"The Design of Thermoplastics Pipes: A Recent Update"

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SYNOPSIS

Over the last 15 years several attempts have been undertaken to establish a design method for plastics pipes (ISO TC138 WG13) and over the last ten years to establish an unified design method for all buried pipes (CEN TC164/165 JWG1). Several national methods are available and it is shown over the last ten years that it is extremely difficult to come to a consensus about the design of buried pipes, when following a clean and straight mathematical approach. In relation to this, the industry is very much concerned about how to implement methods based on such a mathematical approach in real life projects. Furthermore, the need for one method seems to become more and more important especially now that amongst users the wish for a so-called "non-design" pipe is becoming relevant. A first attempt to establish such a pipe, with the use of "W" classes instead of PN was voted down in the ongoing CEN standardization work for pressure pipes. Amongst other reasons also because of the absence of an unified design method. The critical succesfactor for reaching a general agreement on how to design gravity as well as pressure pipes, has been found to be the existence of comprehensive field data. Of course field data is available, as measured by different organisations and published more then once. Although they potentially form a firm basis for a design method based on experience, these data are not detailed enough to allow an accurate judgement of the more complicated design methods. Therefore TEPPFA and APME sponsored a joint research project with the aim to provide the European experts with these data, and to develop a firm basis for tools to be used to inform customers about the excellent features of thermoplastics pipes for buried applications.

This paper reports about the background of the project, the approach taken and the relative place of design versus installation and material capabilities. It presents a design philosophy including all aspects of pipeline design and installation.

INTRODUCTION

The design of buried thermoplastics pipes has until recently been quite simple and straightforward. For pressure pipes the classification is based on results of internal pressure tests. After the application of a safety factor one obtains the design stress value, which can be used for choosing the appropriate pipe class. For gravity pipes the design has been related to the stability (buckling) and ovalisation of the pipe. Here in most cases a Spangler like design for the calculation of the ovalisation, and the Timoshenko formula or variations on this for buckling has been used. As a matter of fact, for gravity pipes in many cases a pipe class approach is used. In the latter approach, certain pipe ring stiffnesses are used depending on the actual buried conditions. For instance in normal installation conditions a SN4 pipe is used and when installation conditions became more difficult, one tends to use an SN8 pipe. The above knowledge was based on results of experimental work carried out by several organisations over a period of 40 years (Ref.1), as well as the results of experience obtained from design calculations using the Spangler like models.
In the late eighties it was decided by the European commission that an unified design method

should be developed for the design of all buried pipes for water and sewage, pressure as well as non-pressure. This task was given to a joint working group under TC164 (Water) and T165 (sewage)`.

This joint working group worked for about 8 years, and produced a document (EN1295-1) in which all European established methods are gathered. It was also found out that it is not easy to agree upon one common method. In 1992 it was decided to form a task group, composed by experts who have been involved in establishing their national method. This group of 6 experts didn't succeed to find a consensus.

The problems were noticed in 1996 by experts from the plastics pipes industry. They identified the following main problems:

* The lack of experimental data, causes the discussions to be very academic and not related to praxis. Furthermore, no decisive information exists to finalize the discussions.

* There is a risk, that the final design method could be quite extensive and dependant upon a lot of parameters, which values in reality are not known or could become questionable. A design method which is not in balance with installation practice will result in confusion amongst end-users and contractors, and cause extra costs for the society.

It is for the above reasons that both APME and TEPPFA decided to put considerable effort in the design of thermoplastics pipes, and by this to promote the mutual understanding about how buried pipes perform in the ground, and to support the work of CEN TC164/165 JWG1 TG1.

DESIGN CRITERIA

Pipeline systems shall be designed in such a way that they fulfil the functional requirements for the design life. The design criteria are summarized below:

* Structural failure of the pipe.
* Structural failure of the soil (excessive settlement)
* Loss of tightness
* Loss of transport capacity

The structural failure of the pipe can be caused by overstraining of the pipe, or by buckling due to high external compressive loads. Structural failures of thermoplastics pipes are rather rare. This is due to the fact that thermoplastics pipes exhibit high flexibility and strainability, and therefore are capable of following the movements of the soil quite easily. This is a very important feature, as by this the movements of the surrounding soil is accomodated and the pipe does not develop high shear and bending stresses. In other words, thermoplastics pipes obtain a high degree of safety against structural failure. From the above it becomes clear that in almost all cases thermoplastics pipes can be designed using a low level of design effort.

Loss of tightness is an important serviceability aspect. For that reason, test and requirements are defined in the relevant product standards.

Loss of transport capacity is related to a change of roughness of the pipes, and the pipe deflection. As far as the deflection is concerned, the discharge capacity decreases only by 2.5 % when the pipe is 10% deflected over its whole pipeline length.

IMPORTANT PIPE CHARACTERISTICS

For the application of buried flexible pipes, the following characteristics are of importance:

- Pipe ring stiffness
- Corrosion resistance
- Elongation at break

From reference 1 it is known that the pipe ring stiffness is of hardly no importance when considering installations using moderate to well compacted backfill, especially when pipes with stifnesses of 4 kPa and up are considered. Only in case of non compacted and dumped backfill the pipe stiffness becomes more important. In Ref. 1 it is also shown that the stiffness only influences the level of pipe deflection during installation, the so-called installation deflection. The settlement deflection occurring after installation, is not significantly affected by the pipe ring stiffness.

Corrosion resistant properties are in general very good for all plastics materials and the pipe will therefore not deteriorate when placed in the soil.

With regard to the strainability properties one needs to distinguish between elongation at break as found in a tensile test, the strain developed under creep conditions and the strain under relaxation condition. For pressure pipes the strain controlled by the stress is the covering factor, although the buried pipe transfers part of the load (internal pressure) to the surrounding soil. For gravity pipes it is known that after installation the pipes are not loaded by a constant load, but they become under a condition of constant strain, giving rise to a stress relaxation condition. For the latter case several studies have been performed in Germany and Scandinavia. Tests carried out in Sweden (Ref.2) showed that PE and PVC pipes can be subjected to significant strain without any risk of cracking. Constantly deflected pipe samples with strain of the pipe wall exceeding 10 % have been tested for more than 9 years without showing any cracks.

In Germany, Hoechst has tested PE pipes which have been expanded circumferentially by 5%. After 40 years of testing there is still no sign of cracks in the material. In Ref. 3 it is concluded that for thermoplastics pipes like PVC and PE no strain limit exists under stress relaxation conditions, however it is proposed to limit the strain to reasonable values anyway. Table I summarizes the values proposed in Reference 3:

Table I : Allowable strain in buried gravity pipes

Pipe material	Allowable strain [%]
PVC	2.5
PE	5.0
GRP	0.5

The strain has a direct relation to the pipe deflection, a shown below:

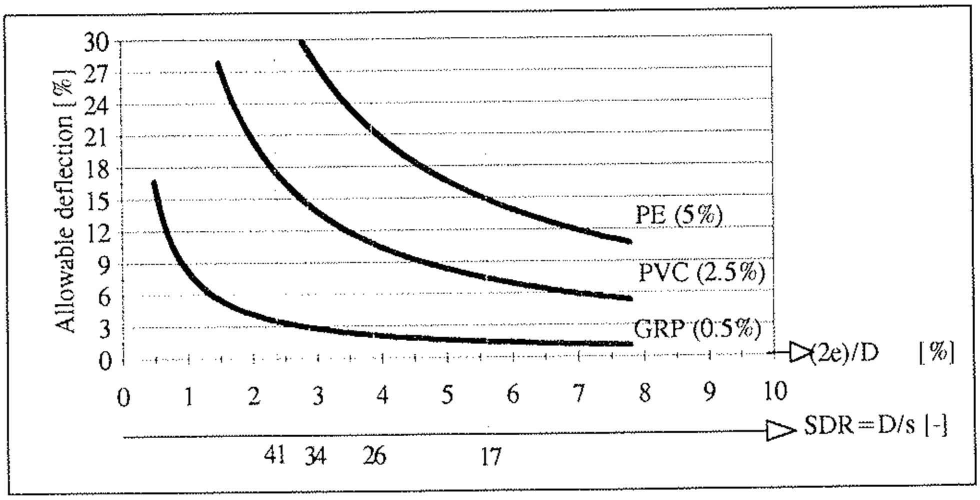
$$\varepsilon = df\,(\delta/D)(2e/D) \qquad (1)$$

in which :

ε	Bending strain [%]
df	Shape factor [-]
e	Distance from neutral pipe wall axis to outer fibre [mm]
D	Diameter of the neutral pipe wall axis [mm]
(δ/D)	Pipe deflection [%]

The relation between deflection and strain has been investigated by many different authors (Ref.3,4,5), resulting in different df values.
From these studies it was shown that a shape factor of 6 can be considered as conservative for all relevant cases. When formula 1 is applied using the strain limits as shown in table I, then allowable deflections as shown in figure 1 are found.

Figure 1 : Allowable deflection based on the strain limit



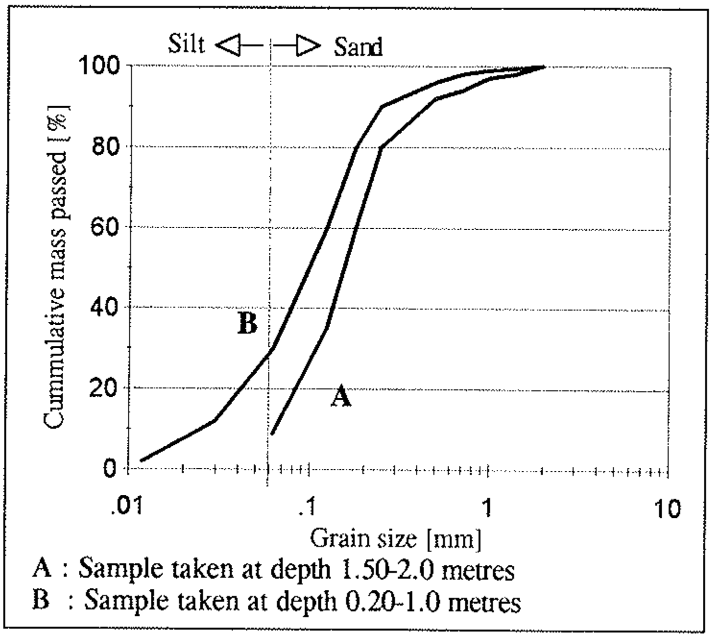
On the horizontal axis the ratio between outer fibre distance and nominal pipe diameter is plotted. Next to this the SDR (Diameter / wallthickness) ratio as valid for solid wall pipes is indicated. For instance a SDR 41 PVC pipe has a pipe ring stiffness of 4 kPa, and a SDR17 PE pipe has a stiffness of 16 kPa. For solid wall pipes the value (2e) is the same as the walltickness. It can easily be proved that when using structured wall pipes, the strain will become slightly higher than for solid wall pipes, at the same pipe deflection.

From the graph it can be concluded that thermoplastics pipes exhibit huge strainability properties, and are able to resist high deflections.

IMPORTANT SOIL PROPERTIES

Next to the properties of the pipes, the soil properties are very important. All calculation methods make use of the soil stiffness, which mostly is based on the soil type and the degree of compaction reflected by a percentage of the maximum Proctor density.
As an example, a grain size distribution graph is shown from the test site 'Haarle' of the TEPPFA project.

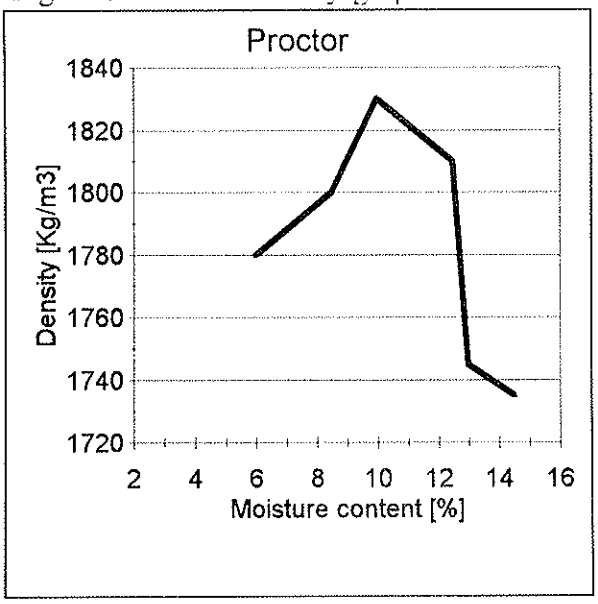
Figure 2 : Grain size distribution



Soil samples have been taken at different depths, and as can be seen, depending on the depth soils might have to be classified differently.

The maximum proctor density is determined in the laboratory, using a standardised test. Especially for granular soils this value has a meaning, whereas for cohesive soils like clay this density can be determined, but does not have a good reflection of real practice. Figure 3 shows the relationship betweent density and moisture content for the soil used at the 'Haarle' test site of the TEPPFA project.

Figure 3 :Proctor density graph



The graph indicates that the density that can be obtained during installation is rather sensitive to the moisture content.

For cohesive soils, parameters like water pressure, strain history and water content are of prime importance. During installation, whether conditions will influence the behaviour of the soil significantly. Next to this the treatment the soil is given during installation will affect the load deformation behaviour of it. Hence it is difficult to predict the properties of such in the design phase.

DESIGN PHILOSOPHY

The design of any construction is not an activity in itself. It is part of establishing that construction. In case of buried pipes, the input parameters have to be defined, like soil and pipe properties, expected loading, as well as the description of the installation. Then the design can be made, predicting the safety margins against a loss of functionality of the system, or the other way around when the safety margins are prescribed, one can select the right pipe class, or adjust the anticipated soil type or installation procedure.

The effort to be put in all three aspects (input parameters, design and installation) is still not defined. In the Eurocode 7 (Ref. 6) however directions are given for the design of geotechnical constructions. This code discriminates the design into three categories. Table II shows a short summary of the categories as defined in Eurocode 7.

Table II: Summary of the design categories as described in Eurocode 7.

Category	Description
1	Simple constructions, negligible risk for property and life. No excavation below water table, or if comparable local experience indicates that a proposed excavation below the water table will be straight forward.
2	Includes conventional types of constructions and foundations with no abnormal risk or unusual or exceptionally difficult ground or loading conditions. This category requires quantitative geotechnical data and analysis to ensure that the fundamental requirements will be satisfied, but routine procedures for field and laboratory testing and for design and execution may be used.
3	Everything that does not fall into categories 1 or 2. It includes very large or unusual structures, structures involving abnormal risks, or unusual or exceptionally difficult ground or loading conditions and structures in highly seismic and mining areas.

The Eurocode 7 dedicates itself especially to foundations, soil retaining walls, tunnels etc. When pipe laying is mentioned, it focuses especially on the risks during installation, like when digging below groundwater level at greater depths. In such case designed sheet piles shall be used. However, the general spirit of the Eurocode is very well applicable to the design for pipes too, as also here the reference to existing experience and limit states is visible.

The Eurocode does not require that the design procedures for a lower category should be covered by the one higher.

Furthermore, the Eurocode 7 clearly states that in many cases of geotechnical design, it is not always easy to carry out such a design by calculations, but alternatively, design may be carried out by using **prescriptive measures**. These involve conventional and general conservative details in the design, and attention to specification and control of materials, workmanship, protection and maintenance procedures. Design by prescriptive measures may be used where comparable experience make design calculations unnecessary. An example of the 'prescriptive measures' approach is the use of recommended practices for the installation of pipes or installation guidelines. The experience published in ref.1 and ref.7 could as such very well be used for design of the most common pipeline installations. Another possible approach is the so-called observational method, in which the installation is monitored against established limits, as has been practised for many years with corrugated metal culverts. This method could very well be used where category three types of design are needed. Based on the ideas of Eurocode 7, one could easily define the different categories for thermoplastics pipeline design. For the most common installations a lot of experience has been gained over the last 40 years, and published at several conferences. Next to this users have developed a day to day practice with installation of pipes, rigid as well as flexible. Table III gives a proposal for the design categories for buried flexible pipes.

Table III : Proposed design categories for buried flexible pipes

Category	Description	Design method
1	Ring stiffnesses 4 kPa and up Depth of cover 0.80 - 6 meter * Soil types: Granular and cohesive Application: Water pressure and sewage Traffic : none to heavy Diameter : up to 1200 mm Pipe Materials : High strainable (> 2 %)	Experience based tables Using local experience at installation as reflected in recommended practices.
2	Ring stiffnesses 4 kPa and up Depth of cover 0.80 - 6 meter * Soil types: Granular and cohesive Application: Water pressure and sewage Diameter : up to 1200 mm Traffic : none to heavy Pipe Materials: Low to medium strainable (< 2%) Other : Crossing vital geotechnical constructions like major water retaining constructions or tunnels	Methods defined in EN1295 extended with a beam design
3	All other situations not covered by the firs two	Methods defined in EN1295 extended with additional engineering where needed.

Note * : At greater depths one shall utilize the design and installation requirements valid for the sheet piles to be used.

It is believed that the same type of table can be produced for rigid pipes as well, except than the criterion will not be the strain, but the crushing strength.

Eurocode 7 also defines the loads that shall be considered. Next to soil and traffic load, also prescribed movements shall be taken into account. These movements can be expected in settlement prone, seismic, landslide and mining areas. Especially in these areas limit state situations might occur.

INSTALLATION PRACTICE

Traditionally, pipes are buried by open trench methods. Although nowadays also, so-called NO-DIG methods are used, still the major part of the installation work is carried out using the traditional methods. Most of the installations are performed using granular materials as sidefill, in combination with some kind of compaction. However, installations are performed in cohesive materials and organic materials as well. Although in general they are in many countries not recommended, good experience has been gained when using flexible pipes made out of strainable materials.

ISO as well as CEN have produced several versions of 'Recommended practice for the design of buried pipes'. Next to this, many national standards as well as manufacturers recommendations exist. These documents all recommend a certain installation procedure.
In practice, non predictable circumstances affect the true installation of the buried pipes. For instance the compaction level that can be reached for sand depends on its water content. So already depending on weather conditions one obtains a better or worse installation than anticipated. In many cases the soil profile changes over a short distance. Using the as dug material again as embedment of the pipe, does not make an extensive design of any pipe very realistic. In order to obtain more reproducible installation conditions it is sometimes recommended to import special embedment materials, like gravels and selected stones. This however makes the installation more costly. Another negative, but in most cases not considered, effect of imported backfill is that the new soil has another density then the native soil, causing on the long term other effects, as settlement differences along the pipeline. Therefore, using the as dug material as much as possible and providing flexibility and strainability in the pipeline system is the best (robust) solution for obtaining a proper functioning pipeline system. Robust here refers to the fact that the long life performance of the pipe is hardly affected by mis fits in design and or installation.

THE TEPPFA / APME PROJECT

It has been indicated that design and feasible installation shall be in balance with each other. There is great worry that especially the more academic approaches will seek confidence in applying extended mathematical procedures, which do not have any meaning in real life. Next to this it was found out that still a lot of confusion exists about the effect of visco-elasticity on pipe performance.

The results aimed for in this project are:

* The establishment of datasets will become available for validating current and future design methods
* One clear design and installation advice to customers
* Avoid an overkill in installation requirements
* Design in balance with feasible installation methods

Approach

The European design experts were invited to comment on the set up of the field trials. The major concern expressed by the experts was, that the soil types used in combination with the compaction effort in the trial would result in rather low deflection values. Most of them expressed the wish to carry out the trials in a way that the limit states would become visible. It is especially these limit states that design methods should be able to predict. In Enclosure 1 a diagram is shown in which the position of the trials are shown in relation to what is generally considered as recommended practice. It is clear from this graph that the trials are carried out at the boundaries of the recommended practice window. These trials should therefore show the limit states if any.

The design experts were informed about the nominal pipe properties, the nominal soil properties, and the installation procedure that would be used. All experts made the design and the results of the design were send back to the project manager, after which the experts were informed about the results of the measurements. This allowed the experts to update the design if found necessary. A comparison of the results resulted in information about how robust a method is, or in other words, how sensitive the method is for small changes in input values. By this it shows how accurate the soil and pipe information shall be known before the design can be started, and also how well the installation has to be followed up.

Results

The calculated results produced by the European experts using all the same design data, showed that different design methods will give different results and that the compliance with measured values will vary considerable.

A detailed discussion of the results sofar achieved in the TEPPFA / APME project is given in Reference 7.

CONCLUSION

- * When designing pipes one shall be aware of the balance between installation and design. Detailed design methods require detailed knowledge about the in-situ conditions and a close control of the installation as well. It is obvious that such a detailed design only applies to the highest design category.
- * Together with levelling up the design and installation, also costs are levelled up. It is in the interest of the end-user and moreover to the society, that costs are kept to an acceptable level, in a way that overkill in requirements, and hence costs, is avoided.
- * Flexibility and strainability of pipeline systems create a huge safety margin, and as such can be designed using a low category approach.
- * Design of buried pipes doe not automatically mean that calculation methods have to be used. Also other ways of securing the proper establishment of buried pipelines can be considered. The authors recommend to make use of established practical experience.

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Enclosure 1: Position of the field trials relative to the normal practical application window

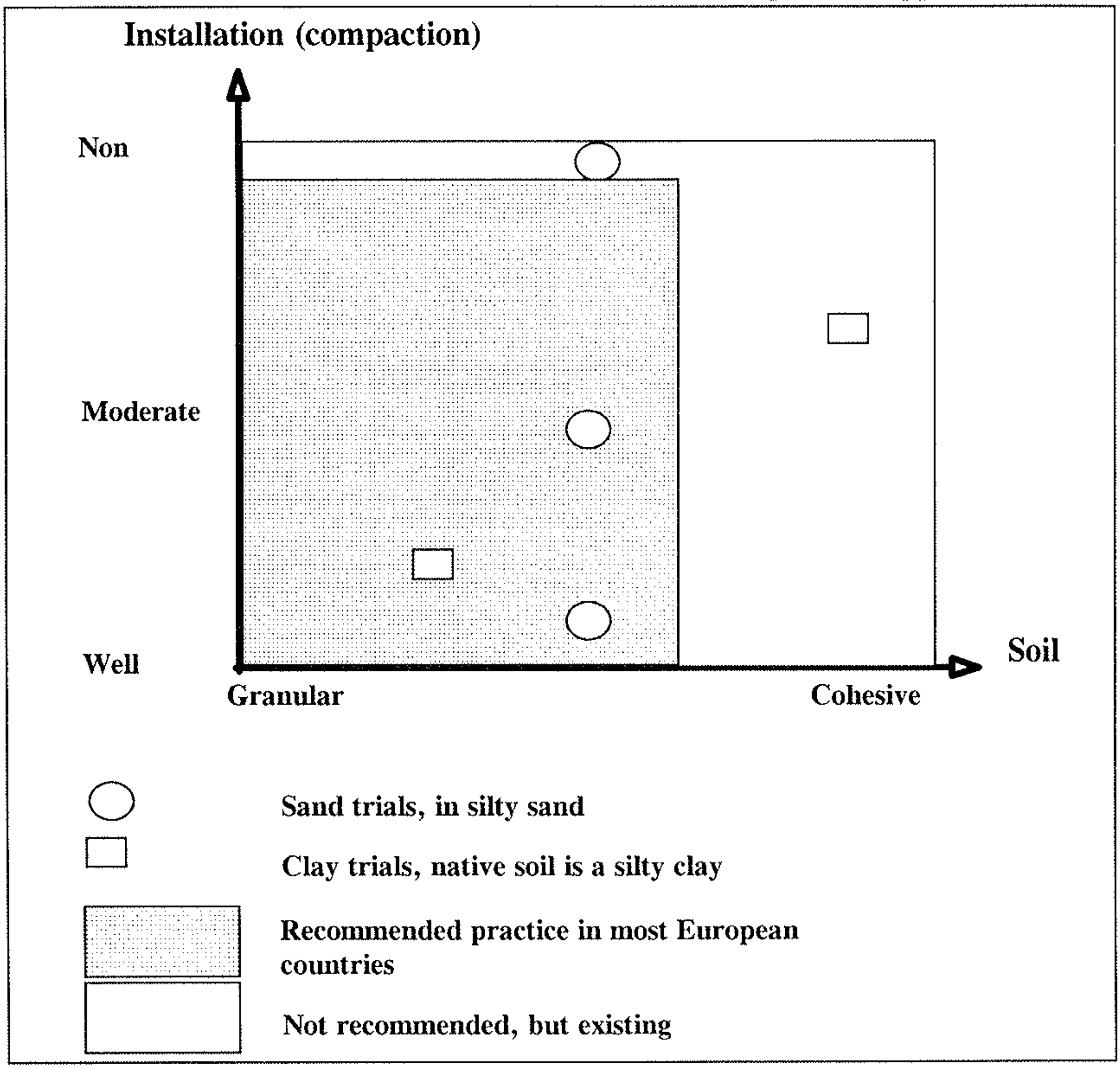

Table 1 : Overview of the trials

Case	H [m]	Pipe material	SN [KPa]	Native soil	Embedment	Compaction
1	1,15	PVC	4,00	Sand	Sand	Well
2	1,15	PVC	4,00	Sand	Sand	Non
3	1,15	PVC	2,00	Sand	Sand	Well
4	1,15	PVC	2,00	Sand	Sand	Non
5	1,15	PE	6,00	Sand	Sand	Well
6	1,15	PE	6,00	Sand	Sand	Non
7	1,85	PVC	4,00	Sand	Sand	Moderate
8	1,85	PVC	4,00	Sand	Sand	Non
9	1,85	PVC	2,00	Sand	Sand	Well
10	1,85	PVC	2,00	Sand	Sand	Non
11	1,85	Steel	4,00	Sand	Sand	Well
12	1,85	Steel	4,00	Sand	Sand	Non
13	1,15	PE	6,00	Clay	Sand	Well
14	1,15	PE	6,00	Clay	Clay	Non
15	3,00	PE	6,00	Clay	Sand	Well
16	3,00	PE	6,00	Clay	Clay	Non