Statistical inverse analysis of the RGP tests at Primrose-Wolf Lake oil sands field

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Summary

Knowledge of the initial in situ stress plays a vital role in the geomechanical caprock integrity and risk assessment problems experienced in projects of in-situ recovery of oil sands, CO_2 sequestration, and underground radioactive waste storage. Traditionally, the minimum in situ stress is determined from diagnostic fracture injection tests or mini/micro-frac tests. However, measurements of the minimum stress from these tests are deemed inconclusive in the shallow oil sands reservoirs in West Canadian Sedimentary Basin (WCSB). Consequently, the pursuit of alternative in situ stress testing techniques results in the development of a reservoir geomechanical pressuremeter (RGP), which can be deployed into the borehole using industry-standard wireline technology. In 2016, five borehole intervals in Formations Westgate, Joli Fou and Clearwater were tested with the deployment of the RGP tool at the Primrose-Wolf Lake oil sands field. Inverse analysis of RGP testing data allows for an integrated assessment of the magnitude and orientation of anisotropic in situ stresses and formation rock stiffness and strength. A statistical method is utilized for the inverse analysis of the RGP tests, from which the mean value and its statistics can be derived. With the statistical method, parameters are first estimated by coupling an analytical, semi-analytical, and numerical model with an optimization algorithm. Then, the non-uniqueness issues in parameter estimation are addressed by uncertainty quantification using statistical assessment methods. With the mean, standard deviations, and confidence intervals, uncertainties from parameter estimation can be quantified. In addition, model fit using the statistical method is examined with the coefficient of determination, R^2, and prediction uncertainty is visualized with the prediction band. Finally, the minimum in situ horizontal stress measured by the microfrac modular formation dynamics tester is used to compare the findings from the statistical inverse analyses of the RGP tests.

Theory / Method / Workflow

The goal of an RGP test is to record the changes in the applied pressure and radial displacements during the expansion, hold, unloading/reloading, and contraction stages. In addition, inverse analysis of an RGP testing curve is performed to estimate the values of in situ horizontal stress and rock properties for geomechanical investigation. With observed data from the RGP test, point estimation with deterministic methods is usually first carried out and then followed by statistical assessments of estimated parameters.

At the beginning of point estimation, the prior probability distributions for unknown parameters must be assumed. The proposed PDFs, such as uniform, normal, and log-normal distribution, represent a priori knowledge of rock properties and in situ horizontal stress from previous publications, expert experience, and personal judgment. This study assumes uniform distributions for all unknown parameters. To simulate an RGP test, an analytical solution, a semi-analytical solution, or a numerical model shall be adopted. To conduct the point estimation, an objective function is formulated with the observed and predicted data. In situ horizontal stress and rock properties can be estimated by minimizing the objective function. Statistics of the estimated parameters are obtained with the statistical assessment methods presented by Zheng et al. (2021).

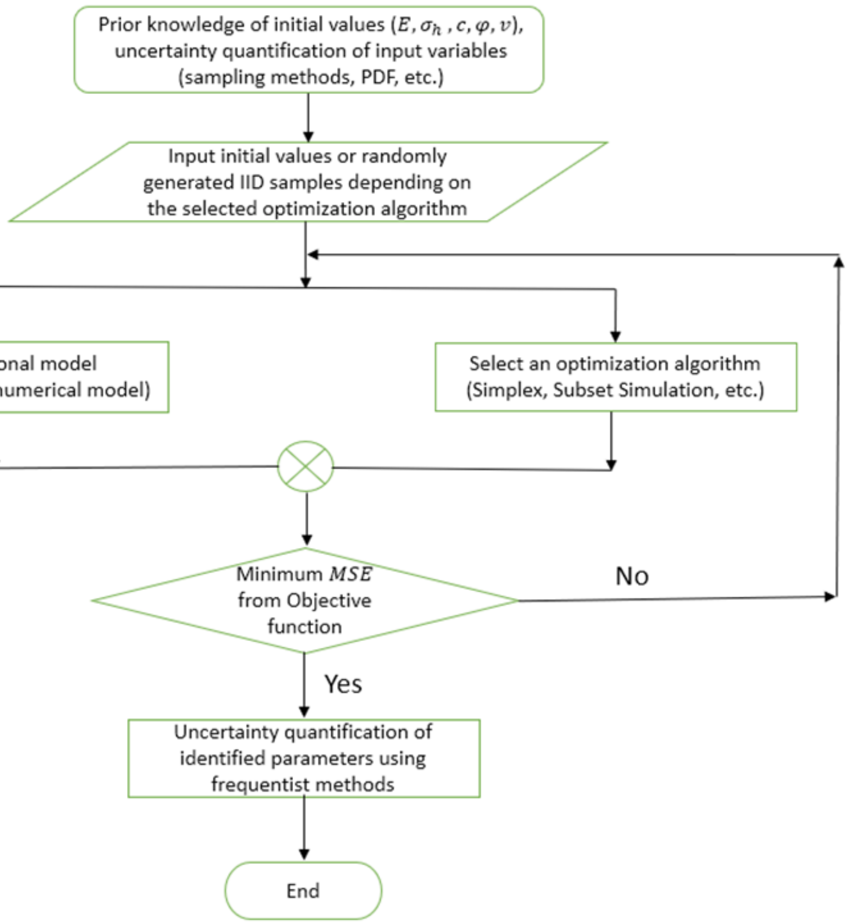
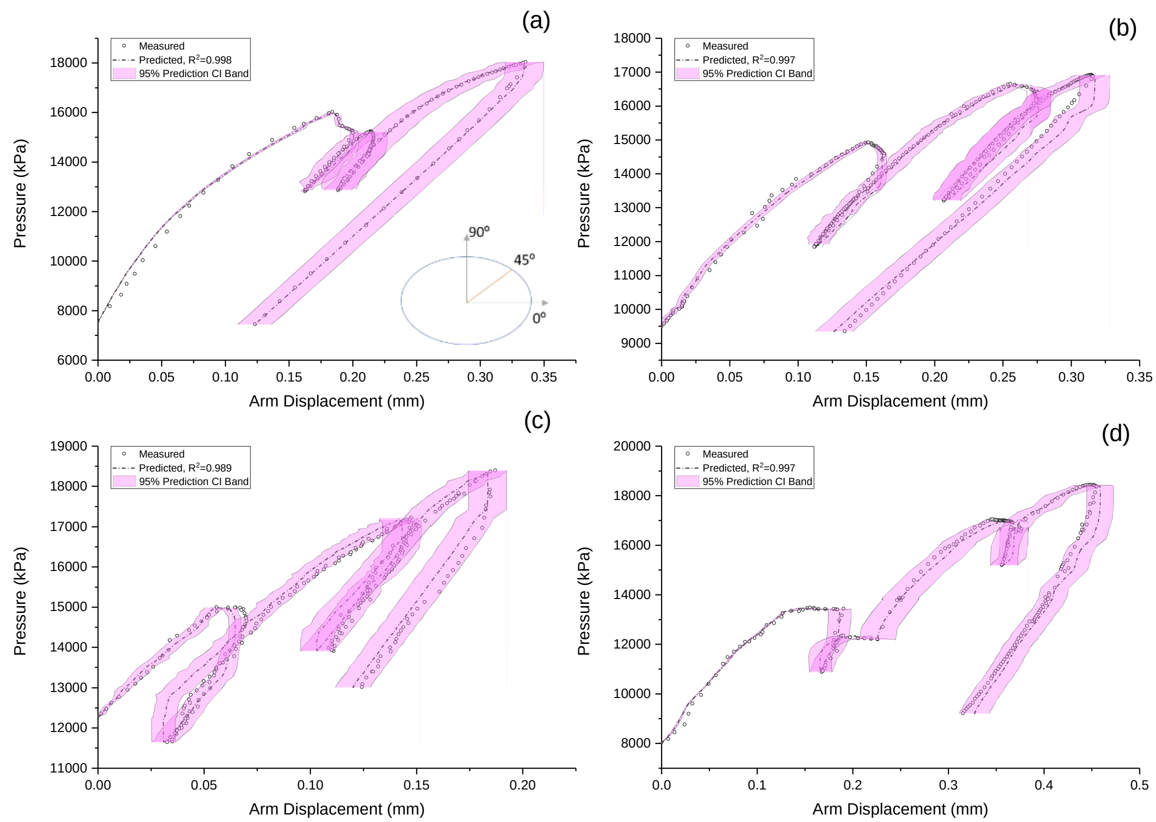


Figure 1 Flow chart of statistical inverse analysis of an RGP test

Results, Observations, Conclusions

The modified SS model has advantages over the analytical and semi-analytical solutions while considering drainage conditions and biaxial in situ boundary stresses. The constitutive behaviours of rock properties in the degraded and elastic zones during an RGP test can be well-reproduced with the proposed modified SS model. However, the computational cost is a challenge encountered in an intense inverse analysis. The SS optimizer is an advanced Monte Carlo method that consistently finds the optimal solutions in an inverse analysis. However, there exists a problem of solution uniqueness using the deterministic approach. In theory, there are unlimited combinations of the datasets to fit the curve mathematically (Houlsby 1989). Therefore, uncertainty should be quantified statistically in the inverse analysis to address the non-uniqueness issue. Compared to the conventional pressuremeter interpretation methods, the proposed statistical inverse analysis can quantify the potential uncertainty and errors from ground properties and in situ horizontal stress.



Note: (a) Westgate, (b) Joli Fou, (c) Clearwater black shale, and (d) Clearwater grey shale.

Figure 2. Fit of observed to predicted data using the numerical modelling for the complete curve at 45°

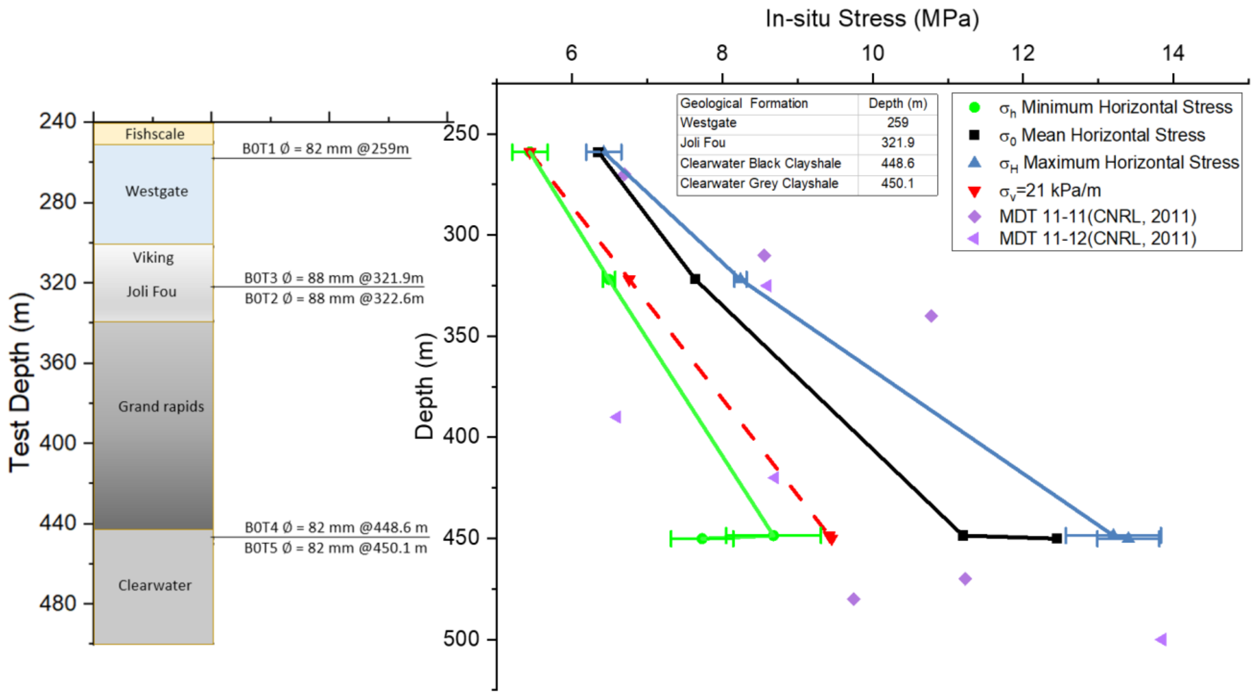


Figure 3 Profile of in situ stresses derived from statistical assessment methods using the numerical model

Novel/Additive Information

The statistical assessments of the optimal parameters can evaluate the statistics defined by the SD and CIs. Also, the model fitness can be further evaluated with the coefficients of determination R^2 and prediction intervals. The uncertainties propagated from rock properties and computational modelling can be quantified statistically. The statistical method described above can be extended to other engineering inverse analysis problems, such as pile load tests, soil nailing and anchoring tests.

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