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Physical modelling of the behaviour of buried gas pipe under surface loading

Modélisation physique du comportement de conduites de gaz enterrées sous chargement de surface

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ABSTRACT: This communication focuses on the behaviour of buried steel pipes submitted to surface loading such as traffic loading. A laboratory small-scale model has been developed to better understand the soil-pipe interaction. The final objective is to assess the existing design method, and develop them if required.The test set-up consists in a rigid tank with metric dimensions, filled with sand. Real steel pipes are scaled down at 1/3 on the length, leading to the relevant use of 100 mm diameter aluminium pipes. No gas pressure is simulated within the pipes, as it is then an unfavourable condition regarding the effect of surface loading on the pipe. Surface loading with up to 1000 cycles is applied using a vertical actuator acting on a plate. The procedure includes an extensive instrumentation, in particular strain gauges on the pipe and inner displacement sensors,. The experimental campaign permitted to assess the effect of the pipe radial stiffness (by varying the pipe thickness) on the pipe response due to monotonic then cyclic surface loading. The small-scale experimental results were upscaled at the real structure scale and compared to the existing design practice, to highlight its limits and the importance of taking the soil-pipe interaction into account.

RESUME: Cette communication porte sur le comportement des canalisations en acier enterrées soumises à des charges de surface telles que les charges de trafic. Un modèle réduit de laboratoire a été développé pour mieux comprendre l'interaction sol-canalisation. L'objectif final est d'évaluer les méthodes de dimensionnement existantes et de les améliorer si nécessaire. Le dispositif d'essai consiste en une cuve rigide de dimensions métriques, remplie de sable. Les canalisations en acier prototypes sont réduites à 1/3 de leur longueur, ce qui conduit à l'utilisation de canalisations en aluminium de 100 mm de diamètre. Des charges de surface jusqu'à 1000 cycles sont appliquées sur une plaque par un verin vertical. La procédure comprend une instrumentation extensive, en particulier par des jauges de déformation sur la canalisation et des capteurs de déplacement interne. La campagne expérimentale a permis d'évaluer l'effet de la rigidité annulaire de la canalisation (en variant son épaisseur) sur la réponse de la canalisation due aux charges de surface monotones puis cycliques. Les résultats expérimentaux en échelle réduite ont été extrapolés à l'échelle de la structure réelle et comparés aux méthodes de dimensionnement existantes afin d'en mettre en évidence les limites et l'importance de prendre en compte l'interaction sol-canalisation.

Keywords: Physical modeling; soil structural interaction; buried structures; gas transportations pipelines.

1 INTRODUCTION

Most of gas infrastructures are buried. During their lifetime, they can be affected by additional loads (roads, railways or embankments) compared to the design load cases, transmitted through the ground. Pipeline network operators then have to guarantee the integrity of the pipes and to accurately assess the stress increase in the pipe due to these additional surface loads. Based on the pioneering works by Marston & Anderson (1913) on rigid pipes and Spangler & Shafer (1938) on flexible pipes, it is well-known that the stress assessment is highly related to a soil – pipe interaction problem.

More recent improvements in the design methods lie on the reliable determination of the horizontal earth pressure (Scarino, 2003) or in the introduction of a parabolic distribution of the vertical load (Tian et al., 2015). Some of these improvements are in use nowadays, such as in the in-house software RAMCES from GRTgaz (one the French gas operator) used to predict the internal stresses inside a pipe, as well as its deformations to decide acceptability of various overloads. The results of the current experimental study will be compared to the results from RAMCES predictions.

2 MATERIAL AND METHODS

The main interest of carrying lab testing (contrary to field testing) is to ensure controlled environnement and variables, with a good repeatability from one test to another. Subsequent sections will describe briefly the protocol and the materials used in the tests, while more details can be found in Mertz, 2023.

2.1 Test tank

The experimental campaign is carried out in a test tank (Figure 1), with dimensions 1 × 0.93 × 1.90 m^3, filled with sand and equipped with a vertical electric jack to apply a model surface loading.

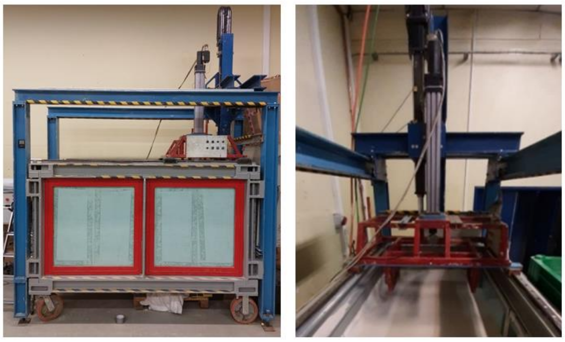

Figure 1. Tank (left) and loading system (right).

The soil used to fill the tank is a siliceous fine sand, uniform and poorly graded, denominated as Fontainebleau NE34 sand. Some of the sand characteristics are presented in Table 1, after Andria-Ntoanina et al. (2010). Filling is done by multiple layers, three of 0.2 m and one of 0.15 m, for a total sand thickness of 0.75 m, with he pipe center being 30 cm deep. Compaction is achieved for each layer using a vibrating plate, as shown on Figure 2, reaching a relative density of around 72 %.

2.2 Pipes

The pipelines used by GRTgaz are mainly made of steel, with nominal diameters ranging from 80 mm to 1200 mm, and thicknesses from 3 mm up to 30 mm. Such structures are not convenient to work with in lab conditions (in term of weight and size for handling, as well as required force to be applied during experiments). Thus, the choice has been made to work with small-scale model. Such scaling needs to be done with care, to avoid introducing bias in the model (scale-effect).

Table 1. Fontainebleau NE34 characteristics.

$d_{50}(mm)$	C_u	$\rho_s\,(g/cm^3)$	$e_{\min}$	$e_{\max}$
0.206	1.49	2.65	0.510	0.882

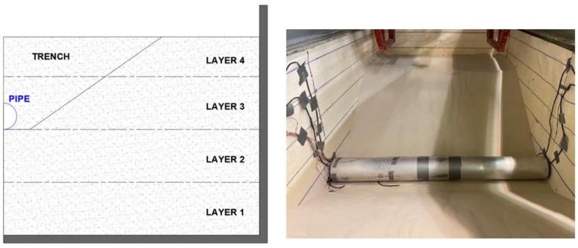

Figure 2. Scheme of the trench in half geometry (left), and pipe installed in the tank (right).

The scaling has been carried out using dimensional analysis, coming from the Vashy-Buckingham Theorem that describes the relationship between the properties of the model and the properties of the prototype, which takes the form of a scale factor λ (Garnier et al., 2007) such as:

$$\lambda = \frac{\text{model property}}{\text{prototype property}} \qquad (1)$$

The scale factor on geometry is set to 1/3, meaning that all lengths of the prototype will be divided by 3 in the model scale. The reference prototype pipe, from GRTgaz catalogue, has a diameter of 300 mm. Therefore, a model pipe of 100 mm outside diameter and three different thicknesses (2 ± 0.05 mm, 1.75 ± 0.1 mm, and 1.35 ± 0.1 mm, respectively), have been considered, to investigate a wide range of annular rigidity of the pipe.

Dimensionnal analysis gives the scale factor on other metrics of the model, such as the stresses, that should also be 1/3 of the one of prototype pipes. This also runs for the Young‘s modulus. Thus, because prototype pipe are made of steel TUE360, with a Young‘s modulus of 210 MPa: the model pipes will then be made of aluminium 6060, with a Young‘s modulus of 69.5 MPa.

The resulting annular rigidity is presented in Figure 3, in which the error bar corresponds to the uncertainty resulting from the measured thickness deviation.

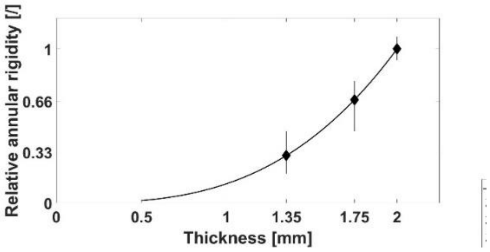

Figure 3. Pipe relative annular rigidity as a function of pipe thickness.

2.3 Loading

An EXLAR IX-40 electric jack ensures a vertical force, which is measured using a 20 kN S-shaped load cell. The load is distributed to the soil through a a 0.1 ×0.1 m² rigid aluminum plate, with four LVDT sensors, measuring the settlement and the tilting of the plate. Loading was applied with a constant velocity of the jack (0.05 mm/s) until the average stress under the loading plate reaches 100 kPa in model configuration (300 kPa in the prototype configuration), with unloading/reloading loops for everytime the loading exeed the previous maximum by 25 kPa. Preliminary tests showed that the bearing capacity of the soil with this surface plate geometry was reached for an average stress of around 110 kPa.

2.4 Instrumentation

This study uses a wide range of instrumentation, for both the pipe and the soil.

Bi-directional 350 Ω strain gauges are placed on the external surface of the pipe, with 45° of spacing between each, see Figure 4, in order to retrieve deformations in both longitudinal and ortho-radial directions at different pipe orientations.

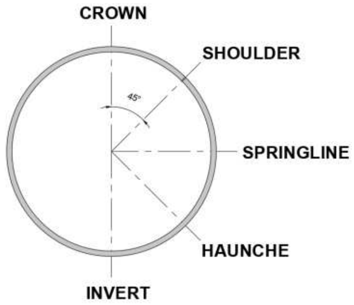

Figure 4. Placement of strain gauges.

Two flexure gauges AU/1 inside the pipe and miniaturized stress sensors placed 20 mm away from the pipe in the soil were also used, for measuring the pipe ovalisation and evolution of stresses in the sand respectively. However, these results will not be presented hereafter.

3 RESULTS AND DISCUSSION

3.1 Pipe stresses and evolution during cycles

The deformations on the pipe given by the strain gauges allow to calculate the acting stresses, in both directions (ortho-radial and longitudinal), assuming that the pipe behaves elastically. For a surface loading of 100 kPa, Figure 5 shows a maximum stress around 5 MPa (far below the yield stress of 60 MPa) for the ortho-radial stress at the springline of the 1.35 mm pipe (relative annular rigidity of 0.33).

Ortho-radial stress plot shows that the pipe is under compression at crown and invert, while experiencing tension at springline, compatible with an ovalisation of the pipe. Shoulders are in tension as well, indicating that the change from tension to compression is happening between shoulders and crown.

It can be seen that decreasing the pipe annular stiffness led to a significant increase in stress in the upper part (crown, shoulders), while variations are small to non-existent at haunches and invert. Longitudinal stresses indicate that the pipe experiences flexion, with compression at crown and tension at invert, as expected by the loading configuration (load concentrated on a small 0.1× 0.1 m² plate). Reducing the pipe thickness does not impose strong variation of the longitudinal stress, due to the fact that the longitudinal flexure rigidity is depending strongly on the diameter, but only marginally on the thickness.

The evolution of stresses during the application 100 cycles of loading between 1 and 100 kPa is presented in Table 2.

Table 2. Stress changes during cyclic loading.

Pipe thickness [***mm***]	***Max stress*** [***MPa***]		***Stress change for* 1000 cycles** [%]	
	Tension	*Compression*	*Tension*	*Compression*
2	0.91	-2.3	+11.7	+2.2
1.35	2.5	-4.5	+18.9	-28.2

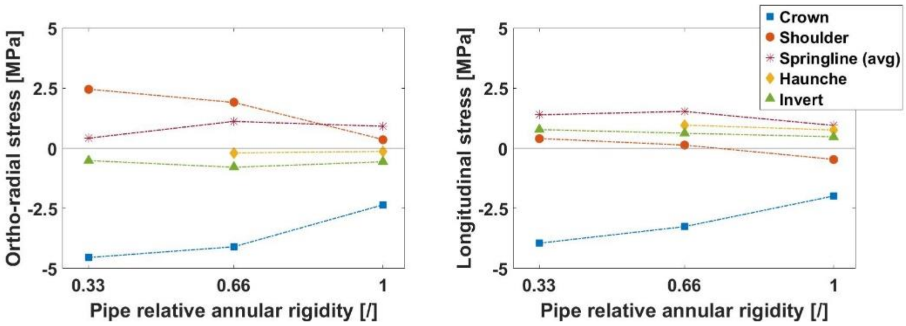

Figure 5. Measured ortho-radial (left) and longitudinal (right) pipe stress, for a surface loading of 100kPa (compression is negative).

Data from the 1.75 mm pipe are excluded due to a malfunction of the strain gauges during cyclic loading. The 2 mm pipe exhibits smaller changes in stresses when compared to the 1.35 mm one, which indicates that the relative stiffness between the soil and the pipe affects the cyclic behaviour.

3.2 Comparison with design models

Results were compared to the predictions made according to the RAMCES software. However, since this software is working at prototype scale, experimental data were upscaled, according to equation 1. This scaling also includes a corrective coefficient for the soil non-linear behaviour, based on numerical simulations, (see details in Mertz, 2023). The prototype situation thus corresponds to 4.25/5.25/6 mm thick steel pipes, with a diameter of 300 mm, loaded with 300 kPa on a 0.30 × 0.30 m^2 surface.

The metric used for the comparison is the safety factor F_s, defined as the ratio of the calculated stress to the experimental stress. A safety factor above 1 indicates that the model overestimates the actual stress of the pipe, leading to an opportunity of optimisation on the calculation method. The detailed analysis (Mertz, 2023) showed that RAMCES software captured the pipe behaviour quite well, but with F_s around 1.4.

4 CONCLUSIONS

Small-scale pipes with different annular rigidities have been tested in laboratory conditions, in which they were buried and subjected to a controlled surface loading. It appears that reducing annular rigidity increases recorded stresses in the pipe on some locations (crown and shoulder mainly), but also changes the observed behaviour during cyclic loading.

Comparisons with the RAMCES code show that there is an opportunity for optimisation, by improving the physical model used, which can lead to higher safety (by better representation of the pipe behaviour), as well as a more efficient design.

This work will be enriched with additional data, such as the pipe displacement and recorded soil stresses near the pipe, both radially and in the horizontal plane above it, and assessment of the soil-structural interaction will be done.

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