Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-486

Reliability of Rockfall Protection Foundations: Insights from Full-Scale Tests

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ABSTRACT: Rockfall protection nets provide effective protection for infrastructure and settlements against rockfalls, but their reliability largely depends on the bearing capacity and durability of the foundation. The design and construction of the foundation are influenced by soil conditions and national standards. Micropiles are commonly used as the foundation and are almost always subjected to impact loading during rockfall events. To date, the design guidelines for these micropiles have mainly been based on measurement results or experiences from static pile load tests. Between 2020 and 2023, extensive real-scale experiments (approximately 175 tests) were conducted at the Geotechnical Department of the University of Innsbruck, in collaboration with partners such as the Bavarian State Building Directorate, Austrian Federal Railways, Swiss Federal Railways, Rhaetian Railway and the Torrent and Avalanche Control Austria. To investigate rockfall protection foundations, micropiles and post foundations were subjected to impact loads in realistic experiments. A pendulum was used to generate impact loads on the micropiles and post foundations. Concrete cubes weighing 1050 kg or 2860 kg were lifted by a steel rope and released pneumatically to create the impacts. These tests, including various steel bars, provided valuable data on load capacity and failure behaviour under realistic conditions. Around 1350 meters of micropiles were tested for load capacity and after the tests, the piles were excavated to examine their grout bodies. The results confirmed the need for concrete foundations in granular soils and revealed optimization potential, especially through the introduction of pipe reinforcements. These reinforcements, installed near the surface, significantly increase the bending stiffness of the micropiles and enhance their resistance to impact loads. The results of these experiments are being integrated into new standards, such as RVS 08.22.02, further improving the reliability and durability of rockfall protection foundations.

KEYWORDS: rock fall, post foundation, micropile, lateral impact load, experiment.

1 INTRODUCTION

Rockfall protection nets are proven and cost effective measures for reducing the risk of rockfall damage. To provide adequate protection the net must both catch the falling rock and absorb its kinetic energy. The forces generated in this process are transferred into the ground by a properly designed foundation. In Europe the certification of rockfall protection nets requires full scale testing in accordance with the European Assessment Document EAD 340059 00 0106 (EOTA, 2018). The foundation itself is not part of the certified system and must be designed and dimensioned according to national regulations and local site conditions.

Measuring the forces acting on a post foundation during a rockfall event is a complex task. Gerber (2005) proposed an early method to estimate the lateral forces on the post foundation using the lower support rope and this method is still used today. Volkwein et al. (2016) developed a sensor capable of recording all forces on a post foundation. The forces measured or estimated in certification tests are used as the basis for designing rockfall protection foundations for specific projects. These structures typically use micropiles which are subjected to high impact loads during an actual rockfall event. Arndt et al. (2013) carried out full scale tests to investigate the load bearing behavior of post foundations though the types tested were very different from those commonly found in Europe.

Cavziezel et al. (2022) performed experiments in natural terrain using instrumented blocks that were given rotational motion. The results showed forces in cables and foundations up to thirty percent higher than those in standard EAD based tests. The load bearing behavior of the foundation under these conditions was not examined. To address this gap the University of Innsbruck began a research project in 2020 to study the capacity and serviceability of rockfall protection foundations.

2 EXPERIMENTAL CONCEPT

The impact on a rockfall protection foundation involves a complex interaction between the micropile and the surrounding soil. To study this behaviour full scale tests were conducted. A pendulum with a mass of 1000 kg or 2500 kg was suspended from a 7 m high steel frame (Figure 1). The pendulum mass was connected to the foundation using a steel rope so that the foundations were subjected to realistic impact loads. To load multiple foundations from a single pendulum setup a pulley was installed behind the pendulum (Wimmer, 2025).

In 2020 initial impact load tests were performed on single micropiles. Both solid and hollow bars were tested under different directions of loading including axial inclined at 45° to the axis and lateral. The results were compared with additional static pile tests. After the tests all micropiles were excavated and the grouting inspected for damage.

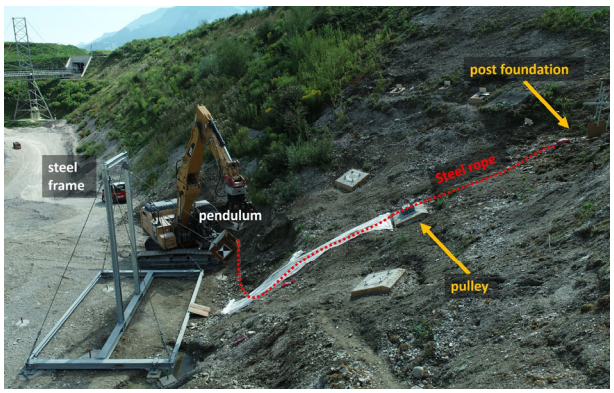

Figure 1. Pendulum for the impact loading of post foundations.

In 2021 testing focused on common post foundations with various steel beam arrangements in flat areas. In 2022, these findings were used to evaluate the performance of various post foundations, both with and without reinforced concrete foundation and pipe reinforcements, in terrain with a slope angle of 35°.

The knowledge gained from these experiments was used to adapt and improve current designs to achieve durable and economical foundations. The pile head system (Figure 2) consisting of pipe reinforcement, with a head connection close to the ground, was evaluated under impact conditions. This system had already been tested by the torrent and avalanche control organization for practical installation in alpine terrain.

In 2023 designs of post foundations were further adapted to significantly improve durability and serviceability.

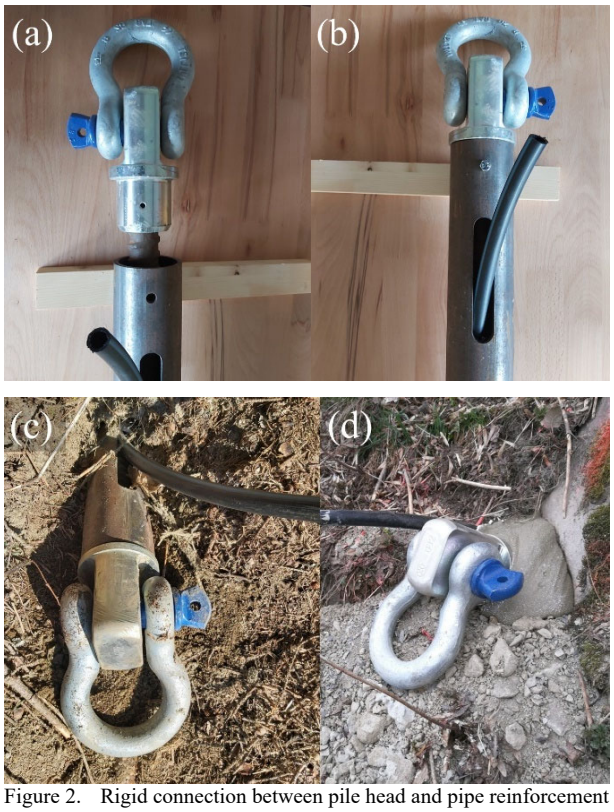

Figure 2. Rigid connection between pile head and pipe reinforcement (a, b) and built-in pile head system in alpine terrain (c, d).

3 FINDINGS AND ANALYSIS

The first guideline focused exclusively on rockfall protection foundations RVS 08.22.02 was developed to provide practical and proven construction specifications. The impact load tests conducted at the Unit of Geotechnical Engineering at the University of Innsbruck with numerous project partners served as the basis for these recommendations.

The tests demonstrated that using a pile head system during an eccentric impact does not damage the grouting. In contrast a classic steel head without pipe reinforcement can lead to flaking of the grout under similar impact conditions. The anchor head system developed by the torrent and avalanche control organization consists of a head connection close to the ground which is rigidly connected to the pipe reinforcement. A slit in the steel pipe guides the grouting tube required for backfilling the micropiles. During filling care must be taken to completely fill the head connection.

Impact tests on previous single pile and post foundation designs in full scale were used to adapt earlier constructions. Even at the investigated load levels of up to 350 kN no ultimate failure of the post foundations was observed. The tests clearly demonstrated that the use of concrete foundations reduces damages of the cement grout at the micropiles. The deformations and damage occurring in the foundations were found to depend on the arrangement of the micropiles within the foundation as well as the size of the concrete foundation. The concrete foundation should have minimum dimensions of 100 x 60 x 30 cm in order to allow proper reinforcement placement and to reduce the occurrence of cracks in the concrete. Examination of the exposed micropiles without pipe reinforcements showed insufficient coverage of the cement grout in the zone from the micropile to the concrete foundation (Figure 3). These deficiencies were significantly improved by using pipe reinforcements extending into the concrete foundation (Figure 4).

Figure 3. No cement grout coverage at the transition to the concrete foundation.

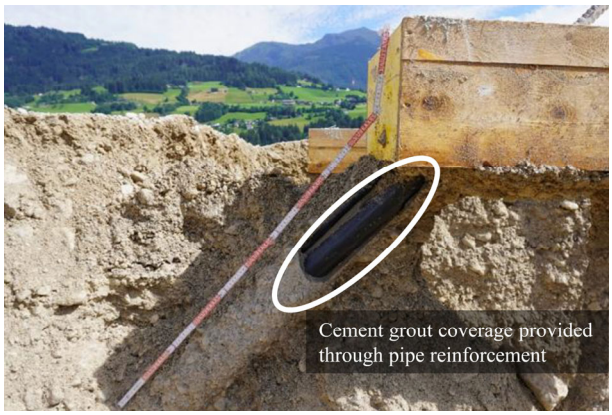

Figure 4. Improved cement grout coverage of the steel bar achieved through pipe reinforcement.

These findings form the basis for durable post foundations and led to the development of new post foundation designs. The recommended system consists of a reinforced concrete foundation and micropiles with pipe reinforcements (Figure 5). The design is intended to be compatible with various types of micropile systems including both solid and hollow bars as well as different post plate configurations. In the experiments the newly designed post foundations were subjected to impact loads at both MEL and SEL and were compared with previous foundation systems.

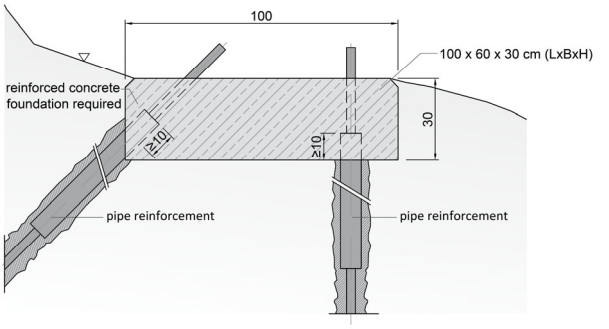

Figure 5. Recommended execution of a post foundation with a reinforced concrete foundation and pipe reinforcement on the micropiles.

Overall the experiments confirmed that the combination of pipe reinforcement and concrete foundations improves the bending stiffness durability and performance of micropiles under impact loads.

4 FINAL REMARKS AND RECOMMENDATIONS

In this research project a total of 175 rockfall protection foundations were analysed under impact loads. Additionally, 60 static pile tests were carried out. After completing the tests all 1350 meters of micropiles were excavated and their grouting thoroughly examined. The data obtained from these experiments together with practical experience form the foundation for current design recommendations for rockfall protection foundations (Figure 6).

It is strongly recommended that single micropiles are constructed using a pile head system. This system which consists of pipe reinforcement and a pile head located close to the ground significantly reduces the risk of grout spalling under eccentric impact loads. The use of such a system ensures that the steel tendon is completely enclosed in grout providing both structural safety and long-term durability.

For post foundations it is essential to use sufficiently large concrete foundations. Reinforcement must fully enclose the tension and compression piles to guarantee that the transition between the concrete foundation and the subsoil is completely protected. The research demonstrated that pipe reinforcements should be applied to all micropiles which ensures the steel support element is fully embedded in grout. This approach considerably increases bending stiffness serviceability and durability of the micropiles under repeated or extreme impact conditions.

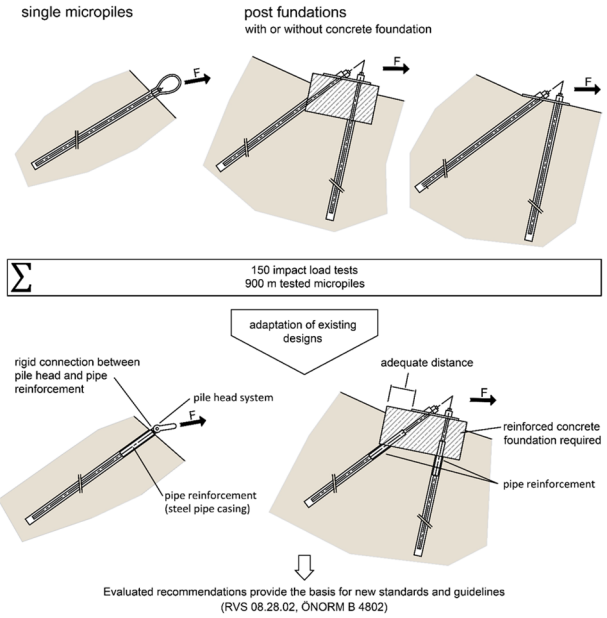

Figure 6. Previous single pile and post foundation designs were tested with full-scale impacts (top). The test results were used to update and improve the designs (bottom).

The results of the project provide a clear and practical basis for improving both existing and future rockfall protection foundations. They emphasize that careful attention to foundation design selection of appropriate reinforcement and the correct execution of pile head systems are critical factors in achieving effective long-term protection. The insights gained through this study allow engineers to design more resilient and economical foundations that maintain their performance even under extreme rockfall events.

5 ACKNOWLEDGEMENTS

The research team acknowledges the outstanding cooperation of all project partners who contributed valuable expertise and support throughout the experimental program.

Finally, we would like to thank our project partners for their excellent cooperation. In particular, we would like to thank:

- ÖBB Infrastruktur AG
- Landesbaudirektion Bayern Referat 55 - Ingenieurbauwerke und Georisiken
- SBB AG
- Rhätische Bahn AG
- Wildbach- und Lawinenverbauung – Sektion Tirol
- Mair Wilfried GmbH

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