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Parametric Investigation on the Response of High-Density Polyethylene Pipes to Eccentric Loading

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ABSTRACT

The durability of water distribution net- works partly relies on the ability of utility pipes to resist surface loading. In this paper, a parametric study is undertaken to investigate the response of high-density polyethylene (HDPE) pipes to eccentric loading. The results taken from a centrifuge model are used to evaluate the ability of a computational model to predict the bending moment distribution along the pipe. Following this validation process, the behaviour of HDPE pipes at a range of burial depths, and loading eccentricities is investigated further using the computational model. The results of this analysis are used to evaluate the High-way Agency guidelines for HDPE pipe burial depths, and they are found to be satisfactory, as they prevent exposure to the significantly higher bending moments experienced at shallow depths.

Keywords: *Load, Pipe/Soil interaction*

1. Introduction

The performance of HDPE utility pipes, in both the short and long term, is an area of study that requires further research and understanding. Damaged pipes result in large volumes of water leaking daily, which wastes resources and raises public health concerns. One of the main sources of dam- age to buried utility pipes is the live loads imposed on them by vehicles. The response of flexible pipes to surface loading has been investigated previously. Arokiasamy conducted a series of full-scale field tests on six pipes, three of which were made of high- density polyethylene (Arokiasamy et al., 2006). Each pipe was 6.1m long, two with a diameter of 600mm, and one of 1200mm. The highest diametric strain in the entire testing regime was 0.5%, and was recorded for the 600mm diameter HDPE pipe, at a burial depth of 0.5m. The researchers also developed a finite-element (FE) numerical model, as well as the Iowa and Meyerhof formulas, to predict deformation and settlement of the pipe. They found that each method over-predicted pipe deflection, al- though the FE model produced the most accurate results. This study will also utilize analytical methods allowing a brief discussion of their effectiveness in comparison to those used by Arokiasamy. Arokiasamy was able to estimate that the maximum strain experienced by the pipe at shallow burial depths is 2%, by using the work of Faragher. Faragher conducted a field test where he applied 1000 cycles of live vehicle loading to buried plastic pipes (Faragher et al., 2000). The tests were conducted in sand and gravel, with pipes with two HDPE pipes of 200mm and one of 1066mm. The researchers were able to establish a power law relationship between the pipe's initial response to cyclic loading, and its deformation after 1000 cycles. The equations predict that the final vertical diametric strain of a pipe is roughly three times that of its initial response. The work of Faragher also provides a reasonably conservative estimation, due to the shallow depths, high surface stresses and lack of pavement cover used in his experiment. However, testing was only conducted at burial depths of 1m, limiting its wider application to this study. The work of Tafreshi and Khalaj, 2011, has also provided insight into the long-term effects of cyclic loading. Accurate computational models are essential for predicting the behaviour of buried pipes under various loading scenarios. Elmrom et al. (2022) re- search underscores the necessity of integrating empirical data from centrifuge tests into computational models to enhance their predictive accuracy. This approach facilitates a more reliable assessment of pipe performance, particularly in complex conditions involving voids and eccentric loads. Guide- lines for the design of HDPE pipes are de- tailed in the British Standards, Institution, 2010. The standards define flexible pipes as being less stiff than the surrounding soil and so under loading they respond by de- forming into an oval shape, as well as being displaced vertically. The design guidelines also include equations to calculate the critical buckling pressure of an HDPE pipe in both the short and long term. The high- way agency has guidelines on the minimum permissible depth of HDPE pipes. A mini- mum cover of 0.9m is specified under main road loading, and cover of 0.6m and 0.7m is required for field loading and filter drains respectively. Despite discussing a number of common loading orientations, the standards do not specify design considerations for pipes that are primarily eccentrically loaded. This study will investigate whether the existing guidelines are suitable for eccentrically loaded pipes. Experimental results taken from a centrifuge model will be used to validate a computational model. This will allow predictions to be made about how HDPE pipes will respond to eccentric loading at a range of depths and eccentricities.

2. Centrifuge Test

Centrifuge modelling has been used to investigate the behaviour of eccentrically loaded HDPE pipes due to its unique ability to replicate the stresses experienced by the soil at prototype scale. This is achieved by rotating the model at a calculated velocity to generate the required increase in gravity to simulate the full-scale soil pressures. Centrifuge modelling also allows for a far more extensive testing regime and greater controls over important parameters.

2.1 Prototype Cases

Figures The purpose of this investigation is to gain further understanding of the response of HDPE pipes to eccentric loading. Two centrifuge tests were conducted, one for an HDPE pipe with a load applied at zero eccentricity and another where the load was applied at an eccentricity of 2D. Both pipes had a diameter of 355mm and were six meters long. The soil conditions and depth of embedment are kept the same in each test. The loading case that is simulated in the centrifuge test is that of a half axle of an articulated lorry. The maximum permissible load in the UK for a lorry is 44 tons, and so that results in a 6-ton load per axle. In both tests the load is applied in line with the lorry, to represent the scenario of a vehicle driving alongside the buried pipe. The force of the half axle is applied to the soil over the contact area of the wheel, which is 0.25m x 0.50m at prototype scale. The depth of embedment in both cases is 1m.

2.2 Scaling of the Centrifuge Model

The test was conducted at a scale of 25 (N=25). There are several key parameters in the model that needed to be scaled to match the conditions in the prototype. Table (1) lists the factors used to scale each parameter.

Table 1. Scaling Laws (N=25).

	Scale Factor
Length	1/N
Volume	$1/N^3$
Mass	$1/N^3$
Force	$1/N^2$
Density	1
Gravity	N
Stress	1
Young's Modulus	1
Moment	$1/N^3$
Second Moment of Area	$1/N^4$

The radius of the centrifuge, the distance from the payload to the centre of rotation is 4m, and so the model was required to spin at 74.5rpm to generate the required 25g acceleration.

2.3 Data Acquisition

A series of sensors were used to monitor the settlement and moments acting on the pipes. Strain gauge sensors were placed at eight positions along the pipe and used to record the distribution of both major axis and minor axis bending moments. The ap- plication of loading through a vehicle wheel was simulated using a footing of the correct scaled size, which was attached to a loading cell. Surface settlement throughout testing was recorded using a linear variable differential transformer (LVDT). Readings from each device were taken every 1.1 seconds, providing comprehensive information about the loading response. Each sensor was calibrated to find a linear scale factor to convert their voltage readings to engineering units suitable for analysis.

2.4 Soil Properties

Both tests were conducted in uniform sand, with a coefficient of uniformity of 1.35, and a D50 of 450 microns. The coefficient of uniformity was very low, which makes these testing conditions less reflective of the likely field conditions. An oedometer test was con- ducted on a sample of the sand, from which the Young Modulus of the material was calculated to be 40 MPa. An important factor in calculating this was the average relative density of the soil in the lab test, which was 94.7%. This was achieved in the lab by pouring the sand into the testing container at a constant rate, and from a fixed height, al- lowing the researchers to closely control the density of the resulting sand layers. A shear box test was also completed, and from this, a peak and critical angle of 40.7° and 31° respectively, were determined.

2.5 Testing Regime

There were two phases of testing applied to each pipe, following the spin-up of the centrifuge. The first phase was a monotonic loading case where a scaled force of 9.6N was applied to the model surface over a period of roughly 100 seconds. This was followed by a series of cyclic loading, where the load was applied 20 times at regular intervals of roughly 20 seconds.

3. Computational Modelling Methodology

A computational model has been developed to aid a parametric study of the impact of burial depth on the pipes' response to eccentric loading. The 3D modeling software package Pdisp has been used in this study. This software is capable of applying both the Boussinesq and Mindlin methods to predict displacements within the plastic range of soils (Eaton, 2013). In this Analysis the Boussinesq method has been used to predict vertical displacements, while the Mindlin method has been used for horizontal displacements. According to the Pdisp manual, the accuracy of the Boussinesq solution is a function of the distance between the points at which stress is calculated (Oasys, 2014). A high density of displacement levels was specified in the model to limit errors due to this effect. The Mindlin method has some limitations, and it is stated in the manual that under vertical surface loading ac- curate results are only achieved when "elastic stiffness does not increase significantly with depth" (Oasys, 2014). The E value of the soil in this experiment is constant with depth, and so that provides some confidence in the suitability of this modelling approach. The method used within the Mindlin model to calculate the stiffness for horizontal displacements was the 'stiffness at displacement point' approach. As the name suggests, this method relies on the stiffness at each displacement point, rather than using the soil properties between the point of ap- plication of the load and the relevant position. The maximum variation between the Young's Modulus at adjacent displacement levels was set at 2. The Pdisp modelling environment does not allow circular structures to be modelled directly, and so pipe was represented as a rectangular layer of stiff soil with a second moment of area equivalent to that of the circular pipe. The input parameters for the Pdisp model can be seen in Table (2). The 355mm diameter pipe was modelled as a 289.8x289.8 layer of soil with the Young's modulus of HDPE.

Table 1. Bold font size 11 and 0.4 before the text.

parameters	Scale Factor
HDPE Young's Modulus (MPa)	1e6
Soil Young's Modulus (MPa)	20000
Soil Poisson's Ratio	0.3
Pipe Poisson's Ratio	0.46
Square Pipe Dimensions (mm)	289.8 × 289.8
Loading Area (m2)	0.125
Load per axel (prototype)	6Ton

3.1 Young's Modulus sensitivity

The Pdisp model relies heavily on correctly inputting the Young's modulus of the soil to obtain an accurate solution. Therefore, a sensitivity test was conducted for the zero-eccentricity loading case, adjusting the Young's modulus input to determine how this alters the predicted major axis maxi- mum bending moment. A Young's modulus of 20MPa to 80MPa was trailed, and the graph in Figure 1 contains the results of this analysis. From the results of the sensitivity analysis, it is clear that Pdisp is much more sensitive to a decrease in the Young's Modulus below the calculated value of 40MPa, than an increase in it. A de- crease in the Young's modulus by 50%, to 20MPa, increased the maximum bending moment by 90.4%. However, increasing the Young's modulus by 50%, to 60MPa, only produced a decrease in bending moment of 33%. Therefore, an incorrect estimation of a low value could have a significant impact on the error in the results of the model. As mentioned earlier, Pdisp relies heavily on an accurate Young's modulus, which is a limitation of the model, as it can be a challenging parameter to accurately measure. The im- plications of this will become clear in the following Pdisp model validation process, where adjustments to the Young's modulus were required to match the experimental results.

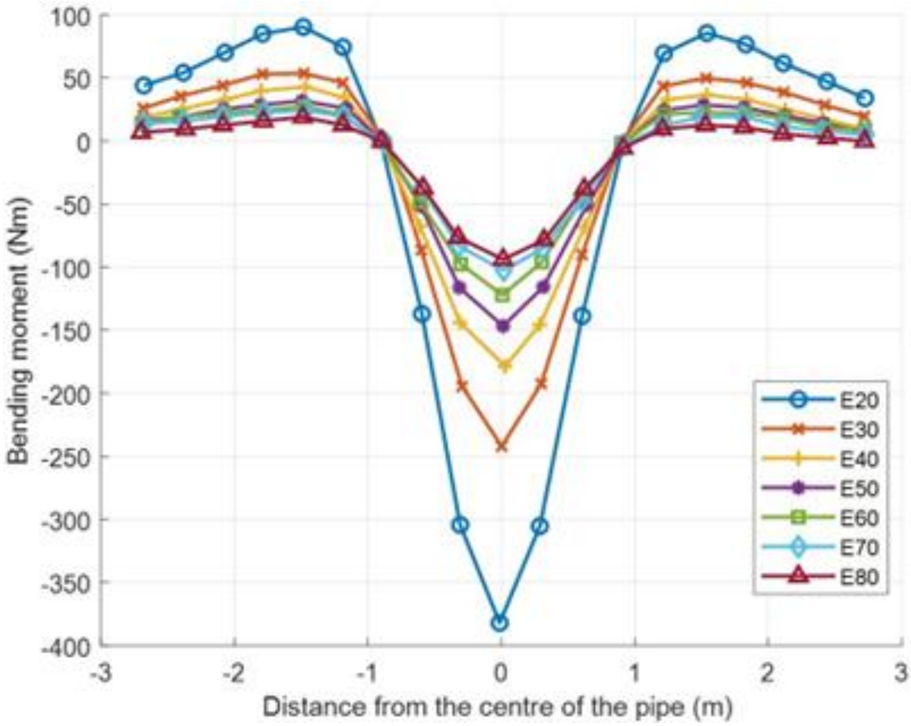

Figure 1: Young's modulus Sensitivity Analysis (Pdisp)

4. Pdisp model validation

The experimental centrifuge testing results were used to validate a Pdisp model, with the objective of making predictions about the effect of changing the burial depth. The results of the model were validated for both the zero eccentricity, and the 2D eccentricity loading case. Comparisons were made between the moments predicted by the Pdisp model, and those recorded in the experimental data. The Pdisp model was first run with a Young's modulus of 40MPa, which was calculated from the lab tests. However, this produced an unsatisfactory result, as the maximum bending moments predicted by Pdisp were far too low. Table 3 contains the details of the Pdisp moment pre- dictions when the Young's modulus was set at 40MPa.

It is clear from Table 3 that an input of 40MPa for the Young's modulus is too high, as the resulting bending moments do not replicate the experimental results. This is likely due to the sensitivity issues raised in Section 3.1. The Young's modulus of a soil can be a difficult parameter to measure, and so there is a possibility that it has been over-estimated. The Manual for Bridge Engineering states that the Young's Modulus of a medium dense sand can range from 17-28MPa, and that of medium dense sand can range from 35-55MPa (Ryall and Parke, 2000). The ranges of values for medium dense sand were trailed to see whether they would produce a better fit. It was deter- mined that a Young's modulus of 20MPa produced the closest match to the experimental data. The bending moment diagrams that Pdisp generated with under those conditions can be found in Figure (2,3,4,5), plotted alongside the experimental results.

Table 3. Comparison of bending moment at E=40MPa.

Load location	Pdisp Result Nm	Experimental Result Nm
M_{max} Major 0e	348	923
M_{max} Minor 0e	0	724
M_{max} Major 2e	181	361
M_{max} Minor 2e	54	390

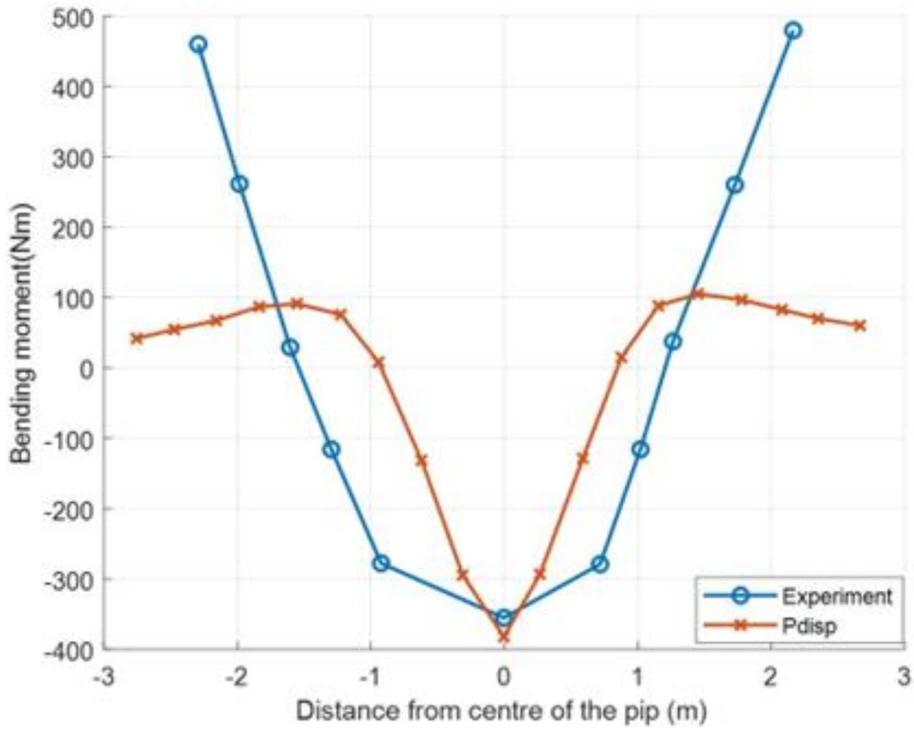

Figure 2: Major axis bending moment diagram (distance 2e)

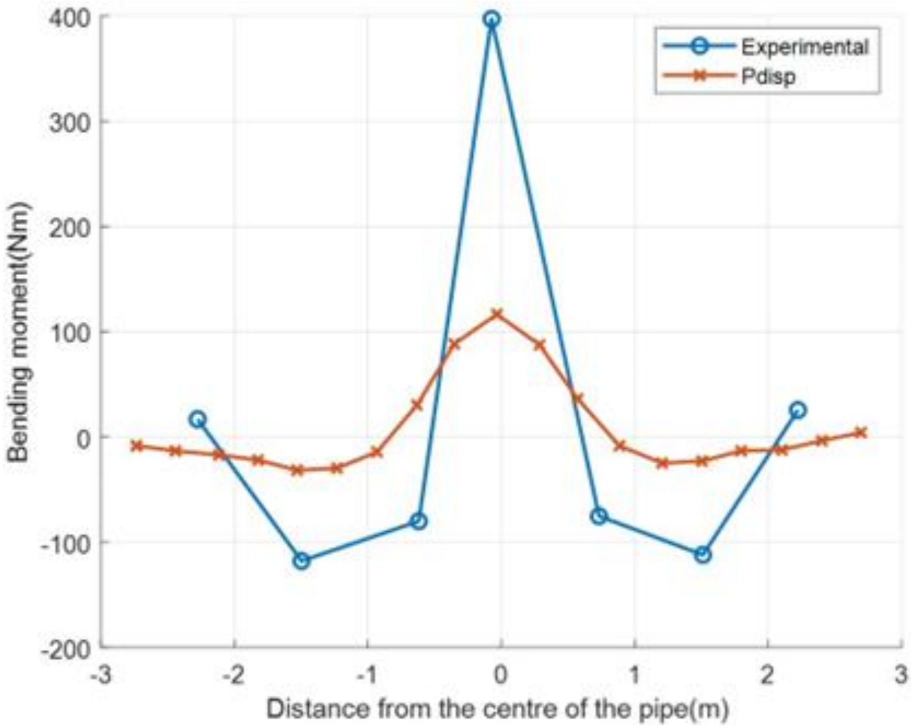

Figure 3: Minor axis bending moment diagram (distance 2e)

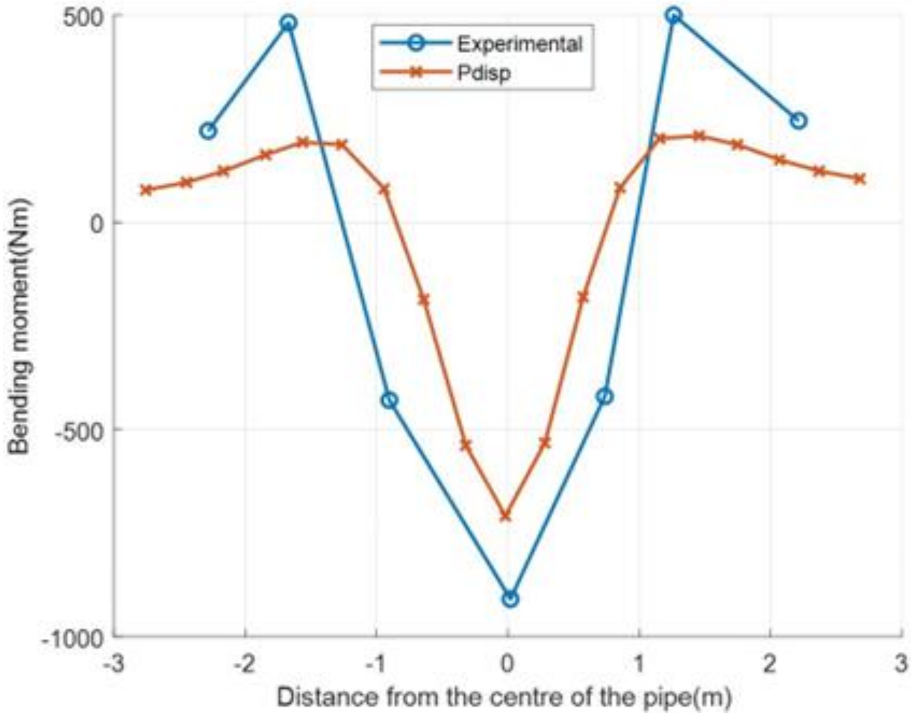

Figure 4: Major axis bending moment diagram (distance 0e)

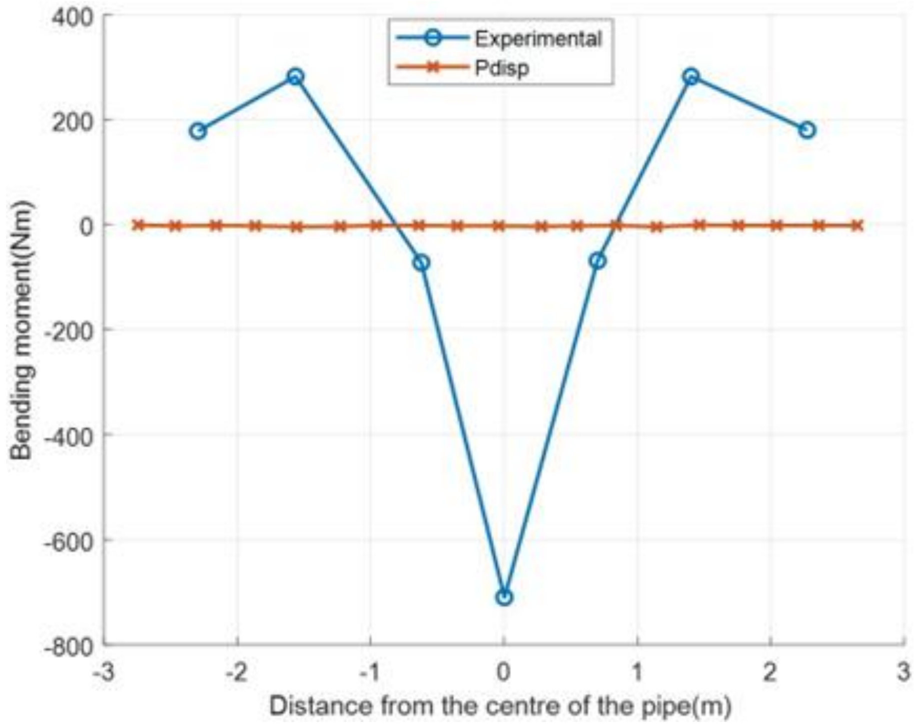

Figure 5: Minor axis bending moment diagram (distance 0e)

4.1 Figures and results

Figure 1 shows the results from the Young's Modulus Sensitivity Analysis and the validation of the Pdisp model. The major axis bending moments generated by Pdisp were within an acceptable range of the experimental results. In the 2D eccentrically loaded case, there is a 5.5% difference between the maximum bending moments predicted by the model and the experimental results. The zero- eccentricity case is less accurate, with a difference of 25% between the maximum bending moments in both sets of results.

The major axis bending moments generated by Pdisp were within an acceptable range of the experimental results. In the 2D eccentrically loaded case, there is a 5.5% difference between the maximum bending moments predicted by the model and the experimental results. The zero-eccentricity case is less accurate, with a difference of 25% between the maximum bending moments in both sets of results.

5. Limitations of Pdisp

Pdisp does not perform well when predicting the minor axis response to loading. In the zero-eccentricity loading case, the model calculates a minor axis bending moment of zero along the length of the pipe. This is due to the model not considering the de- formation of the pipe. The HDPE pipe is classed as flexible, as it is less stiff than the surrounding soil (cite). Therefore, when it is loaded, it deforms, by the vertical diameter decreasing and the horizontal diameter increasing. This deformation of the pipe generates bending in the minor axis, in addition to any bending from lateral loading. In the 2D eccentrically loaded case, the Pdisp model again under-predicts the minor axis bending moment, this time by a factor of four. These results suggest that Pdisp is not a suitable tool for calculating the expected magnitude of minor axis bending, although it can still provide information about the general trends that should be expected. Another limitation of the Pdisp model is its ability to predict the moments at the end of the pipes. Although predicting the maximum bending moment reasonably well, Pdisp consistently underestimates the degree to which the pipe is fixed in place by the surrounding soil and so will predict a low end moment. These regions of error are important to consider in the following parametric study.

6. Parametric Study

Following the comparison of the Pdisp model results to the centrifuge experimental data, a parametric study was conducted to further investigate the response of HDPE pipes of eccentric loading. Two main areas of investigation were set out. The first of which was to consider the response of a pipe to loading from a constant distance of eccentricity but with an increasing burial depth. Following on from that test, the burial depth was kept constant and the eccentricity in- creased. The model inputs were not altered from those outlined in section 4, other than to change the variable under investigation. The results of both investigations can be seen in Figure (6,7,8,9).

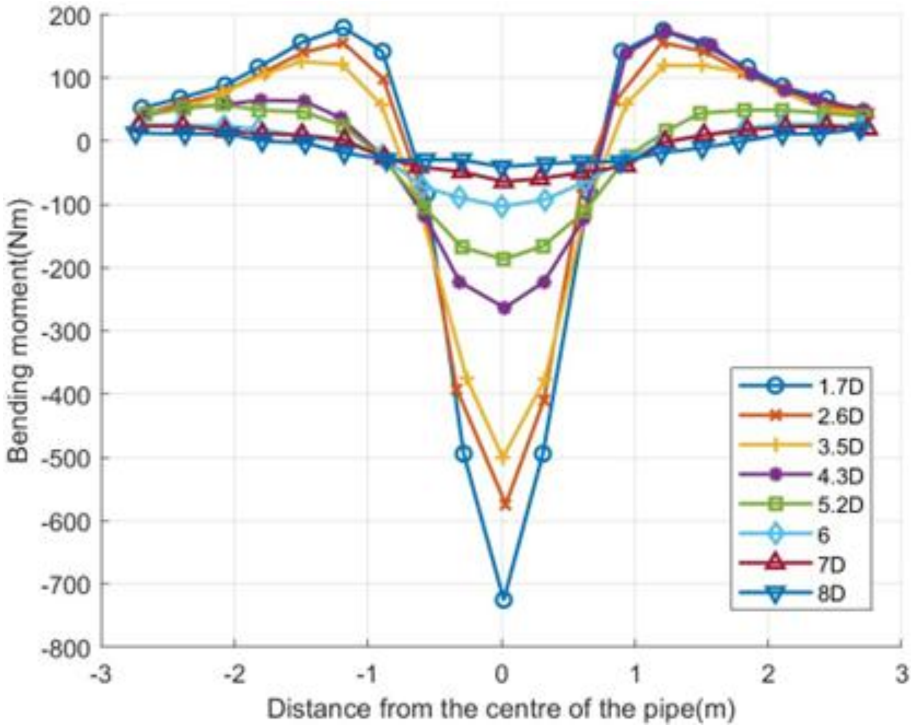

Figure 6: Major axis bending moment diagram (distance 2e) loading at a range of depths of embedment

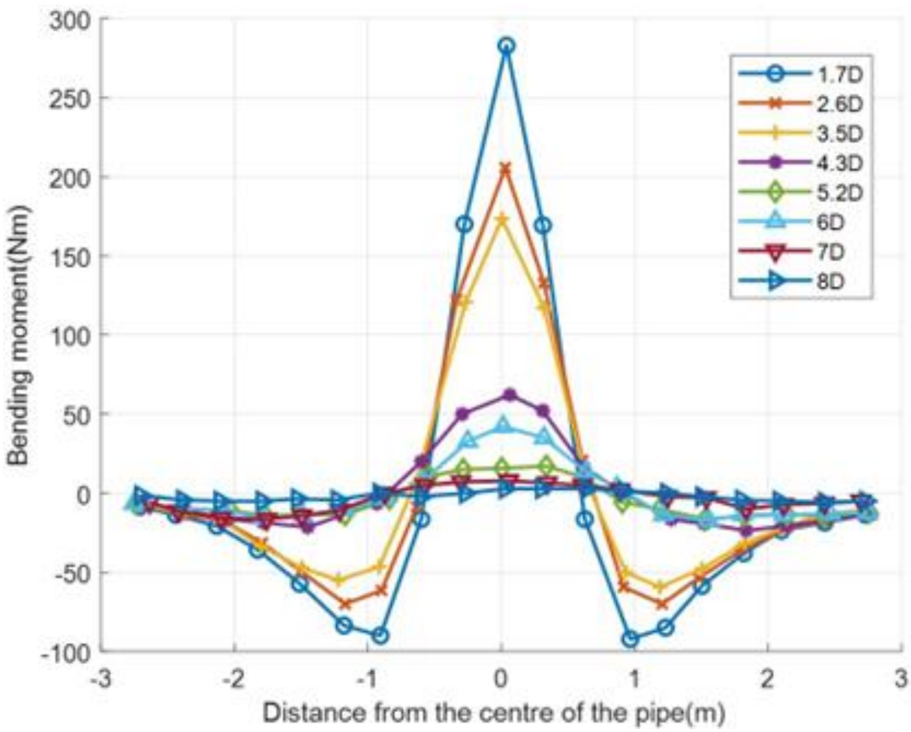

Figure 7: Minor axis bending moment diagram (distance 2e) loading at a range of depths of embedment

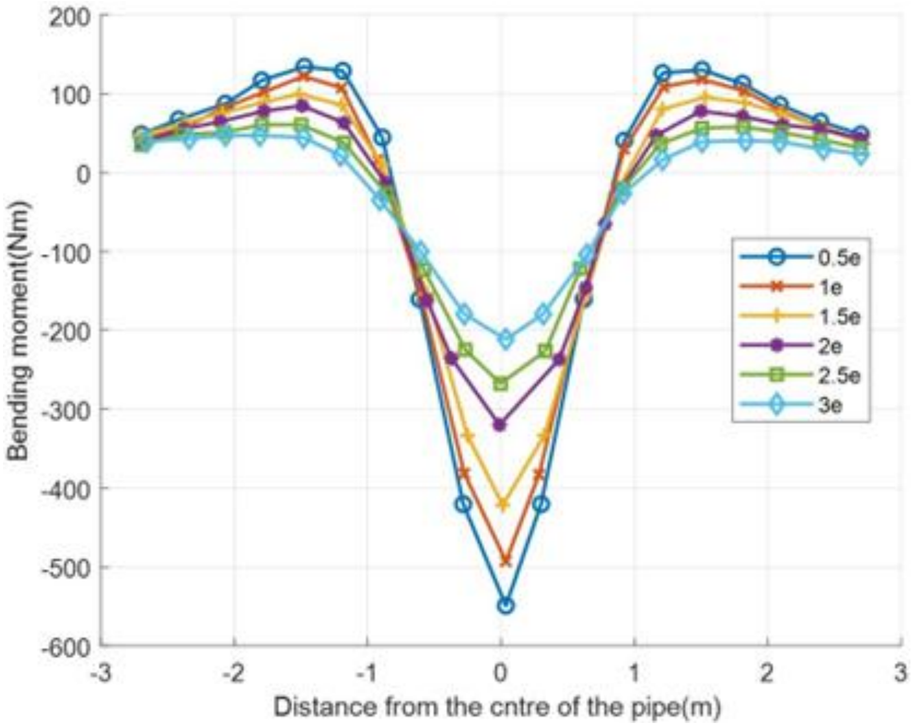

Figure 8: Major axis bending moment diagram 1m depth of embedment, at a range of e values

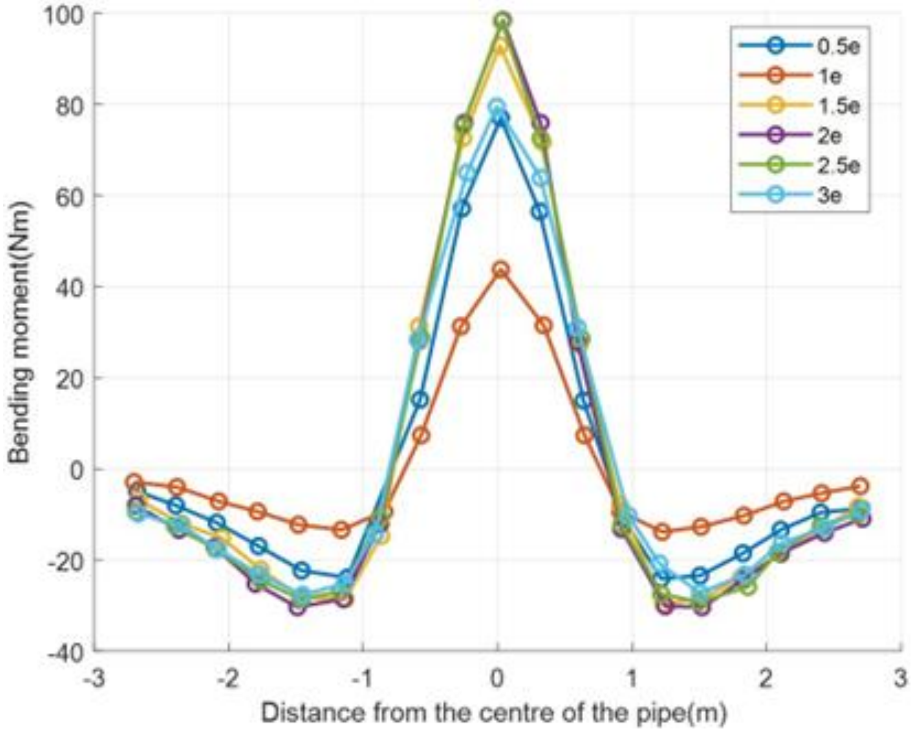

Figure 9: Minor axis bending moment diagram 1m depth of embedment, at a range of e values

6.1 Impact of increasing eccentricity

Figures (6) and (7) show the major and minor axes bending moments predicted by Pdisp because of a half axle load acting at a distance of 2D. A review of the trends in the major axes bending moments reveals that the pipe should be expected to display a very gradual increase in bending moment until depths shallower than 4.3D. This is due to the pipe entering the shallow region of soil where the stresses imposed by the sur- face load are most significant. The minor axes response to a decreasing burial depth follows similar trends with the largest increments in bending moment arising between burial depths of 4.3D and 1.7D. The results of this study show that there is not a linear relationship between burial depth and peak bending moment from an eccentric load.

6.2 Impact of increasing burial depth

Figure 3 (8) and (9) show the predicted bending moments for the HDPE pipe at a constant burial depth of 1m, with a changing distance of eccentric loading. As expected, the major axis moments increase as the eccentricity of the load reduces, and the minor axis moments decrease. The results from this investigation show that the pipe is much less sensitive to changes in eccentricity of the load, than it is to the burial depth. In the minor axis, the difference in the bending moment resulting from eccentric loading between 0.5e and 2.5e was just 20Nm, demonstrating the limited bending response arising from a change in eccentricity. Due to the limitations of the Pdisp model, some of which were discussed in section 4.1, the pre- dictions made in the parametric study are more indicative of the trends that should be expected in similar loading cases, rather than the precise magnitudes of the bending moments. This is especially relevant when considering the predictions of minor axis moments, and end moments on the pipe.

7. Design Guidelines

The Highways Agency has produced a set of guidelines on the design of HDPE utility pipes for sustaining loading from highways. These guidelines include a number of design charts for various loading conditions. The minimum allowable burial depth for HDPE pipes under main road loading is 0.9m, corresponding to 3D in this study. The findings of this paper support this guideline burial depth as it prevents the pipe from being exposed to the large increases in bending moment witnessed at shallower depths of embedment. It also prevents excessive trenching, as Figure 6 demonstrates significantly smaller reductions in maximum bending moments are gained at depths beyond 5.2D.

8. Conclusion

In this paper, the response of HDPE pipes to eccentric loading has been investigated through the use of centrifuge modelling results, and a Pdisp model. The results of the parametric study support the burial depth guidelines of the Highways Agency, as their minimum allowable depth avoided the high bending moment regions at depths shallower than 3D. Further investigation could be carried out to determine whether other computational modelling techniques would be capable of producing more accurate predictions of the experimental results.

References

[1] Arokiasamy, M., O. Chaallal, and T. Limpeteeprakan (2006). “Full-scale field tests on flexible pipes under live load ap- plication”. In: Journal of Performance of Constructed Facilities 20.1, pp. 21–27.

[2] Elmrom, T., S. Byton, and J. Black (2022). “Impact of Voids on Buried Utility Pipes Subjected to Surface Traffic Loading”. In: Journal of Geotechnical Engineering 148.4, p. 04022015.

[3] Eaton, T. (2013). Exploring the application of closed form solutions in geotechnical problems.

[4] Faragher, E., P. R. Fleming, and C. D. Rogers (2000). “Analysis of repeated- load field testing of buried plastic pipes”. In: Journal of Transportation Engineering 126.3, pp. 271–277.

[5] Institution, British Standard (2010). BS 9295:2010: Guide to the structural design of buried pipelines. British Standard Institution.

[7] Tafreshi, S. N. M. and O. Khalaj (2011). “A parametric study of the cyclic loading response of buried pipes using centrifuge testing”. In: Geotechnical Testing Journal 34.5, pp. 456–465.

[9] Oasys, (2014); "Pdisp Version 19.2"