Title	説明可能な機械学習とマルチソース空間データに基づくグリッドレベルの雪害リスク評価とレジリエンスモデリング
Author(s)	楊, 振宇
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Description	Supervisor: 郷右近 英臣, 先端科学技術研究科, 博士

Dissertation Abstract

Approximately 60% of Japan's land area and 20% of its population are affected by heavy snowfall each year. Snow disasters often trigger traffic accidents and congestion, resulting in significant casualties and economic losses. These events pose severe challenges to urban transportation systems, residents' travel safety, and regional emergency response capacity. Traditional disaster response models struggle to accurately and promptly identify high-risk areas, limiting the effective allocation of disaster prevention resources. Against this backdrop, developing snow disaster risk identification and resilience assessment models based on multi-source spatial data and explainable machine learning is of great significance for enhancing urban disaster preparedness and promoting sustainable regional development.

This study takes the 2018 heavy snowstorm in Fukui Prefecture as a case study and proposes a grid-scale risk modeling framework integrating multi-source spatial data, including mobile GPS data, road data, land use data, digital elevation models (DEM), urban area data, snow depth data, traffic congestion data, nighttime light data (DNB), and the Normalized Difference Vegetation Index (NDVI). The dissertation consists of four core components: (1) Based on KDTree nearest-neighbor matching and singular value decomposition (SVD), the study performs dimensionality reduction on the spatiotemporal OD matrix to analyze the evolution of intercity travel patterns during the snowstorm and reveal disruptions in transportation demand structures; (2) A grid-level analysis of major roads in Fukui Prefecture is conducted to identify critical congestion points along National Route 8 and the Hokuriku Expressway. A Random Forest-based traffic congestion identification model is developed to assess snowstorm-induced traffic bottlenecks；(3) A "triangular resilience framework" is established to evaluate robustness, vulnerability, and adaptability across land use types at a 500-meter grid level using elastic triangle theory, quantifying the disaster resilience of various urban functional zones; (4) Multiple machine learning models, including Multilayer Perceptron (MLP), Decision Tree (DT), Random Forest (RF), Support Vector Machine (SVM), Light Gradient Boosting Machine (LightGBM), and Extreme Gradient Boosting (XGBoost), are applied to classify high-risk snowstorm areas. SHapley Additive exPlanations (SHAP) values are used to interpret the models, revealing key influencing factors and nonlinear threshold effects, thereby generating interpretable spatial risk maps to support disaster early warning and emergency response.

The major findings are as follows:

(1) Using KDTree and SVD, the study identifies spatiotemporal patterns of transportation demand in Fukui during the snowstorm. The snow event can be divided into three phases: stable (Jan 27–Feb 2), disaster (Feb 3–Feb 11), and recovery (Feb 12–Feb 16). Intercity travel demand declined by 67.86% during the snowstorm. Demand patterns included regular demand (M_1) from cities such as Fukui, Sabae, Awara, and Sakai, and special demand (M_2), where northbound trips nearly ceased, shifting from a longitudinal pattern along National Route 8 and the Hokuriku

Expressway to a horizontal pattern toward Ono and Katsuyama. Travel outflows from Sakai dropped significantly, while Tsuruga's inflows increased, indicating the snowstorm's primary impact on northern Fukui, particularly Fukui City and Sakai.

(2) GPS data effectively captures population dynamics along road networks. In the case of the 2018 Fukui snow disaster, all locations where traffic volume surged sharply during the snowstorm were situated in urban areas, with predominant land use types being fields and forests. This phenomenon may be attributed to factors such as inadequate transportation infrastructure, the urban heat island effect, and steep terrain conditions. By integrating remote sensing data and GPS data with machine learning models, congested road sections can be effectively identified. Feature importance analysis highlighted the most influential variables in predicting congestion as follows: Snow Depth > Nighttime Light Difference > Elevation > Slope Angle > Urban Area > NDVI > Population Change > Forest > Field > Low-rise Buildings (Sparse) > Low-rise Buildings (Dense).

(3) The resilience of different land use types is evaluated at the 500-meter grid scale using the triangular resilience method. The results show that factory zones, agricultural areas, building land, and mid-/high-rise buildings demonstrate strong resilience, especially in their ability to absorb and recover from shocks. Prioritizing resilient building forms in urban planning can significantly improve disaster readiness. In contrast, sparse low-rise housing, parks, facilities, and dense low-rise neighborhoods exhibit weaker recovery and require targeted strengthening measures.

(4) By combining XGBoost and SHAP, an interpretable spatial risk assessment model is developed. The model quantifies high-risk areas and identifies key drivers with nonlinear relationships and threshold effects. Elevation, slope, DNB, NDVI, road density, and road width show significant nonlinear influences on snow risk. Snowstorms primarily affect primary and secondary roads, while rural roads are relatively less impacted. Real-time GPS monitoring and optimized road layouts can help improve transportation resilience during snow disasters.

The main innovations of this study are as follows:

(1) Integration of multi-source spatial data (GPS, land use, DEM, road networks, nighttime light, NDVI), providing a solid data foundation for high-precision modeling and interpretability analysis; (2) Combination of SVD and trajectory analysis to reveal dynamic disruptions in transportation demand during snowstorms; (3) Proposal of a "triangular resilience index" system (robustness, vulnerability, adaptability) to quantify resilience at a 500-meter grid level; (4) Application of XGBoost and SHAP to identify nonlinear relationships and threshold effects of key factors, enhancing interpretability and practical usability; (5) The proposed modeling framework demonstrates strong adaptability and transferability, applicable to other natural disasters such as floods, typhoons, and tsunamis. It supports the investigation of critical impact mechanisms and resilience under different disaster scenarios.

This research provides scientific evidence for forecasting transportation risks during snow disasters in the Hokuriku region of Japan, optimizing urban functional zone layouts, and guiding disaster preparedness. It contributes to enhancing the overall resilience of urban systems in the

context of climate change.

Keywords: Snow disaster; multi-source data; spatiotemporal characteristics; resilience; machine learning; SHAP