GEO12-FW-081 - Design and Construction Aspects of a Geocomposite Drainage System in a Dam

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ABSTRACT
The drainage system of a dam depends mainly of the available granular material founded near the dam site and it's quantities. In some cases, the use of natural granular materials can reach an impracticable cost considering the transportation and the required quality of the material. Geosynthetic materials and, in particular, drainage geocomposites offers constructive alternatives to traditional solutions on internal drainage systems. This paper discusses the design and construction of a geosynthetics system, and presents a case in which a traditional granular material drainage system was successfully replaced by a geocomposite drainage system.

1. INTRODUCTION

In some regions of Brazil, the use of natural granular materials in internal drainage systems for dams can reach an impracticable cost considering the transportation and the required quality of the material. An alternative system based on geocomposite is being used in an earth dam for hydroelectric generation, located in the center-western region of Brazil.

The system is composed of a filtration geotextile on both sides of a geonet and was conceived to provide a reduced material cost and installation time over the conventional system. Although geosynthetics have been increasingly used in geotechnical engineering works, concerns still persist regarding their utilization in major works, such as embankment dams, mainly because of the possible consequences of the failure of this kind of construction

This paper discusses the design, construction and performance of the geosynthetic system, and presents this case in which a traditional granular material drainage system was successfully replaced by a geocomposite drainage system.

2. PROJECT PRESENTATION

The dam in which the geocomposite was used is part of a small scale hydroelectricity generation project called "PCH Pontal do Prata" located in the center-western region of Brazil. The site of the power plant was first identified in the 2001 feasibility studies of the Apore river basin that identified the total potential for hydroelectric generation on the Rio da Prata, on the southwest region of the Goias state. The power plant is designed to generate 14,2MW from a 34m fall with a medium intake flow of 36 m³/s.

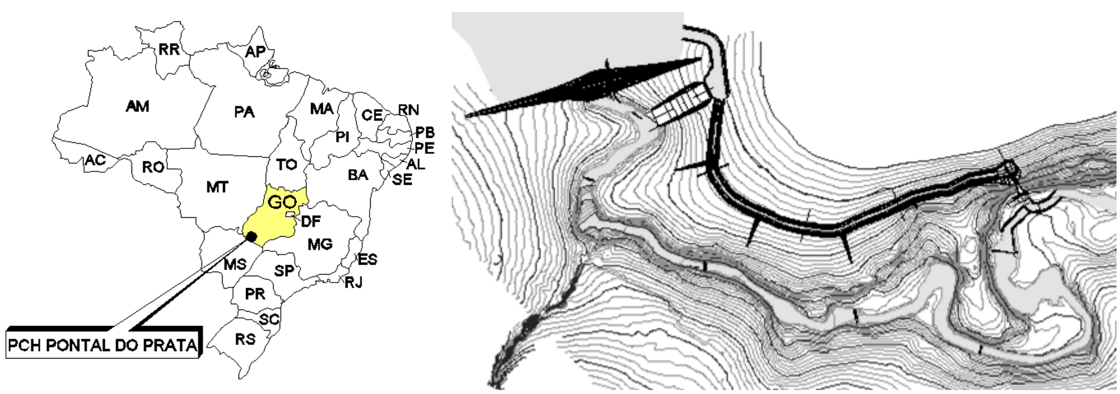

Figure 1- General Layout of the PCH PontaldoPrata.

Composing the general layout of the power plant there is a dam to elevate the water level and consequently the water fall to the hydroelectric generation purposes. The dam has a 762 m long and 6 m wide crest on the 638.5 m level, and a maximum height of 18 m. It was originally conceived as a homogeneous embankment with both vertical and horizontal internal drainage systems. On the left side of the dam there is an intake canal that leads the water flow 1.200 m downstream, where it will be directed to the turbines by two pen stocks and then redirect back to the original riverbed.

For the internal drainage systems of the dam the original idea was the usual drain composed from natural granular materials, however this paper will show how this solution was unconceivable and how it was successfully replaced by a geocomposite.

3. BASE PROJECT STUDIES – DRAINAGE SYSTEMS

During studies for the design of the internal drainage systems it was necessary to understand how the seepage would proceed inside the embankment. For this purpose there were performed finite element analyses to determine the position of the phreatic line as well as its flow rate. After knowing the flow rate, the design alternatives could be completely evaluated in terms of drainage capacity and filter conditions required for the drainage systems.

The simulation results indicated a total flow of about $4.8.10^{-6}$ cubic meter per second per meter of length of the dam. This result multiplied by the 762 m long crest resulted in a total flow of about 3.6 liter per second. The gradient flow was mostly concentrated on the base of the cut-off, nevertheless its results were not considerable critic for the clayed material of the embankment.

3.1 TRADITIONAL OPTION – GRANULAR MATERIAL DRAINAGE SYSTEM

The objective of filters and drains used as seepage control measures for embankments is to efficiently control the movement of water within and about the embankment. In order to meet this objective, filters and drains must, for the project life and with minimum maintenance, retain the protected materials, allow relatively free movement of water, and have sufficient discharge capacity to lead the total flow to a specific point, normally a flow meter on the base of the downstream slope. For design, these three necessities are termed piping or stability requirement, permeability requirement, and discharge capacity.

3.1.1 DESIGN OF THE GRANULAR DRAIN

Vertical and horizontal drains must have sufficient discharge capacities to remove seepage quickly without inducing high seepage forces or hydrostatic pressures. So, the design flow was obtained over the calculated flow within a factor of safety of 10, in order to take in account the natural variability of the permeability coefficient of natural materials. The required minimum thickness of the drainage layer was calculated through an expression obtained from the Darcy's law.

The first option was to use sand as the only material composing the drain, but the permeability of the available sand leaded to a 3,4m thickness drainage layer. This sand founded near the dam site was very fine and uniform and could not even reach the piping criteria to be placed aside by a fine gravel layer. Another complication was that, despite the amount of rock from obligatory excavations, the rock crusher equipment was not able to produce enough gravel for both concrete and drainage system. In this scenario the decision was that the drainage material either would have to be completely bought from a supplier whose sand attended the required needs or the fine and uniform sand that was available would have to be used considering the consequences that would have to foreseen because of the piping criteria not being satisfied.

Considering these conditions, an option to the previous idea was to use screened fine gravel, which has a higher permeability, placed and compacted to conduct seepage water through the horizontal drain. The 50 cm thick screened fine gravel would be protected top and bottom with a 30 cm-thick clean washed sand filter that would have to be bought from an external supplier considering again that the available one could not satisfy the piping criteria. As the dam is 762 m long, the cost of the drain material was impracticable.

So stringers or finger drains were designed to be used as an alternative to a continuous horizontal drain. The cross-sectional area of the stringer drains was sufficient to satisfy the discharge requirements. Although the necessary volume of granular material was relatively smaller, the region near the dam site was also unable to offer the required sand and the closest extraction area available was at least 440 km far away, resulting in a very high transport cost. Table 1 presents the comparison of costs of the different drainage system solutions.

Table 1 – Traditional solution's cost.

Drain's Solution	Material	Volume (m³)	R$/m³	Distance (km)	R$/km.m³	Material Total Cost	Solution's Total Cost
Continuous	Fine Sand	44.200	13	-	-	R$ 574,600.00	R$ 574,600.00
Continuous multi- layer	Sand	7.800	25	442	0.14	R$ 677,664.00	R$ 1,283,464.00
	Fine gravel	6.500	38	240	0.23	R$ 605,800.00	
Stringer	Sand	3.623	25	442	0.14	R$ 314,766.24	R$ 578,988.24
	Fine gravel	2.835	38	240	0.23	R$ 264,222.00	

OBS: By the time of the estimate the American Dollar (USD) was quoted as 1.8 Brazilian Real (BRL).

3.2 PROPOSED OPTION – GEOSYNTHETIC DRAIN

Considering that, unlike natural materials that have to be found near a dam site in suitable quantities and with acceptable qualities, geosynthetics can be selected or manufactured to meet a given set of specifications and then transported easily to the construction site, the designers explored possible solution with geosynthetic products.

Among the many geocomposite types, a probable solution was found, this solution is described by its manufacturer as it follows: "Sheet drains for double sided drainage applications are prefabricated products that consist of a perforated and formed, three dimensional core covered with a geotextile filter fabric bonded to both sides. The filter fabric is securely bonded to prevent soil intrusion into the core flow channel while allowing water to freely enter the drainage channel. Sheet drains with perforated cores are designed to allow water entry from both sides and are typically used to collect and re-direct water from a site or structure. Sheet drains are designed for use in both vertical and horizontal drainage applications. Designed to provide full drainage for large surface areas, sheet drains are constructed to various strength, flow and soil filtration requirements for a wide range of construction applications."

Although the described performance of the geocomposite was exactly what the designers needed, there was performed a bibliographic search in order to examine any previous application of this solution on dam's. Some examples were found, but none of them used this solution as the main drainage system of the dam, several cases presented rehabilitation projects on which the geocomposite was used as an inverse filter.

Geosynthetics have been extensively used in drainage and filtration systems in geotechnical works but it would be an innovative solution for a very critical part of the dam, and considering that the failure of the drainage system in these structures can result in serious stability problems, the designers contacted consulters advices as well as the manufacture's technical engineers to confirm the applicability of this solution to the considered project.

The selection and design criteria for this category of products are generally simple. However, because of the numerous possible applications for subsurface drainage systems and varying performance parameters, designers must pay careful attention to the product-performance parameters applicable to a particular subsurface drainage application.

To obtain approval by the designers, the drainage capability had to be validated by the manufacturer's laboratory under the predicted conditions that were expected for the geocomposite that would be used in the dam.

3.2.1 GEODRAIN REQUIREMENTS

High confining pressures decrease the hydraulic conductivity of fine grained soils, increasing the potential for the soil to intrude into, or through, the geotextile filter. For all soil conditions, high confining pressures increase the potential for the geotextile and soil mass to intrude the flow paths. This can reduce flow capacity within the drainage media.

Although the maximum height of the dam was 18m, the confining pressure due to soil weight should be simulated. So, transmissibility experiments were executed by the geocomposite manufacturer, to assure the product applicability in the presented project under the predicted conditions that were expected for the geocomposite and according to the following standards:

ISO 12958 - Geotextiles and geotextile-related products - Determination of water flow capacity in their plane.
ASTM D 4716 - Test Method for Determining the (in-plane) Flow Rate per Unit Width and Hydraulic Transmissibility of a Geosynthetic Using a Constant Head
ABNT NBR 15225 - Geossintético - Determinação da capacidade de fluxo no plano

The test was performer under a confining stress of 255 kPa and with a hydraulic gradient of 0.01. The flow measurements resulted on a medium flow capacity of $3,2 \cdot 10^{-2}$ l/s.

The next step in the design process was to define the design flow capacity, which is obtained by dividing the flow capacity informed by the manufacturer by appropriate reduction factors. ABINT – 2204 suggests that the overall drainage factor of safety should be applied to take into account possible uncertainties in the selection and determination of the design parameters, as well as for chemical clogging and creep for long term behavior.

The FSD applied over the $3.2.10^{-2}$ l/s results in a design flow of $1.9.10^{-2}$ l/s. Therefore, if an integral drainage layer is considered, the necessary discharge capacity over the available capacity would result in a very high factor of safety on the abutment region. So, the final layout solution was designed considering the flow on four divided sections. The number of geocomposite strips was defined by the minimum necessary spacing to assure the drainage of the required flow in each section.

3.2.2 GEOTEXTILE REQUIREMENTS

The filter fabric that prevents the intrusion of soil particles into the drainage core should also be designed. In order to minimize the clogging process, the designers decided that the geocomposite would be protected top and bottom with a 10 cm-thick fine and uniform sand filter, so that the geotextile would not be in direct contact with the compacted clay.

PERMEABILITY CRITERIA

The requirement of geotextile permeability can be affected by the filter application, flow conditions and soil type. The minimum allowable permeability was pre-determined and compared with the calculated permeability from the permissibility test procedure (ASTM D 4491). This value was available from manufacturer's literature.

RETENTION CRITERIA (CFGG)

The last step in determining soil retention requirements is to evaluate the maximum allowable opening size (O95) of the geotextile, which will provide adequate soil retention. The O95 is also known as the geotextile's Apparent Opening Size (AOS) and is determined from test procedure ASTM D 4751. The CFGG criteria states the expression, where C is determined from table 5 and d_{85} is the diameter bellow which are 85% of the soil particles:

Table 2 - Retention criteria (CFGG).

C1	C2	C3	C4
Granulometric Curve	Soil Influence	Hydraulic Gradient	Function
Uniform	Dense and Confined	i < 5	Filter
0,8	1,25	1	1
$O_f \leq C \times d_{85} = 1 \times 0.35 = 0.35$			

Therefore the geotextile must have an AOS smaller then 0,35 mm. According to the geocomposite specifications the AOS of the geotextile was 14 mm, attending the design needs.

3.2.3 GEOCOMPOSITE DESIGN

The geocomposite from which the drainage capability was validated by the manufacturer laboratory is composed of 7 mm thick geonet core protected top and bottom with two thermofixed polyester nonwoven geotextiles with approximately 100 g/m^2 each. The design was based on the geocomposite laboratory measured drainage capability and the flow results from the finite element method analysis with the appropriate factors of safety. With this data from the four selected regions of the dam a set of four types of geocomposite spacing was designed.

The design defined a central region with a integral layer, with zero spacing between two sets of 2 m wide geocomposite, and three subsequent regions with increasing spacing. The longitudinal layer of geocomposite, that helped redirect the vertical drain flow to the spines of transversal geocomposite, was the same as the cross-section geocomposites, considering that the flow capacity of this geosynthetic is the same for both cross-section and longitudinal directions. The drainage final design is shown in Figure 2.

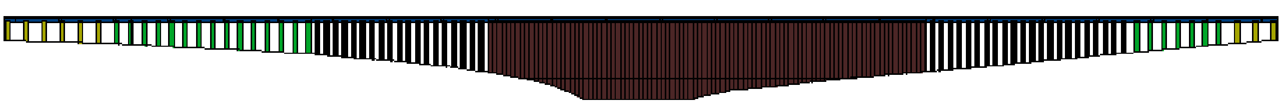

Figure 2 – Geocomposite Design.

After verifying the design safety, including other design requirements by current methods, the design conception was approved by experienced consultants and the appropriate factors of safety were applied. The final decision would be based on the total cost of the solution compared with the traditional alternatives previously presented. The solution cost included the geocomposite rolls, as their transportation was included in the unit cost, and the fine and uniform sand available in the dam site that would protect the geocomposite. The values are described on Table 3.

Table 3 – Stringer Geocomposite + 10cm of sand

Material	Amount	R$/unit	Material Total Cost	Solution's Total Cost
Sand	2.600 m³	13,0	R$ 33.800,00	R$ 148.500,00
Geocomposite	9.250 m²	12,4	R$ 114.700,00	

The geocomposite solution represented 25% of the total cost of the traditional granular solution and was surely chosen as the main drainage system of the dam.

4. EXECUTIVE PROJECT – CONSTRUCTION

This topic was conceived to show some practical construction aspects of this project concerning the geocomposite drain. How some of this aspects should be accounted in terms of working-hours of cutting and sewing to assemble the hole system, how the transportation costs and logistics are extremely advantageous when in comparison with granular drain and why there should be a incisive quality control of this material despite the fact that it's supposedly a homogeneous industrial product.

4.1 EXECUTIVE DETAILMENT

To assure the integrity of the system there was a set of details of how the individual layers should be placed that will be described. The longitudinal layer that is placed right under the dam's crest and bellow the vertical granular drain was set to be composed from aligned individual layers that would be overlapped by 1 m, therefore two layers, that have 25m each would be placed together to form a 49 m line on geocomposite. Considering the width difference between the vertical drain and the geocomposite layer, the 60 cm think vertical drain was placed on the upstream edge of the 2 m wide geocomposite. This is details are shown in Figure 3.

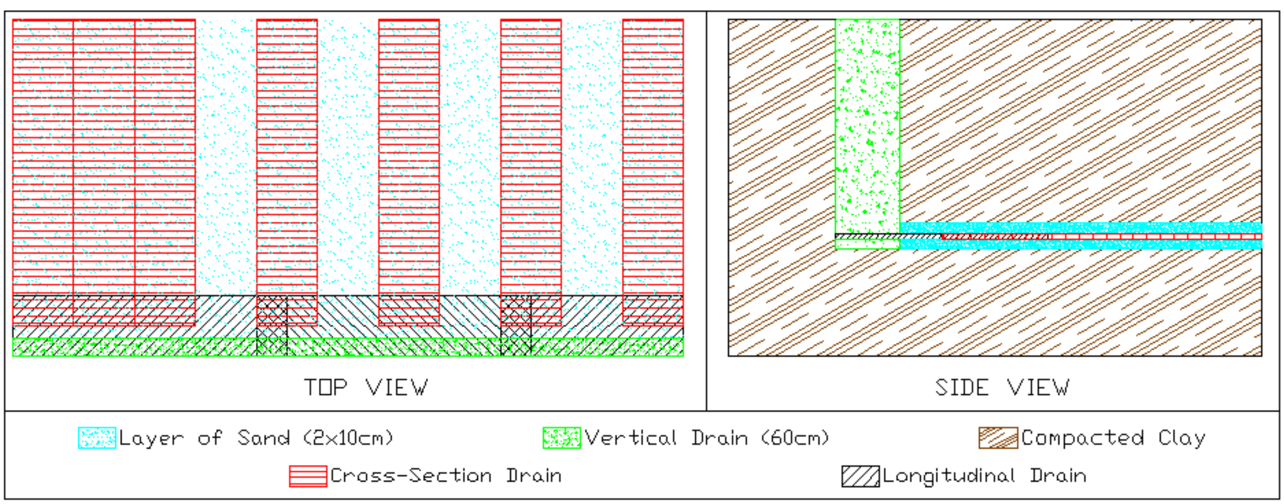

Figure 3 – Design Details.

The cross-section layers were all overlapping the longitudinal layer by 1 m each, therefore each individual layer would stretch 24 m downstream from the downstream edge of the longitudinal geocomposite layer. The cross-section layers that would be side by side where sewed together with the condition that their geonet cores were touching and that the geotextile from both of them was sewed over the connected cores. In the case of the spine drains, where the geocomposite layer was surrounded by sand, the geotextiles over the side were folded over the geonet core and sewed so that the core was always covered and protected from the intrusion of soil particles. This detail is shown in Figure 4.

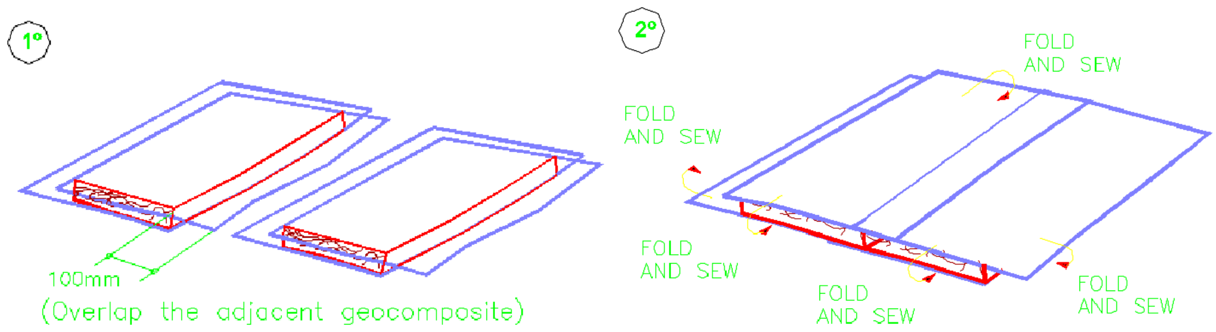

Figure 4–Geocomposite overlapping.

The composite was provided by the manufacturer in rolls of 25 x 2 m. To apply these rolls under the downstream slope it was necessary to set a project of placing this rolls together. The variable dam height that directly determines the slope horizontal projection implies that every line of drainage spine would have a different length, some would be longer and some would be shorter then the 25m long roll. Therefore the decision over how many rolls would be necessary to the project would be a direct result of the optimization of the cutting parts of the longer rolls and how and where this parts could be connected in order to minimize material loss. The detail of how each line of geocomposite has a different length is shown in Figure 5.

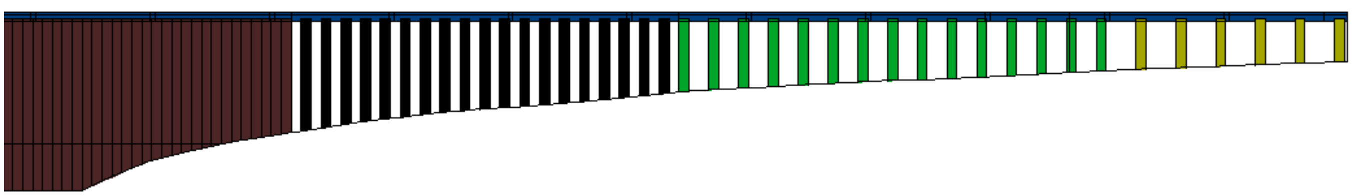

Figure 5–Geocomposite spines.

A system that identified and relocated the cutted pieces was assembled in the form of a table and the set of 168 spines was assembled with 185rolls of 25m, what means a loss of only 1,2 m what represents of 0,4% of the amount of geocomposite that was used in the drainage system.

4.2 INSTRUMENT’S INSTALLATION

As any regular embankment dam there should be instruments to monitor the actual behavior of the structure over the years of operation. The possibility to monitor pore water pressures within the embankment can be obtained with relatively simple instruments, in this project this was done with an open tube piezometer. This instrument consists basically of a plastic tube placed within the embankment. Part of this tube should be able to set an equilibrium of pore water pressure with the soil on its surroundings. This is normally obtained through a perforating the tube and setting a filter layer to assure that only the water will go through these holes. These systems can be installed before the construction of the embankment or after it, in the case of this project the compaction procedures considering the isolation areas of these instruments would implicate in a considerable loss of production, therefore it was decided to install this instruments after the embankment was done.

This postponed installation, however, implies in a more delicate operation in a geocomposite drainage system then in a traditional granular drain. In a regular drain there would be bored a set of boreholes so that the piezometers could be installed, the procedure in a geocomposite system is the same, however, the operation must never drill the borehole until it reaches the geocomposite. The level of the borehole must only reach the layer of sand above the geocomposite. To make this a possible procedure there was performed a complete topographic evaluation of the layer of geocomposite and the layer of sand above so that at any point of the downstream slope were a borehole would be drilled the exact level of the layer of sand and therefore the end of the drilling could be determined.

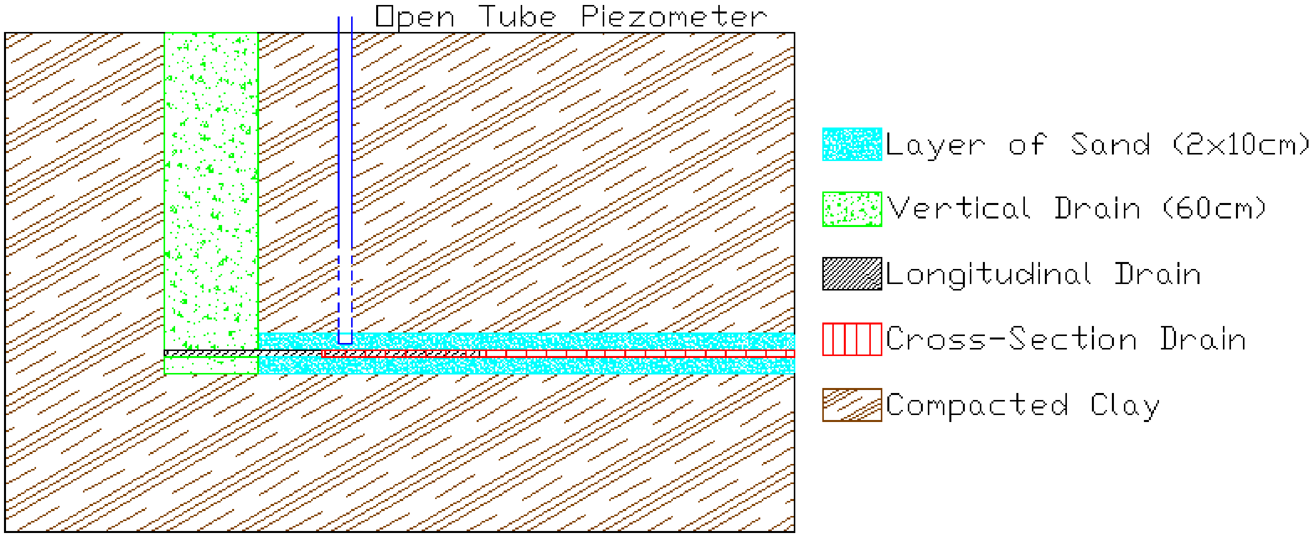

Figure 6 – Piezometer installation.

4.3 GENERAL RECOMMENDATIONS FOR CONSTRUCTION

Considering the lack of experience of the executors regarding constructions operations with geossynthetics, specially considering the importance of this solution on the overall performance of the dam, the geotechnical designers set up a document with a group of rules and procedures for the appropriate procedures when dealing with the geocomposite drain. The most important ones will be listed at next:

The GeoNet core of the geocomposite must never be in direct contact with the soils that is being drained.

The surface where the geocomposite will be applied must be free of piercing objects and very irregular surfaces that could cause damage to the geocomposite. Another factor to be observed at the surface is the slope that will assure the flow direction.

The geosynthetic drainage layer shall not be damaged during placement.

No equipment shall be operated on the top surface of the geosynthetic drainage.

The soil that will directly cover the geotextile must always allow the water flux to reach the geocomposite otherwise the solution's capacity of flow will be limited by the covering soil. Therefore it should be avoided to apply clayed soils in direct contact with the geocomposite because besides it's low permeability the clay particles can clog the geotextile layer, compromising the drainage system.

5. CONSTRUCTION ASPECTS

This topic was conceived to show some practical construction aspects of this project concerning the geocomposite drain. How some of this aspects should be accounted in terms of working-hours of cutting and sewing to assemble the hole system, how the transportation costs and logistics are extremely advantageous when in comparison with granular drain and why there should be a incisive quality control of this material despite the fact that it's supposedly a homogeneous industrial product.

5.1 DELIVERY, STORAGE AND HANDLING

When the traditional solution was considered and designed, 44.200 cubic meters of sand covering the whole downstream projection of the dam, with a layer thickness of 3,4 m. This would be transported, considering 6 m³ trunks, in 1768 trunks full of sand. Considering that the geocomposite solution also involved a 20 cm layer of sand, that sums up to 2600 m³, the difference of sand volume between the two solutions is 41.600 m³ that would count for 1664 trunks of sand.

The geocomposite rolls, the 185 stools of 25 x 2 m, as it's shown in the Figure 7, were all transported in just one trunk, in comparison with the 1.768 trunks of sand that would be necessary in the traditional solution.

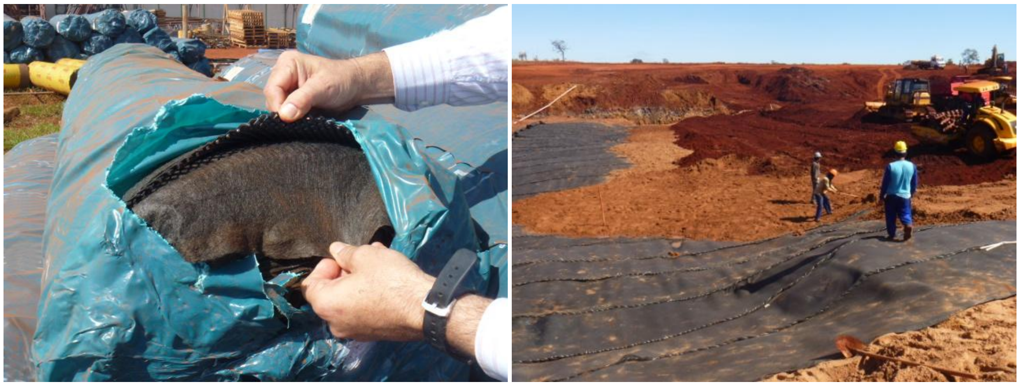

Figure 7–Storage and installation.

As it was described the geocomposite stools were overlapped and sewed together in order to assure the integrity of the drainage layer on the areas of the dam over 10 m of water tablet. On Figure 8 it's also possible to see how this integrity measure assured that even on slope discontinuities of the river bed, the layer would adapt to the topography perfectly and would not separate the two sets of geocomposite.

5.2 INSTALLATION

Prior to placement of the geosynthetic drainage layer, the subgrade shall be smooth and free of all materials which could damage the drainage layer.

The geosynthetic drainage layer shall not be damaged during placement. Despite the measurements of topographic location of the geocomposites and unrolling it's rolls until the end of the downstream dam slope, the workers also had to sew the stools together, side by side over the transversal direction of the dam and also to connect this transversal layers with the longitudinal layer that was placed under the vertical sand drain to assure a homogeneous distribution of this water flow coming from this chimney filter. On Figure 8 it's possible to see a set of workers sewing the geocomposites together and also a mark of two rolls connected together on the transversal direction, probably on a spot that was under cutting and assembling in order to take the drain further then the 25 m long stool dimension.

Figure 8 – Placement of geocomposite.

As it was described, the geocomposite layer was placed between two 10 cm layers of sand. So after the geocomposites were placed and sewed, a layer of sand should be spread on top of it. Considering the constructions recommendations this was done manually, by works with manual tools as it can be seen in Figure 8. This assured a procedure that was less likely to jeopardize the geocomposite integrity. The works were oriented and monitored to spread without reaching the geocomposite with the tools that were used for this procedure, it was recommended that a set of layer was just pulled over the geocomposite and not scratched over it.

5.3 PRODUCT FAILURES

Despite the design requirements for the geotextile over the geonet, there should also be account some production details. By the standard design a 100g/m² geotextile would attend to all the specified requirements, nevertheless such a sparse web of threads are subjected more easily to production failures as it's shown on Figure 9.

Figure 9 - Product Failures

These failures came as a surprise to the designers when they were reported by the field engineers. However after a field research it was reported by experienced engineers that this is still a common occurrence on geotextiles under 400g/m². So there were two possible approaches on the design phase of the project, the first would be to specify a geotextile of 300 g/m² or more, despite the possibility of less dense geotextiles to attend the design requirements, the second would be to inspect the geotextile as they are applied in the field and reinforce the layer of geotextile on this failure points.

Considering that on this project this problem was not foreseen on the design phase, the only option was to assign a responsible worker to inspect all the geocomposites that were applied on the field, and not just from above but also from below as they were unwound, to check for this failure spots. To repair those spots there were also placed a patch of geotextile over the damaged area to assure that there would not be inflow of sand particles to the draining geonet.

6. CONCLUSION

Overall this project has shown how geosynthetic systems can be appropriately applied in geotechnical constructions, including embankment dams. In this project's specific case the geocomposite solution was 75% cheaper than the natural material solution, considering the acquisition and transportation costs.

The construction procedures were not the same as for the traditional solution, nevertheless they were as simple and practical as the traditional ones, it's also important to account the importance of inspecting the geosynthetic material as they arrive on the construction site as well as when they are placed on site, to be able to identify possible failure spots as described.

Taking the main points into account, a comparative table was assembled, and it's shown in Table 4

Table 4

Advantages	Disadvantages
Transportation	Need to inspection in the case of sparse geotextiles
Cost Saving	Construction with manual labor
Small volume of natural granular material that implies in a lower environmental impact	No consistent previous data of solutions performance as horizontal drainage layer on embankment dams
Less time to assemble the hole system	The solution is still limited on a set of compression stress

More than the consecrated applicability of geosynthetics in several engineering projects, this paper tried to show the importance of thinking and having new ideas in the designer's role. There isn`t a standard project for Dams, their parts and related functions can be evaluated and re-designed according to the project conditions. This ideal vision can help create innovative solutions as well as reducing costs and unnecessary construction procedures on engineering works.

7. ACKNOWLEDGEMENTS

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