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# Consideration on Design and Choice of Modern Pipelines for Use in Earthquake Areas

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**Abstract** Pipelines for distribution of gas, water and for the collection of sewage are considered as part of the lifelines of the society. When buried in settlement prone areas or earthquake prone areas, they are loaded by prescribed displacements. In case of settlement prone areas, like in river-deltas, the deformations are slow but considerable. In earth quake prone areas the deformation are also considerable but they are happening in a much shorter period of time. Experience has been gained with the performance of pipelines under these conditions. Reference will be made to these experiences. The experiences show that the performance of the pipeline is very much related to the ability of the pipeline to follow the soil movements. That ability can be created by flexible joints and/or by using flexible and ductile pipeline materials. A beam model will be used in order to better understand the experience as well as to illustrate the relative importance of the pipeline characteristics, such as pipe diameter, type of jointing, Overall Design Coefficient, flexibility and ductility of the pipe system. It is realized that especially in an earthquake event, more types loading then just bending of the pipeline happens. Also longitudinal soil/pipe friction and changes in the volume in the pipe will occur. The latter event results are in a quite different loading for water pipes then for gas pipes. A model will be used to illustrate this. Moreover, the paper also triggers the attention to limit the risks of pipeline failure in case of a possible future earthquake event. When burying a pipeline system, also the potential mal-functioning of the system at an earthquake event, which may occur 30 years after installation, is buried with it. Designers do have the possibility to limit these risks. Designing systems using smaller diameters, making use of a robust type of jointing, and using sliding or partially sliding socketed joints instead of full welded systems, yield a lower risk of failure. Conclusions will be drawn and a table shown, listing the most relevant parameters affecting the risk level for the most common systems.

**Keywords** Earthquake, Flexibility, Ductility, Pipeline Deformation, Water Mains, Pipeline Jointing

**Topic:** Protection of Public Lifeline Services from Intense Natural Events.

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## 1. Introduction

Buried pipes transporting water and gas are vital assets for the above ground society. They bring clean water to the homes and in case gas is used as an energy source, they also provide energy.

Very important during the lifetime is that the system keeps functioning in accordance to the design. That means that the pipe roughness and internal diameter stays the same as was anticipated in the original design. Therefore the best solution is to use pipe materials which are not sensitive for corrosion and encrustation. Another important aspect is the tightness of the system. Water losses are a cost aspect and if a sewer system leaks, then there is a big chance for contamination of the aquifers. This jeopardizes the health of the population.

For a buried pipeline system it is important that it is able to cooperate well with the soils surrounding it . Extensive studies have been performed to determine a good design of the system. Special situations do occur when there are conditions of differential soil settlements. Such situations do occur where pipes are buried in soft soils or when pipes suffer from an earthquake event. In order to survive these displacements, it is important that the pipe follows the settlement / movement of the soil without fracturing Flexibility and Ductility or key in this.

Several papers have been published about the performance of buried pipes in earthquake events. The datasets of pipeline failures are, almost per definition, unbalanced and therefore care should be taken in interpreting them. The unbalance is a.o related to the differences in the age of the pipes, the location of the pipes, the diameters used and the media transported through the pipes.

In this paper some more detail is given on the parameters affecting the pipe performance under earthquake and settlement conditions. Also the parameters that have an influence on obtaining the lowest risk associated to the good performance of the pipeline system under such loading conditions will be discussed.

Another important buried pipe system is the sewer system. The sewer systems collect the sewage from the houses and bring it to the sewer treatment plant in order to treat the sewage and discharge the effluent to the river. Settlement differences may cause leakages and potentially contaminate the aquifers or potable water system. This paper, however, will not discuss the performance of sewer systems further.

## 2. The Dutch Situation

A country with a rich experience with pipelines buried in settlement prone areas is The Netherlands.

It is a country that is for a considerable part located below sea level. The soil types vary from sand in the south-west and east of the country to clay, peat and all kind of mixtures in the other parts of The Netherlands. With a very high population density (Fig. 1) and a lot of industry, it also has a very high buried pipeline density below ground.

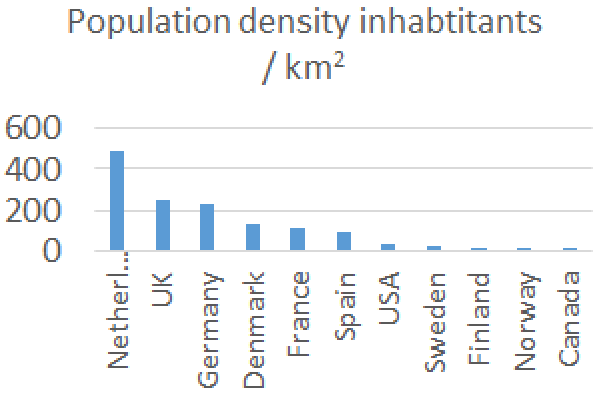
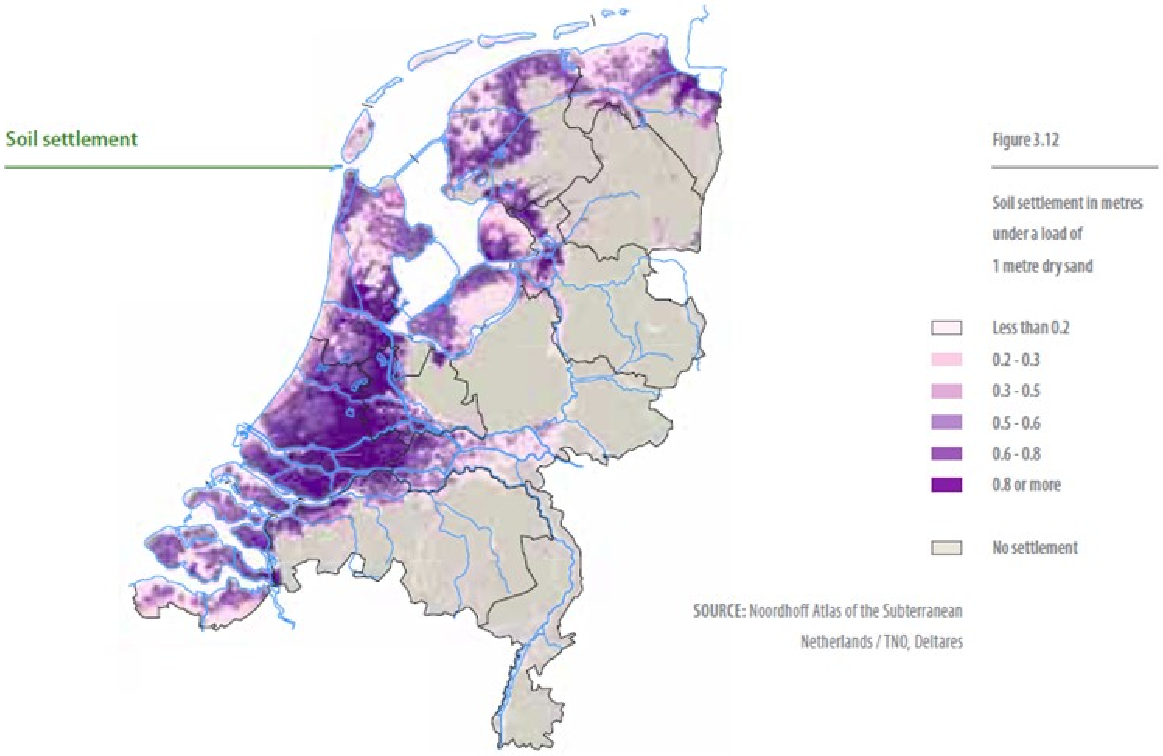


**Figure 1.** Population density of some countries

The pipelines buried under these conditions have to accommodate to rather huge differential settlements. In Fig. 2 the soil subsidence potential for the Netherlands is given. And the areas with a high subsidence potential also are prone to considerable settlement differences.



SOURCE: Noordhoff Atlas of the Subterranean Netherlands / TNO, Deltares

**Figure 2.** Map of potential subsidence of the Dutch soils

The performance of both the Dutch water and gas systems are excellent, despite the considerable settlement differences and intensive below ground constructions works with the risk of third party damage. In Fig. 3 an overview of the materials used in the water system is shown.

Despite the severe subsidence conditions, the Dutch potable water network has the lowest leakage rate when compared to other European countries. Where in The Netherlands that leakage rate or non-revenue water, is only 5% on average, most other countries have higher leakage levels even upto 50% (!) More information about the Dutch water system can be found in literature [1].

Figure 4 shows the materials used in the Dutch gas distribution network[2]

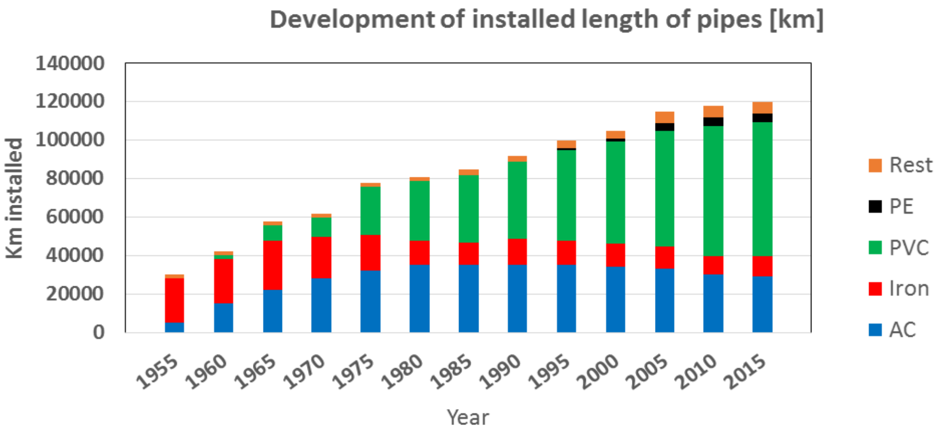


**Figure 3.** Contribution of materials in the Dutch water network

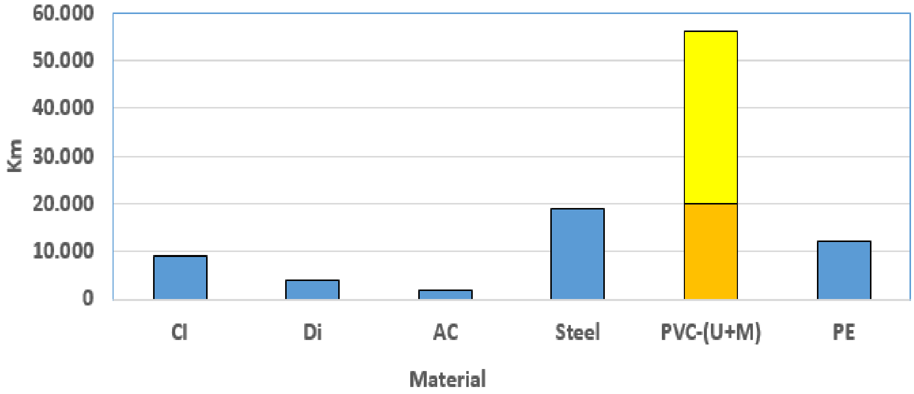


**Figure 4.** Contribution of materials in the Dutch gas distribution network

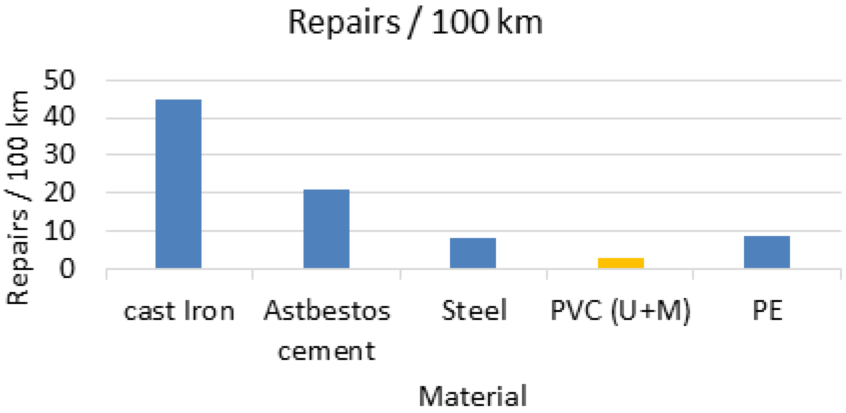


**Figure 5.** Repair rate of the Dutch gas distribution system.

The PVC system both for water and gas are systems using a rubber seal socketed jointing solution which has been is use for more than 60 years. The experience with the gas system is well presented in figure 5, showing the repair rate of the gas systems. [2]

The socketed PVCU and PVCM systems shows to have the lowest repair rate and hence confirms the excellent behaviour of this pipe concept.

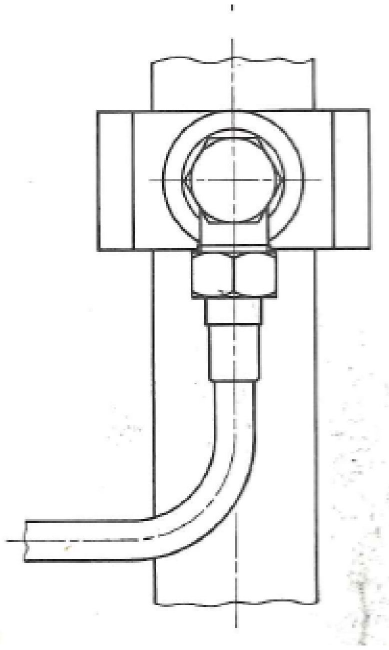
## 3. Design of Systems

Buried pipes networks in earthquake areas should be designed in such a way that they have a minimum risk of failure in case of an earthquake event. In fact, in selecting the right design, it is possible to minimize the risk of failures. If an urban area is supplied with a water supply system then there is the choice to design it as a fully integrated single designed system. Meaning that there is one transportation or feeder pipe of a rather big diameter, connecting the potable water plant to the distribution network. There is however, also an option to divide the urban area in 2 or multiple independent supply systems. For instance using 2 transport pipes and creating two independent distribution systems. The risk that both complementary networks fail during an earthquake event is considerably smaller. And although if one network would fail and part of the population would not have direct access to potable water, the other part of the urban area would still have water and that water is then close to the suffering area and access is then rather easy. Although this may indicate double costs of the network, in reality it is not. The transport pipes will stay considerable smaller and the distribution network to some extend as well. In this paper, it will also be shown that avoiding the use of big diameter pipes helps to minimize the risk of a failure.

A distribution system is built up of feeding pipes, branches and house connections. During a settlement or earthquake event, the best is that the pipe can follow the movement of the soils without limitations. Branches and especially house connections tend to hinder the free movement of the feeder pipe. For that reason it is important to create house connections that do include some over-length. In the Dutch practice, house connections are in most cases installed as shown in Fig.6 the example given is a house connection in a PVC gas system.

## 4. The Use of Failure Statistics

In Literature, several earthquake events have been analyzed. Statistics of failure and repair have been published. These statistics are very useful in understanding the strength and weakness of a system and also help a lot to understand how to minimize the risks of failure or malfunction of a system in case of earthquake events.



The pressure used in the gas distribution network is 100 mbar and in the water distribution network the pressure used varies mostly between 6 and 10 bar. Limiting the pressure is another way to reduce risk, both on the occurrence of problems as well as to limit the consequence of a failure.

**Figure 6.** Connecting the house connection to the feeder pipe

However, the results are not coming from well-balanced experiments, meaning that care should be exercised in interpretation of the results. Parameters like the pipe diameter, the age of the pipe, installed depth, presence of house connections, location of the pipe, soil types / profiles, type of media in the pipe (gas or fluids), are very important parameters that may result in false conclusions when comparing numbers like for like. For instance it might be that certain pipe materials / systems are more used in bigger diameters than others. Some pipe materials may have been used for gas applications where others were mainly present in the water supply system. And also the age of the different pipe systems may be considerably different.

In general, statistics provide a direction, a tendency but not the exact conclusion. Therefore it is important to also use models to be able to better understand the effects occurring during an earthquake event.

In this paper some of the analysis of the earthquake in Christ Church will be used. Reference is made to a paper published by O'Rourke et al [3] in which quite a lot of detail is given.

Using the results from that study and plotting it in a graph shows figure 7.

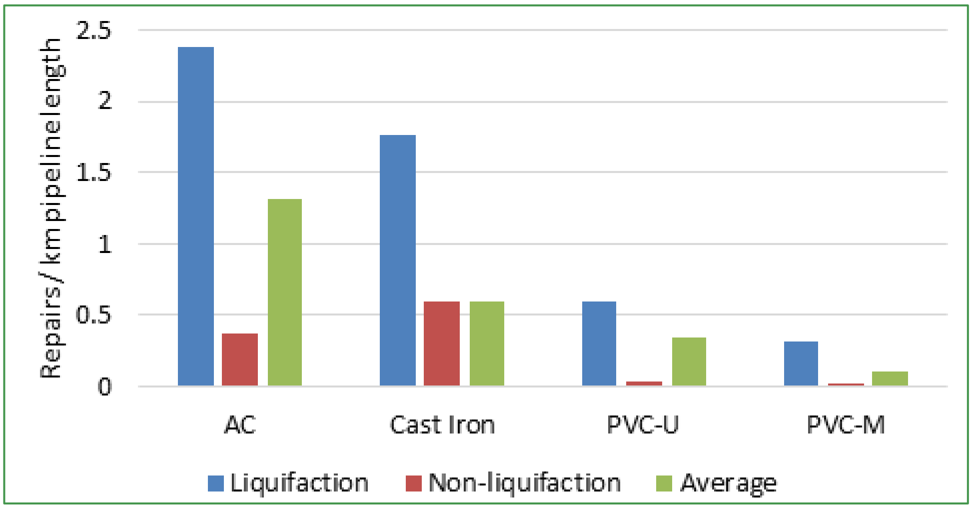


**Figure 7.** Repairs / km water in the water pressure pipes after the earthquake (22/2/2011) in Christ church, NZ, 2011

What can be seen is that the damages referring to Liquefaction are higher than damages related to other events. With the remarks made before about the expected un-balance in datasets, care has to be taken to draw conclusions in relation to the effect of materials used. However when we plot the damages from high to low then we see a tendency that with increasing flexibility and ductility, there is a decreasing damage/repair rate. Interesting are the results found for the PVC pipes. They show the lowest damage / repair rate. Both types, PVC-U and PVC-M are from a socketing point of view similar. The difference is basically the difference in ductility. PVC-M is more ductile and hence, also shows again an even lower repair/damage rate then PVC-U. Materials not present in this earthquake like PE and PVC-O are again more ductile than PVC-M and hence the expectation is that when using these materials, an even lower , close to zero damage/repair rate would be found. Information about PVC-O is given by Alferink et al in [4].

## 5. Model Used to Evaluate Performance of a Buried Pipe System

It is not easy to model a pipe in an earthquake event. Many things happen at the same time in a short period. The pipe may encounter axial frictional forces, either resulting in compression or in tension. But most of all and probably the more severe type of loading are caused by differential soil movements, which causes bending and axial stresses in the pipe. When the soil starts to move, the pipe will follow but at the same time give resistance to the soil movement.

At a certain moment when the resistance of the pipe increases, the soil may fail around the pipe or the pipe will fail because of a lack of flexibility and ductility.

Another important effect that may occur during the earthquake event is a rapid change of volume in the pipeline. The pipe deforms or spigot-ends are moving into the socket or out of the socket. The response to this however is depending mainly on the medium that is inside the pipe. When there is gas inside the pipe, the gas will be compressed, which results in a little increase of the pressure in the pipe.

Without taking into account that an increase in wall stress also increases the internal diameter to some extent, the net stress increase due to a change of volume can be estimated using equation 1.

$$\sigma v=\frac{\frac{d_1}{s}-1}{2}\bullet(\frac{1}{k}-1)\bullet P1 \qquad (1)$$

In which:

| | |
|---|---|
| **σ**v | Stress change due to volume change [MPa] |
| P1 | Nominal internal pressure [MPa] |
| d1 | Nominal outside diameter of the pipe [mm] |
| s | Wall thickness of the pipe [mm] |
| K | Volume change coefficient [-] |

When however there is a fluid in the pipe, an incompressible media, then the pressure change is more severe. When the volume becomes smaller than the response is such that the internal pipe diameter needs to change to make up for the volume change. This results in a stress increase in the pipe wall. Equation 2 gives the formula to estimate the pressure change due to the volume change in case of incompressible media. (It is considered that there are no air pockets in the pipeline)

$$\sigma v=\frac{E}{1-v2}\bullet(\sqrt{(\frac{1}{k})}-1) \qquad (2)$$

In which:

| | |
|---|---|
| **σ**v | Stress change due to volume change [MPa] |
| E | Modulus of elasticity [MPa] |
| K | Volume change coefficient [-] |
| $\nu$ | Poisson ratio [-] |

For both PVC and PE pipes the pressure increase in a water pipe versus the increase in a gas pipe is around a factor of 8-10 higher in the water pipe.

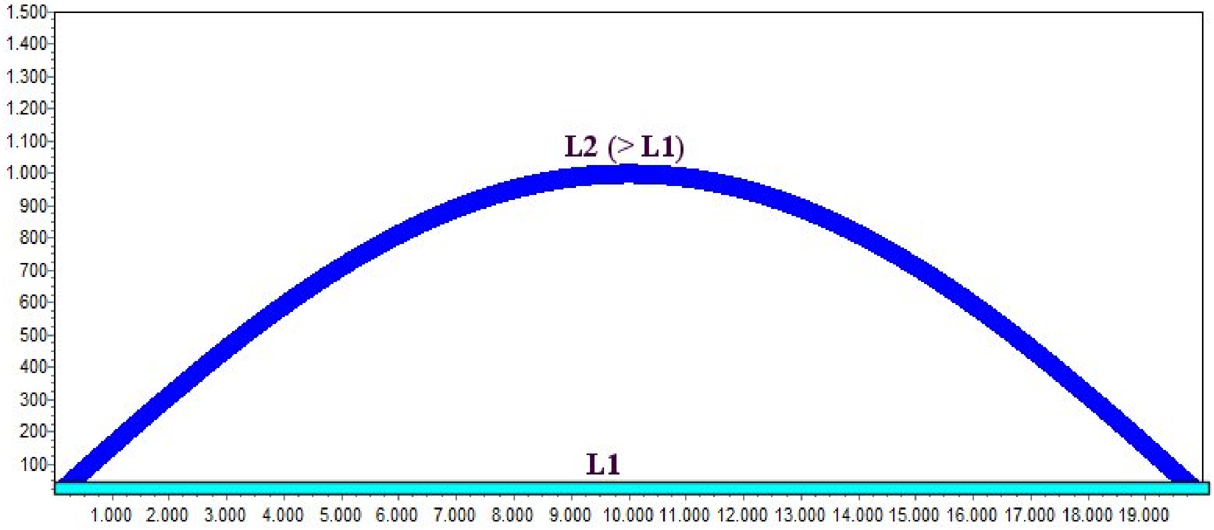


**Figure 8.** Model pipe bending. Pipe before and after earthquake event.

The formulas given result in a slight overestimation of the real pressure increase, because when the internal pressure changes so much, also some pipe or joint displacement may occur and also valves may open.

But what can be seen is that the stress increase is much more severe in a pipe for the supply for water than that of the supply of gas. This is one reason why one should not export results of statistics from gas pipes to the expected behaviour of pipes for water supply or vice versa.

The second model used is that of the pipeline, deforming as a beam. In that model it is assumed that the pipe will follow the displacement of the soil. So we are considering a pre-scribed displacement of the pipe as a beam. The objective of using this model is to define the effects of pipe diameter, type of jointing, type of material etc. It does not have the ambition to simulate the exact behaviour of a buried pipe during an earthquake event, but the results aim to give guidance in designing pipelines with low risk of failure during such an event, whenever that event may happen.

Fig. 8 shows the pipe in an un-deformed state (magenta) and deformed state (dark blue) . The deformation includes a 1 meter displacement in the middle of a 20 meter long pipe section.

The length of the pipe has increased because of the severe bending. The pipe suffers from bending strain. In case the pipe is a tensile resistant pipeline, it will also develop axial strain and stress and when the pipe is non-tensile resistant, like when socketed rubber ring joints (further referred to as "socketed" joints) are used, axial movements of the pipe in the socket will be developed.

The pipes used in the evaluation all have been considered to have been designed using an Overall design coefficient (c) of 2.0. International standards allow using lower values for the different materials, but these international standards refer to the minimum allowed values. In earthquake prone areas it is good practice to use a slightly higher C coefficient. In the comparison furthermore a pressure rating of 16 Bar has been used.

## 6. Results

The first analysis done was to check what the effect of the pipe diameter used is. Three different pipe systems were included. The PVC-O socketed pipe, the PVC welded pipe and the PE welded pipe. The stress (bending + axial) has been calculated. The total stress is shown on the vertical axis as a percentage of the ultimate short term strength. Figure 9 shows the results.

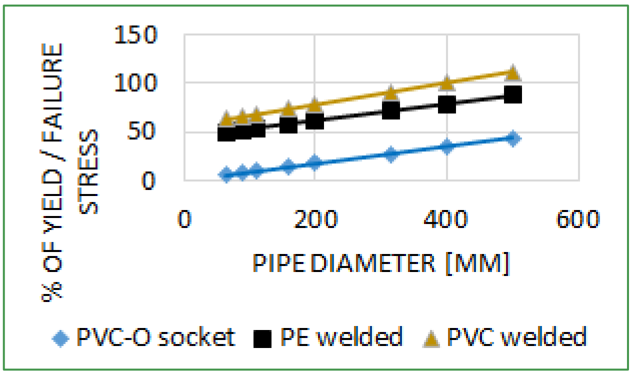


**Figure 9.** Percentage utilised from ultimate strength for welded and non-welded systems.

What can be seen is that with increasing diameter the risk of reaching the ultimate strength is also increasing.

It is also clear that welded systems have a higher risk in reaching the ultimate short term strength than systems which are socketed. What this implies is that if systems can be designed avoiding using bigger pipe diameters, then that is contributive in limiting the risk of a pipline failure. And referring to earlier sections about design, when using multiple water supply systems, the risk of loosing a lifeline during an earthquake effect is considerably lowered. Multiple does not refer here to parallell, but instead of serving a community with one system, separate the community in 2 or more independtly supplied areas.

It is also confirmed, that when analysing data sets of pipeline failure, care should be taken to draw conclusions from it, when different data sets have a different diameter distribution in the data sets.

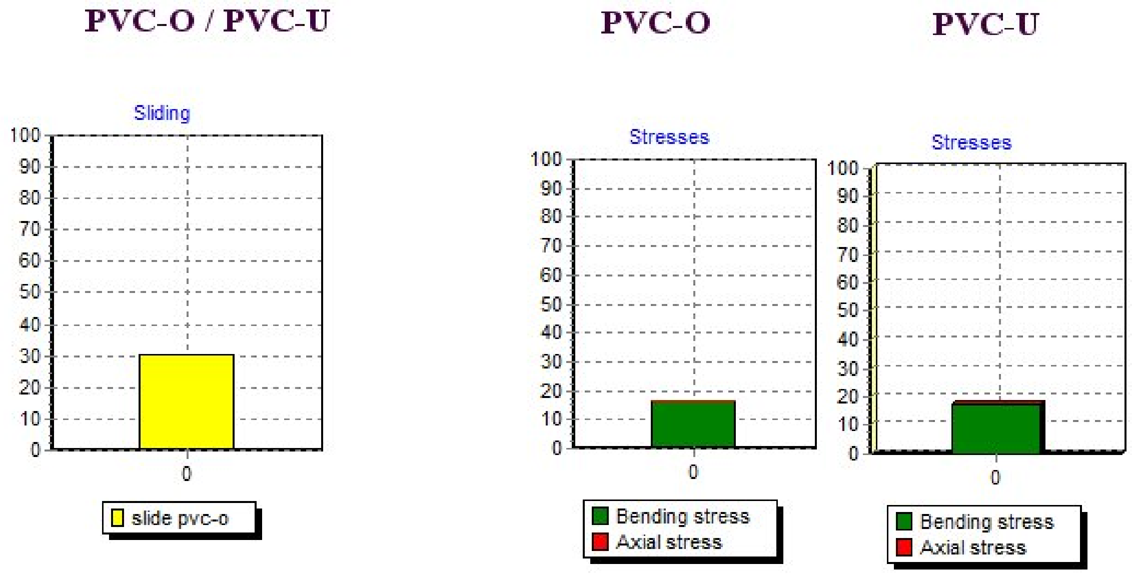
When socketed joints are used in the pipeline, then the development of axial stresses is prevented. The pipe spigot however, will slide to some extend inside the socket. In Figure 10, this effect is illustrated. On the vertical axis the percentage of sliding is shown. A level of 100% represents the situation of a pull-out.

Figure 10 also shows the development of bending stresses in a PVC-O pipe and in a PVC-U pipe, all of them socketed systems. Diameter 160 mm and the length of angagement of the socket is 120 mm.

What is shown in Figure 10 is that in a socketed system with a sufficient length of engagement (in this case 120 mm), the sliding in the socket does not result in a disconnection. If the length of angagement would not have been 120 mm but for instance 60 mm also then the pipe would not have been pulled out, although the sliding would have amounted for approximately 60%. International standards, like for instance the EN1452 requires a minimum engagement length of 71 mm for a DN160 pipe.

At the same time, bending stresses are developed but there is no development of axial stresses. The total stress is only about 10-15% of the ultimate stress and far from failure.

In socketed systems also bends and branches are used. In socketed system thrust blocks are used at these points, in most cases made out of concrete. Also in the situation of an erthquake this normally serves well it's purpose. However, in severe conditions the support blocks may move relative to the pipe and the support to the bend or branch may be lost. In order to minimise the risk of any disconnection, it is advised to use tensile resistent couplers at these positions in the network. They exist in 2 versions, one with an allowance for free sliding and one that does not allow such free sliding. For the situation where the joints are tensile resistent in combination with bends and branches, couplers without sliding allowance can be used. Although the relatively large engagement lengths in PVC socketed systems prevent a complete pull out of the pipe from the socket, in some cases however, it may be advisable to prevent the pull out when most extreme situation could occur. In such situations it is advised to use tensile resistent couplers with some free sliding allowance. The free sliding allowance prevents here the development of axial stresses before the free sliding stroke has been fully consumed.


PVC-O / PVC-U

PVC-O

PVC-U

**Figure 10.** Amount of sliding and stresses developed in socketed pipes during a simulated earthquake event

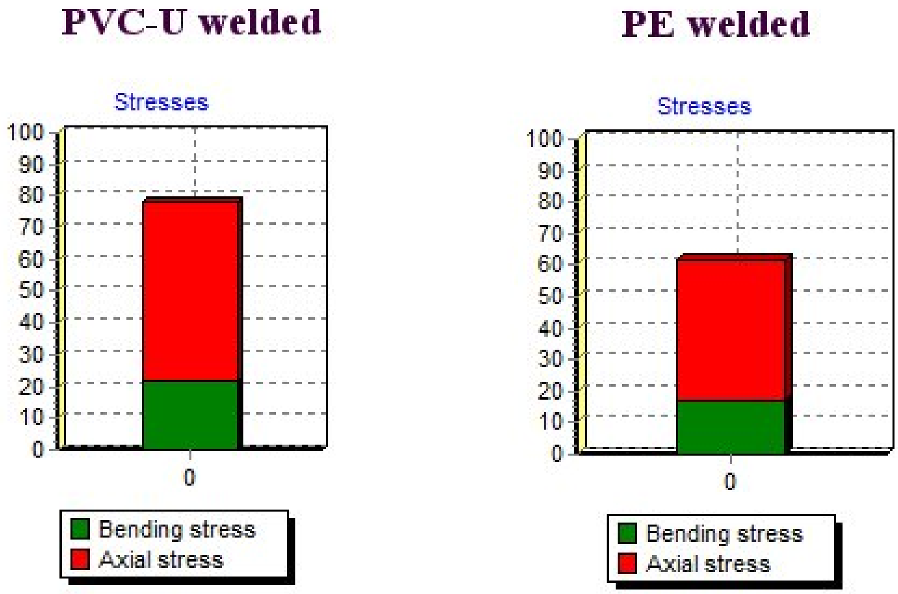


**Figure 11.** Stresses in welded systems (DN160 mm, welding factor 0.8)

**Table 1.** Potential risk contributors for Socketed and Welded systems

| **Socketed systems** | **Verification** | **Welded systems** | **Verification** |
|---|---|---|---|
| Seal in place and clean | Visual | Shaving | Visual |
| Lubrication sufficient | Visual | Alignment | Visual |
| Insertion until marker line | Visual | Determine friction loss of moving pipe | Manometer (calibrated) |
| | | Fusion (jointing) pressure | Manometer (Certified) |
| | | Max heat soak pressure | Manometer (Certified) |
| | | Alignment time | Stopwatch |
| | | Heat soak time | stopwatch |
| | | Plate removal time | Stopwatch |
| | | Jointing pressure built up | Stopwatch |
| | | Cooling pressure | Manometer (calibrated) |
| | | Min. cooling time | Stopwatch |
| **In total** | **3 visual inspections.** | **In total** | **2 visual inspections**<br>**4 manometer inspections**<br>**5 timer inspections** |

Also welded systems have been verified using this model. Figure 11 shows the results of the verification. The same pipe diameter of 160 mm has been evaluated and a rather high welding factor of 0.8 has been used.

What is shown is that considerable axial stress is developed because the system has no chance to slide and release the axial stresses. A welding factor of 0.8 is used here although studies performed by Janson [5] have shown that lower welding factors may be found in practice and when that is the case than there would be a failure.

## 7. Risk Reduction

When making the design and chosing the concept, one is in the position to decide on the actual risk of a pipeline failure during an earthquake event. Which event may happen the day after installation or some 5, 10, 30 or 50 years after installation. From the information available from failure statistics and from the analysis done in this paper, the following design aspects are important in limiting the risks:

1. Instead of designing one network for supplying water to an urbanisation, design two independent smaller networks. Smaller diameters incorporate less risk of pipeline failure then bigger diameter pipelines.
2. Pipeline systems which are not fully tensile resistent but do allow some sliding in the joints are preferred over completely tensile resistent systems.
3. Jointing techniques which are less sensitive in execution are preferred over those more sensitive. Table

1 shows an analsysis of risk associated to socketed versus welded systems.

4. From the above table it becomes clear that a socketed solution is by far more robust in execution than a welded solution. The latter one incorporates a considerable higher risk of not reaching a sufficient jointing quality.

5. Pipe materials which are not sensitive for chemical or galvanic corossion are preferred over materials which are more sensitive for this. We need to realise that the earthquake event may not come the day after the new pipe has been installed but some time later. Therefore it is important that the mechanical propeties of the pipe are still the same as when the pipe was new.
6. Effective verification of a sound installation has been possible.

After installation, the quality of installation of the system is tested by means of a tightness test using 1.5 times the nominal pressure. This pressure tests however is very discriminative for the socketed system. When the seal is not placed correctly or the pipes have been installed with dirt between seal and spigot, then a leak will appear which leak will be found during the site pressure test. This site pressure test however, is not very selective for the welded system. The soil around the pipe prevents the development of axial stresses in the pipe during the pressure test, with the result that the strength of the joint / quality of execution of the joint is not realy verified.

In order to minimise the risk of poor quality fusion joints, a high level of certification of operator and equipment is required. In practice the best solution is actually to utilise a closed robotic system, minimising the influence of man and environment (sand , dust, rain, wind, temperature) on the welding process.

In Figure 12, an overview of all potential risk contributors, the risk tree, is shown.

## 8. Conclusions

1. The excellent performance of the Dutch water and gas systems showed that the use of PVC socketed systems are very successful in medium to strong subsiding areas. Although the movement is not that quick as in earthquake events, the order of magnitude is the same.
2. It was illustrated that one should be very careful in using statistics in a straight forward way. Parameters like pipe diameter, age of the pipes, type of socket, location etc are influencing the results. Tendencies found from the statistics, however can very well be used.
3. One of the tendencies found is that when pipes are more flexible and ductile, the damage / repair frequency is declining considerably.

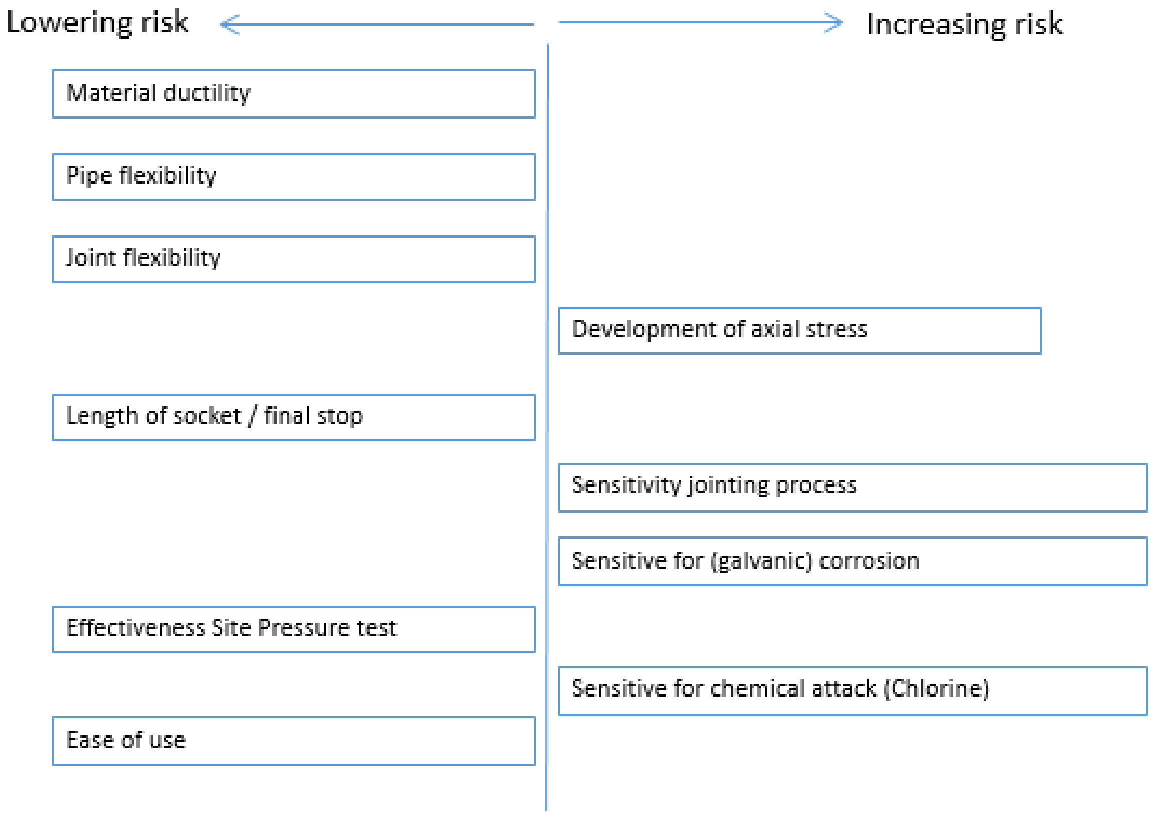


**Figure 12.** Risk tree, overview of potential risk Contributors

4. Transferring experience with gas pipes towards water mains is incorrect, because of the difference of the nature of the medium inside the pipe.
5. It was shown that socketed systems develop less axial stresses than welded systems.
6. On the aspects of risk reduction, the lowest risks are achieved when using pipeline systems that are less sensitive in jointing. Important also is that the jointing technique chosen can be well verified after installation. It is explained that socket joints have a significant lower risk of incorrect installation. Next to that, this type of jointing is very well verifiable after installation, where welded systems are not.
7. Although the good experience with PVC pipes in earthquake events is related to PVC-U and PVC-M, nowadays PVC-O has been in use for more than 15 years. PVC-O has a big advantage over the other PVC materials, because it is even far more flexible and ductile to a level that it is fairly indestructible.
8. The socketed systems with seals are also available, in combination with fully tensile resistant couplers as well as couplers with some sliding allowance. At the end of the sliding allowance, further sliding is not possible and final pull-out prevented. As such it provides a complete solution for pipelines in high subsiding and earthquake areas.

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