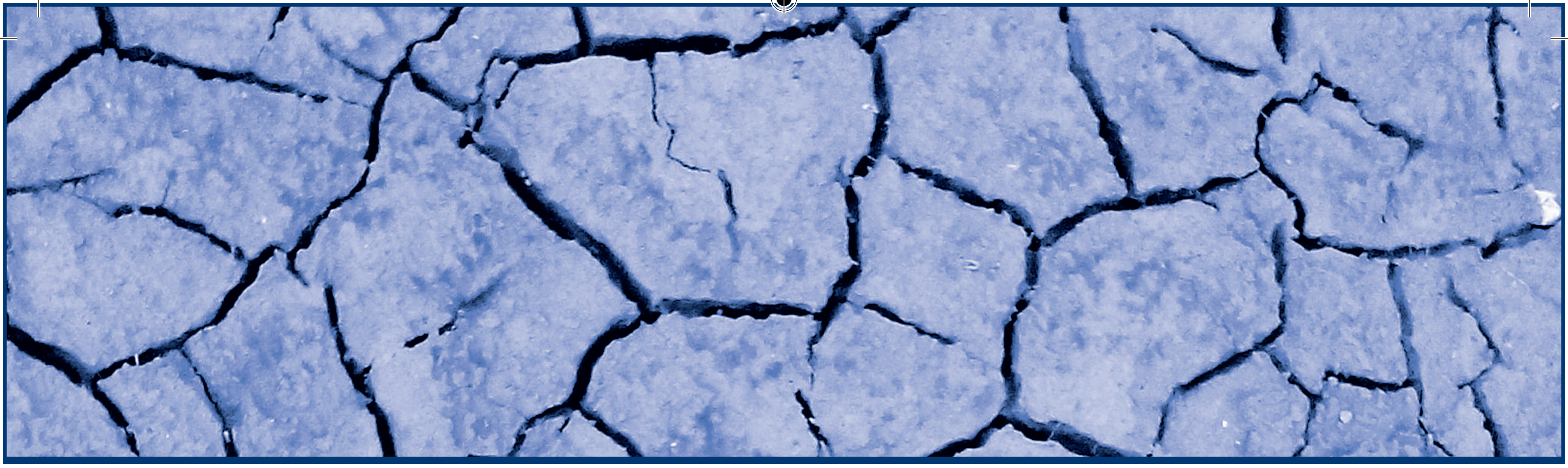
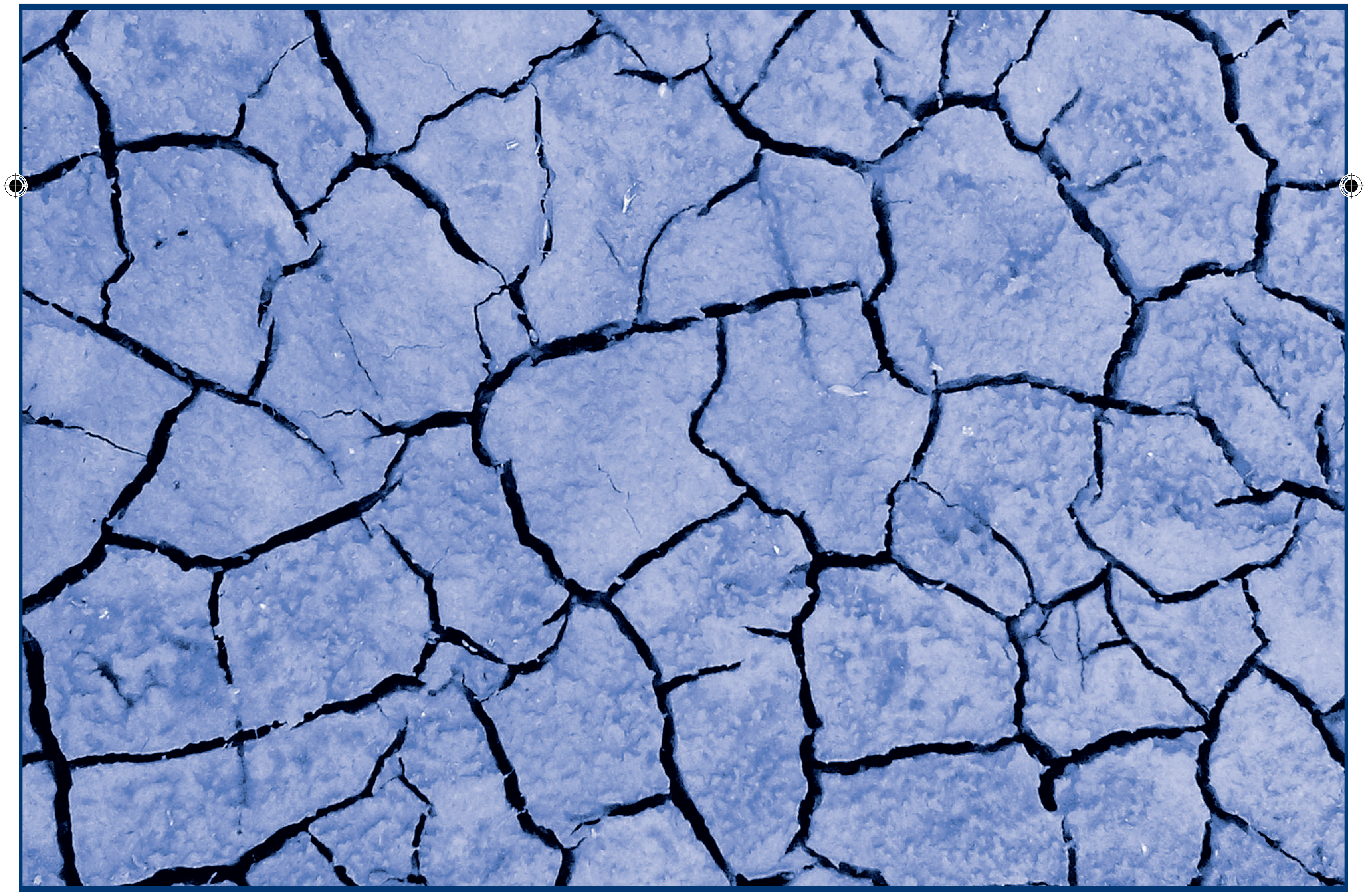


AGS VICTORIA 2017 SYMPOSIUM

Reactive clays and light structures

Wednesday, 25 October 2017, 8:15am – 7:00pm

Rydges Hotel, 186 Exhibition Street, Melbourne



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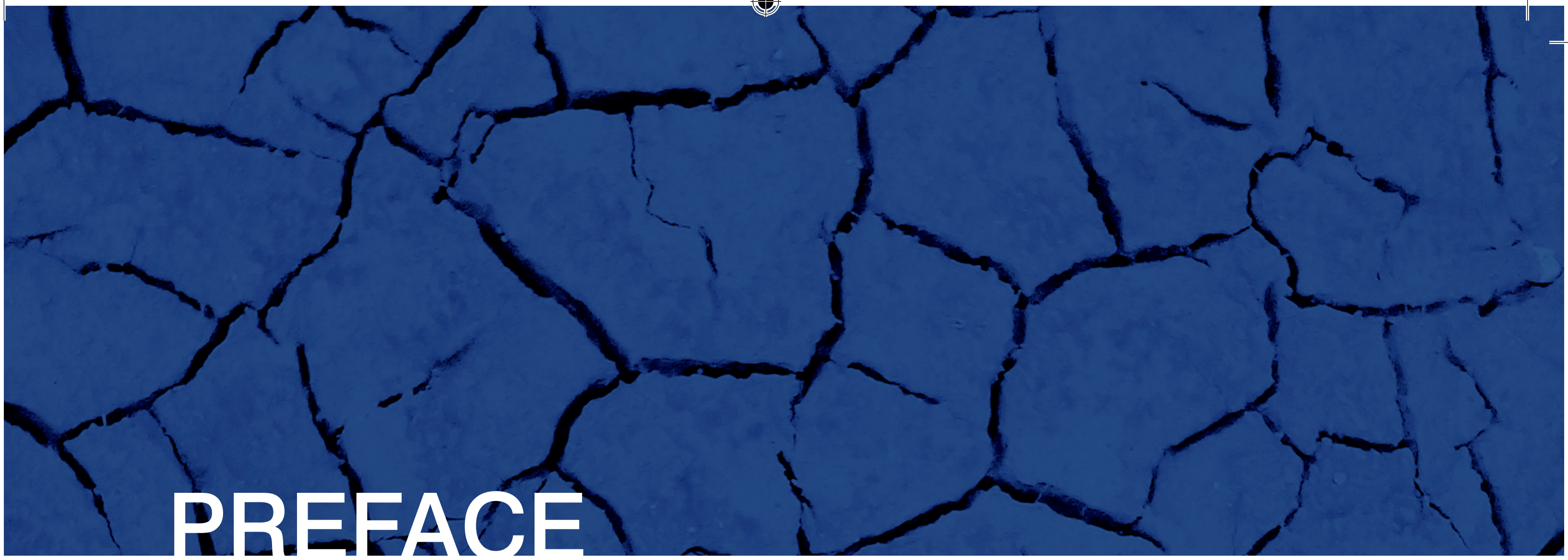

PREFACE

The Victorian chapter of the Australian Geomechanics Society invited academics and practitioners in the field of geotechnical and ground engineering to attend the 2017 Australian Geomechanics Society Victorian Symposium on 'Reactive clays and light structures' held on 25 October 2017.

The reactive soils of the Melbourne region form a large portion of its complex and variable geology. In particular, the basaltic volcanics situated to the north and west of Melbourne, which cover some 40% of the Melbourne region present numerous geotechnical challenges, particularly for lightly loaded structures. The geotechnical design and behaviour of lightly loaded structures on reactive soils is one aspect of geotechnical engineering where the public tend to have greater awareness, which is often not the case for the variety of soil and rock mechanics problems geotechnical engineers deal with. This is often borne out through their experience with their own residence, and rightly or wrongly, this contributes greatly to the public's perception of the geotechnical profession.

The 2017 Australian Geomechanics Society Victorian Symposium covered a variety of geotechnical challenges associated with reactive soils including residential slabs and footings, roads, pavements and other sensitive infrastructure that interact with reactive soils. The Symposium brought together practitioners from consulting, construction and academia to share and discuss their experiences on the topic of reactive soils and their related geotechnical applications.

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A study of reactive soil influence on small diameter pipe failures in Melbourne

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ABSTRACT

Melbourne's water reticulation system experiences about 4000 pipe breakages or bursts in each year, causing difficulties to both water utilities and water users. The majority of these failures are in old cast iron pipes that can be up to about 100 years old. For reticulation or small diameter cast iron pipes (diameter less than 300mm), the failures occur around the pipe circumference (known as broken back failures) mainly due to pipe bending. It is well established that the seasonal ground movement in reactive soil zones in Melbourne has a notable impact on pipe bending and resultant failures. The present study examines in detail the failure process of small diameter pipes that are affected by reactive soils. Finite element models of unsaturated soil-pipe interaction are used to simulate the response of the pipe to reactive ground movements that are governed by soil moisture variations. Locations where high pipe stresses due to ground movements are likely to occur are identified as stress "hotspots" to determine the potential for pipe failure. The concept of these stress hotspots is verified or corroborated by collecting field information from recent pipe failures in Western suburbs of Melbourne where highly/extremely reactive soils are commonly present. The results of this study are presented in the form of a simplified analytical method to estimate pipe stresses based on the soil moisture changes at the pipe level. With this development, mechanistic failure models are developed that could be implemented in a GIS platform for failure prediction and visualisation.

Keywords: Reactive soil, water reticulation pipes, finite element method, pipe bending, broken back failures

1 INTRODUCTION

The influence of reactive soil behaviour on reticulation pipe failures of Melbourne's water pipe network has gained broad attention among service providers and researchers over the past decade. As many pipes in the network are as old as 100 years, Melbourne's water utilities annually experience about 4000 pipe failures at present (Gould, 2011). These failures are generally caused by circumferential or longitudinal cracks on the pipe as a result of excessive stresses due to several reasons such as internal water pressure, ground movements, temperature changes and traffic loads (Kleiner and Rajani, 2001). The past failure data of Melbourne pipe assets have shown that the circumferential crack failures are the dominant mode of failures for small diameter reticulation pipes while the highest failure rates have been reported in reactive soil zones (Chan et al., 2007, Gould and Kodikara, 2008, Gould et al., 2011) (Figure 1). These circumferential failures are commonly known as broken-back failures and they are mainly caused by the stresses in longitudinal direction of the pipe. Further, a field observation of the movement of an in-service pipe in a reactive clay zone in Melbourne has shown that these longitudinal stresses mainly occur due to pipe bending as the surrounding soil moves upwards (swelling) and downwards (shrinking) seasonally (Chan et al., 2015). These observations have provided a conceptual understanding of the interaction between broken-back pipe failures and seasonal ground movements in the reactive soil zones.

However, the absence of an analytical methodology to determine these reactive ground movement induced pipe stresses has been identified as a major knowledge gap for mechanistic analyses of broken-back failures of the small diameter pipes. On the other hand, stress calculation for longitudinal split failure assessments has been advanced recently by the Monash researchers (Rajeev et al., 2014, Rathnayaka et al., 2016, Rathnayaka et al., 2017). Therefore, the present work was started with the main objective of filling this knowledge gap by proposing a detailed methodology to quantify pipe bending stresses due to reactive soil movements.

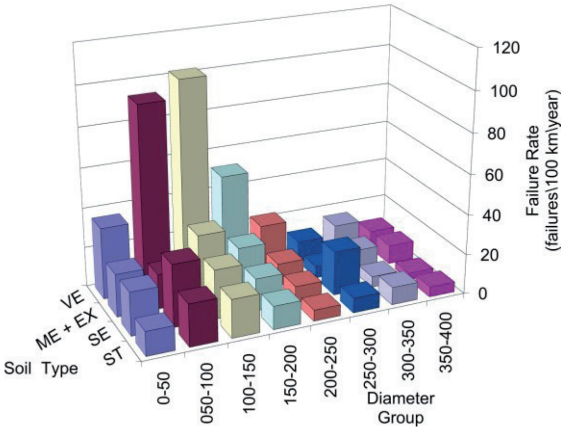

Figure 1. Comparison of pipe failure rates in different soils (VE: Very Expansive, ME: Moderately Expansive, SE: Slightly Expansive and ST: Stable) and different diameters (in mm) (Gould 2011)

Supplemented by the inferences made through previous field studies (Chan et al., 2015), the finite element method was selected to model the interaction of pipe and surrounding reactive soil. The ground moisture variation was used as the major input of the analyses. Available field pipe deformation data were used to verify the finite element analyses. Several field scenarios were analysed to study the effect of the man-made and natural features on soil-pipe interaction leading to pipe bending and resultant stresses. The results of these analyses were compared with the field observations of pipe failure case studies to validate these interaction mechanisms.

2 FINITE ELEMENT MODELLING AND RESULTS

This finite element model was developed by using a general purpose commercial finite element analysis software; Abaqus. The initial analysis was performed on a pipe section in Altona North that was monitored over a one and half year period (Chan et al., 2015). As the soil around the water reticulation pipes (within 1m depth) have been identified as unsaturated (above the water table) under seasonal wet-dry conditions (Chan et al., 2015), the behaviour of unsaturated expansive soil was modelled as a porous medium with moisture swelling properties (Dassault Systèmes, 2014). An elastic constitutive model was selected as the natural soils around pipes have been considered to be in an environmentally stabilised state after being subjected to a large number of wet/dry cycles, thereby responding in a volumetrically recoverable way (Gould et al., 2011, Kodikara, 2012). This modelling technique utilising the Bishop's effective stress concept (Bishop, 1959), was used effectively to model a three dimensional soil-pipe model and results were successfully compared with the previous numerical attempts to compute pipe behaviour (Weerasinghe et al., 2016).

Following the details of the Altona North test site, a 15m long, 1.5m wide and 2m deep soil block was modelled with a concrete driveway at one end (Figure 2). A 100mm diameter cast iron pipe was (wished-in) placed at a depth of 850mm as found in the test site. Moisture variations were applied to the model as observed under the driveway and nature strip during the study period of January 2008 to March 2009 (Chan et al., 2015).

The comparison of simulated and measured pipe strains (flexural) (Figure 3) shows that despite some disagreement, the modelling results reasonably follows the field measurements. However, discrepancies are unavoidable as the initial state of the field pipe is not completely known while it was assumed as an undeformed pipe in the simulation. It is to be noted that all the measured strains have been recorded referenced to the first measurement. Also the variations of soil properties and moisture contents along the pipeline have not been measured, hence possible soil inhomogeneities were not considered. Notwithstanding these limitations, this methodology was applied to further analyses of soil-pipe problems.

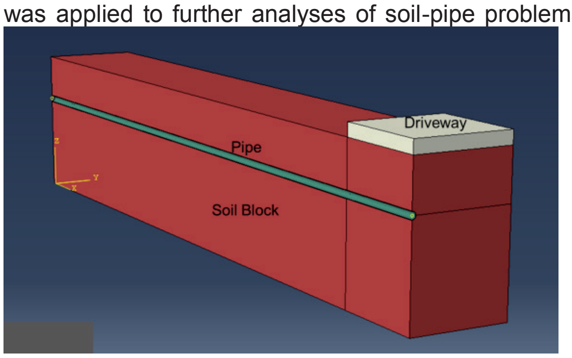

Figure 2. Finite element model of the Altona North test site

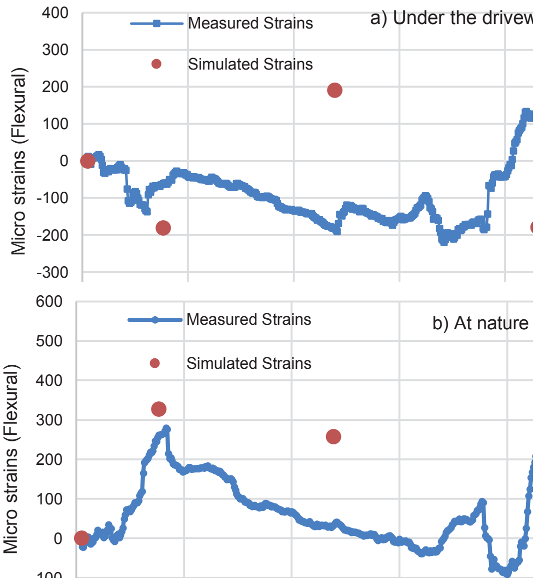

Figure 3. Comparison of simulated strains; a) Under the driveway. b) Under nature strip (measured data from Chan et al., 2015)

This finite element model was further used to analyse pipe response for various expected soil moisture variations. According to field measurements, the moisture content (volumetric moisture content) at the pipe depth (600 to 1000mm) generally varies by about 0.05 in both drying and wetting (Chan et al., 2015). In this analysis, a similar soil-pipe segment as in the previous analysis (Figure 2) was used and the moisture content changes were applied to the soil nature strip. The moisture contents at pipe depth were changed in three steps as 0.01, 0.03 and 0.05 while considering a linearly decreasing change along the depth (zero moisture change at 2m depth). The maximum tensile stresses (flexural) along the pipe wall were monitored. It was observed that these moisture variations cause stresses up to 30 MPa (Figure 4).

In addition, an interesting observation was made when the locations of the maximum stresses on the pipe were examined. It was noticed that the pipe flexural stresses are maximum near the driveway edge and the stresses are negligibly small in the middle of the nature strip zone (as in Figure 5). The reason was identified as the differential soil movements near driveways due to the different moisture variations under the impermeable driveway and the uncovered nature strip. Further, it was found that this differential movement causes pipe bending and resultant stresses.

This observation of negligible stresses at uniform conditions and maximum stresses at differential

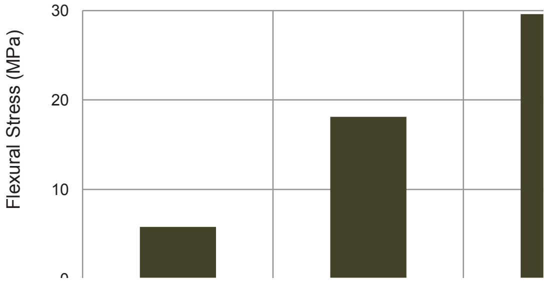

Figure 4. Maximum tensile stresses (flexural) for different moisture changes at the pipe depth

a) Soil drying

b) Soil wetting

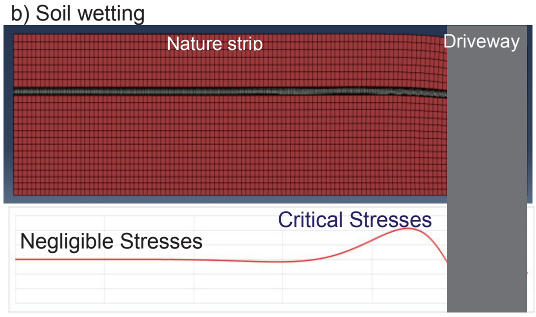

Figure 5. Stress variation along the pipe near driveways; a) for soil drying, b) for soil wetting

conditions guided this study to identify the possible high stress areas along a pipeline where the failures are likely to happen.

3 STUDY OF LIKELY LOCATIONS FOR BROKEN BACK FAILURES IN REACTIVE SOIL ENVIRONMENTS

As differential conditions near the pipe affect the behaviour of pipe more than do uniform conditions, such locations were identified as the likely locations for broken-back failures. In this study, five corresponding scenarios were examined for identification of their effect on pipe deformations as listed below:

- Driveways;
- Irregular bedrock peaking near the pipe;
- Tree roots;
- Water leaks; and
- Soil boundaries.

3.1 Driveways

The possible differential conditions under driveways can be considered as similar as the soil movements under a small slab. As the design guidelines (Australian Standards, 2011) state, the variation of moisture contents gradually decreases towards the centre of the covered area. Therefore the moisture dependent ground movements generate maximum swell/shrink movements near the edge of the slab/driveway and minimum movement at the centre.

During drying, the maximum bending occurs at the centre of the driveway (Figure 5a) as the downward movement of soil and pipe freely follows the moisture variations without any mechanical restraint from the driveway. The maximum tensile stresses are expected on top of the pipe. Therefore broken back failures that cracked from the top of the pipe are likely to occur under the middle of the driveway due to drying. This hypothesis was verified by closely examining several late summer (March-2017) broken-back failures in reactive soil zones in Melbourne (an example is provided in Figure 6).

Figure 6. An example of failure for drying under driveways; failure is at centre of driveway

During wet periods, the maximum bending of the pipe is more likely to occur near the edge of the driveway (Figure 5b). The possible reason for this was identified as the partial restraint of the upward soil movement from the driveway. Therefore bending tends to occur more at the edge of the driveway, creating higher tensile stresses at the bottom of the pipe. Similar to the previous case, this hypothesis was verified by observing several winter (May-June 2016) broken-back failures in the same region (refer example in Figure 7).

However, the loads coming from small vehicle traffic on driveways were not considered for this analysis as the effect of these loads at the pipe depth was assumed to be insignificant. This assumption was strongly supported by the observations of comparatively small effects from heavy vehicle traffic loads on buried pipes (Chan et al., 2016).

3.2 Rock peaking near the pipe

Bedrock underneath the pipe was observed to affect pipe failure in reactive soil because of the variation of the depth to basalt rock in the Western suburbs of Melbourne. A large set of borehole data was analysed to examine the shallow variation of this rock underneath the pipe. It was seen that the depth to rock is varying at significant gradients from 1m to more than 4m deep (Figure 8).

As the rock depth is varying along a pipe line, the reactive clay thickness is also varying along the pipe. This change causes differential movements as the thicker clay layers swell/ shrink more than the thin layers. Also, sharp rock peaks can act as rigid

Figure 7. Example of failure for wetting under driveways: failure is at driveway edge

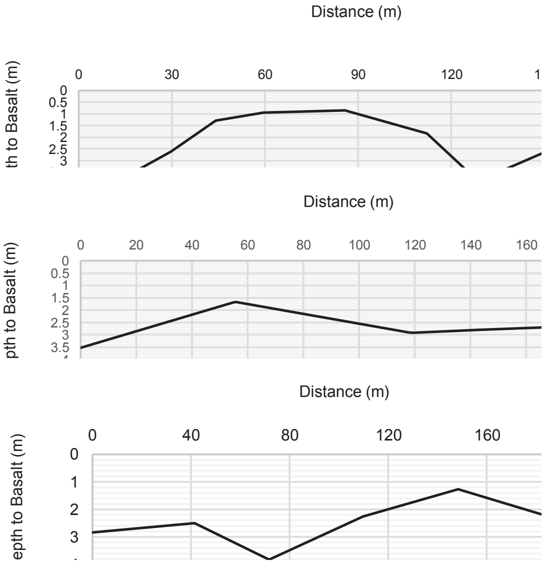

Figure 8. Example set of varying basalt rock profiles of Altona North: from borehole data analyses

supports for the downward moving pipe. These changes can create bending stresses. In addition, finite element simulations suggest that these depth changes are required to be sufficiently steep and close to the pipe to generate appreciable stresses on the pipe. However this hypothesis was not verified as it was unable to find field evidences of pipe failures near rock peaks.

3.3 Tree roots

Pipes can be significantly affected by tree roots when trees are planted in nature strips above and near the pipelines. While tree roots can itself push the pipe, strong tree roots adjacent to pipes restrain the free movement of the pipe when the pipe away from the tree moves with the ground swell and shrinkage. This restraint tends to bend the pipe around the tree root and create excessive stresses. In addition to this mechanical restraint, tree roots can also affect the moisture changes as tree roots absorb water from the soil. However the pipe failures due to movement restraints were commonly observed in field case studies (Example provided in Figure 9), especially in winters (May-2017 and June 2017).

Figure 9. Example failure near tree roots

3.4 Water leaks

Leakages arising from old repairs or through-wall corrosion holes of the pipe seem to affect the movement by locally wetting the leak area, causing localised swelling near the leak. Since the leak area swells more than the adjacent soil, the pipe tends to move up and gets higher stresses on its top. Such leaks form old repairs were frequently observed and few possible failures due to this phenomena were noticed during the field case studies (example in Figure 10).

In extreme cases, the pipe can be further affected by the additional ground movements caused by soil erosion due to continuous leaking.

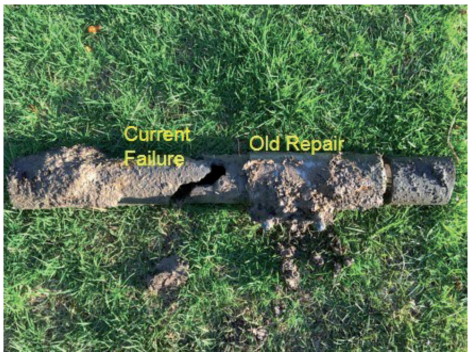

Figure 10. Example failure at a possible leak

3.5 Soil boundaries

Soil boundaries affect the pipe movement by creating differential movements when the reactive properties are changed. This is a common scenario when a pipe goes across a filled area. A deep, stable road base is another example or generally a covered area to an uncovered area. As reactive soils swell/shrink significantly when compared to the stable soils, pipe tends to bend with the differential movements creating high stresses. However, field evidence was not found for this hypothesis during the study period.

4 APPLICATION OF THE FINDINGS

As the final step of the study, the stress estimation methods and the identified likely failure locations were combined to analyse failure risks of the individual pipelines. Here, we present a set of analytical equations that were calibrated and verified with finite element simulations to determine pipe stresses in different scenarios. These analytical equations estimate the bending stresses by considering the possible bending curvature of the pipe similar to the stress estimations of pipes in settling ground (Wols and Thienen, 2014).

The effect of the cast iron corrosion was included in the failure risk analyses by introducing a strength reduction factor. These strength reduction factors for broken back failures are generally determined by considering the circumferential wall thinning of the pipe due to corrosion patch propagations (Antaki, 2003). Then the estimated pipe stresses (σ_p) and the reduced strengths ($S_{reduced}$) were used to calculate damage factors (DF) of the pipe.

$$DF_{broken\,back\,failures} = \frac{\sigma_p}{S_{reduced}} \qquad (1)$$

According to equation (1), the failure possibility increases when the calculated damage factor is greater than or equal to 1 (i.e. the pipe stress is higher than the strength of the corroded pipe).

This methodology is applied in Smart Water Fund project of Innovative Algorithms for cost-effective management of water pipe networks.

5 CONCLUSIONS

The current study presents a broad understanding about the influence of reactive soil movements on small diameter pipe failures. Finite element models were effectively used to study the interaction between soil swell/shrink and the resultant pipe bending stresses that affect the broken back failures. It was found that possible maximum pipe stresses due to field moisture variations are in the range of 20 to 30 MPa and they are sufficient to break a corroded pipe.

Failures are more likely to happen at locations where the differential ground/pipe movement occur due to external factors such as, driveways, bedrock peaks near pipe, soil boundaries, water leaks and tree roots. Observations of field case studies strongly supported the verification of some hypotheses of pipe failure mechanisms and their likely locations.

Development of an analytical equation to estimate pipe stresses for different pipe bending configurations provided the ability to use outcomes of this research in different platforms such as failure predictions.

ACKNOWLEDGEMENTS

Smart Water Fund – Innovative Algorithms for cost-effective management of water pipe networks.

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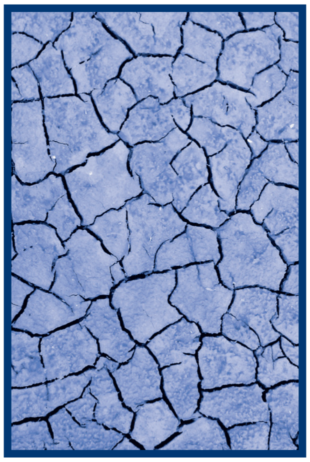

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