

# Protection of infrastructure from surface erosion and shallow hydrogeological instability using nature-based solutions

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**ABSTRACT:** Extensive studies, experimental trials and hundreds of construction sites worldwide—implemented under diverse pedoclimatic conditions—have demonstrated that selected deep-rooted, resilient herbaceous species effectively mitigate both surface erosion and shallow hydrogeological instability, with beneficial repercussions extending to greater depths. This nature-based solution (NBS) represents an optimal technical, economic and environmental approach: it requires no maintenance and entails installation-related energy consumption and emissions up to two orders of magnitude lower than conventional engineering methods. By virtue of their physiological characteristics, these species increase soil shear strength, protect slopes from intense precipitation, transpire large water volumes to reduce pore-water pressure and improve key geomechanical soil parameters. Furthermore, this technology enables the in-situ construction of innovative surface and stormwater capture and regulation systems. It also promotes the homogenization of moisture content—especially within superficial and subsuperficial layers—across slope profiles. Chromatic variations in the turf, corresponding to differential soil moisture, provide a real-time NBS-based hydrological monitoring tool for slopes.

**Keywords:** erosion mitigation; pore-water pressure; stormwater capture; nature-based solutions; hydrogeological hazards

## 1. INTRODUCTION

Over the past decades, theses, research activities, scientific publications and experimental investigations conducted within leading academic institutions have systematically analysed and quantified the role of vegetation in soil improvement and slope stabilisation. These studies have addressed, among other aspects, the reduction of erosion under field conditions, the mechanical reinforcement provided by root systems, the isolation of slopes from direct precipitation, the reduction of pore water pressure induced by plant transpiration, and the use of extensive deep-rooted vegetation as two-dimensional indicators of soil moisture distribution across large areas under varying pedological and climatic conditions (Cecconi et al., 2025).

The present article synthesises field evidence collected over nearly thirty years of professional activity across several hundred sites. From this extensive dataset, three representative full-scale case studies are presented, selected for their exposure to severe meteorological conditions and for the complexity of the geotechnical and hydraulic challenges encountered.

## 2. GEOTECHNICAL, HYDRAULIC, AND ENVIRONMENTAL FIELD EVIDENCE

Three full-scale applications are reported and examined here, each subjected to extreme weather conditions. The first site is located near the Badia exit of the A1 motorway in the municipality of Castiglione dei Pepoli,

where Autostrade per l'Italia–Tecne S.p.A. developed a construction site within a system of dormant landslides. These landslides were reactivated by rainfall events, particularly in 2014, culminating in the collapse of the municipal road Via Sparvo.

Following conventional engineering works carried out by Autostrade per l'Italia S.p.A., an anti-erosion and hydraulic mitigation measure was realized by Prati Armati srl over the landslide body of about 30000 m<sup>2</sup>. This intervention enabled the stabilisation of the slope and the safe reopening of the road (Figure 1).



Figure 1. The Castiglione dei Pepoli site, as observed in June 2021, exhibited no erosion control measures and was affected by severe hydrogeological instability. By June 2024 successful Nature-based solutions were implemented

The second example concerns the RFI construction site along the Alba–Bra railway line in Santa Vittoria d'Alba (Piemonte region). The site was characterised by marked instability of the topsoil, leading to recurrent shallow failures that disrupted railway operations and prevented electrification (Figure 2). After the execution of conventional consolidation works, the application of

Prati Armati technique stopped superficial instability, allowing the safe reopening of the railway line.

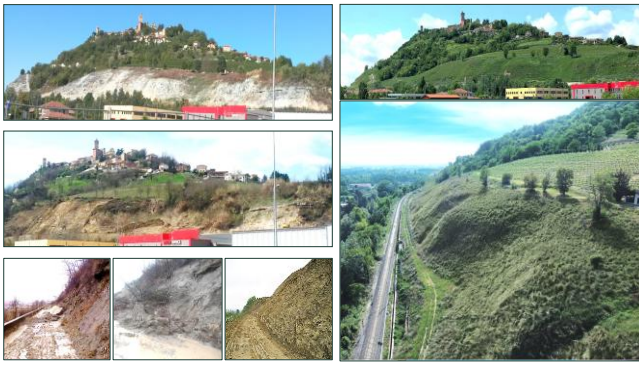


Figure 2. Piemonte, Santa Vittoria d'Alba – RFI: pre-intervention conditions showing superficial deposits affected by landsliding (left); post-intervention results, with hydraulic drainage network installed on the existing soil (right)

The third case study refers to the ANAS bypass of State Road 45 in the Trebbia Valley. This site exhibited significant erosional and hydraulic problems affecting both the upstream trench and the downstream embankment, primarily due to the nature of the spoil material employed (Figure 3).



Figure 3. Torriglia (GE) – ANAS Construction Site; a) unsuccessful erosion control and hydraulic regulation implemented directly on unprocessed material; b) after the Prati Armati application: no erosion-related issues observed and surface water management installed on the untreated soil

Despite differing geological and infrastructural contexts, all three sites presented a full spectrum of critical issues, including surface erosion, shallow hydrogeological instability, and complex surface and stormwater management problems. In each case, these conditions could not be effectively resolved through conventional engineering solutions alone.

### 3. PROPERTIES OF DEEP-ROOTED HERBACEOUS PLANTS

Deep-rooted herbaceous plants exhibit a combination of mechanical, hydraulic and ecological properties that make them particularly effective for the control of surface erosion and shallow hydrogeological instability. Their performance is not limited to a single stabilising mechanism; rather, it results from the synergistic

interaction between above-ground biomass, root architecture, soil–plant–atmosphere exchanges and long-term organic matter dynamics.

From the perspective of erosion control, the dense above-ground biomass forms a continuous protective layer that intercepts rainfall, dissipates kinetic energy and reduces surface runoff velocity. Firmly anchored to the substrate, this vegetative layer acts as a resilient anti-erosion filter. Quantitative field validation of this effect has been obtained through the application of the Universal Soil Loss Equation (RUSLE), as demonstrated by experimental results at the Orvieto site, where soil loss was reduced by several orders of magnitude within three years of intervention (Figure 4).



Figure 4. Field experiments conducted by the Department of Geology at the University of Perugia demonstrate a reduction in soil loss from 1008.84 to 0.06 ton/hect/year, three years after the intervention

Beyond surface protection, the contribution of deep-rooted herbaceous species to slope stability is strongly linked to the mechanical reinforcement provided by their root systems. These roots, capable of resisting tensile stresses exceeding 200 MPa, interact with the soil matrix by mobilising additional apparent cohesion and increasing shear strength in the superficial layers. This reinforcement effect has been quantified through dedicated numerical tools developed by the University of Milan, which isolate the contribution of root systems to soil shear strength parameters (Cecconi et al., 2025).

The stabilising action of vegetation is further enhanced by its capacity to mitigate shrinkage cracking in fine-grained soils. The continuous vegetative cover reduces daily and seasonal fluctuations in moisture content and temperature, which are primary drivers of desiccation cracking in clays (Tagarelli & Cotecchia, 2022). By limiting crack formation, preferential infiltration pathways are suppressed, leading to a reduction in both surface runoff concentration and subsurface destabilisation processes (Figure 5).

In parallel, the organic matter produced by the vegetative cycle plays a key hydrological role. The continuous processes of root growth, senescence and decay lead to the formation of humus-rich layers that act as an effective water buffer. This organic matrix can retain water up to twenty times its dry weight, releasing it gradually and thereby attenuating peak infiltration rates while maintaining more stable moisture conditions

within the near-surface soil horizon (Tagarelli et al., 2024).



Figure 5. Menfi (AG) quarry: clay cracking and consequent hydrogeological instability; above the yellow line, the anti-erosion intervention that limited the soil cracking

The combined action of surface protection and organic buffering results in a progressive isolation of the slope from direct rainfall. As slope gradients and rainfall intensity increase, the above-ground vegetative layer tends to mat down, forming a continuous protective cover that behaves as a large-scale “umbrella”, consistent with the conceptual isolation mechanisms envisaged in Eurocode 7. This effect is particularly evident on steep slopes and in high-intensity precipitation scenarios (Figures 6 and 7).

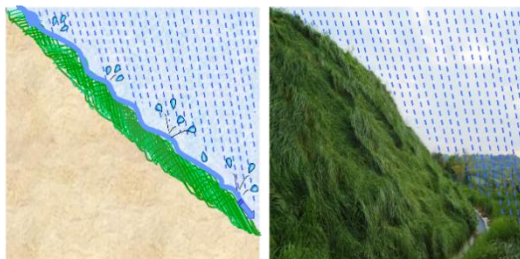


Figure 6. A slope where the aboveground vegetative cover, firmly anchored into the substrate by deep, resilient roots, functions as an isolating layer for the slope



Figure 8. a) and b): hydraulic jumps in the intake works, constructed in situ on the existing substrate with emergent plants, to reduce water velocity; c): protective lining with prostrate deep-rooted species to prevent erosion of the bed and side-walls

One of the most significant operational advantages of deep-rooted herbaceous systems is the possibility of implementing surface and stormwater capture, conveyance and regulation works directly on the in situ ground. By shaping and stabilising the existing terrain, conventional engineered structures such as lined channels and rigid drainage elements can be entirely eliminated. This approach delivers substantial technical benefits, reduces construction time and costs, and results in systems that require no maintenance, as demonstrated by multiple full-scale applications (Figure 8).



Figure 8. Hydraulic regulation works implemented directly on the natural soil on the slope following the collapse of the channels built with cemented stone blocks (Autostrade per l'Italia site on the A1 motorway - Bologna)

At the subsurface level, deep-rooted herbaceous species exert a fundamental influence on soil hydrology through transpiration (Cecconi et al., 2025). The dense, fine and vertically extensive root network promotes the extraction of excess pore water and its transfer to the atmosphere (Tagarelli & Cotecchia, 2022). This process leads to a reduction in pore water pressure, enhances effective stress conditions, and contributes to the stabilisation of shallow soil layers while simultaneously reducing moisture heterogeneity (Figure 9).

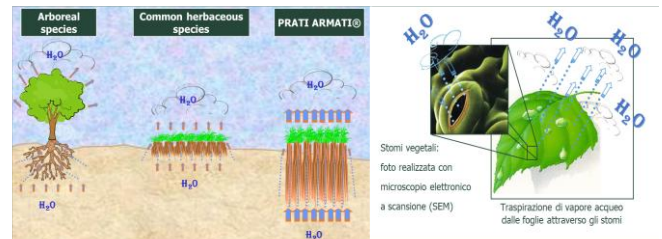


Figure 9. The transpiration of herbaceous species reduces pore water pressure thanks to the specific characteristics of their root system

From an environmental and energetic standpoint, these systems offer substantial advantages over conventional anti-erosion techniques. The energy consumption and associated emissions ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{NO}_x$ ,  $\text{SO}_x$  and particulate matter) required to establish one hectare of vegetation using the PRATI ARMATI® technique are between one and two orders of magnitude lower than those associated with traditional solutions (e.g., Tagarelli & Cotecchia, 2022b). In addition,  $\text{CO}_2$  sequestration capacity can be up to 400 % higher, reaching values of approximately 40 t/ha·yr (Figure 10).

Finally, deep-rooted herbaceous vegetation provides a range of secondary yet highly relevant functional benefits that extend beyond purely mechanical and hydraulic stabilisation. The spatial variability in plant development, density and vigour reflects underlying differences in soil moisture and drainage conditions, offering a direct and continuous visual indication of slope hydrological behaviour. In this sense, vegetated slopes effectively operate as two-dimensional moisture sensors across extensive surfaces, enabling rapid field-scale assessment and early identification of soil state.

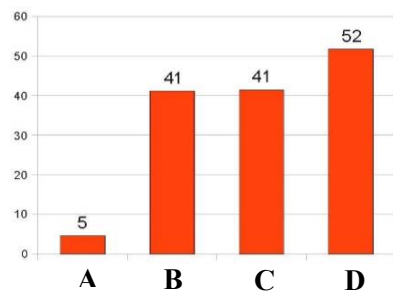


Figure 10. CO<sub>2</sub> emissions (t CO<sub>2</sub>/ha): comparison among various anti-erosion techniques A = Prati Armati srl; B = erosion control mats; C = geocells; D = geotextile mats

From a regulatory and sustainability perspective, the technique is fully compliant with Eurocode 7, EU Regulation 2020/852, the Do No Significant Harm (DNSH) principle and the recently approved EU Nature Restoration Law. The exclusive use of natural inputs allows for rapid implementation, with several hectares established per day, significantly reducing construction durations and associated on-site risks. Once established, these systems require no maintenance beyond that already mandated by road and rail infrastructure laws.

The use of autochthonous species ensures full landscape integration and long-term ecological compatibility, while the inclusion of flowering and melliferous plants promotes the return of pollinator insects and supports the re-establishment of functional trophic networks. In addition, the predominance of herbaceous species with limited above-ground biomass and high moisture content confers an increased resilience to external disturbance agents, including fire (Stasi et al., 2024). Compared to woody vegetation, these systems exhibit reduced combustibility, faster post-disturbance recovery and a lower propensity to contribute to fire propagation, thereby enhancing the overall safety and robustness of vegetated infrastructure corridors under changing climatic conditions.

#### 4. CONCLUSION

Hydraulic erosion driven by intense rainfall events and prolonged droughts has emerged as a critical geotechnical challenge, increasingly threatening the performance and durability of conventional civil engineering works. Herbaceous species characterised by deep, slender and mechanically resilient root systems are capable of establishing and persisting in pedoclimatic and phytotoxic environments previously considered unsuitable for vegetation. Their application provides an effective, low-impact and durable natural defence against erosion and shallow hydrogeological instability across a wide range of contexts.

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