Behavior of Plastic Pipe Systems in Response to Dynamic Ground Movements

Abstract

A wide body of technical evidence for choosing plastic pipe systems on the basis of their behavior to accommodate dynamic ground movements is reviewed by a panel of engineers appointed by the European Association of Plastic Pipes and Fittings Association (TEPPFA). Experience derived from various extreme seismic events as well as technical studies are used in support of their findings.

Introduction

Plastic pipes may not make the earth move for everybody. But science and even extreme conditions such as earthquakes have now shown that when the earth does move, the ductile performance of these pipes is an essential characteristic that conveys vital operational benefits for utility companies and their customers. A team of expert colleagues from The European Plastic Pipe and Fittings Association (TEPPFA) has reviewed the technical evidence that describes and prescribes plastic pipes on the basis of their behavior to accommodate dynamic ground movements. Their findings could prove invaluable for utility companies that deliver vital services such as water, gas, sewer and telecoms.

Terra firma is not what it seems

Extreme seismic activity and weather events produce difficult problems for utility companies that own and operate pipeline systems around the world. Earthquakes, tsunamis and landslides are but a few examples of how acute dynamic ground movements can seriously disrupt the transmission and distribution of essential utility services. Other forms of ground movement are also capable of damaging the integrity of the utility pipe network.

Main examples are as follows:

- Adjacent Deep Excavation
- Soft Ground Tunneling
- Embankments/Spoil heaps
- Collapse of voids in ground
- Soil swelling/shrinking
- Frost heave
- Traffic loading
- Consolidation of made ground/fill material
- Ground impact/vibration and piling
- Unstable ground
- Trenchless construction of services
- Extreme weather conditions
- Discontinuous ground movements

Whereas many of these phenomena are unpredictable, utility companies are faced with mitigating their effects. Soil swelling for example, is known to produce sufficient pressures to dislocate water and gas pipes. This type of soil movement is closely related to seasonal climatic change and particularly to the moisture content of the soil (Gallage, 2011).

Collapse of voids beneath the ground are equally unpredictable. Newspaper headlines often dwell on the ruptured pipelines they create. Usual causes are the erosion of fine sand or silt by ground water or just a freak of nature.

Soil swelling leading to cracked road surfaces above and often cracked pipes below

Collapse of Voids – erosion or a freak of nature?

Bumpy roads are often the result of frost heaves that may displace the soil and thus the pipes they accommodate. Described as nature's speed bumps, these crumpled surfaces are sculptured by a combination of physics and fluid dynamics.

They are caused when water from melting snow or ice is absorbed by dense soil beneath the road surface. This damp sponge expands through the growth of ice crystals when freezing temperatures return. Cryosuction then takes over as this icy mass sucks in more moisture from below to expand upwards and deform the road surface above.

Such pressures often compromise the integrity of buried utility pipes and their connections. Ironically, the remedy is more of the same. Good drainage pipes would redirect the flow of melting waters away from the freeze and squeeze of frost heave. Terra Firma is therefore not what it seems. From the mundane to the catastrophic, dynamic ground movements have a profound influence on the choice of pipe material and the application it serves.

Resistance is futile

Dr. David Walton is a pipe engineer and scientist with over forty years of working with utility companies such as British Gas and Thames Water. "When the earth moves, the pipe system has to move with it," he explains. "Resistance is futile. Rigid pipelines are more vulnerable to dynamic ground movements especially if they are aged, corroded or both."

"The eighties were a wake-up call for the utility companies in the UK. The speed, scale and scope of replacement of cast iron gas and water mains by more flexible and durable plastic pipe systems was fundamental. For British Gas, the conversion to flexible, welded polyethylene systems overcame leakage and significantly reduced the danger of explosions. In addition to solving the obvious safety and regulatory issues, it virtually saved their business."

In the UK, a landmark inquiry pointed towards ground movement as a reason for the tensile failure of cast iron mains. The subsequent "King" *Report of the Inquiry into Serious Gas Explosions* identified such ground movement as caused by natural settlement, disturbance from other services or work on other services, and by drying out during drought and subsequent rewetting of the ground once the drought is broken. Further concern was expressed by uneven ground loading caused by heavy vehicles, particularly in areas where such loads were not expected when the pipes were laid.

This concern was prompted by the increasing use of road based haulage and the numbers of vehicles approaching the weight limit of 32 tons and maximum axle loads of 10 tons. This factor was all the more worrisome given the incidence of vehicles using roads not designed for them (being diverted for example due to road closures), parking on grass verges or pavements without due consideration of the load bearing capacity leading to localized fracture of iron mains.

A proposal to raise the maximum laden weight of vehicles to 40 tons through EEC legislation was viewed with some apprehension. The inquiry recommended that such vehicles be restricted to 'special routes' to avoid fracturing gas mains.

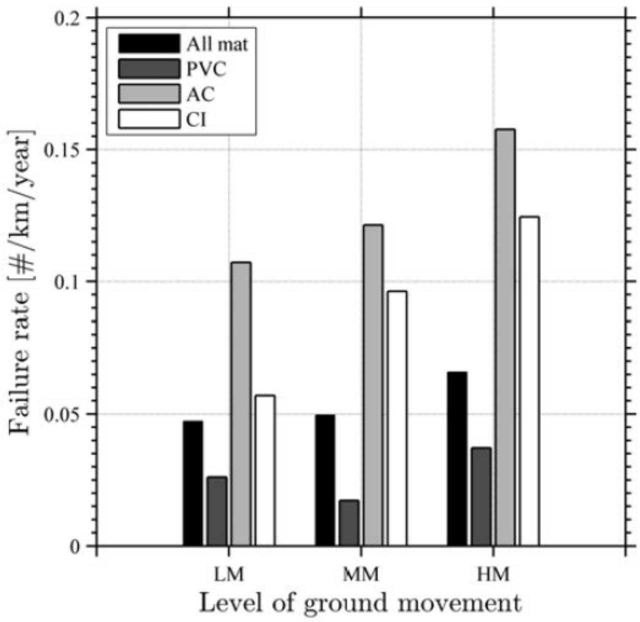
One significant outcome of the King Report was a large scale replacement of 60,000 km of iron pipe with polyethylene pipe materials from 1977 to 2000.

Whatever the size or source of ground movement, the TEPPFA team agrees that the ductile and elongation properties of the material and pipe itself must cushion blows from soil loads. "The pipe must be able to take the strain, move with the ground and yet stay intact, they insist: "Only plastic pipes and their joints can do this by providing a functional safety buffer. Our reflections are based on deflections. Comparative testing of plastic and ductile iron (DCI) pipes for deflection capability as a function of SDR (Standard Dimension Ratio) is conclusive."

Flexible plastic pipes under load will deform and in so doing lower the stress in the pipe wall. This phenomenon of stress relaxation significantly reduces the tendency for the pipe to fail by brittle cracking. Laboratory testing is matched by field experience where flexible plastic pipe materials have significant lower rates of failure during seismic events than those for rigid materials. This is derived from unstable crack propagation that occurs in stiff materials making them brittle in the face of cyclic ground movements (Kyle Haas).

How pipes perform in response to ground movements is just as important as how their in-service connections with stand the push and pull of subterranean life. This previously secretive life was finally revealed in 2013 by a sophisticated study (Arsenio) to measure ground movements and their effects on a service network corresponding to half the supply area of a water company in The Netherlands.

Various levels of ground movement were plotted against consequent failure rates of various types of water pipes (PVC, Cast Iron and Asbestos-Cement). The ductile performance of PVC pipes as well as their sufficiently long sockets were key characteristics in relaying essential service benefits.



Lifetime Prediction of PVC Push-fit Joints

Evidence of long-life performance and flexibility

Predicting the long-life performance of plastic pipes to accommodate ground movements is based on experience combined with technical observation and testing. PVC pipes were first installed commercially over eighty years ago in Berlin for the 1936 Olympic Village. However, it was during the nineteen fifties that the growth in demand for utility plastic pipe systems expanded exponentially. Prompted as much by the urgent needs for urbanization and public health, these plastic pipes also represented and continue to serve as a modern solution for the replacement of aged, corroded and leaking pipelines. They could be mass-produced locally and installed quickly.

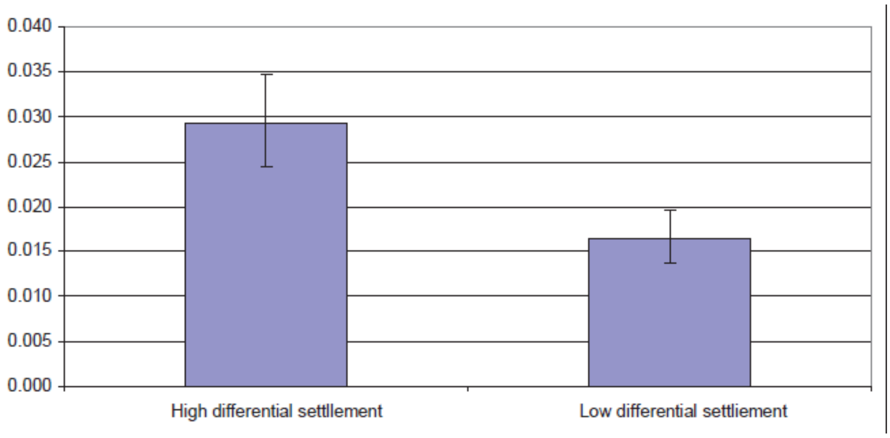
The versatility of these plastic pipe materials combined with the process of industrial innovation meant that new pipe applications proliferated. Following on from the success of PVC for water supply and drainage purposes, other plastic materials and pipe designs were developed specially for gas, sewer, domestic hot and cold water, telecom and electrical applications.

Despite this track record for technical innovation and operational performance, the market for conventional rigid pipes still prevails. Pipe design practices continue to favour rigid pipe systems and flexibility is often misconceived as a weakness.

But age and flexibility of plastic pipe systems have been closely examined and measured to reveal inherent advantages.

Independent scientific studies commissioned by TEPPFA to achieve EU Environmental Product Declarations (EPD's) for many plastic pipe systems have involved regulatory Life Cycle Assessment. This extensive body of work has confirmed that the service lifetime expectancy of PVC and PE pipe systems for the delivery of water, gas, sewer and telecom services is at least 100 years.

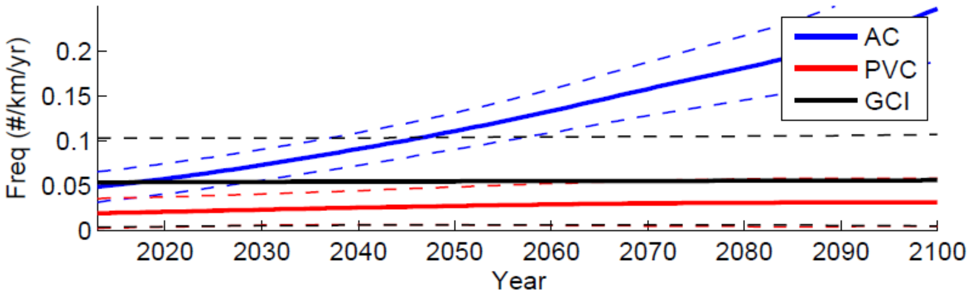
Rigid pipe materials may also face a bleaker future in the context of climate change. Climate change is expected to produce more frequent severe heat waves and long dry periods (van den Hurk et al., 2006). Consequent lower ground water levels are expected to create differential soil settlements (Arnold et al, 2011) that can damage the underground pipe infrastructure.



Degree of differential soil settlement

A study undertaken in The Netherlands (Wols,Thienen, 2016) explored the possible effects of climate change on pipe failures. Data consisting of 10,325 pipe and joint failures over a four year period were examined. Collected from several Dutch water companies, the data excluded third party failures. Historical weather patterns and four possible climate change scenarios were then extrapolated into the predictive model.

The largest increase in pipe failure was forecast by this model for Asbestos-Cement pipes during hot summers. A slight decrease in PVC pipe failures and a larger decrease were predicted for Grey Cast Iron pipes.

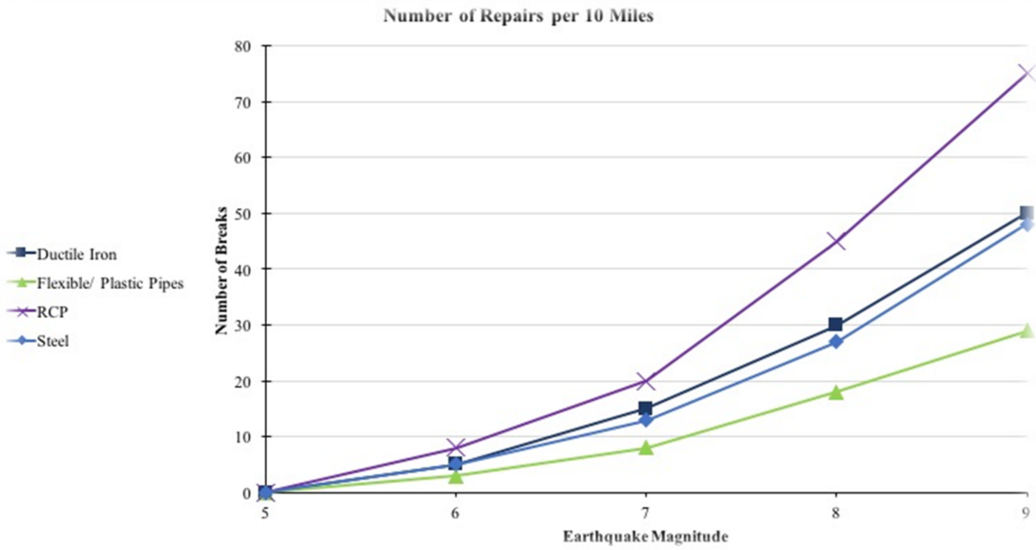


Predicted PVC lifetime performance

Climate change or not, flexibility of the pipe material does make a difference in terms of those important deflections to reduce the effects of ground movements. A European research project (TEPPFA) called the Sustainable Municipal Pipes Project (SMP) concluded that flexibility also favours environmental performance.

Based on examination of CCTV video footage in Germany, Netherlands and Sweden, approximately 1800 km of in-service buried concrete, clay and plastic sewer pipelines were analyzed. This footage was accompanied by original inspection reports of observable defects. These visual defects were recorded using the European Standard visual inspection coding system for drains and sewers (EN 13508-2). Conclusions were that flexible sewer pipes have a significant lower share of defective sections within the networks examined than rigid pipes.

A subsequent research project (Design of Buried Thermoplastic Pipes, TEPPFA, 1999) conducted full-scale field installation trials to measure deflection and strain of plastic and steel sewer pipes under deformation.



A variety of pipe stiffness, soils and installation conditions were employed. Supported by laboratory testing and below ground measurements, the field trials explored traffic load simulations, depth variations, internal pressure and time effect.

Findings were that ring deflection of flexible pipes is controlled by the settlement of the soil. After soil settlement, traffic and other loads do not affect pipe deflection. Deflection and its variation depend more on installation quality than on pipe stiffness and was therefore perceived as a safety characteristic. When pipes are relatively more rigid than the soil, the traffic and other loads have to be resisted by the pipe.

Installation variability results therefore in variations in ring deflection along the pipeline for flexible pipes and in variations in bending moments along the pipeline for rigid and semi-rigid pipes.

This behavior is key to understanding how ground movements under extreme seismic conditions influence the performance of flexible or rigid pipe networks.

“100% chance of an earthquake today”

Natural disasters such as earthquakes or tsunamis are usually chronicled by their immediate human loss, misery and material damage. Often, this human misery is compounded for many days or weeks later by the very disruption of essential drinking water, gas, drainage and sewer services through the devastating effects upon underground utility pipe networks.

Gas pipeline failures are a specific cause for safety concern since fire and explosions may exacerbate emergency situations. Broken water mains may further test the efforts of firefighting services.

Benjamin Franklin famously said “By failing to prepare, you are preparing to fail.” Yet accurate means of predicting the timing, location and magnitude of severe seismic events like earthquakes have not yet been developed. In the US where every state has experienced an earthquake, the advice from the United States Geological Survey (USGS) team is: “There is a 100% chance of an earthquake today.”

But technical methods are used to predict the performance of flexible and rigid pipes under these conditions. One such analysis compares a number of common pipe materials with a prediction of anticipated breaks for a 10 mile section of pipeline against an order of earthquake magnitude (Richter >5) over a 75 year period.

The vulnerability of a pipe to failures from ground movement is a function of its material stiffness.

Pipes made of rigid materials cannot deform and therefore the stresses remain high making them vulnerable to brittle fracture due to cyclic ground movements (Kyle Haas).

Many pipeline failure assessments have been carried out by utility companies in the aftermath of major earthquakes.

Valencia, 1994

For example, the Valencia Water Company of California compared the performance of three pipe materials – asbestos cement, PVC and steel – following the Northridge earthquake (magnitude 6.7) of 17 January 1994.

Three complete tank failures de-watered Valencia’s system in 30 minutes, and main line and service line breaks were in the hundreds. But none of the main lines made of PVC – about half of the city’s total system of approximately 270 miles – failed. The majority of the breaks occurred with the asbestos cement pipe. Breaks were typically beam or collar breaks. Breaks in the steel segments were next in terms of quantity, generally at weld joints or angle points (Abercrombie, 2011).

Great Sichuan Earthquake, 2008

Lifeline lessons were equally learned following a serious earthquake (magnitude 8) in May 2008 in Sichuan, China. Internal building pipes were mostly PVC-U, PP-R and aluminum-plastic for Hot & Cold water, drainage and cable applications. Where buildings survived the earthquake, these pipes remained generally in good condition.

In Mianzhu City, the municipal utilities for water supply were badly damaged. The total length of the main pipeline was 37 km – most of which was made from concrete, cast iron and PE. Of these, the PE performed the best with no failures whereas much of the concrete and cast iron pipe was destroyed.

As for the gas transmission and distribution system in Dujiangyan City, serious failures occurred. Mr. Huang Jianru, Chairman of Dujiangyan Jineng Gas Co. has explained that the flexibility of PE pipes meant that they performed better than the steel pipes. As a result, PE pipe would be used to repair the 440 km of supply network.

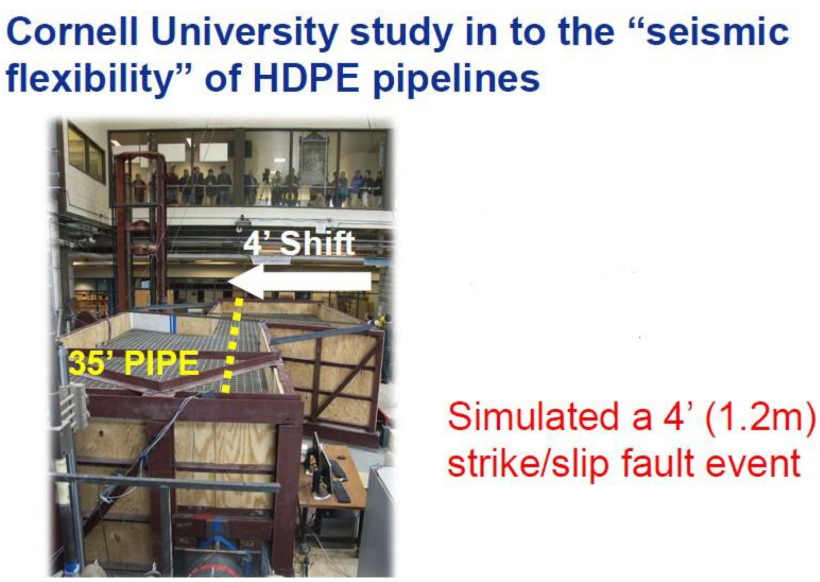
Serious Canterbury Tales

The 2010/2011 series of earthquakes in Canterbury, New Zealand are of particular interest since the material damage was extreme. Estimated at EUR 27 billion, this damage qualifies it as the fifth largest insurance event in the world since 1953. Most destructive was the aftershock that occurred on 22 February 2011 (Christchurch Earthquake).

It is important to note that despite the violent nature of the Christchurch Earthquake (magnitude 6.3), water and wastewater pipe services were restored almost exclusively with PVC and PE pipe materials.

The Christchurch events are viewed as a landmark experience – especially by experts who research the physics of earthquakes and their physical destruction. In the United States, a number of research facilities are linked under the National Earthquake Engineering Simulation (NEES) initiative to develop ways to observe earthquake behavior including the impact on various utility systems.

At New York's Cornell University, a Large-Scale Testing Facility is able to move ground soil in a ruptured scenario that is equivalent to as much six feet displacement. This pipeline research is performed by Professor Harry Stewart.



Cornell University – Large-Scale Fault Rupture Simulation Rig for HDPE pipes

At Rensselaer Polytechnic Institute an associated research team led by professors O'Rourke, Tarek Abdoun and Michael Symans uses a centrifuge that simulates earthquakes while spinning. The device tests soil structures as well as sections of pipe systems through exposure to a force of 200 times the force of gravity.

Both facilities have tested flexible plastic pipe systems extensively. Professor O'Rourke has voiced the relevant connection between the ductile properties of these pipes as tested and the experience of the Christchurch Earthquake.

He points towards a 2.5 km section of HDPE pipe that was installed in the Christchurch area to replace largely cast iron and asbestos cement pipelines damaged after the first earthquake hit the region. The second earthquake displaced two to three meters of earth within the same area and whilst surrounding non-plastic pipelines were destroyed, the HDPE pipeline remained intact.

Further contrast has been made between the water distribution systems that covers a similar area to that of the gas distribution system. Earthquake stress was such that the area was subjected to intense soil liquefaction.

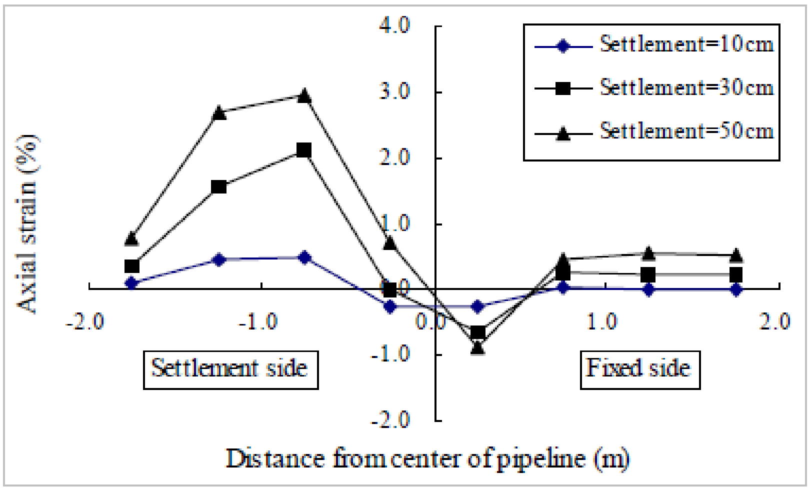
Whereas the water network succumbed to a high failure rate of approximately 1,700 kilometers of water pipe, the gas pipe network comprising mainly flexible pipes retained its integrity (O'Rourke 2013).

Japan

Japan has experienced a fair share of critical seismic events that have led to devastating human and material loss. The more recent example was the 2016 Fukushima earthquake and tsunami.

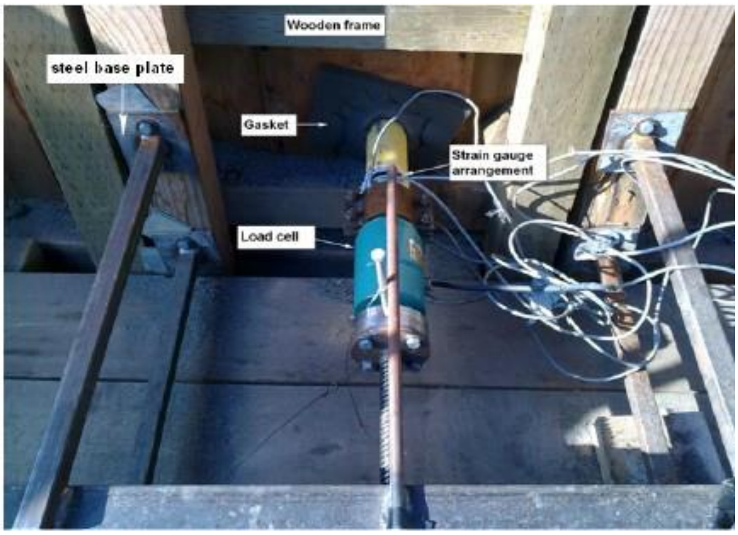
In the aftermath of the 1995 Kobe earthquake (magnitude 6.9), Osaka Gas undertook a review of its pipeline infrastructure and concluded that it found failures in its steel and iron systems but none where HDPE pipe was installed. For these reasons, Japan has been systematically replacing pipelines with HDPE throughout the country wherever and whenever possible (Plastics Pipe Institute 2014).

A significant amount of physical research testing has also been carried out in Japan. Full-scale experiments have been used to test the performance of PE water distribution pipes against ground deformation. Similar to the displacement testing by Cornell University, the Japanese tests rely on high-speed hydraulic actuators to produce longitudinal stretch and compression.



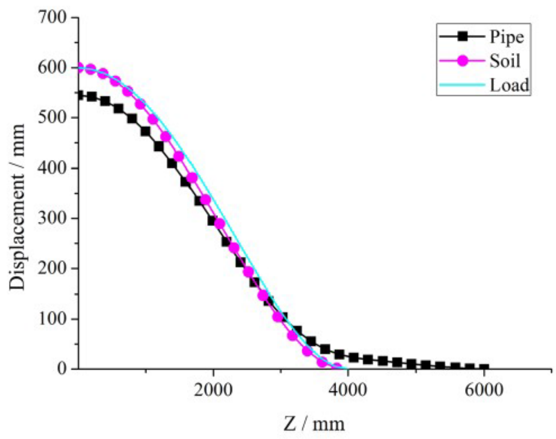
Longitudinal Strain distribution

Soil subsidence experiments that applied 3% maximum strain have produced no leaks whatsoever (Kubota). Soil box tests by the University of British Colombia to measure the non-linear response of buried MDPE pipes under axial loading have further endorsed their performance under pressure from dynamic ground movements (Lalinda Weerasekara, 2007).

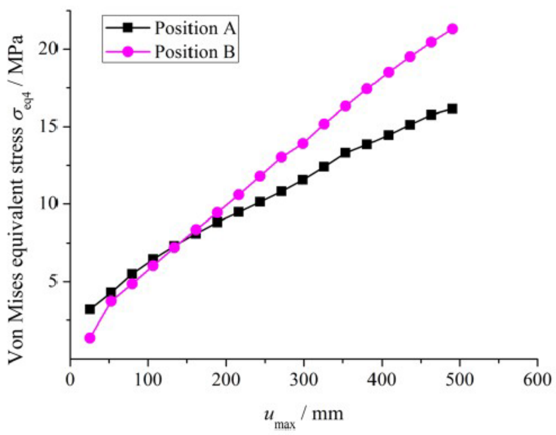


Axial soil box test

Landslides are a further example of dynamic ground movements producing challenging conditions for all kinds of buried pipelines. Often triggered by seismic events (as was the case with the Christchurch Earthquake), their phenomenon has been closely studied and simulations undertaken to predict the performance of flexible pipes as a result of soil displacement and consequent stress. Simulations relying on finite element analysis have endorsed the ductile staying power of buried polyethylene pipes. Displacement of the model in load Von Mises equivalent stress of applying direction (L=8 m) of position A and B with increasing U max (L=8 m).



Displacement of the model in load applying direction (L=8 m)



Von Mises equivalent stress of position A and B with increasing U max (L=8 m)

SIMULATIONS: Finite Element Analysis of buried polyethylene pipes

Shaken not stirred

Whereas seismic events may shake and break stiffer pipe networks, this information has not stirred or steered many engineering and governmental minds towards the field of earthquake preparation.

For example, in the US, the lack of a national seismic code for piping systems has affected critical municipal, industrial, and energy related pipelines constructed over the last 100 years.

Most piping systems have not been designed and detailed properly to resist earthquake loads and movements. Most consulting firms are not required by their clients (owners) to address these hazards. This lack of requirements in seismically active or coastal zones may be due to lack of awareness about the effect of these hazards on pipelines, cost issues, performance, damage and other priorities (Camille Rubeiz, 2010).

Cost issues are often quoted by pipe engineers to default in favour of traditional rigid pipes. Nevertheless, the work of Professor Robert Stein has underlined the significance of the life-long asset value of plastic pipe systems. He has developed an asset value management system that can help utility companies make important decisions about the improvement of their valuable assets.

“In any pipe rehabilitation project, the cost of the pipe rarely exceeds ten percent of total costs,” Professor Stein explains. “With the right pipe technology and the right investment to maintain integrity, their improvement could generate higher shareholder values.”

CONCLUSION

TEPPFA's team of experts are convinced that wherever dynamic ground movements occur, the acceptance of plastic pipes has more to do with attitude than latitude. “Our geophysical world may seem chaotic and totally unpredictable at times,” they conclude. “Flexible pipe systems may be buried and out of sight but their ability to accommodate dynamic ground movements should never be out of mind. And especially not for utility companies who rely on their predictable performance if and when the ground moves...”

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