ATTACHMENT B
THE CITADEL: WAVE DISSIPATION SYSTEM – OC/SS/BWE/HI REPORT

December 8, 2016

The Citadel
Department of Civil and Environmental Engineering
171 Moultrie Street
Charleston, SC 29409

August 28, 2016

Deron Nettles
SI Seawall and Fencing Systems, LLC
1466 Fiddlers Marsh Drive
Mount Pleasant, SC 29466

Re: Wave Dissipation System – OC/SS/BWE/HI
Report – August 28, 2016

Mr. Nettles:

This report is The Citadel research team's "OCRM requested" report on the Wave Dissipation System's (WDS's) one-year study at Ocean Club/Seascape (OC/SS), Beachwood East (BWE), and Harbor Island (HI). It is important to mention upfront that the entire study and associated parameters as described in this report are not in line with how the Citadel research team envisioned the study would take place. The research team strongly believes that the fictitious constraints assigned throughout the study period made performing research unreasonable at best and impossible at worst. Had the research team been allowed to perform the research as described in meetings prior to the study and in conversations and reports during the study, a plethora of data would be available and the WDS would be optimized for the site conditions at the sites described in this report.

The purpose of this report is to present a summary of the performance of the system at each site and to discuss how the system compares to sandbags. As you are aware, our previous study results (2013-2014) led us, in a report dated 11/28/2014, to conclude that:

> "…the Wave Dissipation System is able to:
> 1) protect structures, dunes, flora, and fauna that are landward of the system
> 2) minimize the potential for negative impacts that are associated with hardened devices, and
> 3) allow for natural beach elevation changes while providing better protection of dune lines by using a two tier system with slots in the front WDS line and a second WDS line to stop the erosion effects of fast moving water through or under the front WDS line."

I am happy to report that the results of this additional OCRM requested 4 site study have not changed the conclusions made in the 11/28/2014 report and that the research team believes that the WDS should be allowed as an alternative to sandbags (in emergency situations) along the coast in South

Carolina. On the contrary, please note that we have many recommendations regarding its use that should be adhered to in order to ensure the optimal performance of the system. The main issue to note is that the WDS is a dynamic system that must be configured appropriately for optimal performance and that its use will require modifications and some degree of sand replenishing after severe erosion events. OCRM did not allow most of the recommendations presented in this report to be applied or adhered to during the study since they claimed the results (to be reflected in the surveys) would be affected. As a result, optimal performance could not be maintained throughout the study.

The report contains the following sections:

Executive Summary

Although it was the opinion of Citadel researchers that the 2013-2014 studies performed at Seascape showed clearly that the WDS should be considered a viable alternative to sandbags for emergency use in South Carolina, OCRM staff maintained that more studies at different sites were needed before they could reach a definite opinion. Therefore, SI Systems, LLC, without the help of The Citadel, began to try to find the type of sites that OCRM was requesting and homeowners willing to pay for such a study. The three sites mentioned in this report (OC/SS, BWE, and HI) were proposed to OCRM and approved.

Any good research project requires a hypothesis, and since the study was being performed solely for the benefit and demand of OCRM, Citadel researchers formally approached OCRM about providing a definition of "success". During the kickoff meeting on July 6, 2015, the WDS research team and OCRM agreed to meet together to jointly define what "success" would mean. The research team made it very clear that doing a study without a goal was unreasonable and that the definition needed to be defined immediately. Although further discussion never took place, all parties seemed to agree that something related to "as good as sandbags" would be part of the formal definition. At a follow up formal meeting (October 30, 2015) where Dr. Mays discussed his concerns over no guidance from OCRM as to what success actually means, OCRM updated the team saying they would consider, per Dr. Mays' request, the "as good as sandbags" language as they review project results, but that they would not come up with an agreed upon definition but would instead base their decision on how well the system adheres to the language in the regulations (which is how they view their charge).

The performance summaries presented in the subsequent three sections of this report are intended to describe and detail the overall performance of the system at each of the three study sites. Although researchers are happy with the overall performance of the system and its ability to dissipate energy from waves, some concerns are expressed in the recommendations and conclusions section of this report. Readers should carefully note that unlike research at other universities where structures can be tested in a university wave pool where wave period, wave height, and tide levels can be controlled, these structures were completely loaded by whatever events God allowed to occur at each site over a one year period. As such, the now infamous 1,000 year storm, many nor'easters, and several tropical storms impacted the system. The WDS survived all the events, some of which were beyond levels considered in the original design of the system. It is also important for the reader to note that Citadel researchers were not permitted by OCRM to optimize the system's performance and that the way the systems were tested over the last year is in no way indicative of how they should be used in practice. On the other hand, even though not optimized for performance, the WDS did protect the structures behind the systems for the duration of the study period described in this report.

It is the opinion of the project's principal investigator that OCRM has always had the overall mindset (regarding a study) that the system should be built and then the research team should just step back and watch what happens over the next year. This approach is not applicable to sandbags and should not be applied to the WDS. The research team has always stressed that the WDS is dynamic and needs to be built and modified as often as necessary to address changing beach elevations and dune situations behind the system. To help minimize the negative side effects of hardened structures, the WDS allows water to move behind the system. However, the amount of water allowed through the system should be controlled by renourished sand placed behind the system and dune rebuilding which the system allows via natural accretion needed for such activities.

The only major concern that the research team noted during the study is the temporary local trenching that occurred at times at each site. The trenching never occurred in the previous Seascape studies nor at Ocean Club this year until the last portion of the study period covered in this report. The trenching appears to be related to scour caused by extreme tides, significant erosion events, and the uncontrolled volume of water that is allowed to pass through the system (this same volume of water must escape as the tide goes back out). Although the system is self-healing in all cases, the time required to self-heal after event related local trenching is site specific, and it is the opinion of Citadel researchers that self-healing should not be permitted in all cases. Removing just the horizontal panels in areas of local trenching almost immediately restores the beach profile by eliminating the trenching effect and the horizontal panels are easily removed for this purpose. Researchers spent a lot of time developing vertical panel designs and prototypes for removing the trench since this alternate approach would be much more cost effective (particularly during a study) than complete lowering of the system and since vertical panels could be installed in isolated locations as needed versus lowering which requires a significant portion of the system to be lowered at one time. The use of the vertical panels was not permitted by OCRM. Although an earlier Citadel report stated that "although lowering may alleviate the trenching, we are not planning that this will be the solution. We only propose it to increase energy dissipation," OCRM correspondence to Dr. Mays did not permit the vertical panels and instead OCRM suggested the use of lowering the system which no one was willing to pay for during a short term study. If the sand elevations behind the WDS are maintained on a bimonthly schedule or so, some of this beach compatible sand can be easily and quickly moved to eliminate any potential concerns caused by the temporary trenching on site.

Based on the results of all tests performed to date, the Citadel researchers have concluded that the Wave Dissipation System is able to:

1) protect structures, dunes, flora, and fauna that are landward of the system
2) minimize the potential for negative impacts that are associated with hardened devices, and
3) allow for natural beach elevation changes while providing better protection of dune lines by using a multi-tier system in areas of higher wave energy and a single line system in areas of lower wave energy

At all sites, the WDS protected the structures behind the system and when used as recommended (not as detailed in this study) the results will be even better.

However, The Citadel researchers want to make it very clear, as they always have, that the system is not a one-size fits all solution and that it is a dynamic system that must be designed separately for each particular site, and monitored/adjusted as necessary to optimize its performance.

Ocean Club / Seascape Performance Summary

Installation of the WDS at Ocean Club (see Figure 1) began on April 27, 2015 and continued through the end of June 2015. Although we were not happy with how long it took to install the system, it must be noted that this was the first time the system was installed by the chosen local contractor at Ocean Club and that the tolerance for pile placement is very tight given that the horizontal panels must be placed just right so that they lock into the system. The research team was very disappointed in the small number of piles the contractor was able to install per day (4 or less typical; 8-12 expected) and the precision in which they were located. Many piles were placed incorrectly and had to be reinstalled. Another challenging task was the depth to which the back line of the system was installed. The ocean had not completely lowered the back area closest to the building during the initial install and placing all the housing units back there required a construction excavation area that was challenging to work within. In fact, the contractor didn't even install the full originally proposed footprint since installing housing units and horizontal panels along some portions of the back line was deemed unsafe. On the contrary, the piles for the proposed footprint area were installed, but it was decided that the housing units and horizontal panels would be installed at a later time (after the project kickoff meeting) once the beach lowered the beach elevation in that area. OCRM was notified at the appropriate time and the remaining members were added (see Figure 2). There were also general delays by the contractor where they would have to take days off at a time for scheduling conflicts. Regarding scheduling conflicts, please keep in mind that this is a study and the permitting and approval process (although fully justified and understood) leads to scheduling uncertainty for the contractor making it difficult for them to be able to commit to full time installation services. One could argue that permitting should be done earlier, but the issue the team faces there (on a research project; not on future operations for SI Systems, LLC) is that the property owner has to agree to fund the material and installation costs prior to applications being submitted. These applications (at least for the Corps of Engineers' approval process) require detailed surveys that take additional time. By the time all steps are complete, the property owner is likely in a worse position than when they originally considered doing the study and the team is unfortunately left at the mercy of the contractor's available time.

The baseline configuration for the system was chosen based on the most economical configuration that the research team believed *might* temporarily meet the overall performance objective for the project at this site. It was anticipated that continued beach lowering would require additional tiers of the system since each tier purposely allows some degree of moving water through it. Figure 3 illustrates the research team objective for the WDS at Ocean Club. The site at Ocean Club was not initially inundated by tide waters. As mentioned by the research team during the kickoff meeting, the goal of the Ocean Club study was survival; literally. The purpose of the study was to show that the system can be installed and increased in magnitude to the degree necessary to protect the building similar to the role played by sandbags.

Figure 1. Wave Dissipation System near project start date (photos taken: July 9 (L) and July 19 (R), 2015).

Figure 2. Wave Dissipation System prior to (8/14/15) and after (9/3/15) installation of horizontal panels in area where piles where not covered with housing units during initial construction. Note exposed piles following erosion event on left.

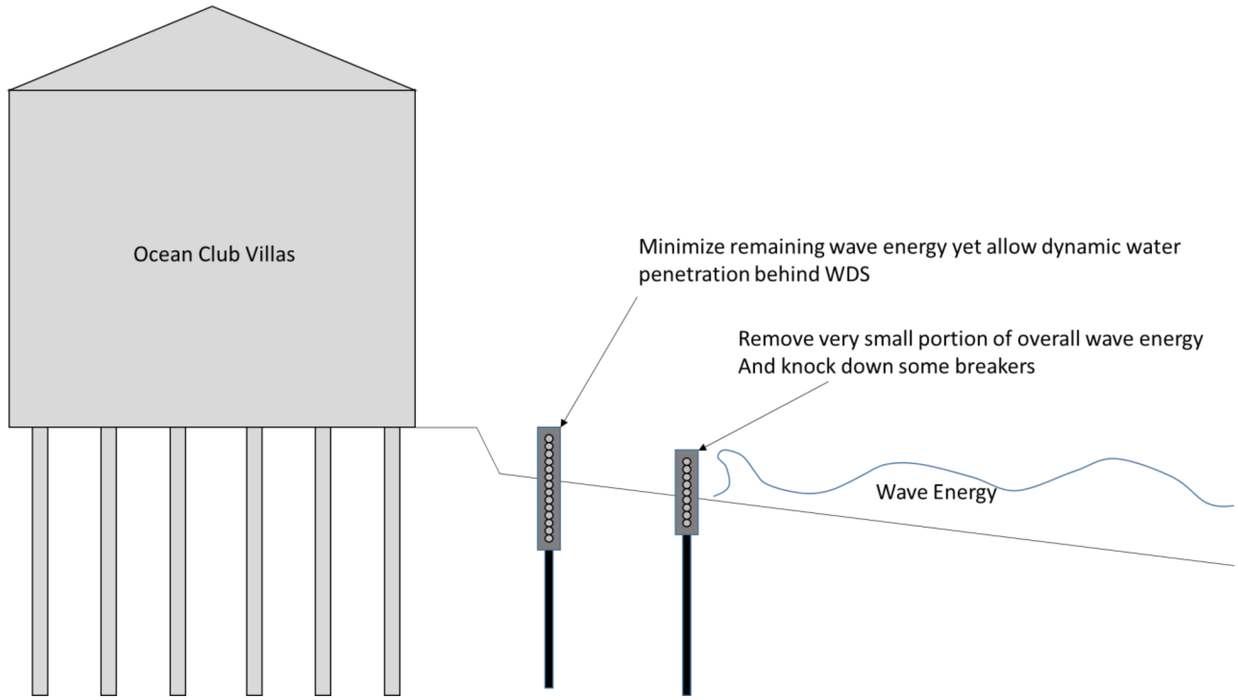


Figure 3. Overall project goal at Ocean Club: minimize energy associated with wave induced moving water behind the WDS.

During the initial part of the study the front line was effectively reducing some of the initial wave energy and the back wall (although it allows complete penetration as designed) kept the wave energy away from the building as much as possible without adding the third tier. Next, the Citadel research team formally requested to make the changes shown in Figure 4. Although OCRM approved the changes (which were always planned), Ocean Club property owners decided to hold off on the third Tier until it was proven that it would be needed and wanted to hold off on extending all the way to the property lines at that time. Dr. Mays made OCRM aware that the overall addition would be only partial due to lack of funding.

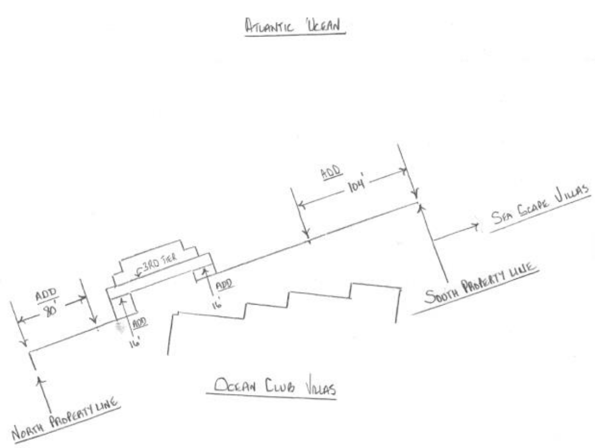


Figure 4. Proposed changes to OCRM dated 9/3/15.

A few negative issues were discovered during the initial portion (1st quarter) of the study. Issue number one was that The Citadel research team and SI Systems, LLC did not, amongst themselves, appropriately communicate the need for the coupling reinforcement (discussed in the Seascape studies of 2013-2014) for all horizontal panels in the project. The Citadel position was that all WDS panels that would see direct hits from breaking waves would need this reinforcement. SI Systems, LLC only placed the coupling reinforcement in the front wall under the assumption that the back wall would not be hit directly by breaking waves but by the run up after the breaking wave (i.e., by broken waves). The back wall was hit by breaking waves and a few panels cracked during the study (at the ends as expected and as discussed in the Seascape studies of 2013-2014). This failure mechanism was listed during the first study as the theoretical controlling mechanism for the panels when couplings were not added. Figure 5 shows one cracked panel. Figure 6 shows the back line receiving breaking wave demands.

The second issue was the extreme tide and extreme surf (relative to typical conditions at Ocean Club) that impacted the area at the end of September (i.e., the since coined "1,000 year storm"). The elevation of the tide was so extreme that waves were actually going over the system. In the best interest of the property owners, the research team recommended that the property owners provide temporary additional protection in the form of sandbags directly in front of the property. Figure 7 shows the advancing scarp line at Ocean Club towards the end of September.

Figure 5. Cracked panel following direct wave hits associated with extreme tides.

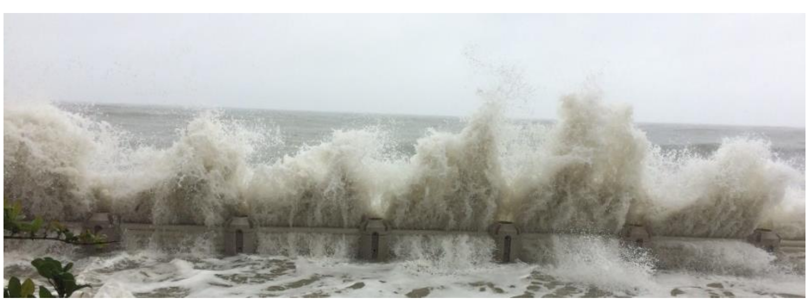


Figure 6. Breaking wave hitting area of WDS with only one line of resistance. Significant penetration is expected without controlled fill behind the WDS (see recommendations and conclusions section).

Figure 7. Advancing scarp adjacent to WDS and insufficient return of WDS (9/23/15). This figure shows how the WDS is intended to work where the scarp line behind the system is reduced relative to the adjacent property. Had the third tier as proposed been provided prior to this figure, the scarp line at the building corner would have been further from the building.

Figure 8 shows the completed WDS installation on site as of 11/19/15. Note that the third tier (2nd line of resistance in picture was added as shown in Figure 9). The system was also extended closer to the property line relative to the 1st quarter of the study.

Figure 8. 2nd quarter configuration on site (with all proposed modifications except full extension to the property line as necessitated by the lowering beach; photo taken: 11/19/15).

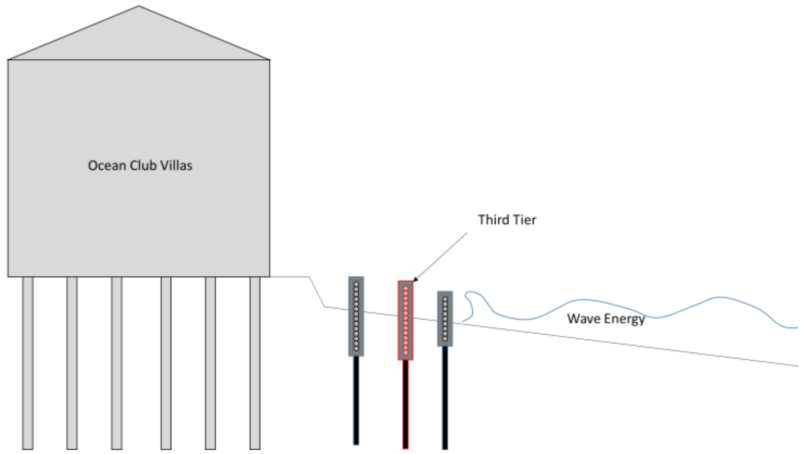


Figure 9. Third Tier installed at Ocean Club (building corner only).

Given the significantly larger wave impacts at OC versus those at the other research sites, the horizontal panels took a beating and the ends of the panels, where they bear on the housing units, and wear down over time. Hence the research team spent time during the third quarter trying several different spacer types made of different materials on the front line of the WDS at Ocean Club during the third quarter of the study. No structural or system changes were made in the process, but the horizontal panels were removed and reset during low tide to see if they would spin less in the slots when the spacers were built of different materials and installed differently.

Ocean club was extended closer to the property line and the Seascape system was installed during third quarter as well. Construction (in two phases) began on December 1, 2015 and ended on February 3, 2015 (see Figure 10).

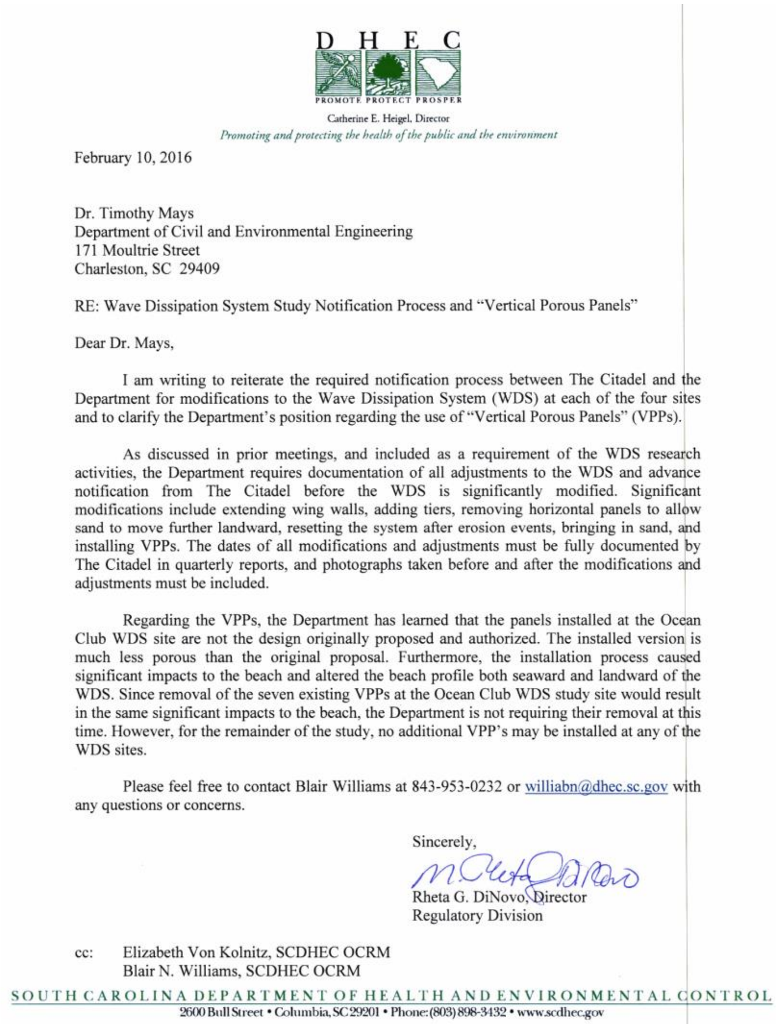
Due to cost and resource constraints, it was decided by the project team that the vertical panels (that were designed over many months) would first be tested on the Isle of Palms. OCRM was notified that the panels would be installed on the Isle of Palms. After the installation of the first basic configuration at one isolated location along the Ocean Club project site, Dr. Mays was sent the letter shown in Figure 11 which stated that vertical panels could no longer be used during the study.

The letter states "Regarding the VPPs, the Department has learned that the panels installed at the Ocean Club WDS site are not the design originally proposed and authorized. The installed version is much less porous than the original proposal." The VPPs are experimental prototypes that must be studied to determine their optimal configuration, hole pattern, length, etc. and the typical sketch given to OCRM was intended to provide an idea of what the panels should like during the first installation. During construction of the panel, the research team found that drilling slots was too difficult (and was damaging the panel) and that holes would work better. Hence the team made the decision to move forward with holes instead of slots. In addition, the actual as constructed version of the panel was actually more porous than the proposed version considering its overall purposely placed installation configuration. The goal of studying the vertical panels was to determine the optimal porosity and configuration. The research team spent hours designing different details for the porosity prior to OCRM saying that the VPPs could no longer be tested. We are very disappointed that the research team's main proposed method (prior to the expensive option of lowering of the system) for removing the team's one major concern from the study at Ocean Club and Seascape was not allowed to be studied for stated technical reasons that are not justified nor based on engineering mechanics, coastal engineering, or coastal geology principals.

It was further stated in the letter that . . . "the installation process caused significant impacts to the beach and altered the beach profile both seaward and landward of the WDS." From a technical and engineering position, the installation sequence has a trivial impact on the surrounding beach profile. One tide cycle later, any offset areas are automatically corrected by the dynamic movement of water on site at Ocean Club.

Finally, the letter states that "since removal of the seven existing VPPs at the Ocean Club WDS study site would result in the same significant impacts to the beach, the Department is not requiring their removal at this time. However, for the remainder of the study, no additional VPP's may be installed at any of WDS sites." On the contrary, the research team decided that a partially installed test configuration cannot be studied and could eventually yield artificially poor results local to the panels. The team notified OCRM of this position and removed the partially installed vertical panels immediately.

Figure 10. OC north extension (1-14-16) and Seascape during installation yet prior to 3rd tier completion (1-9-16).



D H E C

PROMOTE PROTECT PROSPER

Catherine E. Heigel, Director

Promoting and protecting the health of the public and the environment

February 10, 2016

Dr. Timothy Mays
Department of Civil and Environmental Engineering
171 Moultrie Street
Charleston, SC 29409

RE: Wave Dissipation System Study Notification Process and "Vertical Porous Panels"

Dear Dr. Mays,

I am writing to reiterate the required notification process between The Citadel and the Department for modifications to the Wave Dissipation System (WDS) at each of the four sites and to clarify the Department's position regarding the use of "Vertical Porous Panels" (VPPs).

As discussed in prior meetings, and included as a requirement of the WDS research activities, the Department requires documentation of all adjustments to the WDS and advance notification from The Citadel before the WDS is significantly modified. Significant modifications include extending wing walls, adding tiers, removing horizontal panels to allow sand to move further landward, resetting the system after erosion events, bringing in sand, and installing VPPs. The dates of all modifications and adjustments must be fully documented by The Citadel in quarterly reports, and photographs taken before and after the modifications and adjustments must be included.

Regarding the VPPs, the Department has learned that the panels installed at the Ocean Club WDS site are not the design originally proposed and authorized. The installed version is much less porous than the original proposal. Furthermore, the installation process caused significant impacts to the beach and altered the beach profile both seaward and landward of the WDS. Since removal of the seven existing VPPs at the Ocean Club WDS study site would result in the same significant impacts to the beach, the Department is not requiring their removal at this time. However, for the remainder of the study, no additional VPP's may be installed at any of the WDS sites.

Please feel free to contact Blair Williams at 843-953-0232 or williabn@dhec.sc.gov with any questions or concerns.

Sincerely,

Rheta G. DiNovo, Director
Regulatory Division

cc: Elizabeth Von Kolnitz, SCDHEC OCRM
Blair N. Williams, SCDHEC OCRM

SOUTH CAROLINA DEPARTMENT OF HEALTH AND ENVIRONMENTAL CONTROL
2600 Bull Street • Columbia, SC 29201 • Phone: (803) 898-3432 • www.scdhec.gov

Figure 11. Letter from OCRM stating vertical panels could not be tested.

During the 4th quarter of the study, The Citadel recommended a 2 ft reset of many piles downward as the beach had reached it most severe lowering to date (see Figure 12). Although the system is extremely self-healing after significant erosion events (see Figure 13), around mid-April 2016 and mid-May 2016 the piles in the row closest to the ocean in front of the building and much of the entire back row (around the building corner) were lowered 2 ft to improve performance. The back row piles were also spliced using a bolted pile segment with new housing units to keep the top of the pile near its originally installed elevation (see Figure 14). The bolted pile segments performed optimally for the remaining portion of the study period discussed in this report.

As a final note regarding the WDS at OC, just to show how the system performs over a monthly cycle, Figure 15 presents 11 pictures taken over a one and one-half month period where significant erosion, self-healing, and accretion can be clearly seen. If The Citadel had not received the letter stating the study must end on July 28, 2016, they would have recommended dune rebuilding given the huge amount of accreted sand flowing on the test site at that time (similar to BWE recommendation made in December 2015 which was denied by OCRM).

Figure 12. Severe beach lowering at OC prior to pile lowering (picture taken 2/25/16).

Figure 13. Self-healing of WDS (picture taken 3/7/16).

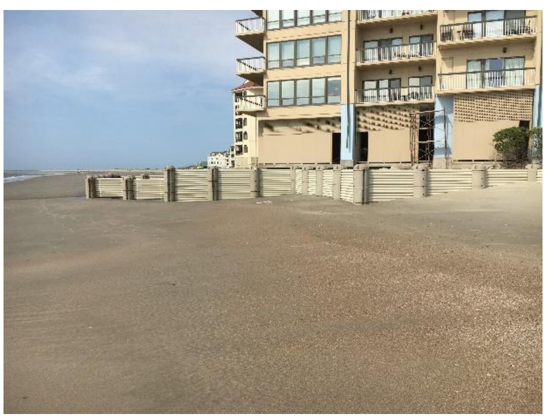


Figure 14. WDS at OC after lowering of front line and back line with extensions at select backline elements (picture taken 5/2/16).

6/16/16 6/21/16 7/1/16

7/5/16 7/9/16 7/16/16

7/18/16 7/19/16 7/21/16

7/24/16 7/30/16

Figure 15. WDS self-healing and accretion following severe erosion event with trenching at WDS line.

Throughout the entire study, The Citadel research team was very happy with the WDS performance as installed *without modification* at Seascape. Figure 16 shows the typical condition of the WDS on site and Figure 17 shows the significant accretion on site at the end of July 2016.

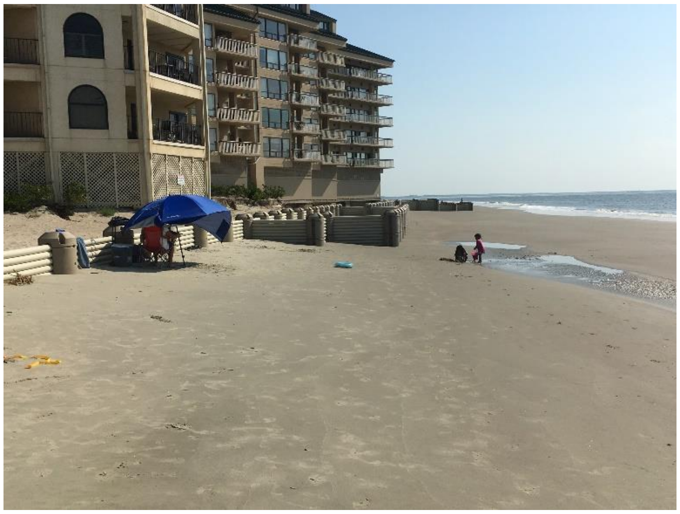


Figure 16. Typical Seascape performance during study (picture taken 6/3/16).

Figure 17. Seascape performance at end of July 2016 (picture taken 7/30/16). Note significant accretion.

Survey data for the OC/SS site is provided as separate files along with this report. Our review of the surveys and the related data (sand volumes gained and lost over time) leads to the conclusion that there is no negative or significant impact by the WDS on the adjacent beach profile at the OC/SS site. The only noted issue is the very temporary occurrence of trenching at isolated locations on the OC side of the site. Trenching, caused by significant erosion events, and related to the system's allowance of rising tide levels (with moving water) behind the WDS can, when deep enough, become a concern. The study has shown that the system is always self-healing and that the trenching is always temporary. On the contrary, deep trenching on site should not be allowed and must be mitigated anytime it appears on site. OCRM did not permit the removal or mitigation of trenching using research means planned for the study and for some reason only permitted the extremely expensive and much more significant site altering option of lowering the entire system. It has always been known that flooding the system using isolated panel removal can easily remove trenching and is almost instantaneous. Citadel recommendations regarding simple trench mitigation (outside of fictitious study constraints) are provided in the overall conclusions to this report.

Beachwood East Performance Summary

Installation of the WDS at Beachwood East (see Figure 18) began on July 28, 2015 and continued through October 20, 2015. We were not happy with the required installation time which was extended as a result of the overall length of the system, coordination with an existing illegal revetment on the project site, working between tides in a relatively low lying area, overall scheduling with the available contractor, and most importantly, issues with the installation which included an improper elevation at the south end and a lack of openings in the housing units to allow them to fill with sand and water.

The baseline configuration for the system was chosen based on the most economical configuration that the research team believed *might* temporarily meet the overall performance objective for the project at this site. It was anticipated that continued beach lowering could require a second tier for the system since each tier purposely allows some degree of moving water through it. Figure 19 illustrates the research team objective for the WDS at Beachwood East. The site at Beachwood East is more complex than Ocean Club and Harbor Island since it is both tidal and subject to larger waves. It was selected as a study site for that reason.

Figure 18. Wave Dissipation System at Beachwood East (10/11/15).

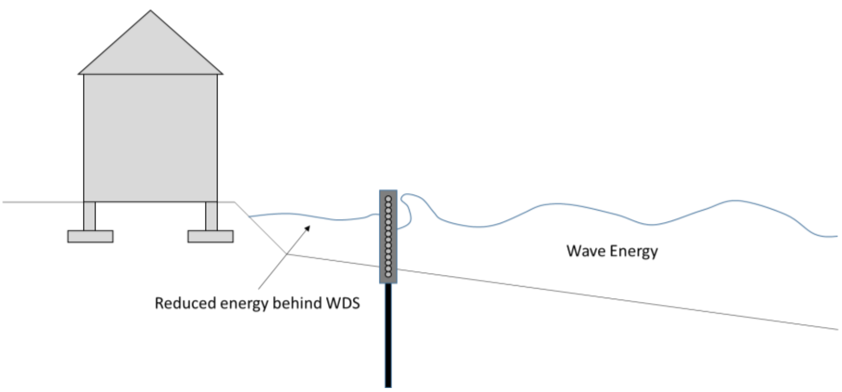


Figure 19. Overall project goal at Beachwood East: minimize energy associated with wave induced moving water behind the WDS.

The only plans for Beachwood East for the 2nd quarter research were to observe performance of the WDS during various tide cycles and wave conditions and to design and test feasible solutions (vertical panels were the primary focus) for removing the trench that had previously appeared (see Figure 20) and sometimes to unacceptable depths and to possibly add a 2nd tier if funding became available. Due cost and resource constraints, it was decided by the project team that the vertical panels would first be tested on the Isle of Palms. OCRM was notified that the panels would be installed on the Isle of Palms. After the installation of the first basic configuration at one isolated location along the Ocean Club project site, Dr. Mays was sent the letter shown in Figure 11 and discussed in the previous section.

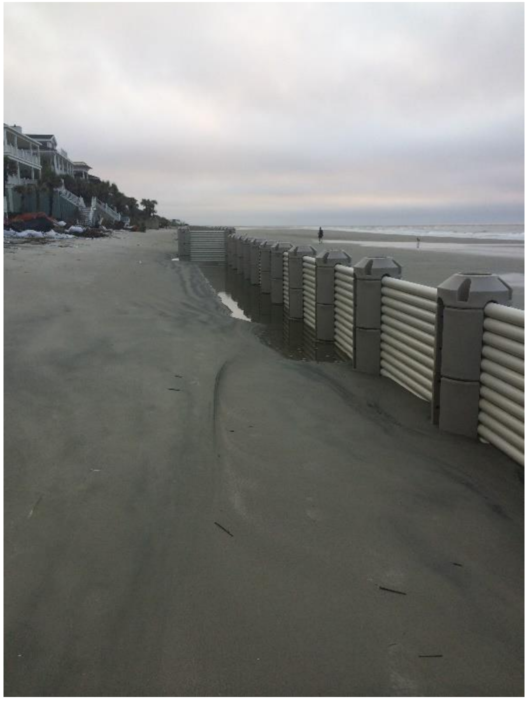


Figure 20. Typical trench at Beachwood East during the previous quarter report period (caused by scour as water exits the WDS; photo taken: 11/4/15).

During the first two weeks of the 2nd quarter, the team quickly discovered that closing all of the slots was causing the trench to quickly subside. A period of massive accretion in front of and behind the system then began and the team quickly provided slots and removed select panel locations for three days to more quickly expedite the accretion behind the wall (see Figure 21). The lightweight, dynamic components making up the system allowed for this action. All slots and openings were then closed to slow the release of the accreted sand. The slots were 4 inches high and placed in every 10th panel (on average) over part of the system length. The slots were placed at or above grade (see Figure 22).

Figure 21. Significant accretion through the WDS during the 2nd quarter. The figures from left to right are dated 11-30-15, 12-8-15, and 12-24-15.

Figure 22. Typical opening used as Beachwood East.

Noticing the enormous level of accretion (as shown in Figure 21) and the research team forecast for several more weeks of accretion, Dr. Mays acted quickly and notified OCRM that the team wanted to test (as shown clearly during the previous Seascape study) that the sand accreting behind the system could be pushed back to allow the homeowners to reclaim the sand they lost from the 1,000 year event, to rebuild the dune to its initial configuration prior to the 1,000 year event, and to allow the removal of sandbags (which served no purpose) that the homeowners bought as added protection after the 1,000 year event damage to their property. It seemed like a perfect win-win for the research team and the community. However, OCRM did not allow the research team to prove that it could function in this capacity. This was disappointing since it is very important to prove that the system can perform as advertised.

With the trenching issue unresolved due to permission denied by OCRM for the vertical panel installation study (which would have been extremely economical) and funding not available to do one of two larger secondary Citadel recommendations which included either lowering the entire system (very expensive) or adding a 2nd tier and opening up the first tier (even more expensive and similar to OCs initial installation), the research team decided to simply watch the system during the final two quarters of the study period covered in this report. The only modification applied in the final two quarters of the study was to extend the wing wall on the north end of the site during turtle season due to concerns that a sea turtle might otherwise get trapped behind the system (see Figure 23).

The performance at Beachwood East was not optimal due to the continued trenching (on and off yet self-healing over time). Recommendations for optimal performance and for simple trenching mitigation methods are made in the conclusions to this report.

Survey data for the BWE site is provided as separate files along with this report. Our review of the surveys and the related data (sand volumes gained and lost over time) leads to the conclusion that there is no negative or significant impact by the WDS on the adjacent beach profile at the BWE site. The only noted issue is the off and on occurrence of trenching at isolated yet significant locations along the site. Trenching, caused by significant erosion events, and related to the system's allowance of rising tide levels (with moving water) behind the WDS can, when deep enough, become a concern. The study has shown that the system is always self-healing and that the trenching is always temporary. On the contrary, deep trenching on site should not be allowed and must be mitigated anytime it appears on site. OCRM did not permit the removal or mitigation of trenching using research means planned for the study and for some reason only permitted the extremely expensive and much more significant site altering option of lowering the entire system. It has always been known that flooding the system using isolated panel removal can easily remove trenching and is almost instantaneous. Citadel recommendations regarding simple trench mitigation (outside of fictitious study constraints) are provided in the overall conclusions to this report.

Figure 23. Sandbag extension on north end to allow for access to sandbags behind the WDS and provide closure to sea turtle access.

<u>Harbor Island Performance Summary</u>

Installation of the WDS at Harbor Island (see Figure 24) began on May 11, 2015 and continued through the end of June 2015. Since the parts were custom ordered, material delays played some role in the longer than anticipated installation time. Getting approval and scheduling were the major hurdles at this site. There was also (a) some initial confusion over whether or not we would be able to protect the open lot between homes, (b) a delay due to a homeowners request to avoid getting too close to a palm tree on site, (c) a delay due to scheduling with ARB on access approval and actually building the walkway over the WDS, and (d) general delays by the contractor where they would have to take days off at a time for scheduling conflicts. Regarding scheduling conflicts, please keep in mind that this is a study and the permitting and approval process (although fully justified and understood) leads to scheduling uncertainty for the contractor being able commit to full time installation services.

The baseline configuration for the system was chosen based on the most economical configuration that the research team believed *might* satisfactorily meet the overall performance objective for the project at this site. Figure 25 illustrates the research team objective for the WDS at Harbor Island. The site on Harbor Island is tidal in that 2-5 ft of water behind the system is typical at high tide and the actual height varies with the site's tide chart. The tide presented new challenges not studied during the 2013-2014 Seascape research projects as discussed below.

Figure 24. Wave Dissipation System near project start date (photos taken: August 8, 2015).

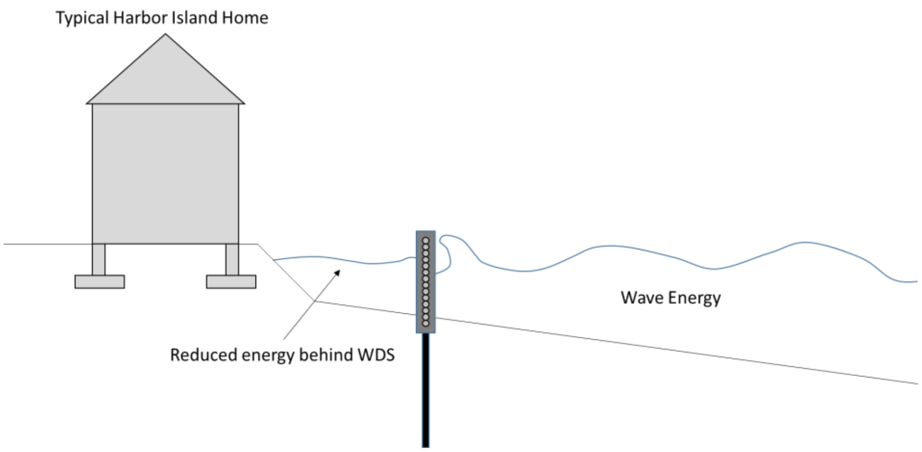


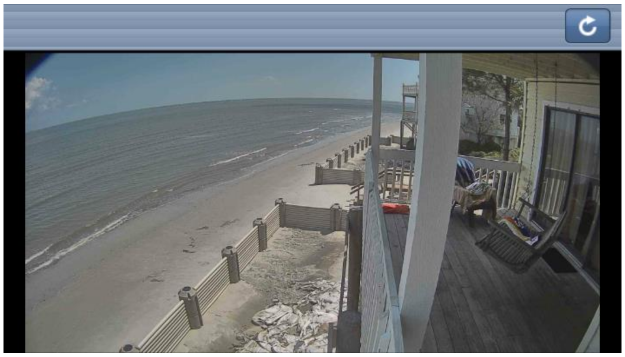
Figure 25. Overall project goal at Harbor Island: minimize energy associated with wave induced moving water behind the WDS.

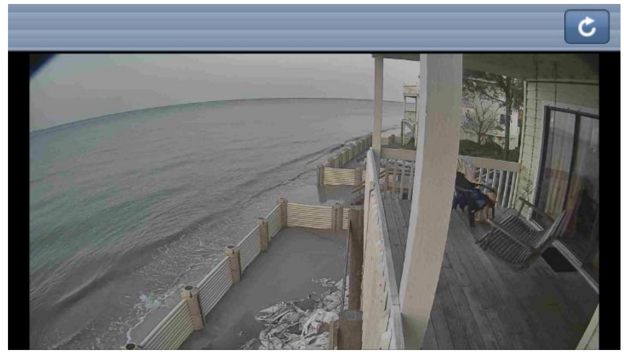
It was decided that the baseline WDS would have no spacers (see Figure 26) between horizontal panels at project initiation. Although at first, there was some accretion, the wave energy was not strong enough to push it more than three ft or so beyond the WDS (see Figure 27). This led to an unacceptable low space (relative to the accreted area) beyond the accreted sand. It should be noted that the horizontal panel system at Harbor Island was designed to be over two times as flexible as the one installed at Ocean Club (and Seascape in 2013-2014). This flexibility alone did not provide adequate "breathing" of the ocean such that a more uniform distribution of accreted sand fell behind the system. For that reason, the research team added some trial spacers to encourage more natural sand accretion behind the system. The initial result of the added spacers was an improved distribution of sand behind the system as shown in Figure 28.

Soon after, the site developed what has been the biggest issue at Harbor Island. As the beach lowered and the added spacer elevations became too high (relative to the beach profile) to allow for exit water to efficiently leave the area behind the WDS, a trench developed directly under the system (See Figure 29).

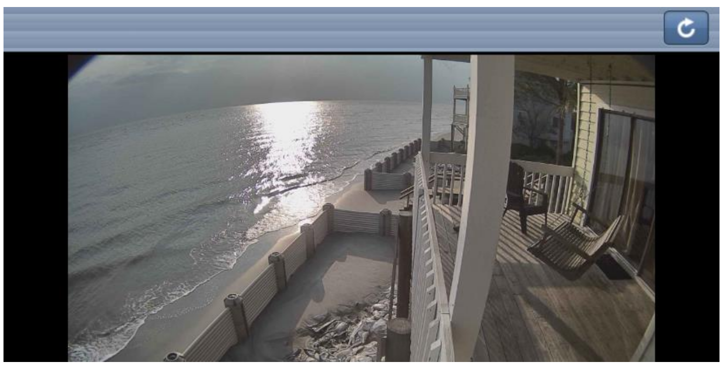
Figure 26. Close-up of typical spacer used in the study.

Figure 27. Initial, very localized, accretion (typical with no spacers) behind WDS (photo taken: 7/17/15).





(A) (B)



(C)

Figure 28. Only adjustment made at Harbor Island in First Quarter and results from the modification. (A) prior to installation of slots on 8/25/15; (B) 24 hours later; (C) 36 hours later. Note that significant sand accretion occurred after the slots were added.

Figure 29. Typical temporary trench issue on site (caused by scour as water exists the WDS and insufficient spacers; photo taken: 9/8/15).

Figure 30 shows the typical trench on site as of 11/20/15. Spacers were located and several locations during the second quarter of this study and it was determined that they are not the ideal solution to trenching. They help at times but they must be constantly adjusted with changing elevations. It should be noted that the entire study area did not trench significantly. The side toward the Hampton's residence didn't trench like the rest of the study area.

Figure 30. Typical trench issue on site (caused by scour as water exits the WDS and insufficient spacers; photo taken: 11/20/15).

One of the biggest issues with Harbor Island involved the lack of funding for changes since the natural scarp retreat caused by the 1,000 year flood event resulted in a definite need for the WDS to extend back to the new scarp location. The team was told that the homeowners wouldn't pay for any changes prior to scraping which was understood since scraping was to occur only a few months later.

The only plans for Harbor Island for the 3rd quarter research were to observe performance of the WDS during various tide cycles and wave conditions, to design and test feasible solutions (vertical panels were the primary focus) for removing the temporary trench that had previously appeared too often (see Figure 30) and sometimes to unacceptable depths, and to temporarily remove panels as needed in conjunction with the island's proposed scraping project. Due to cost and resource constraints, it was decided by the project team that the vertical panels would first be tested on the Isle of Palms. OCRM was notified that the panels would be installed on the Isle of Palms. After the installation of the first basic configuration at one isolated location along the Ocean Club project site, Dr. Mays was sent the letter shown in Figure 11 and discussed in a previous section.

Although the trench remained a temporary issue throughout the 3rd and 4th quarter, it was not present for most of the study and when it did form it was self-correcting over the next few tide cycles as shown in Figure 31. During a site visit purposely made when the trench appeared to be at its deepest level, it was found to be less than 2 ft deep.

Figure 31. Typical trench self-healing and accretion over a three day period (January 25-January 27, 2016). Note bags being covered by accreting sand.

The new scarp location was assessed after the scraping (entire month of February; see Figure 32) was completed and it was determined that the WDS needed extensions. Being as study, the team proposed using alternate materials for the vertical members back into the retreated scarp line (see previous discussion regarding 1,000 year event) since these members wouldn't affect the study, would save thousands of dollars (no funding was available), and could be added more quickly since the plastic elements would require a custom special order be placed. OCRM denied this request and the team was told that all the material would have to be the same as installed for all other vertical elements.

Figure 33 shows the typical scraping size used for the island at participating home sites. The scraping was a pile of sand 12 to 15 ft wide by 5 to 6 ft tall on average.

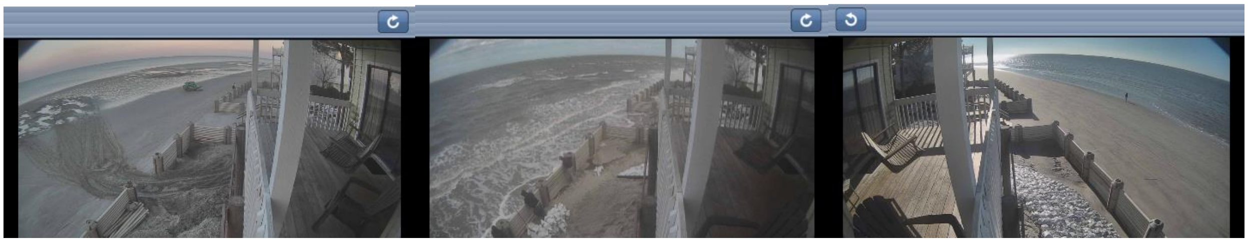


Figure 32. Scraping behind WDS at Gardner's residence (February 29 – March 4, 2016).

Figure 33. Typical scraping adjacent to WDS (February 5, 2016).

Survey data for the HI site is provided as separate files along with this report. Our review of the surveys and the related data (sand volumes gained and lost over time) leads to the conclusion that there is no negative or significant impact by the WDS on the adjacent beach profile at the HI site. The only noted issue is the temporary occurrence of trenching at isolated locations along the site. Trenching, caused by significant erosion events, and related to the system's allowance of rising tide levels (with moving water) behind the WDS can, when deep enough, become a concern. The study has shown that the system is always self-healing and that the trenching is always temporary. On the contrary, deep trenching on site should not be allowed and must be mitigated anytime it appears on site. OCRM did not permit the removal or mitigation of trenching using research means planned for the study and for some reason only permitted the extremely expensive and much more significant site altering option of lowering the entire system. It has always been known that flooding the system using isolated panel removal can easily remove trenching and is almost instantaneous. Citadel recommendations regarding simple trench mitigation (outside of fictitious study constraints) are provided in the overall conclusions to this report.

Sandbags vs. WDS

The purpose of this section of the report is to compare and contrast the subjective and objective relative merit of sandbags versus the WDS in regards to beach erosion. Currently, in South Carolina, minor renourishment, sand scraping, and the use of sandbags are permitted, but only under emergency order regulations. For some property owners, the only feasible and permitted solution is often the continuous and expensive stacking and replacing of large (or small in some cases) sandbags in front of their threatened structure. See Figure 34 for a side by side comparison of a sandbag versus WDS applications on the Isle of Palms.

Figure 34. Sandbags and WDS providing erosion and building foundation protection.

Although Figure 34 shows clearly the aesthetic benefit of the WDS, the situation with sandbags can very quickly deteriorate as sandbags fall apart, fall over, or become buried as dynamic surf pounds the bags. Although the home and building owners are ultimately responsible for their removal, the bags often times wind up permanently buried or floating out to sea (see Figure 35).

The previous sections of this report attempted to show that the WDS could provide a similar level of protection and erosion control to that provided by sandbags. The results are somewhat misleading since the WDS was not tested in the manner recommended by The Citadel but rather using fictitious constraints mandated by OCRM. The remaining portion of this section provides a more quantitative environmental comparison of sandbags versus the WDS.

Figure 35. Deteriorated/buried sandbags and individuals pulling sandbags from the surf.

Environmental Impact

Beyond technical effectiveness, environmental impact is an important factor in selecting an erosion mitigation strategy. One measure of environmental impact is the lifecycle embodied energy of a product, which includes the initial embodied energy associated with raw materials and installation, the recurrent embodied energy associated with operation and maintenance, as well as the final disposal energy (Masters 2001, Crawford 2012). Indeed, a “cradle-to-grave” approach can be used to compare the environmental impacts of competing product alternatives based on overall energy intensity (Meyer, Creux et al. 2006, McAlinden 2015). When conducting a comparative embodied energy analysis, it is important to consider the durability of each product. For instance, a low embodied energy product that has to be frequently replaced may be more detrimental to the environment than a product with high embodied energy that lasts for a long period of time. Consequently, embodied energy per lifetime has been suggested as a more meaningful indicator of environmental impact than total embodied energy (Kibert 2008). Environmental impact of both the WDS and sandbags was captured by considering embodied energy per lifetime over each product’s life cycle, as installed at the three experimental sites (Figure 36). Calculations are intended to be order-of-magnitude estimates. Sample calculations comparing the WDS to sandbags at the BWE site are included in Appendix A.

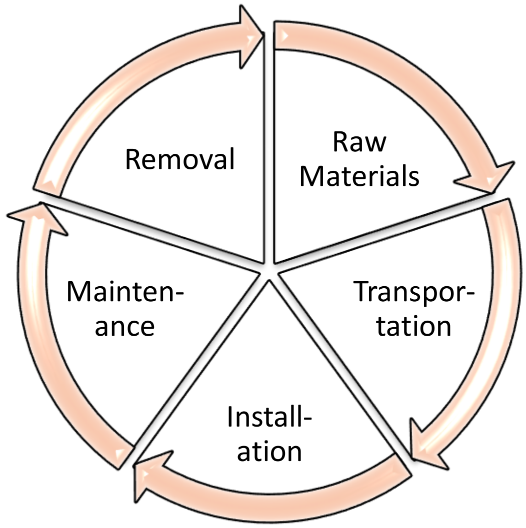


Figure 36. Life cycle of WDS and sandbags for erosion mitigation.

Functional Unit of Analysis

A functional unit is often used during lifecycle analysis in order to compare two different products (Horne, Grant et al. 2009). The WDS functional unit protects approximately 8 ft of coastline at OC/SS and 10 ft at HI. At BWE and HI, the functional unit includes one tier of a single FRP pile and two sets of horizontal panels (one on either side of the pile). At OC/SS, a two-tiered configuration was assumed. For sandbag analysis, the number of sandbags required to protect 8 or 10 ft of coastline, depending on the site, was considered as a functional unit. Initial, functional sandbag configurations were estimated for each site based on observations and photographs. Accordingly, OC/SS, BWE, and HI were assumed to require 4, 4, and 30 sandbags/ft to provide reasonable shoreline protection. "Large" (3000 lb) sandbags were used at OC/SS and BWE, while "small" (50 lb) sandbags were used at HI.

Raw Materials

The raw materials that compose a product contribute to initial embodied energy (Tables 1-2). The WDS is composed primarily of plastic components, including polyvinyl chloride (PVC), high density polyethylene (HDPE), and fiber-reinforced plastic. Given the energy-intensive requirements of manufacturing fossil-fuel-based plastics, the raw materials embodied energy of WDS components is fairly high. However, the relatively long life of plastic components results in a more favorable embodied energy per lifetime. Despite the large quantity of sand required at each site (up to 96,000 lb), the raw materials embodied energy of sandbags is much lower than for the plastic-derived WDS. However, given that the large sandbags begin to photodegrade after 1200 hr, the WDS is less energy intensive on a per lifetime basis.

Table 1. Initial embodied energy (EE) associated with WDS raw materials.

	Tier Weight per Unit (lb)		Coeff-icient[3] (MJ/kg)	Life (yr)	Raw Materials EE (MJ)			Normalized Raw Materials EE (MJ/yr)		
	OC/SS[1]/ BWE[2]	HI[2]	All	All	OC/ SS	BWE	HI	OC/ SS	BWE	HI
FRP Pile	183	183	103	50	83,036	41,518	41,518	1,661	830	830
Panels	192	240	70	2	59,208	29,604	37,004	29,604	14,802	18,502
Housing	210	210	103	25	95,286	47,643	47,643	3,811	1,906	1,906
Cap	10	10	103	25	4,538	2,269	2,269	181	91	91
WDS	595	643	-	-	242,066	121,033	128,434	**35,257**	**17,629**	**21,329**

[1]Two tiers used for calculation of EE.

[2]One tier used for calculation of EE.

[3]From Grams (2005).

Table 2. Initial embodied energy (EE) associated with sandbag raw materials.

	Quantity (#/ft)	Total Weight (lb/unit)	Raw Materials EE Coefficient (MJ/kg)	Estimated Lifetime (yr)	Raw Materials EE (MJ)	Normalized Raw Materials EE (MJ/yr)
OC/SS	4	96,000	0.1	0.137	21,145	**154,361**
BWE	4	96,000	0.1	0.137	21,145	**154,361**
HI	30	15,000	0.1	0.137	3,304	**24,119**

Transportation

Initial embodied energy also includes transportation of raw materials (Tables 3-4). The WDS components arrived via heavy truck from Pennsylvania, Ohio, or Minnesota, while sand for most of the sites originated from Summerville, SC. Energy associated with transportation of freight is weight-dependent (approximately 0.002 MJ/kg-mi) (Cambridge Systematics 2013). Due to the large amount of sand that must be transported and the short sandbag lifetime, both the total embodied energy and embodied energy per lifetime associated with transportation of raw materials is higher for the use of sandbags, as compared to the WDS.

Table 3. Initial embodied energy (EE) associated with transportation of WDS components.

	Origin	Total Distance to SC[1]	Transportation EE (MJ)	Normalized Transportation EE (MJ/yr)
FRP Pile	PA	700	94	2
Panels	OH	600	84	42
Housing	MN	1400	216	9
Cap	MN	1400	10	0
WDS	-	-	404	**53**

[1]Estimated from Google Maps (Search = Origin to SC).

Table 4. Initial embodied energy (EE) associated with transportation of sandbags.

	Origin	Total Distance to SC[1]	Transportation EE (MJ)	Normalized Transportation EE (MJ/yr)
OC/SS	Summerville, SC	40	2,816	**20,555**
BWE	Summerville, SC	40	2,816	**20,555**
HI	Summerville, SC	40	440	**3,212**

[1]Estimated from Google Maps (Search = Summerville to Site) for OC/SS and BWE. Comparable distance assumed for HI.

Installation

The final contributor to initial embodied energy is installation of product components (Tables 5-6). At OC/SS and BWE, setting FRP piles and housing units was completed using a 6,000 lb forklift and an 18,500 lb mini-excavator. At HI, only a 15,000 lb mini-excavator was used. On average, WDS machinery operates for only 20 minutes during the installation of one functional unit. Installation of all other WDS components was completed without the use of machinery.

Several pieces of equipment were assumed to fill sandbags at OC/SS and BWE. An 18,500 lb mini-excavator was used to fill sandbags that were held by a forklift (approximately 4000 lb). A second forklift (approximately 6,000 lb) was assumed to run along the beach to place filled sandbags. It was estimated that each of the three pieces of equipment operated continuously for approximately 7 minutes to fill and place a single sandbag. Only a skid steer (100 hp) was used to facilitate placement of small sandbags at HI. Due to the often continuous operation of machinery and large number of sandbags, the installation embodied energy (both total and normalized) is higher for the use of sandbags, as compared to the WDS.

Table 5. Initial embodied energy (EE) associated with installation of WDS.

	Machinery Operation Time[1] (hr/unit)	Forklift[2] Energy (MJ)		Excavator Energy (MJ)		Total Installation EE (MJ)		Normalized Installation EE (MJ/yr)	
	All	OC/SS/BWE	HI	OC/BWE[3]	HI[4]	OC/SS/BWE	HI	OC/SS/BWE	HI
FRP Pile	0.33	88.8	0	32.4	25.2	121	25	2	1
Housing	0.33	88.8	0	32.4	25.2	121	25	5	1
WDS	0.7	177.6	0	64.8	50.4	242	50	**7**	**2**

[1]Estimated 20 min of operation time per WDS functional unit.

[2]74 kW, based on representative 6,000 lb forklift.

[3]27 kW, based on representative 18,500 lb mini-excavator.

[4]21 kW, based on representative 15,000 lb mini-excavator.

Table 6. Initial embodied energy (EE) associated with installation of sandbags.

	Machinery Operation Time (hr/unit)	Lg Forklift[1] Energy (MJ)	Sm Forklift[2] Energy (MJ)	Excavator[3] Energy (MJ)	Skid Steer Energy[4] (MJ)	Total Installation EE (MJ)	Normalized Installation EE (MJ/yr)
OC/SS	0.117	994.6	658.6	362.9	0	2,016	**14,717**
BWE	0.117	994.6	658.6	362.9	0	2,016	**14,717**
HI	0.0167	0	0.0	0.0	1350	1,350	**9,855**

[1]74 kW, based on representative 6,000 lb forklift.

[2]49 kW, based on representative 4,000 lb forklift.

[3]27 kW, based on representative 18,500 lb mini-excavator.

[4]75 kW, based on representative 100 hp skid steer.

Maintenance

Recurring embodied energy results from regular product maintenance (Tables 7-8). While maintenance events can vary depending on weather and coastal patterns, the most likely energy-consuming event for the WDS is use of a mini-excavator (18500 lb) to vibrate down uplifted piles. One vibration event per year was assumed. In contrast, maintenance of sandbags is more energy intensive (on a per lifetime basis), as a forklift (6000 lb) is required to lift large, sunken sandbags. While the number of lifting maintenance events can also vary widely, it was estimated that on average it takes two weeks for a large sandbag to sink. In addition, it was estimated that it requires approximately 30 hr of operation time to lift 1000 ft of sunken sandbags (depends highly on number of sunken sandbags and degree of sinking). Small sandbags at HI were assumed to be lifted without machinery. Total and normalized recurring embodied energy is lower for the WDS, as compared to sandbags.

Table 7. Recurring embodied energy (EE) associated with vibrating down WDS FRP piles.

	Excavator[1] Operation Time (hr/unit)	Maintenance Events[2] (#/lifetime)	Total Maintenance EE (MJ)	Normalized Maintenance EE (MJ/yr)
OC/SS	0.033	50	160	**3**
BWE	0.033	50	160	**3**
HI	0.033	50	160	**3**

[1]27 kW, based on representative 18,500 lb mini-excavator.

[2]Conservative estimate of one vibration maintenance event per year.

Table 8. Recurring embodied energy (EE) associated with lifting sandbags.

	Forklift[1] Operation Time[2] (hr/unit)	Maintenance Events[3] (#/lifetime)	Total Maintenance EE (MJ)	Normalized Maintenance EE (MJ/yr)
OC/SS	0.24	4	256	**1,867**
BWE	0.24	4	256	**1,867**
HI	0	0	**0**	**0**

[1]74 kW, based on representative 6000 lb forklift.

[2]Lifting assumed to take 5 days (6 hr/day) per 1000 ft. Rough estimate, since maintenance is highly variable.

[3]Required lifting assumed to be needed every two weeks, although could be required sooner or later.

Removal

After the useful life of a product, it must be removed (Tables 9-10). To remove the WDS from the beach, a mini-excavator (15,000 lb) and a forklift (6,000 lb) were used to remove the FRP piles and housing units. On average, WDS machinery operated for 25 min during the removal of one functional unit. Removal of all other WDS components is completed without the use of machinery.

Large sandbags at OC/SS and BWE were removed using two mini-excavators (52,410 and 15,000 lbs). It was estimated that 1.5 min of machine operation time was required to remove a single large sandbag from the beach. Due to the continuous operation of machinery and large number of sandbags, the removal embodied energy (both total and normalized) is higher for the use of sandbags, as compared to the WDS. No machinery was used for filling and placement of small sandbags at HI.

The ultimate fate of waste materials also differs between the WDS and sandbags. When WDS elements are replaced or removed, plastic components are easily collected and recycled. However, even with systematic removal of sandbags, the bags themselves are shredded and often remain on the beach or are washed away by the tides. Consequently, continued use of sandbags can lead to accumulation of solid waste both on the beach and in the ocean.

Table 9. Embodied energy (EE) associated with WDS removal.

	Machinery Operation Time[1] (hr/unit)	Forklift[2] Energy (MJ)	Excavator[3] Energy (MJ)	Total Installation EE (MJ)	Normalized Installation EE (MJ/yr)
FRP Pile	0.42	111.0	31.5	143	**3**
Housing	0.42	111.0	31.5	143	**6**
WDS	0.7	122.0	63.0	285	**9**

[1]Assumed 25 min for FRP pile and 25 min for housing units.

[2]74 kW, based on representative 6000 lb forklift.

[3]21 kW, based on representative 15,000 lb mini-excavator.

Table 10. Embodied energy (EE) associated with WDS removal.

	Machinery Operation Time[1] (hr/unit)	Lg Excavator[2] (MJ)	Sm Excavator[3] (MJ)	Total Installation EE (MJ)	Normalized Installation EE (MJ/yr)
OC/SS	0.8	385.9	60.5	**446**	**3,259**
BWE	0.8	385.9	60.5	**446**	**3,259**
HI	0	0	0	**0**	**0**

[1]Estimated 1.5 min/sandbag. Machinery operation time (hr/unit) estimated based on sandbag configuration at each site.

[2]134 kW, based on representative 52,410 lb mini-excavator.

[3]21 kW, based on representative 15,000 lb mini-excavator.

Lifecycle Embodied Energy

On a per lifetime basis, the WDS is less energy-intensive than the use of sandbags at the OC/SS, BWE, and HI sites (Figure 37). In fact, at OC/SS, BWE, and HI the WDS embodied energy per lifetime was 82, 91, and 42% lower than the use of sandbags. For both the WDS and sandbags, the primary contributor to embodied energy was the extraction and production of raw materials. Despite the fact that plastics have a considerably higher embodied energy per mass (70 – 103 MJ/kg) than sand (0.1 MJ/kg), the normalized raw materials embodied energy was higher for the use of sandbags, due to the high mass of sand required to protect the shoreline and the short lifetime of the sandbags. Based on these three experimental sites, it is expected that use of the WDS will result in less overall energy utilization (and subsequently CO_2 emissions), as compared to the use of sandbags, for erosion mitigation.

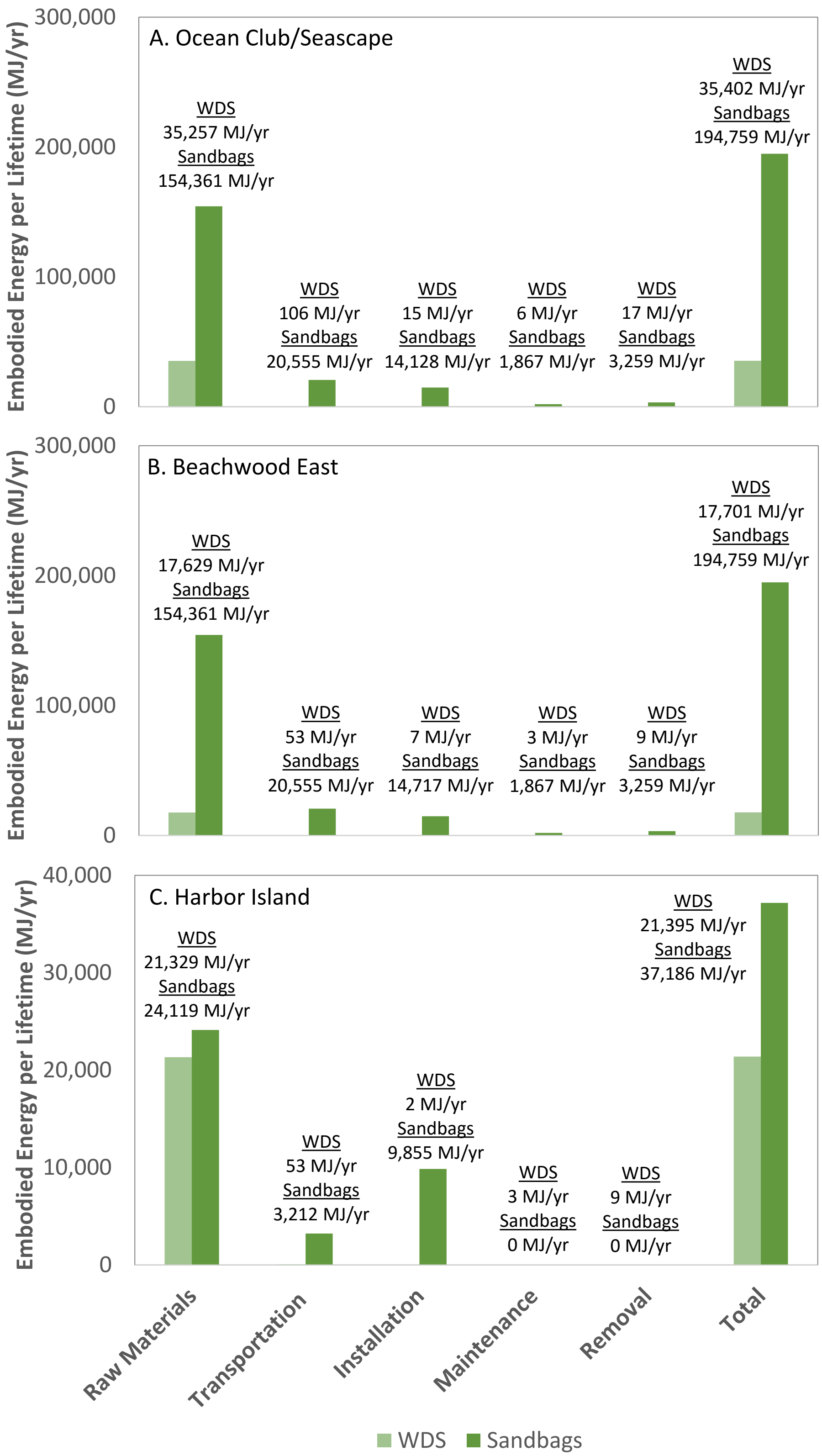


Figure 37. Comparison of life cycle embodied energy per lifetime between WDS and sandbags at (A) OC/SS, (B) BWE, and (C) HI sites. Assumes all components are used for their entire lifetimes.

Conclusions and Recommendations

Conclusions:
Based on the results of all tests performed to date, the Citadel researchers have concluded that the Wave Dissipation System is able to:

1) protect structures, dunes, flora, and fauna that are landward of the system
2) minimize the potential for negative impacts that are associated with hardened devices, and
3) allow for natural beach elevation changes while providing better protection of dune lines by using a multi-tier system in areas of higher wave energy and a single line system in areas of lower wave energy

At all sites, the WDS protected the structures behind the system and when used as recommended (not as detailed in this study) the results will be even better.

However, The Citadel researchers want to make it very clear, as they always have, that the system is not a one-size fits all solution and that it is a dynamic system that must be designed separately for each particular site, and monitored/adjusted as necessary to optimize its performance.

Recommendations:

1. The WDS should be used in conjunction with sand renourishment behind the system. This renourishment is necessary to help minimize the volume of water that gets behind the WDS. The renourshment can be brought in as beach compatible sand or reclaimed using the natural accretion that occurs at different times. Note that the research team requested the use of sand behind the system several times during the study. At the beginning of the study, OCRM was told that sand would be required to be brought in after significant erosion events in the same way that sand is placed behind sandbags. This action was not permitted. After the 1,000 year event, researchers informed OCRM that the site had changed considerably and that sand should be brought in to provide a similar baseline as was anticipated for the study. This action was denied. When significant accretion occurred on site at BWE, the research team requested the opportunity to show that dune rebuilding could be performed (as was shown in the earlier studies). This action was denied.
2. The local trenching that has occurred at times at all three sites is a significant concern to Citadel researchers. Local trenching never occurred in the previous Seascape studies nor at Ocean Club this year until the final portion of the study period covered in this report. It appears to be related to scour caused by extreme tides, significant erosion events, and the volume of water that is allowed to pass through the system (this same volume of water must escape as the tide goes back out). Although the system is self-healing, the time required to self-heal after event related local trenching is site specific, and it is the opinion of The Citadel researchers that self-healing should not be permitted in all cases. Opening up of the entire system in areas of local trenching has immediately restored the beach profile by quickly mitigating the trenching effect and the horizontal panels can be easily removed for this purpose. The research team spent a lot of time developing vertical panels for removing the trench since this approach would be much more cost effective (during a study)

than complete lowering of the system and since vertical panels could be installed in isolated locations as needed versus lowering which requires a significant portion of the system to be lowered at one time. The use of the vertical panels was not permitted by OCRM. Although our earlier report stated that "although lowering may alleviate the trenching, we are not planning that this will be the solution. We only propose it to increase energy dissipation," OCRM correspondence to Dr. Mays did not permit the vertical panels as discussed earlier in this report and instead OCRM suggests the use of lowering the system which no one was willing to pay for during a short term study. Finally, in conjunction with item 1 above, if the sand elevations behind the WDS are maintained on a bimonthly schedule or so, some of this beach compatible sand can be easily and quickly moved to eliminate any concerns caused by the temporary trenching on site.

3. During significant accretion events behind the system, dune rebuilding by moving sand already behind the system should be utilized. This will help eliminate the need for bringing in beach compatible sand. The system's capability was shown clearly in the earlier Seascape studies, but was not permitted by OCRM during these studies when requested by the research team.
4. It is recommended that the system be installed with the horizontal panels fully in place during times outside of turtle season. During turtle season, it is recommended that the system be completely open (only vertical elements in place) except when the structure behind the system is in immediate danger of losing structural support. During the turtle season as occurring during the studies discussed in this report, the system was completely closed off due to concerns over turtles getting trapped behind the system and since OCRM would not allow us to follow this recommendation since much of the system would have been wide open which would have "manipulated results."
5. The horizontal panels have performed well overall but the longevity of the panels, if left unmodified, in areas of significant daily wave impacts was brought into question during the study. SI Systems, LLC needs to develop a better material wrapping of the ends of the panels to reduce the spinning and banging of the panels against the housing units in these areas. This is a simple engineering fix that will cost SI Systems, LLC additional money when constructing similar lines of resistance.
6. For the two homes on Harbor Island, readers of this report should note the serious concerns that the principal investigator has regarding the shallow foundations on which these structures are built. The principal investigator is an expert in coastal construction, a licensed engineer (structural) in South Carolina, a foundation expert, an author or contributing author on V Zone construction and he has been shocked regarding some of the discussions about sandbags around the foundations of these structures (that don't consider the structural ramifications of moving the bags or removal actions). The discussions are not presented in this report. To the best of his knowledge, at the time these homes were constructed, the shallow foundations supporting these structures were approved by the local jurisdiction. Although as a Citadel employee, the project principal investigator is not able to represent these homeowners as their structural engineer, the homeowners are advised to seek options regarding long term solutions in their special case situation which is

very unique and requires input from experts in coastal construction, V Zone regulations, and structural engineering.

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Very truly yours,

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Appendix A:
Environmental Impact Sample Calculations

Wave Dissipation System (All calculations are on a per functional unit basis for BWE)

1. Raw Materials

   A. Fiber-reinforced plastic (FRP) piles:
   - → Embodied energy (EE) for HDPE assumed as a conservative value (103 MJ/kg) (Grams 2005).
   - → Given 183 lb/pile.
   - → Given 50 yr life for pile.
   - → Given 1 item/unit.

$$EE = 1item\left(\frac{183\ lb}{item}\right)\left(\frac{103\ MJ}{kg\ plastic}\right)\left(\frac{kg}{0.454\ lb}\right) = 41{,}518\ MJ$$

$$\frac{EE}{life} = \frac{41{,}518\ MJ}{50\ yr} = 830\,\frac{MJ}{yr}$$

   B. Pipe/panels:
   - → EE for PVC (70 MJ/kg) (Grams 2005).
   - → Given 12 lb/item.
   - → Given 2 yr life.

$$EE = 16\ items\left(\frac{12\ lb}{item}\right)\left(\frac{70\ MJ}{kg\ PVC}\right)\left(\frac{kg}{0.454\ lb}\right) = 29{,}604\ MJ$$

$$\frac{EE}{life} = \frac{29{,}604\ MJ}{2\ yr} = 14{,}802\,\frac{MJ}{yr}$$

   C. Housing units:
   - → EE for HDPE used (103 MJ/kg) (Grams 2005).
   - → Given 70 lb/item.
   - → Given 25 yr life.

$$EE = 3\ items\left(\frac{70\ lb}{item}\right)\left(\frac{103\ MJ}{kg\ HDPE}\right)\left(\frac{kg}{0.454\ lb}\right) = 47{,}643\ MJ$$

$$\frac{EE}{yr} = \frac{46{,}643\ MJ}{25\ yr} = 1{,}906\,\frac{MJ}{yr}$$

D. Locking cap:
   → EE for HDPE used (103 MJ/kg) (Grams 2005).
   → Given 10 lb/item.
   → Given 25 yr life.

$$EE = 1\ item\left(\frac{10\ lb}{item}\right)\left(\frac{103\ MJ}{kg\ HDPE}\right)\left(\frac{kg}{0.454\ lb}\right) = 2{,}269\ MJ$$

$$\frac{EE}{yr} = \frac{2{,}269\ MJ}{25\ yr} = 91\frac{MJ}{yr}$$

E. WDS unit:

$$EE = (41{,}518 + 29{,}604 + 47{,}643 + 2{,}269)MJ = 121{,}033MJ$$

$$\frac{EE}{life} = (830 + 14{,}802 + 1{,}906 + 91)\frac{MJ}{yr} = 17{,}629\ \frac{MJ}{yr}$$

2. Transportation to Site

A. FRP pile:
   → Given transported from PA.
   → Estimated travel distance from PA to SC of 700 mi (Google Maps).
   → Estimated transported by heavy truck (1390 BTU/short ton-mi) (Cambridge Systematics 2013).

$$EE = 1\ item\left(\frac{183\ lb}{item}\right)\left(\frac{1390\ BTU}{short\ ton - mi}\right)\left(\frac{short\ ton}{2000\ lb}\right)\left(\frac{MJ}{947.8\ BTU}\right)(700\ mi) = 94\ MJ$$

$$\frac{EE}{life} = \frac{94\ MJ}{50\ yr} = 2\frac{MJ}{yr}$$

B. Pipe/panels:
   → Given transported from OH.
   → Estimated travel distance from OH to SC of 600 mi (Google Maps).
   → Estimated transported by heavy truck (1390 BTU/short ton-mi) (Cambridge Systematics 2013).

$$EE = 16\ item\left(\frac{12\ lb}{item}\right)\left(\frac{1390\ BTU}{short\ ton - mi}\right)\left(\frac{short\ ton}{2000\ lb}\right)\left(\frac{MJ}{947.8\ BTU}\right)(600\ mi) = 84\ MJ$$

$$\frac{EE}{life} = \frac{84\ MJ}{2\ yr} = 42\frac{MJ}{yr}$$

C. Housing units:
   → Given transported from MN.
   → Estimated travel distance from MN to SC of 1400 mi (Google Maps).
   → Estimated transported by heavy truck (1390 BTU/short ton-mi) (Cambridge Systematics 2013).

$$EE = 3\ items\left(\frac{70\ lb}{item}\right)\left(\frac{1390\ BTU}{short\ ton - mi}\right)\left(\frac{short\ ton}{2000\ lb}\right)\left(\frac{MJ}{947.8\ BTU}\right)(1400\ mi) = 216\ MJ$$

$$\frac{EE}{life} = \frac{216\ MJ}{25\ yr} = 9\frac{MJ}{yr}$$

D. Locking cap:
   → Given transported from MN.
   → Estimated travel distance from MN to SC of 1400 mi (Google Maps).
   → Estimated transported by heavy truck (1390 BTU/short ton-mi) (Cambridge Systematics 2013).

$$EE = 1\ item\left(\frac{10\ lb}{item}\right)\left(\frac{1390\ BTU}{short\ ton - mi}\right)\left(\frac{short\ ton}{2000\ lb}\right)\left(\frac{MJ}{947.8\ BTU}\right)(1400\ mi) = 10\ MJ$$

$$\frac{EE}{life} = \frac{10\ MJ}{25\ yr} =< 1\frac{MJ}{yr}$$

E. WDS unit:

$$EE = (94 + 84 + 216 + 10)MJ = 404\ MJ$$

$$\frac{EE}{life} = (2 + 42 + 9)\frac{MJ}{yr} = 53\frac{MJ}{yr}$$

3. Installation

A. FRP Pile
   → WDS forklift power estimated as 74 kW, based on representative 6,000 lb forklift.
   → WDS large excavator power estimated as 27 kW, based on representative 18,500 lb mini-excavator.
   → Forklift and excavator operation times estimated as 20 min per WDS unit.

$$Forklift\ energy\ consumption = \left(\frac{74\ kJ}{s}\right)(20\ min)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 88.8\ MJ$$

$$Excavator\ energy\ consumption = \left(\frac{27\ kJ}{s}\right)(20\ min)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 32.4\ MJ$$

$$EE = (88.8 + 32.4)MJ = 121.2\ MJ$$

$$\frac{EE}{life} = \frac{121.2\ MJ}{50\ yr} = 2\frac{MJ}{yr}$$

B. Housing units:

→ WDS forklift power estimated as 74 kW, based on representative 6,000 lb forklift.

→ WDS large excavator power estimated as 27 kW, based on representative 18,500 lb mini-excavator.

→ Forklift and excavator operation times estimated as 20 min per WDS unit.

$$Forklift\ energy\ consumption = \left(\frac{74\ kJ}{s}\right)(20\ min)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 88.8\ MJ$$

$$Excavator\ energy\ consumption = \left(\frac{27\ kJ}{s}\right)(20\ min)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 32.4\ MJ$$

$$EE = (88.8 + 32.4)MJ = 121.2\ MJ$$

$$\frac{EE}{life} = \frac{121.2\ MJ}{25\ yr} = 5\frac{MJ}{yr}$$

C. WDS unit:

$$EE = (121.2 + 121.2)MJ = 242.4\ MJ$$

$$\frac{EE}{life} = (2 + 5)\frac{MJ}{yr} = 7\frac{MJ}{yr}$$

4. Maintenance

A. FRP Pile

→ Major maintenance event assumed to vibrating down FRP piles.
→ Assumed 1 maintenance event per year.
→ WDS mini-excavator power estimated as 27 kW, based on representative 18,500 lb forklift.
→ Assumed 2 min per WDS unit for maintenance.

$$EE = \frac{27\ kJ}{s}\left(\frac{0.033\ hr}{event}\right)\left(\frac{3600\ s}{hr}\right)\left(\frac{MJ}{1000\ kJ}\right)(50\ events) = 160MJ$$

$$\frac{EE}{life} = \frac{160\ MJ}{50\ yr} = 3\frac{MJ}{yr}$$

5. Removal

A. FRP pile:

→ WDS forklift power estimated as 74 kW, based on representative 6,000 lb forklift.
→ WDS mini-excavator power estimated as 21 kW, based on representative 15,000 lb mini-excavator.
→ Assumed 25 min machine operation time per unit.

$$Forklift\ energy\ consumption = \left(\frac{74\ kJ}{s}\right)(25\ min)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 111.0\ MJ$$

$$Excavator\ energy\ consumption = \left(\frac{21\ kJ}{s}\right)(25\ min)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 31.5\ MJ$$

$$EE = (111.0 + 31.5)MJ = 142.5\ MJ$$

$$\frac{EE}{life} = \frac{142.5\ MJ}{50\ yr} = 3\frac{MJ}{yr}$$

B. Housing units:

→ WDS forklift power estimated as 74 kW, based on representative 6,000 lb forklift.
→ WDS mini-excavator power estimated as 21 kW, based on representative 15,000 lb mini-excavator.
→ Assumed 25 min machine operation time per unit.

$$Forklift\ energy\ consumption = \left(\frac{74\ kJ}{s}\right)(25\ min)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 111.0\ MJ$$

$$Excavator\ energy\ consumption = \left(\frac{21\ kJ}{s}\right)(25\ min)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 31.5\ MJ$$

$$EE = (111.0 + 31.5)MJ = 142.5\ MJ$$

$$\frac{EE}{life} = \frac{142.5\ MJ}{25\ yr} = 6\frac{MJ}{yr}$$

C. WDS unit:

$$EE = (142.5 + 142.5)MJ = 285\ MJ$$

$$\frac{EE}{life} = (3 + 6)\frac{MJ}{yr} = 9\frac{MJ}{yr}$$

6. Total

$$EE = (121{,}033 + 404 + 242 + 160 + 285)MJ = 122{,}125\ MJ$$

$$\frac{EE}{life} = (17{,}629 + 53 + 7 + 3 + 9)\frac{MJ}{yr} = 17{,}701\frac{MJ}{yr}$$

Sandbags (All calculations are on a per functional unit basis for BWE)

1. Raw Materials
   - → 4 sandbags/ft
   - → 3000 lb/sandbag
   - → EE for sand (0.1 MJ/kg) (Grams 2005)
   - → Lifetime = 1200 hr
   - → Unit = 8 ft of sandbags

$$Unit\ weight = (3000\ lb)\left(\frac{4\ bags}{ft}\right)(8\ ft) = 96{,}000\ lb$$

$$EE = (96{,}000\ lb)\left(\frac{0.1\ MJ}{kg}\right)\left(\frac{kg}{0.454\ lb}\right) = 21{,}145\ MJ$$

$$\frac{EE}{life} = \frac{21{,}145\ MJ}{0.137\ yr} = 154{,}361\frac{MJ}{yr}$$

2. Transportation to Site
   - → Given transported from Summerville, SC.

→ Estimated travel distance from PA to SC of 40 mi (Google Maps).
→ Estimated transported by heavy truck (1390 BTU/short ton-mi) (Cambridge Systematics 2013).

$$EE = (96{,}000\ lb)\left(\frac{1390\ BTU}{short\ ton - mi}\right)\left(\frac{short\ ton}{2000\ lb}\right)\left(\frac{MJ}{947.8\ BTU}\right)(40\ mi) = 2{,}816\ MJ$$

$$\frac{EE}{life} = \frac{2{,}816\ MJ}{0.137\ yr} = 20{,}555\frac{MJ}{yr}$$

3. Installation
   → Sandbag large forklift power estimated as 74 kW, based on representative 6,000 lb forklift.
   → Sandbag small forklift power estimated as 49 kW, based on representative 4,000 lb mini-excavator.
   → Sandbag mini-excavator power estimated at 27 kW based on 18,500 lb mini-escalator.
   → Assumed 7 min machine operation time to fill and place large sandbag.

$$Time\ per\ unit = \left(\frac{7\ min}{bag}\right)\left(\frac{4\ bags}{ft}\right)(8\ ft)\left(\frac{hr}{60\ min}\right) = 3.73hr$$

$$Lg\ Forklift\ energy\ consumption = \left(\frac{74\ kJ}{s}\right)(3.73\ hr)\left(\frac{60\ min}{hr}\right)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 994.6\ MJ$$

$$Sm\ Forklift\ energy\ consumption = \left(\frac{49\ kJ}{s}\right)(3.73\ hr)\left(\frac{60\ min}{hr}\right)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 658.6\ MJ$$

$$Excavator\ energy\ consumption = \left(\frac{27\ kJ}{s}\right)(3.73\ hr)\left(\frac{60\ min}{hr}\right)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 362.9\ MJ$$

$$EE = (994.6 + 658.6 + 362.9)MJ = 2{,}016\ MJ$$

$$\frac{EE}{life} = \frac{2{,}016\ MJ}{0.137\ yr} = 14{,}717\frac{MJ}{yr}$$

4. Maintenance
   → Assumed 6000 lb forklift (74 kW) 5 days at 6 hr/day to lift 1000 ft run of large sandbags.
   → Assumed maintenance event approximately every two weeks (4 events).

$$\left(\frac{5\ days}{1000\ ft - event}\right)\left(\frac{6\ hr}{day}\right)(8\ ft) = 0.24\ hr$$

$$EE = \left(\frac{74\ kJ}{s}\right)\left(\frac{0.24\ hr}{event}\right)\left(\frac{60\ min}{hr}\right)\left(\frac{60\ s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right)(4\ events) = 256\ MJ$$

$$\frac{EE}{life} = \frac{256\ MJ}{0.137\ yr} = 1{,}867\frac{MJ}{yr}$$

5. Removal
   → Sandbag large excavator power estimated as 134 kW, based on representative 52,410 excavator.
   → Sandbag small excavator power estimated as 21 kW, based on representative 15,000 lb mini-excavator.
   → Assumed 1.5 min/sandbag operation time for removal.

$$\left(\frac{1.5\ min}{bag}\right)\left(\frac{4\ bags}{ft}\right)(8\ ft)\left(\frac{hr}{60\ min}\right) = 0.80\ hr$$

$$Lg\ excavator\ energy\ consumption = \left(\frac{134\ kJ}{s}\right)(0.80\ hr)\left(\frac{60\ min}{hr}\right)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 385.9\ MJ$$

$$Sm\ excavator\ energy\ consumption = \left(\frac{21\ kJ}{s}\right)(0.80\ hr)\left(\frac{60\ min}{hr}\right)\left(\frac{60s}{min}\right)\left(\frac{MJ}{1000\ kJ}\right) = 60.5\ MJ$$

$$EE = (385.9 + 60.5)MJ = 446\ MJ$$

$$\frac{EE}{life} = \frac{446\ MJ}{0.137\ yr} = 3{,}259\frac{MJ}{yr}$$

6. Total

$$EE = 21{,}145 + 2{,}816 + 2{,}016 + 256 + 446 = 26{,}679\ MJ$$

$$\frac{EE}{yr} = (154{,}361 + 20{,}555 + 14{,}717 + 1{,}867 + 3{,}259) = 194{,}759\frac{MJ}{yr}$$

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