Water-filled Barrier Walls for Stormwater and Sediment Control on Steep Slopes

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ABSTRACT

The use of water-filled barrier walls for stormwater and sediment control was evaluated for a hillside construction project in Northern California. Water-filled barrier walls were configured along one of the project's exposed hillsides to create a series of nine temporary detention basins. The water-filled barrier walls were evaluated for ease of deployment, construction practicability, and stability for varying slope conditions, surface placement types, and configurations. When properly anchored, the water-filled barrier wall basins detained large volumes of sediment and stormwater along the steep hillside.

INTRODUCTION

A low density polyethylene (LDPE) barrier wall product called "Muscle Wall" was evaluated for its use in stormwater and sediment control on steep slopes. The barrier walls are approximately 4 feet in height, 6 feet in length, 2.5 feet in base width, 0.7 feet in top width, and 120 pounds in weight. The barrier walls are interlocked, secured to each other using ratchet tie down straps, filled with water, and wrapped with a plastic or geotextile liner to produce a linear barrier system. An image of two interlocked barrier walls without ratchet tie down straps or liner is shown in Figure 1.

Figure 1. Two interlocked barrier walls.

The barrier wall product was evaluated for ease of deployment, construction practicability, and stability for varying slope conditions, surface placement types, and configurations during the 2018-19 winter season at a construction project site in Northern California. Northern California has a climate characterized by moist mild winters and dry summers, with a majority of rainfall occurring between November and March. The site's topsoil consisted predominantly of silty sand with a fines content ranging between 13 and 32 percent (percent passing the number 200 sieve). The site's slope grades ranged between 15 and 60 percent.

Prior to the 2018-19 winter season, approximately 10 acres of hillside terrain within the project site was grubbed; the contractor needed to complete mass grading of the hillside during the winter season to meet construction schedule demands. Because of this, traditional erosion control measures such as hydroseed, hydromulch, straw wattle, and woven netting/blanket were not practical to install prior to each storm, since they would need to be immediately removed so that grading could continue following the storm. The steep unvegetated slopes posed a high risk for sediment erosion, which could lead to turbid stormwater discharges if no containment measures were installed. California's Construction General Permit (CGP) requires Best Management Practices (BMPs) be implemented onsite, with the intent of reducing stormwater discharge leaving certain construction sites to a turbidity value less than 250 Nephelometric Turbidity Units (NTU). In order to comply with CGP requirements, the barrier wall product was used to create temporary stomwater and sediment detention basins along the hillside, with the intent of reducing stormwater velocity and detaining turbid stormwater.

METHODS

Shipping and Storage

Approximately 4,000 linear feet (LF) of the barrier wall product was ordered for the project site. The barrier walls, plastic liner, ratchet tie-down straps, and liner clips were shipped to the project site on seven truck trailers (approximately 95 barrier walls per truck trailer). Each pallet of the barrier wall product was observed to take up an approximately 8 feet by 6 feet footprint, and contained 12 barrier wall segments as shown in Figure 2. The barrier wall product pallets were removed from the truck trailer using a forklift and stored on the project site prior to deployment.

Figure 2. Stacked barrier walls.

Placement Strategy
Based on experience from previous winters on the construction site, turbid stormwater that collected in holding ponds often took more than two weeks of settling time before meeting the CGP turbidity threshold of 250 NTU. Because of this, it was assumed that no stormwater runoff from the hillside would be clear enough to discharge offsite during a storm event; the strategy was to install a series of basins to detain and control the hillside's stormwater, which would limit the possibility of discharges exceeding 250 NTU. It was expected that turbid stormwater would seep under the barrier wall basins at the bottom of the hillside, but at a low enough flowrate to be controlled and rerouted as needed to avoid offsite discharge. Polymer flocculant to reduce turbidity in the basins was not considered because it was not approved for use by the Regional Water Quality Control Board. The basins would also act as check dams to slow stormwater velocity along the hillside to reduce erosion and sediment transport. Based on an average watershed slope of 20 percent, shallow concentrated flow velocities were expected to reach 4.5 feet per second (fps) over bare soil, and 9 fps over pavement (USDA, 2010).

The basins were designed to detain the runoff volume produced by a rainfall depth of 2 inches (approximately equal to that of a 10-year-recurrence-interval, 6-hour-duration storm). For storms forecasted to produce greater than 2 inches of rainfall, water trucks were staged at one of the downslope basins so that collected stormwater could be pumped and transported to a high capacity infiltration-evaporation basin in a flat region of the site. While expensive, the cost of the pumping and trucking operation was deemed cheaper than the cost of not completing the mass grading work on time. A series of nine temporary barrier wall basins with an average spacing of 150 feet were placed along the hillside, as shown in Figure 3.

Figure 3. Aerial view (left) and side view (right) of the barrier wall basin locations.

Table 1 summarizes each barrier wall basin's length, cross slope (defined as the average slope perpendicular to the basin length), and surface placement type. Barrier walls that crossed active haul roads were not filled with water to allow for rapid removal during non-storm conditions. All barrier walls that were not located across an active haul road were filled completely with water to increase stability. In addition, all barrier walls were wrapped with plastic to limit seepage beneath the base and connection points of the barrier wall basins. The bottom area of the basins was left unlined to promote infiltration and reduce the need for pumping.

Table 1. Summary of barrier wall basin properties.

Basin number	Length (feet)	Cross slope (%)	Surface type
MW-1	450	~10	Concrete Sidewalk
MW-2	100	~10	Asphalt Concrete
MW-3	100	~18	Asphalt Concrete
MW-4	260	flat	Compacted Soil
MW-5	500	flat	Compacted Soil
MW-6	170	~15	Asphalt Concrete
MW-7	105	~13	Asphalt Concrete
MW-8	80	~5	Compacted Soil
MW-9	160	~10	Compacted Soil

Deployment

The nine barrier wall basins were deployed intermittently from the end of November 2018 through mid-December 2018, based on the project schedule and contractor's availability. In locations where the barrier wall basins were to be placed on soil, grading was performed to provide a level surface for the barrier walls. A level surface was preferred in order to limit seepage under the barrier walls and to increase stability. According to the contractor, it took approximately 9 hours to install 500 LF of the barrier wall product, which included the time to grade a level surface, place the barrier walls, connect the barriers with straps, fill the barriers with water, wrap the barriers with plastic lining, and secure the plastic lining with clips. When the barrier walls were placed on a paved surface where grading a level surface was not necessary, the installation process took about 5 hours for 500 LF.

FINDINGS

During the study period between December 2018 and March 2019, the site received approximately 19 inches of rain. The largest storm occurred between February 13 and February 15, and produced approximately 4 inches of rain over the course of three days. Other storms during the study period generally produced between 1 and 3 inches of rain over the course of 2 to 4 days. Even though the design rainfall depth was exceeded during multiple storms, the downslope basin (MW-4) that collected a majority of the site's stormwater did not overtop due to the pumping and trucking operation.

When each barrier wall basin was properly anchored, the series of basins successfully detained and controlled the hillside's turbid stormwater. The velocity of stormwater was not measured during storm events, but it is assumed that the average velocity along the hillside was reduced, as stormwater was brought to a halt approximately every 150 feet. Turbidity of stormwater entering and exiting the barrier wall basins was not measured, but as expected due to site sediment's high fines content, turbidity did not visually appear to decrease upon exiting the basins. An individual breakdown of each barrier wall basin's performance is discussed below.

MW-1
Basin MW-1 was located at the toe of the hillside along a concrete sidewalk with a cross slope of approximately 10 percent. All barrier walls were filled with water. Basin MW-1 held back large volumes of sediment during the study period, with the contractor removing built-up sediment with an excavator following storms as needed. Turbid water was observed seeping from the bottom of the basin at a low flowrate during storms. This water was routed using sand bags into a traditional excavated sediment basin further downstream to prevent discharge from the site.

MW-2
Basin MW-2 was located at the bottom of an asphalt concrete haul road with a cross slope of approximately 10 percent. The initial configuration (Figure 4, left) was composed of four unfilled barrier walls (red) anchored by three water-filled barrier walls (blue) on each end. Two 90-degree corner walls were used to assist in forming the basin. After the first storm, the entire basin slid (but did not overturn) due to sediment impact and buildup (Figure 4, right). After this storm, two additional water-filled barrier walls were added on each end of the basin (Figure 5, left). Following this addition, Basin MW-2 did not slide during subsequent storm events (Figure 5, right).

Figure 4. MW-2 initial configuration (left) and performance after first storm (right).

Figure 5. MW-2 revised configuration (left) and performance after subsequent storms (right).

MW-3
Basin MW-3 was located across an asphalt concrete haul road with a cross slope of approximately 18 percent. The initial configuration (Figure 6, left) was composed of four unfilled barrier walls (red) anchored by three water-filled barrier walls (blue) on each end. One 90-degree corner wall was used to assist in forming the basin. After the first storm, the basin slid and multiple barrier walls disconnected from each other due to sediment impact and buildup (Figure 6, right). After this storm, three additional water-filled barrier walls were added on each end of the basin (Figure 7, left). Following this addition, Basin MW-3 remained stable during subsequent storm events (Figure 7, right).

Figure 6. MW-3 initial configuration (left) and performance after first storm (right).

Figure 7. MW-3 revised configuration (left) and performance after subsequent storms (right).

MW-4
Basin MW-4 was placed on fairly level compacted soil with all barrier walls filled with water. In addition, an approximately 4-feet-deep sediment basin was excavated on the interior of the barrier wall basin. The barrier wall product and excavated sediment basin combination increased the storage depth to approximately 7.5 feet. Figure 8 shows a conceptual detail of the combined basin system. With the plastic liner overlapping the barrier walls and extending down the 2:1 sediment basin side slopes, water was unable to seep under the barrier walls. Water discharging

from Basin MW-5 (upslope) through seepage or overtopping would make its way to Basin MW-4, where it would then be pumped into water trucks after filling up during storm events.

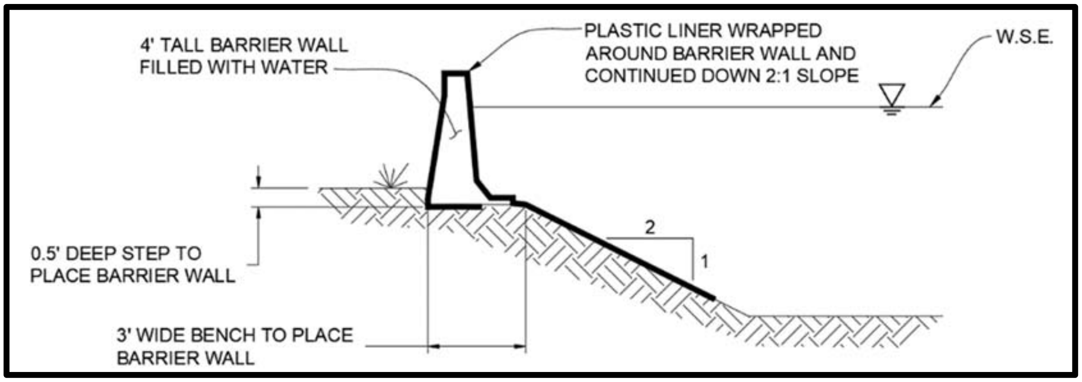

Figure 8. Detail of combined barrier wall and excavated sediment basin.

MW-5

Basin MW-5 was placed on fairly level compacted soil with all barrier walls filled with water. Basin MW-5 was effective at slowing stormwater runoff and trapping entrained sediment; once volumetric capacity was reached during a rain event, stormwater would both overtop and seep under the barrier walls down gradient to Basin MW-4 (Figure 9). Stormwater was able to seep under the barrier walls of MW-5 since the plastic liner did not continue along the interior of the basin like Basin MW-4. In addition, irregularities in the ground surface created small gaps for water to flow through. The turbidity of water leaving the basin appeared similar to that of water entering the basin. Basin MW-5 did not experience any lapses in stability, even when overtopped by stormwater and impacted by sediment buildup.

Figure 9. Seepage under the barrier wall.

MW-6

Basin MW-6 was located across an asphalt concrete haul road with a cross slope of approximately 15 percent. Unlike Basins MW-2 and MW-3, which made use of corner walls, Basin MW-6 had enough width across the haul road to form a semi-circular basin without using corner walls; the connection joints between barrier walls allowed for a deflection of approximately 11 degrees between each wall. Five barrier walls located across the haul road were not filled with water. Like Basin MW-5, Basin MW-6 did not experience any lapses in stability while at capacity with stormwater and entrained sediment (Figure 10). Stormwater was observed to seep under the barrier walls during storm events; the turbidity of water leaving the basin appeared similar to that of water entering the basin.

Figure 10. Basin MW-6 retaining 4 feet of sediment following a storm.

MW-7

Basin MW-7 was located across an asphalt concrete haul road with a cross slope of approximately 13 percent. The initial configuration was composed of five unfilled barrier walls anchored by six water-filled barrier walls on one end and four water-filled barrier walls on the other end. Two 90-degree corner walls were used to assist in forming the basin. After the first storm, the basin did not slide (like Basins MW-2 and MW-3), but the empty barrier walls rotated outward. After this storm, the five previously empty barrier walls were filled with water. Following this reconfiguration, Basin MW-7 remained stable during subsequent storm events.

MW-8

Basin MW-8 was located across a compacted soil haul road with a cross slope of approximately five percent. Like the other basins located across haul roads, five middle barrier walls were not filled with water. Figure 11 below depicts the empty barrier walls set aside during dry weather so that the haul road could be used. Because Basin MW-8 was the furthest upslope basin, it collected the least amount of stormwater runoff and never filled to capacity. However, it succeeded as a check dam for slowing water flow and detaining entrained sediment.

Figure 11: Empty barrier walls set aside for haul road use.

MW-9
Basin MW-9 was located across a compacted soil haul road with a cross slope of approximately 10 percent. Five barrier walls in the middle of the basin were not filled with water, and the basin utilized two corner walls to assist in forming the basin. Basin MW-9 often filled to capacity with water during storms, and accumulated sediment throughout the study period (Figure 12). Over the duration of the study period, Basin MW-9 did not experience any lapses in stability while at capacity with water and sediment. The turbidity of water leaving the basin through overtopping and seepage appeared similar to that of water entering the basin.

Figure 12: Basin MW-9 overtopping during a storm event.

Table 2 summarizes each barrier wall basin's stability results in relation to its configuration characteristics.

Table 2. Summary of basin performance results.

Basin number	Cross slope (%)	Surface type	Empty barrier walls?	Corner walls utilized?	Stability issues?
MW-1	~10	Concrete Sidewalk			
MW-2	~10	Asphalt Concrete	✓	✓	✓
MW-3	~18	Asphalt Concrete	✓	✓	✓
MW-4	flat	Compacted Soil			
MW-5	flat	Compacted Soil			
MW-6	~15	Asphalt Concrete	✓		
MW-7	~13	Asphalt Concrete	✓	✓	✓
MW-8	~5	Compacted Soil	✓	✓	
MW-9	~10	Compacted Soil	✓	✓	

DISCUSSION

The barrier wall basins that had initial stability issues (Basins MW-2, MW-3, and MW-7) were each installed on slopes greater than or equal to 10 percent, placed on asphalt concrete, contained empty barrier walls, and utilized corner walls. While Basin MW-6 was on a slope greater than 10 percent, placed on asphalt concrete, and contained empty barrier walls, it did not experience stability issues. It appears the lack of corner walls in the configuration may have increased the basin's stability. In general, stress tends to concentrate over sharp changes in geometry (Dundurs and Lee, 1972). It was observed that for basins where barrier walls came apart or rotated out of place (Basins MW-2, MW-3, and MW-7), a corner wall was the weak point.

While Basin MW-9 was located on a slope of approximately 10 percent, contained empty barrier walls, and utilized corner walls, it did not experience stability issues. The compacted soil on which it was placed may have been the reason for its increased stability compared to other similar basin configurations that were installed on asphalt concrete; the coefficient of friction between plastic and soil is generally higher than that of plastic and asphalt concrete. In addition, the barrier walls of Basin MW-9 may have been more secure since they were able to "settle" into the soil, as opposed to sitting on top of relatively rigid asphalt concrete.

While Basin MW-8 was placed on asphalt concrete, contained empty barrier walls, and utilized corner walls, it did not experience stability issues. This is likely because the basin was located on a 5 percent slope (compared to 10 percent or greater) and never filled to capacity due to its upslope location on the hillside.

Based on pull-out sliding tests performed by the barrier wall product manufacturer on a flat grade under static water loading conditions, the sliding factor of safety for the barrier wall was 1.37 when placed on asphalt, and 1.44 when placed on soil. These sliding factor of safety values were used to calibrate a static water load retaining wall sliding analysis for a 0 percent slope. The retaining wall analysis was then repeated for slopes of 5, 10, 15, and 20 percent. Table 3 presents the results from the sliding factor of safety analysis for varying slope grades and surface placement types.

Table 3. Sliding factor of safety (FS) results.

Slope (%)	FS on Asphalt	FS on Soil
0	1.37*	1.44*
5	1.18	1.25
10	1.04	1.10
15	0.93	0.98
20	0.84	0.88

*Per barrier wall product manufacturer pull-out sliding tests.

As expected, sliding factor of safety decreases with increasing slope grade, and is slightly greater for a soil surface. The results generally align with field observations, where some barrier walls showed signs of instability on slope grades exceeding 10 percent. To increase barrier wall stability on slope grades exceeding 10 percent, water-filled barrier walls or k-rail can be placed behind and perpendicular to the barrier wall basin. For horseshoe shaped basins, additional water-filled anchor walls can be placed on each end. If enough water-filled anchor walls are used, some barrier walls in the center of the basin can even be left unfilled, as exemplified by Basins MW-2 and MW-3. Basin MW-2 was on a slope of approximately 10 percent, and was initially unstable with a ratio of water-filled to unfilled barrier walls of 1.5:1; however, Basin MW-2 remained stable with a ratio of water-filled to unfilled barrier walls of 2.5:1. Basin MW-3 was on a slope of approximately 18 percent, and was initially unstable with a ratio of water-filled to unfilled barrier walls of 1.5:1; however, Basin MW-3 remained stable with a ratio of water-filled to unfilled barrier walls of 3:1.

Table 4 provides recommended "rule of thumb" ratios of water-filled to unfilled barrier walls to improve basin stability for various slope grades.

Table 4. Ratios of water-filled to unfilled barrier walls for various slope grades.

Slope (%)	Ratio of water-filled to unfilled barrier walls
0-5	2:1
5-10	2.5:1
10-15	3:1
15+	Fill all barrier walls

Leaving some barrier walls unfilled when located across an active haul road was convenient for the contractor's site access; during non-storm conditions, the contractor would disconnect the unfilled barrier walls from the basin and set them aside to allow haul road use. If a storm event was forecasted, the contractor was able to quickly reconnect the unfilled barrier walls across the haul road.

To reduce seepage under the barrier walls, the plastic or geotextile liner could be trenched into the ground on the water side of the barrier wall (if placed on soil). For barrier walls placed on pavement, seepage under the barrier walls could be mitigated by placing sand bags tightly along the toe of the barrier walls. To reduce uncontrolled overtopping, the barrier wall product manufacturer developed a double-orifice discharge port during the end of the study period. A hose could be connected to the discharge port to route stormwater to an active treatment system or other water quality BMP to help reduce stormwater turbidity before offsite discharge. A rendering of the discharge port (left) and photo of the manufactured discharge port at the project site (right) are shown in Figure 13. The discharge port was not tested during the study period.

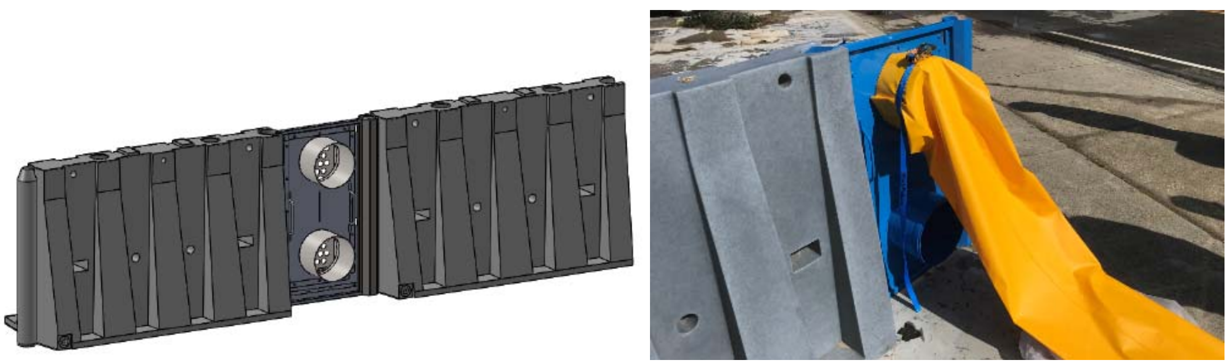

Figure 13. Rendering of the discharge port (left) and photograph of the discharge port (right).

The barrier wall product provides an alternative to traditional barrier BMPs such as sandbags and k-rail. Compared to a sandbag barrier of the same height, the United States Army Corps of Engineers (USACE) concluded the barrier wall product was over 25 times quicker to construct, had four times less seepage, and remained undamaged by waves, overtopping, debris impact, and riverine current (Ramos-Santiago, Blades, and Gutshall, 2020). One 4-foot-tall barrier wall is equivalent to approximately 470 sand bags. Compared to a typical 10-feet-long, 2.7-feet-tall, 4,000-pound section of k-rail, a 6-feet-long, 4-feet-tall, 120-pound barrier wall (when unfilled) is easier and greener to deploy because it does not require heavy machinery. Once filled with water, the barrier wall weighs approximately 1,400 pounds.

CONCLUSION

The use of water-filled barrier walls for stormwater and sediment control was largely effective for the hillside construction project in Northern California. The series of nine temporary detention basins created by the barrier walls held back large volumes of turbid stormwater and transported sediment, and reduced the velocity of stormwater as it made its way down the hillside. Given enough water-filled "anchor" walls, the basins remained stable for various configurations and on slopes of varying steepness and surface type.

Since the end of the study period in March 2019, the barrier wall product has continued to be used at the project site. In addition to being used to create temporary detention basins on steep slopes, the barrier wall product was used as a sediment perimeter control BMP, a secondary containment BMP for liquid construction materials, and a temporary retaining wall for soil. Due to the barrier wall product's LDPE material, it is expected the barrier walls will continue to be reused on the project site for multiple additional years. ENGEO Incorporated is currently evaluating the average effective lifespan of the barrier wall product based on data from its use at the subject project site in Northern California, and two additional project sites in Southern California.

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