The paper was published in the proceedings of the 11th Australia New Zealand Conference on Geomechanics and was edited by Prof. Guillermo Narsilio, Prof. Arul Arulrajah and Prof. Jayantha Kodikara. The conference was held in Melbourne, Australia, 15-18 July 2012.

Field Behaviour of Buried Water and Gas Pipes in Expansive Soil

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ABSTRACT

Failures in ageing buried pipelines have been identified as a major ongoing problem for water, wastewater and gas authorities in Australia. The consequences of such failures can include service disruptions and significant repair costs, as well as external factors including environmental disruptions and health risks. The failure in a given pipeline depends on the local soil conditions, extreme climate, and external loading etc. The soil condition and climate change are the most important factors which can cause unexpected failures. The differential movements in expansive soil (i.e., shrinking and swelling), produced as a result of varying moisture content along the pipeline, can create a stress conditions which may exceed the capacity of the pipe segments, causing them to fail.

A study was conducted by Monash University to investigate the effects of climate and local soil condition on buried reticulation water and gas mains. The instrumentation included sensors to measure pipe wall strains, in-situ soil water content, soil movement, soil pressure and temperature. A weather station was installed to collect the climate parameters such as air temperature, solar radiation, rainfall etc. The performance of water and gas pipe was monitored for more than two years.

On the basis of field monitoring data and long-term climate modelling results, this paper explains the possible failure mechanisms and long-term safety of theses pipelines. It is evident that substantial stresses can develop on the pipes due to seasonal ground movements and pipes can fail under these stresses if they have undergone strength deterioration, as occur commonly due to corrosion in cast iron pipes.

Keywords: Buried pipeline, cast iron, expensive soil, climate modelling, soil moisture, failure mechanism

1 INTRODUCTION

Failure of buried water and gas pipelines due to aging and extreme loading is one of the major problem which does not only results in wastage of precious water and but can also created negative social and economic impacts in many global population centres, including Australian towns and cities. Repairs and replacement of deteriorated pipelines impose major expenditures on councils and state government. Therefore, it is important to improve our understanding on the factors influence the pipe failure and mechanisms of pipe failures to develop an improved pipe asset management models that can predict water and gas pipe failures in order to plan for rehabilitation, replacement, and failure mitigation strategies of the pipe asset.

Analyses of available both water and gas pipe performance data in locally and globally indicate that the pipe failures are influenced by seasonal climate changes, soil type, pipe diameter and pipe material (Rajani and Zhan, 1996; Gould and Kodikara, 2008). Also, several studies have been performed to identify the correction between the water main breaks and the influential factors such as age of pipes, soil corrosivity, pipe diameter, temperature, water pressure, and external loads (Habibian, 1994; Karaa and Marks, 1990; Goulter and Kazemi, 1988; Kettler and Goulter, 1985; Bahmanyer and Edil, 1983; O'Day, 1982).

Previous studies (Ibrahimi, 2005; Chan *et al.*, 2007; Gould and Kodikara, 2008) showed that failure rates of water pipe had risen markedly during summer and to somewhat lesser extent during winter under the Australian climatic conditions. The analysis of pipe failure data indicated that these effects are much more pronounced after a prolonged dry period (e.g. 2001/2002), highlighting the susceptibility of the existing pipe network to the local climatic changes. Gould et al. (2009) conducted an analysis of water pipe failure data obtained from two water authorities in Victoria, Australia, for the period from 1996 to 2006 and concluded that the failure rate increases as net evaporation increases. Net evaporation is negatively related to soil moisture content indicating that soil moisture content decreases as net evaporation increases. Higher failure rate was observed for cast iron pipes which are oldest, with the greatest length in-service, buried in expansive soils, and with the diameter of 100 to 150 mm. Furthermore, the study reveals that the rate of circumferential fractures increases with increase in net evaporation.

In spite of the effects of local climate, soil water content and temperature, pipe material, and pipe diameter on the performance of buried pipes particularly in expansive soils, a little work has so far been carried out to study the behaviour of buried pipes subjected to climatic effects. Therefore, in this paper, a brief account of the field monitoring of two in-service both water and gas cast iron pipeline behaviour for more than two years is presented together with soil response to climate effects and the effect of soil response on the pipeline. The possible long-term soil moisture variation at different depths due to ground-atmosphere interaction at the instrumented field site reported in Rajeev et al. (2012) used to understand the long-term behaviour of those pipelines. Finally, a possible cause of failure of aging cast iron pipe buried in reactive soil is reported.

2 FIELD INSTRUMENTATION

As stated above, Gould and Kodikara (2008) reported that the cast iron water pipes of 100 mm nominal diameter have experienced failure rates higher than that of the other pipe materials and diameters on the basis of the statistical analysis of failure data of water pipeline in Melbourne region. Further, most of the failures were observed in pipelines located in expensive soils. Chan et al. (2007) also reported that over 50% of pipe failures are in cast iron pipes and about 60% of the failed pipes have 100 mm diameter. Based on the above findings, it was decided to undertake the field instrumentation on a 100 mm cast iron water pipe buried in reactive soil at Altona North in Victoria, Australia. Failure data analysis of gas pipeline by Gould and Kodikara (2009) reported that the highest failure rates were recorded in 100 to 150 mm cast iron pipes. Based on these findings, a 150 mm cast iron gas pipe at Fawkner in Victoria, Australia was selected for the instrumentation.

2.1 Soil condition

The soil tests were carried out for the soil sample collected at both sites to study the soil properties and behaviour. Undisturbed soil samples were collected down to 2100 mm and 2000 mm depth, where the basaltic rock was found, at Altona North and Fawkner respectively. The soil samples were then sealed on site to prevent moisture evaporation and were brought to the laboratory for classification tests. Moisture content, dry density, Atterberg limits, linear shrinkage, and saturated hydraulic conductivity were measured at different depths in the laboratory.

The particle size distribution shows high percentage (> 50%) of clay particles in the soils of the two sites. Further, soil samples taken at different depths were tested in oedometer to determine the swelling pressures. Table 1 & 2 summarise the results of these tests at different depths for Altona North and Fawkner, respectively. As given in Table 1 & 2, the swelling pressure of the soil in the site varies from 200 to 550 kPa and 80 to 560 kPa for Altona North and Fawkner, respectively. This variation can be affected predominantly by the initial water content and initial dry density of the samples.

Table 1: Physical properties of soil at Altona North

Depth (mm)	LL (%)	PL (%)	I_p (%)	LS (%)	Dry Density (g/cm^3)	Initial Water content (%)	Swelling pressure (kPa)	Saturated hydraulic conductivity (m/2)	Texture
0 ~ 250 (surface soil)	N/A	N/A	N/A	N/A	1.33	3.37	N/A	5×10^{-5} ~ 8×10^{-6}	Dark Brown/Black
250 ~ 500	72.00	27.80	44.20	21.70	1.46	21.43	205.75	4.5×10^{-9}	Brown
500 ~ 750	87.30	29.50	57.80	24.00	1.53	23.69	551.81	N/A	Brown
750 ~ 1000	99.40	28.90	70.50	21.20	1.41	24.39	371.20	2.5×10^{-9}	Brown

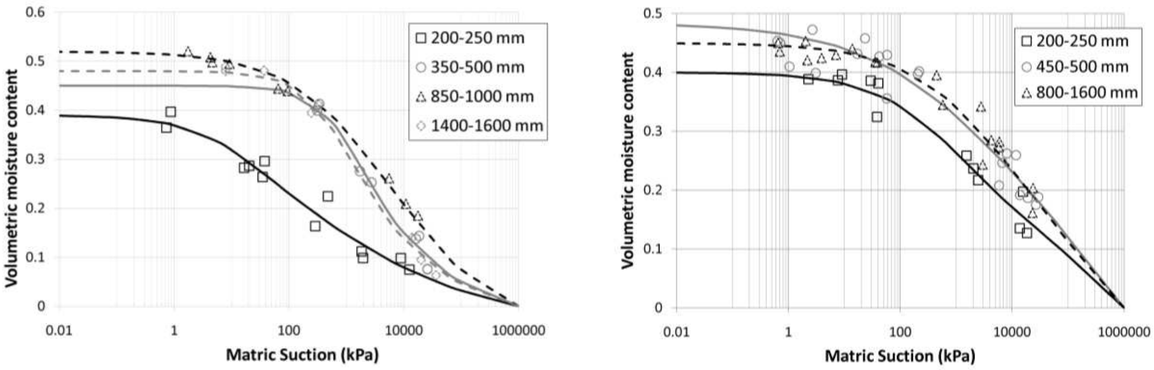
1000 ~ 1300	91.20	23.40	67.80	26.60	1.58	25.13	412.05	N/A	Grey
1300 ~ 2100	101.60	23.80	77.80	24.40	1.58	26.10	331.94	N/A	Light Brown

LL = Liquid Limit, PL = Plastic Limit, I_P = Plasticity Index, LS = Linear Shrinkage

Table 2: Physical properties of soil at Fawkner

Depth (mm)	LL (%)	PL (%)	I_p (%)	LS (%)	Dry Density (g/cm^3)	Initial Water content (%)	Swelling pressure (kPa)	Saturated hydraulic conductivity (m/s)	Texture
0 ~ 150 (surface soil)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2.52×10^{-5}	Brown/ dark brown
150 ~ 300	69.1	22.4	46.7	19.7	N/A	N/A	N/A	N/A	Brown
300 ~ 700	70.4	20.1	50.3	20.0	1.45	33.8	80	1.93×10^{-9}	Brown
700 ~ 1200	60.3	17.5	42.8	18.1	1.59	27.5	380	2.73×10^{-10}	Brown
1200 ~ 1600	65.9	20.7	45.2	18.8	1.70	23.3	560	N/A	Light Brown
1600 ~ 2000	61.5	19.5	42.0	17.7	1.64	26.6	370	N/A	Light Brown

The Soil Water Characteristic Curve (SWCC) of the field soil was obtained using the filter paper method at various depths for both sites. Figure 1 shows the measured suction and water content values together with the fitted SWCC using Fredlund & Xing (1994) equation at various depths for both sites.



(a) (b)

Figure 1. Soil water characteristic curve: (a) Altona North; (b) Fawkner

The instrumentation was carried out on the pipe surface and in the surrounding soil in three primary locations, designated as Pit 1, Pit 2 and Pit 3. The Pit 1 is located beneath the driveway and Pit 2 & 3 are located 3.65 m and 14.25 m away from the driveway, respectively at Altona North. At Fawkner, the Pit 1 is located beneath the driveway and Pit 2 & 3 are located 6.9 m and 14.85 m away from the driveway, respectively. The pipe burial depth is 800 mm and 725 mm at Atonal North and Fawkner respectively. The strain in the pipe due to various loadings is monitored at all three pits. Following sensors were installed to monitor the behaviour pipe and surrounding soil; (1) biaxial strain gauges on pipe surface to measure the axial and flexural strains, (2) thermocouples to measure the soil temperature, (3) thermal conductivity (Campbell) sensors to measure the soil suction, (4) soil moisture sensors (similar to time dependent reflectrometry or TDR) to measure the volumetric soil moisture content, (5) earth pressure cells to measure the soil pressure exerted on the pipe, and (6) pressure and temperature gauges to measure pipe water pressure and temperature respectively. In addition to these sensors, a weather station was installed at both sites to record the local weather conditions that included air temperature, rainfall, humidity, wind speed and solar radiation. Further, a neutron probe was employed to monitor the moisture variation up to the depth of 1.5 m at both sites on a monthly basis. More details about the sensor specification, arrangement, location, and installation can be found in Gallage et al. (2008 & 2009) and the details about the neutron probe measurement can be found in Rajeev et al. (2010).

3 RESULTS AND DISCUSSION

The field monitoring data collected more than two years period from 22nd September, 2008 to 24th May, 2011 only at Fawkner is presented here due to the page limitation. The changes in the flexural stress in the pipe, which is calculated using the difference in axial strain between the top and bottom surface of the pipe, and the variation in average moisture content at the depths of 500 mm and 900 mm are shown in Figure 2. The sign convention used is that tensile stresses are positive. The average moisture content was calculated taking the average of the moisture sensor readings at a particular depth. The flexural stress (i.e., pipe top stress-bottom stress) in the pipe increased beyond the initial level when the moisture content in the soil decreased during December, 2008 to June, 2009 at both Pit 2 & 3. Thus, the pipe bends downward due to loss of support (i.e., soil shrinkage) depicting a cantilever action close to the covered drive way. In July, 2009 to December 2009, the flexural stress in the pipe gradually decreases (i.e., increasing negative stress) while the soil moisture content increases. It confirms that the swelling stresses developed around the pipe, which pushed the pipe upward due to increase in moisture. During December, 2009 to June, 2010; the change in soil moisture content at the depth of 500 mm and 900 mm was not significant, therefore the changes in flexural stress was relatively constant at both pits. The moisture content increased significantly due to frequent rainfall beyond June, 2010 until end of the monitoring period (i.e., June, 2011). Hence, the flexural stresses kept on decreasing in this period at both pits and the pipe was pushed upward. However, in general, it was observed that there was a time lag between the change in moisture content at relatively deep soil due climate effects and the stress development in the pipe due to moisture changes.

The study by Ibrahimi (2005), Chan (2008), Gallage et al. (2008), and Gould and Kodikara (2008) on pipe failures in Melbourne, shows that higher failure rates were recorded in hot and dry summer, where soil shrinkage is the predominant behaviour. However, the long drought was not obese in this data collection period due to the change in seasonal climate in the year 2008 to 2011 that Victoria had experienced higher rainfall and relatively wetter summers. Further, the moisture content change at relatively deeper ground depends on the compound effect of climate events in consecutive years other than the single year climate changes.

Rajeev et al (2012) developed a numerical model of 1-D soil column in VADOSE/W (GEO-SLOPE International, 2010) to simulate the ground-climate interaction and to verify the above statement. The thermal and hydraulic properties of field soil measured both in the laboratory and field were used in the model. The model prediction of soil moisture content at different depths and time was compared with field monitoring data and the neutron probe data. The model is able to simulate the moisture variation reasonably well. The past climate data (obtained from the Australian Bureau of Meteorology) during the 10 year period 1997 to 2006 was considered in the analysis. The climate is relatively random but the extreme weather condition could occur in cyclic fashion. Therefore after considering the availability of climate data and the time required for the model to run, a 20 year model was developed by repeating the 10 year dataset for the long term study in order to capture the possible soil moisture variation at the field site.

The resulted variations in soil moisture content at different depths are shown in Figure 3 together with rainfall data. It is evident that higher fluctuations in moisture content occur close to the surface and these fluctuations diminish with depth. The variation in moisture content is around 30% to 45% (15% change) at 300 mm depth and around 38% to 47% (9% change) at 1000 mm depth were observed. Furthermore, it can be seen that there is a delay in the peaking of soil moisture due to high rainfall as the depth increases. A cyclic behaviour of moisture variation can be clearly observed at 800 mm (i.e., at nominal water and gas pipe depth) and below. This behaviour is due to the low hydraulic conductivity of clay soils; infiltration of moisture to these depths is slower and requires longer time to be affected by the ground surface condition, while the soils at shallow depths have more instant response to the prevailing climate. The change in moisture content indicates that peaking of the moisture content at shallower depths follows the rainfall pattern, while at greater depths the peaking of moisture content has a delay from few weeks to several months.

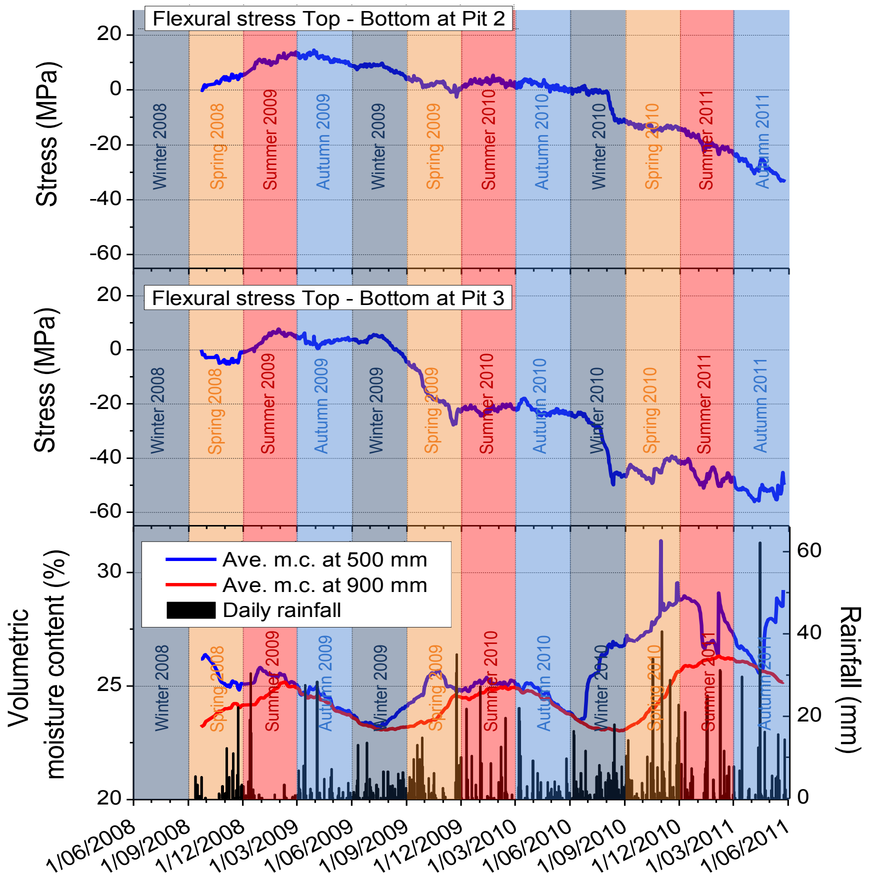


Figure 2. Changes in pipe flexural stresses at Pit 1 & 2 together with average moisture content changes at the depths of 500 mm & 900 mm

However, the increase in moisture content at greater soil depths appears to occur due to a significantly wet period after a long relatively dry period. The cyclic peaking in moisture content occurred approximately at an interval of four to five years according to this analysis. After a significant wet period, the moisture content depletes continually as relatively low wet (or high dry) conditions exist in the following years. The moisture content comes to a minimum prior to the significant wetting period begins. This pattern moisture variation may explain why soil shrinkage is the predominant ground movement that is considered to be responsible for pipeline failures in Victoria.

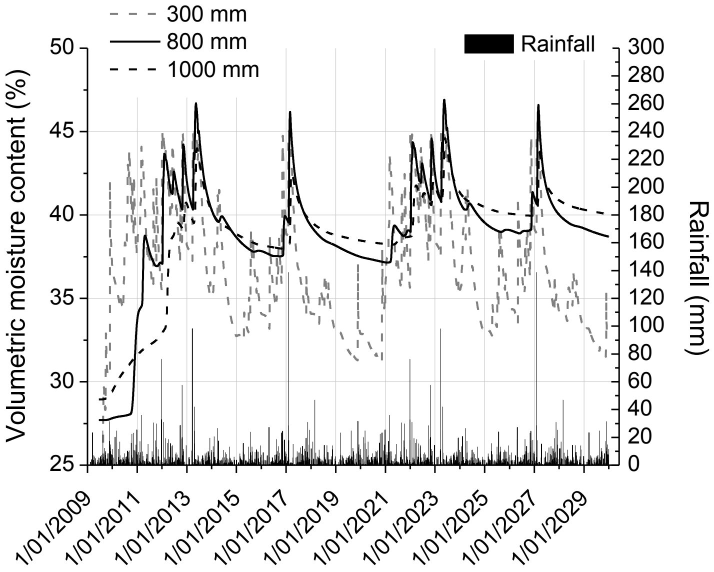


Figure 3. Long term soil moisture content prediction

4 CONCLUSION

This paper presents some aspects of the field behaviour of buried pipeline monitored more than two years at two location in Victoria, Australia. Also, the paper presents the results of numerical model simulation of long-term variation in soil moisture at different depths due to ground-climate interaction at one of the field sites. On the basis of the monitored behaviour of pipeline and long-term moisture variation prediction, it is evident that the variation in moisture content at the pipe depth in reactive soils can significantly control the behaviour of a buried small diameter pipeline. The soil swelling occurred in response to increase of soil moisture content which leads to upward ground movement and induced significant negative flexural stress change in the pipe, on the contrary the downward ground movement is related to drying of soil and induced considerable positive flexural stress change in the pipe due to the loss of support.

The long-term moisture prediction shows that variation in moisture content in relatively deep soil tends to show cyclic moisture fluctuation with moisture peaking in every 4 to 5 years. It is apparent that this peaking is normally associated with a significant wetting that occurs after a long period of drying. In Melbourne region Australia, the soil moisture has increased significantly in 2010 and in 2011according to the monitored data. Therefore, there is a possibility of peaking of pipe failures when the moisture level depletes again if continual dry conditions start to occur since the extensive shrinkage that occurs at the end of drying period is considered responsible for the majority of the damage to pipe in expansive soils.

5 ACKNOWLEDGEMENTS

The authors acknowledge the Australian Research Council, which supported this project via a Linkage Grant of the Australian Research Council (ARC). The authors would also like to thank the industry partners of the ARC project (LP 100200441), namely: City West Water Limited, Jemena, Envestra Limited, Water Corporation, Ipswich Water, South East Water Limited, and Queen's University (Canada) for their financial and (or) in-kind support to this project.

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