Chapter 4

Lace Braiding Machines for Composite Preform Manufacture

David Branscomb, Yang Shen, Vladimir Quinones, Royall Broughton and David Beale

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.82256

Abstract

This paper is an evaluation of a modern lace braiding machine technology for suitability in the manufacture of textile composite material preforms. A brief history of bobbin lace and lace braiding machines is provided along with a discussion of the functionality of a Barmen lace braiding machine—the predecessor to the modern computerized lace braiding machine. It was found that the typical modern lace braiding machine lacked the robustness necessary to produce braided preforms using large, high-strength synthetic yarns such as carbon and aramid that are commonly found in advanced composite materials. Improvements are proposed to enable lace braiding machines to be developed for future applications.

Keywords: lace, jacquard, barmen, torchon, preform

1. Introduction

Lace braided fabrics embody intricate patterns consisting of precisely placed yarns into structures which from an advanced fiber placement standpoint appear suitable for pre-forms in composite manufacture. Lace is characterized by openwork or lattice architecture with regular and irregular patterns propagating the fabric. Much like trusses that offer high strength or stiffness-to-weight reinforcement through strategic reinforcement placement, lace formation technologies could be used to produce efficient textile preforms or composite space trusses directly. The intrinsic structural characteristics of lace such as openness and precision fiber placement could be utilized to eliminate expensive secondary operations such as drilling.

Machining of holes is required for fastening and joining of ancillary components while potentially increasing reinforcement efficiency and minimizing weight. Lace machines can produce either flat or seamless cylindrical structures.

To provide a thorough evaluation of lace braiding technology for composite material manufacture, a brief historical context of industrial lace manufacture along with details of the development of the present-day lace braiding machine is presented. The fundamental features of braided lace are detailed to form a foundation for establishing requisite engineering design fundamentals, and to evaluate the present-day lace braiding machine for immediate suitability to produce structural composite reinforcements.

We find little evidence to suggest that braided lace has been used significantly for structural composite reinforcements. Braided lace does not readily appear to be available in the formation of heavy or industrial fabrics which would imply suitability in advanced composite preforms commonly using 12k and greater carbon fiber tows. However, one manufacturer currently offers engineered lace patterns for a myriad of applications including soft composites, sporting goods, and advanced apparel [1]. Several sources describe the esoteric nature and the lack of readily available design information [2, 3]. Although, lace braiding machines have been used in medical applications and smart textiles [4]. In fact, one reference suggests that lace braiding has no application to composites. For example, The Handbook of Composite Reinforcements provides a list of braiding machines according to the structures formed and the application to composites [5]. Per Lee, the Jacquard braiding machine (a.k.a. lace braiding machine) is used to produce tubes and flat strips with complex lace patterns and does not list composites as being an application. Work evaluating the Jacquard mechanism used in commercially available machines and proposed improvements in the control scheme are presented by Yang [6]. Many articles exist on various details of pillow lace formation techniques, a handful of short articles are dedicated to certain manufacturing aspects of machine lace (mostly trade publications), and very little can be found outside of the patent literature regarding the mechanics of the machines. However, a comprehensive text on the history and development of various lace machines by Earnshaw is recommended to the reader for additional study of the broader topic [7].

2. History of lace, lace machine development, and modern lace machines

Originally lace was produced by hand as a highly skilled art form requiring years of experience due to its almost infinite design possibilities. Handmade lace can be traced to the fifteenth century in Italy, Spain, Germany, and the Netherlands [8]. **Figure 1** shows bobbin or pillow lace as an example. Although there are many forms of openwork lace such as crochet, knitting, and tatting, bobbin lace specifically is formed by braiding.

Various types of lace producing machines exist, such as Raschel and Leavers machines, but the operation mechanisms are fundamentally different from the lace braiding machines. John Heathcoat's bobbinet machine is arguably one of the original lace machines. The lucrative manufacture of lace led to numerous patents issued during the mid-1800s and ultimately to the mass manufacture of lace [10].

Figure 1. Handmade bobbin lace or pillow lace [9].

The dexterous movements performed in bobbin or pillow lace formation have many similarities with the mechanical movements of the lace braiding machine. The fundamental movements are therefore similar. This is not surprising as the lace braiding machines of the nineteenth century were expressly designed to mimic the motion of bobbin lace makers' hands. One of the first patents issued for a bobbin lace braiding machine was issued in 1910 to Gustav Krenzler of Barmen, Germany [11]. Earlier in the same year, a patent was issued to Emil Krenzler for a single-thread lace-bobbin machine [12]. Lace braiding machines have several names including, Barmen, Torchon, and Jacquard lace braiding machines. These machines produce tubular fabrics which are then separated into two flat fabrics of the same design for efficiency. Small monofilament yarns are used to join the two "flat" fabrics which are subsequently removed.

3. Fundamentals of lace braiding

Lace braiding machines utilize rotating plates, analogous in functionality to horn gears of Maypole braiding machines, to control bobbin motion and produce desired designs. To the credit of machine lace and a testament of its versatility, it can be difficult to distinguish from its handmade counterparts [7]. Some limitations are imposed by mechanical aspects of the machine design; however, simple laces such as Torchon lace can be easily made with the lace braiding machine [13].

Braided lace is formed by basic stitches typically applied to bobbin pairs. In this case, a pair of bobbins may simply rotate clockwise or counterclockwise as a twisted pair as well as interchanging with an adjacent bobbin pair. Individual control of a single yarn or yarn pair enables lace designs to be complex with almost infinite possibilities. However, even the most complex designs are derived from two motions. These basic motions comprise various stitches and by combining simple motions, intricate patterns may be designed. In general, the design of lace is described by the stitches, i.e., the basic movements of bobbin pairs. Furthermore, by utilizing various materials and yarn tensions, other desired features such as textures and holes may be imparted to the lace.

4. Stitches of braided lace

During the formation of lace, the yarns form an X that is identified as either a cross or a twist depending on the direction. Twist is defined as a counter-clockwise motion where the right yarn of each pair is laid over the left yarn. The twist motion pairs stay together on the machine plate. Cross is a clockwise motion worked with two adjacent pairs and the inner pairs are crossed so that the left yarn of the inner pair is laid over the right yarn. The cross pairs are interchanged. In **Figure 2**, the first and fourth yarns remain stationary while the second and third yarns cross multiple times. Then the first and third yarn twists multiple times simultaneously with the second and fourth yarns.

4.1. Barmen lace

For various reasons details of the Barmen braiding machine have not been readily available, and known only by a select few. The complexity of these machines tended to require specialized operational expertise as well. Thus, expertise with these machines tended to be concentrated within the immediate geographic region of the machine origin. In the case of the Barmen lace braiding machine, the region was Barmen—an industrial city that later merged with Wuppertal, Germany. Publications, outside of textile trade literature and patent literature, related to the Barmen lace braiding machine are scarce. The descriptions found in the patent literature are inadequate for interested audiences outside those skilled in the art. In general, the lace braiding industry had many trade secrets where knowledge of pattern design, machinery, and operations was confined to an esoteric group of practitioners.

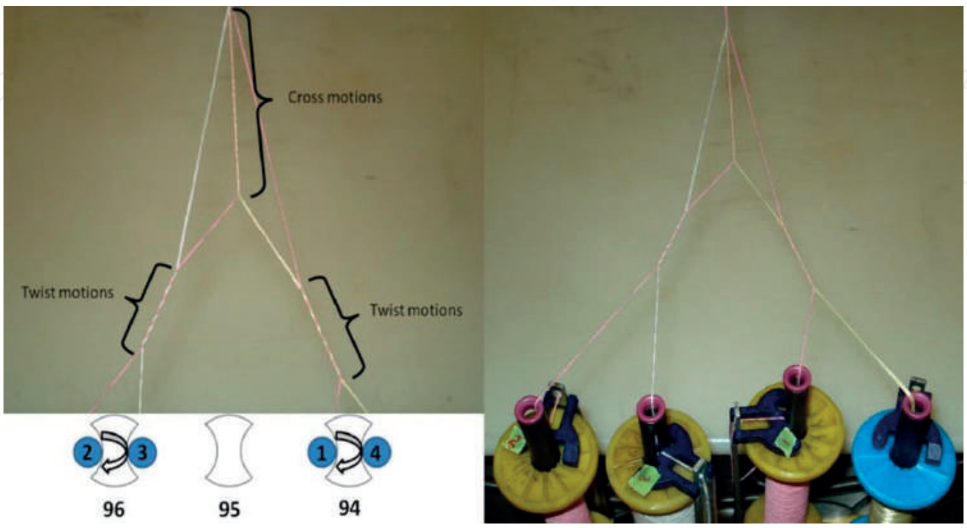

Figure 2. Basic stitches of lace.

http://dx.doi.org/10.5772/intechopen.82256

Although this unique nature of the Barmen lace industry had limited the dissemination of widespread knowledge, it did encourage the production of lace in the region. Barmen lace benefitted from the proximity of lace producers, lace machine designers and many technological developments are evident in the U.S. Patents issued to residents of Barmen and Wuppertal, Germany.

The Barmen lace machine is an evolution of the original mechanically geared braiding machine, often known as a Maypole braiding machine. In the Maypole braiding machine, the yarns are divided into two fixed groups of counter rotating directions producing two oppositely pitched sets of helices. The Barmen braiding machine allows individual yarns to change direction at effectively any point along its path. Similarly, as the Maypole braiding machine was inspired by the Maypole dance, the Barmen machine design inspiration comes from the agile hand motions of bobbin lace makers. The distinct advantage of the Barmen over the conventional Maypole braiding machine is found in the motion control of individual yarns. Pattern control in these machines is implemented using a Jacquard mechanism.

4.2. Barmen lace braiding machine

Figure 3 shows the general structure of a Barmen lace braiding machine. By comparison, this machine is significantly smaller than those other lace formation technologies. The basic components of the Maypole braider are also found in the Barmen braiding machine including frame, spur gear train, spindles, and take-up device. However, the Barmen machine employs more advanced features. The primary difference is the versatility of the driver plates (i.e., horn gears) which can be turned on and off as stipulated by operational rules. **Figure 4** is a schematic view of the top of a Barmen lace braiding machine. The even numbered driver plates turn clockwise and the odd numbered driver plates turn counter-clockwise. The even cycle must finish and the spindles or carriers stop before the odd cycle can begin.

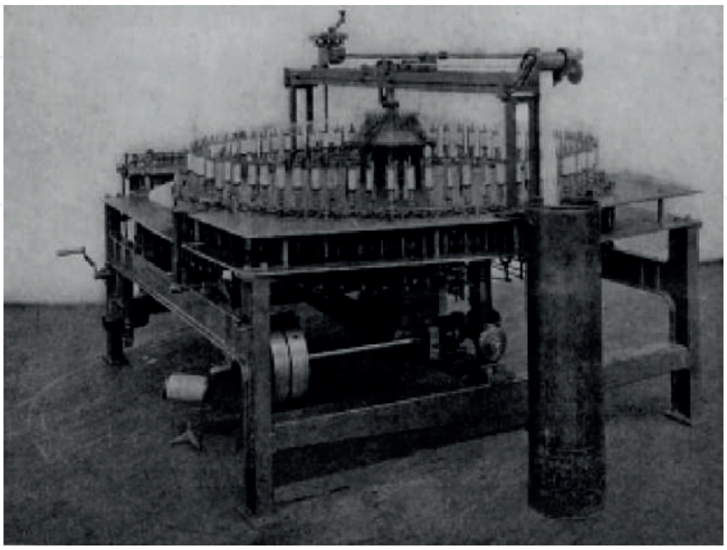

Figure 3. Barmen lace braiding machine circa 1920 [14].

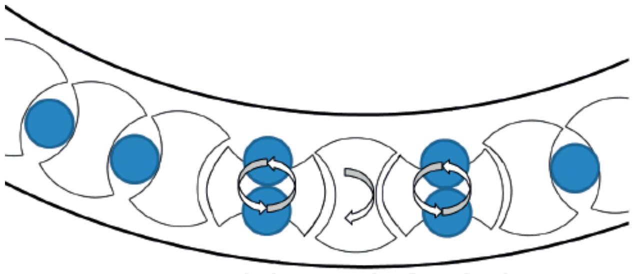

Figure 4. Schematic view of lace braiding machine.

Another notable difference of the Barmen lace braiding machine is the beat-up mechanism. This mechanism is akin to the weaving machine reed used to control fabric density. The beat-up mechanism is found in the center of the machine and consists of a dome with slits to allow reciprocating action of knife blades to compact the yarns following the corresponding beating motion. The blades are deployed as even and odd groups, according to the driver plate and spindle motions. These important advances over the Maypole braiding machine provide the ability to produce complex and irregular fabric structures.

The driver plates are positioned as a series of overlapping circles about the machine radius. The driver plate geometry is symmetric about two orthogonal axes with concave and convex regions. For a plate to rotate adjacent plates are required to remain stationary. Adjacent concave regions precisely permit the moving convex spindle cradle to pass without interference. This motion serves as the primary mechanism for imparting motion to the spindles and ultimately the yarn. In the same way as the traditional braiding machine, two different motions are required to pass a spindle.

4.3. Known materials used

Lace machines have been employed with a variety of materials, both natural and synthetic fibers, in the production of fancy lace and other apparel products. Marenzana [15] describes the use of Rayon fiber with lace braiding machines. Surface fiber treatments, known as sizing, may improve the lace braiding process as well as resin-fiber compatibility in subsequent composite manufacture. The use of high performance fibers such as those commonly found in composite materials has not been reported in the literature.

5. The modern lace braiding machine

The modern lace braiding machine is a direct descendent of the Barmen lace machines. The modern lace braiding machine has been continually improved; as witnessed in the numerous European, Japanese, and international patents. Some notable improvements include electromagnetic actuation of driver plates which allow electronic pattern control and computerized design to operate seamlessly without Jacquard punch paper. The electronic control eliminated the need for a mechanical Jacquard mechanism. Improvements in machine materials have increased the wear resistance and life of components. Certain mechanical features of the modern lace braiding machine protect the components and its lace product during production. For example, if the yarn breaks during production, the machine will automatically shut off as the bobbin carrier shorts an electrical switch so that the lace fabric can be saved and the broken yarn can be repaired by simply tying a knot. If this feature were not available, each time a yarn broke, the whole lace fabric would have to be discarded. A second feature is the construction of clutches out of a low-cost plastic material. If certain components fail to function perfectly, the clutch will fail before machine damage occurs. These inexpensive clutches can be replaced relatively easily and quickly. These two protective features are essential for industrial lace braiding but they limit the size and type of yarn that can be used.

Presently many of the modern machines are produced by Asian manufacturers who are in proximity to the textile manufacturing locations, although the Krenzler Company still manufactures lace braiding machines in Germany [16]. The machine evaluated in this research is manufactured in South Korea and clearly has its engineering origins from the Barmen lace machine. Considering improvements in the Barmen lace braiding machine during the last 30 years and the fact that many lace braiding machines are now manufactured outside of Germany, we refer to these machines as modern lace braiding machines. We acknowledge that the modern lace braiding machines originated from the Barmen lace machines.

Figure 5 is an engineering rendering of the modern lace braiding machine evaluated during this research. **Figure 6** illustrates the bobbin spindle actuation assembly. Spindle cradles are used to move yarns with the driving plates. The solenoid actuates the plastic cam which in turn lifts the plastic fork and plastic clutch and engages the driver plate allowing the spur gear to rotate the spindle cradles and perform the basic cross and twist motions on the yarns. After 180 degrees of rotation, the cam pushes against the inactive solenoid and a compression spring forces the fork and clutch to the resting position while spindle cradles and bobbins remain stationary.

5.1. Bobbin spindles (carriers)

Another important component is the bobbin spindle. Commonly referred to as carriers, they control the tension in the braiding yarn as well as allowing the release of new material during braiding. See **Figure 7** for the following operational details. The yarn is unwound from the bobbin and passed through an initial eyelet making a 90-degree bend where it continues until a second eyelet is located which also requires a 90-degree bend toward the spindle center where another 90 degree turn over a ratcheting pawl is required. The yarn now travels down the center of the spindle tube i.e. bobbin axis of revolution where a tension spring with eyelet requires a 180 degree turn. Finally, the yarn moves up the tube where a final ceramic eyelet allows the yarn to reach the fabric formation zone.

Figure 5. CAD drawing of modern lace braiding machine.

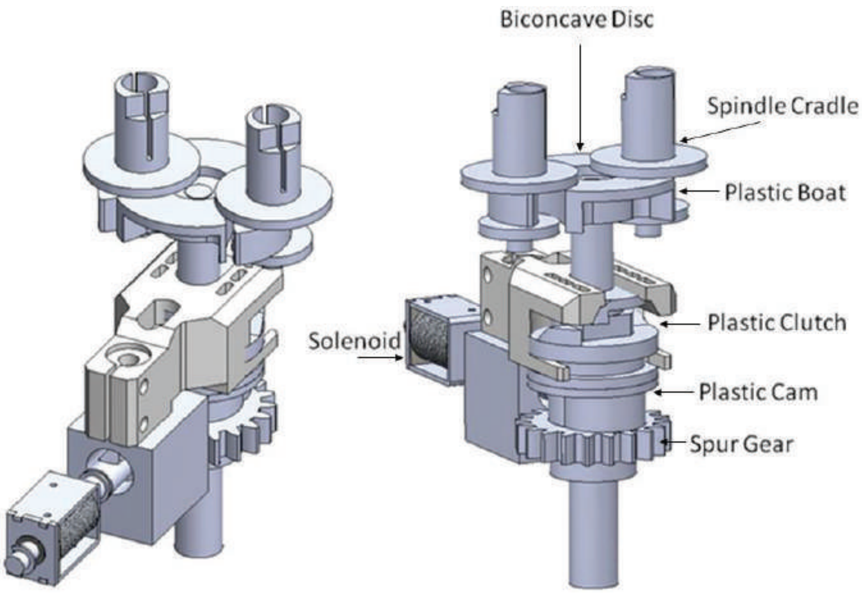

Figure 6. Main bobbin actuation assembly (front and rear views).

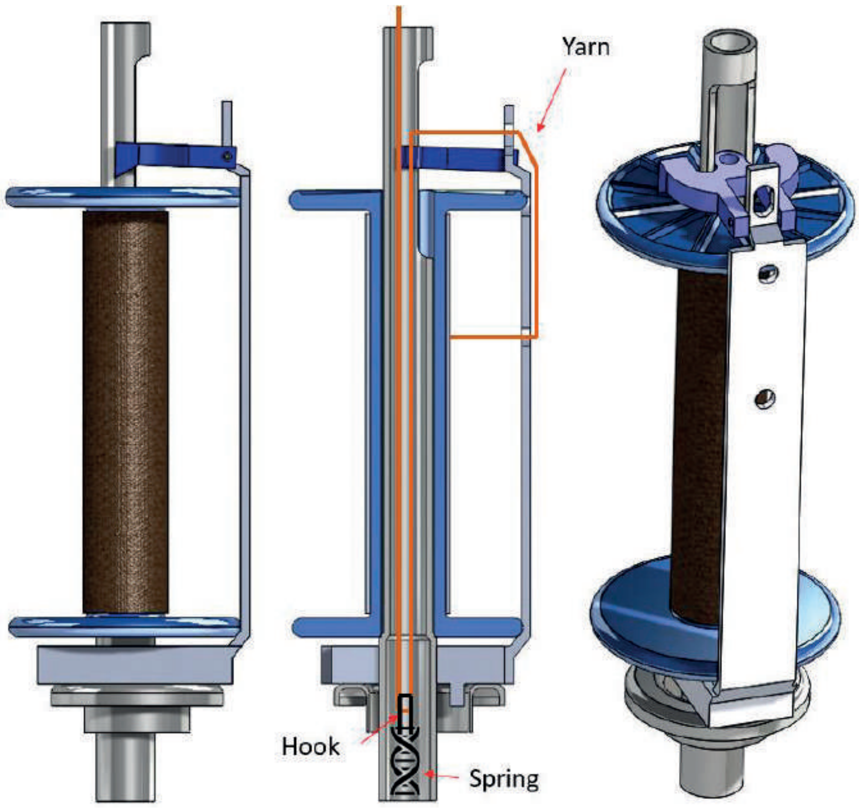

Figure 7. Bobbin spindle (carrier).

6. Analysis of machine for manufacture of structural composite pre-forms

Lace braiding technology has been demonstrated in the manufacture of intricate and decorative fabrics for more than a century. If lace braiding machines are suitable for handling large high strength yarns such as aramid and even carbon fiber prepregs, it was thought that the structures might be suitable for use as planar and 3-D space trusses. An evaluation of a modern lace braiding machine is performed on the typical execution to determine if braided composite strength-to-weight ratio could be improved by utilizing a lace braiding technology. A modern lace braiding machine incorporating a computer controllable electro-mechanical yarn interlacing system was purchased to test the proposition that it might be used to more efficiently orient and interlace yarns to create a truss-like pre-form in either a flat or cylindrical form [17]. **Figure 8** is an example of a CAD model for a proposed composite tube manufactured with a lace braiding machine.

Figure 9 shows the initial lace fabric preform made with a modern lace braiding machine during the evaluation and research phase of this work. The small white yarns are cotton. **Figure 10** shows a flat lace manufactured on a modern lace braiding machine made from larger twisted yarns.

Table 1 denotes a list of advantages of the modern lace and braiding machine.

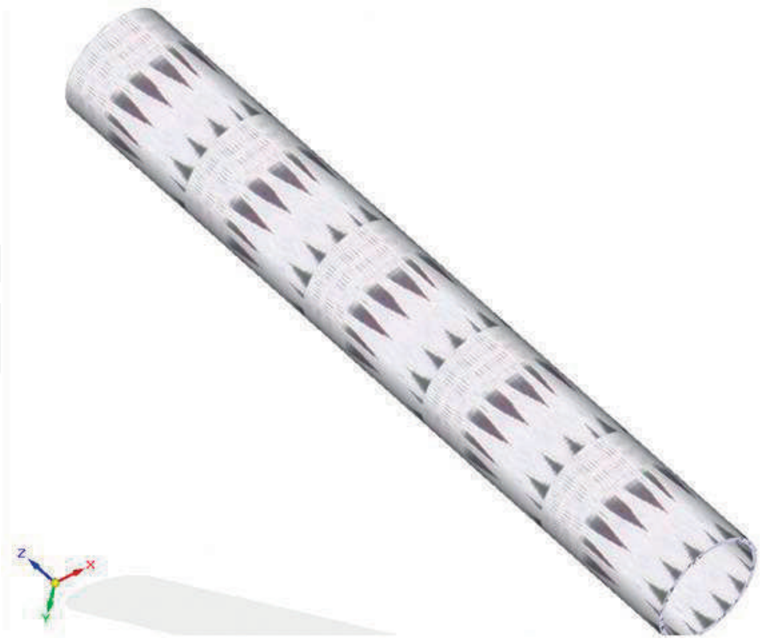

Figure 8. CAD model of lace braided composite tube.

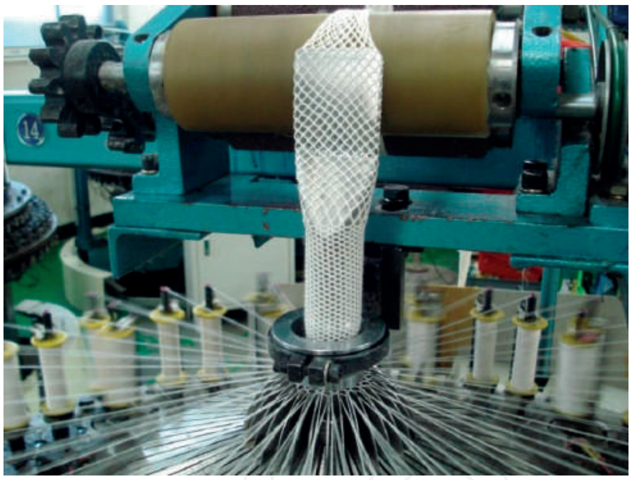

Figure 9. Initial preforms evaluated for composite reinforcement.

Table 2 denotes a list of problems encountered with the modern lace braiding machine during the evaluation of this study and comparison to conventional Maypole braiding machines.

Figure 2 shown previously is an initial attempt to make a lace from high performance yarns (1100 denier). In this attempt, we discovered that the yarn carrier mechanisms supplied with the machine are not well suited for using larger yarns. Large and thus stiffer yarns are needed for producing lace pre-forms suitable for structural composite applications.

When large, high strength yarns (<2400 denier) such as Kevlar®, Vectran®, and carbon fiber were used, the clutches would quickly fail because tension developed in the yarns due the yarn

http://dx.doi.org/10.5772/intechopen.82256

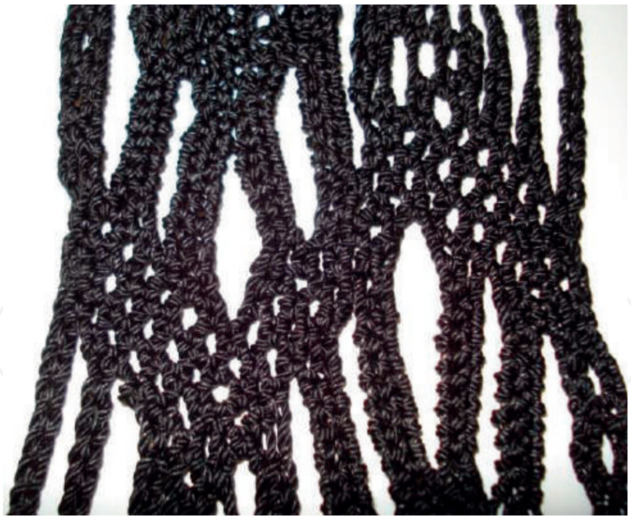

Figure 10. Machine braided lace.

General advantages of modern lace braiding machines
• Control of individual bobbins
• Small driver plates leads to increase in number of total yarns for given machine size
• Bobbin carriers are easily removed
• Cylindrical and flat fabrics produced from the same machine
• Precision fiber placement
• Open structure amenable to truss formation is possible
• Yarn crossovers are stabilized by a 360-degree twist around the adjacent yarn

Table 1. Advantages of lace braiding machine technology.

stiffness and breaking strength exceeded the capacity of the carriers and clutches. Furthermore, these yarns would not break if the machine had payout and tension problems. This would result in excessive clutch failure and machine down time. Constant clutch replacement is time consuming. After repeated adjustments to the machine, it was determined that the machine would not operate consistently with large, high strength yarn without the machine shutting down and/or breaking plastic clutches. Solving this problem will require a more robust machine design of the clutches and improved carrier payout necessary for braiding. In the process of evaluating the lace braiding machine, several other structural deficiencies were noted.

Despite these inherent limitations, the feasibility of using lace braiding technology was "proved in concept" when a more robust machine can be designed and built. To do this, some open structure lace patterns have been designed and produced using the light-weight yarns that the machine could process. Composite preforms using lace-like patterns possible with lace braiding have been made on a conventional Maypole braiding machine and evaluated for strength and stiffness to further promote the structural lattice concept [17].

Modern lace machine	Conventional Maypole braiding machine	Lace machine yarn carrier	Maypole yarn carrier	Lace fabric formation	Maypole fabric formation
Frequent clutch failure	No clutch-direct drive	Excessive yarn bending to payout	No clutch-direct drive	Fixed angle to fell point	Variable angle to fell point
Complex mechanism	Simplified mechanism	Poor tensioning for large HS yarns	Adequate tensioning of large HS yarns	Yarn fiber disintegration due to abrasion with the machine parts	Minimal abrasion with the machine parts
No axial yarns	Axial yarns	Small carrier/ bobbin capacity	Larger carrier/ bobbin capacity	Buildup of yarn twist	Minimal imparted yarn twist
Accumulation of debris in driver plates	Accumulation of debris in driver plates	Non-rotating terminal eyelet	Rotating terminal eyelets	Beat-up mechanism	No beat-up mechanism

Table 2. Problems encountered with lace braiding machine evaluated.

6.1. Other important issues: twisting of yarns, beat-up mechanism, and machine design

The carriers used in lace braiding are free to rotate about the plate. Motion about this additional degree of freedom will be exacerbated at high speeds as inertial effects increase and may potentially cause problems. The freedom of the carrier to rotate during braiding can cause excessive buildup of twist in the yarn. **Figure 11** illustrates an example of this phenomenon

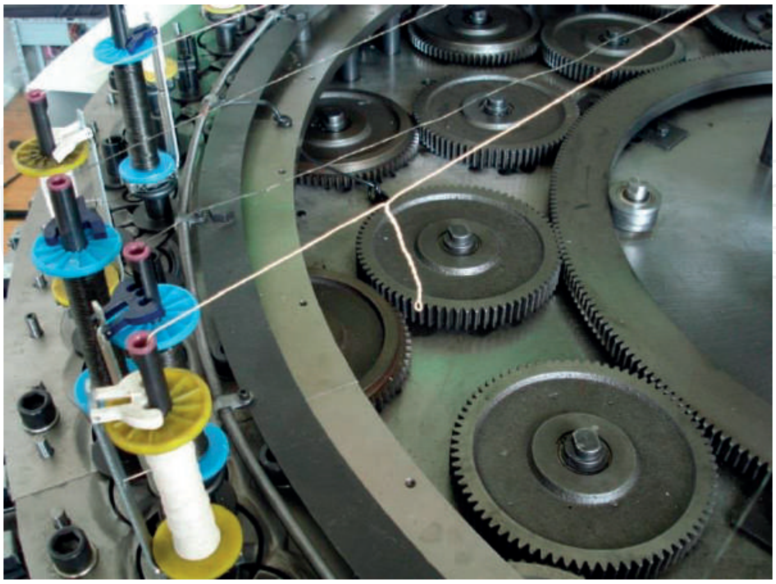

Figure 11. Buildup of excessive twist in yarn.

http://dx.doi.org/10.5772/intechopen.82256

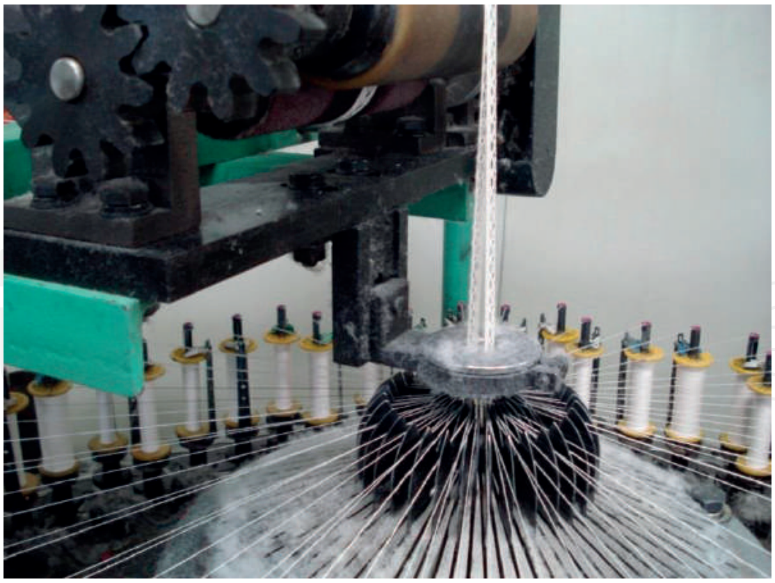

Figure 12. Accumulation of broken fibers at fell point due to beatup knife abrasion.

due to carrier rotation. Twist build up in the yarns can be alleviated by pre-twist that counteracts the twist occurring in the opposite direction, however requires additional processing and reduces yarn stiffness. Careful consideration of the bobbin movements required by the yarn paths in each pattern can reveal the amount and direction of pre-twist required to eliminate the buildup. Alternatively, a rotating terminal eyelet can be employed to reduce yarn twist, else other means are required.

The braiding formation process can cause severe damage to yarns. The violent action of the beatup knife mechanism damages fibers. **Figure 12** illustrates an accumulation of broken fibers resulting from the formation process of lace braiding machines. Minimizing abrasion is especially important if high performance brittle fibers are to be utilized.

7. Conclusion

Lace braiding technology has been introduced and a brief historical context provided. A description of how the components function has been presented. The lace braiding machine components and their functionality were described to demonstrate how the machine works as well as to assess the limitations for producing structural scale composite preforms. Based on the experiments that were made on the modern lace braiding machine, the machine deficiencies for manufacturing composites (listed in **Table 2**) are discussed. Suggestions for remedies in the machine design and operation are presented to enable future progress to be built upon addressing the current limitations while further advancing the future of lace technology in new areas such as space and aerospace. Complete re-design and construction of a machine suitable for composite preforms were considered beyond the scope of the research and left for future work.

Acknowledgements

The authors would like to thank the Alabama Space Grant Consortium NASA Training Grant #NNG05GE80H for supporting this work. The authors would also like to thank Jeff Thompson, Kevin Horne, Austin Yuill, David Jackson, and the Auburn University Department of Polymer and Fiber Engineering Braiding and Composites Research Laboratory.

Conflict of interest

The authors have no conflict of interests to declare.

Author details

David Branscomb[1]*, Yang Shen[1], Vladimir Quinones[2], Royall Broughton[2] and David Beale[2]

*Address all correspondence to: davidbranscomb@yahoo.com

1 Highland Composites, Statesville, NC, USA

2 Department of Mechanical Engineering, Auburn University, Auburn, AL, USA

References

[1] TEF [Internet]. Available from: https://www.tefbraids.com/

[2] Branscomb D, Beale D, Broughton R. New directions in braiding. Journal of Engineered Fibers and Fabrics. 2013;**8**:11-24

[3] Branscomb D, Beale D, Brougthon R. Computer-aided product and process development of lace braided composites. ASME Early Career Technical Journal. 2010;**9**:215-220

[4] Kyosev Y. Braiding Technology for Textiles, Principles, Design and Processes. 1st ed. Oxford: Woodhead Publishing; 2014. DOI: 10.1016/C2013-0-16172-7

[5] Lee S. Handbook of Composite Reinforcements. 1st ed. New York: John Wiley and Sons; 1992

[6] Yang C. Research and melioration on the computerized lace braiding machine [thesis]. Wuhan: Huazhong University of Science and Technology; 2007

[7] Earnshaw P. Lace Machines and Machine Laces. 1st ed. Guildford: Gorse Publications; 1995

[8] Textile World Record. Boston: Lord & Nagle Company. 1909

[9] Blahedo. Bobbin Lace [Internet]. Available from: http://en.wikipedia.org/wiki/File:Ursuline_lace_2.jpg [Accessed: 2012-09-15]

[10] The British Museum. (n.d.). A History of the World [Internet]. Available from: http://www.bbc.co.uk/ahistoryoftheworld/objects/0JxzTILOQLKGBZehim601A [Accessed: 2012-09-17]

[11] Krenzler G. United States of America Patent No. 979,770 SN 534,061. 1910

[12] Krenzler E. United States of America Patent No. 946,445 SN 502,529. 1910

[13] Farrell J. Identifying handmade and machine lace. In: The Museum of Costume and Textiles, Nottingham on 21st February 2008 [Internet]. Available from: http://www.dressandtextilespecialists.org.uk/wp-content/uploads/2015/04/Lace-Booklet.pdf. [Accessed: 2012-09-15]

[14] Middleton G. Imitations of Handmade-Lace by Machinery [Internet]. Available from: https://www2.cs.arizona.edu/patterns/weaving/articles/nb38_ml1.pdf [Accessed: 2012-09-15]

[15] Marenzana R. Yarn limitations in manufacture of barmen Torchon laces—Use of rayon increasing. The Melliland. 1930;**2**:290-293

[16] Krenzler [Internet]. Available from: http://www.krenzler-gmbh.de/index.htm [Accessed: 2012-09]

[17] Branscomb D. Minimal weight composites utilizing advanced manufacturing techniques [thesis]. Auburn: Auburn University; 2012

Chapter 5

Polymeric Synthetic Fabrics to Improve Stability of Ground Structure in Civil Engineering Circumstance

Han-Yong Jeon

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.81246

Abstract

Polymeric synthetic fabrics are continuous sheets of woven, nonwoven, knitted, or stitch-bonded fibers and yarns. The sheets are flexible and permeable and generally have the appearance of a fabric. Among polymeric synthetic fabrics, geosynthetics including geotextiles have special functions of separation, filtration, drainage, reinforcement, and erosion control in civil engineering applications. Also, geosynthetics such as geotextiles and geogrids are used in asphalt pavement reinforcement. An important function of these geotextiles is as cushion layers to prevent puncture of geomembranes (by reducing point contact stresses) from stones in the adjacent soil, waste, or drainage aggregate. Geotextiles, however, are made from a combination of two or more polymeric synthetic fabrics. In this chapter, geotextiles as polymeric synthetic fabrics are introduced not only for improvement but also maintaining stability of ground structure in civil engineering circumstance with their related technologies.

Keywords: polymeric synthetic fabrics, geosynthetics, geotextiles, special functions, cushion layers, stability of ground structure

1. Introduction

Geotextile is classified into woven fabric and nonwoven fabric in a morphological form and it performs functions such as reinforcement, separation, filtration, and drainage when applied to civil engineering structures. Generally, due to its structural form, the nonwoven geotextile has a small permeability coefficient and permittivity despite its small apparent opening size (AOS) compared with the woven geotextile style, it has advantages in function. Woven geotextile is applied to reinforce soil structure with poor shape stability in nonwoven geotextile based on excellent mechanical performance, and it also takes charge of filtration and drainage [1, 2].

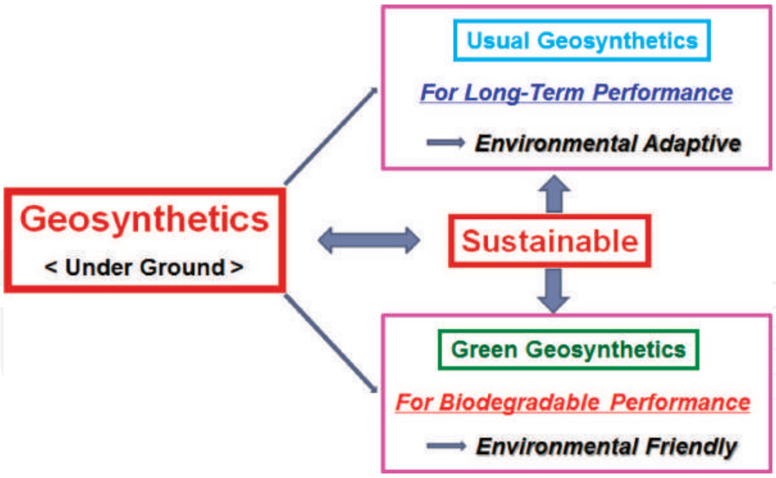

Figure 1. Sustainable geosynthetics.

Geotextile products have the characteristics of so-called tailor-made materials, which are known to function for specific applications. The long-term performance of geotextiles has a close relationship with the stability of the applied structure and practical applications such as continuous new method and new technology [3, 4]. As the demand and necessity to high-performance products gradually increase, composite products, environment-friendly products, environment adaptive products, hybrid, or smart products should be developed. In response to this, the development and advancement of the evaluation method are progressing steadily.

International Geosynthetics Society (IGS) Education Committee established that geotextiles can be classified broadly based on the manufacturing method and geotextiles is a continuous sheet of woven, nonwoven, knitted, or stitch-bonded fibers or yarns. Sheets are flexible and permeable and generally have a cloth-like appearance. Geotextile is used for separation, filtration, drainage, reinforcement, and anti-erosion applications [5].

In general, sustainable geosynthetics mentioned here are classified as "Usual Geosynthetics" and "Green Geosynthetics" based on required performance as shown in **Figure 1**.

In here, "Usual Geosynthetics" refers to the function-oriented long-term maintenance and environment-adaptive products introduced, and "Green Geosynthetics" refers to environment-friendly degradable geosynthetics, respectively.

In this chapter, we will introduce "Sustainable Geotextiles," which is differentiated from geotextile products to hybrid geocomposites except the traditional geotextile products.

2. Raw materials for geotextile products

The geotextile products and the polymeric raw materials are shown in **Table 1**. As the additives, internal fillers, antioxidants, carbon black, emulsions, and plasticizers are used for improving and complementing the physical properties, glass fiber, carbon fiber, aramid fiber,

http://dx.doi.org/10.5772/intechopen.81246

Polymeric raw materials	Geosynthetic products
Polyethylene (Low, middle and high density)	Geotextiles, Geomembranes, Geogrids, Geopipes, Geonets, Geocomposites
Polypropyrene	Geotextiles, Geomembranes, Geogrids, Geocomposites, Prefabricated Board Drain (PBD)
Polyester (High tenacity)	Geotextiles, Geogrids, Prefabricated Board Drain (PBD)
Polyamide	Geotextiles, Geogrids, Geocomposites
Glass fibers, Polyvinyl alcohol(PVA) fibers, Aramid fibers, Carbon fibers etc.	

Table 1. Geosynthetic products with polymeric raw materials.

acrylic fiber, asbestos fiber, and low-modulus fibers such as polypropylene, polyamide, polyethylene, and polyester fiber, etc. are generally used to manufacture geosynthetic products.

Otherwise, antioxidants, carbon black, oils, plasticizers, fillers, etc. are added to improve the specific properties of the polymer, and two or more raw materials may be blended to improve specific properties. In the case of the geotextile made of polyethylene resin, radicals are formed due to sunlight, which causes decomposition and causes embrittlement. Hindered amine light stabilizers (HALS) series oxidation stabilizer is added to prevent radical formation by daylight and ultraviolet rays. Weather resistance is also improved. When geosynthetics are applied for a long period of time, durability depends on the characteristics of the polymeric materials used. Therefore, it is highly desirable to analyze the characteristics of geosynthetics to determine their use.

3. Fibers used for polymeric synthetic fabrics

3.1. Natural fibers

Natural fibers used in geotextile products are very limited, but they were first used as geotextile products. They were mainly applied in fiber, yarn, and knit form, and their demand increased as nonwoven- and woven-type products were developed. Since geotextiles of natural fibers have the advantage of being eco-friendly materials, the utility of geotextile products has recently begun to reappear. The raw materials of the products also include cotton, jute, coir, straw, and other stem forms of waste assembly, and it is very diverse. However, since it is not used much and cannot be mass-produced compared with synthetic materials, it poses a difficult problem to create demand. Some of them use civil engineering natural fiber products as slope stabilization, erosion control, drainage, etc.

3.2. Synthetic fibers

One of the conditions that geosynthetic products must have is economic advantages, which is a very real problem directly linked to manufacturing costs. Polyolefin, polyester, and so on are widely used as synthetic polymer fibers, and polyurethane, glass, and carbon-based polymers are applied to very limited fields in order to give a special purpose and function. Demand creation of geosynthetic products using polymer materials can be increased, and new functional products are expected to be developed in parallel with the development of various additives.

3.3. Recycled fibers

Since the fiber polymer materials used in the manufacture of geosynthetic products are often used in large quantities, therefore, the cost is low. Therefore, if the performance is similar, the manufacturing cost should be low. In view of this, in the case of nonwoven geotextile, products using already recycled polyester materials are being manufactured and sold, and interest and research on recycled polymeric materials are being actively pursued in terms of environment friendliness. However, in the case of the geosynthetic products manufactured using the recycled polymeric material, the physical properties are deteriorated, and therefore, there is a problem that it needs to be supplemented or improved in the future.

4. Manufacturing of polymeric synthetic fabrics as geotextiles

4.1. Geotextiles

Geotextile is a planar, permeable, polymeric (synthetic or natural) textile material, which may be nonwoven, knitted, or woven, used in contact with soil/rock and/or any other geotechnical material in civil engineering applications (**Figure 2**).

There are woven geotextiles which are divided into plain weave and twill weave using staple and filament yarns. Yarn used is usually as of 1000–3000 denier. And fabric density is generally in the range of 19–21 plies per inch in the warp and weft direction, and mainly polyester and polypropylene fibers are used, but polypropylene fiber has a weak light resistance. In addition, nonwoven geotextile, in which long fibers or short fibers are randomly arranged and bonded, is manufactured by using a needle punching and thermal bonding

Figure 2. Photographs of geotextiles.

http://dx.doi.org/10.5772/intechopen.81246

process in the case of short fibers and laminated by spunbonding process in the case of long fibers in a weight of about 200–800 g/m^2.

In general, the constituent fibers form a disorderly entangled structure, so that they have excellent mechanical and mechanical properties, and polypropylene and polyester fibers are mainly used. Normally nonwovens are used for filter and separation functions. A nonwoven is a geotextile in the form of a manufactured sheet, web, or batt of directionally or randomly orientated fibers, filaments, or other elements, mechanically and/or thermally and/or chemically bonded. Nonwovens are used in filtration, drainage, separation, protection, and/or erosion control applications.

Fine soil particles can be captured in between the three-dimensional fiber entanglement of the nonwoven and prevent movement of these into the usually coarse "neighbor" soil. This way the buildup of a filter stable layer is possible. The geotextile filter can be dimensioned with available filter calculations [6, 7].

4.2. Geosynthetic clay liners (GCLs)

It is a geocomposite produced by bonding bentonite clay to a geotextile or geomembrane or filling bentonite clay between two geotextiles. The geotextile-made geotextile clay pottery often has a needle bent through the bentonite layer to increase internal shear resistance. It is effective as a barrier against liquids or gases when bentonite is hydrated. It is commonly used with geomembranes and is used as filler in landfills (**Figure 3**). GCL is also a factory-manufactured hydraulic barrier consisting of a layer of bentonite or other very-low-permeability materials supported by geotextiles and/or geomembranes, mechanically held together by needling, stitching, or chemical adhesives (**Figure 4**).

4.3. Geotubes and geocontainers

There are many opinions on how to prepare measures to be protected against or prevent catastrophic disasters such as tsunami and Katrina which have recently occurred, but one of the obvious ways of doing this is that it is closely related to advance prevention as well as disaster recovery. To do this, the method is the use of geotextile products. Geotextile containers, which are used instead of building rigid structures such as rocks and concrete in rivers, coasts, and harbors, are used as geotextile containers that are currently being used for this purpose worldwide, and they are used to construct flexible structures, and this technique has been successfully applied [8, 9].

Also, geotextile container is classified as geobags, geotubes, and geocontainers depending on the size and manufacturing method. The geotextile container is made by mechanically or hydraulically filling the soil including dredged soil in the geotextile bag. Generally, a geobag is a small geotextile container with a capacity of 0.3–5.0 m^3; it is usually used as a sand filling material, and it is finished with a small sewing machine.

Geotubes are manufactured in permeable geotextile and are filled with sand or dredged soil by hydraulic or mechanical methods. The diameter and length of the geotube depend on site conditions and installation possibilities, usually 150–180 m, 4–5 m wide, and 1.5–2 m high.

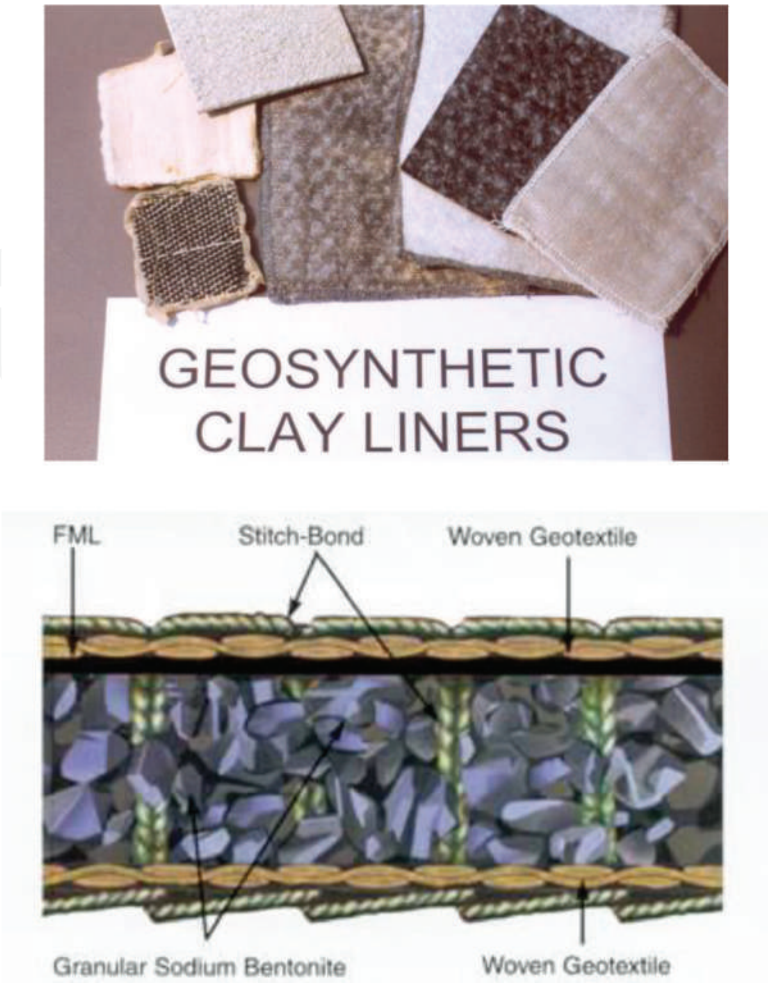

Figure 3. Photographs of geosynthetic clay liners.

In order to fill the upper part of the geotube with hydraulic method, the sandy soil should be closer (about 10 m) and the clayey soil as far as possible. Geotube is a massive pillow-shaped structure made in a permeable geotextile style and is filled mechanically with sand or dredged soil by a hopper or clamshell bucket (**Figure 5**).

Since the first attempt of geotube applications was in Brazil in the early 1980s, geotube application technology has been used as a containment embankment for the prevention and isolation of contaminated soil from France in 1986 and has since been used for underwater embankment or coastal protection in the Netherlands and Germany. Now, geotube was widely used for construction work [10].

Geocontainer is constructed by preliminarily sewing the geotextiles of the proper length together and installing it in the split bottom-dump width of the floor (the two ends are sewn together so as to form slender pillow shapes). And then, fill with sand or dredged soil, and seal the suture with a suture at the site (**Figure 6**).

The capacity of the geocontainer can be increased as the barge opening width of the barge becomes larger and is usually about 100–1000 m^3. When dredged clay is used, geocontainers

http://dx.doi.org/10.5772/intechopen.81246

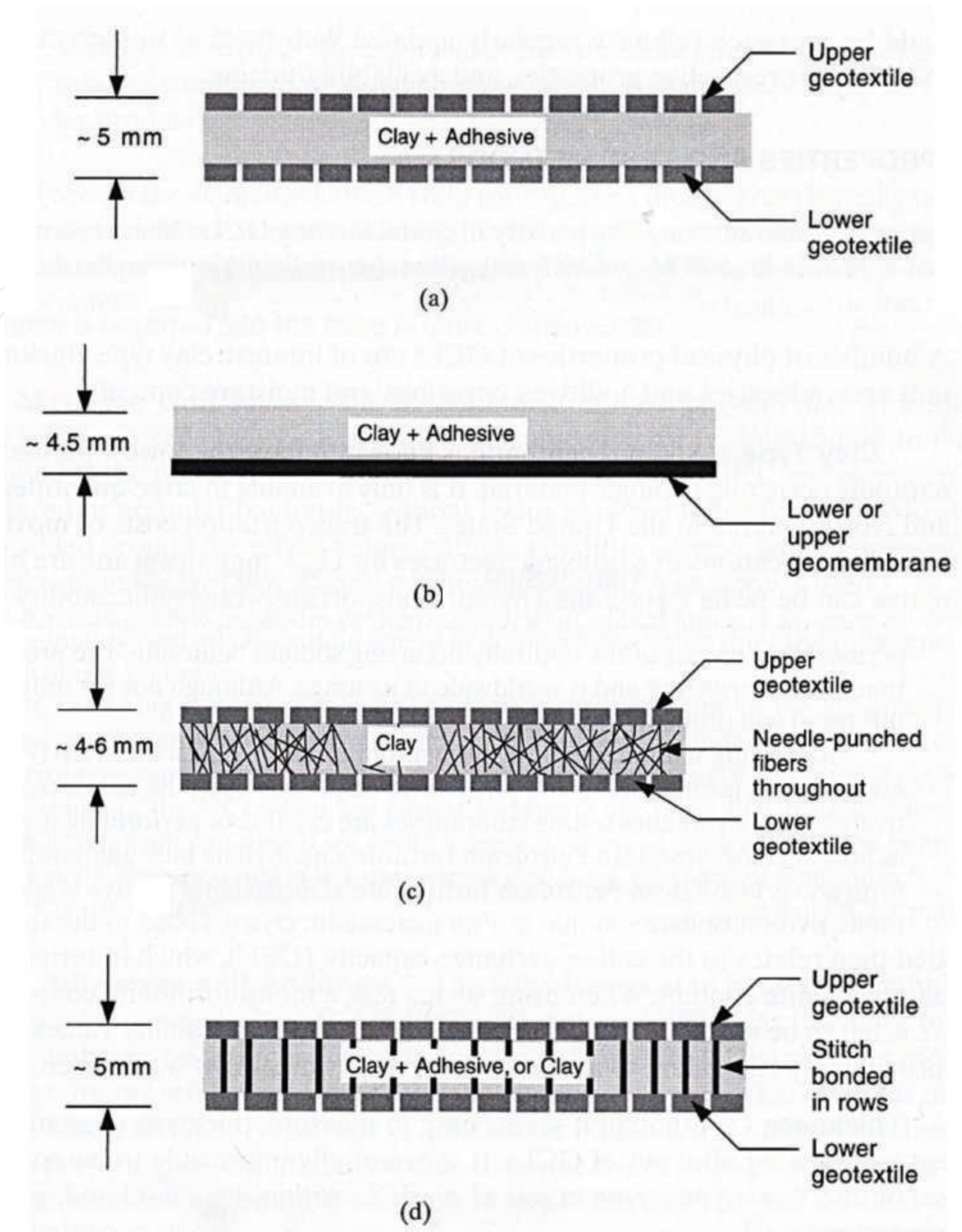

Figure 4. Cross-sectional sketches of currently available GCLs. (a) Adhesive-bound clay between upper and lower geotextiles, (b) Adhesive-bound clay above or below a geomembrane, (c) Needle-punched clay through upper and lower geotextiles, and (d) Stitch-bonded sketches of currently available GCLs.

can be manufactured by using nonwoven geotextile inside and woven geotextile outside. These geocontainers have many advantages such as shortening the installation period and reducing the construction cost due to the use of site-useable materials and workload and minimizing environmental pollution during construction.

Geocontainer application technology was first developed in the Netherlands and was used in 1986 in Germany for the construction of the flow-inducing dikes in the Rhine River and in 1987 in the Dutch-eroded canal's dikes.

The US Army Engineer Waterway Experiment Station (WES), which has recently been the centerpiece of the Army Engineer's Department and has been planned for Construction

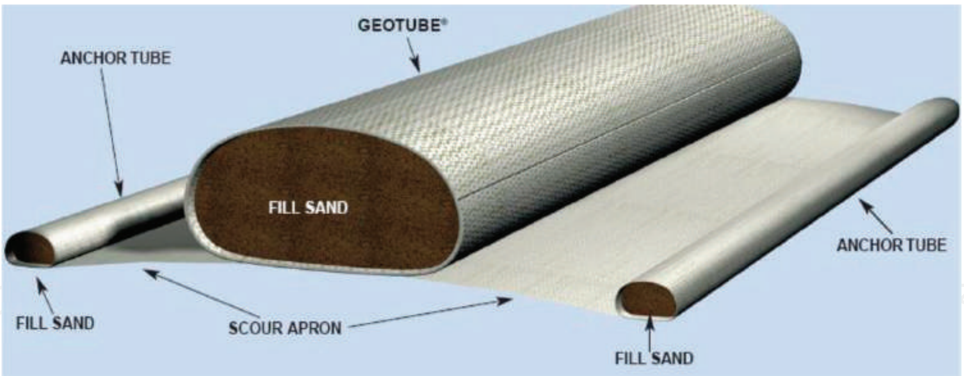

Figure 5. Schematic diagram of geotube.

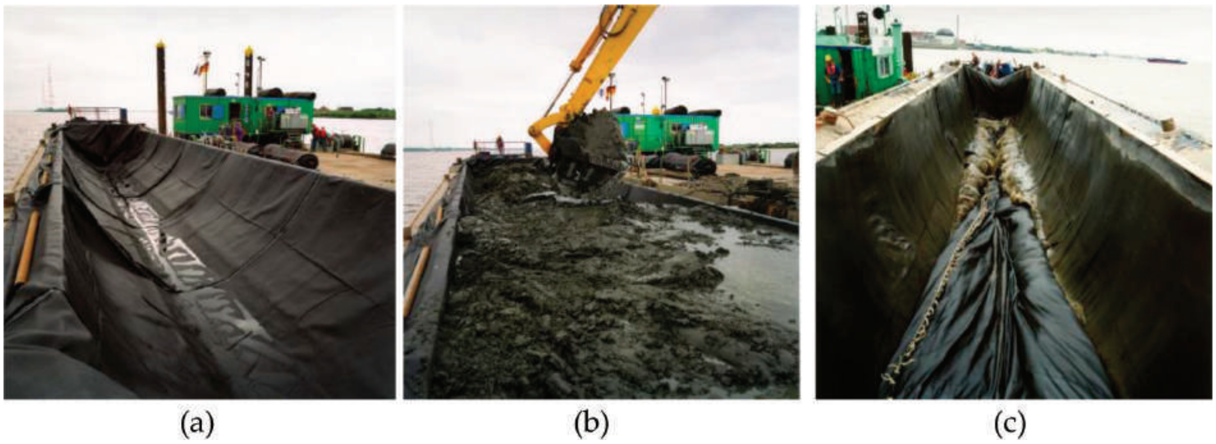

Figure 6. Photographs of geocontainer application. (a) Spreading, (b) filling soils, and (c) dumping.

Production Advancement Research (CPAR) and has been developing innovative technologies using geotextile for the construction and maintenance of seawalls, rivers, canals, harbors, breakwater, dikes, coastal protection, roads, landfills, and reclaimed land.

5. Technical development trend of geosynthetics

Previously, environmental adaptive geosynthetics, which we have described as "Usual Geosynthetics," have not changed much over the past 20 years, but the paradigm of composite products using extreme strength fibers with the keyword of diversification of applications is being created. In other words, the development demand for divergence-targeted products, which means creation of usage as protection, maintenance, and restoration concept from natural disaster, is growing as megatrend of product development [11–14]. We will introduce the recently introduced fiber-reinforced geosynthetic products based on the concept in **Figure 1**.

5.1. Environmental adaptive geosynthetics

Environmental adaptive geosynthetics introduced as "Usual Geosynthetics" has not changed much over the past 20 years, but the paradigm of composite products using extreme strength fibers with diversification of uses has been created.

http://dx.doi.org/10.5772/intechopen.81246

On the other hand, most of the synthetic polymeric materials that have been widely used are polyolefin-based and polyester-based ones. However, polyurethane, glass, and carbon-based polymers could be used to manufacture for special purpose and functions. Since the polymer materials used in the manufacture of geosynthetic products are often used in large quantities, therefore, the cost is low. Therefore, if the performance is similar, the manufacturing cost must be low.

In view of this, products using recycled polyester materials have already been manufactured and sold, and interest and research on recycled polymer materials are being actively pursued from the viewpoint of environmental friendliness. However, in the case of the geosynthetic products manufactured using recycled polymeric materials, the physical properties of the recycled polymeric materials are deteriorated, so that they have to be supplemented or improved in the future.

Recently, as the demand of composite-type geosynthetics has increased, functional and special high-performance materials have been used to improve the field application of geosynthetic products and to improve the stability of geotechnical structures from earthquakes, tsunamis, etc., liquid crystal polymer (LCP), polybutylene oxide (PBO), polypropylene sulfide (PPS), and meta- and para-aramid fibers have been used to combine with fusion technology for the production of hybrid geosynthetics.

5.2. Environment-friendly geosynthetics

"Green Geosynthetics" refers to products that have sustainable degradable geosynthetics and environmental pollution prevention and restoration functions that do not mean long-term implementation of initial performance in terms of environmental friendliness. In the case of geotextiles, "biodegradability" refers to a phenomenon in which initial performance is gradually lost over time due to decomposition by microorganisms or bacteria in the soil, which is a geotechnical structure. In terms of restoring the polluted environment, it is also a new area of geotextiles that meets the issue.

In order to manufacture "Green Geosynthetics," a resin which is biodegradable as a raw material should be used separately, and it is closely related to the reduction factor required for long-term use. Therefore, if the green geosynthetics is used as a filter, the production of a geotextile in the form of nanofibers will help improve filtration efficiency.

6. Development trend with geotextile-related products

6.1. Geotextiles

1. Nonwoven geotextile products

    High weight, over 5000 g/㎡

    Smart fusion multifunction product

    Filter products for nanofiber applications

    Composite products, etc.

2. Woven geotextile products

High strength, 30 ton/m or more tensile strength demanded

Creep property improvement product

Low-elongation high-strength yarn use

Smart fusion multifunction product

Composite products, etc.

6.2. Geosynthetic clay liners (GCLs)

Differentiated hydraulic function product

Salt water swelling improvement product

Products with improved freeze-thaw stability

Selective-order function products, etc.

6.3. Filter and drainage geotextiles

Minimization of penetration by constraint load

Clogging prevention and minimization products

Biodegradable multifunctional products, etc.

6.4. Geotubes and geocontainers

High strength, 50 ton/m or more tensile strength demanded

Creep performance improvement products

Permeability and sealing property improvement products

Ultraviolet and salt water stability improvement products, etc.

6.5. Miscellaneous

Concrete reinforcement geocomposites

Silt fence products

Seam properties improvement products

Ultraviolet and salt water stability improvement products, etc.

7. Functional geotextile-related products

7.1. For separation, filtration, and reinforcement functions

In order to improve the separating function of the geotextile for reinforcement, it is possible to improve physical properties and permeability by designing the smoothness of the woven fabric at a high level and to improve the morphological stability by designing the tissue for controlling apparent opening size (AOS) [11–13]. Especially, it is designed to improve the tensile strength of fabric by improving density of weft yarn and double yarn design so as to improve the tensile strength in weft direction (**Figure 7**).

This product has the overall performance (chemical stability, higher tensile property, and water permittivity, etc.) as the geomembrane protection mat in the landfill construction caused by the working vehicle and the aggregate applied to the leachate drainage layer and at the upper part and can be used as a composite product.

7.2. Multiaxial geocomposite for reinforcement

As shown in **Figure 6**, geocomposite fabrication technology and products were developed to enhance the reinforcement function of geosynthetics by applying multiaxial knit fabric and geotextile composite technology by developing not biaxial but multiaxial knit. In addition, a smart monitoring high-performance multiaxial geocomposite technology is being developed in parallel to embed an optical fiber sensor in a multiaxial geocomposite appropriately to monitor the damage of the geocomposite due to stress concentration in real time (**Figure 8**).

7.3. Geotextiles for preventing reflective crack

Geotextiles applied on the top of the packed and unpacked road subgrade is considered to be the top layer of the bottom layer consisting of roadbed soil and the top layer consisting of soil or aggregate laid for construction. If the two layers are not properly separated, the particles of the lower layer penetrate the upper part, or the particles of the upper part penetrate the lower layer, causing settlement or cracking of the road. Also, when the bedrock is saturated by rain or other conditions, excess pore water pressure is generated by the traffic volume, so that the bedrock is weak and easily broken. Therefore, proper water discharge must be achieved, and

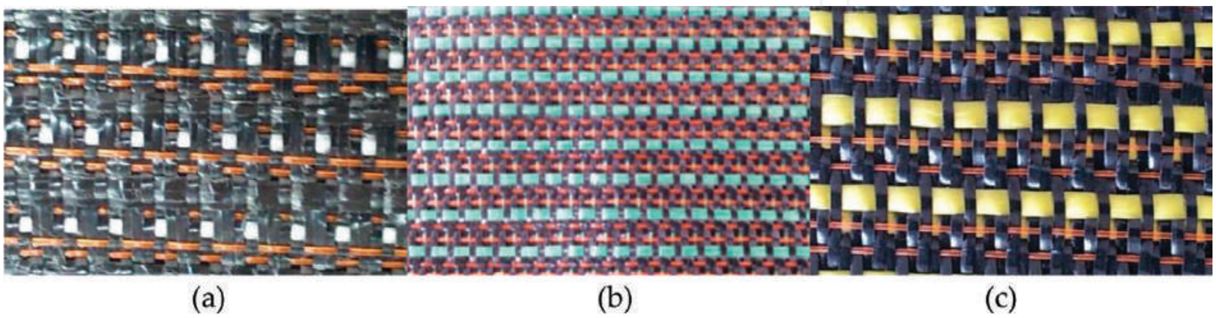

Figure 7. Geotextiles for separation, filtration, and reinforcement. (a) Separation, (b) filtration, and (c) reinforcement.

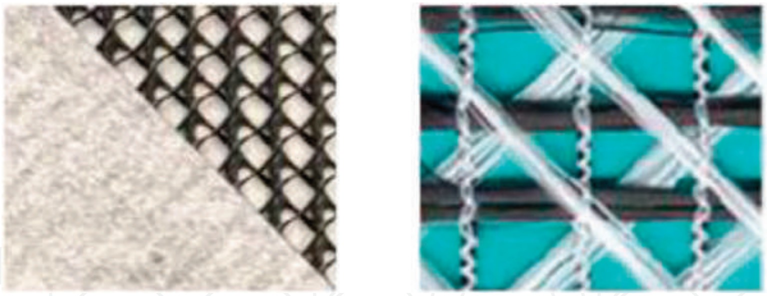

Figure 8. Multiaxial geocomposites for reinforcement.

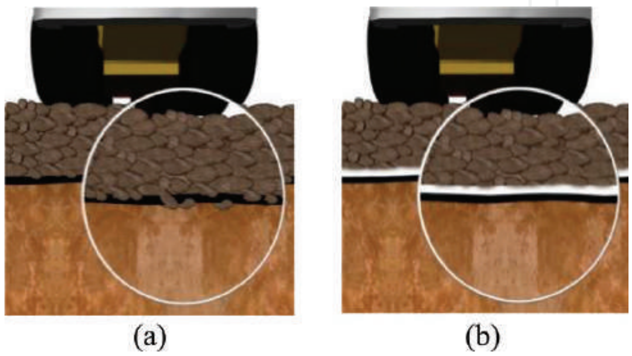

Figure 9. Failure with/without geotextile for pavement protection. (a) Without geotextile and (b) With geotextile.

proper pore size and good permeability coefficient are required because the piping phenomenon is required to prevent the loss of soil along with the flow of water [14, 15].

As shown in **Figure 9**, pavement roads are damaged due to cracks and plastic deformation before the design life due to the surrounding environment and repeated traffic loads, which causes wasted budget for maintenance of road pavement.

This is due to the weakening of the bearing capacity of the pavement ground or the cracking and growth due to the expansion and contraction of the water inside the packed asphalt or concrete. The role of a geotextile as a localized stress reduction layer could be to prevent or reduce damage to a given surface or layer by vehicle passing load.

Therefore, in order to improve the durability of the pavement, development is underway to improve the performance of asphalt or aggregate as a road pavement material and to reinforce the pavement by adding reinforcement materials such as geosynthetics to traditional pavement materials.

On the other hand, asphalt pavement using geotextiles has a great effect on prevention of fatigue cracks and reflective cracks and additionally has an advantage of blocking water penetration due to road crack by increasing water penetration. Advanced geotextiles have been developed, have improved toughness against repeated fatigue loads, and are resistant to various damage loads that occur during the construction process (**Figure 10**).

7.4. Biodegradable geotextiles

In the case of geosynthetics for slope reinforcement or erosion prevention considering vegetation, biodegradable products are required for the purpose of activating the planting of plants.

Figure 10. Various geotextiles for antireflective crack propagation.

However, as mentioned above, even though it is a product of very important issue in terms of being environmentally friendly, it is easy to enter the market only if the stability of raw material supply and supply and product standardization are solved. Here, only the biodegradable vegetation mats and geocells used for vegetation in river maintenance and slope greening are introduced.

As shown in **Figure 11**, the geotextiles for vegetation mats have a very high initial dependency for the purpose of preventing or stabilizing the erosion. Therefore, biodegradation occurs in the course of the planting process after the vegetation mat construction, thus contributing to the improvement of the stability of the structure.

The synthetic resin system used for slope protection and erosion prevention was originally a product using a mat made of a heat-sealable webbing structure using nylon and a product with a reinforcing material (geogrid) combined with a web structure. And polypropylene staple fibers have been developed in the future, but since they are nondegradable products, it has been pointed out that the residues become an environmental pollution source after completion of the desired slope protection and erosion prevention function.

It is now in the process of restoration of various floods due to increasing weather conditions, eco-friendly construction methods, and landscaping and greening. As the demand for

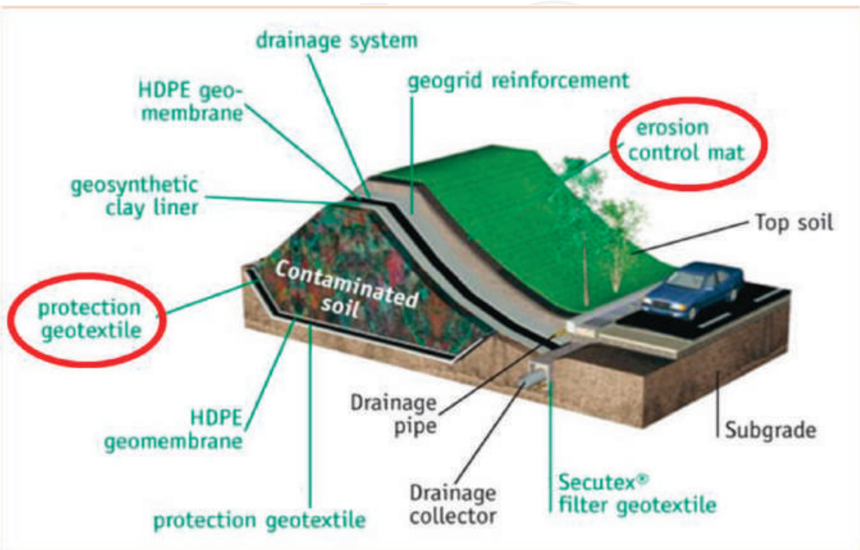

Figure 11. Application examples of geotextiles for erosion control.

products becomes greater, it is possible to apply and expand key technologies for vegetable mats made from biodegradable resins.

8. Nanofiber-used geotextiles

In general, geotextiles can be fabricated with a fiber size of more than 1 denier. However, when the size of a fiber becomes micro fine or nanofiber size, it has a great advantage in restoring the environment from pollution or improving filtration performance (**Figure 12**).

As shown in **Figure 13**, the filtering capacity of the geotextile depends on the number of fibers per unit area, the size of the pores, and the compositional structure. Therefore, when nanofibers are used, the smaller the pores constituting the geotextile, the removal rate of the toxic water is improved. However, at present, there is not a variety of techniques for manufacturing nanofibers, and since the manufactured nanofibers are expensive, the practical use of nanofibers is very slow.

In general, regular fibers are widely used to manufacture geotextiles and geogrids, but filtration efficiency of microfiber and nanofiber geotextiles is better than regular fiber-used geotextiles. To consider this, it is expected that nanofiber geosynthetics could be the smart filtration function in geoenvironmental applications by their composition structure as in **Figure 3**. If the numbers of filled fibers per unit area are increasing, pore size among nanofibers is decreasing. Therefore, the fine particles cannot pass through pores by nanofibers, and the filtration efficiency will be improved. This means that ultrathin geosynthetic filter can be manufactured with high-quality filtration function to absorb the fine impurities and toxic components in water and air media (**Figure 14**).

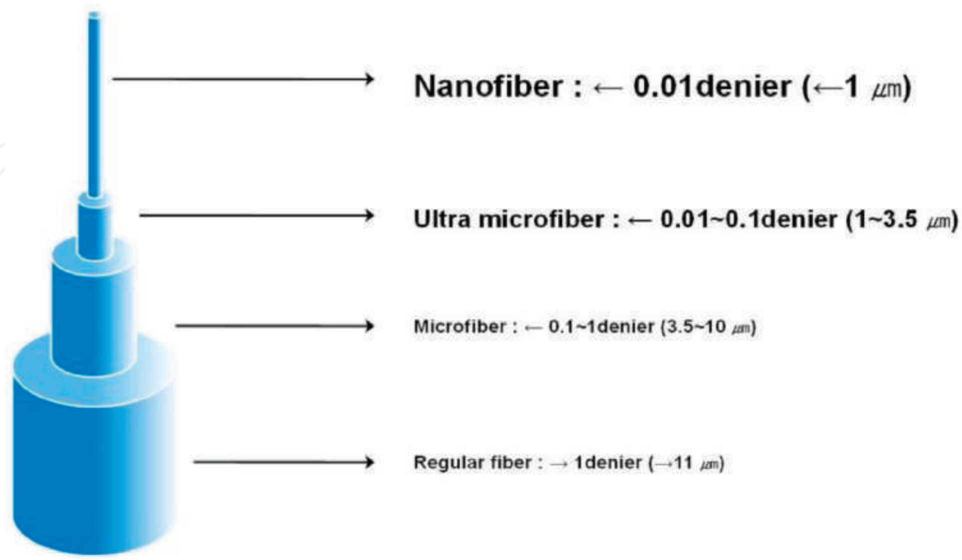

Figure 12. Thickness of fiber for geosynthetic fiber production.

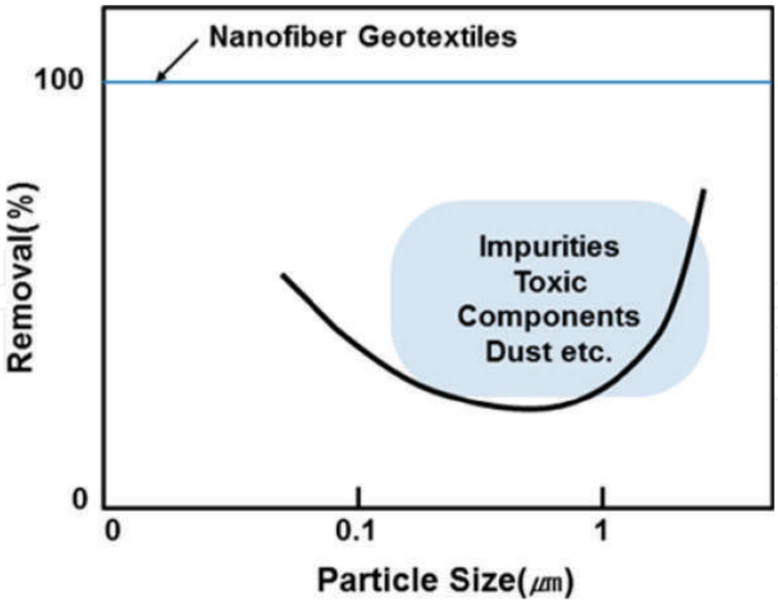

Figure 13. Impurity removal ratio according to geotextile pore size.

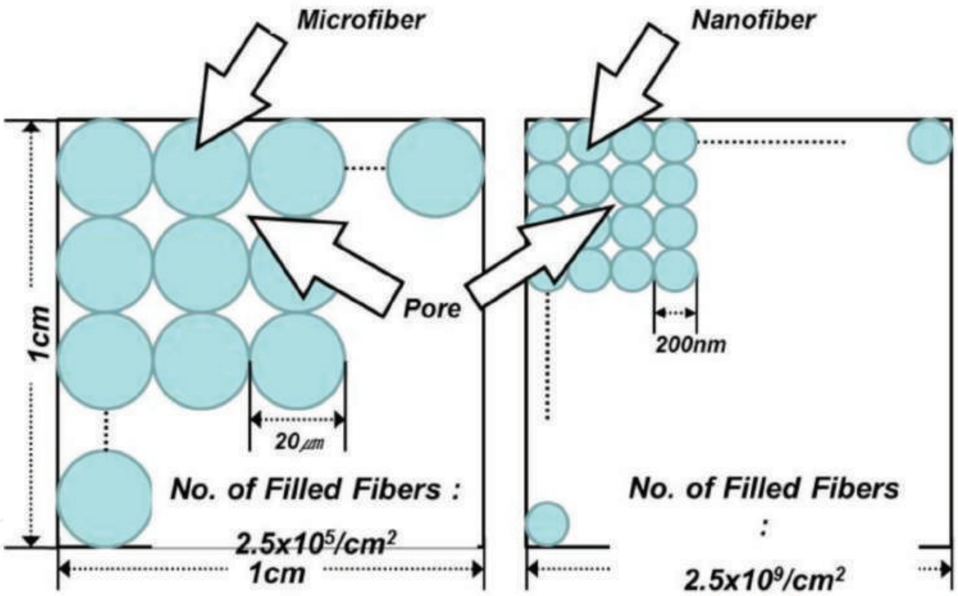

Figure 14. Geotextile filtration ability according to the number of filled fibers.

Figure 15 shows the separation concept of nanofiber air filter by pressure. To be the best air filter, higher particle collection and dust retention rate should be required.

In order to remove the heavy metals and toxic substances contained in polluted soil, nonwoven geotextile is used which is made by mixing nanoparticle clay with polyester fiber (**Figure 16**). Of course, the engineering performance of mixed nonwoven geotextile will vary depending on the composition of clay and particle size, but the strength degradation due to leachate, chemical, and biological degradation of waste landfill is not greater than that of

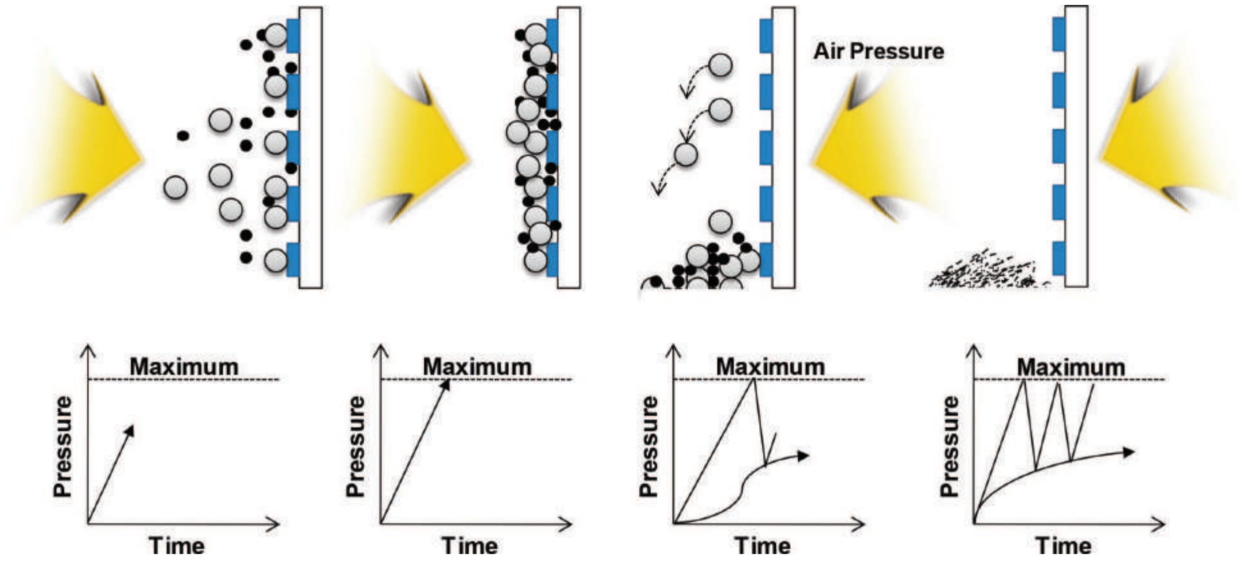

Figure 15. Maintenance of filtration efficiency for nanofiber filter.

Figure 16. Nonwoven geotextiles with/without nano-clay.

nonwoven geotextile without clay. Also, AOS is higher than that of the nonwoven geotextile which is not mixed with clay, so that the permeability is improved.

9. Conclusion

Looking back at the civil engineering industry, product development and construction technology have been growing remarkably. There is also a growing demand for sustainable civil engineering products to protect, repair, and restore structures after recent floods, tsunami, and earthquakes. Considering the product characteristics and functions according to the product material and manufacturing method, civil engineering is rapidly growing with advantages of development of convergence composite geosynthetics using polymeric material, new design with geosynthetics.

http://dx.doi.org/10.5772/intechopen.81246

In addition, it is expected that the utilization of civil engineering products will be further enhanced by various applications of the development and manufacturing methods of geosynthetics. For this, new convergence type composite geotextile-manufacturing technology should be developed not only standardization and reliability of evaluation methods but also design and construction methods and equipment.

Author details

Han-Yong Jeon

Address all correspondence to: hyjeon@inha.ac.kr

Department of Chemical Engineering, Inha University, Incheon, South Korea

References

[1] Giroud JP. Geotextiles and Geomembranes—Definitions, Properties and Design. Vol. 1-3. St. Paul, Minnesota: IFAI; 1984

[2] Koerner RM. Designing with Geosynthetics. 5th ed. New Jersey, USA: Prentice-Hall Inc.; 2005

[3] Rawal A, Shah T. Geotextiles: Production, properties and performance. Textile Progress. 2010;**42**:181-226

[4] Koerner RM, Koerner GR. Lessons learned from geotextile filter failures under challenging field conditions. Geotextiles and Geomembranes. 2015;**43**:272-281

[5] International Geosynthetics Socoity (IGS), Education Resource. https://www.geosyntheticssociety.org/education-resources/

[6] Koerner RM, Koerner GR. Geotextile filter failures: Examples and lessons learned. In: Proceedings of the 25th Central Pennsylvania Geotechnical Conference; Hershey, PA, (on CD). 2011

[7] Maiser M, Myles B. Possible culpability of filter geotextile in the failure of a sea wall. In: Proceedings of the 1st Pan American Geosynthetics Conference; Cancun, Mexico. 2008. pp. 833-841

[8] Lawson C. Geotextile containment—International perspectives. In: Proceedings GRI-17. Hot Topics in Geosynthetics IV, GII; Folsom, PA. 2003. pp. 178-201

[9] Heibaum M. Special issue on geotextile containers. Journal of Geotextiles and Geomembranes. 2002;**20**(5):279-342

[10] Hsieh CW, Lin CK, Chiu YF. The strength properties of geotextiles in ocean environments. In: Proceedings of the EuroGeo3; Munich, Germany. 2004. pp. 377-382

[11] Guglielmetti JL, Koerner GR, Battino FS. Geotextile reinforcement of soft landfill process sludge to facilitate final closure. Journal of Geotextiles and Geomembranes. 1996;**14**(7-8):377-392

[12] Alexiew D, Brokemper D, Lothspeich S. Geotextiles encased columns (GEC): Load capacity, geotextile selection and pre-design graphs. In: Proceedings of the GeoFrontiers 2005; Austin, Texas, (on CD). 2005

[13] Cuelho E, Steve P, Zachary M. Relative Operational Performance of Geosynthetics Used As Subgrade Stabilization, No. FHWA/MT-14-002/7712-251. FHWA, U.S. Department of Transportation, USA. 2014

[14] Suits LD, Koerner GR. Site evaluation/performance of separation geotextiles. In: Proceedings of the Geosynthetics '01 Conference. IFAI Publ.; 2001. pp. 451-468

[15] Perkins SW, et al. Geosynthetics in pavement reinforcement applications. In: Proceedings of the 9th ICG; Guaruja, Brazil. 2010. pp. 115-164

Chapter 6

Behavior of Reinforced Soil Wall Built with Fabrics

Mario Riccio and Mauricio Ehrlich

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.79239

Abstract

This chapter presents an example of use of fabrics in geotechnical engineering construction. Some aspects related to design, construction, and the performance of a 4.2-m-high-reinforced soil wall, located in Brazil, is presented. In this wall, geogrid (fabric reinforcement) was used as reinforcement, and the backfill was a fine-grained residual tropical soil. The wall was monitored during its construction (2 months); load in the reinforcements, vertical and horizontal displacements of the reinforced soil mass, and efforts on block-face were measured. The monitoring of the wall was done by means of load cells for the reinforcements and block-face, and also includes settlement plates, total pressure cells, inclinometers, and topographical marks. The results provided by the instruments showed good performance of the wall. Measurements and calculated tension in the reinforcements were compared, and good prediction capability of the used analytical method was demonstrated. The measured tensile load in the reinforcements was lower than the admissible load of the geogrids used in the wall. Measurements also indicate that the block-face was able to support part of the load that would be carried by the reinforcements.

Keywords: fabrics, reinforced soil wall, monitoring, analytical method

1. Introduction

Reinforced soil walls (RSW) are retaining structures composed by facing, compacted backfill and usually geosynthetic reinforcements. Compacted soils have good strength in terms of compression solicitation, but they have a very low tensile strength. Thus, similar to the reinforced concrete, the use of fabrics as reinforcement is intended to provide enough tension resistance to the composite material. RSW structures can be built with a wide variety of fabrics (geosynthetics). Those fabrics are specially developed and have different applications in geotechnical engineering. **Figure 1** shows some examples of geosynthetics used in RSW construction as reinforcement.

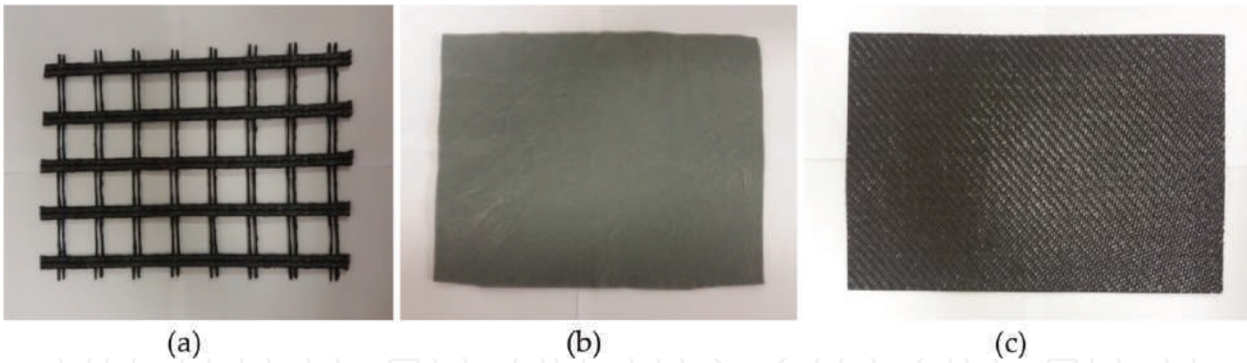

Figure 1. Examples of geosynthetics used for RSW construction as reinforcement: (a) geogrid; (b) nonwoven geotextile; (c) woven geotextile.

The backfill used for reinforced soil wall construction could be purely sands or even soils that contain high percentage of fines. In Brazil, due to the abundance of residual fine-grained soils, it is a common practice to build RSW using this kind of soil. This kind of soils, in spite of its high percentage of fines, has high strength resistance, presents good workability, and achieves a proper density during compaction. **Figure 2** shows the basic concept of RSW; the geosynthetics link the active zone (the unstable zone) to the resistant zone. Design should provide enough reinforcements in order to guarantee no failure or pullout of reinforcements from the resistant zone. Both zones liked together works like a block that may be considered as a conventional retaining wall that provides the stabilization of the nearby nonreinforced soil mass. The mobilized load along the reinforcements is variable, and the location of the points of maximum tension defines the potential failure surface that separates the active and passive zones. **Figure 2** also indicates the shape of the potential failure surface that varies with the stiffness of reinforcements.

The design of an RSW comprises basically two verifications: (a) external stability that is basically the same concept used for the conventional retaining walls, i.e., stability analyses for sliding and

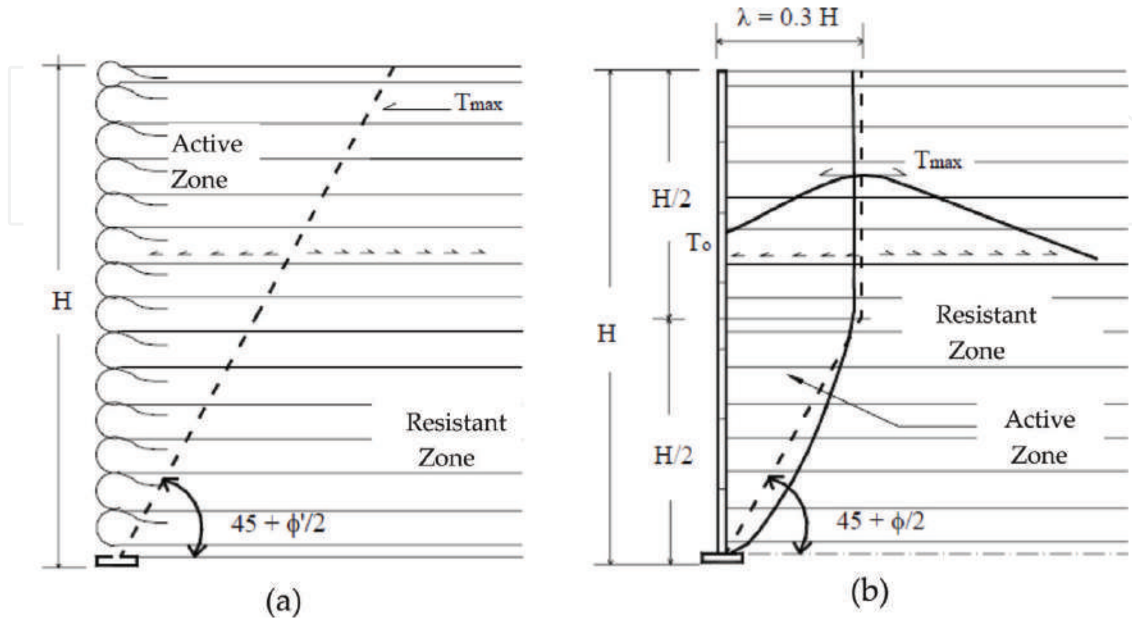

Figure 2. Basic concept of RSW and the potential failure surface: for extensible (a) and rigid (b) reinforcements.

overturning, bearing capacity and general failure and (b) internal stability. The internal stability consists in the comparison of the mobilized load in the reinforcements (geosynthetic) with the tension strength of those ones. There are some methods to evaluate the mobilized load in the reinforcements, such as [1–5]. Through case studies, field instrumentation, physical and numerical modeling [6–11] have been demonstrated that among these methods the more suitable are the ones proposed in [4, 5]. These methods explicitly consider soil and reinforcement properties, the effect of compaction operation, and the relative stiffness between soil and reinforcement. The method described in [5] is based on the one developed by Ehrlich and Mitchell [4]; this method uses simple equations and may take in the calculation facing inclination into consideration.

Figure 3 shows different concepts of facing elements. In the RSW structures, facing has a secondary function, and it is used to avoid erosion and localized soil failure near to the face, besides providing suitable visual appearance. Precast concrete block-face is usually used in RSWs with geogrid reinforcements (**Figure 3c**). Precast concrete block-face is also used in the case of RSW with geosynthetic wrap-around facing (**Figure 3a**). This block-facing is applied after the end of the wall construction, and it is needed to protect geosynthetics from degradation due to exposure to ultraviolet rays and vandalism. Depending on its rigidity, the face may be capable to absorb part of the tension that would be supported by the reinforcements. Nevertheless, the design of internal stability is usually done without consideration of the facing contribution to the global stability, if it exists. Note that this approach is by the side of safety [6]. Moreover, enough drainage must be employed in order to guarantee no positive

Figure 3. Typical facing elements: (a) geosynthetic wrap-around facing before protection application (courtesy: Ober geosynthetics); (b) precast-concrete panels (courtesy: Reinforced Earth Company); (c) precast-concrete blocks facing; and (d) steel mesh facing filled with stones (courtesy: Paulo Brugger).

pore-pressures inside the reinforced soil mass. The drainage system is often composed by a vertical layer of gravel behind the face and a horizontal layer at the RSW bottom.

2. The São Jose dos Campos RSW

This section describes and shows monitoring results of an RSW built in the year of 2006, as a part of a road construction in the city of Sao Jose dos Campos, state of Sao Paulo, Brazil [6]. This RSW has 4.2 m height, segmental concrete blocks composing the face, and geogrid as reinforcements and tropical fine-grained lateritic soil as backfill. In the field, the soil compaction was done through a heavy vibratory roller drum Dynapac CA250PD. Other previous studies have also ensured good mechanical behavior of RSWs where fine-grained soil was used as backfill [12–18]. The wall under consideration was extensively instrumented during 2 months (constructive period) to verify its overall performance. The instrumentation consisted of load cells for measurement of the mobilized loads in the reinforcements and block-face, settlement plates, total pressure cells, inclinometers, and topographical marks. The main results obtained are presented and discussed in this chapter. The instrumentation indicates good mechanical performance of the RSW. The wall under analysis has not indicated any structural problems or excessive deformations. In Section 3, some design considerations and comparison of measured load in the reinforcements and predictions are shown.

2.1. Overall characteristics of the Sao Jose dos Campos RWS

In the wall construction, two residual soils were used as backfill, both with high percentage of fines. The yellow sandy clay (soil A) was used from the top of the wall to the 3.2 m depth, and red sandy clay, from 3.2 m depth to the bottom of the wall. In **Table 1**, the grain-size distribution and Atterberg limits (liquid limit, w_L, and plasticity index, PI) of those soils are presented. Using the Unified Soil Classification System, both soils were classified as CL (low-plastic clays).

Those backfill soils were tested in laboratory by means of plane strain tests. The plane strain condition is representative of typical wall behavior where the longitudinal length of the wall is much greater than its height. Under these conditions, it is a reasonable assumption the consideration of the absence of longitudinal deformations. The soil specimens used on tests were compacted statically with the same unit weight (γ) and water content (w) verified in the field. In **Table 2**, the results of those tests are shown; where ϕ is the friction angle of the soil (total stress envelope); c is the cohesion of the soil (total stress envelope); n, k (for loading),

Soil	≤2 μm (%)	≤20 μm (%)	≤2 mm (%)	w_L (%)	PI (%)
A	42	49	99	38	22
B	42	47	99	49	29

Table 1. Soil grain size distribution and Atterberg limits.

http://dx.doi.org/10.5772/intechopen.79239

Soil	γ (kN/m³)	w (%)	ϕ (°)	c (kPa)	n	k	k_u	Rf
A	16.7	20	36	60	0.47	392	588	0.86
B	16.7	20	38	50	0.36	566	849	0.95

Table 2. Results of plane strain tests performed on the backfill soils.

k_u (for unloading), and R_f are hyperbolic parameters obtained from the triaxial tests according to the procedure followed in [19]. In the absence of plane strain or triaxial tests, the values of n and k can be selected using the suggestion from [20]. The value of k_u can be considered as 1.5 k, and R_f equals to 0.90 as typical values.

Two different PET geogrids were used in this RSW as reinforcements. One was placed in the reinforcement layers 1–3 (bottom to top) and the other in the layers 4–7. In **Table 3**, the characteristics of those fabrics are shown. In **Table 4**, the characteristics of blocks used as facing are also presented. The blocks were filled with crushed stones, in order to increase the pullout resistance of the geogrid-blocks interface and guarantee drainage at the face.

2.2. Instrumentation

Figure 4 shows a general view of the wall just after the end of construction. In **Figures 5** and **6**, are shown a cross section and plan view of the wall with the location of the instruments used for monitoring, respectively. The wall has seven layers of reinforcements with 3 m length each. Four of those layers were instrumented, i.e., reinforcement layers 1, 4, 5, and 6 (see **Figure 5**).

Reinforcement layers	1–3	4–7
Ultimate longitudinal tensile strength (kN/m)	55	35
Ultimate transverse tensile strength (kN/m)	30	20
Elongation at rupture (%)	12.5	12.5
Weight (gf/m²)	360	210
Opening size (mm)	20 × 30	20 × 20
Stiffness modulus, J (kN/m) at 5% strain	400	260

Table 3. Physical and mechanical properties of the fabrics (geosynthetic).

Dimensions (m)	0.2 height, 0.40 long, 0.40 wide
Block weight (kgf)	29
Block with*crushed stone (kgf)	40–50
Compressive strength (MPa)	6–12

Table 4. Characteristics of concrete block used as facing.

Figure 4. General view of the RSW just after construction.

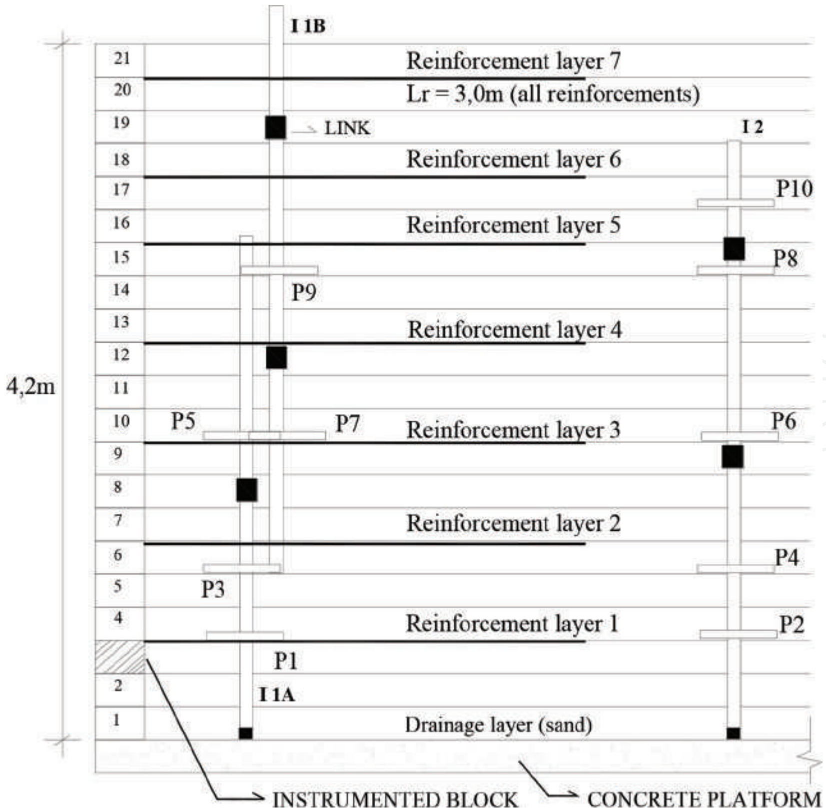

Figure 5. Cross section of instrumented wall: P is settlement plate and I is inclinometer, [6].

http://dx.doi.org/10.5772/intechopen.79239

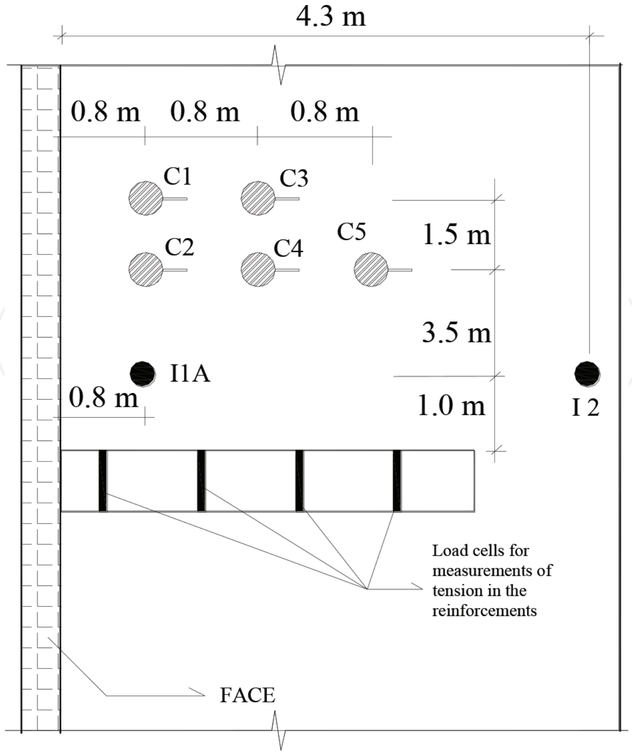

Figure 6. Location of the instruments in the first layer of reinforcement at 3.6 m depth, [6].

Inclinometers (I1A, I1B, and I2) and magnetic settlement plates (P1–P10) were used to measure lateral and vertical movements, respectively.

Topographical measurements were used for monitoring external horizontal displacements at face (topographic marks were located between the blocks 5 and 6 and between the blocks 13 and 14).

Figure 5 also indicates that the wall foundation is composed by a piled slab (concrete platform), due to the presence of soft soil beneath it. **Figure 6** shows the position of the inclinometers (I1A and I2), the load cells used for monitor the reinforcement load, and the total stress cells (C1–C5), located in the first layer of reinforcement at 3.6 m depth. Four load cells were positioned along the reinforcement (see **Figure 7**).

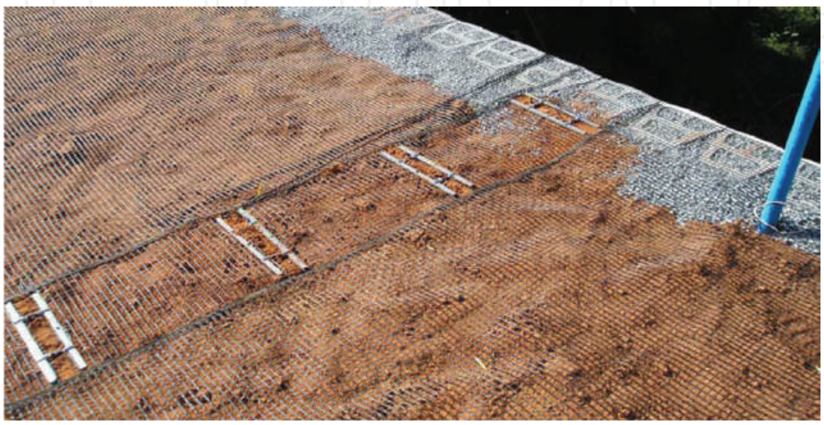

Figure 7. Load cells positioned along the reinforcement [21].

A special device was used for monitoring vertical and horizontal forces at the toe of the bock-face. A bipartite metallic block replaced one of the concrete-blocks that compose the facing (**Figure 8**). Six load cells were used inside this metallic block, four for vertical and two for horizontal load measurement.

Additional details of the instruments used for monitor load in the reinforcements (geogrid) and at the block-face could be found in [21].

2.3. Monitoring results

2.3.1. Tension on reinforcements

Figure 9 shows measured loads in the reinforcement layers at the end of construction (layers 1, 4, 5, and 6, see **Figure 5**). The maximum load recorded was verified in the reinforcement layer 5, and was equal to 7.1 kN/m. Note that the ultimate strength of the geogrid used at the layer 5 was equal to 35 kN/m (**Table 3**). At this layer, the point of maximum tensile load (T_{max}) in the reinforcement at this layer was located 1 m far from face. Notice that considering all layers, the position of the T_{max} does not exhibit a well-defined pattern with respect to the distance from face. This random behavior may be related to the difference of placement of the geogrid and the backfill compaction layers in the field.

2.3.2. Loads at the toe of the wall facing

In **Figure 10**, are shown vertical and horizontal loads measured in the instrumented block located at the toe of the block-face during wall construction. The instrumented metallic block is located in the third block-layer and is monitored by six load cells (see **Figures 5** and **8**).

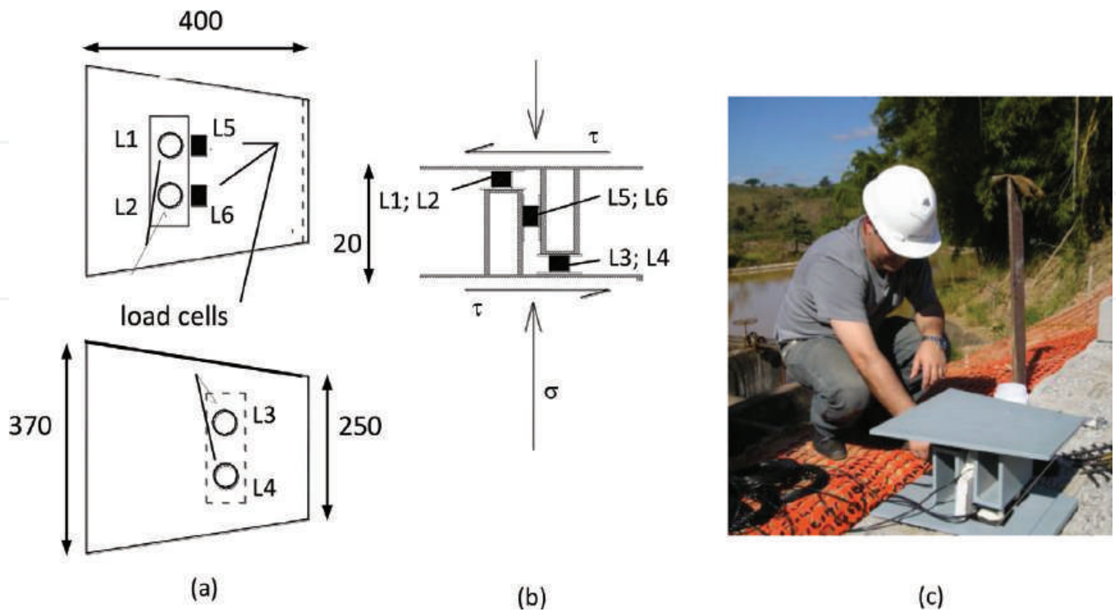

Figure 8. The metallic block used to measure load next to the toe of block-facing: (a) plan view, (b) section view, and (c) block positioned in the field; dimensions in millimeters [6].

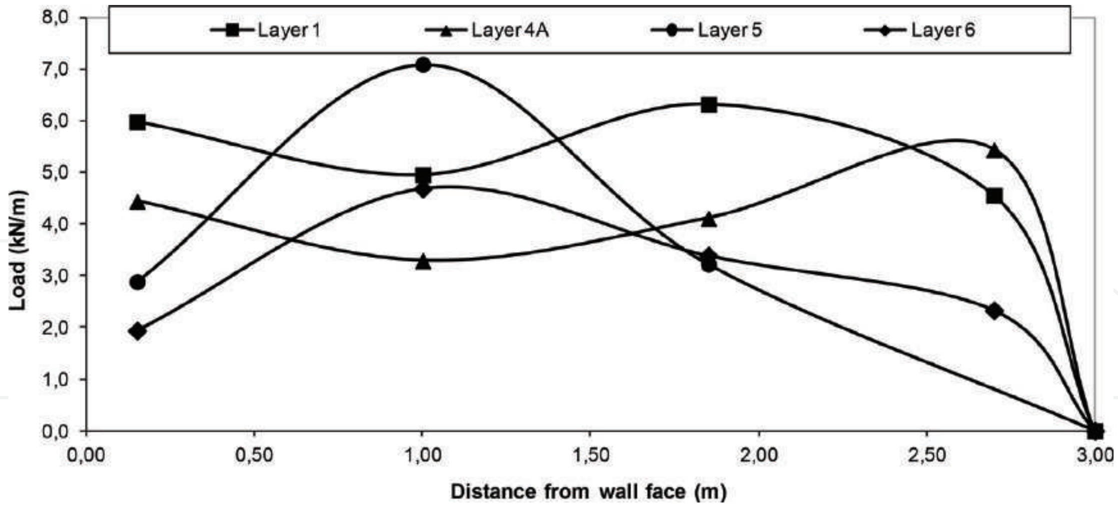

Figure 9. Load in reinforcements measured at the end of construction [6].

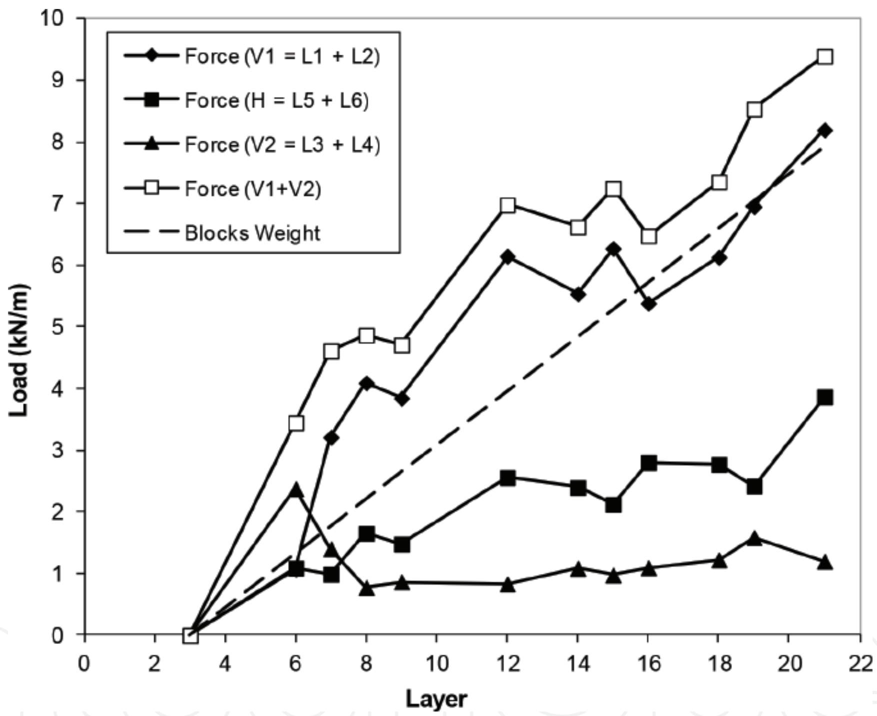

Figure 10. Vertical and horizontal loads measured in the instrumented block during the wall construction [6].

The front (L1 and L2) and rear (L3 and L4) load cells measure the vertical loads acting in the front (V1) and rear (V2) of the block. The load cells (L5 and L6) measured the horizontal load (H) acting in the block. Note that, in **Figure 10**, the front vertical load (V1 = L1 + L2) is often higher that the rear vertical load (V2 = L3 + L4). This behavior is related to the eccentricity of the resultant load due to the self-weight and lateral earth pressure at the interface with the reinforced soil mass that led to an overturn tendency at the block-facing. The dashed line represents the self-weight of the blocks filled with crushed stone, assuming vertical arrangement of the blocks. Notice that the total measured vertical load (V1 + V2) was always higher than the self-weight of the blocks; this increase of vertical load is due to the mobilized friction at the interface of the block-face and backfill. The measured horizontal load at the toe block-face (H) is related to the restrain to the lateral movement at base of the blocks (fix-base condition), as discussed in [22]. Note that in the RSW under analysis, the first block-layer is tied to the concrete slab (see **Figure 2**). At free-base condition, no mobilization of horizontal load at the block-facing would be expected [22–24].

2.3.3. Vertical stresses at the bottom of the wall

Figure 11 presents the vertical stress measured by total stress cells (C2–C5, see **Figure 6**) and calculated values using the Meyerhof approach [25] for the first layer of reinforcement (3.6 m depth) at the end of construction. The Meyerhof approach [25] accounts for the eccentricity of the resultant due to the self-weight and the earth pressure exerted by the nonreinforced zone in the wall. The vertical stress provided by Meyerhof [25] is slightly higher than the vertical stress due the self-weight of backfill without any external load. This behavior is due the earth pressure caused by soil behind the reinforced zone. The study carried out by Riccio et al. [6] presents a more deep discussion about this behavior.

2.3.4. Horizontal displacements

Figure 12 shows the horizontal displacements measured at the end of wall construction by means of inclinometers (I1A, I1B, and I2; **Figure 5**) and by topographic readings at the end of construction. Significant movements were measured in I1A e I1B near to the face (~60 mm). Topographic readings in the facing at heights of 1.60 and 2.60 m unveil lateral displacements equal to 4 and 22 mm, respectively. The ratio of the lateral displacement in the face and the height of the wall was equal to 1.5%. Moreover, the lateral displacements measured in I2 (nonreinforced zone) were negligible (<2 mm).

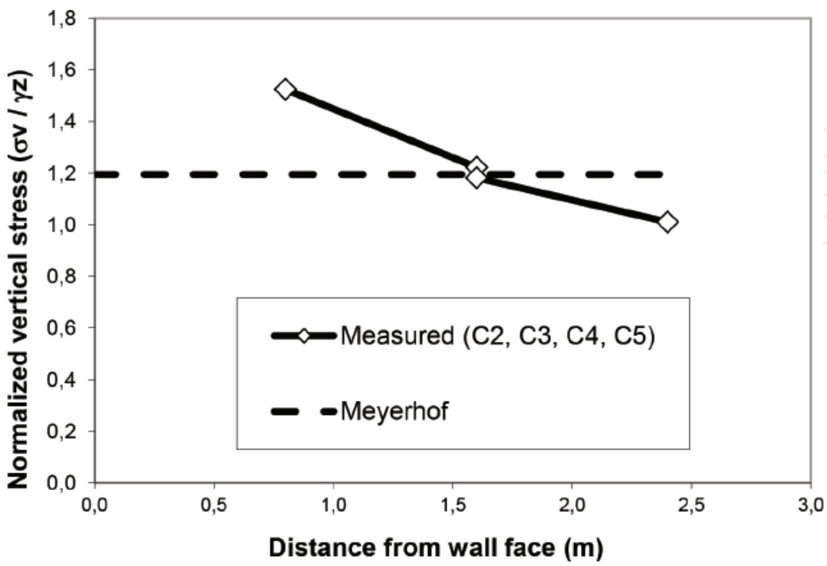

Figure 11. Measured and calculated vertical stress at the base of the wall at the end of construction (third layer).

http://dx.doi.org/10.5772/intechopen.79239

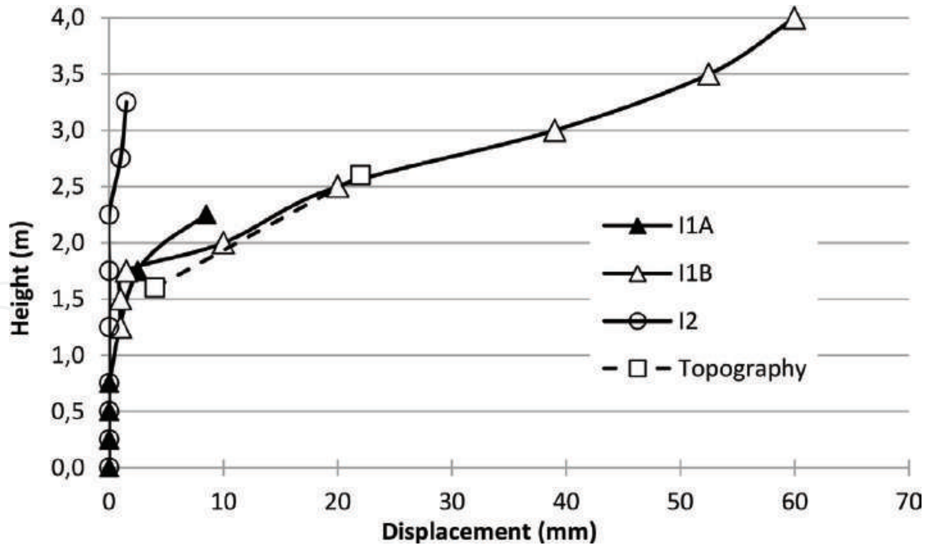

Figure 12. Lateral displacements measured by inclinometers and topographic readings at the end of construction.

2.3.5. Vertical displacements

Vertical displacements were measured during and at the end of construction using magnetic settlement plates (P1–P10; see **Figure 5**). Those plates were positioned both in the reinforced zone and the nonreinforced zone. **Figure 13** presents the vertical displacements at the end of construction; the maximum vertical displacement was equal to 18 mm, recorded by the settlement plate P6. Some plates record values equal to zero or less than 2 mm (P4, P7, P8, and P10). Due to the heavy backfill compaction, most of the vertical displacements have occurred during the wall construction. The heavy compaction induces a kind of a preloading of the soil, and it becomes stiffer, preventing additional vertical deformations during the wall service life [11].

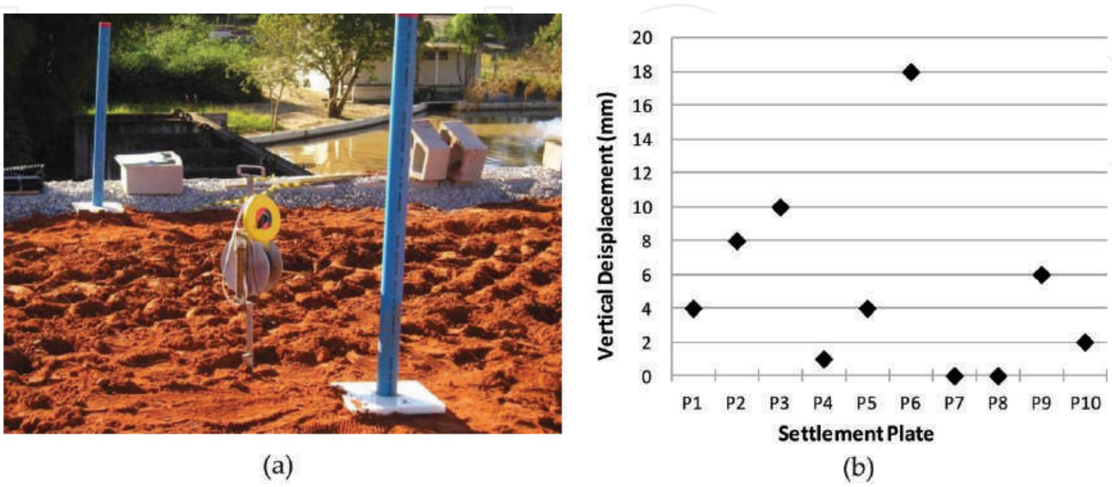

Figure 13. Magnetic settlement plates: (a) view in the field; (b) results at the end of construction.

3. Comparison of measurements and prediction of tension in reinforcements

The basic concept of internal design includes analysis of failure of reinforcement, i.e., it is to verify if the maximum calculated load in the reinforcement (T_{max}) using appropriated method is lower than the design load of the selected reinforcement (T_d). In addition, verification against pullout failure must be done. The design should provide enough length of the reinforcement in the resistance zone (beyond the potential failure surface) to avoid pullout failure. The design strength T_d is estimated at the end of a given reference time (service life) for a particular installation environment and damage that may occur during installation. T_d can be determined by Eq. (1). In this equation, the terms f_f, f_d, and f_a are reduction factors that are dependent of the type of fabric, the service life, the particular installation environment, and damage that may occur during installation.

$$T_d = \frac{T_{ult}}{f_f \cdot f_d \cdot f_a} \tag{1}$$

where

T_{ult} = ultimate tensile strength, i.e., tensile resistance in short-term resistance obtained from the wide-width tensile strength test (the nominal resistance of the geosynthetic);

f_f = creep reduction factor;

f_d = mechanical damage reduction factor;

f_a = reduction factor for chemical and environmental damages.

Table 5 shows the values of T_d and the reduction factors for the installation conditions and geogrids used in the presented wall (see **Table 3**). The reduction values were evaluated considering that: PET geogrid was used as reinforcement; the design service life is 120 years; the pH of residual lateritic soils is around 5 (installation environment); and low damage during geogrid installation (0.30-m thick backfill layers of fine-grained soil and roller drum Dynapac CA250PD). Moreover, in all reinforcement layers, the values of T_d must be higher than T_{max} considering an appropriated factor of safety (FS ≥ 1.5).

Figure 14 shows comparison of measured and calculated load in reinforcements. The determination of maximum load in the reinforcement layers was done using the analytical method presented by Ehrlich and Mitchell [4]. Through this method, backfill shear resistance,

Geogrid	**T_{ult} (kN/m)**	**f_f**	**f_d**	**f_a**	**T_d (kN/m)**
1–3	55	1.67	1.05	1.1	28.5
4–7	35	1.67	1.05	1.1	18.1

Table 5. Reduction factors, T_{ult} and T_d values for the fabrics (geogrids) used in the design of the wall.

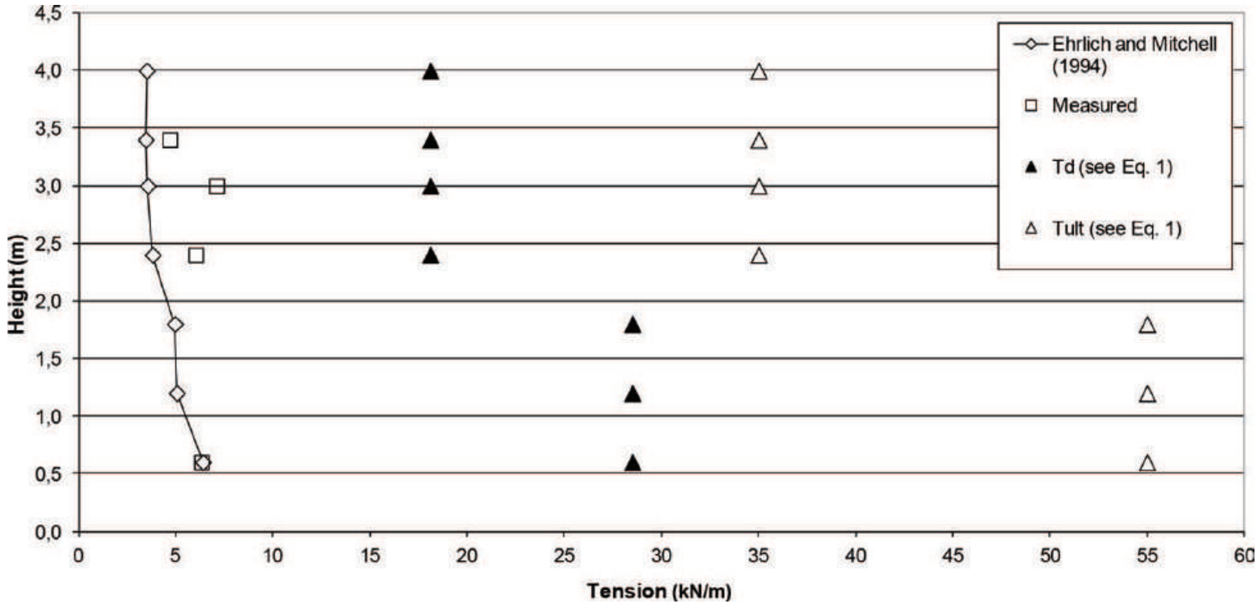

Figure 14. Comparison of T_d and T_{max} measurements and predictions.

reinforcement, and soil stiffness properties are considered, and the backfill compaction stresses are taken explicitly into account. The induced stress due to compaction has the effect of increasing the tension in the reinforcements and the soil cohesion reduced it. In the calculation, the nonconsideration of those factors may lead to poor prediction capability of the real behavior found in the field.

Figure 14 presents that measurements and calculated values of maximum load in the reinforcement (T_{max}) are smaller than T_d. These results also indicate that the predicted values are close to the measured ones, attesting the good performance of the method that was used in the analysis. Additional discussion about measurements and prediction, including determined results using other methods found in the literature, is present in [6].

4. Conclusions

The mechanical behavior of reinforced soil wall built with fabrics (geogrids) is presented based on results of a well-instrumented wall. In this concrete-block-face reinforced wall, tropical fine-grained soils were used as backfill, and two type of fabrics were used as reinforcement. This wall was constructed in 2006 and presents good performance without any structural problem or excessive deformation until nowadays.

Measurements and calculated values of tensions in the reinforcements using an analytical method [4] were compared. Good prediction capability of the used method was verified. In accordance to the good performance of the wall, measurements indicate low vertical and lateral movements, and the mobilized load in the reinforcements was lower than the design load. Measurements also indicate that the block-face supported part of the load that would be carried by the reinforcements.

The fabrics used in the construction were capable to resist the efforts imposed by the structure. The measured mobilized tensions on fabrics (T_{max}) were lower than the design strength (T_d). Considering that T_d is the maximum tension that can act on fabric (T_d is a portion of T_{ult}), it is observed that the wall has safety in terms of internal stability.

Acknowledgements

The authors would like to thank the Brazilian Research Council (CNPq) and HUESKER Synthetics for the support for this work.

Author details

Mario Riccio[1]* and Mauricio Ehrlich[2]

*Address all correspondence to: mvrf1000@gmail.com

1 PEC-UFJF, Federal University of Juiz de Fora, Juiz de Fora, Brazil

2 COPPE-UFRJ, Federal University of Rio de Janeiro, Brazil

References

[1] AASHTO. AASHTO LRFD Bridge Design Specifications. 7th ed. Washington DC; 2014. p. 2150. ISBN: 9781560515920

[2] BSI. BS 8006-1: Code of Practice for Strengthened=Reinforced Soils and Other Fills. London, UK: BSI; 2010

[3] Bathurst RJ, Miyata Y, Nernheim A, Allen AM. Refinement of K-stiffness method for geosynthetic-reinforced soil walls. Geosynthetics International. 2008;**15**(4):269-295. DOI: 10.1680/gein.2008.15.4.269

[4] Ehrlich M, Mitchell JK. Working stress design method for reinforced soil walls. Journal of Geotechnical Engineering, ASCE. 1994;**120**(4):625-645. DOI: 10.1061/(ASCE) 0733-9410(1994)120:4(625)

[5] Ehrlich M, Mirmoradi H. A simplified working stress design method for reinforced soil walls. Géotechnique. 2016;**66**(2):854-863. DOI: 10.1680/jgeot.16.P.010

[6] Riccio M, Ehrlich M, Dias D. Field monitoring and analyses of the response of a block-faced geogrid wall using fine-grained tropical soils. Geotextiles and Geomembranes. 2014;**42**:363-374. DOI: 10.1016/j.geotexmem.2014.01.006

[7] Stuedlein W, Allen T, Holtz R, Christopher B. Assessment of reinforcement strains in very tall mechanically stabilized earth walls. Journal of Geotechnical and Geoenvironmental Engineering, ASCE. 2012;**138**(3):345-456. DOI: 101061/(ASCE)GT.1943-5606.0000586

[8] Mimorardi H, Ehrlich M. Numerical evaluation of the behavior of GRS walls with segmental block facing under working stress conditions. Journal of Geotechnical and Geoenvironmental Engineering. 2015;**141**(3):04014109. DOI: 101061/(ASCE)GT.1943-5606.0001235

[9] Mimorardi H, Ehrlich M. Investigation of the prediction capability of the EM design method under working stress conditions. In: Proceedings of GeoShanghai 2018 International Conference: Geoenvironment and Geohazard. GSIC 2018; Springer, Singapore. pp. 527-536

[10] Ehrlich M, Mimoradi H, Saramago R. Evaluation of the effect of compaction on the behavior of geosynthetic-reinforced soil walls. Geotextiles and Geomembranes. 2012;**34**: 108-115. DOI: 101016/j.geotexmem.2012.05.005

[11] Ehrlich M, Mitchell JK. Working stress design method for reinforced soil walls- clousure. Journal of Geotechnical Engineering, ASCE. 1995;**121**(11):818-821

[12] Mirmoradi SH, Ehrlich M. Modeling of the compaction-induced stress on reinforced soil walls. Geotextiles and Geomembranes. 2015;**43**(1):82-88. DOI: 10.1016/j.geotexmem.2014.11.001

[13] Carvalho PA, Wolle CM, Pedrosa JABA. Reinforced soil embankment using geotextile, an alternative for geotechnical engineering. In: Proceedings from 8th Brazilian Conference on Soil Mechanics and Foundation Engineering; Porto Alegre, Brazil; 1986. pp. 168-178, (in Portuguese)

[14] Ehrlich M, Vianna AJD, Fusaro F. Performance behavior of a geotextile reinforced soil wall. In: Proceedings from 10th Brazilian Conference on Soil Mechanics and Foundation Engineering; Foz do Iguaçu, Brazil; 1994. p. 819e824 (in Portuguese)

[15] Bruno AC, Ehrlich M. Performance of a geotextile reinforced soil wall. In: Proceedings from 2nd Pan-American Symposium on Landslides; Rio de Janeiro, Brazil; 1997. pp. 665-670

[16] Ehrlich M, Delma V, Carvalho P. Performance of two reinforced soil slopes. In: Recent Developments in Soil and Pavement Mechanics. Balkema; 1997. pp. 415-420

[17] Benjamin CVS, Bueno BS, Zornberg JG. Field monitoring evaluation of geotextile-reinforced soil-retaining walls. Geosynthetics International. 2007;**14**(2):100-118. DOI: 10.1680/gein.2007.14.2.100

[18] Brugger PJ, Schmidt CF, Hemsi PS. High height GRW with green wrapped facing. In: Proceedings from REGEO/Geossintéticos; Belo Horizonte, Brazil: CD-ROM (in Portuguese); 2011

[19] Duncan JM, Byrne P, Wong KS. Strength, Stress-Strain and Bulk Modulus Parameters for Finite Element Analyses of Stresses and Movements in Soil Masses. California, USA: University of California, Berkeley; 1980; Report UCB/GT/80-01

[20] Ehrlich M, Becker LB. Reinforced Soil Walls and Slopes, Design and Construction. 1st ed. Boca Raton: CRC Press; 2009. p. 126

[21] Riccio MVF, Ehrlich M. Monitoring of a geogrid reinforced soil wall with segmental block facing. In: Proceedings from Proc. GeoAmericas; Lima, Peru.CD-ROM; 2012

[22] Mirmoradi SH, Ehrlich M. Evaluation of the combined effect of toe resistance and face inclination on the behavior of GRS walls. Geotextiles and Geomembranes. 2016;**44**(3):287-294. DOI: 10.1016/j.geotexmem.2015.12.003

[23] Leshchinsky D, Vahedifard F. Impact of toe resistance in reinforced masonry block walls: Design dilemma. Journal of Geotechnical and Geoenvironmental Engineering, ASCE. 2012;**137**(2):236-240. DOI: 10.1061/(ASCE)GT.1943-5606.0000579

[24] Ehrlich M, Mirmoradi SH. Evaluation of the effects of facing stiffness and toe resistance on the behavior of GRS walls. Geotextiles and Geomembranes. 2013;**40**:28-36. DOI: 10.1016/jgeotexmem.2013.07.012

[25] Meyerhof GG. The bearing capacity of foundations under eccentric and inclined loads. In: Proceedings from 3rd International Conference on Soil Mechanics and Foundation Engineering; Zurich, Switzerland; 1955. pp. 440-445