"DEVELOPMENT OF A WHOLE LIFE COSTING MODEL FOR LARGE DIAMETER WATER MAINS"

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ABSTRACT

In Europe polyethylene (PE) has been chosen almost exclusively for gas mains for many years because of economic, technical and safety reasons but in the water industry a number of different materials are still used for pressure water mains. Indeed at sizes above 355mm (14 inch) most new large diameter water mains are still laid in ductile iron.

Often these large diameter water schemes are designed by consultant engineers who are not familiar with the benefits that can be achieved by using flexible and weldable PE pipes. Therefore material choice is often based on the cost of the pipe itself and the cost of the total installation, including the cost of trenching and the bedding/surround, is not considered. It is even more unlikely that the operational and maintenance costs are taken into account.

Therefore, it was decided to develop a whole-life costing model for large diameter water mains in which the full life cost of Polyethylene (PE), Glass Reinforced Plastic (GRP) and Ductile Iron (DI) water pipes within the range 400 to 900mm (16 to 36 inch) can be compared (N.B. it is possible to adjust the model to cover other size ranges).

1. INTRODUCTION

In Europe polyethylene (PE) pipes have been used almost exclusively for gas mains for many years because of economic, technical and safety reasons but in the water industry a number of different materials are still used for new pressure water mains.

For small diameter house connection pipes 20 to 63mm (½ to 2 inch nominal bore) the water industry almost exclusively uses polyethylene because of their flexibility and ease of installation. In these sizes up to 100 metres can be supplied on a single coil which can be easily handled by one man on the building site.

In mid sized mains 90 up to 300mm (3 to 12 inch nominal bore) PE is also the most popular choice for water mains in Europe. Indeed as shown in table 1(a) below for 2001 over half of the new water mains installed in Europe were manufactured from PE (1). Reasons are that at least up to 180mm (6 inch) PE pipes can be coiled and are still very flexible and easily manoeuvred around obstacles without the need for many special fittings. In addition in certain circumstances the pipes can be installed using "no dig" techniques which further reduce the cost of the project.

However for larger diameter water mains it is more usual for other materials to be chosen in preference to PE in Europe. This is shown in table 1(b) below for all new mains 300mm (12 inch) diameter and above installed in the five largest countries in Europe in 2003 (1). Clearly the most popular choice of pipe material in these sizes is ductile iron but many other materials are chosen indicating that individual circumstances and personal preferences are playing a role.

Table 1(a). Pipe materials used (km) for 90 to 299mm diameter mains in Europe in 2001 (1).

Country	PVC	PE	DI	Steel	GRP	Concrete
Germany	2491	6956	3150	1140	28	0
France	8020	2343	4880	0	0	0
UK	1228	7489	990	0	25	0
Italy	2245	13340	1250	1210	320	0
Spain	3299	8307	1745	39	33	130
Total	17283	38435	12015	2389	406	130
Percent	24.4	54.4	17.0	3.4	0.6	0.2

Table 1(b). Pipe materials used (km) for large diameter water mains in Europe in 2001 (1)

Country	PVC	PE	DI	Steel	GRP	Concrete
Germany	89	350	358	207	91	180
France	29	55	360	27	12	7
UK	56	136	385	7	53	9
Italy	97	190	270	388	170	152
Spain	29	135	376	46	62	245
Total	300	866	1749	675	388	593
Percent	6.6	18.9	38.3	14.8	8.5	13.0

Clearly, if more water companies are to install large diameter PE pipes, they must be convinced that they provide real cost benefits. Unfortunately in most pipeline schemes material choice is based on the cost of the pipe itself and the cost of the total installation, including the cost of trenching and the bedding/surround, is not considered. It is even more unlikely that the operational and maintenance costs are taken into account.

The benefits of a Whole Life Costing model (WLC) is that it allows all these elements plus the longer term service reliability and maintenance costs to be taken into account.

2. DESIGN CONSIDERATION

2.1. Pipe material choices for large diameter mains

Historically in the UK iron pipes have been used for large diameter water mains. These grey cast iron pipes were produced by vertical (“pit”) or more recently centrifugal casting and were very thick walled. Mainly due to this large wall thickness many of these pipes laid in the mid 19th Century are still operating today (2) although they are heavily graphitised and therefore very susceptible to brittle failure.

In the 1960’s ductile iron (DI) pipes were first produced where the internal graphite flakes were formed into spheres to reduce the potential for cracking. As cracking was believed to be less of a problem the wall thickness was also reduced. At a later stage zinc and bitumen coatings were applied to reduce the risk of corrosion. In 2000 the French company Saint

Gobain introduced their "Natural" range of ductile iron pipes into the UK water industry. In these pipes the external surfaces are protected from corrosion with a zinc alloy and an epoxy coating and the internal surfaces cement lined to improve flow properties and reduce water quality problems.

PVC pipes were introduced for pressure water systems in the 1960's but problems of brittleness and premature failures of large diameter thick walled pipes hindered their market penetration. Today in the UK, only modified PVC pipe systems are used. These are either molecularly oriented (MOPVC) or plasticized (MPVC) pipes produced in diameters up to 630mm (24 inch).

High performance filament wound glass fibre reinforced pipes (GFRP) are too expensive for water pipes and therefore the lower cost composite pipes of the "Hobas" sandwich construction are selected. Joint tightness problems and premature failures of large strategic pipelines have lead to the material no longer being used in the UK for pressure pipes.

Polyethylene pipes have been used for small diameter house connection since the 1960's but the first full PE systems were first introduced in the UK water industry in1984. These were MDPE PE80 pipes with socket and butt fusion fittings which immediately proved popular in diameters up to 180mm (6 inch). Above this size the PE pipes tended to be more expensive than the alternative systems and penetration was limited until PE100 systems became available in 1990. The thinner walls of the PE100 pipes, for a given pressure rating, made the pipes more competitive as well as lighter and easier to handle on site, which extended the penetration of PE into larger diameters.

2.2. Hydraulic Design

The "pit" cast iron pipes produced in 19th Century casting were not particularly smooth and typically the initial k_s value (sand equivalent roughness) in Colebrook's formula would be 0.25mm (3). Furthermore as the pipe continues in service the friction factor increases as the internal surface builds up layers of deposits. Therefore for an iron pipe 50 years old, k_s values as high as 2.5mm are frequently used (4).

Most modern ductile iron pipes are cement lined which initially provide a relatively low friction factor – for the Tate lining process DI pipe producers quote a k_s value of 0.38mm. However the longevity of the lining is the subject of some debate and it is not unusual to incorporate wash-outs in cement lined DI pipes to facilitate purging of cement debris as the pipe ages. Long term effective roughness values between 1mm (at 1.5m/s) to 3mm (at 1.0m/s) are usually assumed by the UK Water Utility Companies (5).

The internal surfaces of plastic pipes, including both PE and GRP pipes, are very smooth and it is appropriate to consider long term roughness factors k_s of 0.01 mm for pipes up to 200mm diameter bore and k_s of 0.05mm for larger pipes (6). This reference states that these values are conservative enough to include the effects of internal weld beads (see below) and any minor bio-fouling. It is also pertinent to mention that any build up of grease on the bore of a plastic sewer pipe is more easily removed by pigging than is the case for lined or unlined iron pipes.

For butt welded PE pipes the internal fusion bead will cause a slight flow restriction. If the internal bead is not removed this constriction has to be considered in pipes less than 300mm diameter, especially when conveying gases. However, for water the values quoted above are still valid (7).

Given the above information, the values of k_s used in the Whole Life Cost Model are 0.05mm for PE and 0.5 -1.0mm for DI pipes.

2.3. New lay systems

Most large diameter water mains (>300mm or 12 inches) are feeder mains with very few connections, often running through rural areas, although there will be some road crossings in most schemes. In a rural environment where trench width is not critical it is normal to use a trench width of D+300mm (D+12 inch) for both PE and DI pipes, although for DI greater width is required at joints for man entry.

For GRP pipes extra care is required in jointing and backfilling the pipes which means it is necessary to use a slightly wider trench at D+400mm (D+16inch).

For 400mm diameter PE pipes trench-less installation methods, such as ploughing or directional drilling can be used. However in the UK these methods tend to be limited to special situations such as river crossings or installation of pipes under growing crops.

2.4. Structural design

For buried rigid pipes such as DI there are established models available to calculate the loads on the system (8). However these models have only limited validity for flexible plastic pipes and even less validity for the highly ductile visco-elastic pipes made of modern PE materials. Indeed when these structural models were developed the engineers could have hardly foreseen the emergence of pipe materials that are able to co-exist in harmony with the soil in which they are buried (9).

The unique properties of PE means that under the applied load the pipe will deform which allows the stress in the pipe wall to relax. The stress on the pipe is therefore transferred to the backfill material as pipe and soil move in equilibrium. The main limit to this deformation is therefore only dictated by the requirements for the stability of the top cover, which means that in open field, rural installations quite high deformations can be allowed (N.B. a 10% pipe deflection will only reduce flow capacity by 2.5%).

A major European industry initiative in the 1990's, sponsored by TEPPFA and AMPE (10), provided a realistic design model for more flexible materials such as PE. For the first time this enables pipeline engineers to estimate deflection values under different external loads and in different soils and installation conditions. This work was more recently extended to include the outer fibre bending stresses created by the deflection of the pipe (11). This showed that it was not valid to use the "combined stress" in calculating pipe loading, a recommendation that has now been used to modify the UK annex to BS EN 1295-1.

2.5. Renovation of mains

Where an existing large diameter main is in poor condition it is often possible to renovate it using PE pipe rather than renewing it. This can lead to major project cost savings as well as significantly reducing the level of disruption.

The lower friction factor for PE compared to an old iron main which has been in service for a number of years mean that it can even be possible to reline the pipe with a smaller diameter PE pipe that can be simply inserted into the old main. For example a 710mm (24 inch bore)

PE pipe has the same flow capacity as a 30 inch iron main that has been in service for more than 20 years (4).

Fig 1. Renovating an old iron water main using large diameter PE pipe

3. INSTALLATION & JOINTING

Both DI and GRP pipes are jointed using a push fit spigot and socket joint and rubber rings. Whilst these joints are easy and quick to make they have no end load resistance and therefore at valves, junctions and changes of direction anchor blocks are required. For large diameter pipe anchor blocks can be very expensive and time consuming to construct.

In most projects digging the trench is usually the time bottleneck. Although DI jointing can be faster than butt welding PE the laying rates for PE tend to be higher due to use of longer lengths (DI are 6-7m compared to PE 12m).

PE pipes are usually fusion welded and a well made fusion joint is stronger than the pipe itself. This means that the pipe system can accommodate axial loads without failure and without the need for anchor blocks. The ability of PE systems to withstand end loads and ground movement has been demonstrated dramatically in the Kobe earthquake in Japan in 1995. When Osaka Gas examined their gas system after the earthquake (12) in which 6,000 people died and 440,000 homes were destroyed they found a high level of failure in their iron and steel systems but none in the PE part of their network. Following this analysis PE became extremely popular in Japan and other areas where earthquake events are normal.

Large diameter PE pipes are usually fusion welded using butt fusion techniques. This is a very reliable jointing method and most machines are semi-automatic. Since large diameter welding machines are expensive most installers will either hire a machine or sub-contract the jointing to specialised contractors. The latter option is expensive since a specialised team can cost up to £800 ($1,500) per day but since they can average 8 to 10 joints per day on 500mm pipe (5-6 joints per day on 1000mm pipe) they can easily keep up with trench preparation.

Electrofusion couplers are available up to 710mm and are usually used for road crossings for PE systems when jointing has to be carried out in the trench. On larger diameter pipes flanged joints would have to be used instead. Large diameter electrofusion jointing has proved to be difficult in the past but now new fittings are being introduced which use novel methods to close the gap and make joints more reliable.

4. COMMISSIONING & TESTING

4.1. Tightness testing of large diameter water pipes

When a PE pipeline is subjected to an internal hydrostatic pressure it will creep and give rise to a fall in the measured pressure even if the line is leak tight. Therefore it is necessary to compensate for this pressure reduction in order to assess pipeline integrity.

One method which is suitable for PE pipelines has been developed by L-E. Janson(13). This method relies upon the linear relationship between the strain and the logarithm of the time that the pipe is under test. Since the change in the volume of internal water is also linearly related to the strain it is possible to develop a relation ship for the volume change over consecutive time periods.

If the pipe is tight then the relationship between consecutive time periods should be as shown below in equation 1:

$$\Delta V_{(5h-4h)} = 0.550\ \Delta V_{(3h-2h)} \quad (1)$$

where $\Delta V_{(5h-4h)}$ Water volume change during 4 hours to 5 hours
$\Delta V_{(3h-2h)}$ Water volume change during 2 hours to 3 hours

If the water volume measured between the 4th and 5th hours is greater that that given by equation (1) then there is some leakage from the pipeline.

The UK water industry test procedure is based upon work performed originally by G.P. Marshall (14). This was later incorporated, with some modifications, into a guide prepared by WRc. The UK water industry is currently preparing a new Information and Guidance Note for pressure testing of all materials.

4.2 Leak detection and repair

The cost to locate and rectify a leak in a large diameter pipeline can be very high, typically it can be up to £20,000 ($34,000) per repair.

Most failures during commissioning are at joints. With DI or GRP pipelines any of the many spigot and socket joints can be suspect and therefore the whole pipeline length needs to be halved and retested perhaps a number of times, or the joints uncovered and inspected in the event of a leak being recorded. If the installer is following good practice each 500m (1600 feet) section should be tested separately which limits the investigation but often longer sections are involved.

The butt welded joints on a PE pipeline are very unlikely to leak and therefore the investigation can be focussed on the flanged joints at valves and off-takes which reduce detection times and costs. Due to creep it may be necessary to retighten some of the flange bolts after a period under pressure. To minimise flange leakage problems in large diameter PE pipes operating at pressures above 6 bar it is recommended to use a profiled steel reinforced rubber gasket.

5. DURABILITY & MAINTENANCE OF LARGE MAINS

5.1. Failure rates in water mains

Failures of large diameter mains, which are often strategic mains, are a very important consideration for any operator and for that reason are built into the whole life costing model. Water loss from leaking mains is becoming an increasingly important issue particularly in areas of the UK where restrictions are being imposed on customers due to the recent water shortages.

The cost of "third party damage" can also be very high as water can be extremely destructive to the foundations of buildings, bridges and roads. Although operators are insured against such eventualities the disruption and negative publicity resulting from destroyed homes or major road closures can very damaging and costly to operators.

For iron pipes the most common cause of failure is corrosion. Grey cast iron is prone to graphitisation, which means that the iron corrodes, leaving a matrix of lamellar graphite filled with voluminous iron oxide (rust). The pipe may not leak but the mechanical strength of the pipe is much reduced and the pipe usually then fails due to minor ground movements. Modern ductile iron pipes do not graphitise but are more prone to local corrosion if the protective coating is damaged.

If the glass fibres of a GRP pipe are exposed to water the adhesion between the fibres and the resin will break down and the pipe will swell and loose strength. The manufacturers provide a resin "gel" coat both internally and externally to provide a barrier to protect the fibres from the ingress of water. However if this "gel" coat is damaged during installation water will be absorbed and failure will occur. Indeed there have been a number of "high profile" failures of GRP pipelines in recent years, which means that they are now only used in non critical applications.

Failures on large diameter PE pipes are extremely rare but when they do occur are most likely to be due to bad jointing practice or creep at a flanged joint.

In Denmark, the Århus water supply company have considerable experience with plastics systems which now account for a large part of their network (PVC 50% and PE 23%). They have recorded the failures in their system over a number of years and the data for 2003 is given in table 2 below. Of the materials that they use PE has by far the lowest failure rate.

Table 2. Data from Århus Water Company in Denmark (2003) (15)

Pipe material	Percent of total	Mains length (km)	Av number of leaks per year	Failure rate per km per year
Cast iron	16	216	86	0.40
Fibre cement	10	135	11	0.08
PVC	50	675	48	0.07
PE	23	310.5	7	0.02
Steel galvanised	1	13.5	16	0.30
Totals	100	1350	168	0.11

The UK water industry has been collecting failure data over the past eight years (16) but in the 400 to 1000mm diameter range there is not that much data on PE or GRP since up to now these materials have been little used (refer table 3). In addition the recent high profile failures in GRP systems are not yet recorded and the resulting average failure rate of this material is lower than expected.

Table 3. Large diameter pipe failures (400 to 1000mm) from UK failure statistics

Pipe material	Total failures 400-1000mm	Total length km	Average failures per 100 km	Average failures per 100km per yr
Asbestos cement	74	923.89	8.01	1.00
Ductile iron	405	4824.56	8.39	1.05
Iron	1208	4965.45	24.33	3.04
Steel	348	1783.21	19.52	2.44
PE	19	288.28	6.59	0.82
PVC	353	308.97	114.25	14.28
GRP	16	178.69	8.95	1.12

N.B. The high failure rate on PVC pipes refer to old PVCU pipes which are still failing and not modern MOPVC or MPVC pipes.

6. THE WHOLE LIFE COSTING MODEL

The principle of whole-life cost (WLC) analysis is to calculate all costs associated with a project throughout its life to a common base so that true comparisons can be made between options. Thus the whole-life cost (WLC) represents the sum of money to be set aside today to meet all the eventual costs, both present and future, after allowing for the accumulation of interest on that part of it intended for future commitments.

The WLC is estimated by discounting all the anticipated operation and maintenance costs, calculated at present day prices, by a factor which takes account of time from the start of the project to when the expenditure would be incurred by using the equation below:

$$WLC = \sum_{t=1}^{N} \frac{(c_t)}{(1 + r/100)^t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where
- N Analysis period (years)
- r Discount rate (%)
- t Year of cost/benefit
- c_t Cost (initial cost, operation & maintenance cost)

The computer model has been set up to compare three pipe materials, namely, ductile iron (DI), glass reinforced plastic (GRP) and polyethylene (PE) in two different pipe nominal bore sizes 400mm and 900mm. To overcome the difference in the dimensioning system of PE pipes the two closest outside diameter series from the UK standards were chosen, namely 450mm and 1000mm. The pipe prices are based on the UK water industry price at the time of preparing the paper – June 2006.

Installation costs are based upon costs obtained from UK installers for the following components:

i. Number of joints completed per day
ii. Cost of jointing labour per hour
iii. Cost of plant hire for jointing per day
iv. Purchase cost of pipe per metre
v. Labour cost of testing and commissioning per day

Maintenance costs were calculated using the average cost of repairing a leak and the probability of failure for each type of system as derived from the UKWIR database. This may be revised in the future as more information becomes available particularly relating to the age of the pipe.

Finally to provide a practical basis for the whole costing an example of a typical model large diameter project has been set up, comprising 5km of pipe containing two off takes, four sluice valves and two air valves. The discount rate used in the calculation is 5.1% as this is the current return on capital for the UK water industry.

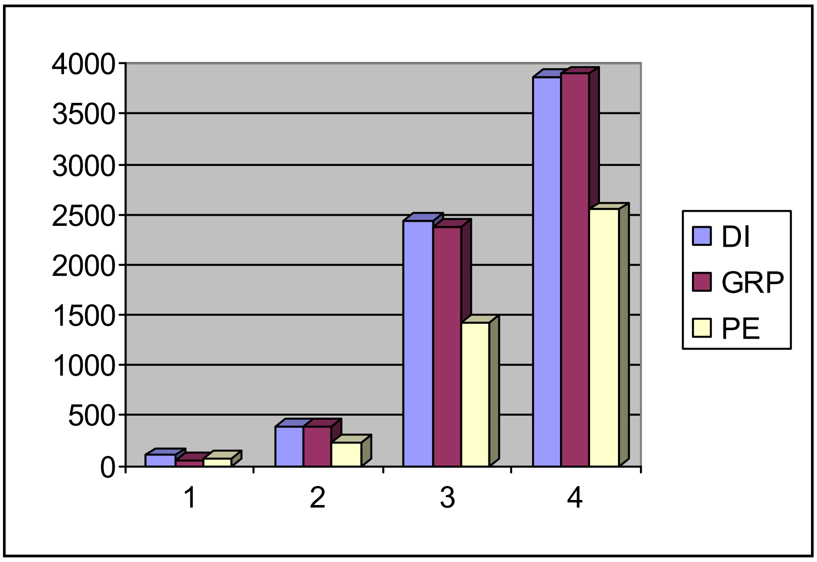
This model provides comparative costs for the following elements:

1. Basic pipe cost (£ per metre)
2. Total installation cost (£ per metre)
3. Total installation cost for model project (£k)
4. Whole life cost for model project over 50 years (£k)

The results for each of these elements for the two different pipe diameters installed in an urban environment are shown in figs. 2 and 3.

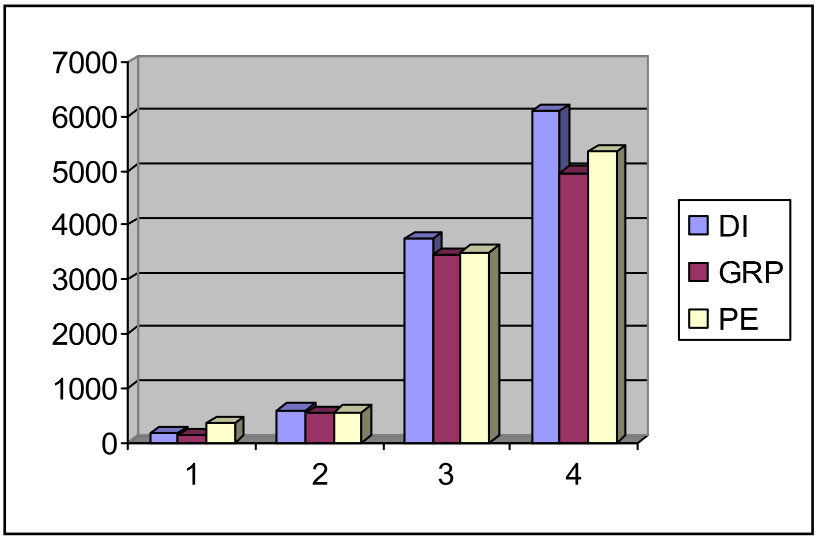
In the 400mm project in an urban environment PE proves to be both the lowest cost to install and the lowest whole life cost despite being significantly more expensive per metre than GRP pipe. Despite the apparent additional cost of butt fusion equipment the longer pipe lengths result in lower joint costs. Narrower trenches also lead to lower installation costs as the cost of the reinstatement of the road surface is expensive.

Fig 2. Comparison for 400mm project in urban environment



At 900mm the GRP pipe is very significantly cheaper than the PE pipe and despite the lower laying costs this difference cannot be overcome. However as discussed before, recently there have been some very costly failures of GRP pipes which will significantly change future statistics. Also these failures have led the UK water industry to reassess its usage of these pipes for critical pressure mains.

Fig 3. Comparison for 900mm project in urban environment



In rural conditions the situation is somewhat different as the reinstatement costs are significantly lower. Therefore whilst PE gives lower costs at 400mm the costs of both DI and GRP are lower for the 900mm project. In these circumstances other benefits need to be taken into account such as the undoubted higher durability of PE systems as shown by the statistics on smaller diameter water networks.

6. SUMMARY & CONCLUSIONS

In most European countries today PE piping systems are well established as the most popular material for small and medium sized water distribution mains. However for large sized water pressure pipes other materials tend to be preferred and in particular ductile iron. This selection is often based upon tradition, "we have always used iron pipes", or because of concerns about the jointing or structural performance of large diameter PE pipes. This paper addresses these issues and shows that in virtually all cases the unique properties of PE work to the benefit of the installer and system operator.

Often material selection for a large diameter project is based on the cost of the pipe rather than a full analysis of the installation costs and the future costs of repair and maintenance. This paper shows that when these other factors are taken into account in the initial project cost then the most economic selection may indeed change and in many cases PE becomes the best option.

Ultimately cost will not be the overriding factor, because as water becomes more scarce the durability and reliability of the system will be the governing factor – under these conditions the corrosion resistance and joint tightness of PE will make it the only choice no matter what the diameter.

"Whisky is for drinking. Water is for fighting over."…………..Mark Twain

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