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Sustainability in Rockfall Protection Works: State-of-the-Art and LCA-Based Approaches

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Abstract

Starting from the early 2000s, the concept of sustainability has been progressively integrated into the design of civil works, through the reuse of excavation and demolition materials, the reduction of non-renewable resource consumption, the mitigation of landscape impacts, and the improvement of structural durability. Considering the high environmental impact of the construction sector - both in terms of natural resource and energy consumption and in the large volumes of waste generated - it is necessary to orient design practices toward sustainability. Geotechnical engineering can make a significant contribution to sustainable development by promoting environmentally friendly and economically viable solutions.
Despite the widespread research on rockfall, it shows a limited correlation between sustainability and rockfall protection structures. Existing studies mainly focus on block trajectory analysis, fragmentation effects or risk assessment, but they don't systematically address environmental aspects of these structures. At present, no comprehensive environmental evaluations have been conducted to consider the full life cycle of rockfall protection works and to compare alternative design solutions from a sustainability perspective. The only available data come from Environmental Product Declarations (EPD) voluntarily published by some of the leading manufacturers in the sector. In contrast, other areas of geomechanics - such as tunneling - already benefit from a regulatory framework that integrates sustainability criteria throughout project phases.
This paper aims to provide a comprehensive overview of the current state of the art concerning sustainability in rockfall protection works, analyzing existing practices and regulatory guidelines. The analysis seeks to identify the main knowledge gaps and to lay the groundwork for future research focused on environmental assessment and the application of Life Cycle Assessment (LCA) methodologies. The ultimate goal is to develop a sustainable design framework for rockfall protection structures, capable of combining environmental responsibility with the high safety standards required for this type of intervention.

Keywords

Sustainability, Rockfall protection structures, Life Cycle Assessment, Environmental impact.

1 Introduction

1.1 The development of the concept of sustainability

The concept of sustainability emergedin the context of the first international reflections on the environmental impact of human activities. In 1972, the United Nations Conference on the Human Environment, represented the first major global summit dedicated to environmental issues. On that occasion, 113 nations adopted an action plan comprising 109 recommendations and a Declaration containing principles concerning human responsibilities toward the environment (United Nations 1973). This marked the official entrance of environmental concerns into the global political agenda.However, it was the United Nations' Brundtland Commission (Brundtland 1987), that in 1987 released the report "Our Common Future", in which the concept of sustainable development was formally articulated for the first time as:*"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. In the following years, efforts intensified to translate the concept of sustainability,into concrete and actionable plans.

The 1992 United Nations Conference on Environment and Development, held in Rio de Janeiro, consolidated the concept of sustainable development on a global scale. One of the oucomes was the well known Agenda 21 which states:*"Each local authority should enter a dialogue with its citizens, local organizations, and private enterprises and adopt a local Agenda 21 of its own Through consultation and consensus-building, local authorities should learn from and draw on the knowledge of local communities and the private sector to formulate the best strategies"*(United Nations 1992).

Following the Rio de Janeiro Conference, since the early 2000s, sustainability has evolved from a political principle into an operational and technical framework. In this context, the LCAmethodology was developed to monitor and control not only carbon dioxide emissions arising from industrial processes, but also the consumption of raw materials and the energy required for production. This approach enables the systematic and scientifically grounded quantification of the environmental impacts associated with the entire life cycle of a product or structure. The quantification of these parameters has been a crucial step, as it has increased awareness of the environmental impacts associated with production processes and pavedthe way for the development of mitigation strategies. The application of the LCA methodology is now regulated by international standards - UNI EN ISO 14040 and UNI EN ISO 14044 (2006)- which define the principles, requirements, and operational guidelines for conducting such assessments.

The 2030 Agenda for Sustainable Development (United Nations 2015), signed on 25 September 2015 by the Member States of the United Nations, established 17 Goals that today serve as the global reference framework for sustainable development. Among these Goals, Goal 9: '*Develop quality, reliable, sustainable and resilient infrastructure*' plays an overarching role by promoting quality, reliable, sustainable, and resilient infrastructures.

1.2 Sustainability applications in Engineering and Geotechnics

In the field of geomechanics, sustainability generally translates into the reuse of excavated and demolition materials, the reduction of energy consumption, the minimization of ecological impacts, and the design for long-term durability. For instance, in the tunnelling sector, both European and Italian regulations have progressively integrated sustainability criteria throughout all stages of the project life cycle which include the reuse of excavation materials as by-products, comprehensive environmental monitoring, improvements in energy efficiency, and the application of LCA methodologies.

Despite the extensive study of rockfall phenomena in the literature, the aspect of sustainability has not yet been sufficiently addressed in the design of mitigation works. No specific regulations or standards currently address the application of sustainability criteria to rockfall protection structures, either at the European or Italian level. A systematic review of the internationalresearch database confirms this regulatory and scientific gap. Available studies mainly focus on specific technical aspects such as volume and shape quantification of unstable rock masses, risk assessment methodologies, block trajectory modeling or fragmentation effects (Fell et al., 2008; Volkwein et al. 2011; Stavropoulou 2014; Umili et al. 2023, 2024). However, no studies have been identified that apply environmental evaluations to rockfall protection systemsor that attempt to integrate environmental impact quantification with mechanical and design parameters such as energy dissipation capacity, material usage, or structural performance. This gap underscores the need for dedicated studies aimed at developing a sustainable design framework for rockfall protection structures that can balance safety requirements with environmental responsibility. It also represents a significant limitation in a context wherethe achievement of climate neutrality objectives requires the integration of CO_2 emissions

assessments into planning and design processes. The common practice of oversizing protective structures, due to rockfall uncertainty, leads to an unnecessary increase in carbon footprint. Therefore, this approach must be re-evaluated through the lens of sustainability, while still ensuring compliance with the highest safety standards. Companies operating in this sector are showing an increasing awareness of and commitment to sustainability objectives. Leading European manufacturers such as Officine Maccaferri s.p.a., Geobrugg and Trumer Schutzbauten GmbH have published Environmental Product Declarations on a voluntary basis, providing verified data on the environmental performance of their products in accordance with the LCA methodology. These initiatives contribute to enhancing transparency and comparability within the construction sector, supporting the transition towards a circular economy in line with European sustainability policies.
The aim of this paper is to lay the groundwork for future research on environmental assessment, integrating sustainability considerations into all phases of the life cycle of rockfall protection structures.

2 Methodologies

2.1 Some guidelines to assess the sustainability of a rockfall protection project

Assessing the environmental impact of rockfall protection projects requires considering both rockfall dynamics and the production of protective systems. To achieve this, it is necessary to explore a series of key aspects that represent the foundation of the analysis and guide its development:

1) Dimensional optimization of protection works to avoid oversizing and reduce consumption of steel and concrete: Accurate estimation of block volumes is the starting point for reducing the environmental impact associated with rockfalls avoiding oversizing.
2) High-resolution geomorphological analysis to identify potentially unstable areas and preferential propagation paths: A detailed geomorphological analysis enables the identification of preferential block paths, thereby minimizing the need for extensive or unnecessary protective measures (Agliardiand Crosta 2003; Leine et al. 2021; Noël et al. 2023).
3) Barriers'planning based on the natural morphology of the slope, using depressions and ridges as natural elements to divert, slow down, or stop falling rock blocks:Utilizing existing slope features can reduce both the number and extent of required protection systems, thereby limiting landscape and environmental impacts.
4) Evaluation of design alternatives based on energy class, favoring nature-based solutions where feasible: Where possible, nature-based solutions are proposed, such as stabilizing vegetation (rockfallprotection forests), controlled slope re-profiling, and hybrid structures that integrate traditional systems with natural solutions (slope greening).
5) Minimizing earthworks and visual impact by using existing roads for site access during construction to limitlandscape disturbance and land consumption.
6) Selection of recyclable and low-impact materials with preference for locally sourced production.
7) Selective dismantling with recycling of metal components and reuse of structural parts: At the end of their lifecycle, rockfall protection structures become construction and demolition waste (CDW) that can be recovered within a circular economy framework.
8) Application of Life Cycle Assessment (LCA) principles: To quantify the actual reduction in environmental impact achieved through the application of the proposed guidelines for rockfall protection systems, it is essential to determine the carbon footprint of each design alternative and compare it with conventional approaches that do not systematically integrate sustainability into the decision-making process.

The proposed points show that reducing the environmental impact of these structures requires a comprehensive assessment beyond production-related emissions, covering all design phases.

2.2 Life Cycle Assessment of a rockfall protection barrier

While the present study considers multiple aspects of sustainability in rockfall protection, including design strategies, material selection, and end-of-life considerations, a Life Cycle Assessment (LCA) of a rockfall protection barrier is presented here as an illustrative example. This case study provides insights into the potential environmental impacts and demonstrates how the general principles outlined in this work can be applied in practice.The Life Cycle Assessment (LCA) of the product under

investigation was carried out using the SimaPro10.2 software environment, drawing on the Ecoinvent 3.11 and Industry Data 2.0 databases. The selected functional unit consists of a 3 × 10 m^2 module of a rockfall protection barrier with a maximum energy level of 2000 kJ, assembled from the following basic components (with dimensions and masses considered as generic reference values derived from the technical-scientific literature and not referring to any specific commercial product):

- Two H-shaped posts, 3 m in height. Total mass = 269 kg;
- Two base plates measuring 790 × 250 × 32 mm. Total mass = 98 kg;
- One 3 × 10 m^2 steel wire mesh with rope diameter of 9 mm. Total mass = 204 kg;
- Six retaining cables, each 6 m long and 22 mm in diameter. Total mass = 90 kg;
- Two longitudinal cables supporting the mesh, each 10 m long and 22 mm in diameter; Total mass = 50 kg
- 36 stainless steel shackles (spaced at intervals of 0.7 m). Total mass = 5.4 kg

With the exception of the stainless steel shackles, all other components of the analysed barrier are made of galvanized steel. In particular, the posts and plates were manufactured using a hot-dip galvanization process in pieces, while the mesh was produced using a galvanization process in coils. The LCA was conducted following a cradle-to-grave approach, as it also accounts for the end-of-life phase of the product. For this specific case study, the environmental assessment of the structure was limited to the Global Warming Potential (GWP) indicator, which quantifies the impact in terms of kg CO_2 eq. All data used in the analysis are secondary data, obtained from established databases and technical literature. The simulation was performed assuming a representative European context; therefore, European energy mixes and realistic transportation distances were considered. In particular, a transport distance of 300 km by Euro 5 heavy-duty lorry was assumed for all transport stages.In the conducted life cycle assessment, the assembly and disassembly phases of the rockfall protection structure are not considered, as their environmental impact is considered negligible compared to the other life cycle stages, and are therefore excluded from the system boundaries. Fig. 1 presents the flow diagram of the production processes and transportation stages involved in the manufacturing of the investigated rockfall protection barrier.

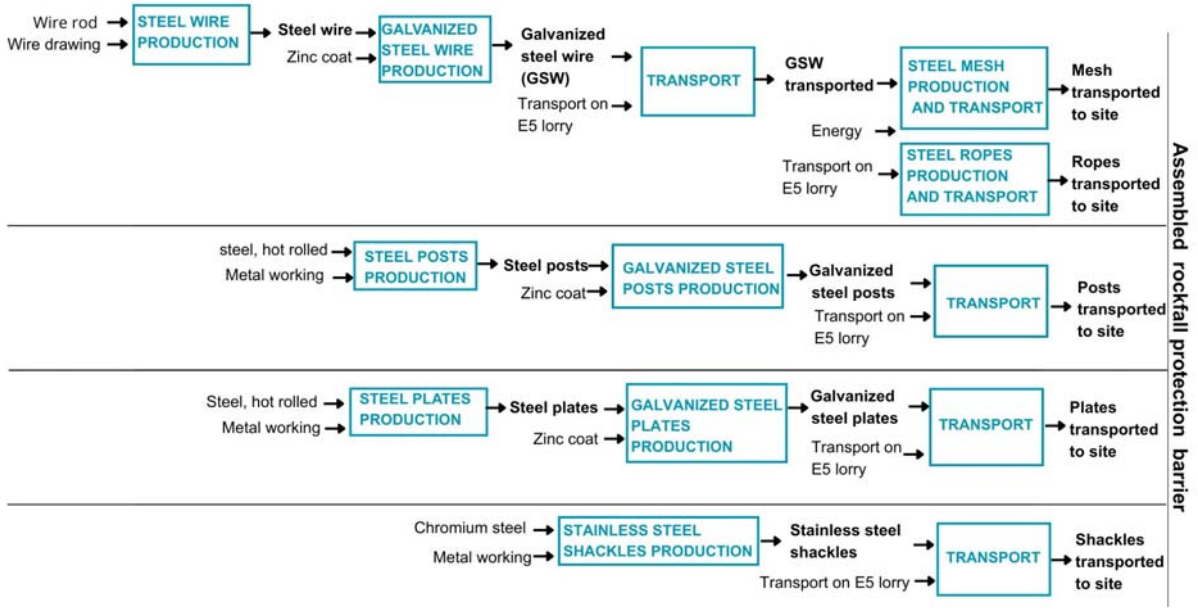


Fig. 1 Flow diagram of the production processes and transportation stages involved in the manufacturing of the investigated rockfall protection barrier.

Once the product was assembled, its end-of-life was modelled through a scenario assuming that the posts and base plates were not damaged during service and could therefore be reused, while the remaining components were recycled. For the recycling treatment, a transport distance of 100 km by Euro 5 heavy-duty lorry was assumed. This distance was estimated as the transportation required to deliver the end-of-life components to recycling facilities.

The ReCiPe 2016 Midpoint (H) method was employed to quantify the impact on climate change indicator associated with the life cycle of the investigated rockfall protection barrier. Rockfall protection structures and their associated components exhibit a highly variable service life, as it depends on the occurrence and frequency of rockfall events.

For this study, two consecutive life cycles of the same structure were modeled. In the first life cycle, all posts and plates are assumed to be reused and therefore enter a second life cycle. At the end of the second life cycle, these components are sent to a recycling facility together with the remaining components of the barrier. As a result, when considering the two life cycles as a whole, an overall reuse rate of 50% is assumed for posts and plates.

3 Results

The life cycle model indicates that the CO_2 eq. emissions associated with the production of the rockfall protection barrier amount to 2.6×10^3 kg CO_2 eq. The majority of these emissions are attributable to the production of the steel from which the structure is entirely composed. Consequently, the implementation of an appropriate end-of-life treatment is crucial for mitigating the overall environmental impact of such structures. Indeed, the end-of-life scenario results in a substantial reduction of total CO_2 emissions, lowering the impact to approximately 1.19×10^3 kg CO_2 eq. (Fig. 2).

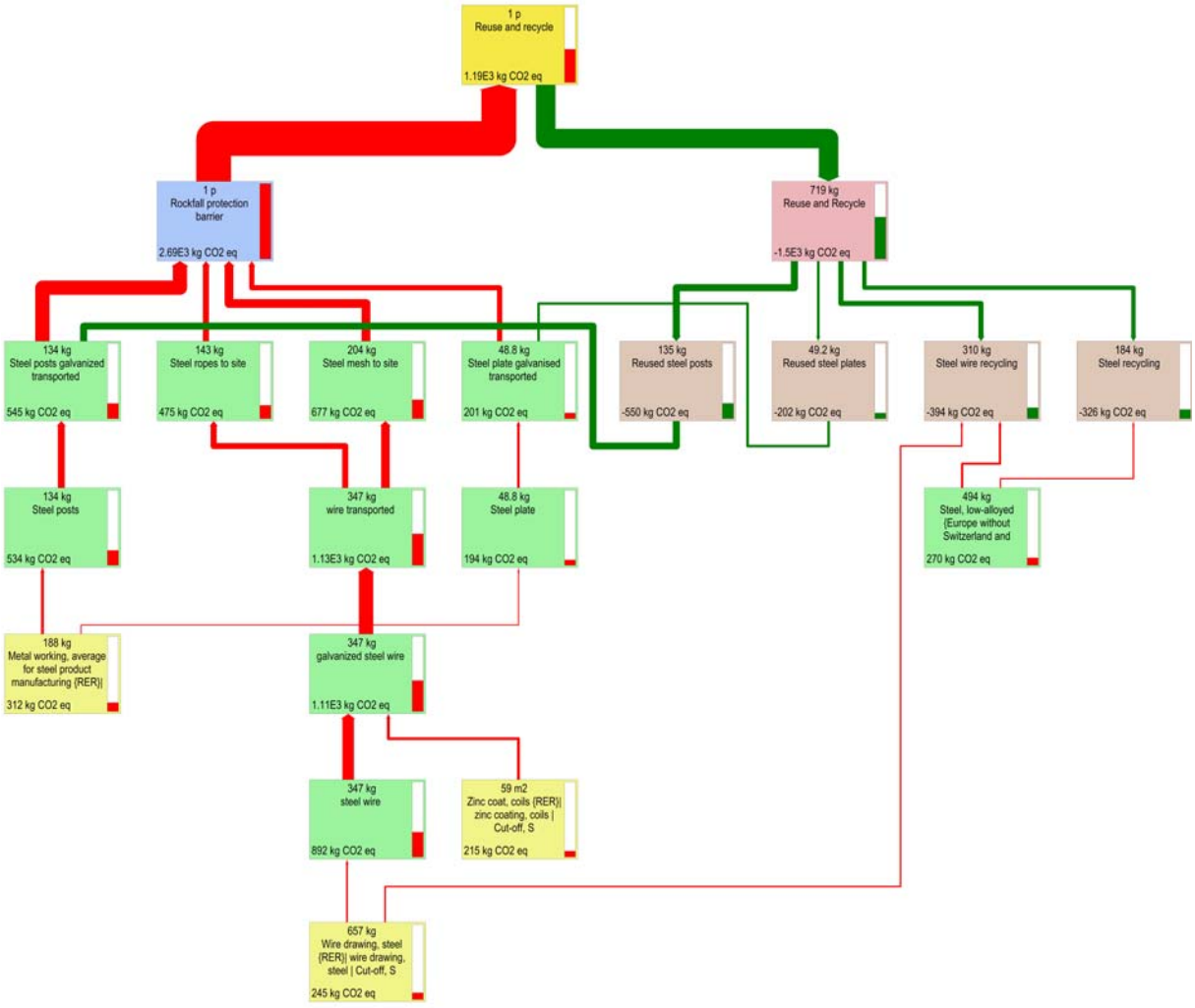


Fig. 2 SimaPro flow diagram of the life cycle of the investigated rockfall protection barrier, including production, transport, and end-of-life processes, with CO_2 emissions quantified in kg CO_2 eq.

The results obtained were compared with the EPDs published by well-known European manufacturers, whose reported total GWP values range from approximately 0.60 to 1.30×10^3 kg CO_2 eq. It should be noted that the consulted EPDs are not always specific to 2000 kJ protection barriers, but generally refer to broader product ranges with energy absorption capacities up to 5000 kJ, which explains the observed variability in the reported results. The outcome of the present study, equal to 1.19×10^3 kg CO_2 eq.,falls well within this range, further supporting the validity of the obtained result.

4 Conclusions

This article provides an overview of the evolution of sustainability concepts in civil engineering and geomechanics from the 1970s to the present, highlighting a regulatory and research gap in the integration of sustainability principles into rockfall protection structures. Furthermore, the paper provides guidance for the integration of sustainability concepts within this sector, highlighting strategies for improving environmental performance in the design of rockfall protection structures. The case study presented here illustrates the application of an LCA to a rockfall protection barrier, demonstrating how CO_2 emissions can be quantified. A logical next step would be to extend the assessment to the structure as a whole, ideally applying LCA to a real case study in which key variables—such as material type, quantity and origin, service life, and end-of-life scenarios—can be evaluated and compared with the variables that ensure the structure has the required safety standards. Moreover, the analysis could be further expanded to include additional impact categories beyond climate change, such as abiotic resource depletion, acidification and ecotoxicity. It should be noted, however, that such barriers represent only one of several mitigation measures available in rockfall-prone areas, and the systematic assessment of their environmental footprint is crucial for understanding and ultimately reducing their impact.

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