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Advanced Abrasion Prediction: High-Dimensional Damage Mapping in Sediment Bypass Tunnel Using Machine Learning

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Introduction

The intensifying effects of climate warming have significantly altered global rainfall patterns, often exceeding normal levels. This increase in rainfall accelerates sedimentation, posing severe challenges to hydraulic infrastructure, including Sediment Bypass Tunnels (SBTs). These tunnels, designed to divert sediment-laden flows around reservoirs, suffer abrasion damage due to the high-velocity, sediment-rich flows, undermining their functionality and longevity. Addressing this issue is critical, as traditional abrasion prediction models often rely on average-based estimates, lacking localized damage detection. This creates a knowledge gap in understanding the spatial variability of abrasion damage and its influencing factors.

Study Objective

To overcome these limitations, this study proposes a novel machine learning (ML) framework for abrasion prediction, incorporating high-resolution topography data, hydraulic conditions from eight successive flood events, and geometric tunnel features[1,2], see **Fig** (1). This approach aims to generalize the 2D Abrasion Susceptibility Model (ASM) and the 3D Abrasion Susceptibility Depth Model (ASDM) as groundbreaking tools for localized abrasion prediction and higher-dimensional analyses, thus paving the way for innovative ML applications in hydraulic engineering.

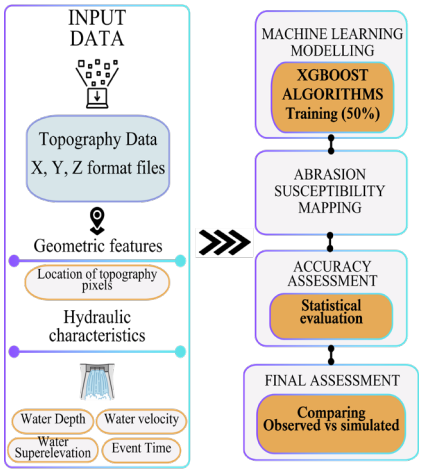

Fig 1. The parameters implemented in this investigation[3].

Methodology

Study Area and Data Collection

The Koshibu SBT in Japan, a four-kilometer-long tunnel with straight (S) and curved (C) sections, was selected as the study area, **Fig** (2). High-resolution laser scanning at 2 cm intervals was conducted to collect floor abrasion data. The hydraulic conditions during eight flood events, spanning 2016 to 2018, were recorded, capturing maximum discharge magnitudes ranging from 60 m³/s to 200 m³/s.

Machine Learning Models

The machine learning framework uses two primary models for abrasion prediction based on the XGBoost algorithm:

- **2D (ASM) model**: A classification model to identify damaged versus undamaged areas.
- **3D (ASDM) model**: A regression model to predict the depth of abrasion in affected zones

The dataset consists of approximately 1,161,352 data

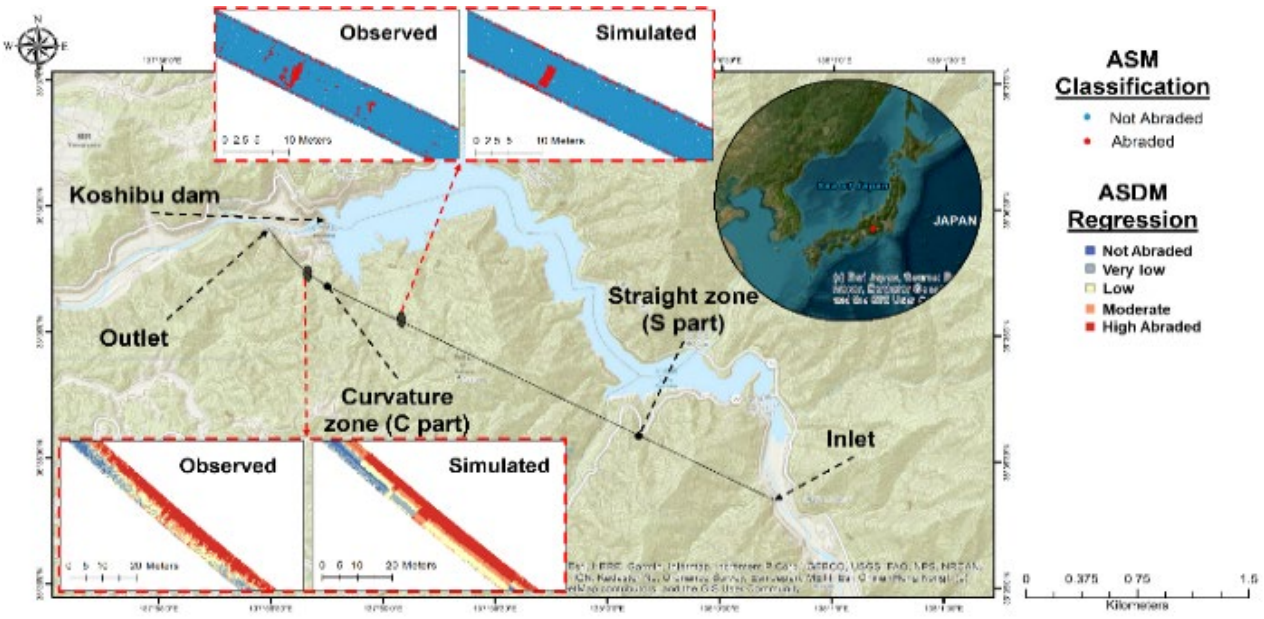

Fig 2. The Considered Parts of Koshibu SBT and Comparative Analysis: Abrasion Susceptibility Mapping.

points distributed throughout the tunnel. Half of these points are designated for training the models, while the other half are allocated for testing.

Results and Discussion

This study shows that the ASM and ASDM models provide high-resolution predictions for abrasion susceptibility and depth (see **Fig** 2). The ASM model achieved about 80% accuracy for (S) sections, while the ASDM had a correlation coefficient of 86%. Excluding individual flood events kept model performance robust at around 80% accuracy (**Fig**.3). Including specific flood events, especially intense ones, improved performance, highlighting the need for event-based data in accurate post-event damage prediction.

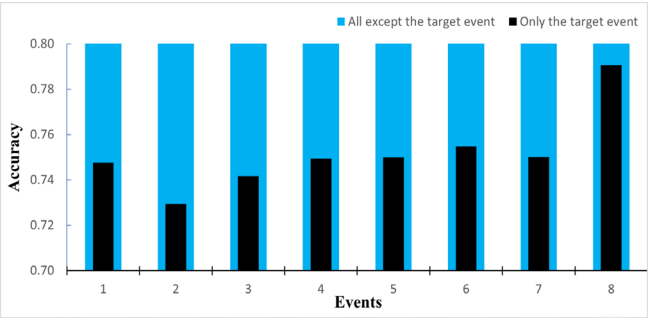

Fig 3. Event-based impact on ASM accuracy[1].

Conclusion and Contribution

This study introduces an ML-based framework for predicting abrasion damage in SBTs, enhancing traditional models reliant on average abraded volume estimates. It provides a detailed approach by integrating high-resolution topography, hydraulic features, and geometric factors. The ASM and ASDM models serve as innovative predictive tools for future flood events, enabling a multidimensional view of abrasion damage prediction.

These findings are vital for optimizing SBT maintenance, aiding sediment management in reservoirs, and reducing abrasion damage risks. They also demonstrate the broader use of machine learning in improving hydraulic infrastructure resilience.

References

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