

| Pre | face | | | | 2 | | |
|----------|-------|---|---|-----------------------------------|---|--|--|
| | | Summa | ary | 3 | | | |
| | | Zusam | Imenfassung | 3 | | | |
| Cor | ntent | S | | | 5 | | |
| 1 | Intr | oducti | ion | | 9 | | |
| | 1.1 | Basis o | of the study | 9 | | | |
| | 1.2 | Aims o | of the thesis | 10 | | | |
| | 1.3 | Structu | ure of the thesis | 10 | | | |
| 2 | Sta | State of the art 12 | | | | | |
| | 2.1 | Introdu | uction | 12 | | | |
| | 2.2 | Nume 2.2.1 2.2.2 2.2.3 2.2.4 | rical modelling of tunnels with the FEM Discretisation and boundary effects Accuracy of results System of equation Management of data and visualisation | 12 14 16 17 17 | | | |
| P | 2.3 | Nume 2.3.1 | rical modelling of tunnels with the BEM Discretisation | 17 19 | | | |

Simulation of Sequential Tunnel Excavation with the Boundary Element Method

Contents :

| | | 2.3.2 Accuracy of results | 19 | | | |
|---|--|---|----|--|--|--|
| | | 2.3.3 System of equations | 20 | | | |
| | | 2.3.4 Management of data and visualisation | 20 | | | |
| | 2.4 | Computation of stresses and loads | 22 | | | |
| | 2.5 | Comparison of results | 24 | | | |
| | 2.6 | Reasons for using the BEM | 28 | | | |
| 3 | Fundamentals of the boundary element method 29 | | | | | |
| | 3.1 | Introduction | 29 | | | |
| | 3.2 | Fundamental Solutions | 29 | | | |
| | | 3.2.1 2-D Elasticity | 29 | | | |
| | | 3.2.2 3-D Elasticity | 31 | | | |
| | 3.3 | Theorem of Betti and boundary integral equations | 33 | | | |
| | 3.4 | Limiting Values of integrals as P coincidences with Q | 36 | | | |
| | 3.5 | Boundary conditions and region definition | 38 | | | |
| | 3.6 | Discretisation and interpolation | 39 | | | |
| | | 3.6.1 2-D Problems - one dimensional elements | 39 | | | |
| | | 3.6.2 3-D Problems - two dimensional elements | 42 | | | |
| | 3.7 | Numerical implementation | 45 | | | |
| | 3.8 | Rigid body motions, azimuthal and singular integrals | 47 | | | |
| | 3.9 | Numerical integration | 49 | | | |
| | | 3.9.1 Integration over one-dimensional elements | 51 | | | |
| | | 3.9.2 Integration over two-dimensional elements | 55 | | | |
| | 3.10 | Assembly of system of equation | 58 | | | |
| 4 | Mu | Itiple regions | 60 | | | |
| | 4.1 | Introduction | 60 | | | |
| | 4.2 | Stiffness matrix assembly | 60 | | | |
| | 4.3 | Calculation of excavation problems | 66 | | | |

Simulation of Sequential Tunnel Excavation with the Boundary Element Method

.

| | | | Contents : | |
|---|----------------------|---|------------|--|
| | 4.4 | Example | 68 | |
| 5 | Corners and edges 72 | | | |
| | 5.1 | I Introduction | | |
| | 5.2 | 2 Two-dimensional elasticity | | |
| | | 5.2.1 Auxiliary equation based on stress symmetry | 74 | |
| | | 5.2.2 Auxiliary equation based on differential equation of equilibrium | 75 | |
| | | 5.2.3 Numerical implementation | 77 | |
| | | 5.2.4 Region assembly with corners | 79 | |
| | | 5.2.5 Examples | 86 | |
| | 53 | Three-dimensional elasticity | 96 | |
| | 0.0 | 5.3.1 Auxiliary Equation based on stress symmetry | 97 | |
| | | 5.3.2 Auxiliary equation based on differential equation of equilibrium | 98 | |
| | | 5.3.3 Numerical implementation | 101 | |
| | | 5.3.4 Examples | 102 | |
| 6 | Equ 6.1 6.2 | quivalent nodal point forces 1 Introduction 2 Assembling of equivalent nodal point forces in comparison with tractio assembly 112 | | |
| | | • | | |
| | 6.3 | Examples | 115 | |
| | | 6.3.1 Excavation of top heading in 2-D | 115 | |
| | | 6.3.2 Excavation in 3-D | 117 | |
| 7 | Pra | ctical examples | 120 | |
| | 7.1 | 7.1 2-D Example | | |
| | 7.2 | 3-D Example | 130 | |
| | | 7.2.1 Full face excavation in 3-D | 130 | |
| | | 7.2.2 Staged excavation in 3-D | 136 | |
| | | 7.2.3 Staged excavation in 2-D | 139 | |
| | | | | |
| | 7.3 | Conclusion | 148 | |

6

Simulation of Sequential Tunnel Excavation with the Boundary Element Method

| | | Contents • | | |
|---|-------------------------|------------|--|--|
| 8 | Summary and outlook 150 | | | |
| | 8.1 Summary | 150 | | |
| | 8.2 Outlook | 151 | | |
| 9 | Literature | 154 | | |

١