The 12th International Conference of
International Association for Computer Methods and Advances in Geomechanics (IACMAG)
1-6 October, 2008
Goa, India

Numerical Simulation of the Mechanical Behavior of Buried Pipes in Trench

Gerscovich, D.M.S., Sieira, A.C.C.F., Ferreira, A.M.
Foundation and Structure Engineering, State University of Rio de Janeiro, UERJ, Brazil

Keywords: buried pipes, trench, numerical simulation

ABSTRACT: Buried pipes are used to transport water in drainage systems or as an engineering alternative for gas and petroleum transportation. In Brazil, the usual design and execution process of the micro drainage consists of pipe installation inside trenches, which are backfilled with local compacted soil. It is not unusual that pipe trenches cross streets or roads and, therefore, may be submitted to large stress variations. To minimize the efforts that are transmitted to the pipe, it is required a minimum thickness superficial soil layer or a concrete slab, which usually results in a substantial raise of the project budget. The mechanical behavior of buried structures is mainly conditioned by its soil interaction. Different approaches are available in the literature to predict the vertical load that is transmitted to rigid pipes. Numerical tools may also be used in the evaluation of the stress-strain behavior of both materials. The present paper shows the results of a parametric study aiming at comparing the different approaches of predicting the load transmitted to the pipe. The numerical analyses were carried out in accordance to typical construction sequence. The results showed that analytical methods present a trend to overestimate the load.

1 Introduction

Urban floods are a chronic issue of great impact in the Brazilian society. The accelerated urbanization after the 60´s, generated highly populated cities with strong deficiencies in the infrastructure. Besides, the usual practice of design and execution process of drainage systems is quite conservative, particularly when it is a public work project. Prefabricated concrete pipes are usually selected and the minimum embedment criterion is mostly defined by local experience.

In Rio de Janeiro, micro drainage systems are settled by the installation of pipes inside trenches which are backfilled with local compacted soil. It is not unusual that pipe trenches cross streets or roads and, therefore are submitted to large stress variations. In these cases, a minimum thickness of the overlying soil layer is required in order to minimize the efforts that are transmitted to the pipe. If the minimum thickness requirement is not achieved, a concrete slab is positioned close to the soil surface, raising substantially the project budget.

The mechanical behavior of buried structures is mainly conditioned to its interaction with soil and different approaches are available in the literature (Marston, 1930; Janssen, 1895; Engesser, 1882) to predict the vertical load that is transmitted to rigid pipes. These approaches are based on equilibrium equations and on soil strength envelope. None of them provide a precise prediction.

On the other hand, numerical modeling appears as a useful tool to predict soil response to stress variations, since it may incorporate more adequate equations to reproduce the complex stress-strain behavior of the different materials (soil and pipe) and also provide answers at different stages of construction.

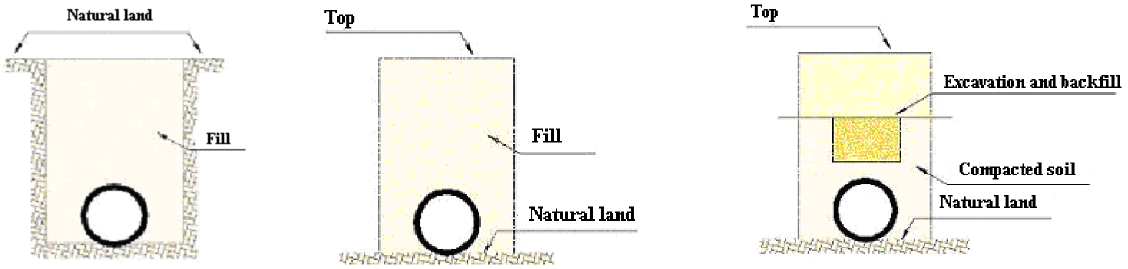
The present paper shows the results of a parametric study aiming at comparing some analytical approaches of predicting the load transmitted to the pipe with the numerical solution.

2 Buried Pipe Design

Soil-pipe behavior is mainly controlled by the stiffness relationship between pipe and soil, by the installation procedure and definitely by the geotechnical properties of soil and.

The stiffness of the pipe controls the distortion capacity and, therefore, the strains that are mobilized by the surrounding soil. Different approaches have been suggested in literature in an attempt to classify pipe stiffness. Marston (1930) used the concept of pipe deformation along the horizontal and vertical axis without occurrence of harmful fissures. Gumbel et al. (1985) appropriately considered that the classification should take into account the stiffness contrast among both materials (soil and pipe).

The standard installation method consists of laying the pipe inside a relatively narrow excavation (Figure 1a) and then covering it with earth backfill up to the ground surface. Other installation methods consist of placing the pipe with its top projecting above natural or compacted ground surface (positive projection - Figure 1b) or installing the pipe in a trench of such depth that the top of the pipe is below the level of the natural ground surface or a compacted fill and then covering with compacted earth fill (negative projection - Figure 1c).



(a) Trench (b) Embankment – positive projection (c) Embankment – negative projection

Figure 1. Pipe classification according to installation process

3 Prediction of Vertical Loads in Pipes in Trench

The basic trench load theory was proposed by Marston and collaborators (apud Tschebotarioff, 1978) and applies to rigid pipes installed in trenches (Figure 2). The theory is based upon the mobilization of shear stress on the sides of the trench due to the backfill settlement. If the soil column above the pipe moves downward relative to the adjacent soil, an aching condition is created and the effective load on the pipe is less than the load due to the overlying soil column. Conversely, in embankment installation schemes if the adjacent soil settles more than the soil column overlying the pipe, an inverted arch condition occurs and the load on the pipe is greater than the load due to the soil column.

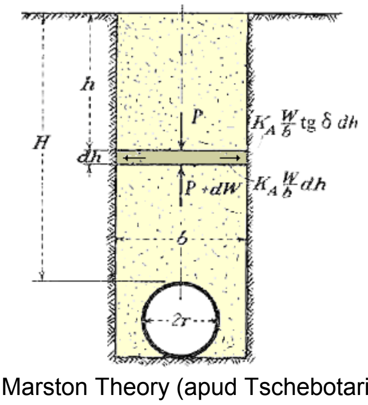


Figure 2. Marston Theory (apud Tschebotarioff, 1978)

Therefore, in narrow trenches, the resulting earth load on the pipe is equal to the difference of the weight of the material in the trench above the pipe and the shearing forces mobilized along both sides of the trench. Cohesion is usually disregarded and frictional forces are computed as a result of active earth pressure and shear forces occurring at the plane of relative movement. The vertical load transmitted to the pipe is computed according to the following equation:

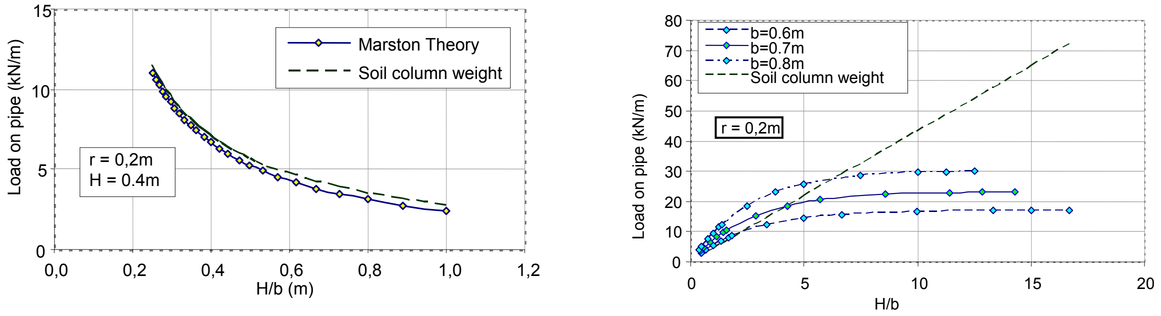
$$P = \gamma . b^2 . \frac{1 - e^{-\left(K_a . \tan\delta \frac{2.H}{b}\right)}}{2.K_a . \tan\delta} \tag{1}$$

where: P is the vertical load per length unit, b is the trench width, γ is the unit weight of soil overlying the pipe, δ

is the friction angle at the sides of the trench, H is the depth of the pipe and k_a is Rankine´s active earth pressure coefficient.

Due to the arching effect, the effective vertical load on the pipe is less than the overlying soil column weight. Its magnitude depends on soil properties and also on the geometric parameters: depth of the pipe (H) and trench width (b). Figure 3 compares vertical loads computed by Marston theory with the corresponding value which would be obtained by the weight of the overlying soil column. The Increase of the trench width (Figure 3a) reduces the influence of the shear strength mobilization along both sides of the trench and the load differences reach values less than 5%. When the trench width is equal to pipe diameter Marston´s theory predicts a load reduction of almost 17%. It is worthwhile to mention that active lateral pressure against the pipe is neglected, but could be taken in account if the trench width is relatively large. Otherwise, the mechanical behavior of the soil-pipe interaction should be evaluated according to the embankment approach, instead of trench approach.

Figure 3b shows the influence of trench depth. According to Marston there is a nonlinear relationship between trench depth and load; the curve tends to be horizontal at a certain H/b value, depending on pipe diameter. This behavior indicates a force balance between the increase of soil column weight and the increase of friction at both sides of the trench. The results also reveal that Marston theory may overestimate loads transmitted to the pipe when the lateral distance between the pipe and the trench is relatively large. The curves presented in Figure 3b were computed considering the lateral distances varying from 0.1 m to 0.2 m, and 0.4 m diameter pipe.



(a) Influence of the trench width (b) Influence of pipe depth

Figure 3. Vertical load on Pipes (γ=18kN/m3; ϕ=δ=30º)

There are other propositions in the literature to quantify the vertical load. Janssen (1895) was the first researchers interested in studying arching effects in silos. The main difference between Marston and Janssen approaches is the consideration of mobilization of the cohesion on both sides of the trench. Janssen equation (apud Terzaghi 1943) is presented bellow:

$$P = \frac{b^2\left(\gamma - \frac{2c}{b}\right)}{2k_r \tan\phi}\left[1 - e^{\left(-k_r \tan\phi \frac{2H}{b}\right)}\right] + q e^{\left(-k_r \tan\phi \frac{2H}{b}\right)} \tag{2}$$

where: b is silo width, γ is the fill unit weight, ϕ effective friction angle, q is a distributed vertical load and k_r a lateral earth pressure coefficient

4 Numerical Simulation

The numeric simulations were accomplished with the program SIGMA/W, version 5.11 (Geo-Slope International Ltd, 2002). SIGMA/W allows evaluating the stress-strain behavior of soils under different stress paths and incorporates various constitutive models to reproduce materials response. Two types of structural elements are available: bar (resistant to axial forces) and beam (resistant to axial forces and bending moments). There is no curved element to entirely reproduce pipe geometry. In the present study, the pipe was simulated by a sequence of small beam elements.

4.1 Geometry and Materials

The geometry consisted of a 0.4m diameter concrete pipe, installed inside a 1m wide trench. The pipe was placed over a 0.2m thick of compacted soil layer and the heights of the soil column (H) above the pipe varied from 0.30 m a 1.50 m.

Mesh geometry and boundary conditions were defined according to the results of a parametric study, in which the vertical and horizontal distances from the trench to the mesh boundary varied from 2b to 6b, where b is the trench width (Ferreira et al, 2006). The analyses indicated that a minimum distance of 3b could guarantee no influence of boundary restraints on the stress-strain response. Figure 4 shows an example of the FEM mesh.

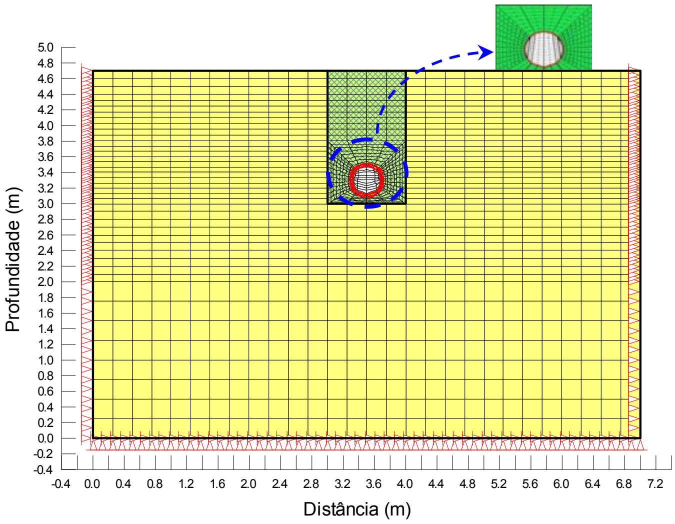


Figure 4. Finite Element Mesh (H=120cm)

An elastic-perfectly plastic model, associated to Mohr-Coulomb failure criterion, was used to predict the behavior of both local soil and fill material. The parameters are listed in Table 1.

Concrete pipe simulation was accomplished through a sequence of beam element, presenting resistance to tension and bending moments. Despite the small differences among the geometry of the beam elements, the inertia moment was computed considering a transverse rectangular area with a unitary width and 0.08m thickness. The beam parameters also shown in Table 1.

The analyses disregarded the existence of groundwater.

Table 1. Geotechnical and structural parameters.

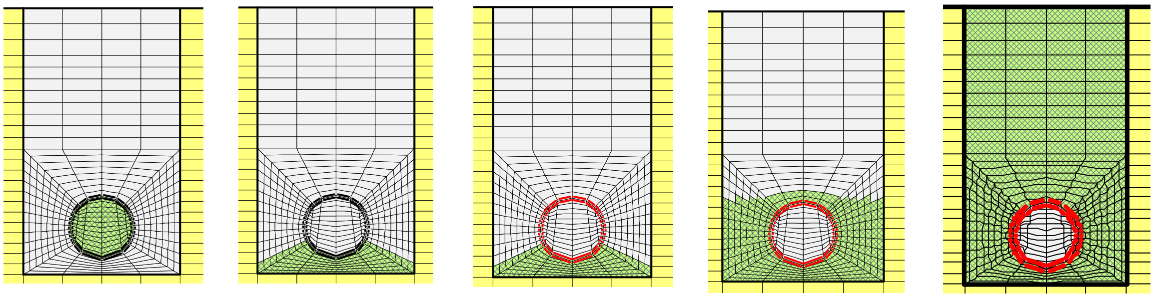
Material	Parameter	Value
Soil	Young Modulus (E_s)	60 MPa
	Poisson's ratio (ν)	0.33
	Earth pressure at rest (k_o)	0.50
	Unit weight (γ)	20 kN/m^3
	Effective friction angle (ϕ)	30°
	Effective cohesion (kPa)	0
Pipe	Young Modulus (E*)	25x10^6 kPa
	Inertia Moment (I)	4.27x10^{-5} m^4
	Thickness (e)	0.08 m

4.2 Construction Stages

The initial in-situ stresses were computed separately according the user's guide manual that highly recommends the use of linear-elastic soil model. At this phase, it is only required to input the coefficient of earth pressure at rest and unit weight; structural elements are ignored.

Figure 5 shows the construction stages that were considered in the numerical analyses: (1) excavation of the soil inside the trench; (2) compaction of a 0,2m thick base layer; (3) laying down the pipe; (4) compaction of the soil around the pipe; (5) compaction of the soil above the pipe. Each numerical step was accomplished by activating or de-activating some elements.

No specific element was used to simulate the sliding along the vertical planes of the trench or at the interface between the soil and the pipe.



(a)Trench excavation

(b) Compaction of base layer

(c)Pipe installation

(d) Pipe embedment

(e) Backfilling the trench

Figure 5. Construction stages – Trench view

5 Discussion

In this paper, numerical simulations of the construction sequence of buried pipes in trenches have been carried out aiming at comparing the numerical prediction of the load transmitted to the pipe with the analytical approaches previously mentioned.
SIGMA output does not provide the load values, but stresses, inside the elements, and node displacements. Taking into account the stiffness contrast between the soil and concrete pipe, the vertical stresses acting above the top of the pipe. would be probably absorbed by the pipe. The total load transmitted to the pipe was, therefore, computed by the integration of the vertical stress distribution, along the trench width, at top of the pipe. Figure 6 shows the vertical stress distribution that resulted from the numerical simulation of a trench with 0.9 m height of overlying soil. The higher values occur at the symmetry axis, and there is a reduction toward the face of excavation due to shear strength mobilization. Similar results have been observed in the other analyses.
Figure 7 compares the vertical loads computed by analytical methods with the ones predicted by numerical simulations. Marston and Janssen theories provide the same results since the compacted soil has no cohesion. The results also reveal that the reduction of the load due to the shear strength mobilization is more significant with the increase of the embedment of the pipe. On the other hand, numerical analyses consistently provide lower values if compared to Marston/Janssen theories. This behavior may be attributed to differences in the magnitude of the shear forces mobilized at both sides of the trench. Marston theory uses Rankine´s active earth pressure theory and Morh-Coulomb criterion to assess the shear force, while the numerical simulation is more complex and computes stresses and strains that satisfy both equilibrium and compatibility equations.

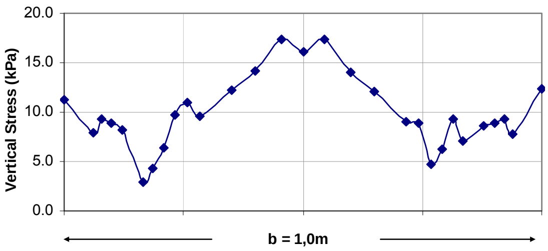


Figure 6. Distribution of vertical stresses at the top of the pipe – H=0.9 m (Ferreira et al, 2007)

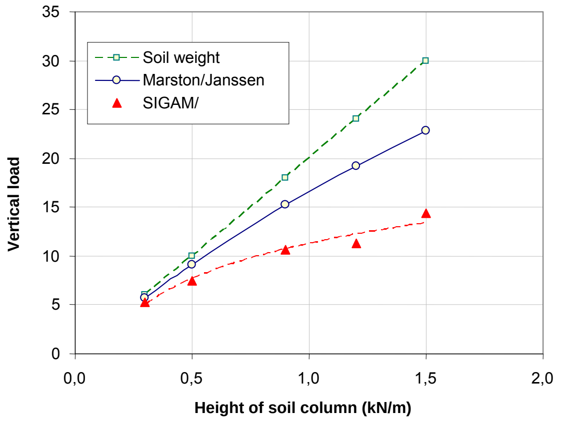


Figure 7. Prediction of the load transmitted to the pipe according to various methods

Figure 8 presents the shear stress distribution along the vertical interface between the compacted soil in the trench and the local soil, for the numerical simulation of a trench with 0.3 m height of overlying soil. Similarly to the approach used to assess the vertical load transmitted to the pipe, the shear forces were computed by the integration of the shear stress distributions. Table 2 presents the numerical and analytical methods prediction. The numerical evaluation gives shear forces that are consistently greater than Marston/Janssen approach, which are in accordance to the lower vertical load values shown in Figure 7.

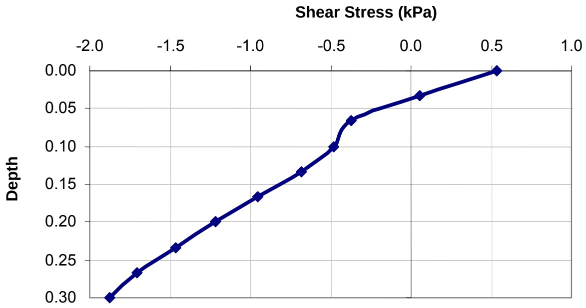


Figure 8. Distribution of shear stress along the side of the trench – H=0.3m

Table 2. Shear loads at a vertical side of the trench

H (m)	H/b	Marston theory (kN/m)	Numerical simulation (kN/m)
0.30	0.30	0.33	0.49
0.50	0.50	0.90	1.57
0.90	0.90	2.78	4.38
1.20	1.20	4.78	7.07
1.50	1.50	7.20	10.06

6 Conclusions

The present paper presented some analytical approaches to compute the vertical load that is transmitted to buried pipes in trenches. Despite its constraints, Marston's theory is the currently used method in civil engineering practice. This method does not account for the actual soil-pipe interaction that is affected by the stiffness contrast between the soil and the pipe; it also assumes that the vertical stress is uniformly distributed along the trench width and also suggests the use of Rankine's active coefficient of earth pressure to compute shear mobilization at the trench vertical boundaries. On the other hand, numerical simulations of the construction sequence may overcome these shortcomings

The present paper compared the numerical and analytical solutions to predict vertical loads and the results revealed that analytical methods constantly overestimate the load transmitted to the pipe. Analytical solutions have shown to be conservative, since greater loads implies in choosing stiffer concrete pipes for engineering design.

The authors agree that numerical analysis is attractive tool for design purposes. Nevertheless, the present analyses should be enlarged in other to address important issues such as: (i) the influence of the geotechnical properties of the local soil and of the soil inside the trench; (ii) the effect of compaction energy on the generation of horizontal stresses, since the build-up of horizontal stresses inside the trench may affect the mobilization of the shear resistance along the vertical sides of the trench and, consequently, reduce the load transmitted to the pipe; (iii) the complex interaction of the soil-pipe interface, by evaluating the need of interface elements or pipes with different stiffness, which certainly respond for different patterns of pipe deflection.

7 Acknowledgements

The authors acknowledge Brazilian research agencies CNPq (National Council of Technological and Scientific Development), CAPES (Coordination for Improvement of Graduate Human Resources) and FAPERJ (Research Foundation of Rio de Janeiro) for the financial support.

8 References

Engesser, F 1982. *Uber den Erddruck gegen innere Stutzwande (Tunnelwande*). Deutsche Bauzeitung, n 36,.

Ferreira, A. M, Gerscovich, D.M.S, Sieira, A.C.C.F 2006. Numerical analysis of the mechanical behavior of buried pipes. In: 2nd Conference of Young Geotechnical Engineers, Brazil.(in Portuguese)

Ferreira, A. M, Gerscovich, D.M.S, Sieira, A.C.C.F 2007. A study of the mechanical behavior of buried pipes in trenches. In: XXVII Iberian Latin-American Congress on Computational Methods in Engineering, Portugal. (in Portuguese)

GEO-SLOPE Int. Ltd 2002. *Sigma/W for finite element stress and deformation analysis.* User´s Guide, v05. Canada.

Gumbel, J.E, O`Reilly,M.P, Lake,L.M, Carder, D.R 1985 . The Envelopment of a New Design Method for Buried Flexible Pipes. Proceedings Europipe Conference, Bastle, paper 8. p 87-98.

Janssen, H.A . 1895. Bersuche uber Getreidedruch in Silazellen. Z.D.Vereins *Deutscher Ingeniere*. V.39, p. 1045

Marston, A. 1930. *The Theory External Loads on Closed Conduits in the Light of the Latest Experiments.* Iowa Engineering Experimental Station. Ames, Bulletin 96, 36 p.

Terzaghi, K. 1943. *Theoretical Soil Mechanics*. Ed John Wiley & Sons.

Tchebotarioff, G. P. 1978. *Foundations, Retaining and Earth Structure*s. Ed Mc Graw-Hill do Brasil

Tucci, C.E.M.; Porto, R.L. e Barros, M.T. 1995. *Urban drainage*. ABRH/ Federal University of Rio Grande do Sul, Brazil, 428p. (in Portuguese)

The 12th International Conference of
International Association for Computer Methods and Advances in Geomechanics (IACMAG)
1-6 October, 2008
Goa, India

The paper may be considered for
***(Please indicate your choice by putting √ in the appropriate box**)*

1. Oral Presentation	
2. Poster Session	