SOIL-PIPE INTERACTION: A NEXT STEP IN UNDERSTANDING AND SUGGESTIONS FOR IMPROVEMENTS FOR DESIGN METHODS

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ABSTRACT

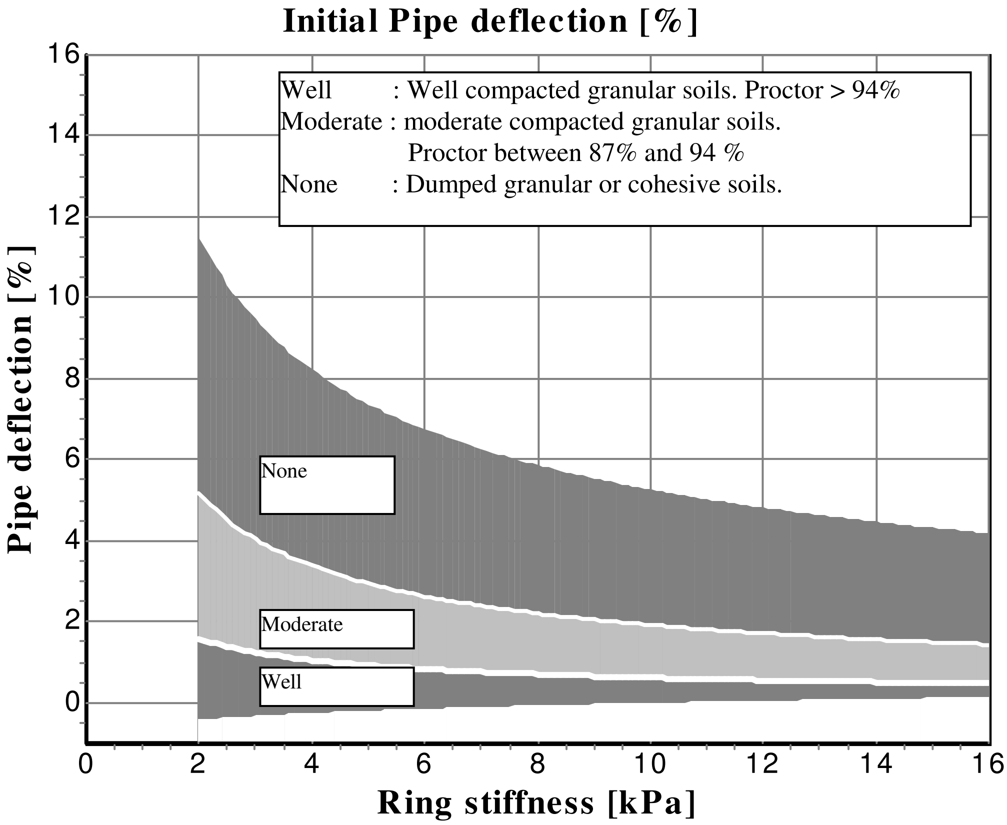
Two papers dealing with the intermediate results of the TEPPFA / APME project on design of thermoplastics pipes has been published at the 10th Plastics Pipes Conference in Gothenburg in 1998 by Alferink et all (1,2). Meanwhile the study has been almost completed and the results discussed with several experts. Pipe installation turned out to be the most important parameter, and contrary to many design methods, burial depth and traffic load is not a real issue for buried flexible pipes. Based on these results, physics of pipes buried in soils were discussed. This was followed by some additional work, with the aim to further back up the results and try to find and propose improvements for the existing design approaches. The work consisted of a few extra field tests and several model tests. Some of these model tests have been performed first in 1999 and were discussed with the European design experts in a workshop. Based on these discussions more sophisticated tests have been peformed and extensively documented. This paper shows part of the results and explains that the soil-pipe interaction proces is primarilly a volume proces in case of flexible pipes. It illustrates the mistake that will be made when geometrical non-linearity is included in load steered methods for flexible pipes and the soil changes are neglected. Finally it proposes a model that can be applied to all existing theories and that will better reflect the actual performance of flexible pipes. Furthermore, it also gives some recommendations for the design of the more rigid pipes. Finally it advocates the use of simple transparent and understandable design methods, as these give by far the most reliable results.

INTRODUCTION

In 1996 TEPPFA and APME realised that the discussions in CEN TC164/165 JWG1 TG1, about establishing a unified design method, could continue for many years. Moreover the fair became realistic that the lack of experimental data and real life experience with pipe projects could lead to a complete misjudgement of the performance of buried pipes with all it's consequences. For that reason, it was decided to carry out an extensive research programme with flexible thermoplastics pipes. The project is steered by experts from the industry and supervised by two external design experts, who have gained experience with the design and execution of real life

projects using different pipe and soil materials. At regular time intervals, the interim results were exposed to the European design experts, as they at that time, were discussing the design issue in CEN TC164/165 JWG1 TG1.
The approach in the project is to gain as much as possible detailed data, data that have not been measured before in similar projects, and to analyse these data in order to learn more about the true physics of a pipe in the ground. The result of this analysis is reflected in a graph. The graph is shown in figure 1.
The graph can also be used as a design tool.

Figure 1: Simple design tool for buried thermoplastics pipes.



Note: Upper edge of an area represents the maximum expected value.
The lower edge, the average expected value.

The graph can be used on it’s own, but can also be used to check the result of design calculations. Next to this simple design approach, some other important effects relating to the effect of depth of burial, traffic load, pipe material and pipe stiffness, were observed. The results were discussed in 1999 with all involved and lead to some extra tests to develop a further understanding of the physics of pipe-soil interaction, with the aim to provide suggestions for improvements of current and to guide the establishment of future methods.

DESIGN METHODS

An excellent analysis of the main design methods is given by Prof. L.E Janson (3).

He showed that all methods could be stripped down to variations of the Spangler formula. The basic approach in this formula is a ring that is loaded by a certain load distributed around the pipe circumference. The load carrying capacity of the ring together with the soil support load exerted horizontally makes equilibrium. The amount of horizontal support load depends on the soil stiffness. The formula takes the general form:

$$(\delta/D) = \frac{A * Q}{B*SN + C*Es} \qquad (1)$$

In which :

(δ/D)	Pipe deflection [-]	
A,B,C	Factors	[-]
Q	Load	[kPa]
SN	Pipe ring stiffness	[kPa]
Es	Soil stiffness	[kPa]

The difference between the methods focus on the different values for A,B and C as well as for the determination of the load.
The use of this formula leads in general to the fact that the deflection (δ/D) changes linearly with the load Q.
If however, one looks closer to this situation from a mechanical and mathematical point of view then this approach would only be valid when pipes experiences small deformations. When deflections get bigger, so called geometrical non-linearity is becoming affective in the model and might need to be accounted for. As a result, when the pipe deflects because of the increased load, the deflection will start to increase more then linear. This however contradicts with field experience, and why is that? This question will be answered in this paper.

THE ISSUE OF VOLUME

In the supervisor group of the TEPPFA project, an explanation for the fact that depth and traffic, as examples of increased load, has hardly any influence on the final pipe deflection was given. Looking at the installation at it's different phases and the measurements it was concluded that the soil undergoes significant changes during and after installation. Janson (4) referred already to this phenomenon in 1985??. In case of good soil and or in combination with proper compaction, these changes are very small. In case of loose soils however, these changes are considerable. But they are however not considered in the current design methods. They all work with constant soil stiffness independent of the changes occurring in the soil. Some reflect that higher in-situ stress results in higher grain stresses and hence higher soil stiffness. Nevertheless, they do not consider the change of volume in the soil by settlement.

The change of volume is first related to the change of relative density.
The relative density can be expressed as follows:

$$Dr = (n_{max} - n_x) / (n_{max} - n_{min}) \qquad (2)$$

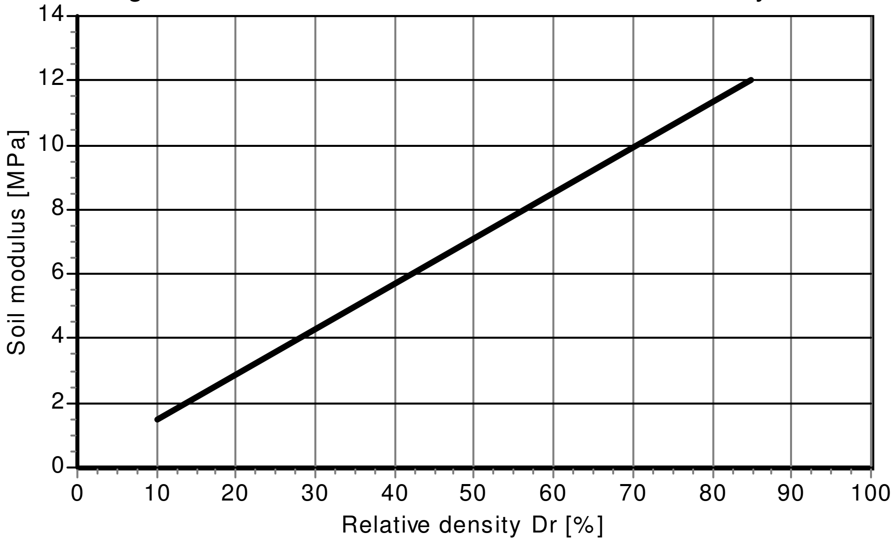
$$n = (V_{tot} - V_{soil}) / V_{tot} \qquad (3)$$

In which :

Dr	relative density	[-]
n_{max}	Maximum porosity	[-]
n_{min}	Minimum porosity	[-]
V_{tot}	Total volume = Vvoid + Vsoil	[m^3]
V_{soil}	Volume of soil	[m^3]
V_{void}	Volume of voids	[m^3]

The change of the relative density depends very much on the type of soil. With well-graded gravel, the change from loosely packed soil and compacted soil hardly involves volume changes. Silty-sand however, involves considerable volume change when it changes from loosely packed to highly packed. Volume change is related to displacements and the soil stiffness related to load-displacement, hence in the latter case the changes affect the soil stiffness considerable. Due to artificial (traffic, groundwater etc) or natural compaction, the value of the relative density will increase up to 80%-100% in the course of time. The effect of the change of relative density on the soil modulus is shown in figure 2. This graph is based on the observations in the TEPPFA project where the soil modulus was measured using several different methods for loose and well-compacted soils. In the literature other curves can be found, depending on the way they have been achieved. The tendency (slope) of the curve fits well with graphs found in literature.

Figure 2 : Soil modulus related to relative density



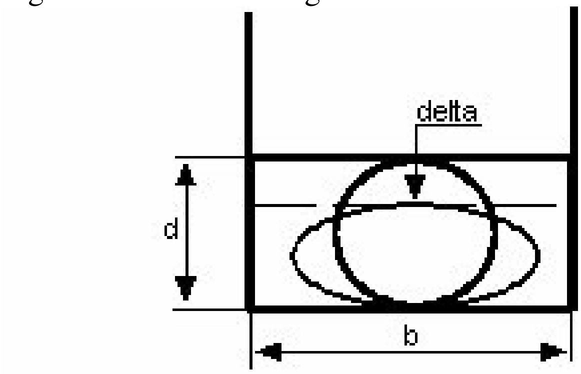
From the comparison of the methods with the field experience it became clear that all design methods are able to predict the pipe deflection well when they consider well compacted soils (2). In this situation, the soil stiffness is not changing and hence the formulas are correct as far as the soil stiffness is concerned. It is also shown by all methods that in such case the pipe deflection or in case of the more rigid pipes the crown load, stay rather low and design of the ring performance is not important.

Design gets more relevant when a good compaction can not be achieved because the soil is poorly graded, cohesive, or the field circumstances are poor.
In such cases most design methods do not represent the performance in a correct way. As an example, when pipes are buried in weak soils, one can no longer utilise the same load distribution around the pipe as with firm granular soils. The soil will slide immediately or in the course of time and hence changing the load distribution around the ring.
It shall be mentioned that some methods, like the one from Molin, has recognised that the deflection could not be explained by means of the Spangler formula only and therefore added installation and bedding factors, which cover the effects of uneven bed and installation.

THE VOLUME APPROACH

The volume approach is not a design method on itself, but an approach that can be used with all of the methods used. It introduces the effect of the changing soil properties on pipe deflection, which is by far more important than the effect of the changing geometry on the pipe deflection.
Figure 3 shows how the volume changes are taken into account.

Figure 3 : Volume changes



The volume of the soil (grains) does not change during the process and is related to the original porosity, so the porosity before the pipe starts to deflect. This volume can be determined by:

$$v_{soil} = (1-n0/100)*(b*d-pi/4*d*d) \quad (3)$$

The total volume changes when the pipe deflects and can be determined by:

$$v_{total} = b*(d-delta)-(\pi/4*(d*d-delta*delta)) \quad (4)$$

The volume of the voids changes affecting the porosity according:

$$v_{void} = v_{total}-v_{soil}; \quad (5)$$
$$n = v_{void}/v_{total}*100; \quad (6)$$

Finally, a new relative density can be calculated, which introduces a new soil modulus, as was illustrated in figure 2

.

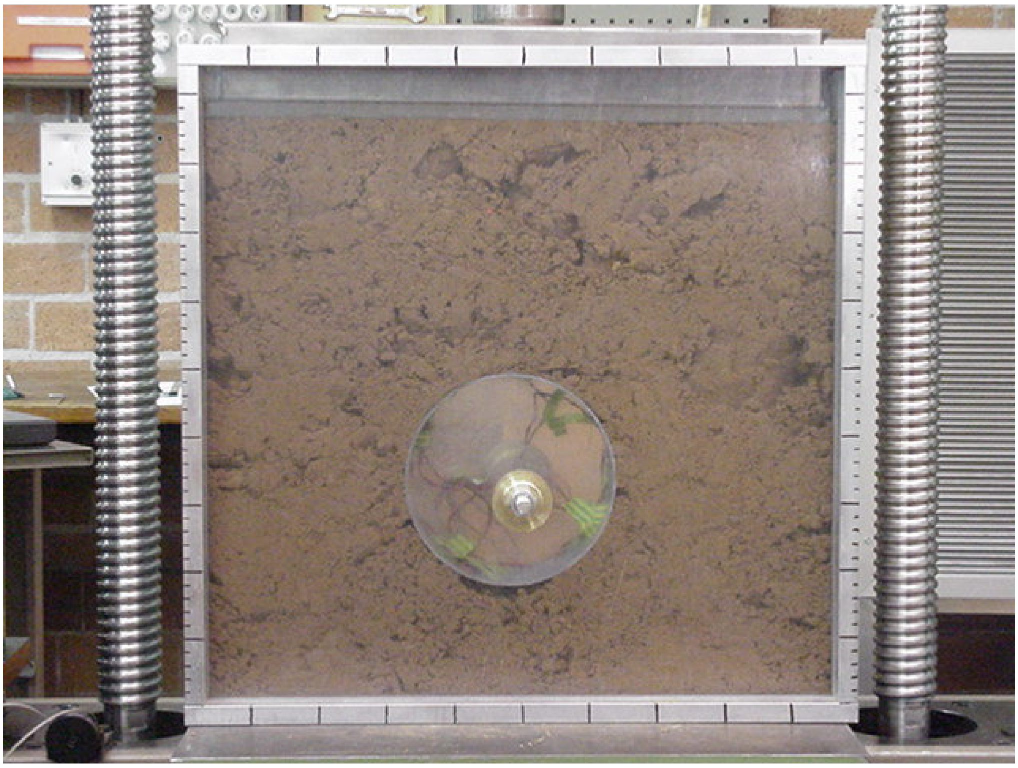
$$d_r = (n_{max}-n)/(n_{max}-n_{min})*100; \qquad (7)$$

In the following, this approach was utilised with a Spangler-like formula; the one proposed by Jan Molin. In order to simulate the process, small load steps are applied. After each step the pipe deflection and the effect on the relative density of the soil is calculated. The next load step is then applied using the increased soil modulus.

EXPERIMENTAL WORK

The best research approach, is to start with experiments before building mathematical models. Such models are only useful when they reflect the physics of a process. If not then they might become very misleading. Especially when the models also get less transparent. As a matter of fact, it shall never be accepted to utilise mathematical or numerical approaches if they have not been reflected against experimental results. Experimental results better come from fully true practice, or when that is not possible, from laboratory type of tests in which at least part of the model can be verified. In the TEPPFA / APME project both types of experimental work was performed. The field tests were carried out to obtain a good estimate of the actual values, and laboratory tests performed in order to verify the understanding of the physics. The field tests have been discussed by Alferink at all (1,2). The test model used was a transparent box in which soil and pipe were built in. The soil was then loaded by means of a cantilever. Pictures were made after short time intervals. These pictures were used to measure the deflections and the pipe subsidence. Moreover, the pictures serve for running animations in order to obtain a better understanding of the pipe soil interaction process. Figure 4 shows an experimental set up.
The load increase by means of a cantilever and the change of relative density is not accurately reflecting the change of density in real life. In real life the soil density changes from bottom to top, whereas in the experiments the density change progresses as a moving front from top to bottom. This also indicates that one shall be careful with the interpretation of results obtained in soil boxes and cells.

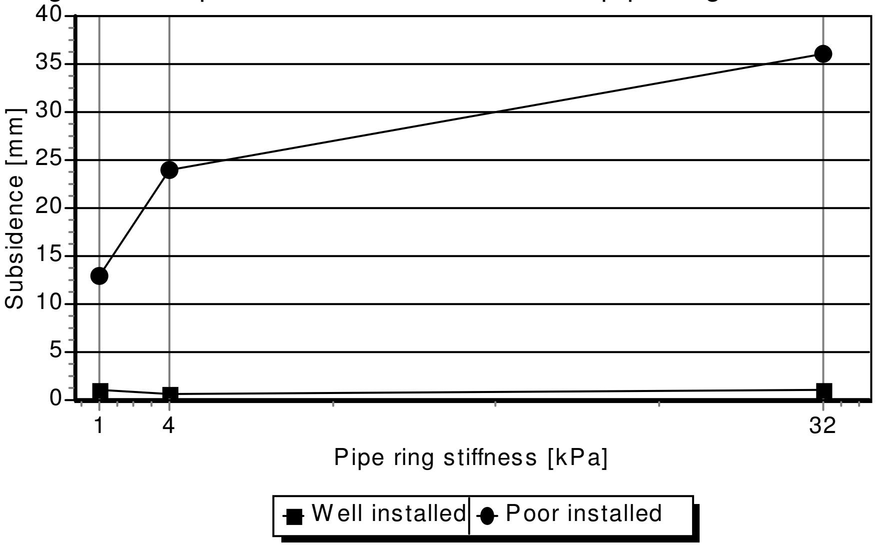
Figure 4 : Experimental set up for the soil pipe interaction analysis.

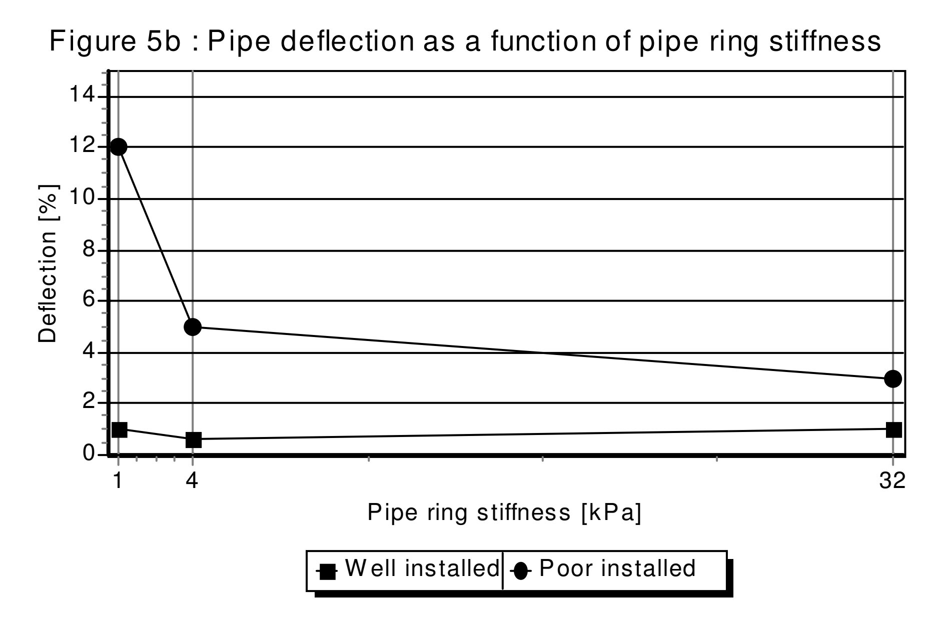


RESULTS OF EXPERIMENTS

The results of the experiments are summarised in the graphs ‘a’ and ‘b’ as shown in figure 5. Two main values were measured. The subsidence of the pipe and the pipe deflection. The subsidence is the amount the pipe sole moves downwards in the bed.

Figure 5a :Pipe subsidence as function of pipe ring stiffness





In Graph 5a the effect of pipe stiffness on pipe subsidence is shown for the situation were the pipes are buried in a good way and buried in a poor way.
The graph clearly shows that the low stiffness pipes suffer less from subsidence then the ones with the higher stiffness. At the same time a higher deflection is observed when using low stiffness pipes, as shown in graph 5b. This proves that rigid pipes transfer load, and flexible pipes deform and the load is transferred by the soil.
A significant decrease of deflection is observed when the ring stiffness increases from 1 to 4 kPa. A further increase to 32 kPa however has a significant lower effect. Pipe ring stiffness is not relevant for the deflection when the pipe is buried in compacted soil. This fully aligns with the observation from field tests carried out in the TEPPFA project. Subsidence, which was not studied in the field tests, shows that an increase of the pipe stiffness from 4-32 kPa results in a significant increase of subsidence.

Until now, design methods do not consider the subsidence and moreover they do not consider subsidence differences resulting in longitudinal bending of the pipe and shear stresses in the cross section. The subsidence differences will also affect the operational performance of gravity sewer pipes.
When the bed is firm, hardly any subsidence takes place hence the stiffness of the pipe has no effect either. However, when the bed is loose or soft, subsidence becomes a real issue and also the effect of pipe stiffness is significant. It is clear that when pipes pass regions with soft and firm beds, they will start to bend and develop shear stresses especially when the stiffness gets higher and the, material less strainable.
In most practical situation pipes do experience significant differences in the stiffness of the bed.

RESULTS OF VOLUME APPROACH CALCUALTIONS

The results of the calculations are shown in the graphs ‘a’ to ‘d’ of figure 6.

Fig 6a: Result for a 4 kPa pipe in loose silty sand

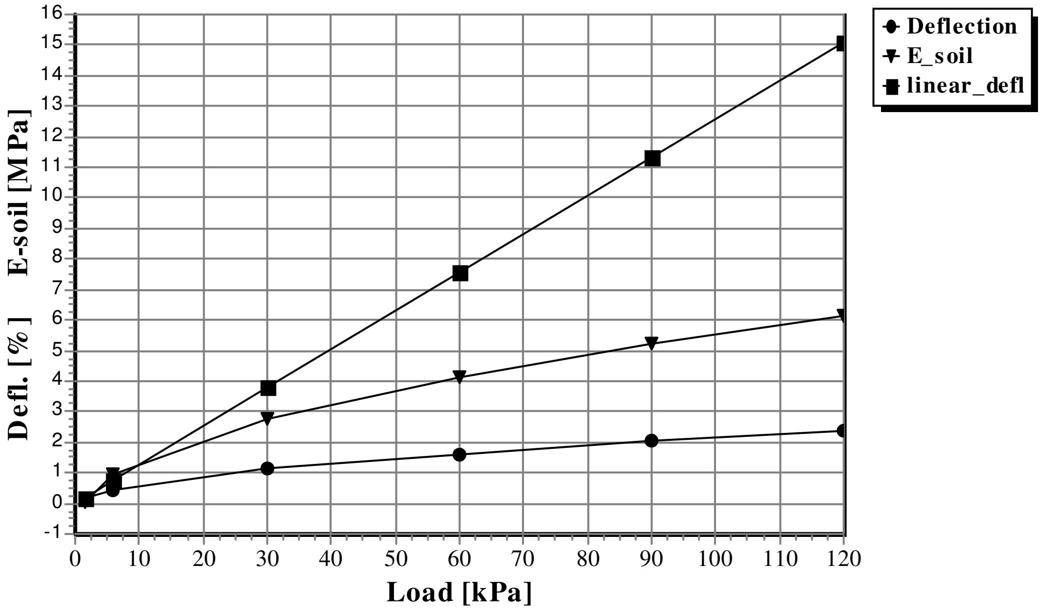
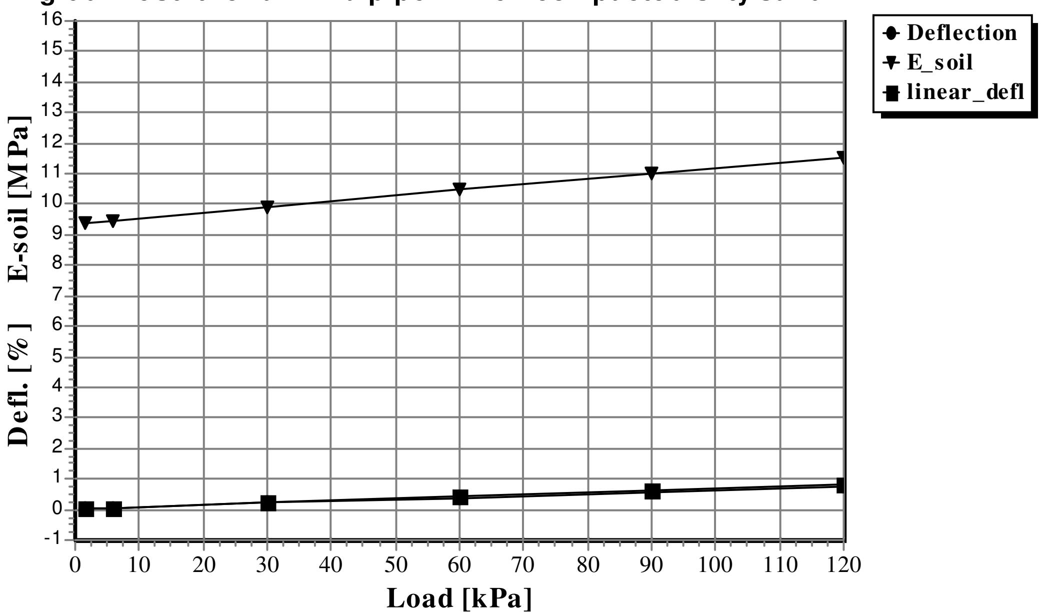
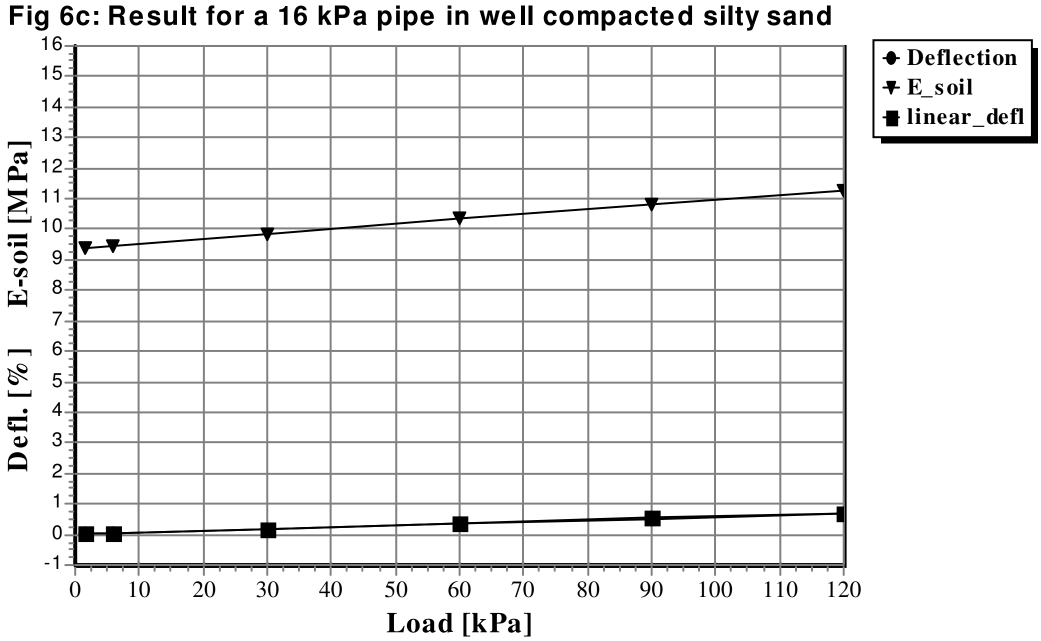


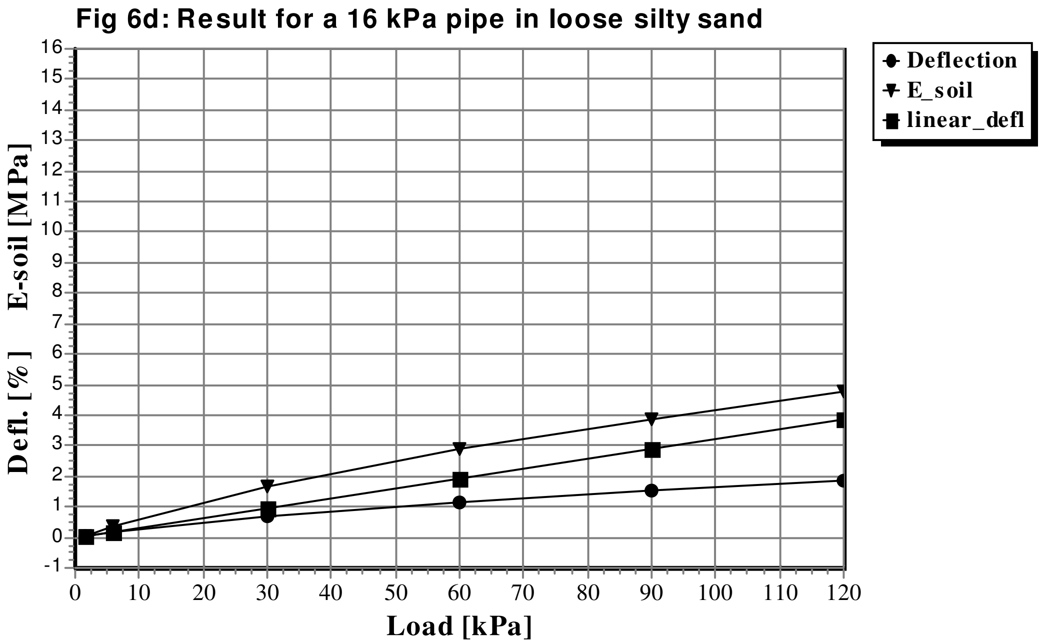
Fig 6b: Result for a 4 kPa pipe in well compacted silty sand



There is no difference between the two deflection calculations when a good installation is considered. For poor installations however such an effect is obvious as shown in figure 6a.

The same analysis is done when a pipe with a stiffness of 16 kPa is considered. The results are shown in figures 6c and 6d.





The soil modulus is changing far less when higher stiffness pipes are considered. Also the deflections are now quite similar.

So in summary what is shown is that the deflection increases and as a result also the soil modulus increases. The normal approach, in which the change of the soil properties is omitted, shows that the deflection increases with load in a rectilinear way. When however the change of soil modulus is taken into account, one observes that an increase in load does not result in a similar increase of deflection. The process is controlled by volume. This is the basic reason why greater burial depth and traffic do not have a significant effect on pipe deflection for flexible pipes.

CONCLUSIONS

The following is concluded:

- An increased load does not result in the same relative increase in deflection. This was already shown by the results of the TEPPFA/APME project and could be explained by considering the volume changes when the pipe deflects. This effect was shown by calculation as well as by experiments.
- Deep burial and traffic load are non-relevant issues for flexible pipes.
- Experimental tests illustrated furthermore that pipes do not only deflect but also subside due to the balancing forces at the pipe bed. The more rigid the pipe, the more subsidence was achieved. The more rigid, the more load is transferred through the pipe. Pipes with a stiffness of more then 8 kPa will suffer more from this effect then those with lower stiffness.

DISCUSSION

Current design methods do not reflect the changes in the soil when the pipe deflects. These changes however are shown to be the reason why an increase of load, either by depth or traffic, do not result in significant higher deflections in practice.
A tendency in developing design methods is noted, which is to involve geometrical non-linearity, which seems to be a logical next step when starting of from the believe that a pipe buried in the ground is in a sustained load condition. Which is then modelled as a ring with a constant load on it. The results of such exercises however do not reflect the true physics, in which especially the soil experiences the biggest changes.
A high level of mathematical sophistication and/or accurate determination of soil properties are rather superfluous, because the execution of the work and the soil performance can never be predicted to the same level of sophistication. Users (contractors, designers, system owners) are better of when they have access to more transparent approaches, which will give them a clear indication to what extend a change of a (field) parameter is affecting the pipe deflection or allowable bending moment.
Two extensive and sophisticated design methods have been written down in a document (part 3 of EN1295), practically all dealing with the behaviour of the pipe's cross section. Subsidence and subsidence differences caused by the transferred load and the stiffness differences of the pipe bed are not considered for the time being. All involved seem to realise that the two methods need a fair period to be evaluated against current practice and experiences. This paper already indicated that the physics

of the pipe in the soil is not well described yet. The evaluation of the methods against real field data will show how serious this discrepancy is, and if improvements are needed.

Another issue that need to be looked closely at by the plastics pipes industry is the evaluation against limit state for pressure pipes involving combined loading. As for deflection, the methods apply the theories established for traditional materials also for thermoplastic materials, which is definitely wrong.

In the industry and amongst users there is the ongoing discussion what is the best pipe stiffness to be used. The choice of pipe stiffness can be based on many ideas, emotional or rational and it is certainly not the intention of this paper to provide a single answer. However the following might be of help to make a good choice.

When installations are done using well graded soils which do not require a lot of compaction energy, then low stiffness pipes (<=2 kPa) can be used.

The combination of poor graded soils and low stiffness pipes (< 2 kPa), creates the danger that the application of a lot of compaction energy might deform the pipe in such away that squaring could be encountered. Especially with high groundwater tables this might reduce the resistance against buckling significantly.

Pipes with stiffness in the range of 4-8 kPa are providing a good choice for most installations. Only in case the installation is done in an extremely poor way, by dumping lumps of clay, pipes should have a stiffness of 8 kPa. Using pipes with stiffness higher than 8 kPa doesn't change the deflection in a significant way, as also shown by the TEPPFA graph.

In relation to this it shall however be noted that poor installations are mostly not recommendable.

They create a kind of uncontrolled situation which can cause high deflection or huge longitudinal settlements which latter becomes especially relevant in case of the more rigid pipes (> 8 kPa). Next to that, poor installations born the potential of obtaining high future infra structure costs, as they will result in settlement of the surface. In agricultural land such settlement might affect the harvest and in the street or footpath it will result in rehabilitation of the street after some years.

It is also for the above reason why TEPPFA and APME advice to utilise good to moderate compaction and pipe stiffness in the range of 4 – 16 kPa. However, as discussed before, it is possible to utilise pipes outside this window at specific circumstances which do not result in the before mentioned drawbacks.

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