Alternative Soil Stabilization Measures Under Rock Energy Dissipators at Culvert Outlets

Requested by

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Executive Summary

This report synthesizes engineering guidance, environmental policy, and materials research to evaluate options for stabilizing the soil directly beneath rock energy dissipators (REDs) at culvert outlets. The document's central aim is to identify feasible alternatives to traditional geotextile filters and to chart a research path toward hydraulically robust, sustainable solutions that balance performance, constructability, environmental protection, and long-term resilience.

Summary of Key Findings

Microplastics policies are reshaping material choices, but geotextile filters remain high performing, particularly under dynamic hydraulic conditions.
Environmental programs are elevating attention on polymer products used in erosion control and filtration. However, engineering references continue to emphasize the durability and filtration reliability of properly buried geotextiles under hydraulic loading, especially in mobile bed environments highlighting a persistent tension between environmental policy direction and hydraulic design practice.

Granular filters can provide effective filtration, but their performance and constructability are highly site dependent.
Granular systems (sand/gravel gradations) provide robust soil retention and puncture resistance and avoid polymer concerns. However, meeting soil-retention and permeability criteria does not by itself ensure satisfactory system performance. Granular filters remain vulnerable to flow bypass at their boundaries, including flanking around the sides or upstream and downstream terminations, and to undermining initiated by scour at the outlet or apron toe. Their performance also depends on maintaining the specified gradation, thickness, continuity, and edge treatment during construction. These requirements are difficult to achieve consistently, particularly on contracts involving numerous culverts with different subgrade soils and potentially different filter-layer prescriptions.

Established culvert/outlet guidance does not address RED specific soil stabilization beyond filter layers.
The literature acknowledges emerging stabilization techniques (e.g., lime, cement, alkali activated binders, enzymes, MICP/biopolymers), yet none are evaluated under the unique hydraulic regimes present under dissipators.

Natural fiber and biodegradable geotextiles show environmental promise but face durability limits in RED applications.
Coir, jute, hemp, and biodegradable polymers (e.g., PBS/PBSA) can aid erosion control and short-term reinforcement on slopes/channels; nevertheless, unpredictable degradation, limited service life, and the absence of testing under heavy rock loads, sustained saturation, uplift, and turbulence make them unsuitable as sole long term filter substitutes beneath REDs.

Vegetation and soil bioengineering are effective on upland slopes and streambanks but not beneath RED rock.
Techniques like willow walls, fascines, and vegetative mats are documented for slope stabilization and living shorelines. They are not designed to withstand high energy culvert outlet hydraulics or to provide the critical filtration/separation function under rock dissipators.

Innovation trends (intelligent geotextiles, high performance fibers) are expanding capabilities but have not been connected to RED subgrades.
Research on sensing fibers, nanofiber composites, and heavy metal adsorption is maturing; applications to RED subgrade environments (high shear, turbulent seepage, cyclic outflows) remain unexplored in the literature reviewed.

Identified Gaps

No direct evaluation of alternative stabilization methods under REDs.
Across manuals, research papers, and industry guidance, the report finds no focused studies validating alternatives specifically for subgrades beneath rock dissipators.

Absent hydraulic performance testing.
Promising techniques (biopolymers, microbial cementation, alkali-activated binders, enzyme stabilizers) lack testing under representative hydraulic conditions.

Limited durability data for natural/biodegradable materials under RED loads.
There is no evidence base for service life and mechanical integrity of natural fiber or biodegradable geotextiles under heavy rock contact, continuous saturation, and turbulence typical of outlet basins.

Microplastics risk from geosynthetics in RED applications is unquantified.
The long term microplastic emission profile of buried filters under riprap has not been independently assessed.

Policy-practice disconnect
Environmental policy is trending toward reducing polymers; hydraulic design guidance still leans on synthetic geotextiles for reliable filtration under high energy flow. Validated natural/biodegradable alternatives for RED applications are absent, leaving agencies without a bridge between sustainability goals and hydraulic performance requirements.

Recommended Next Steps

Launch a hydraulics specific stabilization research program for RED subgrades.
Design a structured program to evaluate chemical (lime, cement, AABs), biochemical (enzymes), biopolymer (chitosan, gellan, lignin), and biomediated (MICP, nitrate-reduction pathways) treatments under RED-equivalent hydraulic regimes.

Conduct controlled experiments comparing filters and stabilized soils.
Prototype tests can compare conventional geotextile filters, single/multi-layer granular filters, alternative filters and candidate stabilized soils beneath riprap/structural dissipators. Evaluate constructability at the project rather than individual-culvert level.

Quantify environmental impacts and microplastics risk for buried RED filters.
Conduct long duration studies to measure environmental impacts and microplastics risk for buried geotextiles under riprap.

Engage cross disciplinary partners to vet sustainable materials for RED duty.
Collaborate with materials scientists, geomicrobiologists, geosynthetics manufacturers, and environmental regulators to identify candidates that meet RED service life and hydraulic loading demands while advancing sustainability goals

Develop preliminary RED specific selection criteria.
From early results, draft a decision framework indicating when stabilization may supplement or replace filters, keyed to soil type (cohesive/non cohesive), hydraulic severity (Froude number, tailwater variability), constructability (wet placement, underwater constraints), and environmental considerations (microplastics exposure risk).

Detailed Findings

Culvert outlets are critical components of transportation drainage systems, where high-velocity discharges can generate severe erosion, undermine structures, and compromise long-term performance of roadway embankments. To manage these hydraulic forces, rock energy dissipators (REDs) and similar outlet protection systems are commonly used to reduce flow velocity and protect downstream channels. The subgrade beneath REDs plays a vital role in resisting piping, winnowing, scour, and uplift forces. In addition, evolving environmental regulations and growing concerns over microplastic pollution are prompting agencies to re-evaluate the use of polymer-based geosynthetics traditionally relied upon as filter and separation layers beneath riprap. Recent policy initiatives at the state and national levels have increased scrutiny of synthetic materials, particularly those exposed to sunlight, abrasion, or long-term degradation. This shift has intensified interest in natural-fiber and biodegradable alternatives, as well as chemical, mechanical, and biological soil-stabilization methods that may reduce reliance on plastics. However, these emerging materials and techniques have not been evaluated under the unique hydraulic conditions present beneath rock dissipators.

This report synthesizes the current state of knowledge across engineering literature, environmental policy, and material science to assess the feasibility of alternative soil stabilization approaches beneath REDs. It examines microplastic policy drivers, evaluates the performance characteristics of geotextile and granular filters, reviews advances in natural-fiber and biodegradable geotextiles, and surveys research on chemical, microbial, and biopolymer-based stabilization methods. Importantly, it identifies significant gaps where existing studies do not address hydraulic performance, long-term durability, or field applicability under culvert outlet conditions.

By integrating findings across these diverse domains, this preliminary investigation lays the groundwork for future research needed to develop reliable, sustainable, and hydraulically robust soil stabilization solutions for rock energy dissipators. The goal is to support agencies in making informed decisions that balance performance, constructability, environmental protection, and long-term resilience.

Microplastics Policy Drivers and Geosynthetics

California's Water Board created the first statewide program to define, detect, and monitor microplastics in drinking water. It sets a formal definition, standardized testing methods, and a multi-year monitoring and reporting plan to better understand health risks and guide future protections[1]. California's microplastics strategy also aims to coordinate statewide monitoring of microplastics in aquatic environments, focusing on sediment, water, and biota sampling, with special attention to urban runoff and wastewater as major sources. It emphasizes phased implementation, harmonized methods, open data sharing, and community engagement to generate actionable data for policy and management decisions[2].

Geotextiles in a paper are described as synthetic-fiber materials used in landfill liner systems, where they function mainly as filtration layers and as the outer layers of geosynthetic clay liners (GCLs) that sandwich a bentonite core. The paper notes that while these materials help control leachate movement, they are themselves polymer-based and can therefore become long-term sources of microplastics as they age or degrade within landfill environments[3]. Geotextiles are widely used in Sweden and currently contribute a

[1] https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/microplastics.html
[2] https://opc.ca.gov/wp-content/uploads/2026/02/Plastic-Strategy-Report-Public-Review-February-2026-508.pdf
[3] https://www.mdpi.com/2073-4360/13/23/4129

relatively small amount of microplastics, but improper installation, UV exposure, and long-term aging could make them a significantly larger microplastic source in the future[4].

Geosynthetics industry groups explain that geosynthetics including geotextiles are highly engineered, robust, and extremely durable, especially when they are properly buried and protected within soil systems. It states that these materials are designed to maintain performance for decades, and when required, they can function effectively for more than 100 years, highlighting their long-term durability in buried conditions. They contrast them with disposable plastics, emphasizing that geosynthetics are not easily lost into the environment, typically do not contain harmful chemicals, and can be responsibly recycled or disposed of at the end of their long service life. Nowhere in their document does it claim that geosynthetics themselves are a meaningful source of microplastic pollution and instead, they are portrayed as a key engineering tool for containing, capturing, and reducing microplastic release. They note that geosynthetics are highly durable, engineered materials that are not easily lost into the environment, unlike single-use plastics that readily fragment into microplastics. Their report further explains that geosynthetics have been used for decades in containment systems (especially landfills) to prevent microplastics and toxic substances from leaking into soil and groundwater. Additionally, geosynthetics are shown to reduce microplastic generation by enabling recycling of waste plastics (e.g., bottles, tires) into long-lived geosynthetic products[5].

The guidance for addressing plastic pollution in coastal development permits emphasizes that many common stabilization products such as geotextiles, plastic netting in erosion control blankets, spray-on polymer soil stabilizers, plastic sheeting, and plastic sandbags break down under sunlight, abrasion, and weathering, releasing persistent microplastic fibers and fragments into soil, waterways, and coastal environments. Because these materials also pose wildlife-entanglement risks and are often mis-labeled as biodegradable, this document strongly recommends using natural-fiber alternatives like jute, coir, sisal, wood fiber blankets, straw mulch, biodegradable tackifiers, and non-plastic erosion control products whenever technically feasible. For long-term stabilization on slopes, shorelines, and channels, it advises avoiding synthetic turf-reinforcement mats, geocells, and plastic-mesh rock bags because they degrade invisibly over time and cannot be practically removed once covered. Instead, it supports natural or mineral-based solutions (e.g., vegetation, rock riprap, articulated concrete blocks, gabion baskets without plastic coatings, burlap-based concrete sacks, and living shoreline approaches) as these provide structural stability without contributing to plastic pollution. When plastic products must be used, the guidance stresses frequent inspection, prompt removal, and careful containment during application to prevent plastic fragments from entering the environment[6].

The NCHRP Synthesis 643 report documents how state DOTs across the U.S. are working to reduce their reliance on plastic-based erosion and sediment control (ESC) materials due to concerns about wildlife entanglement, microplastic pollution, and long-term environmental impacts. ESC products such as erosion control blankets (ECBs) and silt fence are widely used but often contain plastic netting or geotextiles that degrade into persistent microplastics and can trap snakes, amphibians, and birds. Through a literature review, a nationwide survey of 42 DOTs, and six detailed case studies, the report finds growing interest in natural-fiber and net-free alternatives such as jute, coir, wood excelsior, hemp, and slash mulch berms which generally perform as well as or better than traditional plastic products and do not require additional installation or maintenance effort. While several DOTs (notably Minnesota, Vermont, Washington, Colorado, Georgia, and North Carolina) have advanced policies or programs phasing out plastics in temporary ESC, many agencies still lack formal guidance, struggle with product evaluation, and face limited alternatives for certain practices (especially silt fence, for which no fully plastic-free, high-performing option currently exists). The report concludes that further research is needed on natural

[4] https://www.diva-portal.org/smash/get/diva2:1722263/ATTACHMENT01.pdf
[5] https://www.geosyntheticssociety.org/wp-content/uploads/2022/05/IGS-Sustainability-Benefits-of-Geosynthetics-05-22.pdf
[6] https://documents.coastal.ca.gov/assets/water-quality/Plastic_Pollution_Prevention_Guidance_CCC_10-24-25.pdf

replacements for geotextiles, microplastic generation and biodegradation, hydromulch dye impacts, and cost analysis to support a broader shift toward sustainable ESC practices. However, the scope of this report is limited to erosion and sediment control practices that rely on plastic-based or natural-fiber materials and it focuses on issues like wildlife entanglement, microplastics, DOT policies, and alternative biodegradable materials. It does not address outlet protection design, riprap aprons, scour countermeasures, or subgrade stabilization techniques for culvert energy dissipation systems[7].

A bibliometric analysis reveals three dominant thematic clusters shaping the global research landscape on sustainable soil stabilization. The first and most prominent cluster centers on traditional geotechnical performance, emphasizing long-standing binders such as lime, cement, and fly ash, alongside metrics like compressive strength, durability, swelling behavior, and microstructural characterization, indicating that much of the field still advances through familiar engineering paradigms. The second cluster focuses on soil biogeochemistry and climate-related interactions, bringing together topics such as organic carbon, soil carbon dynamics, microbial activity, carbon sequestration, and broader climate-soil feedbacks, reflecting the growing recognition of soil stabilization as part of larger environmental and ecological systems. The third cluster highlights environmental applications and contaminant management, where stabilization techniques are studied as tools for controlling heavy metals, reducing leaching, and enabling soil remediation and bioremediation. Together, these themes illustrate a field that is expanding in scope but still largely anchored in traditional engineering concerns while increasingly engaging with ecological and environmental dimensions. This paper stays at a high-level, literature-wide view of soil stabilization research and does not address site-specific hydraulic or structural stabilization topics[8].

Functional Requirements at the Rock-Subgrade Interface

Hydraulic Engineering Circular No. 14 (HEC 14) is a comprehensive guide from the U.S. Department of Transportation that provides design procedures for energy dissipators used at culvert and channel outlets to prevent erosion and structural damage caused by high-velocity water discharges. The document outlines a systematic approach for identifying site conditions, evaluating velocities and potential scour, and selecting the most appropriate energy dissipator from a wide range of types including internal dissipators, stilling basins, streambed-level dissipators, riprap basins and aprons, drop structures, and stilling wells. It covers the hydraulic principles behind energy dissipation, provides empirical equations and design charts, and includes detailed worked examples. The circular also addresses the prediction and mitigation of scour, the design of flow transitions, and the use of riprap for erosion protection, making it an essential reference for engineers involved in highway drainage and hydraulic design[9]. HEC 14 itself does not provide detailed guidance or specifications for filter design, instead referring readers to HEC 11 for further information on this topic[10]. In environments with mobile bedforms, geotextile filters are strongly recommended due to their superior performance under dynamic conditions. Proper installation is essential, especially underwater, where specialized products like weighted geotextile mats or sand-filled containers may be used to ensure stability[11].

A general procedure to identify cases when outlet protection may be required offers only brief, indirect references to soil-related considerations (such as using soil plasticity index and saturated shear strength when evaluating scour potential, noting that nonerodible layers like bedrock can limit scour depth, and mentioning that filter material may be used under riprap in outlet basins to prevent migration of underlying soils) but it does not include any focused guidance or design procedures for stabilizing soil beneath rock dissipators. These short notes appear only as ancillary design considerations, not as a

[7] https://www.nationalacademies.org/publications/29034
[8] https://link.springer.com/article/10.1007/s43621-025-01540-y
[9] https://www.fhwa.dot.gov/engineering/hydraulics/pubs/06086/hec14.pdf
[10] https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec11sI.pdf
[11] https://www.fhwa.dot.gov/engineering/hydraulics/pubs/09111/09111.pdf

defined methodology or treatment of soil stabilization practices[12]. Similar document explains how to design a riprap-lined outlet apron that dissipates flow energy from culverts and storm drains by selecting the correct riprap size, apron length, and width based on pipe diameter, discharge, and tailwater depth, while ensuring the apron is flat, aligned with the pipe, and built with well-graded stone. It also does not discuss subsurface soil stabilization, geotextiles, subgrade preparation, or any structural soil-support measures beneath rock energy dissipators[13]. Another similar document outlines acceptable materials including (turf reinforcement mats, riprap, concrete, and gabions) for constructing outlet protection and stresses proper installation on stable slopes, alignment without bends, and use of filter fabric[14]. Gabion culvert outlets are wire-mesh baskets filled with stone and installed at culvert ends to slow, guide, and dissipate flowing water, preventing erosion and protecting surrounding soil and infrastructure. These structures are durable, flexible, and resistant to corrosion, making them well-suited for areas with fluctuating water levels or unstable ground. They help stabilize slopes, reduce sediment buildup, and extend the lifespan of drainage systems. Gabion outlets are easy to install, environmentally friendly, and adaptable to different project sizes, making them a practical solution for managing stormwater and safeguarding culvert discharge zones[15] [16].

Filters beneath riprap are needed whenever there is a significant gap between the soil and riprap particle sizes, when the underlying soil is erodible or non-cohesive, or when hydraulic conditions such as seepage, high velocities, or rapid drawdown could cause soil to pipe through the riprap. In practice, agencies report using filters more than 80% of the time because missing filters frequently contributes to riprap failure. A properly designed filter must prevent soil migration while still allowing adequate drainage, and it can be either granular or geosynthetic. Granular filters are designed by matching soil-filter and filter-riprap grain size distributions using methods such as the Cisten-Ziems chart or Terzaghi criteria, checking permeability (typically at least 10 times the soil), and selecting an appropriate thickness. Geosynthetic filters require choosing an apparent opening size based on soil gradation and flow conditions, ensuring sufficient permittivity, verifying mechanical strength for installation, and evaluating long-term clogging potential[17].

These design procedures primarily address particle retention, permeability, and compatibility between adjacent materials. They do not, by themselves, address failure caused by incomplete filter coverage or inadequate treatment of the filter boundaries. Flow can bypass a granular filter at its lateral, upstream, or downstream edges (a flanking or outflanking mechanism) and initiate erosion of the underlying soil. Similarly, scour at the downstream edge or toe can progress beneath the granular filter and RED, causing undermining and loss of support even when the filter material satisfies the specified gradation criteria. Consequently, granular-filter performance depends on adequate lateral extent, keyed or otherwise protected terminations, toe protection below anticipated scour, and continuity between the subgrade, filter, and rock layers. FHWA guidance specifically identifies the head, toe, and flanks as locations requiring special treatment and describes toe undermining as a primary riprap failure mechanism[18].

Granular systems may require two granular layers or a granular-geotextile combination and that granular filters are generally harder and more expensive to install than geosynthetics on land[19]. Site-specific granular-filter design also presents substantial implementation challenges on multi-culvert projects. Differences in native-soil gradation and RED rock size can result in different aggregate gradations, thicknesses, or numbers of transition layers for individual culverts. Requiring a contractor to procure, transport, segregate, stockpile, place, and verify multiple custom aggregate blends can be unrealistic and

[12] https://www.nashville.gov/sites/default/files/2021-08/SWMM-Vol2_Ch10.pdf
[13] https://efotg.sc.egov.usda.gov/api/CPSFile/12159/000_WV_ENGT_Design_Note_RipRap-Lined_Outlet_Protection_2018
[14] https://des.sc.gov/sites/des/files/docs/Environment/docs/eros-outlet.pdf
[15] https://www.gabion.us/gabions/application/gabion-culvert-outlets.html
[16] https://epgtest3.modot.org/index.php?title=611.4_Gabions
[17] https://library.ctr.utexas.edu/hostedpdfs/tti/0-7091-r1.pdf
[18] https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec11sI.pdf
[19] https://library.ctr.utexas.edu/hostedpdfs/tti/0-7091-r1.pdf

creates risks of material substitution, cross-contamination, segregation, incorrect placement, and inadequate layer thickness. Where granular filters are considered, designers should evaluate whether culverts can be grouped into a limited number of soil and hydraulic classes served by standard, locally available gradations. If a constructible standardized design cannot satisfy the applicable compatibility and hydraulic criteria, the granular alternative should be screened out.

In NCHRP Report 568, filter requirements for riprap installations are emphasized as essential for preventing soil loss and ensuring the long-term stability of the system. Filters either granular (sand, gravel) or geotextile (synthetic fabric) must be designed to retain underlying soil particles while allowing water to pass freely, balancing soil retention with permeability. Granular filters should have a gradation curve roughly parallel to the base soil, a minimum thickness of 6-8 inches (increased by 50% for underwater placement), and permeability at least 10 times that of the underlying soil. Geotextile filters must meet specific criteria for apparent opening size, permeability, strength, and porosity, with non-woven fabrics required to have a mass density greater than 12 oz/yd^2 and woven fabrics a percent open area above 4%. For bridge piers and abutments where mobile bedforms may be present, only geotextile filters are recommended, and these should terminate at two-thirds the riprap extent to reduce edge failure risk. Proper filter installation, field testing, and inspection are critical to ensure performance and prevent common failure modes such as piping, winnowing, or undermining of the riprap[20].

According to another report, granular filters, composed of sand, gravel, and crushed rock, provide a natural, durable, and internally stable transition layer that can be designed to be compatible with underlying soil conditions and resists puncture or construction damage. However, they are thicker, more expensive, heavier to transport, and difficult to install. Geosynthetic filters, typically woven or nonwoven synthetic fabrics, are preferred in most modern applications because they are more economical, easier to install, lightweight, and offer consistent material properties, while still effectively preventing soil piping and allowing drainage. Yet, geosynthetics can be challenging to place underwater due to buoyancy and sail behavior in flowing water, can be punctured by angular riprap if not properly selected, may clog over time without appropriate opening size and porosity, and can sometimes act as a sliding plane on steep slopes. Overall, the report concludes that filters (particularly geosynthetics) significantly enhance riprap performance, but the choice should reflect site-specific constraints such as water conditions, slope geometry, soil properties, and constructability[21].

Filters in bridge scour countermeasures serve as a secondary layer of protection, working alongside primary armoring methods like riprap or gabions to prevent fine soil particles from being washed away through the voids in the protective layer. Their main function is to maintain the stability of the underlying soil by allowing water to pass while retaining sediment, thus avoiding the buildup of pore pressure and potential erosion. Filters can be made from geotextile fabrics or granular materials such as sand and gravel, with each type offering specific advantages and limitations depending on site conditions. Geotextile filters are quick to install and cost-effective but may be less durable in abrasive environments, while granular filters provide better contact. Proper design and installation including considerations for permeability, strength, and anchorage, are essential for long-term effectiveness. Regular monitoring and maintenance are recommended, especially after flood events, to ensure the filter remains intact and functional[22] [23]. European practices include the use of fascine mats (woven bundles of natural material over geotextile) to facilitate filter placement in deep water, and geotextile containers (large sandbags made of non-woven fabric) that serve as adaptable filter layers beneath riprap[24].

[20] https://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_568.pdf
[21] https://library.ctr.utexas.edu/hostedpdfs/tti/0-7091-r1.pdf
[22] https://www.utrc2.org/sites/default/files/pubs/Handbook-of-Scour-Countermeasures-Designs.pdf
[23] https://www.fhwa.dot.gov/engineering/hydraulics/pubs/09111/09112.pdf
[24] https://rosap.ntl.bts.gov/view/dot/57156/dot_57156_DS1.pdf

A guide from GEOSINCERE explains that geotextile fabric is a key material for stabilizing weak or unstable soil by separating soil layers, reinforcing the ground, and allowing controlled water flow. It distinguishes woven geotextiles (strong and suited for heavy-load reinforcement) from nonwoven types, which excel in filtration and drainage. By adding tensile resistance, geotextiles reduce deformation, prevent aggregate from mixing with soft subgrade, and improve long-term performance in roads, embankments, slopes, and retaining walls. The guide emphasizes selecting fabrics based on tensile strength, puncture resistance, permeability, and opening size, and highlights the importance of proper installation practices such as subgrade preparation, correct overlaps, anchoring, and careful placement of fill. It also notes innovations like smart and biodegradable geotextiles and stresses choosing reliable manufacturers for consistent quality[25].

A study investigates how waste concrete powder (WCP) can be transformed into an alkali-activated binder (AAB) for stabilizing sandy soils, offering a sustainable alternative to ordinary Portland cement. Laboratory testing showed that combining WCP with sodium hydroxide and sodium silicate can produce strengths up to 3.1 MPa under ambient curing, while direct shear tests confirmed substantial increases in cohesion and friction angle. Overall, the research shows that WCP-based AAB is a technically effective and lower-carbon solution for soil stabilization. However, the paper does not evaluate its suitability beneath REDs at culvert outlets. while the mechanical improvements in this study indicate that WCP-based stabilization could be promising, the paper does not provide the hydraulic evidence needed to consider it suitable for use beneath rock energy dissipators[26].

Natural-Fiber Geotextiles

An article explains that although microplastics are a serious environmental issue, polymer-based civil engineering products such as geotextiles, geogrids, and erosion control materials are engineered to avoid generating them when used correctly. Most of these products are installed underground, where they are shielded from UV light, abrasion, and chemical degradation, and are designed with additives and safety factors that give them service lives exceeding a century without breaking down into microplastics. For above-ground applications, manufacturers use UV-stabilized polymers, surface treatments, or biodegradable natural fibers to prevent fiber shedding and environmental release. Overall, the article argues that these engineered materials differ fundamentally from single-use plastics and, when properly designed and applied, do not contribute meaningfully to microplastic pollution while often reducing environmental impact by replacing heavier, resource-intensive construction materials[27].

A paper provides an extensive review of geotextiles, focusing on their materials, functions, performance, environmental impacts, and recent innovations in geotechnical engineering. It explains that most geotextiles are made from synthetic polymers (primarily polypropylene (PP), polyester (PET), and polyamide) which enable critical engineering functions such as separation, filtration, drainage, reinforcement, erosion control, and barrier performance. However, because these polymers are non-degradable, long-term exposure to UV radiation, moisture, friction, and chemical environments can cause fiber breakdown and lead to microplastic accumulation in surrounding soils, posing environmental concerns. In response, the paper examines three major trends shaping the future of geotextiles: green geotextiles, intelligent geotextiles, and high-performance geotextiles. Green geotextiles, made from natural fibers such as jute, coir, flax, kenaf, and sisal, offer biodegradability, good erosion-control performance, and beneficial water-retention characteristics, though limited durability and moisture sensitivity restrict their long-term structural use. Intelligent geotextiles integrate fiber-optic sensors such as Fiber Bragg Grating (FBG), distributed Brillouin sensing, or polymer optical fiber systems allowing

[25] https://www.geosyntheticscn.com/comprehensive-guide-to-geotextile-fabric-for-soil-stabilization
[26] https://www.nature.com/articles/s41598-026-44832-7
[27] https://geosyntheticsmagazine.com/2024/01/22/microplastics-in-the-environment/

real-time monitoring of strain, deformation, temperature, humidity, and pore pressure in structures like embankments, railways, and slopes. High-performance geotextiles enhance mechanical and functional capabilities through chemical modification, additives, or composite fiber systems that incorporate materials such as glass, basalt, carbon fibers, or nanofibers, offering greater strength, durability, filtration reliability, and even specialized functions like heavy-metal adsorption. Overall, the paper concludes that advancements in environmentally friendly materials, sensing technologies, and high-performance fiber systems will continue to expand the capabilities and sustainability of geotextiles in modern geotechnical engineering[28].

An article provides a comprehensive review of coir geotextiles (CGs) and their use in soil reinforcement, emphasizing that coir fibers' high lignin content and large elongation at break give them greater durability and toughness than most natural fibers, making them strong candidates for sustainable geotechnical applications. It summarizes the engineering properties of coir fibers, the mechanical behavior and degradation patterns of woven and non-woven CGs, and the interaction mechanisms between CGs and soil under shear, pull-out, triaxial, and numerical analyses. The review highlights that CGs can significantly improve bearing capacity, settlement performance, and dynamic resistance of soils, though their service life is limited by biodegradation. To address durability challenges, the paper outlines physical, chemical, and natural treatments such as coatings, fiber hybridization, lime or nanoparticle modification, and cashew shell oil that enhance mechanical performance and slow degradation. It concludes by identifying research gaps, including the need for long-term durability data, environmentally friendly treatments, better numerical modeling for natural fibers, and advanced testing methods such as transparent soil and centrifugal modeling.[29]

Another paper reviews the growing use of natural fibers such as jute, coir, sisal, hemp and bamboo as sustainable alternatives to synthetic geosynthetics in geotechnical engineering, highlighting their roles in soil reinforcement, drainage enhancement for consolidation, and erosion/filtration control. Natural fibers improve soil strength by increasing interlocking, providing tensile resistance, and fostering long-term biological bonding, while biodegradable fiber drains have shown discharge capacities and field performance comparable to synthetic Prefabricated Vertical Drains (PVDs) across major projects worldwide. Fiber-based geotextiles and mats also effectively reduce erosion and promote vegetation, with soil-loss reductions frequently ranging from 40% to 99%. Despite strong environmental benefits and demonstrated engineering performance, widespread adoption is hindered by challenges such as variable material properties, limited durability, higher production costs, and a lack of standardized manufacturing and design guidelines, prompting the need for further research and field validation[30].

A document provides broad guidance on using vegetation to stabilize soil and reduce erosion, but it does not address applications under rock-lined dissipators, stilling basins, or culvert outlet protection systems[31]. A report also evaluates the use of soil bioengineering (living plant-based stabilization techniques) as an alternative or complement to traditional engineering for controlling erosion and shallow landslides on upland roadside slopes in Washington State, documenting the planning, design, construction, and performance of three major project sites at Chelan, Lost Creek, and Raymond. It finds that methods such as willow walls, brush layers, live cribwalls, terracing, and targeted planting can effectively stabilize slopes across diverse climates and soil conditions, often providing enhanced vegetation cover, reduced erosion, and long-term environmental benefits[32]. However, the report focuses exclusively on upland slope stabilization at roadside locations (not hydraulic structures). All techniques described are applied to erosional slopes, shallow rapid landslides, and cut/fill slopes, not culvert outlet

[28] http://dx.doi.org/10.3390/ma13071774
[29] https://doi.org/10.1080/15440478.2025.2519623
[30] https://doi.org/10.3390/su15118603
[31] https://www.adb.org/sites/default/files/publication/577066/bioengineering-green-infrastructure.pdf
[32] https://www.wsdot.wa.gov/research/reports/fullreports/491.1.pdf

erosion. The scope of another report is limited to the use of bioengineering for streambank and shoreline protection, focusing on erosion caused by flowing water and wave action. All techniques described (e.g., live stakes, fascines, brush mattresses, toe wood, and rootwad revetments) are applied only to natural streambanks or shorelines, and the report does not address dissipation of culvert outlet energy or erosion control specific to outlet scour[33].

Biodegradable & Biopolymers Geotextile

Rolled Erosion Control Products (RECPs) including geotextiles, mats, and biodegradable or synthetic blankets are used to stabilize disturbed soils, reduce erosion from rainfall and runoff, and support vegetation establishment on steep or long slopes, channels with moderate flow, stockpiles, and areas where vegetation is slow to grow. A document focuses exclusively on RECPs and their purpose, materials, installation methods on slopes, channels, and disturbed soil areas, costs, and maintenance. However, it does not discuss culverts, outlet protection, rock energy dissipators, riprap underlayment, or any related hydraulic energy-dissipation soil treatments[34].

Researchers in the Bioshoreline project, led by Fraunhofer UMSICHT, have developed a biodegradable geotextile made from renewable raw materials to provide temporary bank stabilization on inland waterways while supporting more natural, plant-based erosion control. The biodegradable geotextiles described in the article are not suitable for soil stabilization beneath rock energy dissipators at culvert outlets, because they are designed for temporary, nature-based riverbank protection where hydraulic forces are moderate and vegetation can eventually take over the stabilizing role[35]. An article explains that while many geotextile applications require long-lasting materials, others (such as erosion control) benefit from products that biodegrade once vegetation is established, avoiding the long-term microplastic pollution caused by polypropylene and polyester fabrics. Natural-fiber options like jute and coir degrade too unpredictably to be reliable, which has limited their commercial use. The article highlights poly (butylene succinate) or PBS as a promising biodegradable alternative because it offers mechanical performance comparable to conventional synthetics, can be produced from bio-based feedstocks, and allows controlled degradation when blended with poly (butylene succinate-co-adipate) or PBSA. PBS enables fully biodegradable nonwoven geotextiles suitable for applications ranging from road construction to coastal protection. The article also notes that the patent landscape for PBS geotextiles is still sparse, creating opportunities for innovation in materials, manufacturing processes, and new application areas[36]. Several recent product and industry articles describe commercial biodegradable geotextiles relevant to microplastic-free soil stabilization[37] [38] [39] [40].

A paper reviews biochemical soil stabilization as an environmentally friendly alternative to traditional mechanical and chemical methods, which can be costly, carbon-intensive, or disruptive. It explains how microorganisms, enzymes, extracellular polymeric substances (EPS), and biopolymers enhance soil by promoting bioaggregation, bioclogging, and biocementation, leading to increased strength, durability, and resistance to erosion. Microbial processes such as ureolysis, nitrate reduction, and cyanobacterial mineralization can precipitate minerals like calcium carbonate, phosphate, and sulfate to bind soil particles, while EPS and biopolymers (including lignin, gellan gum, and chitosan) improve cohesion and structural integrity at relatively low dosages. Enzyme-based approaches offer controlled reactions without

33 https://directives.nrcs.usda.gov/sites/default/files2/1712930924/31800.pdf
34 https://cleanwaterprogram.org/wp-content/uploads/2024/01/EC-07_2023.pdf
35 https://geosyntheticsmagazine.com/2025/02/10/securing-banks-close-to-nature-with-biodegradable-geotextiles/
36 https://geosyntheticsmagazine.com/2023/06/06/pathway-to-truly-sustainable-geotextiles/
37 https://www.naue.com/products/geotextiles/secutex-green/
38 https://texaserosionsupply.com/blog/innovative-erosion-control-solutions-2023-new-materials-and-techniques-to-try/
39 https://www.erosioncontrol-products.com/biodegradable-erosion-control-products.html
40 https://biocompositesgroup.com/sustainable-hemp-geotextiles/

introducing live microbes, though performance varies with soil type and environmental conditions. Overall, biochemical techniques show strong potential as sustainable, cost-effective solutions for improving geotechnical and agricultural soil properties, provided their interactions with soil systems are well understood. However, everything in the paper is centered on microbially driven or biopolymer-based soil improvement, with no reference to culverts or rock energy dissipation[41].

Another document describes ECOROADS as a soil-stabilization product for road bases, haul roads, parking areas, slopes, and similar load-bearing applications, and while it highlights improved soil strength and resistance to water penetration, it provides no claims related to hydraulic performance, high-velocity flow, scour resistance, or stabilization beneath energy-dissipating rock at culvert outlets. ECOROADS is a biomass-based, non-toxic, multi-enzyme soil stabilizer that strengthens and densifies local soils to create durable, water-resistant road bases while significantly reducing the need for imported aggregate material, cutting road construction costs by up to 60% and maintenance by more than half. It works by accelerating the bonding of cohesive fines to form a dense, stable subgrade that resists erosion, rutting, frost heave, and water penetration, and is easily applied using standard equipment by mixing the liquid concentrate with water during compaction[42].

Summary of Findings

Microplastics concerns are reshaping material selection.
State and national policies increasingly target microplastic reduction, influencing the scrutiny of synthetic geotextiles used in civil infrastructure. While engineered geosynthetics are designed for longevity and minimal environmental shedding when properly buried, several regulatory and environmental guidance documents identify polymer-based erosion control materials as potential microplastic sources when used above ground or when subjected to UV exposure, abrasion, or improper installation.

Geosynthetics remain high performing filter and separation materials, especially under hydraulic loading.
Multiple engineering references (HEC 11, NCHRP reports, FHWA guidance) consistently support the use of geotextiles as filter layers beneath riprap, particularly in conditions with mobile bedforms, high seepage forces, or erosion prone soils. Their uniform properties, ease of installation, and reliable filtration make them a preferred option in most modern hydraulic designs.

Granular filters have conditional hydraulic benefits but significant failure and implementation risks.
Granular filters can provide effective soil retention and puncture resistance when properly graded, uniformly placed, and continuously confined. However, they can fail through flanking, toe scour, and progressive undermining if their boundaries and extent are not adequately designed. Their thickness, material quantities, placement tolerances, and quality-control requirements also make them difficult to implement across projects containing many culverts with varying soils. Therefore, granular filters should be treated as a site-specific or standardized-class option, rather than a broadly applicable replacement for geotextile filters.

Current practice and literature do not address dedicated soil stabilization methods beneath REDs.
Despite extensive research on soil stabilization (lime, cement, biopolymers, microbial methods, alkali activated binders), none of these approaches have been evaluated specifically for subgrade stabilization under rock energy dissipators, where hydraulic forces dominate rather than structural loading alone. Existing culvert and outlet design guidance lacks any established methodology for alternative RED specific soil stabilization.

[41] https://www.scirp.org/journal/paperinformation?paperid=131212
[42] https://ecoroads.com/wp-content/uploads/2024/12/ECOROADS-BROCHURE-25.pdf

Natural fiber and biodegradable geotextiles offer environmental benefits but have significant durability limitations.
Materials such as jute, coir, hemp, and new biodegradable polymers (e.g., PBS/PBSA blends) show promise for erosion control and short term stabilization. However, their limited service life, unpredictable degradation, and lack of testing under high velocity hydraulic conditions make them unsuitable for use beneath rock dissipators, where long term filtration and soil retention are essential.

Soil bioengineering and vegetative measures are not applicable beneath REDs.
Although effective for upland slopes, streambanks, and shallow landslides, vegetation based stabilization and bioengineering methods do not provide the structural or hydraulic performance required under rock-lined outlet protection systems.

Industry trends emphasize durability, sustainability, and advanced sensing but not hydraulic soil stabilization.
Emerging technologies such as intelligent geotextiles and advanced fiber systems improve monitoring and mechanical performance, but the literature does not extend these innovations to energy dissipation subgrade environments.

Gaps in Findings

Lack of research directly linking new soil stabilization methods to rock energy dissipators (REDs).
Across engineering manuals, academic studies, and industry reports, no source provides a focused evaluation of new soil stabilization methods specifically for subgrades beneath rock-lined dissipators.

Absence of hydraulic performance testing for alternative stabilizers.
Emerging materials such as biochemical binders, microbial treatments, biopolymers, alkali activated binders, and enzyme based stabilizers show promise in geotechnical applications, but none have been evaluated under scour, drawdown, seepage, or turbulent flow conditions representative of outlet basins. Their suitability beneath REDs is therefore unknown.

Limited data on long term durability of natural fiber and biodegradable geotextiles in harsh hydraulic environments.
While natural fibers (coir, jute, sisal, etc.) and new biodegradable polymers (PBS/PBSA) are documented for erosion control, no studies examine their performance beneath rock loads, sustained saturation, uplift forces, or turbulence.

No evaluation of microplastics risk from buried geosynthetics in RED applications.
Although some environmental guidance warns that polymer stabilization products may shed microplastics, none of the reviewed engineering documents assess whether buried geotextiles used under riprap contribute measurable microplastic release over time.

Lack of lifecycle, cost, and environmental tradeoff analyses.
There is no integrated assessment balancing hydraulic performance, long term durability, installation practicality, microplastic generation risk, and sustainability impacts for different stabilization approaches and filter types.

Limited evidence on granular-filter field failures and multi-culvert constructability.
Existing design guidance primarily addresses gradation, permeability, and thickness. It provides limited evidence on the frequency and causes of flanking, undermining, incomplete coverage, layer mixing,

segregation, and thickness deficiencies beneath REDs. There is also little guidance on translating site-specific granular-filter calculations into practical specifications for contracts containing many culverts with different soils and hydraulic conditions.

Disconnect between policy direction and engineering practice.
Environmental agencies are increasingly discouraging polymer-based materials due to microplastic concerns, while hydraulic engineering guidance continues to rely heavily on synthetic geotextiles due to their superior performance. No studies bridge this gap by proposing validated natural or biodegradable alternatives suitable for high energy hydraulic structures.

Next Steps

Develop a structured research plan focused on hydraulic specific soil stabilization.
Initiate targeted studies that evaluate chemical, mechanical, biopolymer based, and bio mediated soil stabilization methods under hydraulic loading conditions representative of culvert outlet flows, including high shear stresses, rapid drawdown, uplift, and fluctuating turbulence.

Conduct laboratory testing of stabilized vs. unstabilized subgrades.
Design controlled experiments comparing riprap performance over untreated soils versus soils stabilized with lime, cement, biopolymers, enzymatic products, alkali activated binders, and other candidate materials to quantify improvements (or drawbacks) in resistance to piping, winnowing, scour, and undermining. Testing needs to evaluate not only erosion through the center of the protected area but also flanking at lateral and upstream boundaries and undermining initiated at the downstream edge or toe.

Develop preliminary selection criteria for stabilization beneath REDs.
Based on initial testing, begin outlining decision frameworks addressing when (and whether) soil stabilization should supplement or replace conventional filter layers beneath dissipators. Criteria may include soil type, hydraulic severity, constructability constraints, and environmental considerations.

Evaluate compatibility between soil stabilization treatments and filter designs.
Investigate how different stabilization methods interact with geotextile, granular, and alternative filters, including effects on soil retention, permeability, pore pressure dissipation, clogging potential, and long-term interface behavior.

Evaluate constructability at the project rather than individual-culvert level.
Using soil and RED design information from a representative multi-culvert project, calculate the requirements for each location and determine how many distinct configurations would theoretically be required. Evaluate whether culverts with similar native-soil gradations, RED rock sizes, and hydraulic conditions can be grouped into a limited number of design classes. For each class, identify a standard configuration that satisfies retention and permeability requirements across the applicable range of conditions.

Assess long term environmental impacts, including microplastic generation.
Conduct independent studies assessing whether buried geosynthetics used beneath dissipators shed microplastics over decades, and whether alternative biodegradable or natural fiber products can offer comparable hydraulic performance without environmental tradeoffs.

Coordinate with environmental and materials experts to explore sustainable alternatives.
Engage researchers in biopolymers, natural fibers, and biodegradable geotextiles to identify potential materials capable of meeting the durability, filtration, and hydraulic loading requirements for RED applications.

Update agency guidance and specifications as evidence emerges.
As research progresses, begin drafting updates to culvert outlet protection standards, material specifications, and design manuals to incorporate validated stabilization methods and clarify when they are appropriate.