Enhanced Metamodeling and Sensitivity Analysis for Complex Models Using Tree-PCE. Applications to Hydro-Morphodynamics Modeling.

Faten Ben Said*[1,2], Aurelien Alfonsi[2], Anne Dutfoy[3], Cédric Goeury[1,4], Julien Reygner[2], and Fabrice Zaoui[1]

[1]Laboratoire National d'Hydraulique et Environnement (LNHE) – EDF Recherche et Développement – France

[2]Centre d'Enseignement et de Recherche en Mathématiques et Calcul Scientifique (CERMICS) – Ecole Nationale des Ponts et Chausées – France

[3]PERformance et prévention des Risques Industriels du parC par la simuLation et les EtudeS (PERICLES) – EDF Recherche et Développement – France

[4]Laboratoire d'Hydraulique Saint-Venant (LHSV) – Ecole Nationale des Ponts et Chausées – France

Résumé

Numerical modeling of flow and sediment transport in open channels is a challenging issue in various engineering applications, such as river restoration, flood protection, navigation and reservoir sedimentation. Accurate numerical results are essential for optimizing strategies and reducing operational costs. However, hydro-morphodynamic modeling is affected from different sources of uncertainty, which occur in process-based models, such as inaccuracy in the model inputs, errors in model structure (e.g., poorly described or omitted physical processes), and limited computing resources. This study aims to analyze and characterize some of these uncertainties, elucidating the factors contributing most significantly to the variability of the model output. Employing Sobol sensitivity indices, a widely recognized variance-based sensitivity analysis approach, our goal is to identify influential factors, ultimately reducing model uncertainty.
In practice, the computation of Sobol indices, which involves the stochastic estimation of statistical moments and sensitivity indices, is commonly performed using the Monte Carlo method. However, this technique requires a lot of computation time that can be reduced when a surrogate model is used in place of the hydraulic solver, for instance a polynomial chaos strategy.

To conduct our simulations, we use the hydro-informatics system TELEMAC to model flow and morphodynamic changes in a channel bend. Morphological models are often nonlinear, causing model outputs to show low sensitivity to input variations until a critical morphological threshold is crossed. Accurately capturing this variability through a global polynomial approximation would require high-degree polynomials, increasing computational complexity.

Inspired by regression trees in supervised learning, we propose an adaptation of the Polynomial Chaos Expansion (PCE) method, called Tree-PCE, to address this challenge in complex

*Intervenant

models. This approach decomposes the input domain into hyper-rectangular subdomains, indexed by a binary tree, where local PCE is applied within each subdomain. By minimizing the influence of irregularities within these subdomains, the method enables the use of local low-degree polynomial approximations. The resulting local metamodels effectively capture the model's behavior in each region, significantly improving the representation of complex dynamics. In contrast, a global polynomial model would require a much higher degree to achieve comparable performance. Moreover, a by-product of this approach is an analytical formula allowing the computation of global Sobol indices from the coefficients of the local PCE with almost no additional cost.

In summary, the proposed method provides a cost-effective solution for uncertainty quantification of complex model behaviors, particularly in hydro-morphodynamic modeling, by enhancing the precision of metamodeling and Sobol indices estimation. The results demonstrate its potential to significantly improve the accuracy and reliability of model predictions, especially when addressing complex dynamics.

Mots-Clés: Hydromorphodynamic, TELEMAC, Sensitivity Analysis, Sobol' indices, Polynomial Chaos Expansion, Tree Polynomial Chaos Expansion