

## “Technical Research and Development for Road Policy Quality Improvement” Study Summary

| No.        | Title                                                                                                                                                                                                        | Principal Researcher                                  |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|
| No. 2023-3 | Technical Research and Development on Residual Bearing Capacity Evaluation and Rational Restoration/Reinforcement of Rockfall Protective Soil Embankments Subjected to Impact Histories Using Soil Materials | Nagoya Institute of Technology<br>Prof. Kenichi Maeda |

To realize robust and environmentally harmonized road slope disaster prevention systems, this study focuses on rockfall protective soil embankments with superior cost-efficiency, constructability, durability, and restorability. The objective of this research is to establish residual bearing capacity evaluation methods, new reinforcement technologies, performance-based design flows, and maintenance/restoration technologies after rockfall capture through an integrated approach combining experiments, numerical simulations, and investigations of actual embankments.

### 1. Backgrounds and Objectives

In recent years, the risk of rockfall disasters has rapidly increased due to frequent heavy rainfall events, earthquakes, and long-term weathering of rock slopes. At the same time, aging infrastructure and increasing maintenance costs have become serious social issues, requiring long-life, rational maintenance, and resilient road disaster prevention systems. Under these circumstances, “rockfall protective soil embankments,” which have advantages in constructability, economy, and restorability, have attracted increasing attention. However, deformation and failure mechanisms during rockfall impacts, residual bearing capacity after impact, and rotational rockfall behavior had not been sufficiently clarified, and performance-based design and maintenance systems had not yet been established. Therefore, this study aimed to establish:

1. residual bearing capacity evaluation methods,
2. new reinforcement technologies,
3. rational performance verification methods using numerical simulations,
4. restoration and maintenance decision-making methods after impact events, and
5. performance-based design flows.

### 2. Activities in Research Period

This study integrated small-scale, medium-scale, and full-scale-equivalent impact experiments, DEM analyses, FEM analyses, and field investigations of actual embankments to establish a performance verification system for rockfall protective soil embankments.

Pendulum-type and rotational drop-weight impact experiments were conducted to investigate rotational rockfall behavior, internal shear band formation, damage propagation, and residual bearing capacity mechanisms. Colored sand markers, UAV-SfM measurements, 3D displacement measurements, dynamic cone penetration tests, and soil hardness tests were used to relate surface deformation to internal damage.

Furthermore, DEM analyses reproduced rotational motion, frictional resistance, and stress propagation, while FEM analyses were performed to investigate the impact resistance behavior of full-scale embankments. In addition, new reinforcement technologies combining steep slope embankments and soil-cement reinforcement were developed. A performance-based design flow integrating maintenance, life cycle cost (LCC), and restorability was also proposed.

### 3. Study Results

This study clarified that the capture performance of rockfall protective soil embankments consists of:

- ① penetration-induced local energy absorption,
- ② rotational energy dissipation by rotational resistance and friction,
- ③ effective height against run-up behavior, and
- ④ punching shear resistance capacity.

Furthermore, this study clarified the “trade-off structure” (the synergistic and competing relationships) among steep slope geometry, soil-cement reinforcement, and soil deformation characteristics. The study demonstrated that embankments are not structures that should simply be made “stronger,” but

structures that require optimization between energy absorption and failure control.

This study also redefined soil embankments:

- from “fragile structures” to “energy absorption structures,”
- from “weak structures” to “rational and sustainable protective structures,”

thereby demonstrating a “paradigm shift” from “empirical structures” to “designable structures.”

In addition, scaling laws were discovered:

- peak load proportional to scale ratio<sup>2.4</sup> / ultimate load proportional to scale ratio<sup>2.7</sup>,

providing a pathway toward rational performance verification methods without excessive dependence on costly full-scale experiments. Furthermore, a maintenance framework integrating: “damage triage (maintenance prioritization based on damage level)” and “inspection → residual bearing capacity evaluation → partial repair → continued use” was proposed together with a performance-based design flow.

#### 4. Papers for Presentation

*Selected peer-reviewed journal papers are listed below.*

Yoshiyuki Oguri, Kenichi Maeda, Keisuke Kondo, Takuro Nakamura, Yuji Ushiwatari, Naoto Naito, Masato Komuro: “Deformation, resistance characteristics, and scale effects of rockfall protection soil embankments under static loading,” *Soils and Foundations*, 65(4), August 2025.

In addition: 4 international conference presentations (including 1 invited lecture), 45 domestic conference presentations. Academically, the paper published in *Soils and Foundations*, one of the world’s leading geotechnical journals, received the Japanese Geotechnical Society Paper Award. In addition, the study team received 15 awards including excellent presentation awards, demonstrating the originality and social significance of this research

#### 5. Study Development and Future Issues

This study established the foundation of performance-based design, residual bearing capacity evaluation, maintenance, and restoration systems for rockfall protective soil embankments. In the future, it will be necessary to develop an integrated “rockfall protection system design” considering slopes, pockets, and embankments as one system. Important future issues include:

- advanced rotational rockfall behavior models,
- optimization of energy sharing,
- residual bearing capacity evaluation under multiple impacts,
- massive rockfall groups and simultaneous multiple rockfalls.

Furthermore, large-scale rock slope collapses and massive rockfall groups observed during the 2024 Noto Peninsula Earthquake will become increasingly important issues in future road disaster prevention. In addition, further verification of the proposed scaling laws using full-scale embankments is expected to establish rational performance verification methods using scaled models. This study aims to contribute to low-cost and highly resilient road disaster prevention technologies applicable nationwide and internationally.

#### 6. Contribution to Road Policy Quality Improvement

This study systematized rotational capture performance mechanisms, residual bearing capacity evaluation methods, performance-based design flows, and maintenance/restoration methods for rockfall protective soil embankments, thereby redefining embankments from “empirical structures” into “designable resilient protective structures.”

Particularly, the proposed rational maintenance framework:

“inspection → damage triage → residual bearing capacity evaluation → partial repair → continued use” is expected to significantly improve decision-making processes for road administrators.

Furthermore, the proposed scaling laws:

- peak load proportional to scale ratio<sup>2.4</sup>,
- ultimate load proportional to scale ratio<sup>2.7</sup>,

provide a pathway toward rational performance verification methods without excessive dependence on costly full-scale experiments.

Life cycle cost evaluations including maintenance, restoration, and replacement demonstrated that long-term costs over 100 years could differ by factors of 5–10 compared with conventional countermeasures. The outcomes of this study are expected to contribute to future technical standards such as the “Rockfall Countermeasure Manual,” nationwide deployment of low-cost and highly resilient road disaster prevention technologies, and the establishment of next-generation road slope disaster prevention systems.

#### 7. References, Websites, etc.

Laboratory Website: <https://www.maeda-lab.org/>

Introduction article on the Japanese Geotechnical Society Paper Award (To be published)