DEFORMATIONS IN BURIED FLEXIBLE PIPES

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Knowledge about the behaviour of buried flexible pipes has become more and more important in the Netherlands.
It serves several objectives, for instance, to evaluate stress corrosion, installation techniques and new materials, as well as drawing up new design codes and test procedures for pipes and components.
This contribution reports on the development and the application of a method to evaluate the deformation of buried flexible pipes. The results of the measurements, so far, showed the effects of laying depth, traffic load and soil type on the deformation of the pipe.

INTRODUCTION

In the Netherlands an extensive gas distribution network is in operation. The major part of this system is built up of plastics pipelines. About 20,000 km of rigid PVC (UPVC), 25,000 km of impact-modified PVC and 10,000 km of PE pipes are present in the Dutch gas distribution network exceeding now 90,000 km in total. The Dutch gas industry is interested in detailed information on the stresses and strains developed in these buried, flexible (plastic) pipelines. There are several reasons for this interest. The information is required for design purposes, evaluation of materials, laying methods, etc. (The design of plastics pipelines has so far been based mostly on experience and empirical data). Up to now virtually no quantitative information on stresses and strains in plastics has been available.
That's why VEG-GASINSTITUUT n.v. has started a theoretical and experimental study into the deformation of buried plastics pipelines.

The loading of buried flexible pipes is very diverse. The transverse section of a pipe deforms as a result of soil pressure differences. These pressures are generated by the weight of the soil, the installation procedure and by superimposed loads (e.g. traffic loads).
In axial direction the pipe is loaded by prescribed displacements due to settlement differences of the soil along the pipe. Further loading of the pipe may be generated by other pipes and cables and by excavation works by third parties.

The soil/pipe system can first be approximated by a model in which the stiffness of both pipe and soil are incorporated.

This general schematisation is valid in the elastic range of pipe and soil. When relatively large displacements are considered, then the yield behaviour of the soil also plays an important role.
Furthermore, it should be realized, that the soil stiffness will be influenced by environmental effects, like: moisture and frost. Current design models do not allow accurate evaluation of the pipe-soil mechanism.

Many authors have tried in the past to calculate the stresses and elongations in plastics pipes by analytical models, among them Spangler (1) and Leonhardt (2).
In some cases these models give reasonably accurate values. Usually the calculated values can only be used, however, as an approach to reality.
A few of the shortcomings of these analytical models are:

- In general, it is difficult to incorporate the way of installation in these models. It is obvious, however, that the way of installation may have a large influence;
- local differences in soil properties, for instance below beside or above the pipe, cannot be reflected in the analytical models;
- plastics show a non-linear, time-dependent behaviour: creep and stress relaxation.
  These effects are also not taken into account in the analytical models.

For modeling reality, analytical models are therefore insufficient.
A numerical Finite Element Model (FEM) may possibly give a better description of the mechanical stress situation of the pipe.
Such a model is presently being developed in the Netherlands by the Delft Laboratory of Soil Mechanics. This study has been commissioned by VEG-GASINSTITUUT n.v. and N.V. Nederlandse Gasunie. The development of this numerical model will not be further discussed in this paper.
The main part of this contribution will deal with the development of a measuring device as well as measurements carried out with this device. A restriction will be made to the deformation of the cross section of the pipe. Although all the measurements were performed on UPVC or impact-modified PVC pipes, the results can be applied to other flexible pipes as well.

DEFORMATION MEASUREMENTS

The actual behaviour of a pipe in the soil is a three-dimensional problem. So, for accurate calculations a three-dimensional Finite Element model should be developed, and relevant input parameters such as soil stiffness, pipe stiffness, settlement lines, soil compactability and installation quality should be provided.

It is difficult to develop a three-dimensional Finite Element model for such a complex loading case. However, it would be disirable to have such a model for system design purposes.
When considering the deformation of old pipes the use of a mathematical or numerical model is even more difficult.
Especially the provision of relevant input parameters is difficult or even impossible. For instance, how should the installation quality be estimated of pipes installed 20 years ago?.

For these reasons VEG-GASINSTITUUT n.v. developed a measuring device, called DEFLEC, which is capable of measuring the whole circumferential shape of the buried pipe.

The DEFLEC series

The DEFLEC is made up of a hull on which a rotating head is fitted (Fig. 1). The hull itself is mounted on a skid for a stable positioning within the pipe. The back of the hull contains all necessary electrical and pneumatical plugs. The complete device can be pushed into the pipe over a length of approximately 15 metres, by using bars of one meter each.
The rotating head can be put into any position at a rotation speed of approximately 360 °/minute. A synchronous motor mounted within the hull is used as the driving gear. The measuring pressure exerted on the pipe by the sensor is approximately 500 grams. Within the rotating head the displacement of the sensor is converted into an electrical signal. To avoid interference cable loops instead of train contacts have been used.
To prevent damage to the cables a blocking system is used which restricts the rotation to a maximum of 390°. The hull contains a provision which detects the position of the sensor in relation to the vertical axis. The DEFLEC-110 to be used in pipes with a nominal diameter of 110 mm can be used for measuring diameters between 92 mm and 118 mm. This means that deflections up to 13% can be measured in pipes with an inside diameter of 104.6 mm. This is quite a wide span for such a small head. When other rotating heads and skids are mounted, also pipes with a diameter of 160 mm or 200 mm can be measured.

The sensor can be pulled back into the rotating head by means of air pressure (1.5 bar).
This is of importance when the DEFLEC is being pushed through the pipe. Otherwise, sharp edges at joints or at service connections might damage the sensor.

Method of measurement

Fig. 2 gives a survey of the measurements. A pipeline section of approximately 12 metres is made free of gas, after which a 1 metre length of pipe is cut and removed from each end of the isolated pipeline section. During the first part of the measurement the pipe still carries the soil. Standing in the manhole the operator pushes the DEFLEC into the pipe, the sensor being pulled back into the rotating head.

The sensor can then measure in any number of angle steps the distance between central point of measurement (CPM) and pipe wall. By every step the angle of rotation and the sensor are monitored and stored on cartridge by a desk computer. When the sensor has rotated over 360 degrees, the DEFLEC can be moved to another position, where the cycle can be repeated.
After the pipe has been measured, it can be dug up and remeasured. The difference between these two measurements provides the data for calculations of the elastical component in the strain, from which the tangential stress can be estimated.

When new pipes are measured, first the original shape of the unloaded pipes is measured. Then after the pipe has been installed the measurement is repeated. Sometimes, when time dependence is expected the pipe will be remeasured again after some time.

Data evaluation

The next step after data acquisition is to calculate deflections, tangential strains and stresses. To do this the following procedure is applied. First, an interpolation polynomal is fitted through the measured values. Then the curvature along the pipe wall is evaluated. Therefore, a simple, numerical stable method was applied.
Figure 3 gives a presentation of this method.
The chords I and II, as well as their perpendiculars are calculated. Then the point of intersection M can be found.
Now the curvature in point 2 is the distance between M and point 2. The curvature in point 3 can be calculated by deleting point 1 and adding point 4. So the curvature at every point along the pipewall can be calculated by repeating the foregoing procedure.
Now, the tangential strain at every point can be calculated by using formula 1.

$$\varepsilon_{tan} = \frac{S}{2} \left(\frac{1}{R_o} - \frac{1}{R_i} \right) \qquad (1)$$

After the strain has been calculated, it is also possible to estimate the tangential stress.
Therefore an assumption must be made concerning the axial stress or strain. Assuming a plane strain condition, the tangential stress can be calculated by:

$$\sigma_{tan} = \frac{E}{1 - v^2} \, \varepsilon_{tan} \qquad (2)$$

RESULTS OF MEASUREMENTS

At various locations in the Netherlands measurements have been carried out and are still being carried out.
Measurements were performed on old as well as on new pipes. Not only the deformation of the pipe was measured, but also a limited amount of soil properties.
The following properties were evaluated:
- soil classification;
- grain size distribution;
- porosity;
- density;
- water content;
- plasticity index.

So, the deformation measurements are well documented.
The results of the measurements will be divided into two sections. One section will summarize the results of measurements on old

existing pipes, and in the second section the results of a case study of measurements on a new pipe will be reported.

Old pipes

From measurements on old pipes two strain levels can be obtained. First, by measuring the buried pipe, the total strain can be calculated.
After the pipe has been dug up and remeasured, the remaining (plastic) strain can be calculated, and by subtracting the plastic strain from the total strain, the elastic strain can be found. Figure 4 shows an example.
The measurements are classified according to soil type. Figure 5 shows the results. The total strain as well as the elastic strain is represented. In the Figure, the 95% confidence interval of the measurement is given.
The results indicate, that the strain in pipes buried in sand is higher than that in clay.
A possible explanation for this effect is that the yield strength of clay is generally smaller than the yield strength of sand. So pressure differences along the circumference of the pipe cannot be so large, because that would require a high shear strength. This results in a smaller deformation of the pipe. This implies that in design models not only the stiffness, but also the yield strength should be included.
The measurements are also classified according to the buried depth. Figure 6 shows the results. From this Figure it can be seen that pipes buried at shallow depths are more deformed than those buried deep.
Further classification of the measurements would make drawing conclusions difficult, because the number of measurements in one class will get rather small. So, the installation quality, which can never be evaluated when old pipes are considered, might overrule all other effects.
It was noticed, that even over a pipe length of approximately 8 metres a considerable scatter in deformation is found. This is shown in Figure 7. In this case the extreme values were caused by the traffic load at the entrance of a storage house, but in many cases no plausible explanation is available.
Another interesting effect observed is the shape of the deformed pipe. An example is given in Figure 8, showing that deformations are not always symmetrical.

New pipes

Not only old pipes have been measured, but also new pipes.
Here we will demonstrate the application of the DEFLEC in evaluating the effects of traffic loading.
A pipe with a diameter of 110 mm and a wallthickness of 2.7 mm was buried in a ditch.
The soil type used was sand. The covering depth after installation was 50 centimetres.
After installation the deformation of the pipe was measured. During the next seven months the pipe was loaded by the weight of heavy trucks used for the supply of building materials.
The pipe was then remeasured.

The effect of traffic loading first showed in the decrease of the covering depth from 50 to 34 centimetres.
Not only measurements, but also a Dutch design code, normally used in the Netherlands when dykes have to be crossed, was applied in order to predict the pipe deflection.
In this code, a stripped version of Spanglers IOWA formula (3) is used.

$$\delta v = 0{,}113 \ \frac{QR^3}{EI_W} \qquad (3)$$

where Q is the sum of the weight of the soil above the pipe (Q_n) and the traffic load (Q_t)

$$Q_n = \rho h g D \qquad (4)$$

Q_t is calculated by using the Pipeline code (ref. 3), which is based on Boussinesq. For a covering depth of 50 cm and an axle load according to VOSB 1963 class 45, a vertical pressure of about 0.14 N/mm² is found. So $Q_t = 0.14 * D$.

According to the code, the Young's modulus in formula 3 should be half the short-term modulus.
So the input parameters are:
covering depth h = 50 cm
pipe diameter D = 110 mm

Soil density ρ = 1740 kg/m³
E pipe E = 1250 MPa

The results of the calculations are summarized below.

	Q_n	Q_t	δV_n	δV_t	δV	δV_{mea}
	N/mm	N/mm	mm	mm	mm	mm
after installation	0.94	-	8	-	8	2.9
after seven months	0.94	15.4	8	131	139	6.5

where δV_n is the deflection due to Q_n, δV_t is the deflection due to Q_t, $\delta V = \delta V_t + \delta V_n$ and δV_{mea} is the measured average deflection. The maximum deflection found was 8.5 mm.

It is obvious, that the values for deflections obtained from the traffic load calculations are too high.
So it could be concluded, that the above described calculation method is not applicable to evaluating the effect of traffic loading.
There are several reasons for this. First, the Boussinesq method is only applicable in determining the stress in a semi-infinite elastic body. This is definitely not the case for traffic loading of buried pipes.
Secondly, the covering depth has decreased from 50 centimetres after installation to 34 centimetres after a seven months period. So, the theory of elasticity on which Boussinesq is based cannot be applied anymore.

CONCLUSIONS

- DEFLEC measurements have shown that the strains in buried PVC pipes are limited to about 1.2%.
  The maximum elastic strain stays below 0.8%.
- Deflections up to 12% were only found under rather severe circumstances (low covering depths).
- Measurements on new pipes showed, that by using normal installation procedures e.g. backfilling and compaction in two layers, the deflection can be limited to about 8%, even at shallow depths and with traffic loads.
- The methods commonly used for calculating the deflection as a result of traffic loading are highly inaccurate. It is recommended that more research be carried out on the subject of "traffic loading" to get a better understanding of the real pipe-soil behaviour.
- The only way to evaluate the tangential strain and stress in existing buried pipes, is to perform deformation measurements. To that aim a reliable device (DEFLEC) has been developed.

SYMBOLS USED

ε_{tan}	= tangential strain	(-)
ε_{ax}	= axial strain	(-)
σ_{tan}	= tangential stress	(MPa)
σ_{ax}	= axial stress	(MPa)
E	= Young's modulus	(MPa)
V	= Poisson constant	(-)
S	= wall thickness	(mm)
D	= outside diameter	(mm)
h	= covering depth	(mm)
R_o	= original curvature of the inside pipe wall	(mm)
R_i	= curvature at point i of deformed pipe wall	(mm)
Q	= load	(N/mm)
δv	= vertical deflection	(mm)
I_w	= moment of Inertia $\frac{t^3}{12}$	(mm^4/mm)
ρ	= density	(kg/mm^3)

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3. Pijpleidingcode Zuid-Holland Provinciale Waterstaat, Zuid-Holland. (South-Holland Pipeline Code, Provincial Dept. of Transport and Communications, South-Holland.)

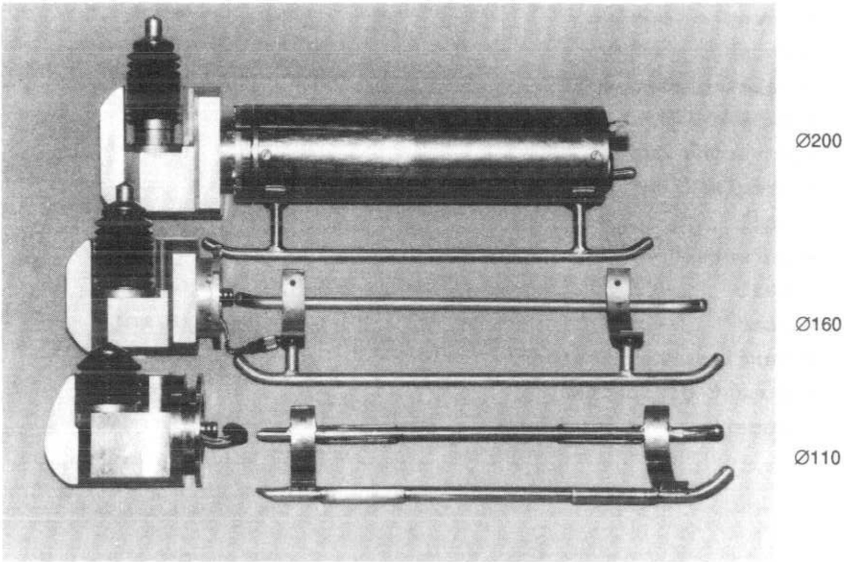

Figure 1 DEFLEC Ø200 with interchangeable head's and skids for Ø160 and Ø110 mm

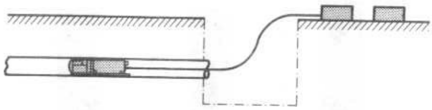

Figure 2 Survey of the measurement

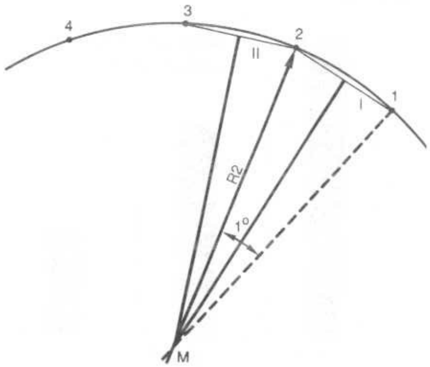

Figure 3 Estimation of the curvature

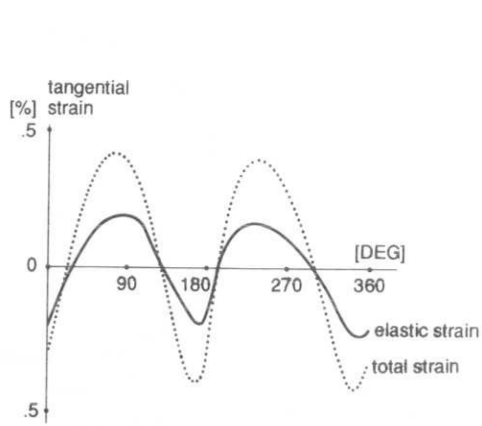

Figure 4 Total - and elastic strain

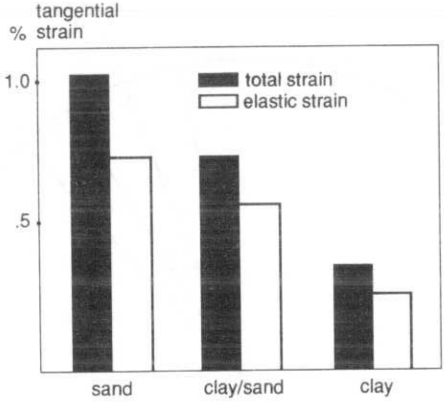

Figure 5 Effect of soiltype on tangential strain

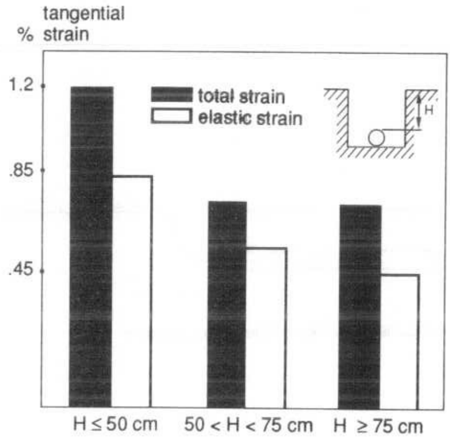

Figure 6 Effect of buried depth on tangential strain

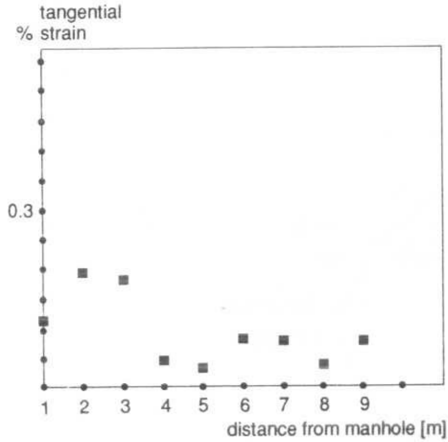

Figure 7 Scatter in tangential strain along the pipe

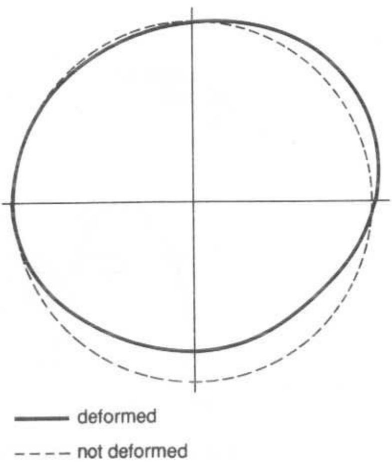

Figure 8 Shape of a buried pipe