

Physics-Informed Neural Networks for monitoring slow slip events in a spring-slider system

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The episodic transient fault slips called slow slip events (SSEs) have been observed in many subduction zones. These slips often occur in regions adjacent to the seismogenic zone during the interseismic period, making monitoring SSEs significant for understanding large earthquakes. Various fault slip behaviors, including SSEs and earthquakes, can be explained by the spatial heterogeneity of frictional properties on the fault. Therefore, estimating frictional properties from geodetic observations and physics-based models is crucial for fault slip monitoring. In this study, we propose a Physics-Informed Neural Network (PINN; Raissi et al., 2019)-based new approach to simulate fault slip evolutions, estimate frictional parameters from observation data, and predict subsequent fault slips. PINNs, which integrate physical laws and observation data, represent the solution of physics-based differential equations using a neural network (NN). As a first step, we validate the effectiveness of the PINN-based approach using a single-degree-of-freedom spring-slider system obeying a rate and state friction law (Yoshida & Kato, 2003) to model SSEs.

In the PINN-based approach, we construct NN for solving the physics-based differential equations as a forward problem. NN learns the behavior of the equation by defining the loss function considering the misfit between target equations and derivatives of the network output calculated by automatic differentiation. To calculate the temporal evolution of the slip velocity v and state variable θ in a spring-slider model, we constructed NN using the loss function as $L = L_{\text{ini}} + L_{\text{ode}}$ where L_{ini} and L_{ode} represent the residuals of the initial conditions and those of the governing equations, respectively. We optimized NN parameters to minimize the loss function L by the L-BFGS method. The calculation result indicates that the PINN-based method can calculate the temporal evolution of SSE similar to the ordinal numerical integration approach.

Next, we extend a forward problem for simulating fault slips to an inverse problem for estimating unknown frictional parameters from the observation data. We estimate three frictional parameters a , $a-b$, and d_c by giving the slip velocity as the observation data into the neural network. To extend to the inverse problems, we add a misfit term related to observed data L_{data} to the loss function used in the forward problem, allowing us to simultaneously learn from the observation data and physical laws. We optimized three frictional parameters and NN parameters to minimize the loss function, which enables us to obtain the estimated frictional parameters and the solution of the differential equation simultaneously. We utilized synthetic slip velocity data to verify whether we can estimate the frictional parameters using the PINN-based approach. After the training, we successfully estimated true frictional parameters and obtained the true solutions. This indicates that PINNs have the great potential for frictional parameter estimation.

Furthermore, we discussed the potential of the predictability of the subsequent fault slips using limited observation data. We consider situations where slip velocities are partially observed, meaning that SSE is currently ongoing, and we aim to predict its future evolution. Finally, we achieved the evaluation of the probability of future fault slip using the PINN-based approach, and the likelihood of accurate fault slip prediction increased with longer observation periods.

Reference

Rikuto Fukushima, Masayuki Kano, Kazuro Hirahara. Physics-Informed Neural Networks for fault slip monitoring: simulation, frictional parameter estimation, and prediction on slow slip events in a spring-slider system. ESS Open Archive. July 20, 2023.