Innovative Geosynthetic Technology Saves 100-Year-Old Panama Canal Locks

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ABSTRACT
The Panama Canal opened for business 105 years ago and was hailed as the eighth wonder of the world and an engineering marvel of the time. Since 1914, the originally three sets of dual parallel lane locks are still in operation in their original chamber dimensions of 33m wide x 300m long x 12m deep. However, ships have become larger and the tugs to maneuver them in and out of the locks have become more powerful. The latest version of Panama Canal tug is a 25m long 4,400 HP tug of azimuthal propulsion. With this increase in tug power prop wash combined with the continual flow of water out of the canal has created erosion along the dividing wall foundation and 2.0m thick approach slab. This erosion reached the extent that all three sets of locks were in danger of a catastrophic structural collapse. Scour erosion was detected using sonar digital imaging in areas to -20m of depth. This paper will detail how the Panama Canal Authority (ACP) Engineering and Maintenance Division's used an innovative technology and marine construction techniques to keep the canal operating 24 hours a day without any unscheduled interruptions to tonnage of operations. The paper will detail the science of testing of this innovative technology and the resulting design that enabled this process to successfully solve the erosion problem using more than 300 sand-filled geotextile bag units that weighed up to 90 metric tons each.

1. INTRODUCTION

1.1 History

The Panama Canal became the most consequential global waterway when the passenger ship SS Ancon entered the canal thru the Gatun Locks from the Atlantic Ocean on the morning of August 15, 1914, and it has continued to be so today. Traffic thru the canal has risen year over year thru the original locks from 807 transits the first year of operation up to 13,114 transits in 2016 when the new set of locks opened. On September 4, 2010 the Chinese freighter Fortune Plumb became the 1,000,000th ship to pass thru the canal. Total tonnage of transit has increased to more than 330 million metric tons (363 tons) in 2016 with revenue exceeding $2.4 billion/USD per year. All of this has been accomplished thru the three sets of 104-year-old locks.

Figure 1 SS Ancon first ship to transit the Panama Canal Aug. 14, 1914

1.2 The Locks

The original French design of the Panama Canal by Ferdinand de Lesseps was a sea level design without locks. Construction started on January 1, 1881 and continued until 1987 when it was realized that the sea level design was not practical, and an elevated canal and lock design was adapted. However, by this time tropical disease and construction difficulties had bankrupt the French effort. In 1903 a revolution occurred in Panama creating the Republic of Panama followed by the Hay – Bunau- Varilla Treaty. These events allowed the Unites States to take over the French property where the canal was being constructed. On May 4, 1904 and a new canal design was approved and construction restarted.

The new US design required three sets of locks. The Gatun Locks with three sets of parallel chambers would be constructed on the Atlantic side. The Pedro Miguel Locks with one step of parallel chambers and the Miraflores Locks two sets of parallel chambers would be built on the Pacific side. Each chamber would be 33.5 meters (110 ft.) wide by 305 meters (1,000 ft.) long. The Gatun Locks would raise or lower ships 26 meters (85 ft.) to and from the Atlantic Ocean allowing ships to transverse over the continental divide. The Pedro Miguel and the Miraflores Locks would raise or lower ships 26 meters (85 ft.) to and from the Pacific Ocean. The first concrete was poured at the Gatun Locks in August 1909. The final set of locks were completed four years later in May 1913. At the time or their construction, their overall mass, dimensions and innovative design surpassed any similar existing structures, and they are still considered to be an engineering wonder of the world. However, time, the environment, and shipping technology have taken a toll on these magnificently designed yet simplistic operating structures.

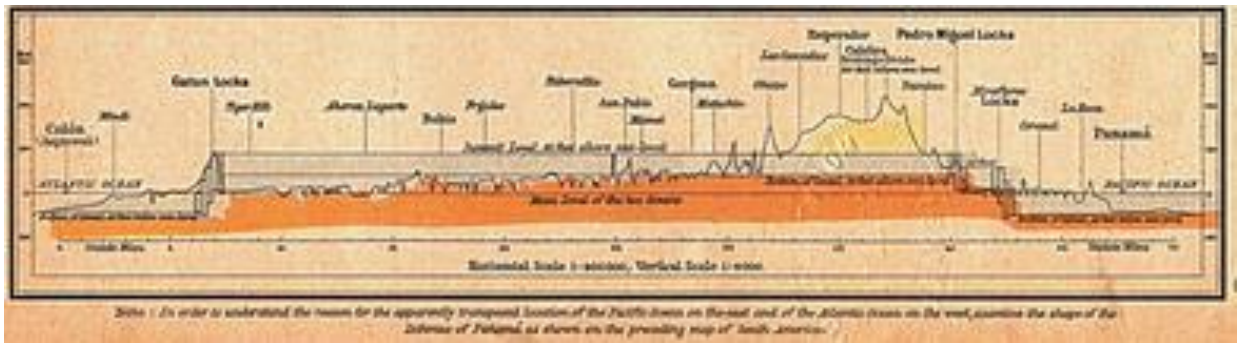


Figure 2 The 1907 US Design for The Panama Canal

Figure 3 The Gatun Locks (looking north) Under Construction in 1911

1.3 The Problem

After construction, the Panama Canal was administered by the United States until 1979 when the Canal Zone was transferred to Panama and it has since been administered and operated by the Autoridad del Canal de Panama (ACP). The ACP Engineering and Maintenance Division has insured that the canal has been continually operated under safe conditions with modern upgrades and expansions. In December 2013 the ACP Engineering and Maintenance team conducted the annual comprehensive sonar investigation of the entrance and exit of each chamber of all three sets of locks. It was discovered that there were numerous areas of erosion scour that were occurring at the leading edge and under the approach slabs, along the dividing wall foundations, and around the base of several wing walls. This erosion was significantly more advanced and extensive than had been observed in previous years as detailed in Figures 4. The worst areas of erosion scour which were occurring at the Atlantic entrance to the Gatun Locks approach slab and dividing wall. These areas were monitored every month during 2014. In early 2015 ACP determined that the scour areas were continuing to progress, and two areas were becoming critical. Figure 5 details the extent of the erosion under the Gatun Locks Atlantic dividing wall in July 2015.

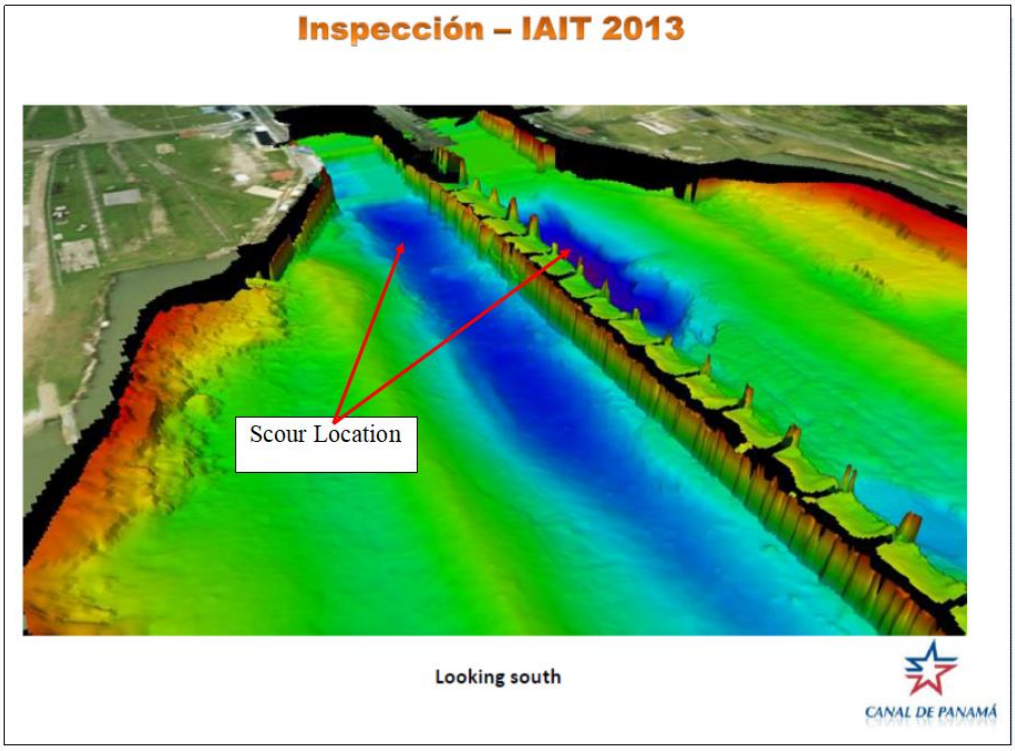


Figure 4 Erosion Scour at Gatun Locks Atlantic Entry

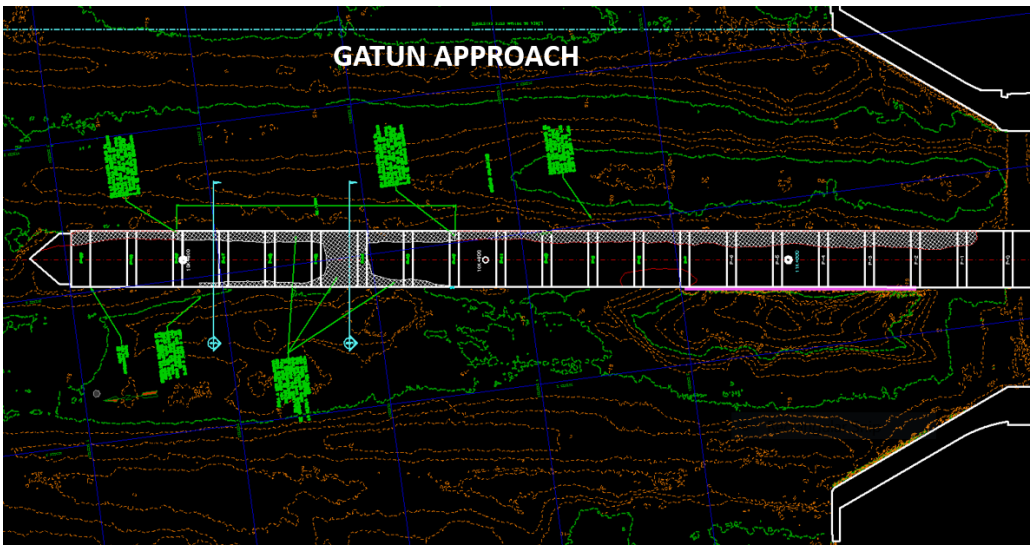


Figure 5 Dividing Wall Erosion Scour Areas of Concern in 2015

1.4 The Challenge

The ACP engineers determined in March 2015 that immediate action should be taken and that the challenge was three-fold; 1) the repair of the damage must not inhibit the flow of traffic thru the canal, 2) that the repairs must be done during routine maintenance schedule windows when one side of the locks was temporarily shut down for a 12 hour maintenance operation, and 3) the repairs must be able to be performed by the ACP construction and maintenance division due to the emergency nature of the repair.
Given these challenges, it was obvious that the repairs would be performed in water depths of up to -20m (66 ft.) with limited visibility and there was zero margin for error. Also, all the preparations for the repairs would be required to be performed at an offsite location and be able to mobilize and then demobilize in short order to stay within each 12-hour maintenance window.

2. THE SOLUTION

2.1 The Design

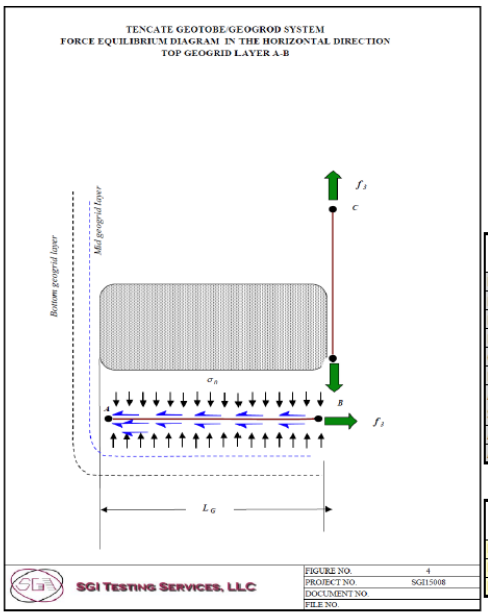
At the time the erosion scour was defined as critical, the ACP Engineering and Maintenance Division was working with the TenCate Geosynthetics group on a separate land-based slope erosion project. A joint meeting was scheduled between the two to brainstorm innovative solutions that may be incorporated to overcome the project challenges and to make the required repairs that would solve the erosion problems. This team quickly arrived at a potential solution that would meet all the challenges and could be rapidly executed.
The solution called for an underwater coffer dam to be installed adjacent to the base of the concrete structures under which erosion scour was occurring. The coffer dam would be formed using large flexible geosynthetic Geobag® containers that would be filled above water and lifted and placed underwater with a crane. Once in place, concrete would be pumped behind the coffer dam filling the void caused by the erosion scour. This could be a two-step process; Step 1) construction of the underwater coffer dam, and Step 2) filling the void with concrete. Each step would be performed separately during successive scheduled 12-hour maintenance windows.
TenCate had previously developed the system of filling, lifting, and placing 50m3 (65.4 yd3) sand filled Geobag® containers weighing 90 metric tons (99 Imperial tons). See Figure 6. The bags were fabricated from a 200 kN/m (1,142 lb./in.) woven polypropylene geotextile in a 5.0m wide x 5.0m long x 2.m high (16.4 ft. long x 16.4 ft. wide x 6.56 ft. high) configuration. The bag had a top lid that was open for filling with sand and could be closed and mechanically sealed to permanently contain the sand. A unique 400 kN/m (2,284 lb./in.) friction geogrid harness was designed to provide a flexible system of lifting and placing. See Figure 7 for the calculations of the Geogrid Friction Lifting Harness Pull Out Resistance and Figure 8 for the Geobag strength and factors of safety. The keys were: 1.) to have a barge mounted crane that could lift and place these Geobag containers as required within the Panama Canal Locks, 2.) that these Geobag containers were massive enough that the propwash of 4,400 HP tugs could not move the 90 metric ton (99 tons) Geobag containers, and 3.) yet to be flexible enough to contour to the eroded bottom of the canal to protect against future erosion scour.

ACP decided that the first repair operation would be the Atlantic side approach slab of the Gatun Locks. The design was finalized and the Geobag and Geogrid Friction Lifting Harness materials were ordered and delivered to the site in August 2015.

Figure 6 First Test Lifting of the 50 m3 Sand Filled Geobag Container weighing 90 Metric Tons

TENCATE Geotube

Program:	Grid Layer Pull Out Resistance Calculations and Factors of Safety
Project:	Panama Canal
Date:	6/13/2015



$$F_{TG} = \frac{F_1 + F_2}{2}$$

$$P_{AB} = 2\sigma_n L_{AB} W_G F_{TG}$$

$$FS = \frac{2\sigma_n L_{AB} W_G F_{TG}}{\left(\frac{\sigma_n L_G W_G}{2}\right)}$$

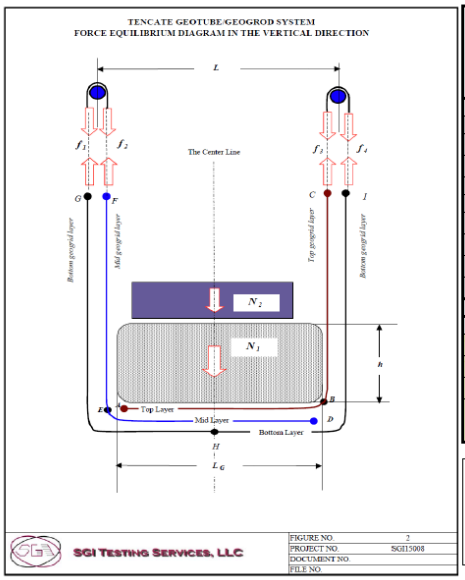
Input Data		
Project:	Ocensa - oleoducto Central	
N1 Total Gravity Force of Geobag Container	882.90	kN
N2 Total Gravity Force of Geobag Container	0.00	kN
Embedment Length, L_{AB}	5.00	m
Geogrid Width, W_G	5.00	m
Pull Out Force, f_3	220.73	kN
Average Geogrid/Geotextile/Geogrid Interface Normal Stress	35.32	kPa
Apparent Friction Coefficient (Top Geogrid Pullout)	0.36	
Apparent Friction Coefficient (Mid Geogrid Pullout)	0.32	

Output Data		
Pull Out Resistance P_{AB}	600.37	kN
Factor of Safety against Top Geogrid Pullout	1.44	FS
Factor of Safety against Mid Geogrid Pullout	1.28	FS

Figure 7 Geogrid Friction Harness Pull Out Resistance Calculation

TENCATE Geotube

Program:	GEOBAG® LIFT HARNESS CALCULATIONS AND FACTORS OF SAFETY:
Project:	Panama Canal
Date:	6/13/2015



TENSILE LOAD ON GEOGRID LIFTING HARNESS

$$FS = \frac{4W_G T_{ult}}{N_1 + N_2}$$

Input Data		
Project:	Ocensa - Oleoducto Central Pipeline Project	
Geogrid Lifting Harness Ultimate Strength T_{ult}	400	kN/m
Bulk Density of Geobag Fill material	1.8	Ton/m^3
Dimension of Geobag Container:		
Length	5.00	m
Width	5.00	m
Height	2.00	m
Lifting Geogrid Width in contact with Geobag:	5.00	m

Output Data		
Total Geobag Volume	50.0	m^3
Total Weight of Geobag Container	90.0	Ton
N_1 Total Gravity Force of Geobag Container	882.9	kN
N_2 Total Gravity Force of Geobag Container	0.0	kN
Lifting Harness Against Rupture FS	9.06	FS

where:
W_G = geogrid width defined in Figure 1;
T_{ult} = ultimate tensile strength of the geogrid;
N_1 = total gravity force of a sand-filled geotube; and
N_2 = total surcharge load acting on top of the sand-filled geotube.

Figure 8 Geobag Calculations

2.2 The Operation

The ACP determined that the Geobag® filling operation would be conducted at an ACP maintenance dock facility adjacent to the canal near the Gaillard Cut. The ACP 300 metric ton (330 Imperial ton) Titan barge mounted crane lifted the sand filled 90 metric ton (99 Imperial ton) Geobag containers on to a transfer barge that was moved to the Gatun Locks to be ready to start as soon as the 12-hour maintenance window opened. See Figure 8. The first repair was to the scour erosion underneath the approach slab to the left chamber of the Atlantic approach to the Gatun Locks. The scour was the entire 33.5m width (110 ft.) of the slab down to a depth of 4.0m (13.1 ft.) below the slab and 8.0m (26.2 ft.) underneath the slab. This repair would require constructing the coffer dam using 10 or 12 of the 90 metric ton (99 Imperial ton) sand filled 50m3 (65.4 yd3) Geobag containers. See Figure 9 for the first Geobag® placement using the 300 metric ton (330 Imperial ton) Titan barge crane. Figure 11 is the engineers sketch of the first 8 Geobag® positions as they were placed and the position of the Geobag® #9 ad #10 that are to be placed. It only took 10 bags to form the coffer dam and all were placed within the first scheduled 12-hour maintenance window that was a nighttime operation. During the next month's 12-hour nighttime maintenance window more 300 m3 (393 ys3) of concrete was pumped behind the Geobag coffer dam and under the approach slab to fill the scour void under the slab.
This same procedure was followed to make the scour erosion repair to both sides of the dividing wall to the approach to the Gatun Locks as detailed in Figure 12, 13, and 14. The same methodology was followed to perform similar repairs to the Miraflores and Pedro Miguel Locks. Figure 15 details how the Geobag coffer dam functioned in retaining the pumped concrete under the canal entry slabs, dividing wall and wing structures.

Figure 9 The 300 Ton Crane Placing the 90 Ton Geobag® Containers on Transfer Barge

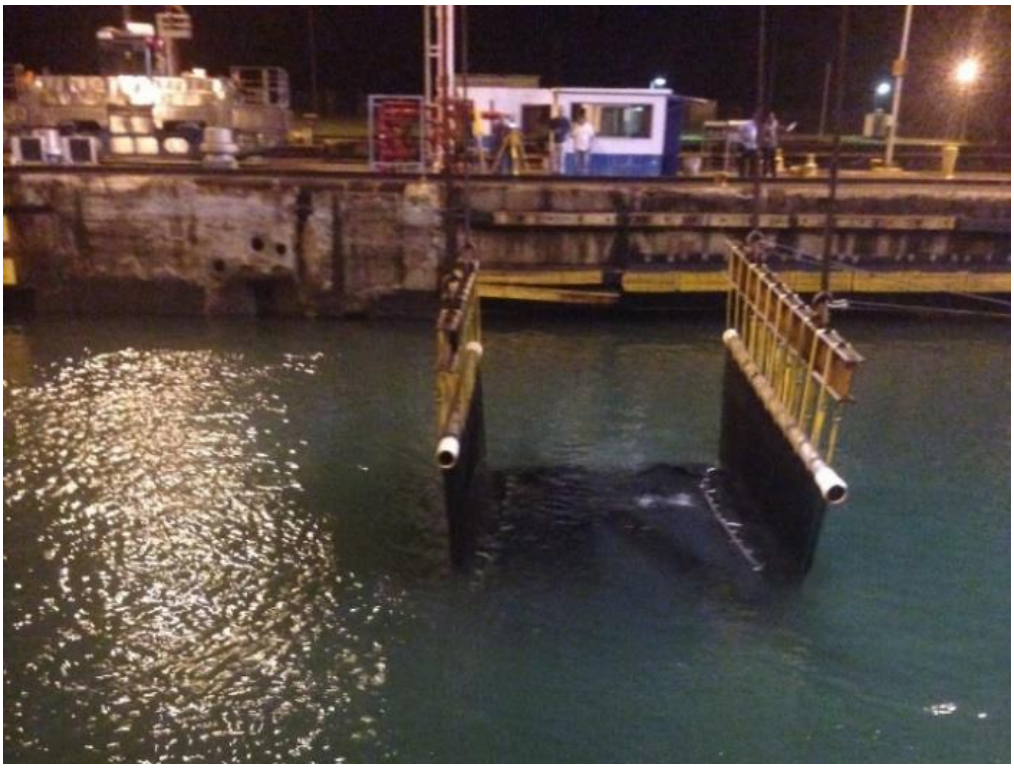


Figure 10 Placing the first 50m3 Geobag® in the Bottom of the Gatun Locks

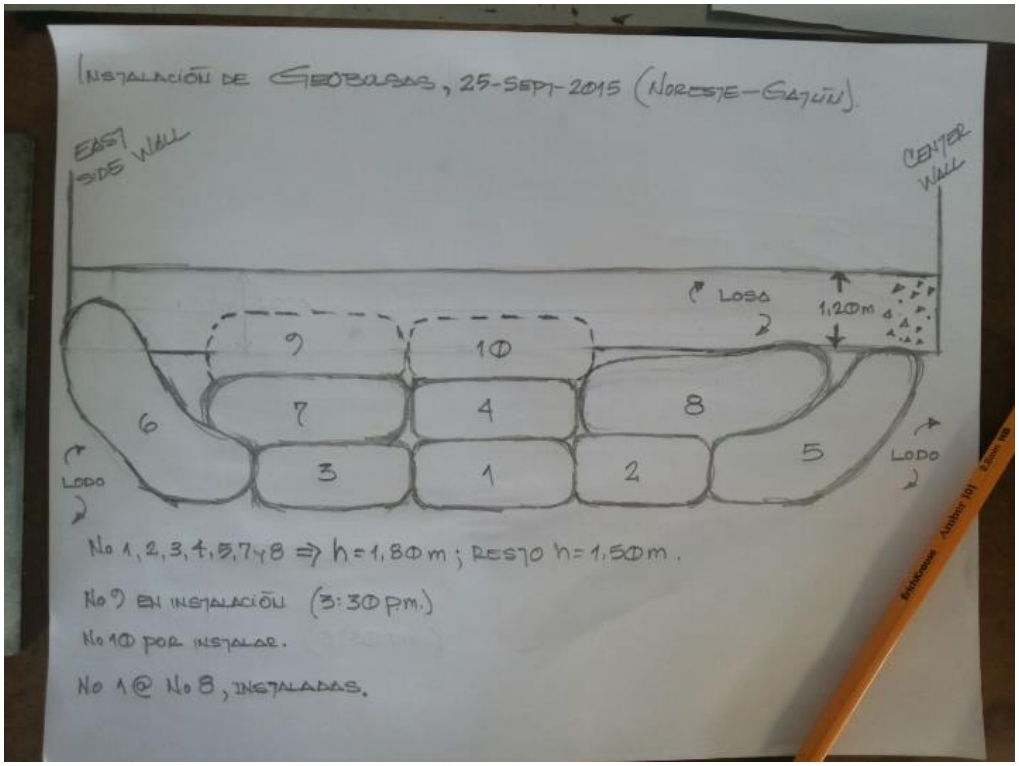


Figure 11 Engineers Drawing of Geobag® Placement

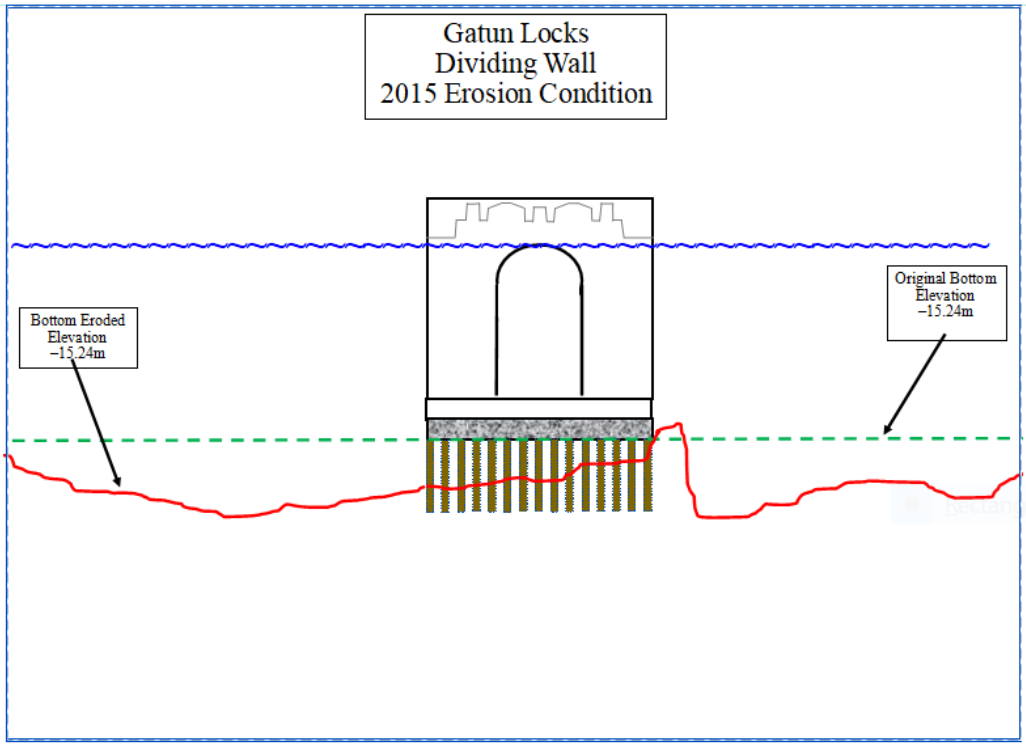


Figure 12 Cross Section of Gatun Locks Dividing Wall Before Repair

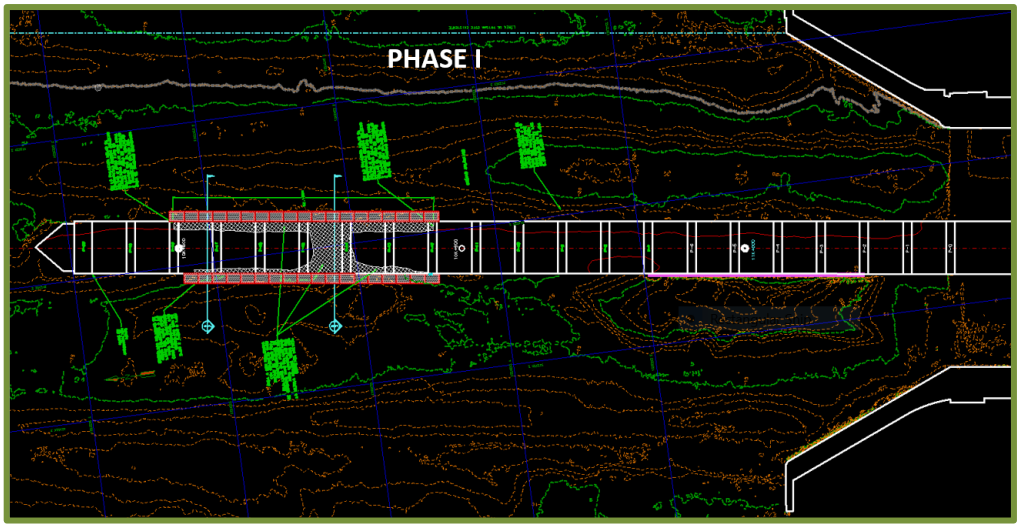


Figure 13 Phase 1 Repair to the Gatun Locks Dividing Wall

Figure 14 Installing Geobag® Units Along Gatun Locks Dividing Wall

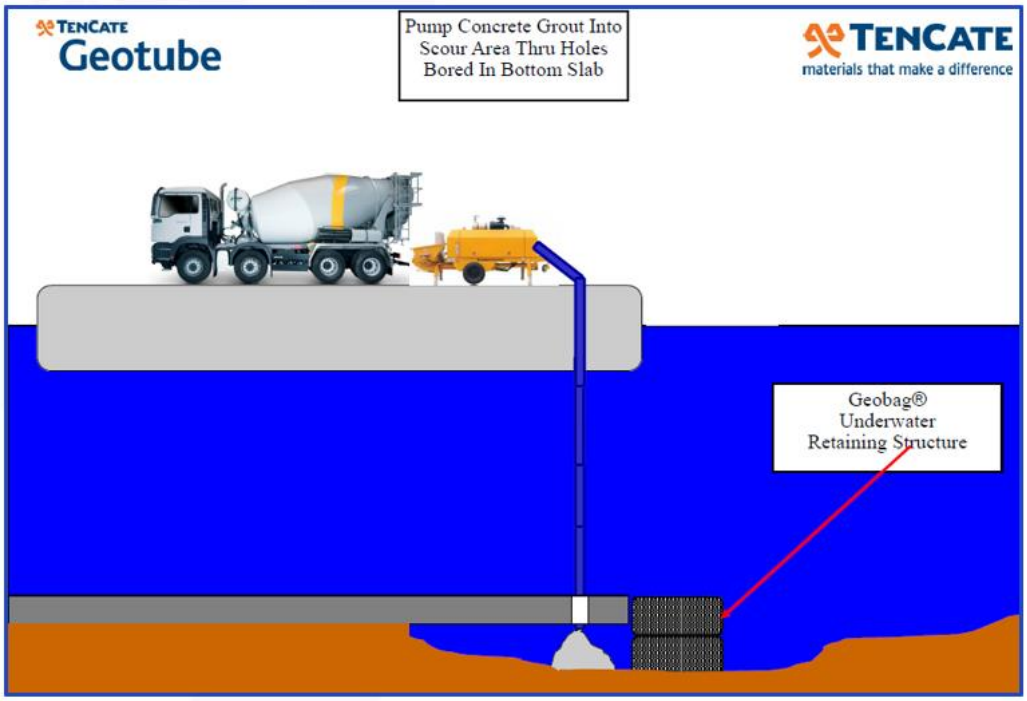


Figure 15 Method of Repair to Scour Erosion Under Slabs and Dividing Walls

3. THE RESULTS

There has been on scour erosion detected under the two Gatun Locks structures since the repairs using the Geobag coffer dam technology in September 2015. In addition, the ACP has installed more than 300 Geobag® units to construct underwater coffer dams within the Panama Canal to allow the filling of under structure voids with concrete at other detected scour erosion at the Gatun Locks and the other two sets of Panama Canal locks.
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4. CONCLUSION

This innovative geosynthetic geogrid and Geobag technology combined with the installation methodology are credited in allowing the ACP's Engineering and Maintenance Division to be able to respond rapidly to a serious threat to the +100-year-old Panama Canal Locks that if not addressed in a timely fashion could have caused serious consequences or catastrophic damage resulting in the loss of millions of dollars of revenue and cost millions in construction cost to the Panama Canal. In addition, the innovative solution allowed for all the required repairs and erosion protection to take place during scheduled maintenance windows without any loss of

ACKNOWLEDGEMENTS

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