DESIGN OF BURIED PIPELINES

João José Campino de Carvalho
Departamento de Engenharia Civil e Arquitectura, Instituto Superior Técnico - Lisboa, Portugal

ABSTRACT

The installation of buried pipelines requires an adequate hydraulic analysis and structural constraints in the selection process: diameter, type of material, type of settlement, and bearing capacity required for piping installation.

The classification of pipes and their installation methods are also important for the design of buried pipelines.

After estimating the flow to be transported, the hydraulic design is carried out, in general, through the verification of transport capability by using an expression for the calculation of load losses such as the Manning-Strickler expression, to define the diameter to be adopted.

The determination of loads applied on pipes is composed of static and dynamic loads. The grounds beyond the determination of static loads are based on the theories of Marston and Spangler, whose concepts, theories and procedures are considered the most suitable for the design of buried pipelines. Considering that these methods have a significant degree of complexity in its implementation and that its physical meaning is not easy to grasp, alternative expressions of simpler physical understanding and application, have been developed. Graphical comparisons between the proposed methodology and the theory of Marston and Spangler are presented.

To calculate the dynamic loads imposed on buried elements, two different methods were used - the expression of Boussinesq and the method of linear degradation of loads. The comparison between the two is presented graphically.

Aspects relating to laboratory tests of resistance of diametric compression, with reference to the European Standard, and the maximum value of diametric deformation through Spangler's formula, the empirical expression of Anderson & Watkins and the Iowa formula, are also approached.

Keywords: loads on buried pipelines, degradation of dynamic load, diametric compression data, Boussinesq expression and Marston theory.
1. Introduction

The development of this work is to be a contribution for better understanding of the design of buried pipelines, since this is a subject of great importance nowadays. In order to obtain the most economically advantageous solution, the designer must draw a detailed study covering a wide range of material types and their different geometrical characteristics. The comparison of all deliverables, often considering the cost of the project as a determining factor in the choice of the final solution, is performed so that the solution that best fits this project is chosen. The following work was developed with this purpose.

2. Pipeline Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Vantagens</th>
<th>Desvantagens</th>
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<tbody>
<tr>
<td>Stoneware</td>
<td>- Good resistance to chemical attack</td>
<td>- Poor structural resistance</td>
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<tr>
<td></td>
<td></td>
<td>- High weight and price</td>
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<td></td>
<td></td>
<td>- Difficult handling and application</td>
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<tr>
<td>Cement</td>
<td>- Low coefficient of roughness</td>
<td>- Poor resistance to chemical attack</td>
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<td></td>
<td>- Competitive pricing</td>
<td>- Fragile resistance to flexure</td>
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<td>- Reduced weight</td>
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<tr>
<td>Concrete</td>
<td>- Competitive pricing</td>
<td>- Reduced hydraulic sealing</td>
</tr>
<tr>
<td></td>
<td>- High structural strength</td>
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</tr>
<tr>
<td>Steel</td>
<td>- High mechanical strength</td>
<td>- Need for corrosion protection</td>
</tr>
<tr>
<td></td>
<td>- Waterproofing</td>
<td>- Cost very high</td>
</tr>
<tr>
<td></td>
<td>- Wide range of diameters</td>
<td></td>
</tr>
<tr>
<td>Cast iron</td>
<td>- Good resistance to high pressures</td>
<td>- Weight and high cost</td>
</tr>
<tr>
<td></td>
<td>- Waterproofing</td>
<td>- Possibility of corrosion</td>
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<td>- Accessories of the same material</td>
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<tr>
<td>HDPE</td>
<td>- Good flexibility</td>
<td>- Degradation by solar radiation, heat, detergents, solvents and hydrocarbons</td>
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<td></td>
<td>- Very low weight</td>
<td>- Difficult to detect leaks</td>
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<td></td>
<td>- Good resistance against chemical attacks and vibration</td>
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<tr>
<td>PVC</td>
<td>- Weight and lower prices</td>
<td>- Sensitivity to shock and UV exposure</td>
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<td></td>
<td>- Wide range of accessories</td>
<td>- Risk of ovality</td>
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<tr>
<td>Plastic with glass fiber</td>
<td>- High resistance to corrosion and heat</td>
<td>- Vulnerability to shocks</td>
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<td></td>
<td>- Reduced weight</td>
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<td></td>
<td>- Easy manufacturing process</td>
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<td></td>
<td>- Low coefficient of roughness</td>
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<td></td>
<td></td>
<td>- Requires good compaction of soil surrounding</td>
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</table>

3. Classification of pipelines

The rating of the pipeline refers to the concept of rigidity (Viana, 1998) and the higher the rigidity of an element, the higher the load absorption (Alves e Viana, 2006).

The types of classification of the pipes differ from author to author, since some just mention rigid and flexible pipes, while others also refer to semi-rigid or semi-flexible conducts.

Rigid pipes are more rigid than the surrounding soil, which means that the pipes support almost the entire load applied at the level of surface and the weight of soil.

For flexible pipes the soil is more rigid than the pipe, allowing the ground to support most of the applied load.
Pipes which are initially classified as rigid, but have very large diameters and a level of flexibility which allows them to bear an extra load increase are usually classified as semi-flexible or semi-rigid pipes (Young and Troy, 1984). On the other hand, pipes which are classified as flexible but have a small diameters or relatively low flexibility, are also classified as semi-flexible or semi-rigid ducts.

4. Installation methods

4.1 Installation in a narrow trench

One of the most commonly used method in the installation of buried pipelines is definitely the narrow trench, since it is easy to perform comparatively to the remaining methods (Júnior, Lages, et al, 2008). This method consists of opening of a section, larger than the diameter of the pipes to be placed, in order to ensure good working conditions when placing the pipelines.

4.2 Installation in embankment

One of the possibilities for an installation in embankment is the positive projection installation method, which stands as the only pipe accommodated on the surface of natural soil (Debs, 2003).

The installation of positive projection only requires a small opening in the ground, named trench, with the purpose of ensuring that the pipe stays immobilized in the site where it was placed.

In negative projection installations the height of the trench must be greater that the diameter of the pipeline, so that there is a landing area above the upper end of the pipe made of natural soil.

These types of installations also include two projection modes, the incomplete projection and the complete projection, distinguished by the existence or inexistence of an equal laying plane, respectively. This plane, as suggested by its name, refers to the horizontal plane from which the laying of the soil is equal in all this level.

5. Design

5.1 Hydraulic design

The main purpose of the hydraulic project is the calculation of the diameter required to ensure a good hydraulic performance of the network, regardless of the type of flow, pressure flow or free surface flow.

The design flow depends on whether there are storms sewers or community sewers (domestic, industrial and commercial), since the origin of discharge is different. In community sewers, the flows’s estimate is based on the populations served and respective capitations. To estimate the rainwater flows they can use the formula of the Rational Method.
The use of Manning-Strickler’s formula can also be used to determine the velocities or diameters of the two networks previously mentioned (Quintela, 1981).

The value which represents the Manning-Strickler coefficient is tabulated and depends on the material of the pipeline. In order to verify this idea, a study is carried out on the dependence of other factors in the choice of the correct level of roughness coefficient.

To evaluate the effect of the duct’s diameter in the roughness coefficient, the friction factor determined by the Colebrook-White equation was equaled to the friction factor determined by the Darcy-Weisbach formula, with the load losses given by the Manning-Strickler expression. The level of absolute roughness of the pipes, according with Baptista (1980) represents the diameter of the grain of sand needed to coat a glass pipe in order for the level of roughness of the glass pipe to be equal to the project’s pipes. The results obtained are described in the graphic below:

![Chart 1 - Relation between the Manning-Strickler’s roughness coefficient and the diameter of the pipes.](image)

From the analysis of the graphic, it is concluded that the Manning-Stricker roughness coefficient to be adopted may suffer significant changes, depending not only on the material, which is the characteristic with the highest weight in the relation with the coefficient, but also on the adopted diameter.

### 5.2 Structural design

#### 5.2.1 General considerations

The basis for executing the structural design is the theories of Marston and Spangler, who have created some works which prove that their concepts, theories and procedures are appropriate for designing buried pipelines. Solving the Marston and Spangler equations involves some level of difficulty and the load coefficient is not multiplied by the weight of the soil volume above the buried element. For these reasons, a few simplifications of the original formulas were used for calculating the load applied on buried pipelines.

#### 5.2.2 Fill load in a narrow trench

To calculate the load level in a narrow trench according with Marston and Spangler, the value of the applied load, $V$, is:
\[ V = \gamma B^2 \left[ 1 - \exp\left( -\frac{2K\mu' H}{B} \right) \right] = \gamma B^2 C_v \]

where \( \gamma \) is the volume weight of the soil, \( B \) the width of the trench, \( K\mu' \) characteristic data of the soil, \( H \) the height of the soil and \( C_v \) the trench coefficient.

Thus, to calculate the load of the soil in trench conditions for rigid and flexible pipes, the following expressions should be applied:

- **Rigid pipes**
  \[ V = C_v \times \gamma \times B^2 \]

- **Flexible pipes**
  \[ V = C_v \times \gamma \times B \times D \]

**Alternative formulation proposal**

Since the intention is to present an expression for the calculation of the acting load which relates this load to the weight of the soil prism (\( \gamma HB \) for rigid pipes and \( \gamma HD \) for flexible pipes), an alternative expression to the original formula is presented, using a unitary load coefficient, \( \alpha_v \), related with the trench coefficient (\( C_v \)) as follows:

- **Rigid pipes**
  \[ \alpha_v \times \gamma \times H \times B = C_v \times \gamma \times B^2 \iff \alpha_v \times H = C_v \times B \iff \alpha_v = C_v \times \frac{B}{H} \]

- **Flexible pipes**
  \[ \alpha_v \times \gamma \times H \times D = C_v \times \gamma \times B \times D \iff \alpha_v \times H = C_v \times B \iff \alpha_v = C_v \times \frac{B}{H} \]

These new expressions are physically easier to understand since they result from the application of factors directly to the weight of the volume of soil.

Chart 2 shows how the coefficient of unit load, \( \alpha_v \), changes depending on the relationship between the height and width of the trench, \( H/B \), according with the new formula.

The fact that the unit load coefficient, \( \alpha_v \), is less than 1 easily shows that, in a trench, the load over the pipeline is always lower than the weight of the soil prism above the pipeline (rigid pipes) or above the pipeline (flexible pipes).
5.2.3 Fill load in embankment

Within the two alternatives of installation in embankment, positive and negative projection, there are also two different installation conditions, the complete conditions and the incomplete conditions. Therefore, it can be concluded that in embankment installations, there are four calculation alternatives for determining the embankment coefficient. The general expression is the same for both rigid and flexible pipes:

\[ V = C_a \times \gamma \times D^2 \]

where \( V \) is the total vertical load, \( C_a \) the load coefficient, \( \gamma \) the weight of the soil prism and \( D \) the diameter of the pipe.

**Complete positive projection**

\[
V = \gamma D^2 \left[ \exp\left(2K\mu H/D\right) - 1 \right] = \gamma D^2 C_a
\]

**Incomplete positive projection**

\[
V = \gamma D^2 \left[ \frac{\exp\left(\pm 2K\mu H_e / D\right) - 1}{\pm 2K\mu} + \left(\frac{H}{D} - \frac{H_e}{D}\right) \exp\left(\pm 2K\mu H_e / D\right) \right] = \gamma D^2 C_a
\]

**Alternative formula**

The formula for calculating the acting load is changed so that the applied load becomes a function of the weight of the soil prism above the pipeline (\( \gamma HD \)) multiplied by a new embankment coefficient, \( \alpha_a \). The new formula for determining the load for rigid and flexible pipes is the following:

\[ p = \alpha_a \times \gamma \times H \times D \]

To explicitly estimate the value of the unit load coefficient, an exhaustive analysis of the correlation between the values obtained by the Marston theory and the parameters that contribute to the value, namely \( H/D \) and \( K\mu \), was carried out. The explicit formulas for which the best correlation levels and their graphic representations are as follows:

**Rigid pipes**

\[ \alpha_a = \left(\frac{H}{D}\right)^{0.096} \times (K\mu)^{-0.021} \times e^{1.14K\mu - 0.006 \frac{H}{D}} \]

**Flexible pipes**

\[ \alpha_a = \left(\frac{H}{D}\right)^{-0.194} \times (K\mu)^{-0.024} \times e^{0.095 \frac{H}{D} - 1.955K\mu} \]
To prove the reliability of the equations obtained for determining the unit load coefficients, tables were presented containing the calculations made to compare the results from the two alternatives for determining the load applied to the pipelines. The major advantages of using the proposed alternative formulas are the explicit way in which the coefficient is applied and its calculation through a simple spreadsheet.

5.2.3.3 Negative projection

Negative complete projection

In the negative projection there are a few changes in the identification of coefficients so that this analysis can be distinguished from the previous one. These differences include the value of the diameter D, which no longer has any interest, being replaced with the width of the trench, B, and the value of the embankment coefficient is now represented by \( C_n \), coming to the following formula:

\[
V = \gamma B^2 \left[ 1 - \exp\left( \frac{-2K\mu H_{e}}{B} \right) \right] = \gamma B^2 C_n
\]

Negative incomplete projection

\[
V = \gamma B^2 \left[ \left( 1 - \exp\left( \frac{-2K\mu H_{e}}{B} \right) \right) + \left( \frac{H}{B} - \frac{H_{e}}{B} \right) \exp\left( \frac{-2K\mu H_{e}}{B} \right) \right] = \gamma B^2 C_n
\]

Alternative wording

Applying the same logic to the positive projection, the new formula for determining the load, for rigid and flexible pipes, is:

\[
p = \alpha_n \times \gamma \times H \times B
\]
where \( p \) is the load on the pipeline per length unit, \( \alpha_n \) is the load unit factor, \( \gamma \) is the weight of the soil prism, \( H \) is the height of the embankment and \( B \) the width of the trench.

Below is the explicit expression for which the best correlation was obtained and its graphic representation:

\[
\alpha_n = e^{-1.13924-0.13924,1} \times e^{0.02683,0,2683,0} \times \left( \frac{H}{B} \right)^{-0.31550}
\]

Charp 5 – Load unit coefficient in embankment with negative projection, \( \alpha_n \)

### 5.2.4 Dynamic fill loads

In this section, only the effect of loads from roadways will be analyzed and only two calculation methods will be used, the Boussinesq expression and the linear degrading of loads. Both methods use the typical vehicle presented in RSA (2006).

#### Expression of Boussinesq

Boussinesq assumes the loads on the surface are concentrated (\( P_s \)) and applied to a given distance (\( d \)), transmitted uniformly to the pipeline (\( P_p \)) of known diameter (\( D \)) at a given depth (\( h \)), and according with Pereira and Ferreira, 2000, is determined by the following expression:

\[
P_p = \frac{3P_s}{2\pi h^2 \left[ 1 + \left( \frac{d}{h} \right)^2 \right]^{2.5}}
\]

#### Linear degrading loads

Calculation through this method assumes that from the application of load with a rectangular surface area, area from the wheel of a typical vehicle, the load will degrade as its influence area increases its depth according with the angle of soil friction. Therefore, for each wheel, a reduction of the load by area occurs since it results from the relation between the value of the load applied at surface, which remains constant, and the influence area projected in the horizontal plane, which increases with depth, until the place where the pipeline is installed.
Comparison between the two methods

From the analysis of the graphics shown above it can be seen that the methods have similar load values, which leads to the conclusion that the simplest method, linear degrading, is an alternative to consider for calculating dynamic loads.

However, the Boussinesq method has greatly exaggerated load values for values of height soil below 0.5 m, but can come as close when you want reality, simply divide the load of each wheel at various point loads, and it is more accurate as the number of point loads considered. Because of these errors for very low depths, is not advisable to apply the expression of Boussinesq (one off charge per wheel), which is why the function determined by the expression of this method is shown dashed in Figure 10. Thus, it is recommended only as a method for calculating height of land of less than 0.5 m the method of linear degradation of loads.

For depth levels higher than 0.5m values do not differ much and when they do, the values obtained through linear degrading are often higher, which makes of this a more conservative method.

The existence of “peaks” in the values of the linear degrading is justified by the soil height levels for which the number of wheels that contribute for the total value of load applied on buried pipelines must be increased.

5.2.5 Fill loads calculation

The sum of the loads acting over the pipelines includes all the actions applied on buried elements, namely static loads, dynamic loads and other loads that might exist in the pipelines’ influence area.

Finally, a coefficient was applied, which readjusts the final value of load, since the contribution of lateral soil pressures on the pipelines allow for an improvement of resistance against vertically applied loads. The expression which represents this idea, according with Neto and Figueiredo (2002) is the following:
\[
Q_{cálculo} = \frac{Q_{estáticas} + Q_{dinâmicas} + Q_{outra}}{f_e}
\]

where \(Q_{design}\) is the load acting on the pipe, \(Q_{static}\) represents loads related with the weight of the soil, \(Q_{dynamics}\) represents mobile loads, \(Q_{another}\) represents other possible loads, and \(f_e\) is the equivalence factor as a function of the type of settlement of the pipeline.

The contribution of lateral pressures is different whether in trench or in embankment, and is related with the settlement conditions of buried elements and respective resistance factors.

The values for this factor vary between 1.1 for weak conditions and 3.4 for optimal conditions.

### 5.2.6 Tests to determine the resistance

In order to evaluate the resistance of the pipelines, lab tests are frequently carried out with the purpose of determining the resistance of the pipes, depending on the existing regulation for the project’s area of intervention.

According with European Standard EN 1916:2002, there are three types of tests that should be carried out to determine the resistance of the pipeline. Two of the tests are independent of the diameter and only one of them is executed for large diameters (DN>1200), as illustrated in Figure 28. In foreign bibliographies, especially in Brazilian paper works such as Zaidler, 1983, four types of tests are considered for determining the resistance of the pipes, all of which are presented in Figure 29.


![Zaidler, 1983](source: Zaidler 1983).

All of these methods of determining the resistance load, both the European Standard methods and the Zaidler methods are applied only to rigid pipes, because in this case the pipes are tested in isolation from the soil and surroundings, reason for which it is not possible to do these tests for flexible pipes.

### 5.2.7 Deformation

Deformation means the change in the vertical diameter of the pipes, which can occur both on rigid and on flexible pipes.
In order to determine the theoretical value of the long term deformation of a certain section, the formula of Spangler is applied:

$$\frac{\delta}{D} = K \frac{D_r \times q_t \times q_m}{8 \times CR + 0,061 \times E'}$$

where: $\delta$ is the long-term deformation, $D$ is the initial diameter of the section, $D_r$ is the deformation coefficient, $K$ a flow constant, $q_t$ the load due the weight of the soil, $q_m$ the load due to mobile loads, $CR$ the rigidity class of the pipe, and $E'$ is the relative module of the ground.

Other alternatives for determining the level of vertical deformation of the pipes are the two following formulas:

empirical expression of *Watkins&Anderson*  

$$\frac{d}{\varepsilon} = \frac{R_s}{30 + R_s}$$

formula of *Iowa*  

$$\frac{d}{\varepsilon} = \frac{R_s}{80 + 0,61R_s}$$

where $d$ is the long term vertical deflection (reduction of the vertical diameter), $\varepsilon$ is the vertical extent of the soil and $R_s$ is the ratio of rigidity of the section.

In both expressions presented above, the ratio of rigidity of the section is given by:

$$R_s = \frac{E'D^3}{EI}$$

where $E'$ is the module of elasticity of the ground, $D$ is the initial diameter of the section, $E'$ is the module of the elasticity of the material of the pipe, and $I$ is the inertia of the section of the pipe.

According with European Standard EN1916:2002, the level of deformation should be limited to 65% of the element’s diameter, in order to ensure that no disturbances in the structural and hydraulic performance of the pipes occur.

### 5.3 Determination of the transition width

In trench conditions, where the ration $H/B$ has high values, frequently called “narrow trenches”, the friction force may have the same magnitude as the soil weight. On the other hand, in wide trenches, where friction is constant because the height of the soil is the same, but the soil weight increases significantly as its prism widens, the parcel of the friction becomes negligible before the level of weight. This limit translates the width of the trench or embankment where the buried pipeline is subject to load, independently of the installation method applied, more specifically referred to as “transition width”.

Determining the “transition width” begins with the calculation of the load over the pipeline by applying the equation for the narrow trench condition and then performing the calculation for the positive projection embankment. As long as the first result is lower than the second, it can be said that there is a narrow trench condition, but as soon as the result of the equation for the embankment becomes lower, a situation of embankment should be considered.
After getting these results, a regression analysis with different explanatory factors was performed, with the purpose of determining an expression for calculating the transition width, $B_t$, which resulted as follows:

$$B_t = H^{0.9822} \times \frac{1}{K^{0.1251}}$$

The obtained expression is characterized for being slightly conservative in what concerns the value calculated for the transition width.

6. Conclusions

The presentation of the several factors which influence the design of buried pipelines and of the studies on some of the relevant aspects concerning this subject, result in several conclusions, which are summarized in this chapter.

In the opening chapter, despite the explanation of the advantages and disadvantages of the different materials, it was not possible to say which was the best material to be applied without knowing beforehand the rest of the conditions of the project.

In what regards the classification of the pipes, the concept of rigidness in buried pipes and the relation between rigidness and the diameter of the pipes should be noted. It is also important to note that a pipeline made of a material individually classified as rigid can be classified as flexible when applied to a pipeline with a large diameter.

When describing the various types of installation of buried pipelines, the most frequent methods of installation are described and, within those methods, there are two distinct classifications, incomplete installation and complete installation, which depend on the existence or inexistence of an equal soil settlement plane.

In chapter 5, which is the most developed and most important part of this work, the procedures to follow when designing buried pipelines are described. A study was carried out on the roughness coefficient used in the Manning-Strickler expressions, from which it is concluded that the roughness coefficient does not remain constant as the diameter of the pipeline section changes, since its value becomes lower as the diameter of the pipe increases.

The structural calculation of buried pipes was carried out in two different phases. On a first phase, the static loads deriving from the weight of the soil above the pipelines was determined. The second phase concentrated on the dynamic loads due to the mobile loads of vehicles that circulate on the surface. The calculation of static loads was based on the theories of Marston and Spangler. With the purpose of obtaining new expressions, easier to understand physically and faster to apply, new formulas were deduced which relate the value of the static load on the pipeline with the volume of soil above the buried pipes and regression analysis were carried out in order to obtain explicit expressions of some of the coefficients. The first conclusions to obtain from these new expressions are illustrated in the graphics of unit load coefficients, where it can be easily understood that the function begins with a unitary value, which corresponds to the weight of the volume of soil, and then decreases gradually.
With the explanation on the procedures to follow to determine the value of dynamic loads coming from vehicles that circulate on the surface, a comparison was made between the results obtained from the two methods used, the Boussinesq expression and the method of linear degrading of loads. The first conclusion to be reached from this test is that the Boussinesq method should not be applied to depths higher than 0.5m, unless the concentrated load is divided into several spot loads. The analysis of the results in this chapter leads to the consideration of two very similar methods, since the results obtained have small differences and when they do show large differences, the linear degrading method shows the highest values.

The definition of the level of settlement allows the application of an equivalence coefficient which reduces the effect on the pipeline of the value of the fill load calculated. At this point, the conclusion to be reached is that the higher the attention and quality of the settlement of the buried pipes, the higher the decrease in the resistance to diametric compression necessary to resist a given load.

After completing the calculation process, the only thing left was to test the pipes against the load values calculated, through the existing methods for testing pipelines, having reached the conclusion that the existing methods in Europe are similar to the methods used for example in Brazil.

The limit to the value of diametric deformation that the section may suffer can be calculated through the European Standard, which is the easiest method that can be applied, since only the ratio between the value of the deformation and the initial diameter of the section will be determined, with the maximum level being 65% of the diameter.

Finally, the calculation of the transition width is also presented. This process makes it possible to calculate the width of the trench and the load over the pipelines, which should be calculated through the expressions for embankment situations. The expression calculated and presented in this point is a little conservative since it frequently registers levels of load slightly above real load levels.

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