# Contents

Abstract i  

Contents iii  

1 Introduction 1  
1.1 Motivation ......................................................... 1  
1.2 Overview of inverse analyses for ground condition characterization .... 4  
1.2.1 Settlements based identification of soil parameters ..................... 4  
1.2.1.1 Tunneling-induced settlements ..................................... 4  
1.2.1.2 Settlements based inversion ......................................... 5  
1.2.2 Elastic waves based mapping ahead of the tunnel face .................. 7  
1.2.2.1 Elastic waves ......................................................... 7  
1.2.2.2 Ahead-of-tunnel prediction using tunnel seismic waves ............. 10  
1.3 Contributions of this thesis ........................................ 15  

2 Nonlinear Kalman filters for model calibration of soil parameters 19  
2.1 Background ......................................................... 19  
2.1.1 State-space representation of the forward model for parameter iden-
     tification .............................................................. 20  
2.1.2 Recursive Bayesian filtering and nonlinear Kalman filters for pa-
     rameter identification .................................................. 21  
2.1.3 The extended Kalman filter ......................................... 23  
2.1.4 The sigma-point Kalman filter ...................................... 25  
2.2 Application for parameter identification and optimization to test models 27  
2.2.1 Identification of hidden parameter in a nonlinear noisy time series 27  
2.2.2 Optimization of nonlinear multi-minima Ackley’s function ........... 28  
2.3 Model calibration of soil parameters in mechanized tunneling .......... 30  
2.3.1 Forward model and noisy synthetic measurement data ................ 32  
2.3.2 Results and discussion ............................................ 35
3 Particle filter-based data assimilation for uncertainty quantification 43
  3.1 Data assimilation for inversion of model parameters 43
    3.1.1 State-space formulation 43
    3.1.2 Sequential data assimilation using particle filter 44
  3.2 Identification of elasto-plastic soil parameters for tunnel model 46
    3.2.1 Tunnel model and tunnel-induced settlements 46
    3.2.2 Results and discussion 48

4 A global optimization approach for inversion of the tunnel seismic waves 53
  4.1 Concept 53
  4.2 Unscented hybrid simulated annealing 57
    4.2.1 Unscented Kalman filter for local minimization 58
    4.2.2 Unscented hybrid simulated annealing 61
  4.3 Finding global minimum of a multimodal optimization test function 64
  4.4 Tunnel seismic waveform inversion 67
    4.4.1 Forward modeling of tunnel seismic waves 67
      4.4.1.1 The spectral element method 67
      4.4.1.2 2D tunnel seismic model 70
    4.4.2 Inverse analysis 73
      4.4.2.1 Misfit functional 73
      4.4.2.2 Test 1: Inversion for an inclined layer change 75
      4.4.2.3 Test 2: Inversion for a concrete remnant 78

5 Full-waveform inversion supported by parametric level-set representation 85
  5.1 An effective approach to reconstructing multiple geological disturbed zones 85
    5.1.1 Level-set method for flexible representation of the disturbance 86
    5.1.2 The proposed inversion technique 88
  5.2 Inversion tests with cross-hole acoustic wave measurements 92
    5.2.1 Acoustic waves in frequency domain 92
    5.2.2 Inversion results 93
  5.3 Application to tunnel reconnaissance 97
    5.3.1 Tunnel seismic waves 97
    5.3.2 Qualitative analysis of the recorded waves 100
    5.3.3 Inversion results and discussions 101
      5.3.3.1 FWI test 1 — single disturbance 104
      5.3.3.2 FWI test 2 — multiple disturbances 105
      5.3.3.3 Discussion 107
## 6 Conclusions and outlook

6.1 Conclusions ............................................. 113

6.2 Outlook .................................................. 116

6.2.1 Integration into a tunnel information system .......... 116

6.2.2 Validation against laboratory measurements .......... 116

### Bibliography

118

### List of Figures

132

### About the author

137