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Relevance of environmental product declarations in slope stabilization and the challenges of technical assessment

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ABSTRACT: Environmental Product Declarations (EPDs) are increasingly used to support sustainability-oriented decision-making in geotechnical engineering. In slope stabilization, however, EPDs are commonly expressed per unit mass of material, which limits their applicability for comparing functionally equivalent protection systems installed over large surface areas. This paper proposes an area-based assessment framework for evaluating Global Warming Potential (GWP) in slope stabilization systems, expressed as CO_2-equivalent per secured square meter. The approach is applied to high-tensile steel mesh systems and benchmarked against conventional stabilization solutions using documented case studies. The results demonstrate that material strength, required nail spacing pattern, and expected service life significantly influence environmental performance when assessed on a functional unit basis. The paper discusses boundary conditions, limitations, and implications for tendering and design practice, and highlights how EPD-based metrics can be interpreted more consistently for surface protection systems.

KEYWORDS: slope stability, EPD, CO_2-equivalent, geotechnical engineering, sustainability.

1 INTRODUCTION

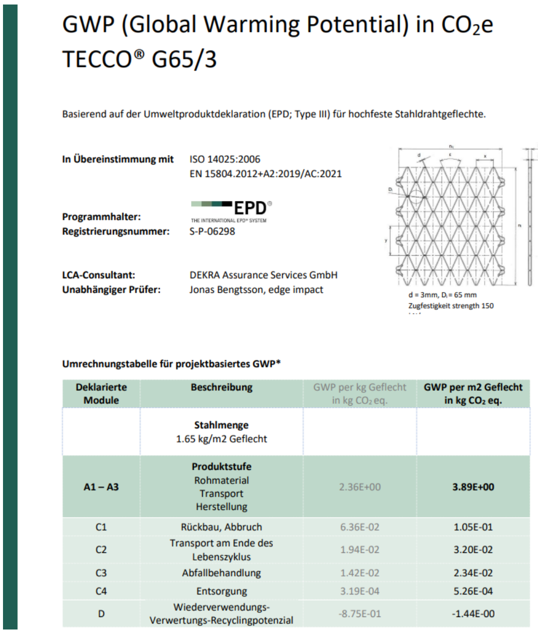
An Environmental Product Declaration (EPD) is a standardized document that provides transparent and comparable information about the environmental impact of a product or service. It is based on international standards and serves as an important tool for promoting sustainability in product development and construction. An EPD encompasses data on the entire life cycle of a product – from raw material extraction to production, use, and disposal, and ultimately, recycling (a cradle-to-grave approach). It provides an objective and comprehensible representation of a product's environmental impact.

The fundamentals of an EPD are defined by standards such as ISO 14025, ISO 14040, and ISO 14044, as well as EN 15804 (ISO, 2006a, b, c; CEN, 2012). ISO 14025 specifies the general principles and requirements for Type III environmental declarations, while ISO 14040 and ISO 14044 regulate the preparation of life cycle assessments (LCA), which are necessary for the preparation of an EPD. EN 15804 establishes specific rules for construction products and services and guarantees consistency and comparability between different EPDs.

The benefits of an EPD are manifold. It ensures transparency and comparability by directly comparing the environmental impacts of different products. This makes it easier for engineers, planners and builders to make informed decisions about more sustainable materials and products. Companies benefit from EPDs by optimizing their production processes while meeting legal requirements. In addition, EPDs enhance a company's competitiveness by showcasing its commitment to sustainability and thereby meeting the growing demands of customers and investors.

EPDs also contribute to achieving climate targets by enabling companies to understand their carbon footprint better and support targeted measures to reduce their environmental impact. Figure 1 is an example of a widely used slope stabilization mesh.

They also promote circular economy by providing detailed information about a product's life cycle, which facilitates the development of recycling and reuse strategies. The EPD is a valuable tool for highlighting sustainability and environmental awareness, driving ecological optimization and adapting to the increasing requirements of regulatory authorities, customers and markets.



GWP (Global Warming Potential) in CO_2e
TECCO® G65/3

Basierend auf der Umweltproduktdeklaration (EPD; Type III) für hochfeste Stahldrahtgeflechte.

In Übereinstimmung mit: ISO 14025:2006
EN 15804.2012+A2:2019/AC:2021
Programmhalter: EPD® THE INTERNATIONAL EPD® SYSTEM
Registrierungsnummer: S-P-06298
LCA-Consultant: DEKRA Assurance Services GmbH
Unabhängiger Prüfer: Jonas Bengtsson, edge impact

d = 3mm, D_i = 65 mm
Zugfestigkeit strength 150

Umrechnungstabelle für projektbasiertes GWP*

Deklarierte Module	Beschreibung	GWP per kg Geflecht in kg CO_2 eq.	GWP per m2 Geflecht in kg CO_2 eq.
	Stahlmenge 1.65 kg/m2 Geflecht		
A1 – A3	**Produktstufe** Rohmaterial Transport Herstellung	2.36E+00	**3.89E+00**
C1	Rückbau, Abbruch	6.36E-02	1.05E-01
C2	Transport am Ende des Lebenszyklus	1.94E-02	3.20E-02
C3	Abfallbehandlung	1.42E-02	2.34E-02
C4	Entsorgung	3.19E-04	5.26E-04
D	Wiederverwendungs-Verwertungs-Recyclingpotenzial	-8.75E-01	-1.44E-00

Figure 1. GWP for a standard slope stabilization system focuses on the system component, high-tensile steel chain-link mesh.

1.1 *OBJECTIVE AND SCOPE*

The objective of this contribution is to critically assess how Environmental Product Declarations can be meaningfully applied to slope stabilization systems whose primary function is defined per unit area rather than per unit mass. The paper aims to (i) define an area-based functional unit suitable for surface stabilization measures, (ii) illustrate how material strength, system layout, and service life affect EPD-based Global Warming Potential (GWP), and (iii) discuss the applicability and limitations of such metrics in engineering design and procurement. The focus is on flexible, mesh-based stabilization systems; however, the proposed assessment framework is intended to be transferable to other surface protection measures.

1.2 *EPD in slope stabilisation*

In slope stabilization, it can be assumed that environmental product declarations (EPDs) will play an increasingly important role, as they enable a transparent assessment of the environmental impact of protection systems. Sustainability and resource efficiency are becoming particularly important in infrastructure projects such as rail and road safety systems. The use of high-strength meshes with tensile strengths greater than 1650 N/mm², compared to systems with lower strengths of around 500 N/mm², influences EPD-based assessments by enabling larger nail spacing and reduced material demand (Rüegger et al. 2002).

These include increased nail spacing, which can reduce the number of nails by up to 30%, thereby conserving resources, shortening construction time and saving overall costs (Flum et al. 2014).

Under certain conditions, high-strength wire mesh can be used as an alternative to structures made of shotcrete. Here, too, resource consumption is lower, and up to four times fewer emissions are produced (Kytzia & Mosimann, 2010).

An EPD is based on an analysis of a product's entire life cycle. In the case of slope stabilization systems, all phases are taken into account – from raw material extraction, production, transport and installation to maintenance and disposal.

Due to their significantly higher load-bearing capacity, high-strength systems require less material to achieve the same effect and performance (Rüegger et al., 2004). This reduces raw material and energy consumption, leading to a lower overall environmental impact.

EPDs also enable a direct comparison of the environmental impacts of different slope stabilization systems.

In addition, stainless steel systems are now available that are suitable for a long service life of 100 to 300 years or more, depending on the level of corrosion, and therefore require less frequent replacement or maintenance. This not only saves resources but also reduces long-term costs (Krauter et al., 1996; Gröner et al., 2013).

Infrastructure projects, such as rail and road networks, benefit from robust and durable solutions, as these minimize the risk of damage from slope instabilities, thereby reducing repairs, traffic disruptions, and the associated environmental impact. These ecological and economic benefits can be quantified in an EPD and presented as a contribution to sustainability. Under defined boundary conditions, cumulative greenhouse gas emissions may be reduced over the service life of specific projects.

Furthermore, EPDs are an important tool in project tenders and in meeting environmental certification standards such as LEED (Leadership in Energy and Environmental Design) or DGNB (Deutsches Gütesiegel Nachhaltiges Bauen) (dgnb.de; 2025). They provide an objective and transparent representation of a product's environmental performance, helping companies communicate their sustainability strategies to clients and authorities. High-strength slope stabilization systems can reduce material demand and associated transport and installation efforts.

2 METHOD: AREA-BASED EPD METRIC

With regard to EPDs, the challenge is that these often focus on the mass of a product, for example, by specifying the environmental impact per kilogram of material. However, this type of assessment falls short in the case of high-strength meshes, as the functionality and efficiency of the systems in practice are not taken into account. Standard meshes with lower strength may initially appear more advantageous in a mass-based EPD, as they contain less material per square meter. However, in practice, they often require additional reinforcement or overlap to achieve comparable stability, which worsens their environmental performance.

An area-based assessment of the EPD, which considers the environmental impact per square meter of secured area, is therefore much more meaningful. High-strength mesh provides higher performance per square meter, resulting in less material being required overall to secure the area. This efficiency advantage becomes clear when considering the area.

In conventional EPDs, the Global Warming Potential (GWP) is typically expressed per unit mass of material (kg CO_2e/kg). For slope stabilization systems, this metric does not adequately represent functional equivalence, as the secured surface area, load-bearing capacity, and service life govern system performance.

In this contribution, the functional unit is therefore defined as: 1 m² of stabilized slope area over the design service life.

The area-based GWP is calculated as:

$$\mathrm{GWP}_{area} = \frac{\sum(m_i \cdot \mathrm{GWP}_i) + \mathrm{GWP}_{installation} + \mathrm{GWP}_{maintenance}}{A_{secured}}$$

where m_i represents the mass of system components i, GWP_i its corresponding EPD value, and $A_{secured}$ the stabilized surface area. This formulation enables the comparison of systems with varying material strengths, nail spacings, and service lives on a consistent functional basis. Table 1 presents a comparison between area-based and mass-based metrics.

Table 1. Comparison of mass-based and area-based EPD assessment approaches for slope stabilization systems.

Aspect	**Mass-based EPD metric (kg CO_2e/kg)**	**Area-based EPD metric (kg CO_2e/m² secured area)**
Functional unit	Unit mass of material	Secured slope surface over defined service life
Primary focus	Material production efficiency	Functional performance of stabilization system
Typical use case	Material comparison across industries	Comparison of functionally equivalent protection systems
Influence of material strength	Indirect (higher strength may increase kg CO_2e/kg)	Direct (higher strength may reduce total material per m²)
Nail spacing and auxiliary components	Typically excluded or weakly represented	Explicitly included through system-level material quantities
Representation of overlaps and reinforcement	Not captured	Captured through actual installed area and material demand
Sensitivity to service life assumptions	Low	High
Suitability for slope stabilisation comparison	Limited	High
Risk of misleading conclusions	Elevated when comparing different system concepts	Reduced when boundary conditions are clearly defined
Transparency requirements	Moderate	High (requires explicit assumptions and system boundaries)
Applicability in tendering	Limited for system comparison	Suitable as a decision-support metric
Main limitation	Ignores functional equivalence	Sensitive to service life and maintenance scenarios

3 RESULTS – CASE STUDIES

The following case studies are used to illustrate how area-based EPD metrics are influenced by site-specific boundary conditions, particularly corrosivity, climatic exposure, accessibility, and assumed service life. They are not intended to be statistically representative comparisons, but rather applied examples that demonstrate how sustainability assessments for slope stabilization systems depend on realistic durability assumptions and functional equivalence.

3.1 *Slope stabilization in Nasugbu*

3.1.1 *Project context and boundary conditions*

The Nasugbu slope stabilization project is located in a tropical environment southwest of Manila, Philippines, along the East–West Road connecting coastal and mountainous regions (see Figure 2). The area is characterized by average daily temperatures exceeding 25 °C, a pronounced monsoon season, and annual rainfall above 2000 mm. The geological setting consists predominantly of volcanic rocks such as andesite, basalt, tuff, and their weathering products.

The road alignment required steep embankments, which are subject to recurrent saturation during the monsoon season. These conditions repeatedly triggered shallow landslides and surface instabilities, necessitating a permanent stabilization measure (see Figure 3).

Figure 2. Location of the security measure in the Philippines, southwest of Manila (base map: Google Maps, accessed April 2025, modified by the authors)

Figure 3. Example of a landslide on East-West Road after heavy rainfall (image source: Google Maps, accessed June 2025).

3.1.2 *Initial design and observed performance*

The original stabilization concept was designed using the RUVOLUM approach (Flum et al., 2014) and implemented with a flexible high-tensile steel mesh system combined with soil nailing. Corrosion protection was provided by a Zn/Al coating, which typically allows for an expected service life of 50–100 years in corrosivity class C2.

However, within less than three years of operation, extensive corrosion and a marked reduction in steel cross-section were observed across large areas of the installation (see Figure 4). Subsequent investigations revealed highly aggressive environmental conditions, including seepage water with a pH value of approximately four and elevated sulphur and iron contents in the subsoil. These parameters significantly exceeded the environmental conditions assumed during the original design.

Figure 4. Severe corrosion during the Nasugbu operation in the Philippines. The corrosion is visible in almost all areas due to the rust-red discoloration.

3.1.3 *Implications for sustainability assessment*

Although the initial design may have exhibited favorable material-based indicators, premature degradation led to an early loss of structural function and required replacement of the stabilization system. The cumulative environmental impact per secured square meter, therefore, increased substantially compared to a design aligned with the actual corrosivity conditions.

As part of the remediation, a seawater-resistant stainless steel mesh system was selected with a pitting resistance equivalent number (PREN) greater than 32, combined with a locally adapted geometry (see Figure 5). While this solution involved higher initial material impacts, the revised design was aligned with the aggressive exposure conditions and a substantially extended service life.

This case demonstrates that neglecting environmental boundary conditions in durability assessments can undermine both technical performance and sustainability objectives, and that area-based EPD metrics must be evaluated over realistic design horizons.

Figure 5. Renovated embankment in Nasugbu.

3.2 *Retaining wall stabilization in the Black Forest*

3.2.1 *Project context and exposure conditions*

The second case study concerns the stabilization of a retaining wall along the L126 road between Oberried and Notschrei in the Black Forest, Germany, at an elevation of approximately 700 m above sea level. The road is regularly exposed to de-icing salts during winter maintenance.

These conditions result in cyclic chloride exposure, leading to temporarily high corrosivity levels corresponding to classes C4 to CX. Such exposure conditions are critical for steel components located near the road surface.

3.2.2 *Design options and durability considerations*

The stabilization concept combined soil nailing with a flexible mesh facing. Several material options were evaluated in terms of durability and maintenance requirements. For conventional corrosion protection systems, the anticipated service life under the given exposure conditions was estimated at approximately 10–30 years.

The selected solution employed a stainless-steel mesh system designed for high chloride resistance (see Figure 6). The primary design rationale was to avoid mid-life replacement of the stabilization measure, which would involve additional material consumption, construction activities, and repeated traffic restrictions.

Figure 6. Retaining wall on a bend on the L126 between Oberried and Notschrei. At the top right, you can see the vehicle restraint system and, directly adjacent to it, the road surface, which is treated with de-icing salt in winter.

3.2.3 *Implications for area-based EPD metrics*

When assessed using an area-based EPD framework, this case illustrates how higher initial material impacts can be offset by extended service life and reduced maintenance requirements. Over a design horizon spanning several decades, the cumulative environmental impact per secured square meter is primarily determined by the replacement frequency rather than the initial material intensity alone.

The case underlines that, particularly in infrastructure applications with limited accessibility and high socio-economic relevance, durability-driven design decisions play a key role in sustainability assessments.

3.3 *Synthesis of case study findings*

Interpreted with Table 1, both case studies demonstrate that mass-based EPD metrics fail to capture key drivers of sustainability in slope stabilization, particularly service life and replacement frequency. The Nasugbu case highlights how premature degradation can negate favorable material-based indicators, while the Black Forest case shows that higher initial material impacts may be offset by extended durability.

4 LIMITATIONS

The proposed assessment framework relies on simplified assumptions regarding installation processes, maintenance frequency, and service life. Site-specific factors such as local construction logistics, variability in corrosion exposure, and differences in design standards may significantly influence results. Furthermore, EPD data availability and system boundary definitions vary between manufacturers, limiting direct comparability. The presented case studies should therefore be interpreted as boundary-condition analyses rather than statistically representative datasets.

5 CONCLUSIONS

This contribution examined the application of Environmental Product Declarations (EPDs) to slope stabilization systems whose functional performance is defined per unit area rather than per unit mass. It shows that conventional mass-based EPD metrics are of limited suitability for comparing functionally equivalent surface protection measures, as they do not adequately capture differences in structural efficiency, anchorage density, and service life.

By introducing an area-based functional unit expressed as Global Warming Potential per secured square meter, a more representative basis for comparison is provided.

The results emphasize the need to explicitly define functional units, system boundaries, and design horizons when applying EPDs in geotechnical engineering. Area-based metrics should therefore be used as complementary decision-support tools, with transparent assumptions regarding durability and maintenance, to support sustainability-oriented planning and tendering processes.

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