Numerical Analysis and Laboratory Test of Concrete Jacking Pipes

by

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A thesis submitted for the
Degree of Doctor of Philosophy
at the University of Oxford

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ABSTRACT

Pipe jacking is a trenchless construction technique for the installation of underground pipelines. Although pipe jacking is widely used, fundamental research is still needed to understand fully the factors affecting the process and to prevent unexpected failure. With the time and financial limitation, it is difficult to explore all aspects of these factors with experiments; and it is also difficult to study them by analytical methods because of the complexity of the problem. This thesis describes the use of the finite element technique to study the pipe performance under different environments and the laboratory tests of several different joint designs.

The emphasis of the current research is on the performance of the concrete pipes during jacking under working conditions and to seek possible improvements in the design of pipes and pipe joints by numerical modelling. In the finite element modelling, a simplified two-dimensional model is used for a preliminary study, then the analyses are carried out with three-dimensional models A, B and C representing a complete pipe, a pipe with surrounding soil and a symmetric three-pipe system respectively. Several factors affecting the pipe performance have been examined, for example, the properties of the packing material, the stiffness of the surrounding soil, the misalignment angle at the pipe joint, and the interaction between the pipe and surrounding soil.

The numerical results show that the misalignment of the pipeline is the dominating factor inducing both tensile stresses and localized compressive stresses in the concrete pipe, especially with a high misalignment angle which results in separation between the packing material and the pipe. The packing materials with high Poisson's ratio and high stiffness also induce higher tensile stresses in the pipe, and the influence of the Poisson's ratio is significant. Under 'diagonal' loading, both the stiffness of the surrounding soil and the interaction between the pipe and the surrounding soil have a significant effect on the stresses within the concrete pipe. Under 'edge' loading, the greatest potential damage is at the pipe joint due to the tensile stresses in the hoop direction; while under 'diagonal' loading, the damage is most likely the cracking on the external surface of the pipe along a line connecting the two diagonal loaded corners. The results also show that the Australian model gives somewhat good prediction about the maximum normal stress and the diametrical contact width at pipe joint.

Based on the numerical results, several different joint designs for improving the pipe strength have been proposed and tested in the laboratory. Both the laboratory tests and the back analyses suggest that the local reinforcement and the local prestressed band at the pipe joint will improve the pipe strength.

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Nomenclature

a	Initial packing material thickness
Δa	Compression of the pipe joint
Δa_p	Compression of the packing material
c	Cohesion of soil or interface
$[D]$	Material matrix
E	Young's modulus
E_c	Young's modulus of concrete
E_p	Young's modulus of packing material
Es	Young's modulus of soil
f	Yield function
$f_1 \ldots f_8$	Element shape function
f_c	Compression strength of concrete
f_t	Tensile strength of concrete
g	Plastic potential
G	Shear modulus
G_c	Shear modulus of concrete
G_p	Shear modulus of packing material
I_1, I_2, I_3	Stress invariant
I_c	Second moment of cross-section area of concrete pipe
K_n, K_s	Normal and shear stiffness of interface
$[K]$	Stiffness matrix

L	Pipe length
M	Bending moment at pipe joint
P	Total applied load
{P}	Vector of applied load
{dP}	Vector of increments of applied load
q	Intensity of pressure
R	External radius of pipe
{R}	Vector of unbalanced /residual force
r	Internal radius of pipe
t	Wall thickness of pipe
u,v,w	Displacements
du, dv,dw	Increments of displacements
{U}	Vector of displacements
{dU}	Vector of displacement increments
x,y,z	Co-ordinates of a node / point in Cartesian system
r,θ,z	Co-ordinates of a node / point in cylindrical system
Z	Diametrical contact width at pipe joint
β	Angular deflection at pipe joint
β_c	Angular deflection of concrete pipe at pipe joint
β_p	Angular deflection of packing material at pipe joint
γ	Shear strain
ε	Normal strain
{ε }	Vector of strains

$\{d\varepsilon\}$	Vector of strain increments
σ	Normal stress
σ_{max}	Maximum normal stress at pipe joint
$\{\sigma\}$	Vector of stresses
$\{d\sigma\}$	Vector of stress increments
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
$\sigma_x, \sigma_y, \sigma_z$	Normal stresses in Cartesian co-ordinate system
τ	Shear stress
$\tau_{xy}, \tau_{xy}, \tau_{xy}$	Shear stresses in Cartesian co-ordinate system
ϕ	Frictional angle of soil or interface
ψ	Dilation angle of soil or interface
μ	Poisson's ratio
μ_c	Poisson's ratio of concrete
μ_p	Poisson's ratio of packing material
μ_s	Poisson's ratio of soil
ξ, η	Isoparametric co-ordinates of a node / point