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**Thrust restraint design of buried flexible pipes.**

Högni Jónsson[1]

## Abstract

Unbalanced thrust at bends in buried pipelines has historically been resisted by cast in-situ concrete thrust blocks. In recent years methods have been developed that allow the design of buried piping systems without the need for thrust blocks, i.e. pipes and fittings that carry axial thrust and bending moments. Stiff pipes made of isotropic materials behave in a manner, and have enough reserve axial strength, that warrants simplified analytical methods. Because of the low strain levels of such pipes, the effects of displacements and bending stresses can be ignored in many cases.

Pipes made of flexible and/or orthotropic materials such as glass fibre reinforced plastics (GRP), however, require more rigorous analysis, to ensure that displacements and stresses are kept within limits. This paper presents a structural analysis method that incorporates the necessary parameters for such a design. The non-linear soil-pipe interaction, both in the lateral and axial directions, is accounted for and the appropriate stiffness matrix for each pipe element is compiled. A solution based on a simple spreadsheet algorithm, is presented.

## Introduction

One of the more common unbalanced thrust situations in buried pipelines occur at elbows, and emphasis will be on that case here. The concept consists of attaching to the elbow a string of axial load bearing pipes (referred to as biaxial pipe) with harnessed joints, such that the load is transferred to the surrounding soil by lateral pressure and axial friction. The design seeks to determine the biaxial pipe length required in each direction to balance the thrust, while keeping stresses and deformations within allowable limits. The ends of the biaxial pipe strings are then connected by non-restraining joints to standard uniaxial pipe. Since only a few pipe

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[1]Research Engineer, Flowtite Technology, PO Box 2059, 3239 Sandefjord, Norway, Ph:+47-334 49218, Fax:+47-334 49221, email:hogni.jonsson@flowtite.no

segments are needed for the analysis, it can be incorporated into a relatively simple calculation spreadsheet, which facilitates the design process.

Combining the above with other loading conditions, such as drop in temperature and axial contraction due to Poisson's effect, an iterative algorithm is used to solve for unknown displacements. From these the axial forces, bending moments and shear forces are calculated and the resulting stresses are computed and compared to the material strength.

Proper selection and use of safety factors for the geotechnical analysis is addressed in the accompanying example. Assessment of the soil properties for the combination of native and backfill soil is also addressed.

The methods presented herein thus form a complete design tool for the thrust resistant design of buried flexible pipelines. Although the method was developed to design flexible pipes, it can also be used for stiffer pipes, such as steel and ductile iron, to gain better insight into their structural behavior.

## Structural behavior

The unbalanced thrust is resisted mainly by two factors: firstly, close to the elbow itself, load is transferred directly by lateral bearing of the pipe and elbow wall against the soil, and secondly, the longitudinal tension in the pipe is transferred through friction from the pipe to the soil (see Figure 1).

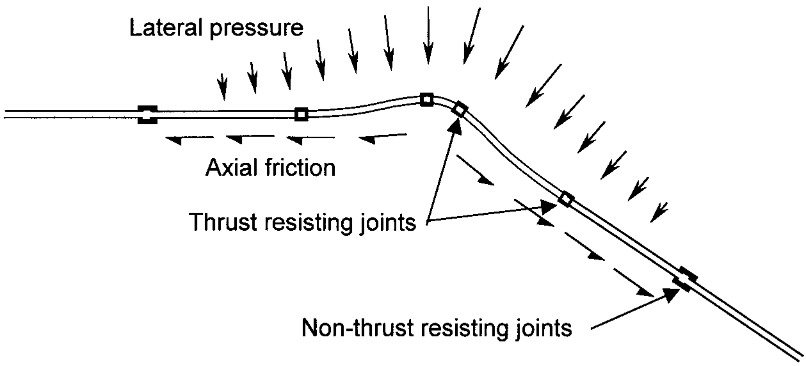


**Figure 1.** Lateral and axial soil resistance at an elbow

For both cases a certain movement in the soil is required to generate the transfer of load from the pipe to the soil. The lateral load transfer is proportional to the stiffness of the pipe-soil interaction, which is greatly influenced by the stiffness of the soil. The amount of load transferred thus varies along the axis of the pipe. Close to the elbow more movement occurs and thus more load is transferred. Further away from the elbow the movement is less and the load transferred gradually diminishes.

The axial movement in the pipe results from three factors: movement due to the unbalanced thrust, contraction due to drop in temperature and contraction due to Poisson's ratio. The thrust movement is greatest close to the elbow, while the Poisson and temperature movements are largest at the free ends, and decreases towards the center of the pipe.

The pipe and the joints needs to be strong enough to take both the axial load due to friction and the bending stresses resulting from lateral movement, as well as the hoop stresse developed from internal pressure. A sufficient number of pipe sections need to be joined together to balance the thrust, while keeping the displacements within acceptable limits.

To analyze the displacement of the pipe, the stiffness of the system needs to be expressed. Singhal and Meng (1983) developed both the lateral and axial structural stiffness matrix of a pipe element surrounded by an elastic media. For the engineering accuracy required for this analysis, this structural stiffness matrix provides the necessary basis to adequately describe the structural behavior of the system.

In addition to the classical bending and axial stiffness of the pipe as a structural element, the lateral and axial soil stiffness factors, $K_y$ and $K_x$, become factors in the element stiffness matrix of the pipe-soil structural element.

This stiffness matrix was generated assuming that the soil stiffness factors are constant, i.e. that the system is linearly elastic. In many instances this is an acceptable assumption. However, to fully understand the structural behavior of the system, and thus to be able to fully utilize the potential of the concept, the non-linear behavior of the soil needs to be incorporated into the analysis.

**Joints.** The joints for the restrained pipe section need to be able to carry the longitudinal load which results from the normal forces and the bending moments induced in the pipe. There are several types of joints that will allow transfer of these loads. For GRP pipes these joints can be butt-strap laminates, bolted flanges, glued joints or key-locked joints, to name a few. Some types of harnessed joints will be quite stiff, i.e. have limited or no rotational capacity, while others will rotate to some extent before the load is fully transferred. For the current analysis only the former joint is addressed, but if the moment rotation curve for the more flexible joint is known, it can easily be included in the analysis.

At the end of the restrained pipe section the pipe is connected with a standard joint, that does not transfer axial load to the non-restrained pipe. This joint will have to be designed such that it allows the movement of the pipe end, without leakage, with adequate safety margin.

**Fittings.** The most common types of fittings that are subjected to unbalanced thrust in buried pipelines are elbows and tees. Of the two, elbows are much more common, be they of the mitred or sweep type, and are the main subject of this paper. However, the same principles apply for other types of fittings.

The movements caused by the unbalanced thrust, result in uneven soil pressure around the fitting. This in turn results in deformations, both in the circumferential and the longitudinal directions. These deformations of the fitting, especially in the circumferential direction, will cause stresses which could govern the design of the fitting laminate. Analysis of these stresses are beyond the scope of this paper.

## Lateral pipe-soil interaction

**General.** The non-linear relationship between interactive pipe-soil pressure and lateral movement of pipe buried in granular soil is presented by Audibert and Nyman (1977). Based on soil-box tests using several, albeit rather small, pipe diameters and varying installation conditions, they derived a normalized pressure-displacement relationship for this condition:

$$p(y) = \frac{y \cdot q_u}{0.145 y_u + 0.855 y}$$

where $p(y)$ is the lateral soil pressure corresponding to displacement $y$, $q_u$ is the ultimate soil resistance and $y_u$ is the ultimate displacement. This curved relationship represents the average behavior for the various parameters tested. To determine this curve for any given case the factors $q_u$ and $y_u$ need to be determined.

**Ultimate soil resistance.** The ultimate soil resistance is expressed as:

$$q_u = \gamma Z N_q$$

in which $\gamma$ is the unit weight of soil, $Z$ is the depth to center of pipe and $N_q$ is the Brinch Hansen bearing capacity factor (Hansen 1961, Audibert and Nyman 1977).

**Ultimate displacement.** The ultimate pipe displacement as observed from the Audibert and Nyman tests indicate that for pipe diameters larger than 300 mm the ultimate displacement is only dependent on the soil compaction and the depth of embedment, $H_e$. For loose sand the ultimate displacement tends towards 2% of the embedment depth, while for dense sand this value is apparently 1.5%.

The data presented by Audibert and Nyman is based on rigid rather than flexible pipes and thus the soil-pipe interaction will be different due to circumferential flexure of the pipe. However, when pressurized, the cross section of a flexible pipe will re-round and thus tend to behave as a rigid pipe in this respect and one may assume the *p-y* curves developed by Audibert and Nyman to be valid with reasonable accuracy. This aspect needs to be studied further.

**Native soil.** The stiffness of the native soil around the trench will have direct influence on the movements of the pipe. The relative stiffness of the backfill and native soil affects lateral pipe movement and needs to be incorporated into the analysis, similar to the way this is addressed the AWWA M45 Fibreglass Design Manual (AWWA, 1996). This can be accomplished by applying a correction factor to the ultimate soil resistance.

## Axial pipe-soil interaction

**General.** Information on the axial movement between pipe and soil is scarse. However, this situation is analogous to the behavior of friction bearing piles, where the relationship between pile driving load and vertical displacement is measured. Given the availability of such data one can create the appropriate characteristics of pipe movement in the soil.

Most observations on load-settlement behavior of piles indicate a relationship that can be approximately characterized as bi-linear, i.e. the deformation is proportional to the load up to a certain limit, after which the load is constant. This maximum load is dependent on the ultimate skin friction of the pipe-soil system. The deformation at which the ultimate skin-friction is reached has been measured to be between 4 and 5 mm for a variety of conditions.

The ultimate skin friction between soil and pipe is equal to the sum of friction plus adhesion on the pile face or the shear strength of the soil immediately adjacent to the pipe, whichever is smaller. This can be expressed by the following equations (from Sowers and Sowers (1970)):

$$f_u = c + \sigma_h \tan \phi$$
$$f_u = c_a + \sigma_h \tan \delta$$

where $\sigma_h$ is the soil pressure against the pipe, $\phi$ is the angle of internal friction, $\delta$ is the angle of friction of soil against the pipe face, $c$ is the cohesion of the soil and $c_a$ is the adhesion of the soil to the pipe. The last two parameters are applicable for clayey soils only. For most pipe surfaces $\tan \delta$ is less than $\tan \phi$.

Assuming that the backfill around the pipe is granular, the problem reduces to determining the soil pressure on the pipe and the friction between the pipe and soil.

**Soil pressure.** One of the most widely used methods for determining the vertical deflection of buried flexible pipes is the one presented in AWWA Fibreglass Design Manual M45 (AWWA 1996). The origin of this method can be traced back to the work of Spangler on flexible culverts (Spangler 1941). To determine the circumferential deformation of the pipe, certain assumptions about the soil pressure on the pipe are made. These will be taken advantage of here.

The soil pressure, $\sigma_h$, against the pipe varies around the circumference of the pipe. At the top, the soil pressure is assumed to be equal to the overburden pressure. At the bottom of the pipe the pressure is equal to the overburden pressure plus the load from the weight of the pipe and the water. At each side of the pipe, the load is assumed to be distributed parabolically over a 100 angle, with the peak pressure equal to:

$$\sigma_{hp} = \Delta x \, E'/D$$

where $\Delta x$ is the horizontal deflection, $E'$ is the soil stiffness parameter and $D$ is the pipe diameter. The total soil pressure distribution around the pipe is thus defined by these parameters.

**Friction coefficient.** The coefficient of friction, $\tan \delta$, between the pipe wall and the soil can only be determined by testing. Such tests were conducted at the Flowtite Technology laboratory in Sandefjord, Norway, for glass fibre reinforced plastic (GRP) pipes and granular soils. Several pipe samples, of varying surface roughness, were tested with sand and gravel as surrounding media. The results of these tests are summarized in Table 1.

| Pipe outer surface<br>Soil type | Smooth | Normal | Rough |
|---|---|---|---|
| Dry sand | 0.54 | 0.57 | 0.57 |
| Wet sand | 0.53 | 0.57 | 0.59 |
| Crushed gravel | 0.56 | 0.57 | 0.58 |
| Rounded gravel | 0.54 | 0.53 | 0.55 |

**Table 1.** Average coefficient of friction between GRP and granular soils

The table shows that the friction factor does not vary much for these conditions. The lowest value measured during the tests was 0.51. As a lower bound for design that value can be recommended.

**Programming techniques**

Since the problem requires computing the displacement at several points along the pipe, it is most easily solved by the direct stiffness method. However, due to the relative simplicity of the problem, no elaborate finite element software is required. Only a few elements adjacent to the unbalanced thrust (elbow or tee) are needed, which means that a standard spreadsheet with macro capabilities can be used for the whole non-linear analysis. The spreadsheet can be used for all input and output. This greatly facilitates the whole process and allows easy access to all data and for constructing graphs.

The solution algorithm requires building an element stiffness matrix as described in Annex A. Then a global stiffness matrix equation is built from that by adding the stiffnesses for the connected degrees of freedom. If any degrees of freedom are restricted the equations are corrected for that condition. Finally the equations are solved for the unknown displacements and rotations, and the axial forces and bending moments computed. Details of such an algorithm can be found in many textbooks dealing with structural analysis and finite elements (see for example (Vanderbilt, 1974)).

An iterative procedure is required to deal with the nonlinear soil-pipe interaction. A simple approach is to include the interaction equations in the solution algorithm and compute the $K_x$ and $K_y$ factors as secant moduli in the stiffness equation for the appropriate deformation at each iteration step. This approach may require several iterations before convergence is achieved.

In addition to the above the effect of Poisson's ratio and temperature drop need to be included. In the example that follows the procedures as described here were used for the structural analysis of the system.

**Conclusions**

The procedure presented herein is a comprehensive design and analysis tool for thrust restraint design and analysis of buried flexible pipes, without thrust blocks. By relatively simple computations, it takes into account the main forces and displacements that such a system is subjected to, and gives the design engineer a good insight into the behavior of the system, without having to resort to advanced finite element analysis.

### *Example*

**General.** The 1800 mm diameter PN7 inlet pipe to the Cañaveralejo Waste Water Treatment Plant in the city of Cali in Colombia was designed, and successfully installed, using the above procedure. The pertinent aspects of that design are shown below.

**Load Cases.** There are basically two pressure conditions that need to be considered, i.e. working pressure and test pressure. The working pressure, i.e. long term sustained pressure in the system, is assumed to be equal to the nominal pressure class, PN, of the pipe. Usually the pipe is designed for this condition, although in many cases the pressure class of the pipe is chosen somewhat higher than the working pressure.

For Cali the installation was designed to have adequate margin of safety during the site hydrotest. In many cases the hydrotest is performed at 1,5 x PN; in this case it was done at PN and the calculated deformations and stresses were checked. In all cases, the system has to be designed for the hydrotest.

In addition to the internal pressure and Poisson's contraction, the effect of temperature change was considered, since it generates movements, and thereby introduces forces within the system. It is not unusual to assume a temperature drop of 17° C (30° F).

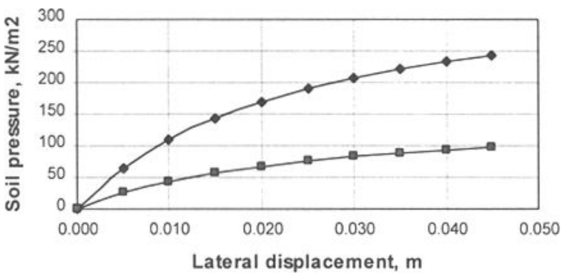


**Figure 2.** Soil pressure as a function of lateral displacement

**Safety Factor**. The total safety of the system comprises the control of material stresses in the pipe, soil bearing capacity and joint displacements. The safety factor chosen for Cali was 2.5 for the ultimate lateral soil strength. This factor was applied to the bearing capacity of the soil (see figure 2) prior to analyzing the soil-pipe system. The factor thus also decreases the slope of the pressure displacement curve (i.e. the stiffness).

It was considered that the safety factor for friction in the axial direction need not be so high, since this does not constitute a structural failure. A safety factor of 1.5 (see figure 3) was applied combined with a limit on the induced movement at the joint.

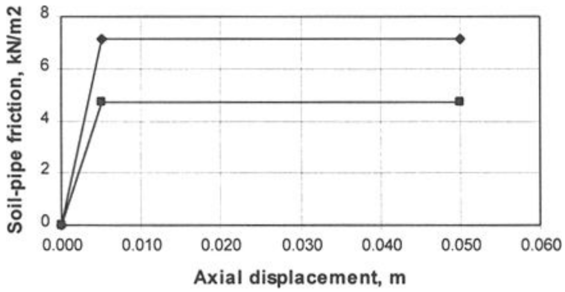


**Figure 3.** Soil-pipe friction as a function of axial displacement

**Displacements.** The ultimate allowable lateral displacement of the pipe at the bend was limited, to ensure a safe design. After analyzing the system the lateral displacement was compared to the failure displacement, and checked that the ratio between the two was less than 1/1.5 (see figure 4).

The axial displacement was also have to be contained within limit. This limit is not related to soil strength, but rather to the axial displacement capacity of the non-restrainded coupling. Appropriate safety factor against excessive axial movement is 1.5 (see figure 5).

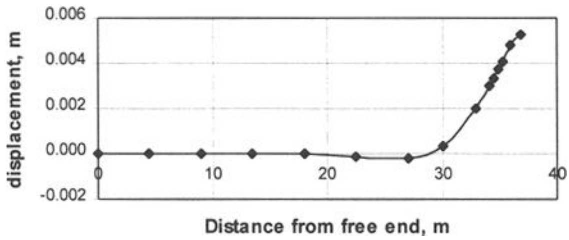


**Figure 4.** Lateral displacement of pipe as a function of distance from elbow

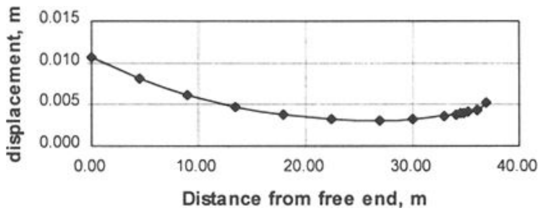


**Figure 5.** Axial displacement of pipe as a function of distance from elbow

**Stresses.** Figures 6 and 7 show the bending moment and the axial force in the pipe along its length. The stresses in the pipe are to be calculated from these loads, and should be compared to the allowable stresses in the pipe material.

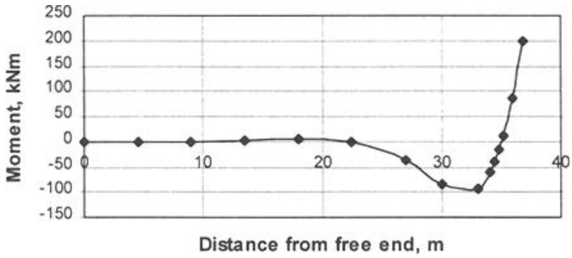


**Figure 6.** Bending moment in pipe as a function of distance from elbow

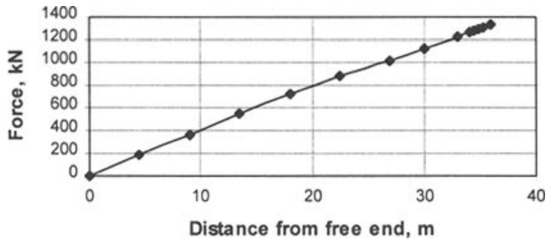


**Figure 7.** Axial force in pipe as a function of distance from elbow