradation and Proctor density, are likely to exhibit similar percent of Proctor and DCP penetration indexes for similar compactive efforts. The following generalizations can be drawn between penetration indexes and percent of Proctor for this set of research data: (a) penetration indexes of 75 mm (3 in.) per blow or less generally indicate compaction at or above 93 percent of standard Proctor, (b) penetration indexes greater than 125 mm (5 in.) per blow generally indicate compaction at or less than 89 percent of standard Proctor, and (c) percent of standard Proctor values from 89 to 93 percent yield variable penetration index values, ranging from 50 mm (2 in.) to greater

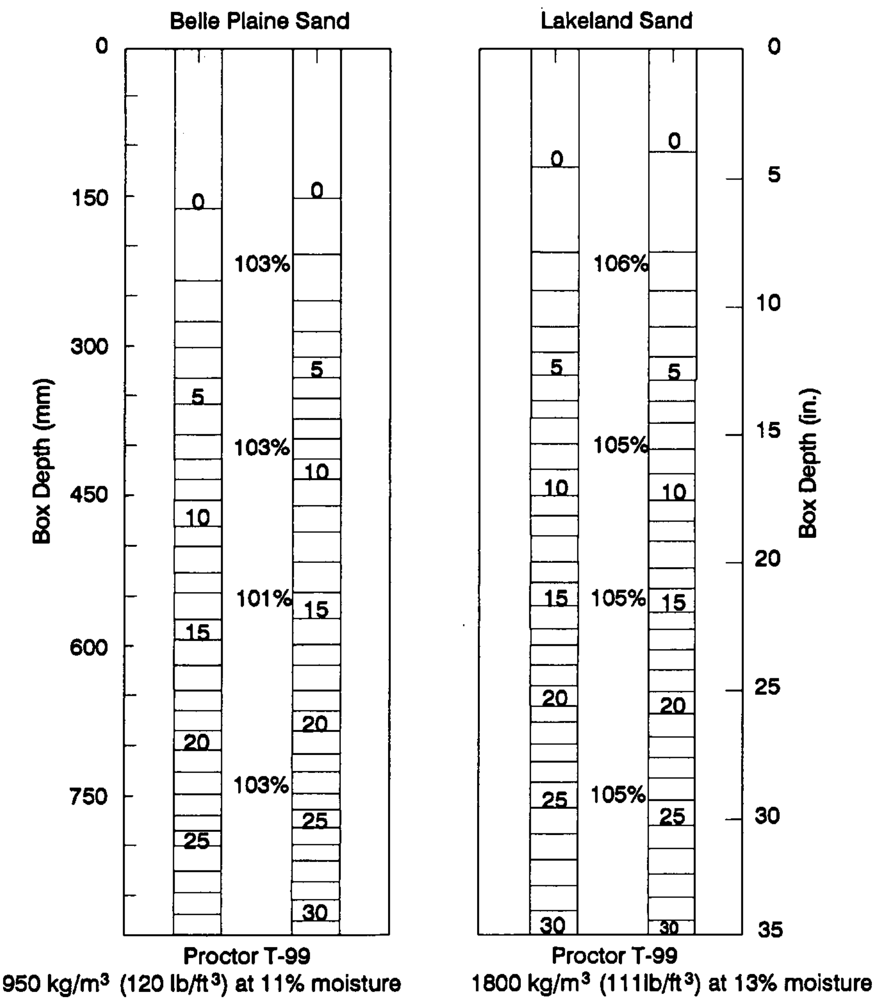

FIGURE 13 Laboratory compaction results in test box.

than 125 mm (5 in.) per blow, and thus are not easily distinguished by penetration index data. Using these general relationships, the DCP can be easily and quickly used by construction inspectors to evaluate and approve the use of different types of compaction equipment on the basis of field test installations. Depth of satisfactory compaction can also be easily verified. Such evaluations could be done on a project-by-project basis or possibly for specific types of equipment commonly used by contractors.

One issue for which this research does not provide a satisfactory answer is the possible effect of sidewall friction. In a trench deeper than 600 mm (24 in.), if the upper 600 mm (24 in.) are compacted to at least 95 percent of Proctor while the lower portion of the trench is not, will the sidewall friction of the upper portion still minimize long-term settlement, even with traffic vibrations and vehicle loading? Skok (*1*) reports that compaction to 95 percent of Proctor is most critical in the upper 600 mm (24 in.) because this is the area where the majority of the settlement occurs. It is possible that densities of 90 to 95 percent of Proctor below 600 mm (24 in.) may still yield minimal trench settlement.

These results likely apply to granular materials similar to those tested but should not be extended to significantly different granular materials, nongranular materials, or wider trenches without additional research. As a general conclusion and to paraphrase Skok (*1*), trench settlement can never be totally eliminated (regardless of compaction method and density achieved), only minimized to a satisfactory extent.

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