CHAPTER 10 SUMMARISATION AND RECOMMENDATIONS

The purpose of this research is to understand the performance of concrete jacking pipes under working conditions and to suggest improvements to the design of pipes and pipe joints. There are many factors affecting the performance of concrete pipes during jacking, and it is therefore impractical to conduct an extensive study of these factors by experiment. From the previous research (Ripley 1989, Milligan and Norris 1993b, Norris 1992, Boot and Husein 1991, Husein 1989), the performance of concrete pipes is determined by local cracking due to high tensile stresses at the pipe joint and within the concrete pipe induced by the pipeline misalignment. This makes the problem complicated and difficult for analytical methods to examine in detail. In this research, the finite element method was used to examine the pipe performance with limited laboratory tests. After some developments of the finite element model as described in Chapter 2, an extensive parametric study was carried out in this research to examine the influence of several factors affecting the pipe performance.

10.1 PIPELINE MISALIGNMENT

Previous research (Concrete Pipe Association of Australia 1982, Haslem 1996, Ripley 1989, Milligan and Norris 1993b, Norris 1992, Boot and Husein 1991, Husein 1989) shows that pipeline misalignment causes high stress localization at pipe joints (on the interface between jacking pipe and packing material). These localized stresses induce high tensile stresses within the pipe, which would damage the pipe under severe conditions. However, the interaction mechanism between the pipe and the packing material is still not very clear. To improve the design of the pipe, it is necessary to investigate the distribution patterns of the localized stresses at the pipe joint (on the interface) and within the pipe. In this research, the

influence of the pipeline misalignment was examined with the simplified two-dimensional plane strain model and the symmetrical three-pipe system, numerical model C, as discussed in Chapter 3 and Chapter 6 respectively. Both numerical models were used to simulate the 'edge' loading condition under different misalignment angles (refer to Figures 3.1 and 6.2).

In this research, the analyses were carried out assuming the concrete pipe was linearly elastic since the purpose of the research is to understand the pipe performance under working conditions. However, due to the pipeline misalignment, the pipe may separate from the packing material. To model the interaction between the pipe and the packing material, the Mohr-Coulomb frictional model was extended to include a gap zone as described in Chapter 2. This makes the problem highly non-linear when a big gap forms on the interface between the pipe and the packing material (refer to Section 6.4 in Chapter 6).

The numerical results show that the pipeline misalignment induces some shear stresses and high localization of normal stresses on the interface between the pipe and the packing material, which in turn cause high tensile stresses within the concrete pipe (mainly in the hoop direction and in the region of the pipe joint under 'edge' loading). The higher the misalignment angle at the joint, the higher the tensile stresses within the concrete pipe. The results also show that the displacements and the normal stresses at the pipe joint are almost linearly distributed over the joint when the misalignment angle is small (no gap between the pipe and the packing material). However, when the misalignment angle is high, there exists a big gap between the concrete pipe and the packing material, and the displacements and the normal stresses are highly non-linear over the joint. The result comparison under the 'edge' loading condition between the numerical model and the analytical models suggest that under a small misalignment angle (without a gap) both the Australian model and Haslem's (1996) flexible pipe model give good predictions of the displacements and the normal stresses at the joint. When under a high misalignment angle (with a big gap on the interface), the Australian model gives good predictions of the maximum normal stress and the diametrical contact

width on the joint, and the predictions from Haslem's (1996) model are poor due to the assumption of tensile stresses in the axial direction within the concrete pipe since the tensile stresses are mainly localized in the region of pipe joint and in the hoop direction.

10.2 PACKING MATERIAL

The packing material plays an important role in the practice of pipe jacking by increasing the contact area over the pipe joint which in turn reduces the stress localization. Previous research by Ripley (1989), Milligan and Ripley (1989), Boot and Husein (1991) and Husein (1989) shows that the packing material with low Poisson's ratio and low stiffness is a good packing material, such as chipboard and plywood. However, its influence on the stresses on the interface between the pipe and the packer and within the pipe still needs to be examined for a better understanding of its working mechanism. In this research, an extensive parametric study of the influence of the properties of the packing material was carried out using both the two-dimensional model and the three-dimensional model as described in Chapter 3 and Chapter 6 respectively (refer to Figures 3.1 and 6.2). The analysis was carried out with three typical Poisson's ratios and three typical shear moduli (two shear moduli in the three-dimensional analysis) under different misalignment angles. In the analysis, both the pipe and the packing material were linear elastic, and the interaction between the pipe and the packing material was modelled by a layer of interface elements as discussed in Section 10.1. The influence of two extremely different packing materials, plywood packing with an almost zero Poisson's ratio and rubber packing which is considered as almost incompressible, was also examined by laboratory tests in this research.

The results confirm that a good packing material should have a low Poisson's ratio and a low stiffness (or a low shear modulus). The numerical results show that the packing material with a higher shear modulus and a higher Poisson's ratio generates higher stress localization

on the interface between the pipe and the packing material. The shear stresses on the interface between the pipe and the packing material are mainly due to a high Poisson's ratio of the packing material. Unlike the normal stresses, the shear stresses are always non-linearly distributed on the interface. The shear stresses and the localized normal stresses on the interface induce high tensile stresses in the concrete pipe as discussed in Chapters 3 and 6. The influence of the Poisson's ratio of the packing material on these stresses is significant. There is no analytical model to deal with the shear stresses on the interface.

10.3 SURROUNDING SOIL

The interaction between the concrete pipe and the surrounding soil is another important factor affecting the pipe performance during pipe jacking. In practice, there may be an initial gap between the pipe and the surrounding soil due to overcut, or the pipe is squeezed by the surrounding soil due to the swelling of surrounding overconsolidated clay or the collapse of surrounding sand (Thomson 1993). However, in this research, the effort was on the interaction between the pipe and the surrounding soil caused by the pipeline misalignment. It was assumed that there was no initial gap between the pipe and the surrounding soil and that there was no initial pressure on the pipe from the soil. The parametric study was carried out using a three-dimensional model, Numerical model B, as described in Chapter 5 (refer to Figure 5.1). Three cases were examined, that is, the pipe and elastic surrounding soil with and without an interface between them, and the pipe with plastic surrounding soil. In each case, the analysis was carried out with three different soil stiffnesses under both 'edge' loading and 'diagonal' loading conditions.

The numerical results show that the high tensile stresses are mainly located at the pipe joint in the hoop direction under the 'edge' loading condition, and that under 'diagonal' loading the high tensile stresses are located on the external surface of the pipe in the normal

direction of the line connecting the two loaded corners. The numerical results with interface elements show that the pipe separates from the surrounding soil over a large part of the interface and the reaction stresses from the surrounding soil are mainly located in the region adjacent to the loaded area. The results with elastic soil without an interface are considered to be unreliable due to the unrealistic tensile stresses acting on the pipe from the surrounding soil. The research results also demonstrate that the displacements at the pipe end under the 'diagonal' loading condition are mainly due to the rigid body rotation of the pipe in the soil and that the surrounding soil has a significant effect on the stresses in the pipe under the 'diagonal' loading condition due to the rigid body rotation of the pipe in the soil as discussed in Chapter 7. (In practice, prediction of the rigid body rotation of the pipe under the 'diagonal' loading condition is difficult because the load distribution at the pipe end is affected by the rotation of the pipe. There is no analytical model for the 'diagonal' loading condition). Under the loading condition in the research the soil seems to reduce the stresses at the pipe joint and in the pipe in both 'edge' loading and 'diagonal' loading cases, especially with stiff soil (It should be stressed here that the frictional force from the surrounding soil will increase the jacking load in practice. This aspect is not included in the current project).

10.4 PIPE WALL THICKNESS AND LOAD DISTRIBUTION

The analysis in this research also included the influence of the pipe wall thickness and the influence of the load distribution on the pipe end. The analysis was carried out with a single small scaled model pipe, Numerical model A, as discussed in Chapter 4 (refer to Figure 4.1). The numerical results show that the more localized the applied load on the pipe end, the higher the tensile stresses at the pipe joint and within the concrete pipe. Due to the local bending effects in the pipe wall, the stresses within the thin wall pipe exceed those in the thick wall pipe by more than the thickness ratio. The results also show that the constraints under the 'diagonal' loading condition have a great effect on the stresses in the pipe. Husein (1989)

has found a similar effect of the hoop geometry, as discussed in Chapter One. This means that laboratory tests of pipe jacking without surrounding soil should be carefully designed in order to simulate the situation in practice.

10.5 IMPROVEMENT OF PIPE DESIGN

A few proposed design improvements, based on the numerical results in this research, were investigated by laboratory tests. An extended numerical back analysis of the experiments was also carried with a simple modified Matsuoka model proposed in this research. The reinforcements were modelled by curved bar elements as discussed in Chapter 9 (refer to Figure 9.2). Both the experiments and the back analysis demonstrate the effectiveness of the local reinforcement and local prestressing on the improvement of the pipe strength. The experimental results show that the local reinforcement and local prestressing also prevent the spalling problem at the pipe joint. The results from the extended back analysis suggest that the reinforcement located near the internal surface of the pipe may produce better results because the high tensile stresses are mainly located on the internal surface under the 'edge' loading condition, and that the magnitude of the prestress should be well controlled to produce good results.

10.6 RECOMMENDATIONS

The current research has demonstrated that the finite element method is very effective in the analysis of pipe jacking. Many interesting results have been obtained. However, due to the complex nature of the problem, some subjects are not included in this research, such as the cracking behaviour of the pipe and the influence of the lubricant on the frictional force. To improve the current understanding of pipe jacking and to make better design of pipe and

pipe joint, further research is still needed. A few of important research topics are recommended as following:

(1) Numerical analysis with a complex concrete model including crack failure,

(2) Numerical analysis with a generalized numerical model, three pipes including two pipe joints with packing material and surrounding soil, under both 'edge' loading and 'diagonal' loading condition,

(3) Numerical analysis with different material constants of the interface between the pipe and the soil to model the influence of the use of lubricant in practice,

(4) Laboratory tests of the 'diagonal' loading condition with local reinforcement at the pipe joint and at the middle pipe length,

(5) Laboratory tests with instrumented pipe to examine the load distribution on the pipe end under different pipeline misalignment angles.