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The Pacheco Silva Lecture 2024 – Geosynthetics and sustainability: solutions to preserve the environment and reduce the effects of climate change

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Lecture

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Abstract

Geosynthetics are construction materials that can assume different functions in geotechnical engineering and environmental protection works, such as drainage, filtration, reinforcement, protection and as barriers. They are easy to install, to transport to remote areas and provide engineering solutions that impacts less the environment. This paper presents and discusses the use of these materials in environmental protection works, as well as sustainable solutions using different types of geosynthetics and combinations between them and alternative construction materials such as scrap tires and plastics. Applications in waste disposal, drainage, soil reinforcement, etc. are described and discussed. The use of sustainable geosynthetics such as biodegradable mats for erosion protection and geosynthetics manufactured from recycled plastics and scrap tires is also discussed as well as solutions incorporating geosynthetics to minimize the consequences of climate change. The results from experimental studies and case-histories monitoring presented show that geosynthetics can make a significant contribution to environmental preservation and protection, especially in view of the future consequences of the increasing frequency of extreme events caused by climate change.

1. Introduction

Geosynthetics are established construction materials aiming at different functions in geotechnical and geoenvironmental works such as reinforcement, drainage, filtration, barrier, separation, stiffening and protection, as schematically shown in Figure 1. Some of the advantages of these materials are that they are easy and quick to install and can be transported to remote construction sites. Different products are available capable of meeting the requirements of engineering projects, providing durable and cost-effective solutions. Another advantage of geosynthetics of increasing importance is that they can enable solutions that have less impact on the environment than conventional geotechnical engineering solutions. As an example, Figure 2 compares some environmental impact parameters associated with two different solutions for the filter layer at the base of a pavement (Stucki et al., 2011), one of them a conventional sand filter layer and the other a geotextile layer. The latter solution showed a reduction of more than 90% in the emission of gases that contribute to global warming, water consumption, acidification, eutrophication and consumption of renewable energy. Over 80% reduction was observed for the consumption of non-renewable energy. Figure 3 presents results of a similar study but comparing environmental impacts from different retaining wall solutions subjected to the same conditions (Damians et al., 2017). In this case, the environmental detrimental effects of a rigid concrete wall and a concrete cantilever wall were compared to those of a geosynthetic reinforced wall. It can be seen that the energy consumption and CO_2 emissions were significantly smaller for the geosynthetic reinforced wall. The results in Figures 2 and 3 are evidence of more environmentally friendly solutions provided by geosynthetic than by conventional geotechnical solutions. Similar conclusions for other geosynthetic applications can be found in Frischknecht et al. (2012), Heerten (2012) and Jacob et al. (2024).

Besides providing better engineering solutions to the environment, geosynthetics can be used in several environmental protection works or can make viable the use of alternative construction materials that would otherwise

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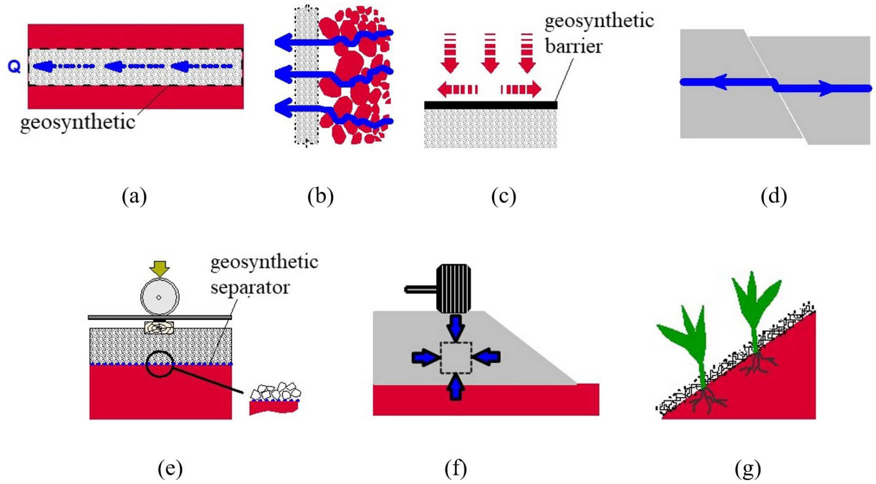


Figure 1. Typical functions of geosynthetics: (a) drainage; (b) filtration; (c) barrier; (d) reinforcement; (e) separation; (f) stiffening; (g) protection.

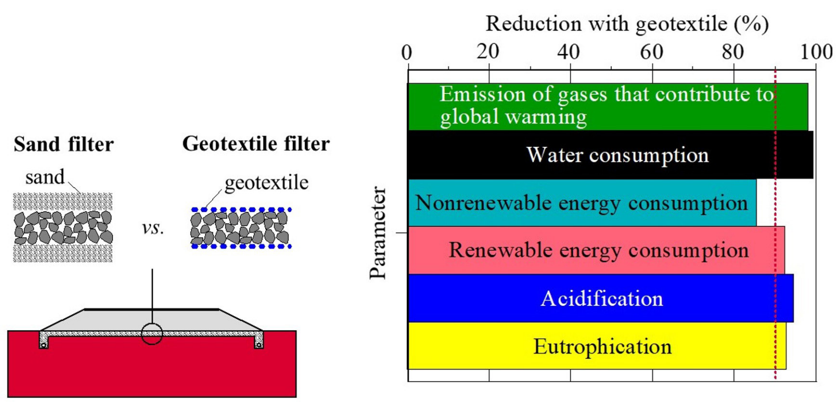


Figure 2. Reduction of some environmental impact parameters with the use of geotextile filter. Source: Stucki et al. (2011).

occupy space in landfills or might be improperly disposed (Palmeira, 2016; Palmeira et al., 2021a; Dabrowska et al., 2023). This paper presents and discusses the benefits to the environment with the use of geosynthetics in different applications, some of them to avoid or mitigate the effects of climate change.

2. Sustainable and environmentally friendly solutions in waste disposal

One of the largest applications of geosynthetics is in waste disposal works, where they can be used for different functions, as schematically shown in Figure 4 in the case of a landfill. Geomembranes and GCLs can be used as barriers, geotextiles as filters and geocomposites as drainage layers; geogrids, geotextiles, geocells and fibres can be used for soil reinforcement etc. Because of the possibility of these multiple functions, geosynthetics can avoid or minimize the use of soils in landfills, reducing the environmental impacts caused by their exploitation and transportation to the site. Besides its traditional use in filtration and drainage, geotextiles can also be employed to protect geomembranes against mechanical damage (Figure 5a) or to serve as capillary barriers against infiltration of rainwater across cover layers of waste disposal areas (Lima et al., 2018), as schematically shown in Figure 5b. Another environmental application of geomembranes is as vertical barriers to confine regions of contaminated ground, avoiding the lateral spreading of contaminants.

Silva (2014) and Silva & Palmeira (2019) studied the use of nonwoven geotextiles as filters for pre-treatment of the effluents from a landfill. In this case, experimental geotextile panels were used to reduce the pollutant potential of the effluent of the landfill of the city of Cuiabá, MT, Brazil, as shown in Figure 6a. The experimental setup of the research is also presented in this figure, showing a canal (2000 mm long, 500 mm high and 500 mm wide) through which part of the effluent of the landfill was forced to pass. In this canal, one to three vertical panels of nonwoven, needle-punched, geotextiles (mass per unit area, M_A, ranging from 130 g/m^2 to 1800 g/m^2 and filtration opening size, FOS, from 0.08 mm to 0.15 mm) were installed to serve as filters for a pre-treatment of the effluent. For comparison purposes, a sand filter (d_{50} =

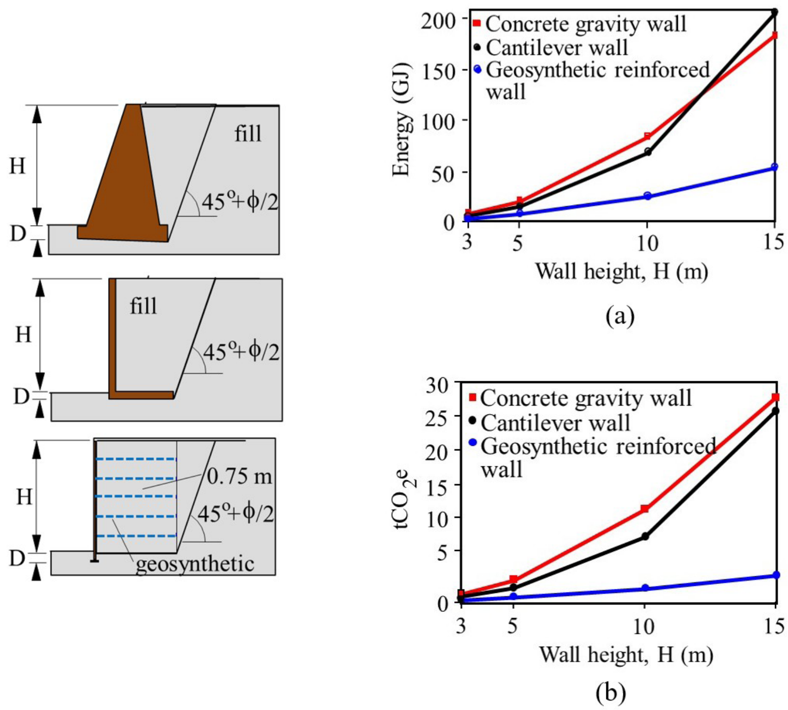


Figure 3. Comparison between environmental impacts from different retaining wall structures: (a) energy consumption; (b) emission of CO_2 (Damians et al., 2017).

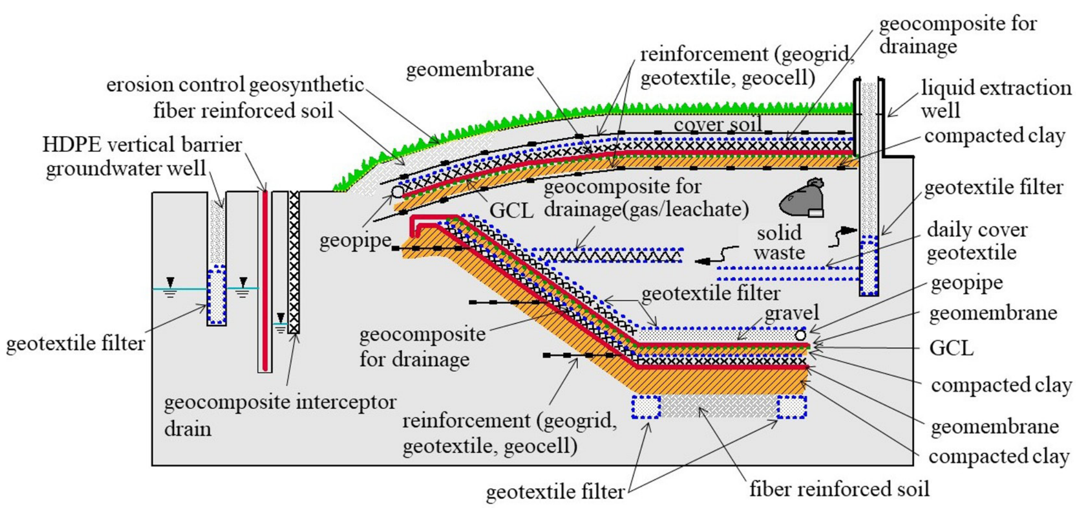
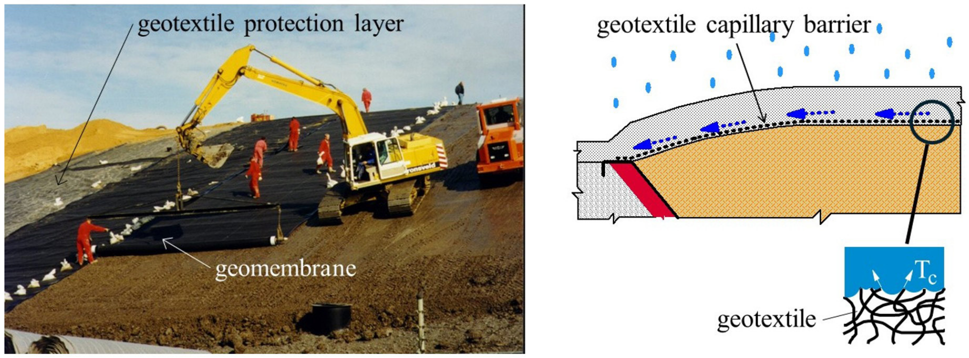


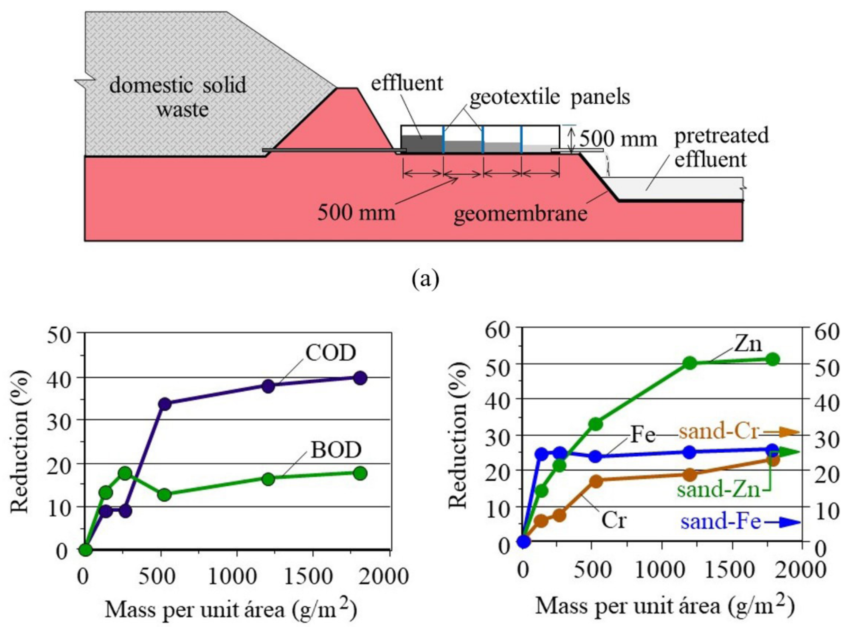
Figure 4. Possible applications of geosynthetics in landfills (modified from Bouazza & Zornberg, 2006).

0.29 mm, d_{85} = 0.50 mm, $C_U = d_{60}/d_{10}$ = 1.7 and d_c = 0.048 mm, where d_n = diameter for which n % of the remaining particles are smaller and d_c = constriction diameter), 500 mm long, was also tested in the same canal. The results in Figure 6b show reductions of leachate chemical (COD) and biological (BOD) oxygen demands reaching up to 40% and 18%, respectively, for heavier geotextile layers. Significant reductions in the presence of heavy metals in the pre-treated effluent with geotextile mass per unit area were also observed (Figure 6c), particularly for zinc (up to 51% reduction). Figure 6c also shows the reductions in heavy metals in the case of the sand filter and it can be noticed that except for chrome, the reductions observed with the geotextile filter panels were significantly greater. The pre-treatment with geotextiles also reduced the toxicity of the effluent to some extent (Silva & Palmeira, 2019). An additional benefit of using geotextile rather than sand as filter in this type of application is that the geotextile layer may be reused after washing or easily and quickly substituted, besides avoiding the use of a natural filter material. This type of leachate pre-treatment



(a) (b)

Figure 5. Other uses of geotextiles in waste disposal areas: (a) geomembrane protection; (b) capillary barrier.



(b) (c)

Figure 6. Pretreatment of a landfill effluent with nonwoven geotextile panels (Silva, 2014): (a) experimental setup; (b) reductions of COD and BOD with geotextile mass per unit area; (c) reduction of heavy metals with geotextile mass per unit area.

may be interesting for smaller to medium size communities as a measure to reduce effluent pollutant potential and to reduce the costs of additional effluent treatment processes.

Engineering solutions combining geosynthetics and alternative or low-grade construction materials or that enable the use of wasted materials in geoenvironmental works certainly increase the sustainability of the solutions. Several examples of these combinations can be found in the literature. Junqueira et al. (2006) describe the use of a drainage system in an experimental domestic waste cell consisting of a geotextile filter combined with a drainage layer made of scrap tires (Figure 7). Comparisons between the effluent volumes of this cell and another experimental cell with the same dimensions and conditions, but with a traditional granular drainage layer, showed no difference in the variation of effluent volume over time.

Palmeira & Silva (2007) investigated the performance of drainage trenches (300 mm wide, 300 mm deep) (Figure 8) consisting of geotextile filters and recycled construction and demolition residues (RCDR) or scrap tire chips for drainage of leachate in large experimental containers (3500 mm × 2500 mm × 1000 mm). The results obtained for different leachate parameters showed the good performance of the alternative drainage system tested (Palmeira et al., 2021a). Kaushik et al., (2017) also investigated the combination of nonwoven geotextile filter encapsulating different sizes of scrap tire chips or mixtures of gravel and tire chips in drainage systems subjected to leachate flow under up to 500 kPa

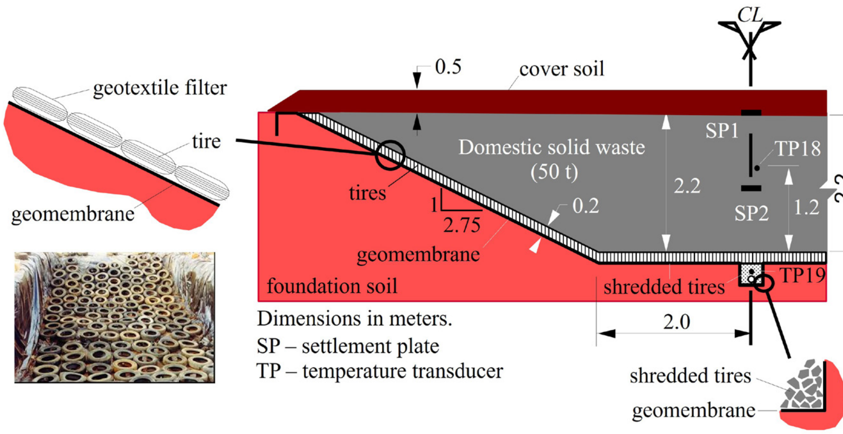


Figure 7. Waste cell with alternative drainage blanket consisting of a geotextile filter and scrap tires (Junqueira et al., 2006).

(a) **(b)**

Figure 8. Drainage trenches combining geotextile filter and alternative drainage materials (Silva, 2004): (a) RCDR; (b) scrap tire chips.

vertical stress. According to the authors, these combinations could allow landfill designers and managers to reuse scrap tire chips on a large scale in a more suitable way.

3. Sustainable and environmentally friendly solutions in soil reinforcement

As commented earlier in this paper, geosynthetic reinforced walls and slopes result in less environmental impacts than conventional retaining structures. If alternative construction materials are used in such structures, the additional environmental benefits are twofold: natural building materials will not be used, and a better destination will be given to alternative materials that will not take up space in landfills or be illegally disposed of. An example of the use of alternative construction material associated with soil reinforcement is described in Santos (2011), where two 3.6 m high experimental geosynthetic reinforced retaining walls were constructed using recycled construction and demolition residues (RCDR) as backfill material. Figure 9a depicts the geometrical characteristics and the instrumentation used in the walls, whereas Figure 9b presents a bird-eye view of the walls at the end of construction. Wall 1 was reinforced with a polyester geogrid (20 mm × 20 mm apertures, tensile stiffness, $J_{5\%}$, of 300 kN/m, maximum tensile strain, ε_{max}, of 12%) and Wall 2 was reinforced with a nonwoven, needle-punched, geotextile made of polypropylene ($J_{5\%}$ of 15 kN/m, under in-air conditions, and ε_{max} of 70%). The RCDR used as backfill had a d_{50} of 2.5 mm, d_{10} of 0.032 mm, C_u equal to 106, unit weight of 17.6 kN/m^3, cohesion of 6 kPa and a friction angle of 41°. Because the walls were constructed on a porous collapsible soil, water reservoirs were constructed at the wall faces to increase the infiltration of water in the subgrade, aiming at enhancing the structural collapse of the foundation soil to investigate the effects of such collapse on the performance of the walls.

Figures 9c and d show the settlement profiles of the wall top surface one year after the end of construction, when the first rainy season in the region had already occurred, and after the artificial inundation of the foundation soil, respectively.

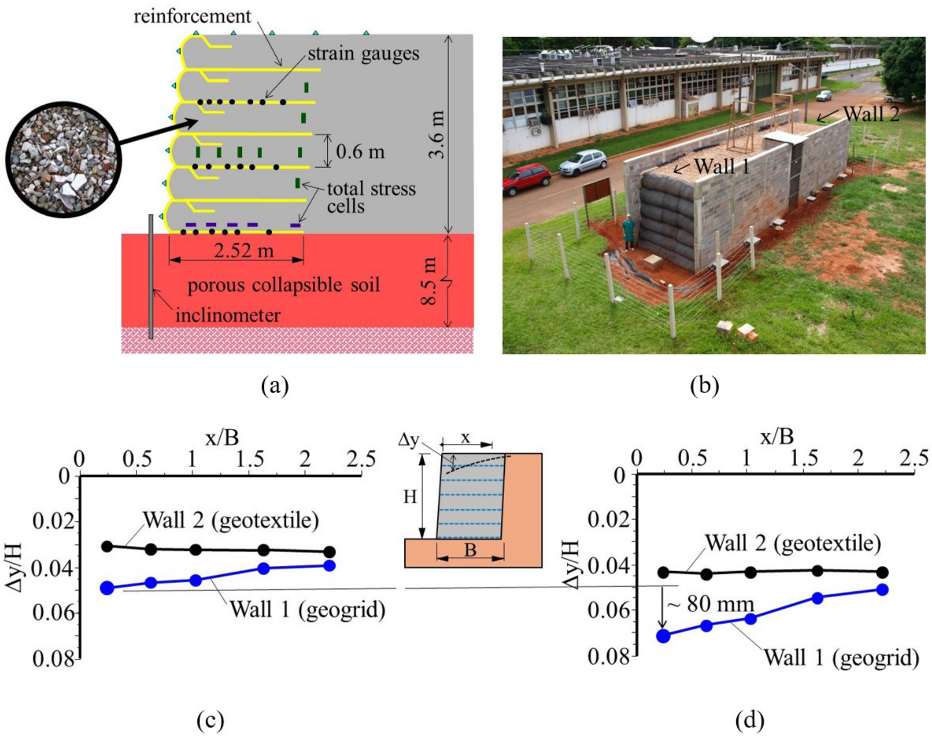


Figure 9. Geosynthetic reinforced walls built with RCDR backfill (Santos, 2011): (a) geometrical characteristics and instrumentation of the walls; (b) walls at the end of construction; (c) settlement profile of the wall top 1 year after construction; (d) settlement profile of the wall top after subsoil inundation.

Uniform settlement profiles of Wall 2 can be noted, contrasting with the non-uniform and larger settlements observed for Wall 1. These larger settlements in the latter case were due to the more collapsible nature of the soil underneath Wall 1 in comparison with that underneath Wall 2. Artificial inundation of the foundation soil increased the settlement close to Wall 1 face by 80 mm. Similar settlement mechanisms during rainy seasons have caused damages in retaining structures in the region because of structural collapse of the unsaturated foundation soil, as shown in Figure 10. However, strains in the reinforcement and wall face displacements (the latter particularly for Wall 2) were not significantly influenced by the foundation soil collapse. Bearing in mind typical values of deformation of walls built with conventional backfill materials, the results obtained showed similar magnitudes for the walls constructed with RCDR, showing the potentials of using such backfill material in these structures. Additional information on the performance of the walls can be found in Santos (2011), Santos et al. (2013, 2014) and Palmeira et al. (2021a). Other studies investigating combinations of RCDR and geosynthetic reinforcements are reported by Fleury et al. (2019), Corrales et al. (2023), Moncada et al. (2024) and Oliveira et al. (2024).

Another sustainable solution involving the combination of geosynthetic reinforcement and alternative construction material is reported by Fernandes (2005) in a railway application (Victoria-Minas railway). In this case, an alternative geogrid reinforced subballast was employed in substitution to the conventional one. The alternative subballast consisted of a mixture of 50% (in weight) of a local soil (silty sand), 25% of fine ore mining tailings and 25% of the conventional subballast material (sandy gravel), resulting in a subballast material considerably finer than that traditionally used in the region. The reinforcement employed was a polyester geogrid, with 30 mm × 30 mm apertures, tensile stiffness ($J_{5\%}$) of 520 kN/m, tensile strength (T_{max}) of 65 kN/m and maximum tensile strain of 10%. The results obtained in the monitoring of 4 experimental sections subjected to the same traffic as on the real railway revealed that the presence of the geogrid reinforcement improved the performance of the alternative subballast material to the point that it presented deformability similar to that of the unreinforced conventional subballast in the Benkelman Beam tests. Smaller horizontal strains and less breakage of the the grains of the ballast layer were also observed in the experimental sections with the reinforced alternative subballast layer. Additional information on this experiment can be found in Fernandes (2005), Fernandes et al. (2008) and Palmeira et al. (2021a).

Martins (2000) e Martins & Gomes (2002) present the use of ore mine tailings as fill material of a 3-tier reinforced structure in the Fernão Dias highway (BR381), Brazil. In this case-history, each of the three tiers was 6 m high with a 1:2

(a)

(b)

Figure 10. Damages to retaining walls due to structural collapse of the foundation soil: (a) geosynthetic reinforced wall; (b) conventional concrete gravity wall.

(h:v) face batter, resulting in a total reinforced mass height of 18 m in a slope 28 m high, as shown in Figure 11. In the bottom tier, the reinforcement used was a nonwoven geotextile (200 mm reinforcement spacing), made of polypropylene, with M_A equal to 445 g/m^2, T_{max} of 70 kN/m and ε_{max} of 20%. The middle tier was reinforced with a nonwoven geotextile (300 mm spacing), made of polyester, with M_A equal to 600 g/m^2, T_{max} of 40 kN/m and ε_{max} greater than 40% and the upper tier was reinforced with the same geotextile as in the middle tier, but with a spacing of 400 mm between reinforcement layers. The mine tailings fill of the reinforced tiers had a d_{85} in the range 5 mm to 14 mm, d_{50} in the range 0.3 mm to 1.4 mm, 30% to 40% of particles smaller than 0.075 mm, cohesion of 19.6 kPa and 38.9^o friction angle. The structure has performed well for 28 years, showing the feasibility of using appropriate mine tailings as a cost-effective backfill material in geosynthetic-reinforced structures.

Combinations of geosynthetic reinforcement and alternative or low-quality fill materials have also been employed in unpaved roads over unstable grounds (Palmeira, 1981; Ramalho-Ortigão & Palmeira, 1982; Góngora & Palmeira, 2012; Mehrjardi et al., 2020; Liu et al., 2025). Palmeira (1981) and Ramalho-Ortigão & Palmeira (1982) describe a pioneer application of geosynthetic reinforcement in Brazil, in which an unpaved road was constructed with a fill material having 66% of particles passing in the #200 sieve and was reinforced with nonwoven geotextiles. Despite the poor quality of the fill material for this type of application and the type of reinforcement used (only type available in the country at that time), its presence improved the performance of the road and reduced fill consumption between 9 and 24%, depending on the type of reinforcement arrangement.

Góngora & Palmeira (2012) present a study on the performance of unpaved roads on compressible subgrade with RCDR as fill material using large-scale model tests. Tests on roads with conventional gravel (d_{50} = 10.5 mm, C_u = 7.1) as fill were also performed for comparisons. The RCDR had a d_{50} of 34 mm and C_u of 6.8. The subgrade had a d_{50} of 0.025 mm, 63% of fines (< 0.075 mm), liquid limit of 39%, plasticity index of 10%, dry unit weight of 14 kN/m^3, moisture content of 27.1% and CBR of 4.2%. Three geogrids were used as reinforcement, with values of tensile stiffness ($J_{5\%}$) ranging from 130 kN/m to 1500 kN/m. For a 25 mm rut depth limit at the road surface, the results showed that the geogrid reinforced RCDR fill outperformed the conventional gravel, with a number of load repetitions to reach that rut depth 2.2 times greater for the former type of fill. The results also showed the good performance of the reinforced RCDR after maintenance of the road surface. Mehrjardi et al. (2020) also observed a good performance

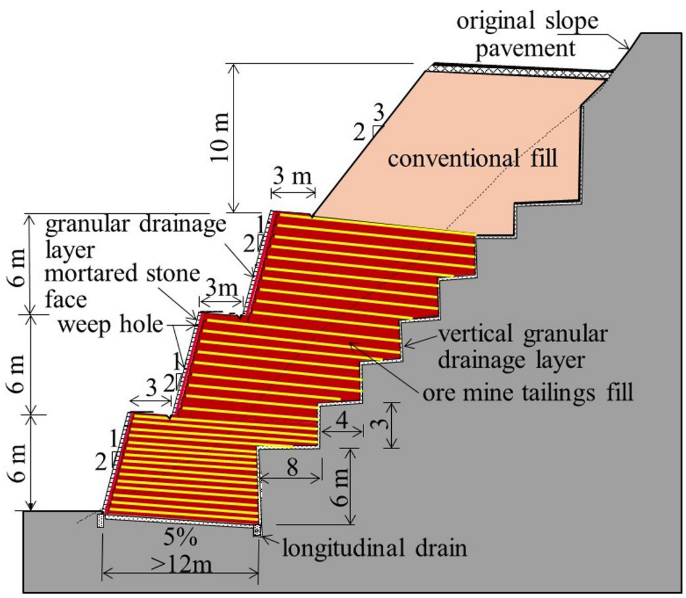


Figure 11. 3-Tier superimposed wall system in BR381 highway (Martins, 2000).

of a RCDW fill reinforced with geocell in large-scale tests on unpaved roads on a compressible subgrade, with similar results of rut depth versus number of loading cycles for the alternative fill material and the reference unreinforced natural aggregate. Liu et al. (2025) describe the use of steel slag as infill material of floating geosynthetic-encased columns in soft clay under cyclic loading, also showing good performance. A summary of the combinations of geosynthetics and alternative construction materials can be found in Vieira (2022).

4. Environmentally friendly solutions in mining

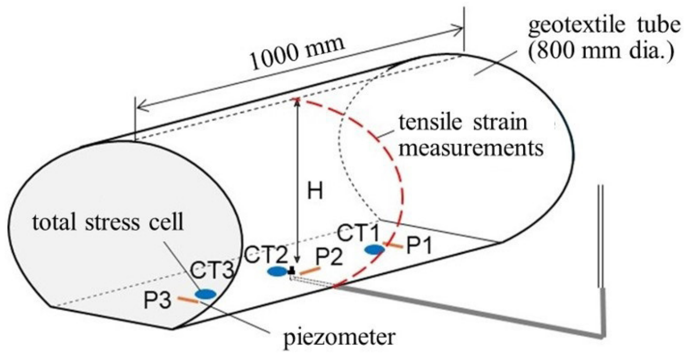
Geosynthetics have a wide range of applications in mining as barriers, filters, reinforcement and in drainage. One increasingly popular application is the use of geotextile tubes and mattresses to dewater mine tailings (Figure 12). This solution can provide a safer method for tailings storage in contrast to traditional tailings dams and this is particularly relevant in Brazil considering recent major disasters involving this type of dam.

Barrantes (2023) and Barrantes et al. (2023) studied the use of geosynthetic tubes to dewater fine grained materials using large-scale laboratory equipment. The dimensions of the tubes tested are presented in Figure 13a, as well as the instrumentation used to monitor tube behaviour. General views of the experiments are presented in Figures 13b (single geotextile tube) and 13c (stack of tubes). The tubes were 800 mm in diameter and 1000 mm long. The geotextile used to manufacture the tubes was a nonwoven, needle-punched, geotextile made of polyester, with a mass per unit area of 200 g/m^2, tensile strength of 9.8 kN/m, tensile stiffness ($J_{5\%}$) of 11.5 kN/m, maximum tensile strain of 83% and filtration opening size of 0.115 mm. The infill fine-grained material had a d_{10} of 0.0036 mm or 0.040 mm (depending on the use or not of dispersing agent in the grain size analysis), d_{50} of 0.027mm or 0.120 mm, d_{85} of 0.063 mm or 0.259 mm, C_u of 8.4 or 3.7, 87% or 29% in weight passing the #200 sieve, liquid limit of 37% and plasticity index of 9%. The tubes were filled with the use of a pump in 1 or 3 filling stages to assess the influence of the number of filling stages on tube performance. Figure 14a shows the variation of tube height with time for one and three stages filling processes. It can be noted that the storage capacity of the tube increases with a larger number of filling stages. The drainage capability of the tubes is revealed in Figure 14b, where it can be noticed that the pore pressure measured by piezometer P2 at the middle of the tube base (Figure 13a) is quickly dissipated after each filling stage. Figure 14c shows the tensile strain distribution along the tube perimeter. As expected, larger strains were obtained for 3 filling stages, although the strains were much smaller than the maximum geotextile tensile strain at failure. Particles that piped through the geotextile during the tests were collected for grain size analyses and the results obtained (Figure 14d) revealed that the diameters of the piped particles were considerably smaller than those of the original infill material and smaller than the geotextile FOS.

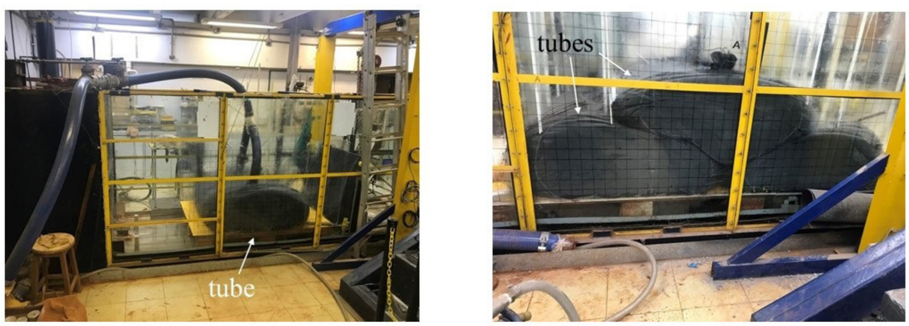
Barrantes et al. (2023) also evaluated the accuracy of some available analytical methods for the prediction of geotextile tube behaviour. Figure 15a and b show comparisons between different tube geometrical parameters measured and predicted by the methods by Plaut & Suherman (1998), Lawson (2008) and Guo et al. (2014). In general, predictions and measurements compare well in terms of tube cross-section area, maximum tube width and vertical stress at the base of the tube (Figure 15a). Regarding final tube height, Lawson (2008) and Plaut & Suherman presented satisfactory

(a) (b)

Figure 12. Geotextile tubes for dewatering of mine tailings: (a) isolated geotextile tube; (b) stack of geotextile tubes (courtesy of Prof. M.G. Gardoni).



(a)



(b)

Figure 13. Tests on geotextile tubes (Barrantes et al., 2023): (a) single tube; (b) stacked tubes.

predictions (Figure 15b), but significant deviations between predictions and measurements for the tube base width were observed in the cases of the methods by Guo et al. (2014) and Plaut & Suherman (1998). Despite some deviations, the results obtained are encouraging regarding the potential of those analytical methods for the prediction of geotextile tube behaviour under conditions similar to those employed in the experiments carried out.

The dewatering efficiency of geotextile tubes and geomattresses has also been investigated under field conditions. An example of this is the research reported by Silva (2017) and Morais et al. (2020) on the behaviour of stacked geotextile tubes in the Fazenda Brasileiro gold ore tailings dam, Bahia, Brazil. The gold ore tailings had 75% of fine particles and a stack of 14 geotextile tubes (2 m wide and 6 m long each) was monitored. The geotextile used to manufacture the tubes was a woven product, made of polypropylene, with a mass per unit area of 554 g/m^2 and a tensile strength of 100 kN/m. A plan view of the experimental setup is shown in Figure 16a and Figure 16b shows a view of the staked geotextile tubes. Significant tailings dewatering was observed after 72 hours, when the solids content in the tubes reached 80%, as shown in Figure 16c. This high level of reduction in the moisture content of the tailings was confirmed at the end of the experiment after cutting the geotextile to extract tailings specimens for additional tests

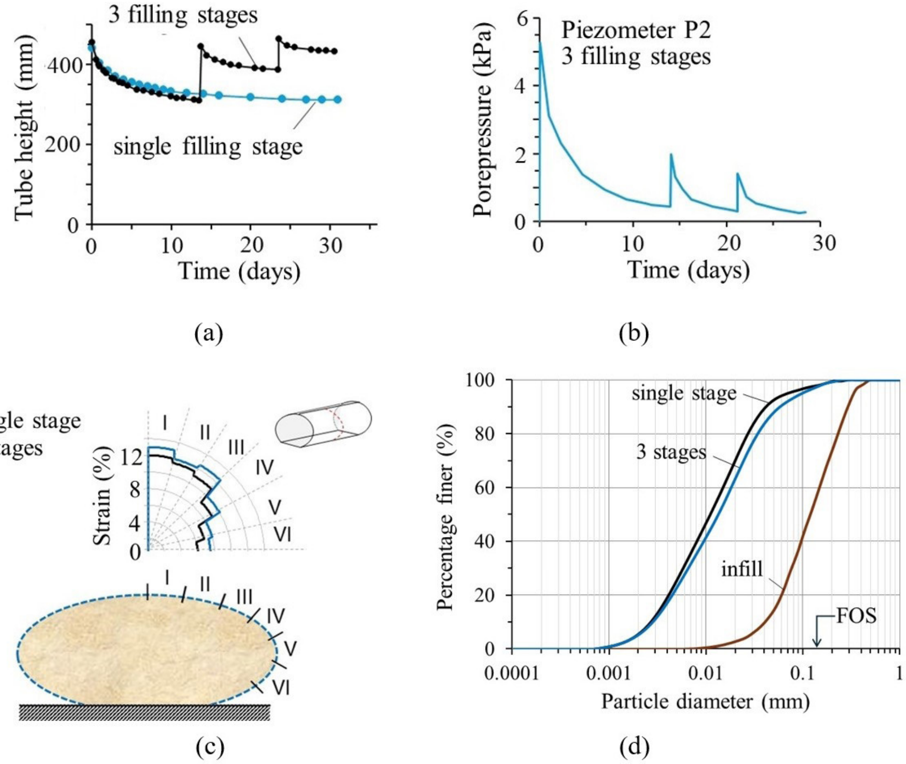


Figure 14. Behaviour of an isolated geotextile tube (Barrantes et al., 2023): (a) tube height versus time; (b) pore pressure versus time; (c) tensile strain distribution along the tube perimeter; (d) grain size distribution of the particles that pipped through the geotextile.

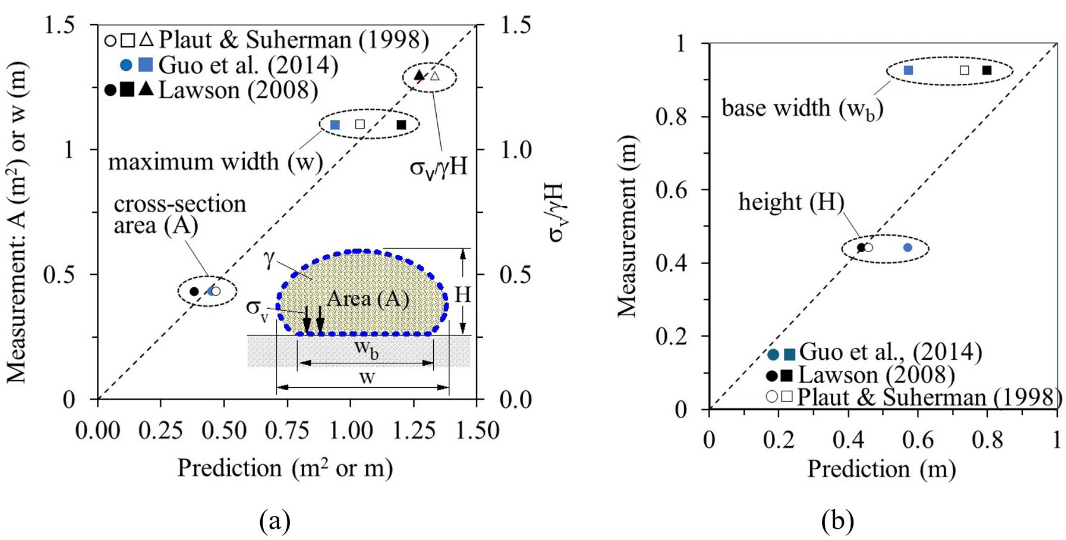


Figure 15. Comparisons between predictions and measurements (Barrantes et al., 2023): (a) tube cross-section area, maximum width and vertical stress; (b) tube height and base width.

(Figure 16d). Further information on the behaviour of the geotextile tubes can be found in Silva (2017), Morais et al. (2020) and Palmeira et al. (2021b).

Geomattresses were used for dewatering of dredged material from the Risoleta Neves dam reservoir (Terratek, 2017a, b; FOS, 2017; Ortigão, personal communication, 2024; Fahel, personal communication, 2024). The silting of the dam reservoir was a consequence of the failure of the Fundão tailings dam, in 2015, Bento Rodrigues District, state of Minas Gerais, Brazil. The dredged material had a unit weight of 22.5 kN/m^3, a friction angle of 37° and a cohesion of 20 kPa. The geomattresses were manufactured with a nonwoven, needle-punched geotextile, made of polyester, with a mass per unit area of 950 g/m^2. The tensile strength

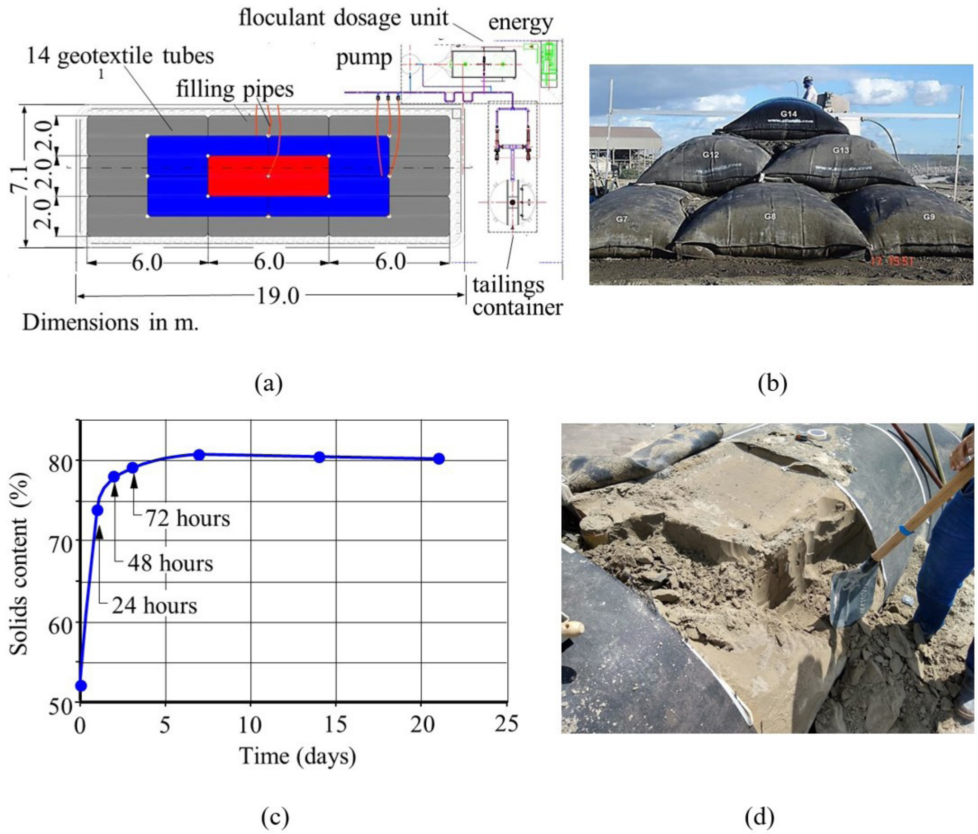


Figure 16. Dewatering of gold ore tailings with geotextile tubes: (a) experimental setup; (b) stacked geotextile tubes (courtesy Prof. M.G. Gardoni); (c) solids content versus time (Morais et al., 2020); (d) view of the tailings at the end of the test (courtesy Prof. M.G. Gardoni).

and the maximum tensile strain of the geotextile were equal to 60 kN/m and 79%, respectively, and its filtration capacity was greater than 500 $m^3/m^2/h$. Each geomattress was 18 m wide, 50 m long, 1.8 m maximum height, with a storage capacity of approximately 2350 m^3. Figure 17a shows the geometrical characteristics of the geomattresses and Figure 17b shows one of the geomattresses during filling. The geomatresses were stacked, as depicted in Figure 17c. An isolated geomattress was instrumented with 3 vibrating wire piezometers installed at its mid-height and with vibrating wire extensometers at three locations along its top surface (Figures 17b and d). Figure 18 shows a geomattress during the dewatering process.

Figure 19a presents the variation of porepressure at the three measuring points (Figure 17d) versus time. In general, the porepressure increased during the mattress filling stages, but dissipation was fast thereafter, showing the geomattress good drainage capacity. The variation of geotextile tensile strain with time at the middle of the mattress length is shown in Figure 19b. The strain increased during the filling process, reaching a maximum tensile strain of 8.6%, only approximately 11% of the maximum tensile strain of the geotextile. There was some reduction in the geotextile strain after mattress filling as a consequence of drainage and consolidation of the infill material. As in the laboratory study by Barrantes (2023), the experiments under field conditions have confirmed the excellent performance of geotextile tubes and mattresses for the dewatering of tailings, muds and similar materials.

Another interesting solution related to reducing the environmental impacts due to mining activities is the use of floating silt curtains (FSC) to favour sedimentation of solids in suspension aiming at reducing silting of rivers and lakes, as schematically shown in Figure 20. The curtains change the flow pattern and reduce the water speed to favour significant sedimentation of solids in suspension before they reach important regions or water bodies.

An interesting application of FSC took place in the municipality of Patrocínio, state of Minas Gerais, Brazil. In this case, two FSC's were installed in a sedimentation pond to reduce silting of nearby rivers caused by surface erosion of a mining sterile dump. Figure 21 shows a bird-eye view of the mine sterile dump, which occupies a total area of 9.34 ha, with a maximum height of 137 m, volume of 35.5 Mm^3 and 2:1 (h:v) slopes (Macedo, 2023). This figure also shows the drainage ditches that carried the run-off from the sterile dump to the sedimentation pond and from the latter to the Bonito stream.

The two FSC's installed in the sedimentation pond were manufactured from a woven geotextile, made of polypropylene,

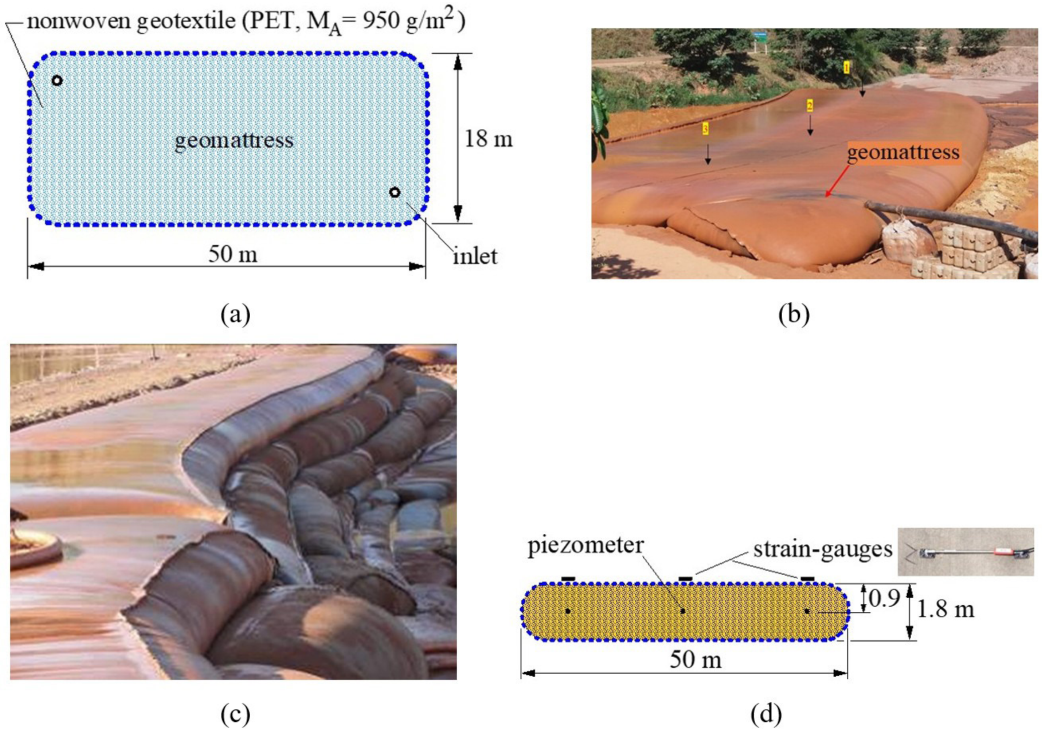
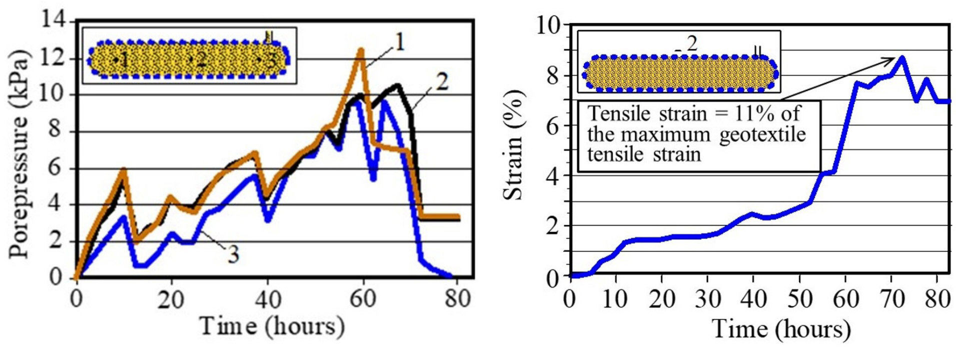


Figure 17. Dewatering of iron ore tailings using geomattresses: (a) geometrical characteristics of the geomattresses; (b) geomattress during filling (courtesy Dr. A. Fahel); (c) view of the stacked geomattresses in the field (courtesy Dr. A. Ortigão); (d) characteristics of the instrumented geomattress.

Figure 18. Geomattress during the dewatering process at Risoleta Neves dam site (courtesy Dr. A.R.S. Fahel).

3 m deep, with a mass per unit area of 440 g/m^2, tensile strength of 105 kN/m, maximum tensile strain of 10%, normal permeability of 0.2 cm/s and filtration opening size of 0.24 mm. The installation of the floating silt curtains is presented in Figures 22a-c. To reduce even further the discharge of solids in suspension in the nearby stream, a geotextile fence (similar to a silt fence for erosion control) was constructed at the exit of the sedimentation pond (Figure 22d).

Figure 23a presents grain size distribution curves of the sediments downstream and upstream of the curtains, showing the significant reduction in the sedimented particle sizes because of the presence of the curtains (Macedo, 2023). Significant reduction in effluent turbidity downstream of the curtains can also be visualized in Figures 23b and c. It should be pointed out that the performance of the curtains can be influenced by factors such as flow rate intensity, wind direction



(a) (b)

Figure 19. Porepressure dissipation and geotextile strain versus time: (a) porepressure dissipation; (b) geotextile strain at point 2.

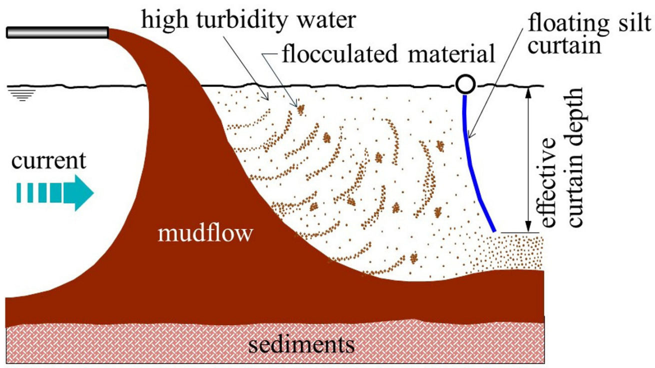
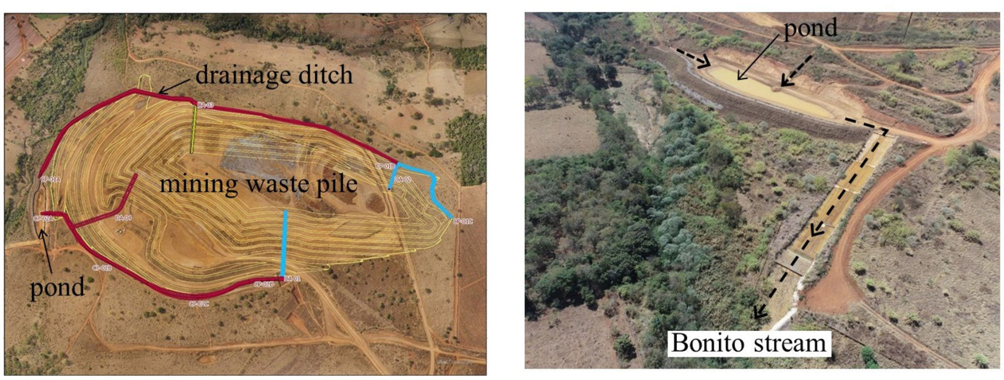


Figure 20. Operating principle of a floating silt curtain (modified from Johanson, 1978).



(a) (b)

Figure 21. Mine sterile pile and drainage system (modified from Macedo, 2023): (a) mine sterile pile and drainage ditches; (b) sedimentation pond.

and temperature. During the rainy season in the region, under higher flow rate conditions (lotic flow regime) in the pond, the reduction in turbidity reached up to 93% downstream of the curtains. However, little turbidity reductions were observed under unfavourable wind directions and low flow rates (lentic flow regime) in the pond (3.2% to 3.6% reductions downstream of the curtains in comparison with the turbidity upstream of the curtains). Indeed, low contribution from the presence of the curtains should be expected under lentic or still water conditions, because these conditions by themselves favour sedimentation of solids in suspension. The results obtained showed that the use of floating silt curtains can effectively reduce silting of relevant water bodies. Additional information on this case-history can be found in Macedo (2023).

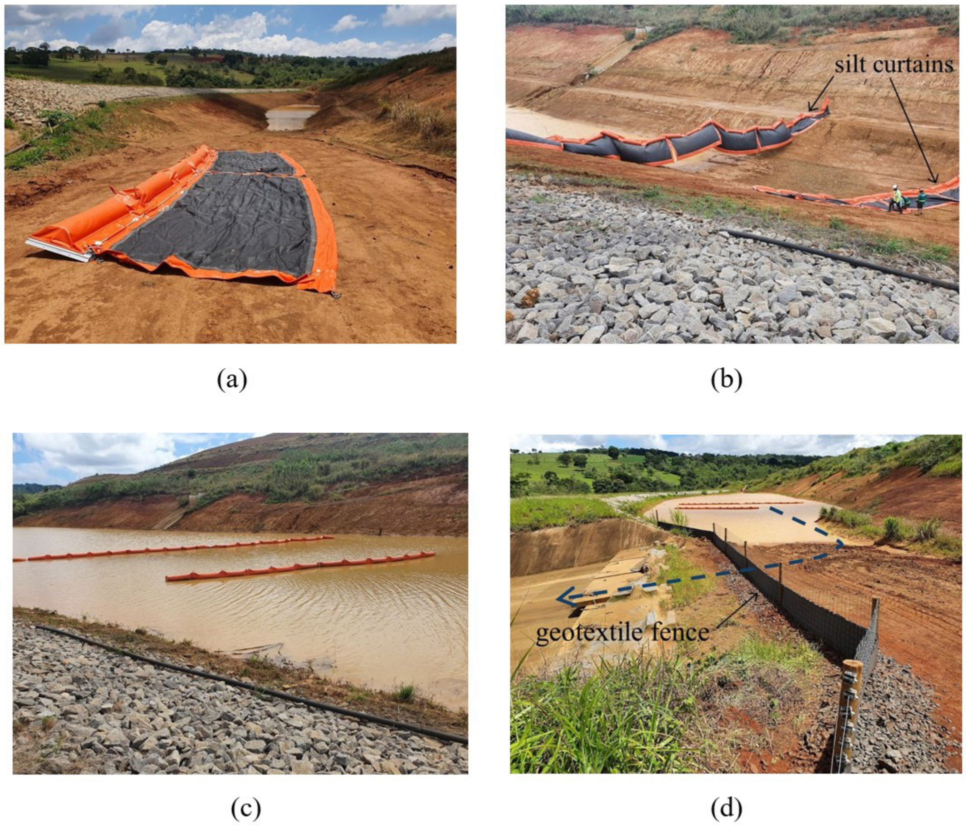


Figure 22. Installation of the floating silt curtains (modified from Macedo, 2023): (a) view of a silt curtain; (b) silt curtains during installation; (c) view of the silt curtains in place with a full pond after a rainy period; (d) silt fence at the exit of the pond.

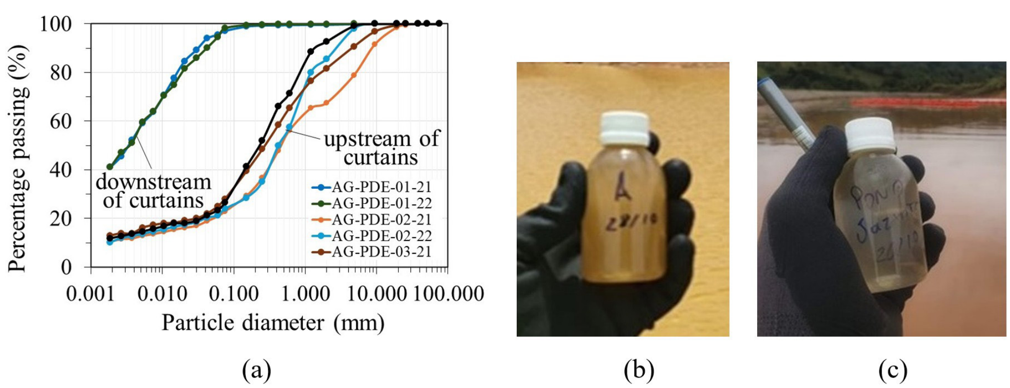


Figure 23. Particle size of sediments and turbidity (Macedo, 2023): (a) grain size distribution downstream and upstream of the curtains; (b) liquid specimen upstream of curtains; (c) liquid specimen downstream of curtains.

5. Sustainable geosynthetics and sustainable solutions with geosynthetics

Some geosynthetics are sustainable in their own right, as they can degrade under natural environmental conditions after they have fulfilled their functions. These are the cases of geosynthetics manufactured from natural fibres (coir, jute, sisal, hemp, palm fibre, cotton etc.) or from biodegradable synthetic fibres. Figure 24 shows some examples of such products that can present a wide variety of functions, particularly in erosion protection works (Prambauer et al., 2019; da Luz et al., 2021; Melo et al., 2021; Pimentel et al., 2024). They can also function as temporary reinforcements in geosynthetic reinforced structures if they are durable enough (Mathur et al., 2011; Hegde & Sitharam, 2015; Evangeline et al., 2021; Ahirwar & Mandal, 2021). It is estimated that synthetic materials may be successfully substituted by natural fibres and biopolymers in 50% of all applications (Daria et al.,

(a) (b)

Figure 24. Examples of geosynthetics manufactured with natural fibres: (a) woven geotextiles from sisal fibres (courtesy J.R.M. Pimentel); (b) geomat for erosion control.

2020). Hegde & Sitharam (2015) describe the use of geogrids and geocells made from bamboo for the reinforcement of a sand fill overlying a clayey subgrade. They observed up to 3 to five times increase in the load-carrying capacity of the system due to the use of the geogrid or geocell made from bamboo. Mujawar et al. (2025) also investigated the use of geogrids made of bamboo to reinforce a sandy subgrade. The results obtained showed the suitability of using geogrids manufactured from bamboo as a sustainable soil reinforcement technique. Evangeline et al. (2021) compared the performance of unreinforced and coir-geotextile (T_{max} of 8.8 kN/m and 8.2 kN/m, MD and CMD, respectively) reinforced roads (Figure 25), observing a reduction in the thickness of the bituminous Macadam overlay with the use of the coir-geotextile reinforcement. Ahirwar & Mandal (2021) also observed good performance of bamboo grid and jute geotextile for the reinforcement of unpaved roads on soft subgrade with 1.9-to-2.3-fold increase in the bearing capacity of the reinforced road-soft subgrade system compared with the unreinforced one.

Melo et al. (2021) show results of large-scale laboratory tests where geomats manufactured from natural fibres were employed to protect a slope from surface erosion caused by intense rainfalls. Reductions of erosion intensity close to 100% were observed with the use of the geomats, particularly for vegetated slopes. Figure 26 presents the results obtained in some of the tests after 15 minutes of rainfall with an intensity of 131 mm/h in terms of reduction in eroded mass versus percentage of vegetation cover on the slope. Even before vegetation cover is present, a reduction of 93% in the eroded mass can be noted. As vegetation coverage increased the efficiency of the protection against surface erosion also increased, reaching 99% reduction in surface erosion. It should be noted that the use of a biodegradable geomat in this type of application may not be the most appropriate choice for short-lived vegetative covers, because the geomat will degrade after some time, leaving the slope unprotected. In these cases, more durable products may be required because the geomat will remain in place, protecting the slope to some extent against the impact of rain drops and facilitating periodical maintenance of the slope surface with water seeding. Mathur et al. (2011) describe several applications of jute geotextiles in geotechnical works for the protection against surface erosion, drainage and reinforcement.

Conventional geosynthetics products can be combined with other materials to form alternative geosynthetics. This can be interesting in regions where suitable waste materials (PET bottles, scrap tires etc.) are plentily available (like in landfills, for instance) to be combined with conventional geosynthetics to produce low-cost barrier or drainage systems. Figure 27 shows the combination of a geotextile filter with scrap tires and compressed PET bottles, forming alternative geocomposites for drainage in a landfill and in an urban street in the Federal District, Brazil. Tire shreds have also been used combined with geotextile filters in drainage trenches and blankets in landfills, as mentioned earlier in this paper (Figures 7 and 8). The use of recycled plastic is another sustainable measure to produce low-cost geosynthetics. Hasheminezhad et al. (2025) show comparable performance of unpaved roads reinforced with geosynthetics manufactured from virgin and recycled PET. I should be pointed out that it would be wise to use geosynthetics from recycled plastic in temporary works only, due to the great variety of origins, compositions, quality and properties of recycled plastics, unless the properties of the product considered, obtained in appropriate tests, fulfil the requirements of the design.

Silva (2007) and Silva & Palmeira (2013) tested geocomposites for drainage combining nonwoven geotextile filters with alternative drainage cores. One of the alternative drainage cores investigated consisted of scrap tire strips assembled in a square pattern and the other waste PET bottle caps assembled in a triangular pattern (Figure 28a). Figure 28b shows transmissivity tests on three conventional commercial geocomposites and on the geocomposite made with tire strips. As expected, the compressibility of the geocomposite depends on the core stiffness and as the spacing between the tire strips increases so does its compressibility, resulting in reductions in the discharge capacity of the product along its plane. Nevertheless, the result for the alternative geocomposite with 30 mm spacing between strips compared

Figure 25. Coir-geotextile reinforced road during construction (Evangeline et al., 2021).

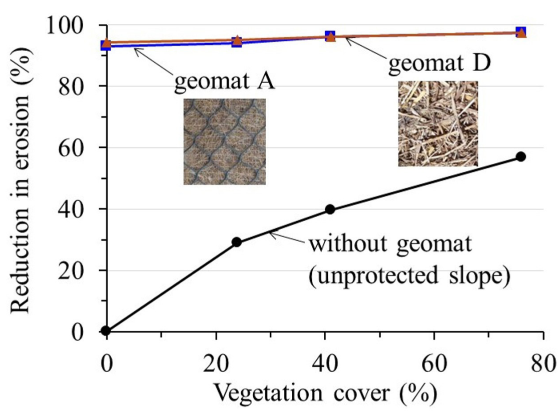


Figure 26. Reduction in slope erosion caused by rainfall with the use of biodegradable geomats (modified from Melo et al., 2021).

well with those of the commercial geocomposites up to a vertical stress of 100 kPa. The same behaviour was observed for the geocomposite with PET bottle caps with 40 mm distance between caps. For the test on the geocomposite with 6 mm distance between caps, the discharge capacity remained constant (≅ 0.2 l/s/m) up to 400 kPa vertical stress and similar to those of the conventional commercial products tested (Figure 28b).

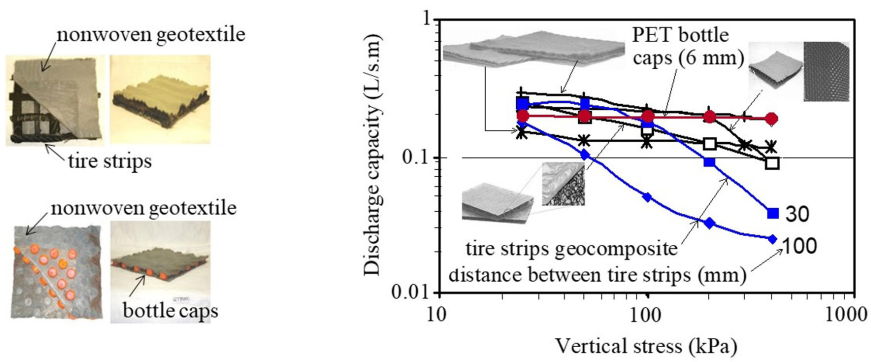
The combination of perforated waste PET bottles with a nonwoven geotextile filter in trenches to favour the infiltration of rainwater in the subsoil is described in Silva (2012). This can be a low cost and environmentally friendly solution to reduce floods during rainy seasons in urban areas. Figure 29 shows one of the experimental infiltration trenches tested. Additional information on this type of solution can be found in Silva (2012). Aiming at a better destination of PET bottles, Moghaddas-Tafreshi et al. (2021) present a large-scale laboratory study on subgrade reinforcement combining PET bottles and geogrid subjected to cyclic loading where lower settlement accumulation rate and a higher resilient (elastic) settlement in the reinforced subgrade were observed compared with the unreinforced one. Dandin et al. (2024) carried out large scale laboratory tests on fly ash backfills reinforced with geocell manufactured from waste PET bottles, showing the feasibility of using this alternative geocell for soil reinforcement.

The use of geocells made of scrap tires as reinforcement in retaining structures and unpaved roads is reported by several researchers (Yoon et al., 2008; Sayão et al., 2009; Hidalgo & Bustamante-Hernández, 2020; Arango, 2023; Susunaga, 2025; Susunaga et al., 2025, for instance). Hidalgo & Bustamante-Hernández (2020) performed large-scale pull-out tests on geocells made of scrap tires, showing the good interaction between the geocell and the surrounding soil. Susunaga (2025) carried out large-scale tests (1200 mm dia. container, 1000 mm high) on unpaved roads with and without scrap tire geocell reinforcement subjected to cyclic loading from a 180 mm diameter platen. The scrap tires were assembled in the pattern shown in Figure 30a to form the geocells. Figure 30b shows the significant improvement in road performance in terms of surface settlement versus number of load cycles of the geocell-reinforced road compared with the unreinforced one.

Viana & Palmeira (2010) mixed different percentages in mass of scrap tire shreds to bentonite to manufacture alternative geocomposite clay liners (GCL, Figure 31a). The presence of the tire shreds may reduce the cost of GCL manufacture but certainly changes some of its properties. The reduction in the expansibility of the alternative GCL is particularly relevant and Figure 31b shows the variation of GCL expansion with time due to submersion in water for two conventional commercial GCLs and an alternative GCL

(a) **(b)**

Figure 27. Combination of geotextile filter with alternative drainage materials: (a) geotextile and scrap tires in a landfill; (b) geotextile and compressed PET bottles in an urban street.



(a) (b)

Figure 28. Alternative geocomposites for drainage (Silva & Palmeira, 2013): (a) geocomposites with scrap tire strips or plastic caps drainage core; (b) discharge capacity versus vertical stress-comparison between some conventional and an alternative geocomposite.

(a) **(b)**

Figure 29. Combination of PET bottles and geotextile filter in experimental infiltration trenches to minimize the consequences of floods (Silva, 2012): (a) during construction; (b) end of construction.

with 50% of tire shreds mixed to bentonite. A reduction of approximately 50% in GCL expansibility can be noted. Despite this limitation, alternative GCL such as the one described may be interesting as low-cost products in temporary barrier applications or as an additional safety barrier layer in landfills, bearing in mind that scrap tires and plastics in general are commonly present in large volumes in landfills.

The examples presented above show how some residues and waste materials can have better destinations than taking up space in landfills or worse, being illegally disposed of in nature. However, the use of these materials in construction must be done with due care, as some of them can be harmful to the environment. For instance, scrap tires are major contributors to the generation of microplastics

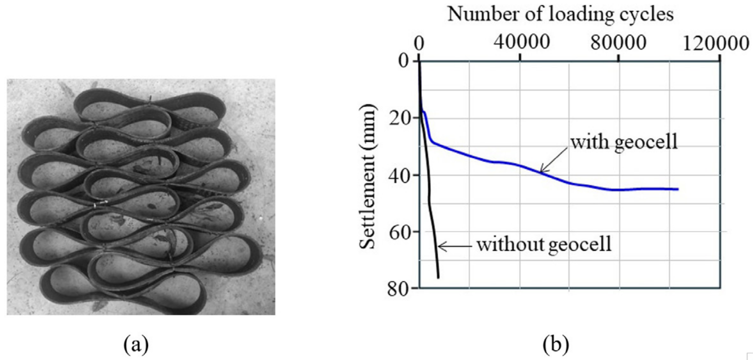


Figure 30. Alternative geocells manufactured from scrap tires (Susunaga, 2025): (a) plan view of the geocell; (b) comparison between road performance with and without geocell reinforcement.

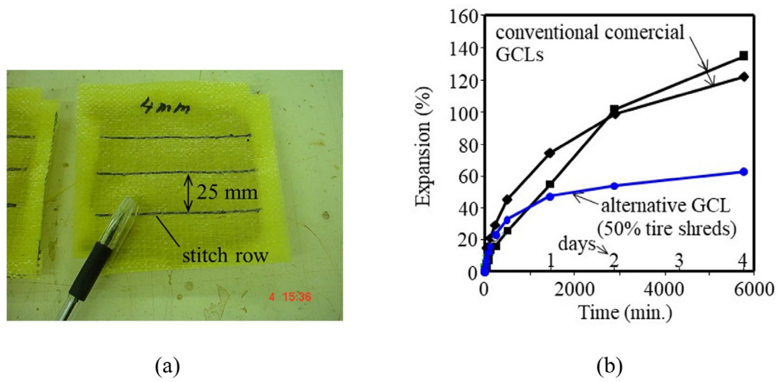


Figure 31. Performance of an alternative GCL (Viana & Palmeira, 2010): (a) view of the GCL; (b) comparison between expansibility of conventional and alternative GCLs.

(Giechaskiel et al., 2024). It should be noted that in most potential geotechnical applications, used tires would be nowhere near as worn to produce microplastic particles as when in contact with a road surface during its operational life. In addition, when used (usually buried) in remote areas, away from important water bodies and infrastructure, the consequences of the generation of microplastics over time can be considered insignificant compared to those of the normal use of tires or other types of plastic waste. Environmental damage is even more negligible when scrap tires and other types of waste and residues are used as construction materials under confined conditions, such as in landfills with properly designed lining systems and effluent treatment plants.

6. Geosynthetic against natural disasters and to minimize climate change effects

Natural disasters can cause significant damage to or destroy existing civil infrastructures. One typical example is the detrimental effects caused by rockfalls and debris flow, which are quite common in mountainous regions. In these situations, the use of soil barriers reinforced with geosynthetics may provide a quick and cost-effective solution. Descoeudres et al. (1999) and Maheshwari et al. (2024) show that this type of barrier tends to be the one that allows greater energy dissipation in the event of rock impacts. Figure 32a and b show examples of geosynthetic reinforced barriers against rockfalls. Case-histories of this type of solution can be found in Brandl (2010), which shows the significant greater total sum of impacts to barrier cost ratio for complete barrier destruction of reinforced barriers compared with unreinforced ones. Thus, this can be a solution easy to implement for the protection of infrastructures against rockfalls when space is available on the slope.

Other applications of geosynthetics in barrier systems are for the protection of existing infrastructure against floods and tsunamis. The frequency of occurrence of the former has increased significantly in recent decades due to climate change. A recent example of this were the damages caused by the floods due to extreme heavy rains in the southern states of Brazil, particularly in Rio Grande do Sul state, in 2024. Barrier systems such as those presented in Figures 32c and d can be considerably easier and faster to construct than conventional alternatives. Figure 32c shows an example of a dam constructed with geomembrane tubes that can be used for water accumulation during river floods and Figure 32d

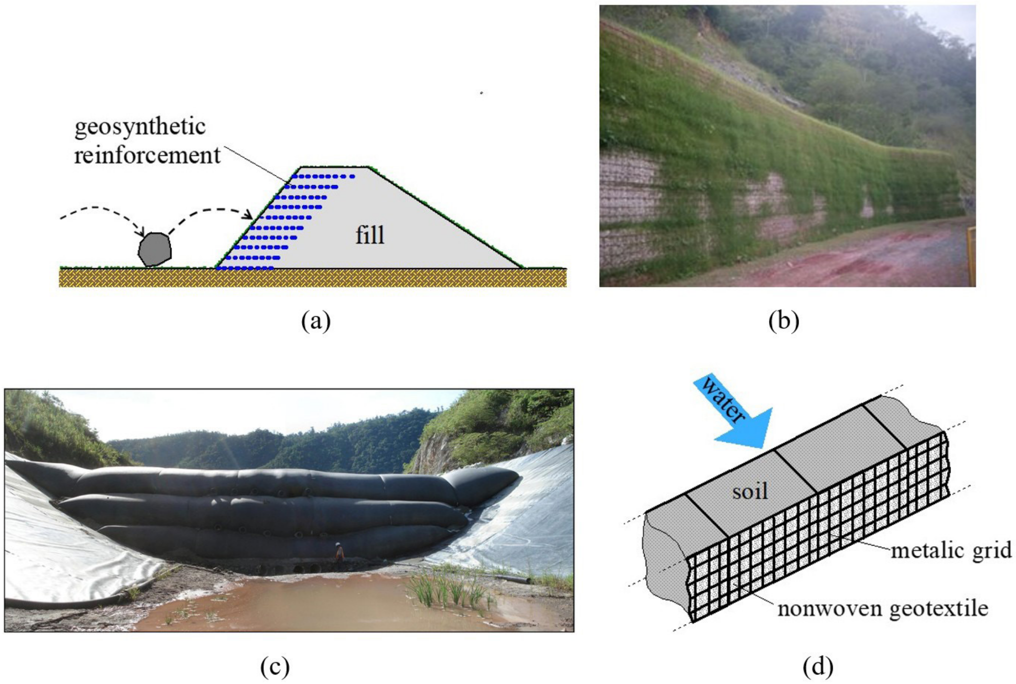


Figure 32. Different types of barriers incorporating geosynthetics: (a) schematic typical cross-section; (b) example of a rockfall barrier (courtesy Dr. P.M.F. Viana); (c) geomembrane tubes stack dam (IGS, 2010); (d) geotextile lined grid boxes for flood control.

depicts a mobile flood protection system consisting of metallic grid boxes lined with nonwoven geotextiles and filled with soil that can be installed along relevant stretches of riverbanks subject to flooding (Brandl, 2010). The same type of protection can be achieved with stacks of geotextile bags, tubes or mattresses. Geosynthetic reinforced dykes can also be used to prevent damage caused by flooding, as described in Heerten & Horlacher (2004), Heerten (2006), Heibaum et al. (2006) and Brandl (2010), for instance.

Geosynthetic reinforced soil barriers and stacks of geotextile tubes can also be employed to protect infrastructures and to avoid or minimize damage to the environment due to failure of tailings dams and reservoirs of pollutant substances, as schematically shown in Figures 33a, similarly to what was described above for the protection against floods. In mining regions, the tailings can be used as fill or infill material in reinforced barriers and geotextile tubes, depending on the nature and properties of the tailings (Figures 33b and c).

The Japanese experience on structures for the protection against tsunamis is certainly applicable in most cases for the protection against mud flows from failures of tailings dams and floods (Mohri et al., 2007; Shindo & Tatsuoka, 2017; Kuwano et al., 2018, for instance). Figure 31d (Shindo & Tatsuoka, 2017) presents the arrangement of a reinforced embankment designed to resist tsunamis. Of relevance is the possibility of erosion of the slopes of embankments such as the one in Figure 31d due to water impact or overtopping. Shindo & Tatsuoka (2017) describe a case-history in which a geocell with concrete-filled pockets (shotcrete) was used on the slopes for erosion protection (Figures 31e and f). Alternatively, Kuwano et al. (2018) describe the use of geobags and geomattresses to protect the slopes of these barriers against surface erosion.

Because they are typically easy and fast to build, engineering structures incorporating geosynthetics can be used in emergency situations where time for proper action is a key factor. Several other environmental protection-related solutions using geosynthetics can be found in the literature (Pilarczyk, 2000; Koerner, 2012; Palmeira, 2018; Touze, 2021, for instance).

7. Conclusions

Geosynthetics are construction materials that can be used in a variety of applications in geotechnical and geoenvironmental engineering. This paper presented results of research activities and case history performance where geosynthetics were used to make feasible environmentally friendly solutions, which would not be possible with conventional geotechnical engineering alternatives. The main conclusions obtained are as follows.

As the consequences of climate change reach unprecedented levels and are only set to worsen, it is increasingly important to think ahead and investigate engineering solutions that are cost-effective, sustainable and quick to implement in case of emergencies. In this context, geosynthetics bring these advantages together in most situations. In case of flooding, failures or leakages of tailings dams, geosynthetics can be used

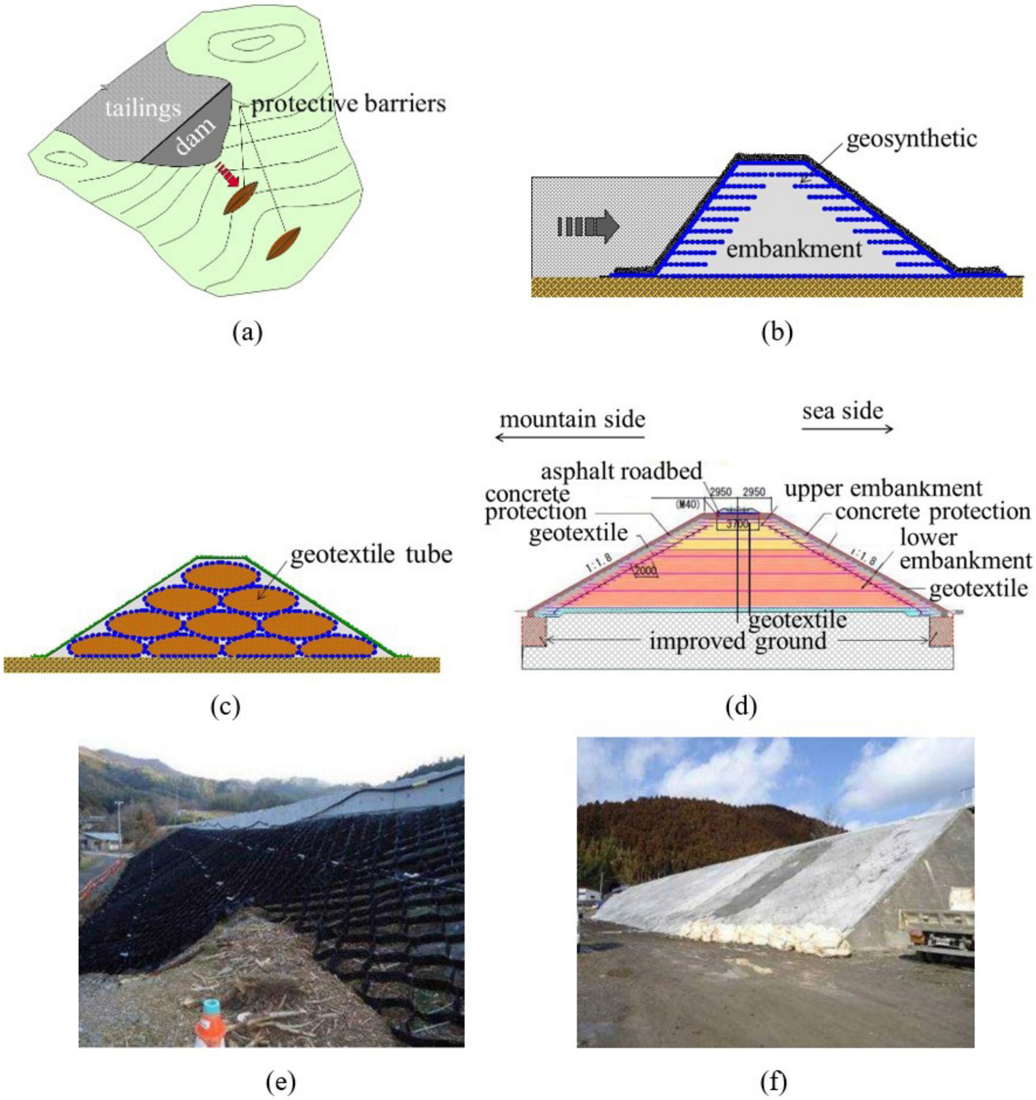


Figure 33. Other applications of protective geosynthetic reinforced barriers: (a) protection against failures or leakage from tailings dams; (b) geosynthetic-reinforced fill barrier; (c) geotextile tubes barrier; (d) tsunami barrier (modified from Shindo & Tatsuoka, 2017); (e) geocell during installation on the slope (Shindo & Tatsuoka, 2017); (f) concrete-filled geocell at the end of construction (Shindo & Tatsuoka, 2017).

to construct barriers in the form of reinforced embankments or stacked geotextile tubes or mattresses to protect existing structures or minimize environmental damage in case of any accident. In the mining industry, if the tailings are not harmful to the environment and have suitable geotechnical properties, they can even be used to construct the barriers, which gives a better destination for such tailings. Floating silt curtains can also be employed to reduce the extent of water bodies affected by silting.

Biodegradable natural and synthetic geosynthetics are expected to be increasingly used in the coming years, especially in temporary works, due to their sustainable nature. Chemically treated natural fibres can extend the service life of natural geosynthetics to the point where they can be used for soil reinforcement in some circumstances.

Reducing waste disposal in landfills through changes in societies habits, recycling and better destination of waste is extremely important. In this case, the use of some wastes and residues combined with geosynthetics may be feasible and sustainable solutions. Examples of this are combinations of mining or recycled construction and demolition residues in reinforced soil structures such as pavements and retaining walls. Another sustainable destination for some waste materials or recycled plastic is in the manufacture of alternative geosynthetic products. Successful examples of the use of scrap tires and PET bottles in the manufacture of geocells or as drainage layers wrapped by geotextile filters have been presented in this paper. These types of alternative geosynthetics may be particularly interesting in regions where waste materials are abundant, such as in landfills. However, it is of utmost importance to evaluate the potential damage to the environment caused by using waste and residues, depending on their nature, properties and polluting potential. Good engineering judgment must be applied when using waste as construction materials in geotechnical and geoenvironmental works.

It has already been demonstrated that engineering works with geosynthetics can be significantly more sustainable than conventional ones. Due to their easy transport and rapid installation, these materials can be particularly interesting in emergency situations, when the time necessary for a given solution to be implemented is a key factor. However, like any other construction material, the use of geosynthetics must be based on sound engineering principles that also ensure that it will meet the project requirements satisfactorily. Continuous research will certainly not only improve the quality of geosynthetic products, but will also find new fields of application for these materials in sustainable engineering solutions to meet the challenges brought about by climate change.

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Declaration of interest

The author has no conflicts of interest to declare. The author has observed and affirmed the contents of the paper and there is no financial interest to report.

Data availability

The datasets generated analysed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of generative artificial intelligence (GenAI).

List of symbols and abbreviations

d_c	constriction diameter of a sand filter
d_n	diameter for which *n* % of the remaining particles are smaller
w	maximum geotextile tube width
w_b	width of the geotextile tube base
x	distance along the horizontal direction
y	settlement
A	cross-section area of a geotextile tube
B	retaining wall base width
BOD	biochemical oxygen demand
CBR	California Bearing Ratio
CL	centre line
CMD	cross-machine direction
COD	chemical oxygen demand
C_U	soil coefficient of uniformity
FOS	geotextile filtration opening size
GCL	geosynthetic clay liner
H	height
$J_{5\%}$	secant tensile stiffness at 5% strain
M_A	geotextile mass per unit area
MD	machine direction
PET	polyester
PP	polypropylene
PVC	polyvinyl chloride
RCDR	recycled concrete and demolition residue
SP	settlement plate
TP	temperature transducer
T_c	capillary tension
T_{max}	maximum tensile strength
γ	soil unit weight
ε_{max}	maximum tensile strain
σ_v	vertical stress

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