6 Conclusions and outlook

6.1 Conclusions

Nonlinear Kalman filters and particle filter for soil parameters identification

Overall, the EKF and SPKF presented in this work are very capable of doing model calibration for geomechanical modeling in mechanized tunneling. Fast convergence of the parameters being identified and ability to tolerate measurement uncertainty are the main advantages of the two Kalman filter algorithms. One other prominent advantage is that the choice of initial model parameters must not be very close to the true parameter set as for other gradient-based optimization methods. These nonlinear Kalman filters are potential to apply for calibrating model parameters to modeling geotechnical structures other than tunneling as well.

In particular, the use of the EKF requires approximations of the derivatives of measurement data with respect to the model parameters due to identification. These approximations may be inaccurate for highly nonlinear and non-smooth FE responses. On the other hand, the use of SPKF for parameter identification frees us from doing this brute-force numerical calculation of the derivatives. But, in order to have this great advantage, more cost is paid for forward calculation of the model: $2n + 1$ runs for the SPKF compared with $n + 1$ runs for the EKF in every iteration, with $n$ number of parameters. However, the number of forward simulations required is still much less than those required by other global optimization algorithms such as metaheuristic and generic Monte Carlo optimization methods.

Also, particle filter based data assimilation is shown to be suitable for identification of unknown constitutive parameters in modeling of mechanized tunnel excavation. The assimilated results in the form of probability distributions are very convenient for judgment and utilization of the identified parameters for further prediction and analysis of the forthcoming tunnel excavation steps. The advantage of using the particle filter as a mechanism
to update the posterior distributions is that it can intrinsically work with nonlinear models and non-Gaussian densities representing model parameters and uncertainties. Besides, this method is very noise tolerant as it shows high accuracy of the identified parameters even with a level of observation noise.

Although noisy information can be incorporated into the filters in the form of covariance of zero-mean Gaussian distribution, the authors have observed that a large amount of measurement uncertainty can cause great difficulty in achieving the true parameters set especially for the parameters that contribute low sensitivity to the model outputs.

Careful design of measurement campaigns in tunneling and other geotechnical projects will help provide Kalman filters inverse analysis with quality data. As the tunnel boring machine advances, the nonlinear Kalman filtering schemes introduced in this work can be continuously employed for updating the relevant hidden parameters about the soils and rocks surrounded the TBM.

**Global optimization approach for inversion of the tunnel seismic waves**

An improvement of the SA algorithm is proposed to solve tunnel seismic waveform inversion whose purpose is to develop an efficient method for prediction ahead of underground tunnel face. The multimodal misfit functional can be effectively searched for the global minimum by combining the exploration and exploitation capabilities of SA algorithm and UKF procedure respectively. The benefits of using waveform inversion by the proposed derivative-free global optimization include i) information of the full waveforms can be utilized which promises high-resolution of the imaged geological structure ahead of the tunnel face, ii) no good initial model and no gradient calculations are required to run waveform inversion, and iii) not only the global minimum model is found but also other dominant local minima which may help in expert judgment of the likely geological situations.

Overall, the UHSA algorithm does not require so many sample points in the parameter space compared with the standard SA algorithm because 'bad' random sample points can be improved locally by the UKF. This local improvement is essential to accelerate the convergence of the proposed algorithm.

Although the demonstrated example of the tunnel seismic model is very simply parameterized, inversion based on modeling of tunnel seismic wave propagation with a standard PC still takes considerable calculation time. A high power computing facility is likely to allow the application of this method to the characterization of more complicated geological scenarios, or even for more realistic waves propagation in 3-dimensional space.
The proposed method in this work can benefit from future development of the SA and UKF algorithms. Within the current standard implementation of the two constituted algorithmic components, the method can perform better by improving local convergence behavior of the UKF. For example, measurement data can be partitioned into several data blocks, then in each iterative run of the UKF, the data blocks are successively fed to the filter. This data partition scheme may work well because with little data used at the beginning of the filtering ease convergence. Later data increments are expected to guide the solution to the global minimum.

Full-waveform inversion supported by parametric level-set representation

This work presents an inversion scheme enhanced by the PaLS parameterization of the geometry to achieve effective and fast inversion of multiple arbitrarily shaped disturbances ahead of the tunnel face. This parameterization technique is very well suited for reconstructing the object of complex geometries while allows for implicit handling of the object’s interfacial boundary on a fixed computational mesh. The use of the UKF as an inversion method results in an efficient derivative-free inversion process. The proposed combination of parameterization and inversion methodology for FWI — the UKF-PaLS — is effective in reconstruction capability and computing requirements. As computational time is one of the largest difficulties preventing the application of FWI in tunneling practice, the use of the proposed inversion scheme can help to achieve reliable reconstruction of arbitrary objects while keeping the computational time acceptably low.

More validations with experimental or in-situ data are important to prove the robustness of the method against measurement errors. One other important work is to take into account the wave propagation simulation in 3D with a detailed study of the influence of the excavation damaged zone close to the tunnel wall and the hydrostatic confining pressure for deep tunneling to build the high fidelity initial model.

Fast and quality reconstruction results achieved using only a few seismic sources and receivers are encouraging to use FWI in tunneling practice and is especially appropriate for tunneling projects in high-risk ground conditions where repeated data acquisition and ground reconnaissance are required as the TBM advances.