RELATIVE IMPORTANCE OF EXTERNAL FACTORS ON PIPE PERFORMANCE

Chan, D.[1], Shannon, B.[1], Kodikara, J.[1]
1. Monash University, Melbourne, VIC, Australia

ABSTRACT

The performance of a buried pipe is affected by various external factors related to the pipe properties, the buried environment, and internal and external loads. Each of the factors has a different degree of influence on the pipe. Traffic loading tests and pipe burst tests were performed, and the results suggest that internal pipe pressure has a greater influence on the performance of the pipe than external loadings from traffic and the ground. On the basis of the field measurements undertaken, the strains induced on the pipe may be about 7 times higher due to water pressure than those due to traffic loads.

INTRODUCTION

Failure of pipe occurs when the applied stresses exceed the strength of the pipe material. Water pipes are commonly subjected to significant stresses due to internal and external loads such as water pressure, traffic load and soil weight. As many pipe networks were constructed in the last century or earlier, the condition of the pipes has deteriorated, primarily caused by electro-chemical and micro-biological corrosion. In general, corrosion activity at the internal and external surfaces of the pipe will lead to reduced pipe wall thickness, which in turn leads to an increase in pipe stresses. The performance of a pipe can be predicted from a stress equation based on the external factors that can be divided into three categories, (1) static factors that are related to the pristine pipe properties and installation practice as applicable to a certain pipe cohort; these factors can be considered static over time; (2) dynamic factors from the surrounding soil and environment, such as soil moisture content, electrical resistivity and dynamic loadings such as traffic loads; and (3) factors related to the operational conditions, such as the internal water pressure. The pipe stress analysis models currently used by practitioners require input parameters such as the elastic modulus of the pipe material, pipe wall thickness and diameter, vertical load due to backfill and surface loads, internal pipe pressure, and soil deformation parameters. The accuracy of prediction is dependent on the accurate determination of the input parameters. Therefore, it is necessary to obtain reliable input parameters as far as possible. This paper describes the results of field tests and laboratory experiments that have been undertaken to study the influence of some external factors on the performance of buried pipes, and their relative importance for pipe stress development.

EXPERIMENT

Pipe testbed

A pipe testbed, known as the Sydney Water Pipe Test Bed, was established using a decommissioned large diameter pipeline in Strathfield, Sydney, NSW for condition assessment improvement and examining external/internal factors (e.g. traffic loading, soil pressure and water pressure) on pipe performance. The test pipe is a 660 mm external diameter pit-cast iron pipe with in-situ cement lining that was laid in 1922. The pipe section considered in the field tests was across the roadway in a residential area with moderate traffic. The pipe was buried at the depth of 960 mm below the surface of the road. The average pipe wall thickness was measured to be 30 mm and was relatively uniform around the pipe barrel. Borehole testing on site showed a consistent layer of inorganic, low-plasticity silty clay found below the road base, which suggests that the pipe was backfilled with the original natural clay soil. Figure 1 shows the layout of the testbed section. The pipe section buried under the road was installed with sensors on and around the pipe and the surrounding soils to record pipe strain, pipe joint movement and soil pressure. A dynamic data logging system was used to log data at a fast speed (i.e. 500 Hz) during traffic events.

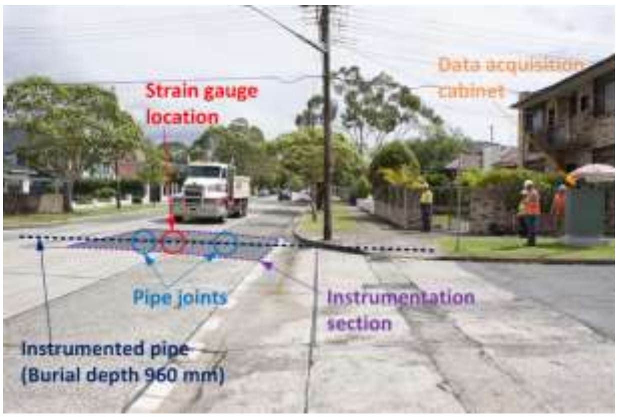


Figure 1: Layout of the pipe testbed

Traffic tests

The traffic tests were intended to examine the behaviour of the buried pipes due to passing traffic. Based on the data recorded under normal traffic conditions, the effect of light vehicles such as passenger cars on the pipe is minimal, and only heavy vehicles such as buses and trucks showed any influence on the recorded pipe strain and soil pressure. Even in road pavement design, the effect of light vehicles is ignored. Therefore, it was decided to use two test trucks of different axle configurations and loads for the traffic tests. The two test trucks were a 22.5 tonne three axle truck and a 38.5 tonne semi-trailer, referred to as Truck A and Truck B respectively in this paper. The weights of the trucks selected for the tests were chosen according to the "Project traffic axle load distribution" in the Austroads Standards (Austroads 2012). The load case with higher proportion in each axle group was used, with sufficiently high total axle load. The axle loads used for the test trucks are shown in Table 1. The test trucks were loaded with sand to the design load and measured on a weigh-bridge prior to the tests. Figure 2 shows the schematic diagram of the test trucks.

Table 1: Truck types and associated loads used in the tests

Truck	Axle type	Total axle load (kN)	Load per tyre (kN)	Tyre pressure (kPa)
A	Single axle single tyre (SAST)	56.7	28.4	1064.5
	Tandem axle dual tyres (TADT)	164.5	20.6	771.7
B	Single axle single tyre (SAST)	58.9	28.35	1063. 9
	Tandem axle dual tyres (TADT)	152.2	19.1	717.2
	Triaxle dual tyres (TRDT)	171.7	13.7	514.4

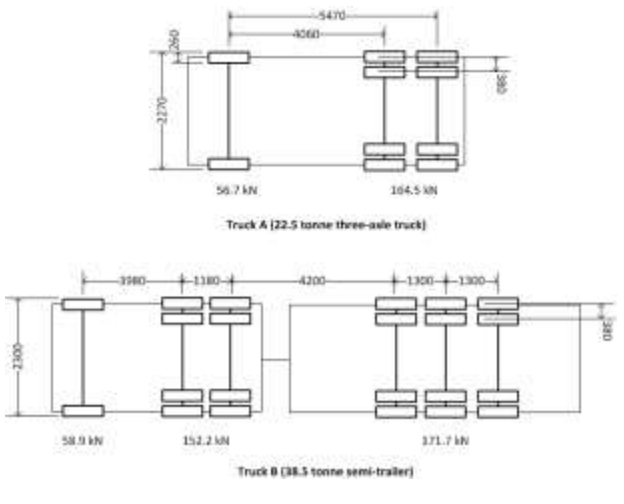


Figure 2: Schematic diagram of the test trucks with axle loads

A series of tests was performed using the test trucks to simulate a number of traffic scenarios, including passing, braking, cornering, traversing a pot-hole (simulated using a temporary speed hump), and stopped. Table 2 shows the summary of the traffic loading tests. The passing test was the simplest to perform by driving the test trucks past the testbed at the required speed. The braking test was performed by driving the test trucks at the required speed then applying the brake from approximately 2 m away and over the instrumented pipe, so that the impact of braking was recorded by the sensors. The cornering test was similar to the passing test, where the test truck was driven past the testbed at the maximum safe speed and the truck made a left turn into the side street. The speed hump test was designed to simulate the impact caused by a truck passing over a pot-hole. During the speed hump test the speed hump was placed approximately half a meter away from the sensor location, so that maximum impact was recorded when the truck's wheels landed on the road surface on top of the sensors. The stopping test was carried out by stopping each axle of the truck on top of the sensor location and recording the data.

Table 2: Summary of traffic loading tests

Type of test	Truck speed
Passing	15 km/h and 50 km/h
Braking	15 km/h and 50 km/h
Cornering	Max safe speed (i.e. 22-29 km/h)
Passing speed hump	20 km/h
Standing at each axle	-

Internal pipe pressure tests

Over the testing period, the instrumented pipe was pressurised and depressurised to study the response to change of internal pressure. The test pipe was connected to an in-service pipe in the network by a valve. During the test the valve was slowly opened to pressurise the test pipe from 0 to 688 kPa (i.e. live pressure of the in-service pipe) in 100 kPa increments. Each pressure step was maintained for five minutes to ensure change in pipe strain was recorded. Depressurisation was carried out by opening the outlet valve to empty the water inside the pipe. The internal pipe pressure was reduced from 540 to 137 kPa in 50 kPa decrement. The change in pipe hoop strain corresponding to the change in internal pressure was recorded.

Traffic test modelling

Three-dimensional (3-D) finite element analyses were carried out using ABAQUS 6.12 to simulate the traffic tests conducted on the compacted bitumen surface. The soil was represented by 8-noded brick reduced integration elements and the pipe was represented by 8-noded shell reduced integration elements. The soil was assumed to be over-consolidated and to behave elastically during the range of tested traffic loads. The soil side boundaries of the FE model were assumed to be smooth and located far (i.e. 5 m) from the pipe to eliminate any boundary effects. Figure 4 shows the mesh discretisation. 11,000 shell elements were used for the pipe and 238,000 solid elements were used to represent the soil.

The properties of the pipe and soil (including road base and asphalt) used in the analysis are shown in Table 3. The stiffness of the cast iron and subgrade material were obtained on the basis of tensile coupon tests and triaxial tests (consolidated undrained). Other properties were assumed to be as given in the relevant standards (such as Austroads). The dimensions and the axle configurations of the test trucks are shown in Figure 5, in parallel with the FE model idealisation for both trucks. The axle load types, the corresponding tyre loads, and patch pressures are shown in Table 1. The tyre loads were idealised in the FE model as patches of diameter 192.1 mm, as recommended in the Austroads pavement guide (Austroads 2012).

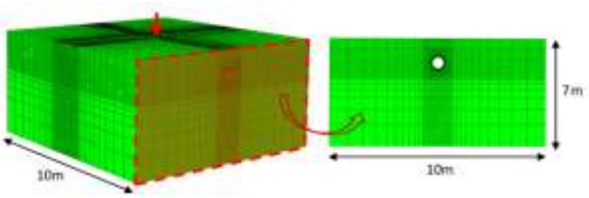
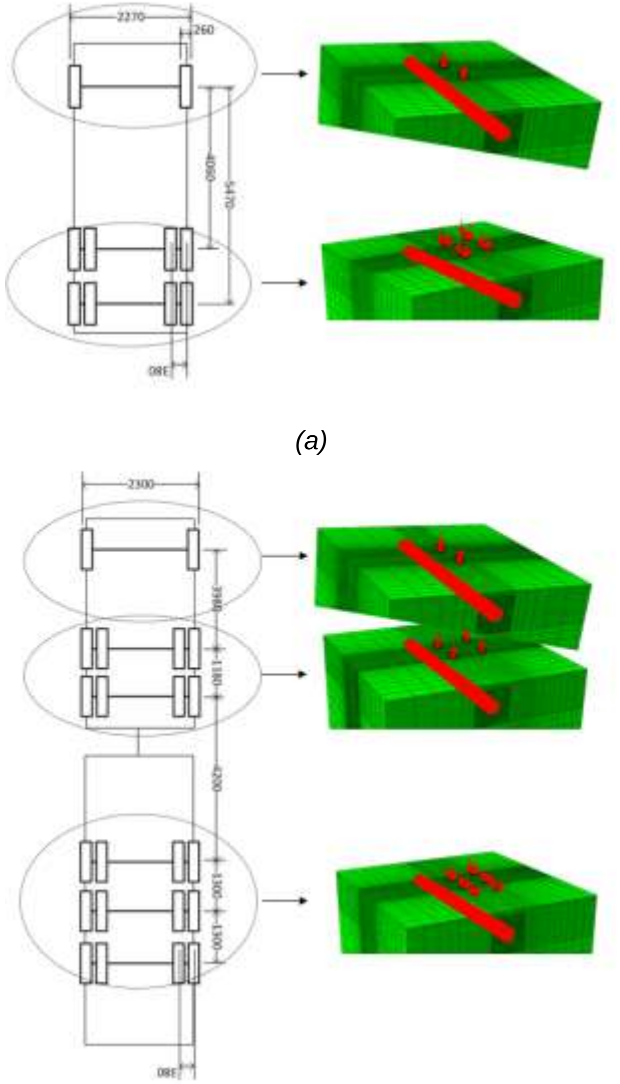


Figure 4: Dimensions and mesh discretisation of the finite element model

Table 3: Material properties used in the FE model

Description	Properties		
	Stiffness (MPa)	Poisson's ratio	Density (kg/m^3)
Pipe	76000	0.3	7850
Asphalt	175	0.3	2230
Road base	100	0.3	2000
Subgrade	8	0.3	1850



(a)

(b)

Figure 5: Dimensions of the trucks and axle configurations: (a) Truck A; (b) Truck B

RESULTS AND DISCUSSION

Pipe strain and ground pressure from traffic tests

In the traffic tests, strain gauges were installed on the outer surface of the test pipe at 30° and 15° intervals, as shown in Figure 6. As shown in the cross-section diagram in Figure 6, the test trucks travelled from right to left during the tests, and therefore more strain gauges were installed on the side of the pipe that was facing the traffic. The magnitudes of strains measured from different types of tests (i.e. passing, braking, cornering tests etc.) were very similar and were in the order of 8 to 15 microstrain for the front axle (SAST) load of 56.7 kN and 14 to 22 microstrain for the tandem axel (TADT) load of 164.5 kN. A comparison of changes in strain of different tests measured by the hoop strain gauges around the pipe (i.e. from -120° to 120°) is shown in Figure 7. The hoop strains were measured when the front axle (SAST) of Truck A was immediately on top of the sensors. The maximum strain measured on the pipe was 15 microstrain at the pipe crown. It can be observed that the magnitude and shape of the curves are very similar; the pipe crown was under compression and the pipe springlines were under tension, as would be expected from a mechanics point of view. For instance, the test pipe behaved like a ring being loaded from the top, and slightly deformed into an oval shape with the spring-lines being extended. The strain results plotted in Figure 7 also suggest that different types of traffic tests produced very similar results on the buried pipe. Hence, the influence of the type of traffic tests on the pipe is small.

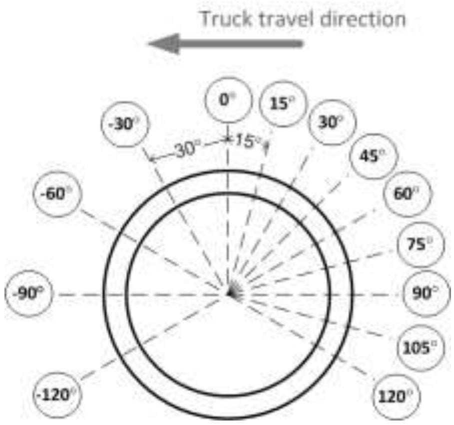


Figure 6: Strain gauge locations on instrumented pipe section

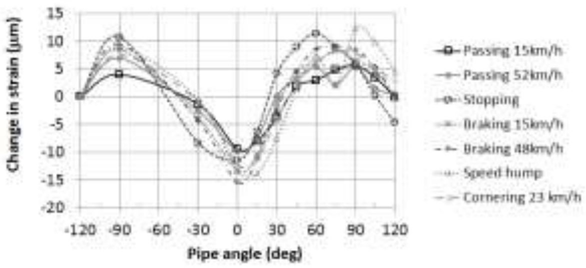


Figure 7: Pipe hoop strain measured from different types of tests by the front axle (SAST) of Truck A

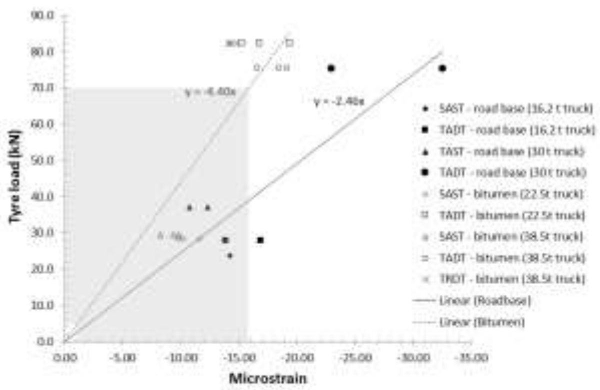
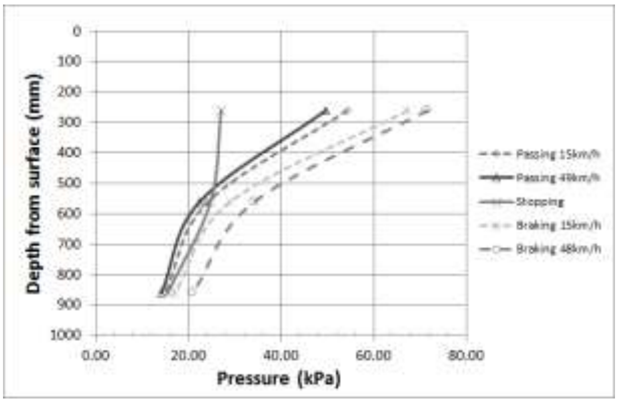


Figure 8: Relationship between hoop strain on pipe crown and tyre load

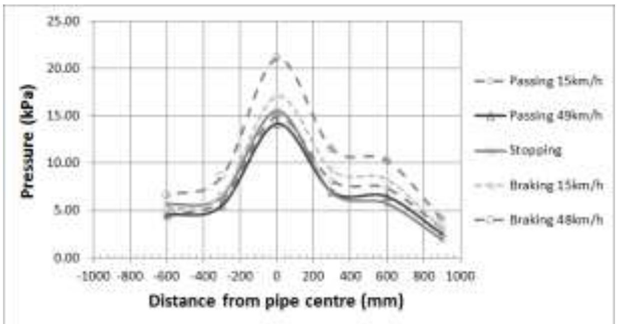
Figure 8 shows the plot of pipe strain measured on the pipe crown during the truck passing test (i.e. passing at 50 km/h) with the tyre loads resulting from various axle groups. The results of traffic loading tests on the road base that were undertaken after the field instrumentation (refer to Chan et al. 2015) are also included in the plot. The resultant hoop strains from the road base tests are approximately twice those of the bitumen tests for the same load type (i.e. they ranged from 11 to 34 microstrain). However the magnitudes of strain are still too small to have a significant influence on the pipe, considering the hoop strain of a burst pipe from the pipe burst test is typically over 4000 microstrain (the results are discussed in the next section). A likely linear pipe strain and tyre load relationship can be obtained from Figure 8. The pipe strain and tyre load relationship may be used to back-calculate the tyre loads of passing vehicles from traffic events measured on site. According to Austroad standards (2012), the projected traffic axle load distribution for SAST ranges from 10 to 140 kN, equivalent to a per tyre load of 5 to 70 kN. The grey-shaded area in Figure 8 shows this load region, and the expected hoop strain on the pipe is 1 to 16 microstrain for loading from SAST.

Ground pressure cells were installed at the testbed below the road pavement at various depths down to the burial depth of the test pipe. Figure 9 shows the locations of pressure cells installed around the pipe. The pipe strain results from different traffic tests showed that the type of test had a small influence on the results. Therefore, only the ground pressure results of the front axle (SAST) of Truck A passing, stopping, and braking are shown here. The distribution of applied axle load to the buried pipe resulting from different traffic tests are plotted in Figure 10 (a) and (b) for the pressure measured from the depth of 260 to 860 mm and the ground pressure measured across the pipe section, respectively. The pressure was plotted when the truck axle landed immediately on top of the sensors (i.e. when the pressure recorded by the pressure cell at 260 mm depth was at its peak).

Figure 10 (a) shows the ground pressure dissipates from the road surface to the pipe depth as the pressure is taken by the soil on top of the pipe. The measured ground pressure reduced up to 50 kPa for some tests over the depth of 600 mm. Higher pressures were measured from the braking tests than the passing tests close to the road surface. The lowest pressure was measured for the stopping tests at 22 kPa, which is lower than the value measured by the other tests by 50% or more. The ground pressures measured close to the pipe (100 mm above the pipe crown) were very similar, regardless of the type of tests and are in the range of 14 to 21 kPa. Figure 10 (b) shows the ground pressures measured across the pipe section during traffic tests (trucks travelling from right to left, as shown in Figure 9). Slightly higher pressures were recorded for the braking tests above the pipe than for other tests. Variations in ground pressure on top of the pipe from the tests were about 7 kPa from the various tests (ranging from 14 to 21 kPa). These test results show that the ground pressure at the pipe depth is small and of an order that can be computed from the soil depth using the soil density. (for example, if the density is 15 to 20 kN/m^3 , then for 1m depth, vertical stress is 15 to 20 kPa).



(a)



(b)

Figure 10: Ground pressures measured from different type of tests by the front axle (SAST) of Truck A: (a) at different depths below the road surface; (b) at 100 mm above the pipe crown

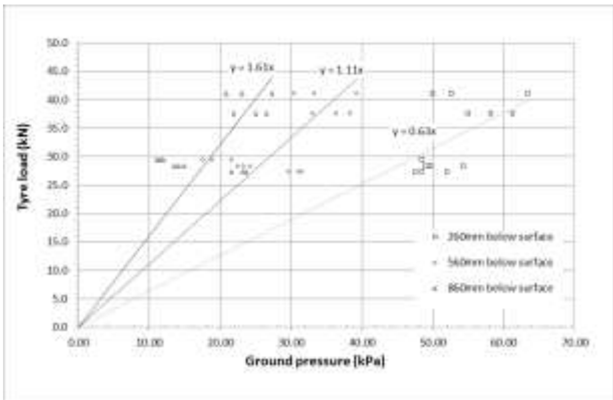


Figure 11: Relationship between ground pressure and tyre load at different depths

Figure 11 shows the plot of ground pressures measured at various depth above the pipe against the tyre load resulting from different tyre loads. The likely linear ground pressure and tyre load relationships at each depth are drawn on Figure 11. It can be used to determine the ground pressures due to traffic events when the weight of the passing vehicle is known.

Internal pressure tests results

The results of the internal pressure tests are plotted in Figure 12 with the measured internal pressure against the hoop strain at pipe crown and two spring-lines. The loading and unloading path can be observed in the figure. The approximately linear relationship between internal pressure and measured pipe hoop strain shows that the change in strain is within the elastic region. The maximum pipe strain is 126 microstrain at 688 kPa measured on the pipe crown; this is well below the typical failure strain of cast iron, which is typically over 2000 microstrain. However when compared with the pipe strain from traffic tests (i.e. 14 to 22 microstrain), the pipe strain resulting from internal pressure is about 7 times higher. In the internal pressure tests, strains measured at pipe crown are slightly higher relative to the spring-lines, indicating greater lateral support of the soil on both sides of the pipe.

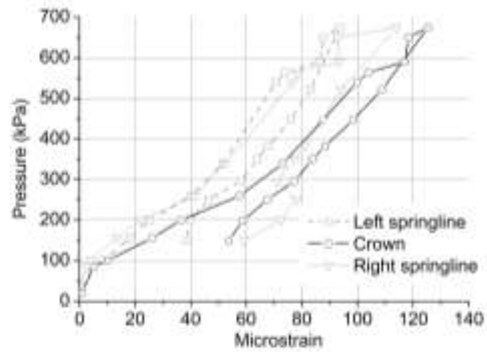
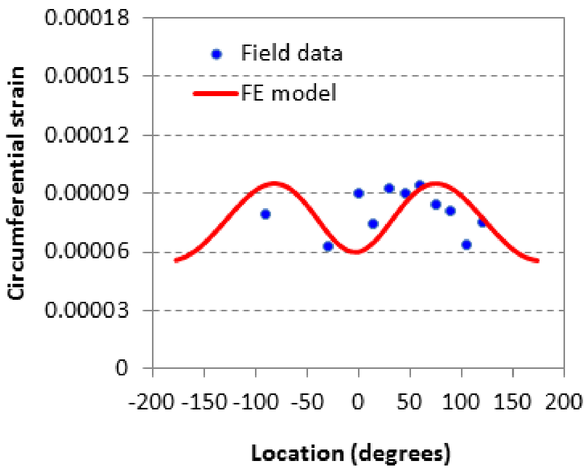


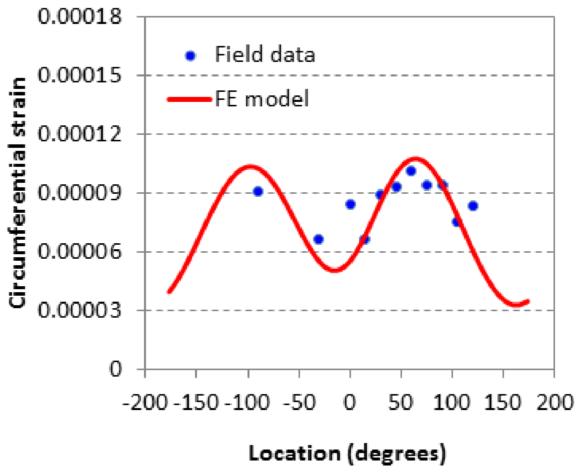
Figure 12: Change in pipe hoop strain corresponding to internal pressure

Traffic tests simulation results

The results of the FE analysis are presented in terms of pipe circumferential strains with the truck test results and an internal water pressure of approximately 660 kPa. The traffic results from the truck stopping tests are useful to compare with the FE analyses results, as the model was based on static loading. Figures 13 (a) and (b) show the plot of FE model results and the truck test results for Truck A with SAST (front axle) and TADT (rear axle). Good agreement can be seen in both figures, showing that the FE model is capable of simulating the truck test results. Similar FE models can be set up for other tests or traffic events to predict the response of buried pipe.



(a)



(b)

Figure 13: Circumferential strain from FE model and stopping test with Truck A: (a) SAST; (b) TADT

CONCLUSION

This paper describes the importance of external factors on the performance of pipe based on test results from traffic loading and a large-diameter pipe bursting experiment. The traffic test results show that the pipe hoop strains resulting from different types of traffic tests (i.e. stopping, passing, braking etc.) have small differences. The maximum strain measured was 15 microstrain on the pipe crown as a result of truck braking. The measured strain suggests that the influence of traffic loading on the pipe strain is small. Ground pressure measured from the traffic tests dissipates from the surface to the pipe depth due to support from the bitumen road surface and clay soils. The magnitude of pressure imposed on the buried pipe is in the range of 14 to 21 kPa as measured at 100 mm above the pipe crown. The effect of different types of traffic tests on ground pressure at the depth of the pipe was found to be insignificant. The traffic test results showed that loading arising from heavy traffic passing over the buried pipe has only a minor effect on the pipe strain and ground pressure close to the pipe. The FE model was capable of predicting the traffic tests results for the 'stopping' scenario. It can therefore be used for the prediction of other testing scenarios and traffic events.

Internal pressure testing was performed to load and unload the buried pipe with internal water pressure. It was found that water pressure dominates the pipe strain in comparison to traffic loading, as the strain generated by water pressure is in the order of 7 times that due to traffic loading. Based on the field test results, changes in pipe hoop strain and ground pressure resulting from traffic loading have a small influence on the pipe. In this regard, traffic loading and ground pressure are not factors with the greatest influence for pipe failure prediction. On the other hand, the internal pressure test results suggest that internal pipe pressure has a greater influence on pipe strain than traffic and ground loadings. The importance of other factors needs to be checked further, prior to being used in pipe stress models for failure prediction.

ACKNOWLEDGMENTS

This publication is an outcome of the Advanced Condition Assessment and Pipe Failure Prediction Project funded by Sydney Water Corporation, Water Research Foundation of the USA, Melbourne Water, Water Corporation (WA), UK Water Industry Research Ltd, South Australia Water Corporation, South East Water, Hunter Water Corporation, City West Water, Monash University, University of Technology, Sydney and University of Newcastle. The research partners are Monash University (lead), University of Technology Sydney and University of Newcastle.

REFERENCES

Austroads (2012). "Guide to Pavement Technology Part 2: Pavement Structural Design", Sydney, NSW, Australia.

Chan, D., Kodikara, J. K., Rajeev, P., Robert, D. J., and Rajalingam, J. (2015 under review). "Field study of large diameter cast iron water pipe buried under a roadway." Journal of Structural Control and Health Monitoring.

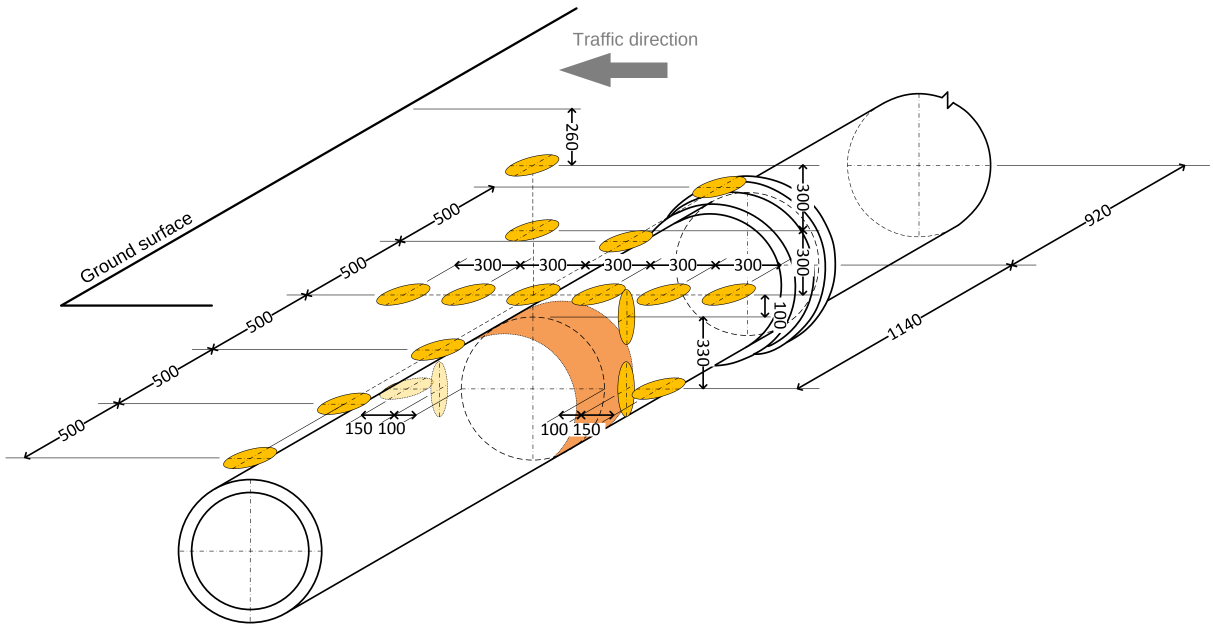


Figure 9: Locations of pressure cells around the test pipe