FIELD INVESTIGATION OF THE STRUCTURAL BEHAVIOR OF RIBBED PVC FLEXIBLE PIPES ENVELOPED BY SAND

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ABSTRACT

PVC ribbed flexible pipes were installed in four experimental ditches to analyze the pipe-soil system mechanical behavior and attribute resistance design values to the pipe envelope uniform sand. Cyclical and static loadings were applied onn the system surface, that ranging from 30 kN to 60 kN by means of a linear traffic simulator, installed at Pavement Research and Tests Area at Rio Grande do Sul Federal University, Brazil. Respective pipe vertical displacements were measured by LVDT installed inside the pipes. The results indicate the significance of relative compaction and gradation for the behaviour of granular materials, the need of a minimum backfill thickness, and the importance of verifying recovered displacements under wheel loads, that could be in conformity with the soil-flexible pipe system design but is unacceptable for the pavement performance.

INTRODUCTION

A good structural performance of Portland concrete or asphalt pavements depends significantly on the drainage system. Flexible pipe technology was especially developed for buried gravity flow conduits, and has been successfully used in highway drainage.

The low stiffness of a flexible pipe allows high displacements under applied vertical loads, with consequent vertical diameter reduction and horizontal diameter increase. The structural mechanism of a flexible pipe buried in a soil trench is based on the strength of the soil envelope around the pipe. The surrounding soil offers resistance to the horizontal compression by virtue of its shear strength, and is ultimately responsible for carrying the major portion of the vertical load. The soil that involves the pipe acts in the flexible pipe-soil system as a resistant material, differently from rigid pipes, for which this material does not have structural function. Therefore, the buried flexible pipe stability is significantly controlled by the properties of the envelope material.

The technology of spirally wound ribbed PVC pipes was recently introduced in Brazil, mostly for highway drainage. Specifications for envelope materials must be revised taking into account local available materials and compaction practice. With this purpose, a research on pipe-soil system structural behavior was carried out in real scale, with a typical Brazilian coastal sand as envelope and backfill material, and application of cyclical loads by a liner traffic simulator.

STRUCTURAL MECHANISM OF A FLEXIBE PIPE-SOIL SYSTEM

A schematic representation of a buried pipe is presented in Figure 1.

The structural mechanism of a flexible pipe-soil system is based on the interaction between pipe and the surrounding material. The low stiffness of a flexible pipe allows high displacements under applied vertical loads, with consequent vertical diameter reduction and horizontal diameter increase. The horizontal displacements mobilize the passive thrust of the envelope soil. The passive thrust may be understood as the resultant of horizontal stresses developed in a soil mass, which act at the contact surface of a structure compressing the soil mass, at the failure limit state. In this situation, horizontal stresses are higher than horizontal stresses at rest (K_0 condition). The effective horizontal stresses in the passive condition depend on the coefficient of passive stress, which is a function of the friction angle, and on the cohesion of the soil. In situations where soil reaction against compression displacements is required, without however achieving the failure limit state - which is the case for a flexible buried pipe with satisfactory performance-, horizontal stresses are between K_0 and passive values.

Spangler proposed in 1941 an equation for the calculation of the diametrical displacement of a buried flexible pipe, known as Iowa equation, taking into account the redistribution of soil stresses around the pipe caused by the significant displacements allowed by the low stiffness of the flexible pipe (1). In 1958, Watkins (2) verified by means of dimensional analysis that the parameter related to the envelope material in the Iowa equation was not an intrinsic property; another parameter, the soil reaction modulus E', was defined, resulting in the Modified Iowa Equation (1).

$$\Delta y = \frac{D_L \cdot K \cdot (p+q)}{8 \cdot RA + 0{,}061 \cdot E'} \tag{1}$$

Where:

Δy = vertical diametric displacement (m)

D_L = time lag factor

K = bedding constant

p = vertical soil pressure on the horizontal plane at the top of the pipe due to permanent load ($kN/m^2/m$)

q = vertical soil pressure on the horizontal plane at the top of the pipe due to wheel loads ($kN/m^2/m$)

RA = pipe ring stiffness (kN/m2)

E' = soil reaction modulus (kN/m^2)

RA is defined by equation (2).

$$RA = \frac{E \cdot I}{r^3} \tag{2}$$

Where:

r = mean radius of pipe (m);

E = modulus of elasticity of pipe material (kN/m^2);

I = moment of inertia of the wall cross-section per unit length of the pipe (m^4/m);

The bedding constant K is related to the response of the buried flexible pipe to the opposite and equal reaction to the force load derived from the bedding under the pipe; the bedding constant varies with the width and angle of the bedding achieved in the installation (1). The bedding angle defines the bedding resistant area, the consequent stress distribution and magnitude and, therefore, the level of deformation. Variations of the bedding angle from 0 to 180^o relate to values of bedding constant from 0.110 to 0.083 (1); as a general rule, a value of K=0.1 is assumed.

The time lag factor accounts for the consolidation of the soil at the sides of the pipe with time. If the prism load (i.e. weight of the soil prism over the pipe) is used for design, a value of D_L = 1.0 should be used.

The soil reaction modulus E' is the most difficult factor to determine in equation (1). It expresses the pipe-soil interaction and cannot be measured directly. The determination depends on tests in reduced scale or on field tests, with measurement of vertical diametrical displacements of a buried pipe under applied loads; the E' value is evaluated by means of back-analysis using the Modified Iowa equation.

Howard (3) determined average E' values for different soils and relative densities based on field and laboratory tests, concluding that the most important factors that influence the vertical displacements are the nature and the relative compaction of the envelope material.

For the design of soil-flexible pipe systems, a limit of 5% vertical diametric displacement has been stablished, accounting for most failure modes (1).

EXPERIMENTAL PROCEDURE

The experiment consisted of the study of the influence of relative compaction on the vertical displacement of a buried flexible pipe enveloped by sand, considering also the proximity of the wheel load to the top of the pipe.

Granular materials are traditionally recommended as envelope materials for buried flexible pipes. In Brazil, crushed stone is generally expensive, and gravels are not easily available. Coastal sand was selected for this experiment, because it is an abundant material, what is enhancing the utilization of flexible pipes at seashore civil construction. In this case, pipes are commonly placed near the surface, which indicated the need to study the effects of the live load, since excessive displacements have been observed in some applications of flexible pipes in road construction in the last years.

The experiment consisted of four ditches at the Pavement Research and Tests Area of the Federal University of Rio Grande do Sul, where 800mm-diameter ribbed plastic pipes were installed: two shallow ditches, with the pipe next to the surface, and two deep ones, where the influence of the wheel load is less significant. For each pair of ditches of same depth, one had a strongly compacted envelope material, and in the other the envelope materials was simply dumped. In spite of the fact that envelope material should be well compacted around flexible pipes, Brazilian construction practice consists of dumping backfill into the trenches, as until recently only rigid pipes were employed. Ditches width and length were 1.4 and 5.0 meters, respectively. The backfill thickness on the top of the pipe was only 0.3 meters for the shallow ditches and 1.5 meters for the deep ones.

Compaction control was carried out using two methods: the core-cutter method according to Brazilian standards (DAER/RS – EL 302/99) and the Dynamic Cone Penetrometer (4). Six tests were carried out for each compacted layer.

After the compaction of the backfill, the ditches were covered by a pavement of concrete blocks.

Load was applied by the traffic simulator at increasing stages, ranging from 30 kN to 60 kN, first as a cyclic load at an average speed of 6 km/h, and in sequence statically, maintaining the wheel over the ditch surface for five minutes.

Pipe vertical diametrical displacements were registered during the loading by means of linear variable differential transformers (LVDTs), with measurement range of ± 50 mm (Figure 2). Rutting was measured at the surface of the ditches after the loading.

Materials

Pipe

The pipe used in this research was a ribbed plastic flexible pipe made of PVC, with internal diameter of 800 mm and ring stiffness of 0.7 kN/m^2. Figure 3 shows a flexible plastic pipe being rolled *in situ.*

Envelope Material

Fine sand from Guaiba River, near the coast in the southern region of Brazil, was used as pipe envelope material. The grain size distribution, shown in Figure 4, was determined according to Brazilian standards (NBR 7181-78). The uniformity and curvature coefficients are 2.1 and 0.9, respectively. The soil is classified as SP by the Unified Classification System and as A3 by the AASHTO-HRB Classification, indicating uniform sand without fines or cohesion. Maximum and minimum void ratios are, respectively, 0.85 and 0.61; and the specific gravity of solids is 2.66.

Maximum dry unit weight and optimum water content determined by standard compaction test are 16.6 kN/m^3 and 7.4%, respectively. CBR tests were carried out on specimens compacted in the laboratory at different relative densities (D_r). D_r is defined as:

$$D_r = \frac{e_{max} - e_{nat}}{e_{max} - e_{min}} x100\% \tag{3}$$

Results of CBR in function of D_r are shown in Figure 5. It can be noticed that the CBR value increases significantly for relative densities higher than 60%. Sands are considered dense for D_r above 66%, what is corroborated by the experimental results in Figure 5. This demonstrates the difficulty of getting high CBR values, and probably E' values as well, for uniform sands, even with a high relative compaction.

RESULTS

Compaction Control

Compaction control in the field carried out on the compacted ditches provided relative compaction range of 96 to 99%, which corresponds to a relative density range of 75 to 96%. The dumped material, on the other hand, presented relative compaction ranges of 86 to 87%, which corresponds to approximately zero relative density. It is interesting to observe that relative density is a more sensitive parameter for this particular material than relative compaction, normally used for compaction control.

Vertical Diametrical Displacements

Results of vertical diametrical displacements are shown in Table 1.

The permanent displacements were measured under geostatic or prism loading, at the end of experimental ditch construction, before the placement of the traffic simulator. As expected, there was insignificant displacement in the shallow ditches (due to only 0.30 m of backfill material). In the deep ditches, permanent displacements ranged from 11 mm (compacted ditch) to 15 mm (shallow ditch), due to 1.5 meters of backfill material.

In the deep ditches, measurements showed that the pipes did not suffer any recovered vertical diametrical displacement under loading, even for the dumped envelope material. This can be explained by the very low stresses due to wheel load that reach the top of the pipe, because of the thickness of backfill over the pipe in these ditches. On the other hand, high recovered vertical displacements under wheel load were measured in both shallow ditches, even for the compacted material. An example of recovered displacements registered under the 60 kN loading stage of the pipe installed in the compacted shallow ditch is presented in Figure 6.

It was expected that the recovered displacements due to static wheel load would be higher that those measured under dynamic load. However, placing the static load exactly over the pipe vertical diameter was a very difficult task. For that reason, in some cases, displacements measured under cyclic load were higher than those under static load.

E' Soil Reaction Modulus

The soil reaction modulus was calculated by means of the Modified Iowa Equation. Vertical soil pressure on the horizontal plane at the top of the pipe due to permanent load (p) was considered equal to the prism load and vertical soil pressure on the horizontal plane at the top of the pipe due to wheel load (q) was calculated by means of the Elsym5 software.

For E' evaluation, two different situations were considered:

- permanent load (p) and respective vertical diametrical displacement due to permanent load (ΔYp);
- wheel load (q) and respective recovered displacements (ΔYrd or ΔYrs).

Table 2 presents the results of E' soil reaction moduli. For well compacted uniform sand, E' is approximately 3 to 4 MPa, even for the shallow ditch; for the dumped material, E' ranges from 0.5 to 2.5 MPa, corresponding to shallow and deep ditches, respectively.

It can be observed that relative compaction is a very important parameter for the system performance. For deep ditches, however, even for dumped condition, the confinment, the low stresses derived from the wheel load and a certain densification achieved by the weight of the backfill material improve E' to a value near to the compacted situation.

Even though compaction and depth contribute to an increase in E' values, it should be noticed that uniform sand as envelope material provides very low E' values when compared to crushed stone or well-graded granular materials, which according to Howard (3) can reach 14 MPa. Another problem related to uniform sand is the extreme variation of E' (from 0.5 to 4 MPa) in function of construction and geometric characteristics.

This study corroborates the importance of gradation on the performance of granular materials as envelope for buried flexible pipes.

Finally, the research has shown that shallow ditches and low relative compaction of envelope material result in a high-risk combination.

Pavement Performance

Rut depths measured on the surface of the ditches are shown in Table 1. The only acceptable values are those relative to the deep ditch with compacted envelope material. Therefore, the substitution of uniform sand as envelope material by cohesive soil or gravel must be investigated.

Dynamic recovered displacements of the pipe can be asssociated to equivalent deflections of the pavement structure. Analyzing results in Table 1, dumped uniform sand as envelope material is unacceptable because of the extremely high deflections. Compacted uniform sand in shallow ditches also presents high deflections that could cause premature failure of the pavement structure, even though totally acceptable for the soil-pipe system and lower than the design limit of 5%.

The only possible combination from the pavement performance standpoint is a deep ditch with compacted uniform sand as envelope material.

CONCLUSIONS

Data from the experimental ditches allow some important conclusions for the design of soil-flexible pipe systems in road drainage and pavements constructed over such systems:

- In agreement with previous researches, the importance of relative compaction was demonstrated;
- Uniform sand should not be dumped as envelope material for flexible pipes;
- Uniform sand provide E' values much lower than those for well-graded granular materials as presented in the literature, pointing out to the importance of gradation for the behaviour of granular materials;
- For shallow ditches, recovered vertical displacements are too high for the soil-flexible pipe system, even for compacted envelope material, indicating the need of studying a minimum backfill thickness;
- The only acceptable combination considering performance of soil-flexible pipe system and pavement structure is the deep ditch with compacted envelope material;
- The most important contribution of this real scale experiment with traffic simulator is to emphasize the importance of verifying recovered displacements under wheel loads, that could be in conformity with the soil-flexible pipe system design but unacceptable for the pavement performance. Most researches consider static loads for E' evaluation and maximum depth of pipe location, missing the efffects of recovered vertical displacements on the pavement structure.

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TABLE 1 Measured vertical displacements

Ditch	Load (kN)	Recovered dynamic displacement ΔYrd (mm)	Recovered static displacement ΔYrs (mm)	Permanent Displacement ΔYp (mm)	Rut depth (mm)
Compacted deep	30	0	0	11	10
	45	0	0		
	60	0	0		
Compacted shallow	30	17	9	-	45
	40	15	6		
	50	17	19		
	60	18	19		
Dumped shallow	30	17	11	-	46
	40	83	90		
	50	75	68		
Dumped deep	30	0	1	15	50
	45	0	1		
	60	0	-		

TABLE 2 Soil Reaction Modulus E' (MPa)

Vertical displacement	**Ditch**			
	Compacted Deep	Compacted Shallow	Dumped Shallow	Dumped Deep
Permanent	3.7	-	-	2.4
Recovered	-	3.4	0.5-1.5	-

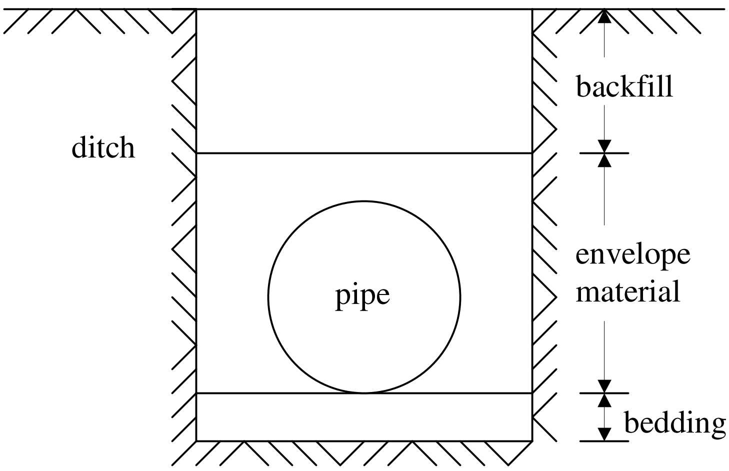

FIGURE 1 Schematic representation of a buried pipe.

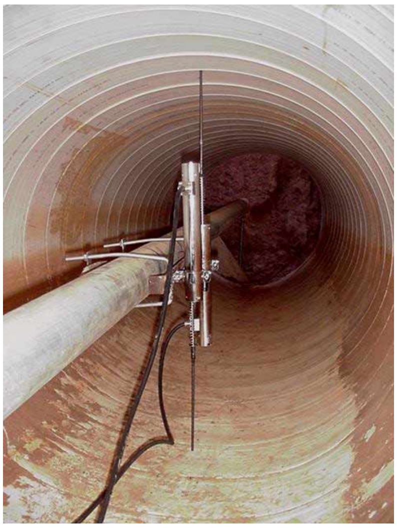

FIGURE 2 Measurement system installed inside a pipe.

FIGURE 3 Ribbed flexible plastic pipe being spirally wound.

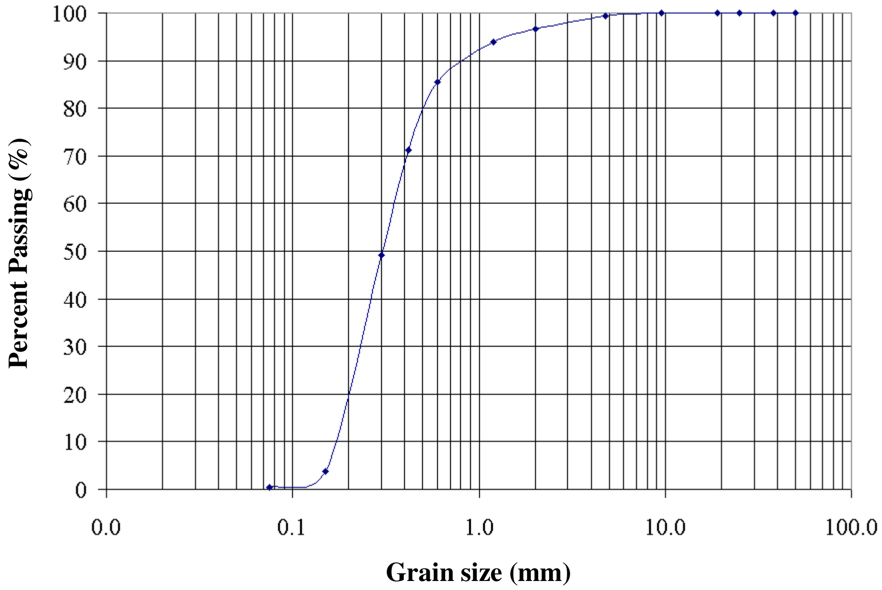

FIGURE 4 Grain-size distribution of the tested sand.

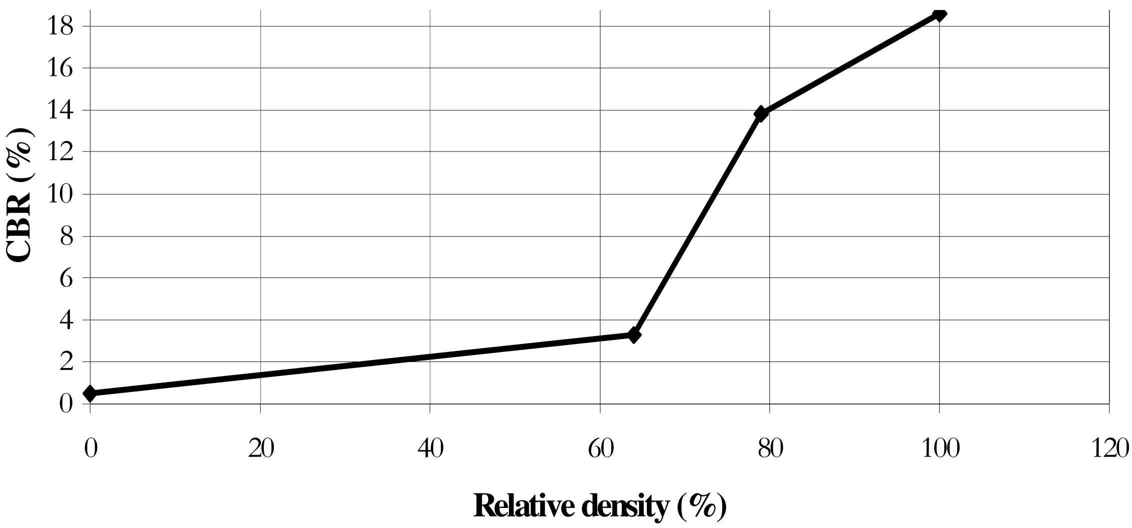

FIGURE 5 CBR in function of relative density for the tested sand.

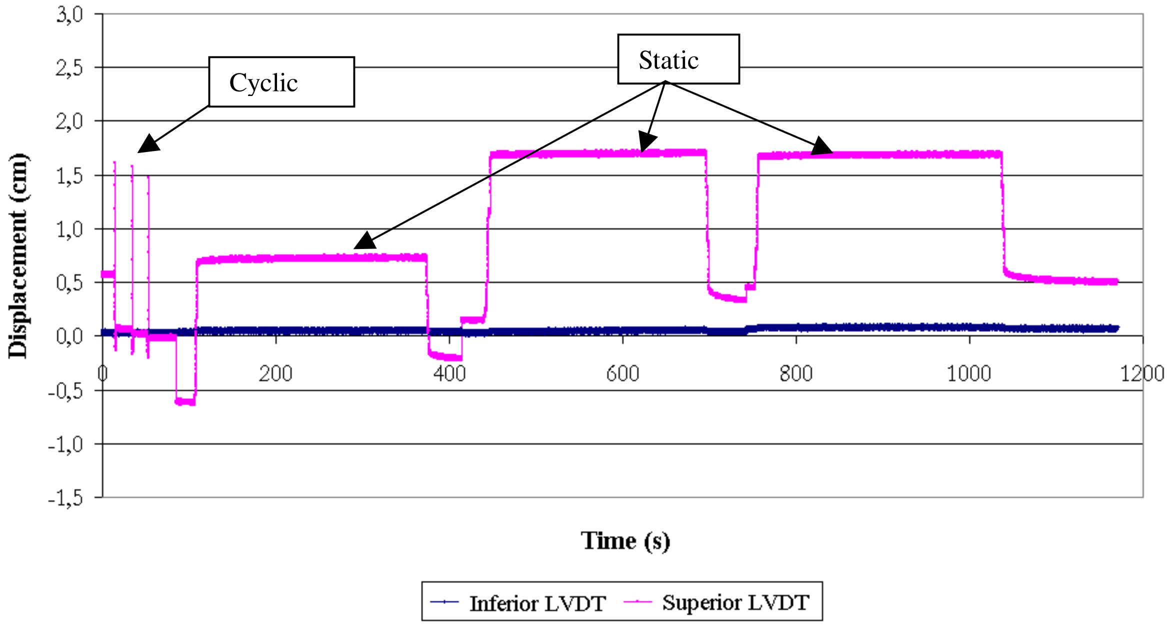

FIGURE 6 Pipe vertical displacements under 60kN wheel load for the compacted shallow ditch.