Coastal protection with Concrete Block Mattres in “Punta Negra” Dam

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ABSTRACT
The present work describes the main technical aspects related to geosynthetic coastal protection in "Punta Negra" Dam, San Juan, Argentina. Concrete Block Mattress system was placed in the embankment of the new route n°12. Geosynthetic solution appears as an alternative for the traditional rock armour. A polypropylene woven geotextile with loops was used; do to its high tensile strength and good adherence with concrete blocks. Geosynthetics was chosen for several advantages in comparison with traditional methods. It represented a cost effective solution, reducing the environmental impact and the construction period. In this way, geosynthetic coastal protection avoided exploding over 1.000.000m3 of mountain to obtain rocks. This paper describes the design methodology used and the contractor execution method for over 100.000 sqm of coastal protection at a rate of 70 Concrete Block Mattresses per day.

1. INTRODUCTION

The geosynthetic based coastal protection works were part of the construction of two hydroelectric power plants 20 km away on from each other in San Juan River. Each hydroelectric facility took its name from the local name area where it was built: "Los Caracoles" - in km 53 of the Provincial Route N° 12 - and "Punta Negra" - in km 34 of the same road. The main objectives of the project were the water storage to expand the existing irrigation system and the electricity generation.

Punta Negra Dam is a concrete-face rock-fill dam in San Juan River about 28 kilometres (17 mi) west of San Juan City in San Juan Province, Argentina. The purpose of the dam was to provide water for irrigation and hydroelectric power. The 101 metres (331 ft) tall dam supports a 62-megawatt (83,000 hp) power station and together with Los Caracoles Dam upstream, they provide water to irrigate 15,000 hectares (37,000 acres). The dam construction began in 2009 and was finished in August 29, 2015.

This project was complimentary to Los Caracoles dam, a hydroelectric complex developed by Techint E&C and inaugurated in 2009. Between the two of them, a Lakeside road was created in order to promote future touristic undertakings. Additionally, the work done within Punta Negra project will fit out 12,000 new hectares with watering capacity, increase the amount of annual energy production by 300 GWC and allow a better regulation of water volume. The dam is 730 meters long and 120 meters high, while the adduction tunnel has a length of 400 meters. In addition to that, it has an overflow channel without gates with an excess channel in the open air, a machine house with two Francis turbines of 32.5 MW each and a maneuver station of 132 KV connected to the high-tension line that runs between Los Caracoles and San Juan City. The construction took 72 months and employed over 1,350 people, being 90% of them local workers.

550 million dollars were invested for the new hydroelectric plant and it will provide 65 additional megawatts to Argentine´s interconnected power system.

Filling the Punta Negra Dam forced the construction of a new road on the lake’s perimeter to give continuity to the route RP N°12 re-establishing the connection with the “Caracoles” Dam, whose original layout was below the water level of the reservoir.

The 24km road construction included more than 3 million m3 of embankments, 7 new bridges, more than 70 large culverts and almost 100,000 m3 of rock excavation.

Strong winds (such as the Zonda) blowing on the wide water’s mirror created by the dam would generate waves that could damage the embankments’ slopes (up to 40 m height and 1V: 1.5H). For this reason, in the original project was established protecting the slopes with rock armour, which was finally changed to a geosynthetic protection.

2. DESIGN CRITERIA

It was necessary to calculate the impact wave height to design the embankment protection.
These waves are generated by the blowing winds in the reservoir and depends on the wind speed, its duration, fetch, water depth and the lake dimensions.

2.1 Wind speed

Maximun wind speeds values were taken from records between 1989 and 1999 of the station located at the km 47.3 of San Juan river. This wind records were also used to calculate the maximum wave height at Punta Negra reservoir, in order to determine its free board.

2.2 Fetch

The fetch or wave generation lengths were estimated as the embankment intersection lines at the reservoir highest level of 950m, at the most critic zone located between 3+900 to 5+600.

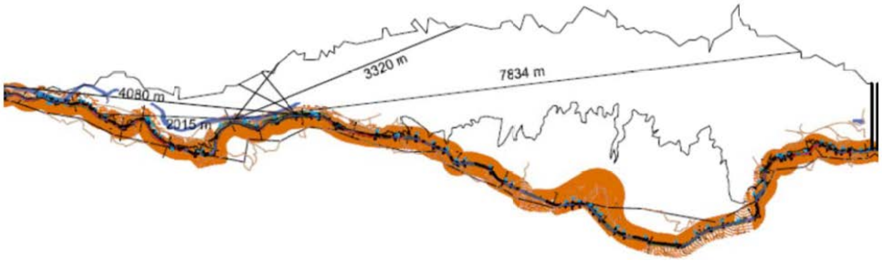


Figure 1. Wave generation lengths.

2.3 Wave Height

Determination of the design wave was made from the JONSWAP method, considering the existing wind data. This calculation is detailed below:

The following results were obtained for the different directions:

Table 1. Wind Data

Direction	Length [m]	Speed reference [m/s]	Significant Wave Height [m]
W-NW	4080	32.2	1.05
E-NE	7834	22.6	1.02
W	2015	32.2	0.41
N-NE	3320	22.6	0.66

Based on this analysis, a 1.05m wave height was adopted as the design load.

2.4 Design values summary

From the foregoing analysis were obtained:

- Wave height Hs = 1.05 m
- Wave period = 3,2 s.

3. ORIGINAL SOLUTION

Hudson mathematical expression was used to calculate the rock weight needed for the embankment protection.

3.1 Hudson equation

Hudson mathematical expression was used to calculate the rock weight needed for the embankment protection.

Rock armour size adopted in next range:

$0,9\ Dc < Dc < 1,1\ Dc$ [1]

Or in weight terms:

$0,75\ Wc < Wc < 1,25\ Wc$ [2]

External rocks layer thickness equals two design diameter, and it is placed over a smaller sub-base rip rap to avoid embankment fine soil material loss.

Weight percentage criteria Internal Rock size where adopted by using the external armour weight percentage criteria:

- Sub-layer: W/10 to W/15
- Core and Filter: W/200 to W/6000

3.2 Results

External protection layer:

- 45cm middle diameter rock size (0,40 m < Dex < 0,50m)
- 2 Diameter thickness layer (equals 0,9m)

Internal protection layer:

- 20cm middle diameter rock size (0,15 m < Din < 0,25m)
- 0.4m thickness layer

Internal filter layer:

- Only if embankment soil particle size is less than 0.01mm
- 5cm middle diameter rock size (0,02 m < Din < 0,08m)
- 0.08m thickness layer

However, the increasing difficulty to obtain enough quantity and quality rocks, also generated a strong environmental impact and at least one year construction´s schedule extension. This motivated the contractor to look for other alternatives to achieve the deadline and presented an efficient performance against the waves, meanwhile reducing environmental impact.

4. GEOSINTHETICS SOLUTION

Waves height and stones size needed for a conventional method protection forced the designer to look for another option and materialize a protection by using concrete blocks mattress.

BetonFlex® is a continuous and flexible protection that consist of a uniform rectangular pattern of square truncated pyramidal concrete blocks, casted into a polypropylene fabric linked together with a network of high-strength polypropylene loops (loop matting).

Figure 2. Concrete block mattress (CBM) in Punta Negra Dam

4.1 Woven geotextile

BetonFlex® concrete block mattress (CBM) was made from a woven geotextile PlusTex® T 80/60 HLT SCL, wich has 80 kN of longitudinal resistance (MD: machine direction), especially manufactured with additives to provide UV radiation and thermo-oxidation long term protection, improving its durability. The fabric has more than 2500 small circle loops per sqm that guarantee the anchoring of the concrete blocks.

Woven geotextile was especially produced with high molecular weight HALS (Hindered Amine Light Stabilizers) additive to improve UV radiation resistance and increase revetment useful life.

The expressions considered in this calculation are the ones proposed by Mark Brteler & Krystian W Pilarczyk, in Chapter 16, “Alternative revetments, 1998, Dikes and Revetments, where stability conditions for protection blankets with concrete blocks exposed to waving and flux actions are analyzed.

Concrete block thickness was obtained by the following expression:

$$D >= H_s \, . \, \xi^{0,66} \, / \, (\Delta \, . \, F. \cos(\alpha)) \qquad [3]$$

Where:

D= Mattress thickness
Hs = Significant height of the wave = 1.05 m
F = Calculation factor between 4 and 6 depending on the type of joint.
$\xi = \frac{tg(\propto)}{\sqrt{\frac{Hs}{Lo}}}$
α = slope angle with the horizontal
Lo = wave length in a far from the coastline environment = $\frac{g.Tp^2}{2.\pi}$
Δ = concrete/water relative density = $(\rho_s / \rho_w) - 1$
Tp = Average of the highest values of wave periods (s) = 3.2 s

Note the following comments on the calculations made:

- The former expression was conceived for blocks with parallel faces, which slightly deviate from the geometry of the blocks proposed for this solution. This may lead to reducing the influence of the weight of the block by a reduction of the concrete density for the calculation.
- On the other hand, the stability factor of the revetment F contemplates the conditions of the emplacement, strongly linked to the characteristics of the land where the protection will rest. As it was pointed out, this factor can vary between 4 and 6, or even to higher values in case the characteristics of the underlying material favors the stability of the mattress. In this case, a value of 7 for this factor would be suitable.
- Keeping in mind both effects, and considering a balance between safety factors and constructive possibilities, it is appropriate to maintain the characteristics of the concrete and not upgrading the stability factor, keeping a value of 6 for the calculation.

Using this expression, with a 1:1,5 slope; the minimum block thickness is obtained:

$D_{min} = 0.285$ m

Based on these results, it is suitable to use a geosynthetic protection consisting on a loopmatting fabric with 0.30m thick blocks.

$D_{adopted} = 0.30$ m

Figure 3. 30cm height concrete blocks linked to high-strength polypropylene loop matting fabric

4.2 CBM Placing conditions

According to the information stated above, CBMs were placed progressively in 6m sections measured over an exposed slope of 1:1.5. The expected total initial length is 7m, leaving a one free block meter space for frictional anchoring the mattress in to the slope.

This layout was considered for stability verification considering CBMs self-weight on the slope.

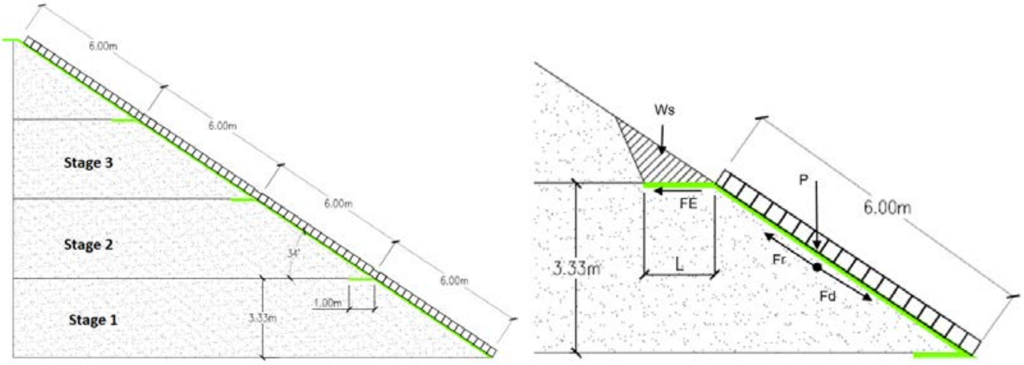
4.3 CBMs Stability

The stability conditions were calculated as the difference between the dead load forces on the inclined section and the resistance forces in the horizontal sections with the soil weight.

Requested condition is:

$$F_{resisting} > F_{slope} \quad [4]$$

The following placement detail was considered for this calculation:



a) CBMs slope layout

b) Calculation Scheme

Figure 4. Steel pegs evaluation

In this scheme, the horizontal length of the blanket was considered variable to achieve the balance against the destabilizing forces (Fd) given by the component of the blanket weight (P).

In this case, the weight of the blanket was calculated as:

$P = L.D.\ \gamma_{avg}$ [5]

Being:
L = Length of the blanket,
D = thickness (given by the blocks height)
$\gamma_{\mathbf{avg}}$ = the average specific weight between concrete and the joints, which can be (or not) filled with a porous concrete.

A weighted average of 81% and 19% is assumed among blocks and porous joints which specific weight were 2400 kg/m^3 and 1600 Kg/m^3 respectively. In this project, the average weight considered was 2250 kg/m^3.

As porous concrete joints filling is not considered, the specific weight to use should only be the block covered surface and would result in 1951 kg/m3. This last scheme was considered the most suitable for in-site implementation.

Considering the constructive anchorage method needed, CBMs length over the embankments slope results in L = 6,15 m A slope of 1,5:1 (n=1.5) is considered, equivalent to an angle of 33.7° aprox. The weight of the 6m long mattress is then P =3600 Kg/m.

Involved forces in the calculations are:

Destabilizing forces over the slope.
$Fd = P.\ sen\ (\alpha) = 1996.92$ kg/m [6]

Resistant forces over the slope.
$Fr = \mu\ P.\ \cos\ (\alpha) = 1396.77$ Kg/m [7]

Several references have been consulted for friction coefficient determination, which establish a minimum value close to 0.3. However, in the case of geomembranes, higher coefficients have been found, corresponding to friction angles ranging from 23° to 30°.

In this case, a friction angle of 23° was considered, which determines the following friction coefficient:

$\mu = 0.42$ (soil – geotextile)

Resulting Force on the Slope during constructive stage

$Fslope = Cs\ .\ Cd\ (Fd - Fr) = 1620{,}41$ Kg/m [8]

Where

Cd = 2 (Coefficient in definitive stage with dynamic load by surge action).
Cs=1.35 (Structural safety coefficient)

Available Resistant Force

The resistant force will be given by the friction of the horizontal section of the blanket exerts on the ground, with a length L. In this friction force intervenes the portion of soil included on top of the blanket in the constructive process of the embankment.

$FE = \mu.\ Ws\ .\ L$ [9]

Forces balance evaluation has been carried out to verifying the stability condition established, considering that the forces vary depending on the length of the horizontal section of the blanket.

Obtained results are shown in the following chart:

Table 2. Obtained results

Lenght	$F_{required}$	$F_{stabilizing}$	Status
1,00	1621	354,13	Does not verify
1,50	1621	796,80	Does not verify
2,00	1621	1416,54	Does not verify
2,23	1621	1669,75	Check
2,50	1621	2213,34	Check
3,00	1621	3187,21	Check

As shown above, to achieve the limit balance it is required a length of 2.23m of the horizontal section of the blanket. Therefore, it is suggested that a section of 2.3m or longer is installed, depending on the constructive and operative possibilities on site.

It is important to point out that in the case of incorporating concrete blocks in the horizontal section of the blanket, the length is not substantially modified, achieving a maximum reduction of the section to 1,80m.

4.3.1 Hydraulic properties

Soil granulometry was defined from embankment lab sample testing, and then compared with geotextile hydraulic properties.

PlusTex® T HLT SCL 80/60 was the CBM fabric for this project, which has 0.250mm max. pore opening size.

D_{15} = 0.43 mm, D_{50} = 19 mm y D_{85}= 100 mm are the values obtained from the soil granulometry curve. These values are higher than the geotextile pore opening size, which means the non-leakage of materials.

The placement of a second non-woven geotextile, acting as a filter its not needed to avoid the leakage of the embankment soil materials, being only a complementary layer to prevent the finest material leakage.

This second non-woven geotextile could lower friction values between the CBMs, situation that would result in a change in the stability conditions assumed in the present verification, which leads to increase at least 1 m the CBMs anchoring length in each embankment construction stage.

4.4 Steel Pegs Anchoring Option

Steel pegs were considered as another option for CBMs staged anchoring, reducing the anchoring fabric length. This option was studied both, in the construction stage without wave action and once finished, in the operative stage.

4.4.1 Construction stage study

In the previous calculations, an unbalanced force of 600 kg/m was determined between the weight of the blanket in the direction of the slope and the friction with the ground. Increased by a coefficient of 1.25 for the constructive stage, the effort taken by the anchors should be 750 kg/m.
Considering that the blanket is 2.5m wide, the total effort per blanket will be:

750 Kg/m x 2,5 m = 1875 Kg. [10]

A disposition of 7 stakes Ø 20 mm per blanket is adopted, equivalent to one every 0.36m, resulting in a required strength of:

1875 Kg/ 7 = 268 Kg per anchor [11]

A verification of the anchorage strength is presented below

4.4.2 Steel Pegs diameter selection

ADN- 420 Ø20 steel pegs were pre-selected:

Maximum bending moment calculated was 0.29KNm, but admissible bending moment of a Ø20 steel bar is 0.33KNm, so this solution was satisfying as anchoring system.

Horizontal length can be reduced to 1,08m by adding Ø 20 mm steel bars every 0,36 m at the CBMs top between staged embankment.

4.4.3 Steel pegs durability

In order to assure adequate conditions of durability for these steel bars against future corrosion, they would be treated with a heavy electrolytic galvanizing process.
Another protection treatment involves epoxidic coating, which requires the application of two layers of 200 microns each. This bicomponent coating is used for steel and concrete structures that are submerged or buried underground, given the high chemical resistance of the coating and its resistance to abrasion and impact.

Figure 5. Steel pegs in every block

4.4.4 Definitive stage study

The staged execution of the embankment and its erosion protection means that the second step of the embankment will rests on the horizontal part of the CBMs, improving the friction resistance and greatly contributing to the secure the mattress with its own weight. The steel pegs also complement this frictional anchoring effect.

Load intensity increase by the wave's dynamic effect, that it is considered by adding a load factor design to the CBMs weight. Also a resistance factor desing is used to increase the anchorage capacity considering the soil embankment weight in the horizontal fabric and the use of steel pegs.

$$Fc = \mu . Wc = 0,42 \times 2120 = 890 \text{ Kg/m} \qquad [12]$$

$$890 \text{ Kg/m} + 750 \text{ Kg/m} = 1640 \text{ Kg/m} \qquad [13]$$

$$1640 \text{ Kg/m} / 750 \text{ Kg/m} = 2,19 \qquad [14]$$

Additional resistance in the final configuration (considering de soil friction and the steel pegs acting together) is more than twice than the required resistance at the construction stage, also it support all dynamic wave effect that can happen.

4.5 CBMs details

Every CBM was built considering all the calculations made previously, with 25cm longitudinal space for joint overlap and a 1,5m block free length for steel peg staged anchoring.

Steel pegs were Ø 20 mm diameter and 70cm long, fixing the CBMs to the soil by entering 60cm in the soil and 10cm in a special designed block linked to the fabric by the loops.

4.6 CONSTRUCTION

More than 7,500 CMBs where precasted in site at a specially facility built for this purpose, which had 8 tracks of 150 m each, a gantry crane and a formwork with steam curing system that allowed a fast stripping and movement of the CBMs. Every CBM had 65 square blocks of 0.40 m on each side, covered 12 m2 and weighed more than 7 tons each.

a) On- Site facility for precasted CBMs

b) Still Wet Precasted CBM

Figure 6. Steel pegs evaluation

The selected solution included a new anchoring system to fix the CBMs to the embankment by using galvanized steel pegs into a special designed block that acts as a transfer beam. CBMs lifting method was optimized several times due to strong winds risks, making it able to work faster and more safety. Lifting method passed from one side only to 5 points. The regular yield was 60 CMBs per day (build, transport and place)

a) CBM lifted from the side

b) CBM lifted from 5 concrete blocks rows

Figure 7. Different lifting methods used

5. ENVIRONMENTAL IMPACT

The environmental impact that would have meant dynamiting more than 1 million m3 of mountains for traditional rock armour was avoided by using a geosynthetic erosion protection system.

On the other hand, the construction of this reservoir allows irrigation of almost 112.000 San Juan productive acres. Also, increase cultivable area in 12.000 acres and will give more waters reserves currently available for irrigation, improving mainly vine and olive agricultural production, with high added value

In 2007, the productives farm lands in San Juan reached 104.000 acres, but after Caracoles and Punta Negra Dam construction, this areas now increased 29.000 more acres.

6. CONCLUSION

- 30cm height block was designed for a 1,05m wave height and 3,2 sec period considering the slope angle.
- Concrete Block Matress system was a suitable alternative option for slope protection replacing traditional rock armour.
- Each CBM was precasted for covering 6m slope length. Several stages were needed to achieve the embankment final height.
- A high strength woven geotextile was used to lift the 7 tons weight of each CBM.
- The concrete blocks were linked to the fabric by over 2500 loops/sqm.
- The CBMs anchorage system was made by the soil frictional resistance in every construction step. The necessary length was 2,3m, however the anchorage system was improved by using steel pegs that also allowed a better performance in the construction stage when next level embankment wasn’t yet placed.
- Different lifting methods were considered in every part of the CBM life (concreting, lifting, transportation and placing)

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