ABSTRACT
This paper presents the measurements of strain and the subsequent stress analysis on an in-service cast iron water main buried in reactive soil.

The results indicate that the pipe crown experienced predominantly tensile stresses during drying in summer and, subsequently, these stresses reduce eventually leading to compressive stresses as the soil swells with increase in moisture content with the approach of winter. It is also evident that flexural movement caused by thermal stresses and soil pressure has led to downward bending of the pipe in summer and subsequent upward movement in winter.

The limited data collected from pipe strains and strengths indicate that it is possible for pipe capacity to be exceeded by thermal and soil stresses leading to pipe failure. Provided the pipe has undergone significant corrosion.

INTRODUCTION
In many global population centres, including Australian towns and cities, dealing with frequent buried water pipe failures due to aging assets has become a major problem. Failures of these pipes can lead to the loss of water service to the local community and have negative social and economic impacts. Hence, it is important to improve our understanding of these failures and develop improved pipe asset management models that can predict failures in order to plan rehabilitation and failure mitigation strategies of the asset.

There is clear evidence locally and globally that pipe failure is significantly affected by seasonal moisture and temperature changes (Ibrahim 2005; Jarrett et al. 2001; Kassiff and Zeitlen 1962; Rajani et al. 1995). The existing models for pipe failure consider only some of the influencing physical variables, and the influence of soil and climate are not properly taken into account. Under Australian climatic conditions, it has been established that water pipe failure rates rise markedly during summer and to somewhat lesser extent during winter (Chan et al. 2002; Gould and Kodikara 2008; Ibrahim 2009). Furthermore, the pipe failure data indicates 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.

In spite of the importance of low soil moisture content and high temperatures on the performance of buried pipes, particularly in reactive soils, little work has so far been carried out to model the interaction and quantify this relationship. Quantitative understanding of this interaction would enable engineers to improve the design, construction, maintenance and management of buried pipes in reactive soils. Therefore, as part of an ARC Linkage Project, an in-service water main and surrounding soil were instrumented to monitor the performance of a buried water main in reactive soil subjected to seasonal climate variations.

This paper reports the details of the aforementioned field instrumentation and the results of the strain measurements on the water pipe and subsequent stress analysis for a period of 7 months starting from January 2008.

FIELD INSTRUMENTATION
In order to monitor the response of an in-service cast iron water main in expansive soil subjected to seasonal climate variations, the pipe and surrounding soil were instrumented.

As shown in Figure 1, twelve biaxial strain gauges, three sets of four biaxial strain gauges were installed on the pipe. Each biaxial gauge consists of two gauges: one gauge is oriented along the longitudinal axis of the pipe to measure the longitudinal strain and the other gauge is oriented perpendicular to the first gauge to measure the circumferential strain.

In addition to strain gauges, pressure and temperature transmitters to monitor pipe water pressure and temperature, two earth pressure cells to measure soil pressure underneath the pipe, rod-extensometer to
monitor to measure sub-soil displacement, soil water content sensors (15), soil suction probes (15), thermocouples (15) to measure soil temperature, and a weather station to measure rainfall, air temperature, relative humidity, and solar radiation at the site were installed. Figure 2 shows the locations of soil sensors.

**Soil at the site**

A uniform soil layer down to 2 m depth was observed at the site. The particle size distribution of the soil in the site obtained using sieves and a particle size analyser in accordance with Australian standards is shown in Figure 3. Soil samples collected from the site were further analysed for liquid limit, plastic limit, linear shrinkage, and swelling pressure. The swelling pressure was determined by the oedometer test conducted on a soil sample with initial dry density of 1.39 g/cm³ and with initial water content of 23%. The results of these classification tests are summarised in Table 1. According to the results of the mineralogy analysis conducted on a soil sample collected from the site, the significance presence of clay minerals, including smectite (31%) and kaolin (2%) impart a high reactivity to the soil.

![Particle size distribution of soil in the site](image)

**Figure 3: Particle size distribution of soil in the site**

<table>
<thead>
<tr>
<th>Colour</th>
<th>Light brown / beige</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit</td>
<td>70.2</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>21.8</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>48.4</td>
</tr>
<tr>
<td>Linear shrinkage</td>
<td>16%</td>
</tr>
<tr>
<td>Swelling pressure</td>
<td>660kPa</td>
</tr>
<tr>
<td>Soil group</td>
<td>Inorganic clays of high plasticity</td>
</tr>
</tbody>
</table>

**Table 1: Summary of soil classification**

Pipe condition and mechanical properties

According to records of the relevant water authority, the instrumented in-service cast iron water main has the internal diameter of 100 mm and was installed in 1961. Given the installation date it is likely that the pipe has an internal cement lining applied in the factory at the time of manufacture. During the pipe instrumentation, the wall thickness of 8.5 mm was measured by a non-destructive test using an ultrasonic gauge.

Figure 3 shows the variation of the tensile strength with the ratio maximum corrosion pit depth and the specimen thickness obtained from the tensile testing of collected cast iron water pipes used by Melbourne water authorities. The testing further revealed that the average Young’s modulus (Tangent Modulus) and Poisson’s ratio of aged cast iron are 150 GPa and 0.21, respectively (Gould et al. In Prep).

![Variation of tensile strength with corrosion](image)

**Figure 4: Variation of the tensile strength with corrosion**

**MEASURED FIELD DATA**

This section describes some of measured field data which can be affected for the development of pipe stresses.

**Pipe water pressure**

As shown in Figure 5, the pattern of daily pipe water pressure (PWP) change is cyclical, where a maximum pressure of 754 kPa and the minimum pressure of 650 kPa are indicative. A plot of the average water pressure on weekdays and weekends during the observation period is shown in Figure 6. The maximum daily pressure is seen at approximately 5:00am. A significant pressure drop can be observed from 6:00am to 9:00am on weekdays, possibly due to the morning activities of the users. A similar but slightly smaller pressure drop is also seen on weekends 1.5 hours later than on weekdays. The pressure then increases until 6:00pm before a second decrease from 6.00pm to 8.00pm. This decrease, however, is significantly lesser than that seen in the morning but appears to coincide with the evening activities of the users. Subsequently, the pressure...
again increases to a maximum at approximately 5:00am, and the cycle continues.

Figure 5: Pipe water pressure between the 7th of April and the 27th of April, 2008

Soil temperature

Figure 7 shows the soil temperature measured at four different levels down to the maximum depth of 1.75 m in the nature strip and the variation of air temperature measured by the weather station and pipe water temperature (PWT) by the temperature gauge connected to the pipe.

The data clearly show that when the soil is closer to ground surface (at 300 mm depth), it is more affected by the variation of air temperature, while the soil at greater depths (550 mm to 1750 mm) features a more reduced variation in temperature, but is still influenced by the air temperature fluctuations.

Figure 8: Sub-soil displacement measured by rod-extensometer

Soil movement

Soil movement was measured using the rod extensometer. Figure 8 shows the results of ground displacement at each anchor depth, along with the rainfall measured by the weather station.

As expected, the amount of soil displacement decreases with depth; anchor at 400 mm showing greater displacement than those below. These sensors showed stable behaviour during the dry conditions prior to the rain experienced in April. From this time soil swelling occurred. The influence of the rainfall events on the ground movement is also apparent.
Pipe strains

The detailed locations and labelling of the strain gauges are shown in Figure 9. The location of the joints as shown in Figure 9 is based on pipe joints being 6 m apart and the known location of a joint found under the driveway next to the first set of strain gauges during instrumentation.

Figures 10 and 11 depict the responses of longitudinal strain gauges with time, in Pit 1 and Pit 2 respectively. The sign convention used is that tensile strains are positive and compressive strains are negative, following the traditions of structural engineering. Also shown in these figures is the pipe water temperature, which in fact shows close correlation with measured strain responses. It should be noted that water temperature was measured from a tap made to the in-service pipe. In generally strain was positive during the initial dry period, during and following summer, and then reducing before becoming negative towards and during winter. Similar results can be seen in the plots of hoop strain (Figure 12) showing the significance of thermal effects on the pipe.

Figure 13 shows the variation of the longitudinal strains with time at the top of the pipe at three pit locations. The strain values at each pit were different even though each section of the pipe experienced the same pipe water temperatures. While thermal effects could also lead to longitudinal stress variation, this may also imply that the pipe has been subjected to additional stresses beyond those induced by thermal effects. Analysis of the strains implies that the pipe is bending (the pipe sections at Pits 2 and 3 are moving with respect to Pit 1).
It is important to note that three strain gauges noted as: longitudinal strain gauge at the bottom in Pit 1, hoop strain gauge at the pipe top in Pit 1, hoop strain gauge at the left spring line in Pit 3 were malfunctioning and were ignored in the analysis.

**Pipe stress analyses**

Longitudinal stresses in the pipe at strain gauge locations were calculated using the measured strain values, internal pipe water pressure, and external pressure on the pipe exerted by soil. Temperature and Poisson’s effects were taken into account for these calculations. Details of pipe stress analyses are available in Gallage et al. (In Prep).

It should be noted that the calculated stresses are in fact the change in stress between the stress that pipe was experiencing at the time of strain gauging and the stress at the time of measurement. The sign convention used in this analysis was that tensile stress is positive and compressive stress is negative. The calculated stresses reveal that these changes in stress could be positive (tensile) or negative (compressive) depending on the strain measuring location on the pipe and the climatic conditions at the site. According to pipe stress analyses, these tensile or compressive stress changes can be as high as 30 MPa.

It is important to note that these calculated stress changes ignore the residual stresses that the pipe was experiencing at the time of instrumentation. Since this instrumentation was undertaken in summer, the pipe would have been experiencing greater tensile stress than compressive stress with respect to the results obtained. When the calculated maximum tensile stress of 30 MPa is compared with the existing it is possible that the total tensile stress could reach the maximum tensile strength of the cast iron (see Figure 4).

The results of stress analyses suggest that the pipe could move downwards in summer, possibly due to soil shrinking, and then start to move upwards in winter possibly due to soil swelling, as shown Figure 14. Further the pipe under driveway has less rotation against bending (relatively fixed conditions at A and C) compared to that of joint B (relatively pinned condition), which is located at the middle of nature strip and could be subjected to maximum displacement. Because of the different fixity conditions of the pipe at A, C, and B, the pipe sections AB and BC could deflect like cantilevers.

It is important to note that joints could have different fixity conditions when pipe bending about different axes. It is proposed that testing of joint stiffness in different axes is undertaken on field samples to help this interpretation and future modelling.

**CONCLUSION**

It was found that surficial soil temperature was closely related to the air temperature and the rate of temperature change with the depth during summer and winter periods are about -2.5°C and +2.5°C per metre depth, respectively. The measurement of soil displacement using the rod extensometer showed upward movement of soil after a rainfall event. The pipe water pressure measurements indicated that water use has the effect of changing pipe water pressure, but overall these variations appear to be very consistent. These pressure variations may lead to a small variation in the pipe stresses. But they may be important for pipe failure, specially, when pipes are stressed close to failure due to other factors such as soil stresses and corrosion.

It may be inferred from this study that the pipe failure in the temperate climate is dominated by downward bending which is particularly clear in summer. However if prolonged wetting occurs it may be possible to get significant upward bending as well, which may lead to increased pipe failures during winter. In Melbourne, it appears that downward bending seems to be more critical in response to the characteristics of the local climate. These results show that the tensile stress developed in summer can exceed the maximum tensile strength of the cast iron pipe and failures could occur as a mode of capacity failure. As shown in Figure 4, the tensile strength of cast iron pipe may register as low as 25 MPa with the increase in the ratio between the maximum corrosion pit depth and the pipe thickness.

**ACKNOWLEDGMENT**

The authors would like to acknowledge Australian Research Council (ARC) for being the main financial contributor of this research project. This field instrumentation was conducted in co-operation with City West Water.

**REFERENCES**


Ibrahimii, F. 2005. Seasonal Variations in Water Main Breaks Due to Climate Variability and Ground movement. Ozwater 2005, Brisbane, Australia


Figure 1: Detailed plan of the field instrumentation site

Figure 2: Vertical section of instrumentation Pits

- Thermocouple
- Suction sensor
- Soil moisture sensor

All dimensions are in meters
Scale: Horizontal: 1:50
Vertical: 1:37.5

Past failure: Circumferential Fracture - 2001
Past failure: Circumferential Fracture

BH (0.075 m diameter bore hole)
for installation of radon exsorber

Electricity & Telephone overhead

Figure 1: Detailed plan of the field instrumentation site

Figure 2: Vertical section of instrumentation Pits
Figure 9: Location and labelling of strain gauges on the pipe

Figure 14: Predicted vertical pipe movement in winter and summer based on stress analysis