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Article

Large-Scale Performance Evaluation of Various Woven Silt Fence Installations under Nebraska Highway Conditions

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Abstract: Sediment barriers are used on construction sites to protect downstream waterbodies from the impacts of sediment-laden stormwater runoff. Although ubiquitous on construction sites, many sediment barrier practices lack performance-based testing to determine effectiveness and treatment mechanisms, with previous evaluations being limited to conditions local to the Southeastern U.S., with conditions in other regions remaining untested. Testing was conducted to determine the effectiveness of woven silt fence barriers and provide structural improvements to common installation methods. Testing was conducted using a large-scale sediment barrier testing apparatus at the Auburn University—Stormwater Research Facility. The results from testing indicate that Nebraska DOT standard silt fence installations can be improved to reduce the risk of structural failures such as undermining, complete installation failure, slow dewatering, and overtopping. To improve structural performance, four modifications (a 15.2 cm [6 in.] offset trench, wooden posts, a dewatering board with an overflow weir, and a dewatering board with an overflow weir with adjusted post spacing) were tested. On average, 83% of introduced sediment was retained behind the tested barriers. The water quality results across the testing of standard and modified installations indicated that stormwater treatment was due to sedimentation within the impoundment formed by silt fence installations and not filtration through geotextile fabric.

Keywords: silt fence; erosion control; sediment control; construction stormwater

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1. Introduction

Construction activities, when improperly managed, can be a large contributor to non-point source pollution sources in the U.S [1]. Disturbing earth removes natural vegetation that protects soil, causing an increase in soil detachment and leading to sediment discharge running off site and into neighboring stormwater sewer systems or bodies of water. Sediment-laden stormwater runoff can cause negative impacts on water quality: increasing turbidity, decreasing stream capacity, and transporting pollutants such as heavy metals, hydrocarbons, and other toxic substances [2].

The U.S. Congress passed the Clean Water Act of 1972 to protect water bodies by making it unlawful to discharge pollutants without proper permitting. The Clean Water Act established the National Pollutant Discharge Elimination System and the Construction General Permit (CGP), managed by the U.S. Environmental Protection Agency (USEPA) [3,4]. The CGP outlines regulatory requirements for protecting water bodies from pollutant-laden runoff for the eight states and territories that have not been delegated regulatory permitting authority by the USEPA. The NPDES requires construction sites to develop Stormwater Pollution Prevention Plans (SWPPPs) to protect adjacent areas from uncontrolled polluted stormwater runoff. Erosion and sediment control practices are required to be installed and maintained as part of the maintenance of the SWPPPs.

Sediment control practices, such as sediment barriers, are installed downstream of disturbed areas to treat sediment-laden sheet flow runoff by facilitating impoundment and reducing stormwater runoff velocity, which allows for large-sized suspended particles to settle [5,6]. The most commonly used sediment barrier practice is silt fence, which is a geotextile anchored into the ground and supported by posts, often with plastic or metal backing for additional reinforcement [6]. Silt fences can vary in their types of fabrics, backing, post material, post spacing, height, and trenching method; Figure 1 shows an installed silt fence that was erected as part of a highway construction project in Nebraska. Under conditions local to the southeast United States, silt fence barriers can remove up to 96% of sediment by impounding runoff behind the practice. In comparison, other barriers, such as compost logs and wattles, can have sediment removal efficiencies of upwards of 80% [7,8].

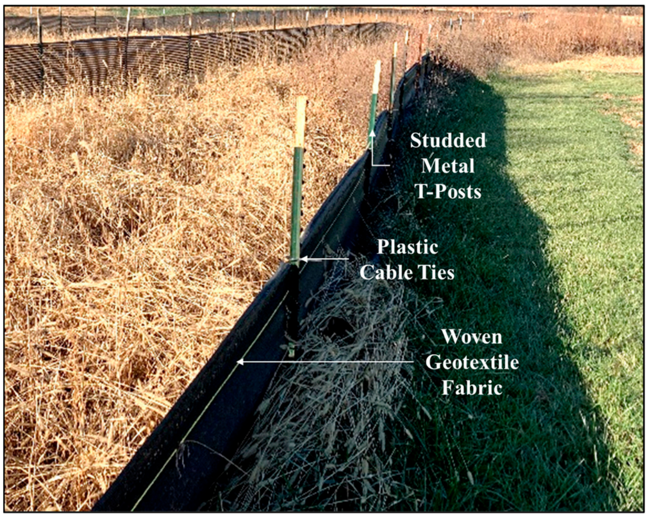


Figure 1. Silt fence from Nebraska highway construction project.

Erosion and stormwater runoff rates depend on site-specific conditions such as vegetation, climate, soil characteristics, and topography. Rates can vary widely region by region, even within states [9,10]. Due to this variation in conditions, developing a single sediment barrier installation that would provide adequate protection while being cost-effective for every site and location is not feasible. Each state's Department of Transportation (DOT) has its own specifications and plans for sediment barriers that are approved for use on highway construction projects in that state. Silt fences are approved for use in all 50 U.S. states, while wattles and slash mulch berms are approved for use as sediment barriers in 19 and 8 states, respectively [11]. For example, the Nebraska DOT, in their standard specifications for highway construction, outlines acceptable sediment barriers as silt fences, slash mulch berms, and wattles. The silt fence designs outlined in these standard specifications employ a woven geotextile fabric material that is trenched along the base and used steel t-posts [12,13].

Despite their widespread use, the sediment barrier designs for most regulatory bodies are based on rules of thumb rather than the scientific-based testing of the entire system. Most of the sediment barrier testing that has been conducted has been on installations and conditions local to the Southeastern U.S. [7,8,14–16]. There is currently a lack of available data and performance testing for how silt fence installations perform under conditions local to highway construction projects in other parts of the country, such as the Midwestern U.S, which receives far less rainfall on average than the Southeastern U.S. For example, areas in Nebraska receive between 445 mm (17.5 in.) and 925 mm (36.4 in.) of annual precipitation, while the state of Alabama averages 1407 mm (55.4 in.) of annual precipitation [9,16]. Despite past GIS analysis indicating that the state of Nebraska has more erosive soil on average than areas in the southeast, the increased rainfall results in states in the southeast, such as Alabama, being more prone to erosion than states in the Midwestern U.S. [8]. Due to the large difference in sediment and stormwater load, it is difficult for regulatory agencies to use testing conducted under conditions local to other regions to develop erosion and sediment control installation standards, especially for sediment barriers.

1.1. Background

Sediment barrier designs are typically based on rules of thumb, with little scientific research being used in the design of most standard practices [10]. Some sediment barrier testing has been conducted to improve silt fence designs and implementations and increase the body of knowledge on the state of practice [9–19]. Past testing efforts can be divided into three general testing methods: (1) small-scale testing (typically in flumes), (2) the field monitoring of installations on active construction projects, and (3) large-scale testing that subjects entire installations to controlled conditions. Each testing type has its advantages and limitations in determining the overall performance of sediment barriers.

1.1.1. Small-Scale Laboratory Testing

Wyant [20] conducted some of the first sediment barrier tests to determine the filtration efficiency of 15 different silt fence fabrics, including 6 woven fabrics and 9 nonwoven fabrics with various weights. A flume with an 8% slope was used, and Virginia's three dominant soil types (clayey, silty, and sandy) were all tested. The fabrics had a dam-like effect, leading to high removal efficiencies as sediment could fall out of the suspension in the impoundment formed, with removal efficiencies of 92% and 97% for silty soil and sandy soil, respectively [20]. This research led to the development of the ASTM D5141 Standard Method for Determining Filtering Efficiency and Flow Rate of the Filtration Component of a Sediment Retention Device [21]. This test method introduces 50 L (13.3 gal) of water mixed with 0.15 kg (0.33 lb) of soil into a section of geotextile; water samples are taken to compare water quality upstream and downstream of the fabric to determine removal efficiency. The impoundment remaining upstream of the fabric after 25 min is also recorded [21].

Barret et al. [4] aimed to outline a method for the treatment of the geotextiles used in silt fence installations by evaluating detention time, permittivity, and flow on TSS reduction. The major finding of their testing was the direct correlation between the detention time behind the fabric and the sediment removal efficiency. A sediment removal rate of 75% was achieved and determined to be realized through sedimentation and not filtration through the fabric. Lower flow-through rates of sediment-laden water through the fabric also led to increased detention time and removal, with the flow rate being a function of apparent opening size and the permittivity of clean water flow. The results for woven and nonwoven fabrics were also compared; the nonwoven fabric removed 90% of suspended solids on average, while the three woven fabrics removed 68, 70, and 90% on average. The differences between the two types of fabrics were suggested to be due to the fact that subsequent tests removed the sediment clogging openings in the woven fabrics, while the nonwoven fabric remained clogged [22]. An increase in the detention time due to sediment clogging openings in the silt fence fabric was found in other studies involving flume tests of silt fence fabrics. Additionally, flume testing indicates that the smaller soil particles in the impoundments formed cannot be removed from flow through the process of sedimentation [23].

In an effort to improve the state of practice of small-scale sediment barrier testing, Whitman et al. [18] tested geotextile fabrics in a flume that replicated realistic runoff conditions with a 33% slope facilitating sediment-laden sheet flow that leads into a 1% slope before reaching the installed geotextile. Each of the five fabrics (two nonwoven and three woven) tested showed an average sediment capture of over 87%, with the nonwoven fabrics having an average capture upwards of 97%. Additionally, each of the woven fabrics showed a decrease in effluent flow rate as the test period ran; however, there was not a statistically significant difference in flow rates between woven fabrics with different densities of pore openings. During the test period, turbidity improvement was found to be due to sedimentation, with the water at the top of the impoundment being less turbid than that at the bottom [18].

Small-scale flume testing has been shown to be instrumental in determining whether any sediment removal or water quality improvement facilitated by the geotextile fabrics of silt fences is due to sedimentation in the impoundment formed and not filtration through the fabric. However, small-scale testing has the key limitations of only being able to test the geotextile of a silt fence, which is just one of the many aspects that can determine the performance of an entire silt fence installation.

1.1.2. Field Monitoring

The field monitoring of silt fence installations can provide insight into installation methods and the full-scale performance of sediment barriers. Barrett et al. [22] monitored water quality upstream and downstream of silt fences on a roadway improvement project in Austin, Texas, through ten stormwater runoff events. The removal efficiency ranged from a 61% degradation in water quality to a 54% improvement with a median of 0%. The lack of sediment removal efficiency was due to the smaller on-site soil particles being able to pass through the silt fence installations; in the on-site soil, silt and clay accounted for 68% to 100% of the soil. Additionally, maintenance and structural performance were identified as critical factors in performance; silt fences that were damaged (e.g., tearing of fabric, overtopping, inadequate trenching into the ground, or flow bypass) due to excessive impoundment or other factors and were not repaired showed far less treatment [22].

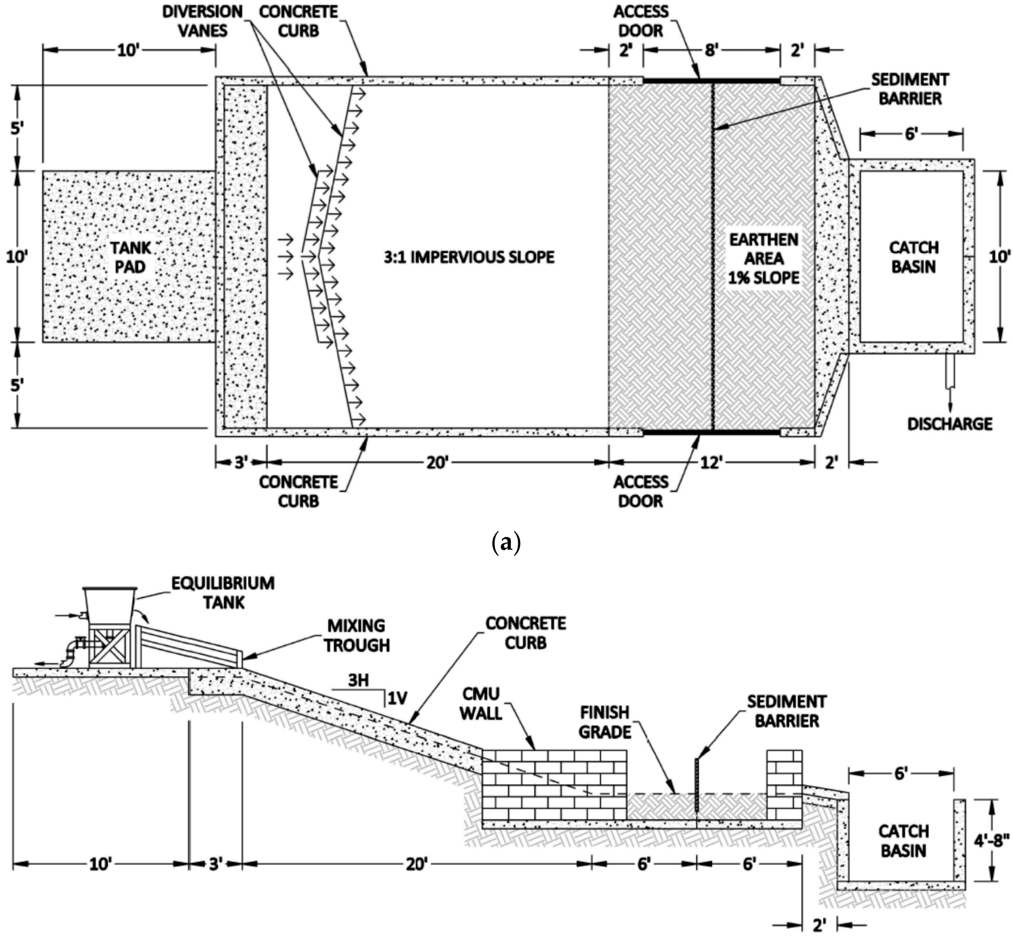
Standard and modified silt fences on an Iowa Department of Transportation site in Tama County, Iowa, were monitored to determine whether modifications improved performance compared to standard installations when subjected to similar stormwater runoff events. The standard silt fence, consisting of a woven geotextile trenched in at the base and attached to metal T-posts with 2.4 m (8 ft) spacing between posts, experienced excessive sedimentation, leading to post deflection and overtopping. Deflection was reduced in modified installations that had reduced post spacing from 2.4 m (8 ft) to 1.5 m (5 ft) or additional wire reinforcement backing; however, these modifications did increase the cost of material and installation. Additionally, offsetting the trench at the toe of the silt fence by 15.2 cm (6 in.) reduced undermining at no additional cost and was recommended to be put into practice [24].

One of the key takeaways of field monitoring is that there are five common failure modes of silt fence installations: overtopping due to an excessively large drainage area, undercutting, flow bypass, improper installation, and the excessive accumulation of material due to a lack of maintenance, which, in turn, leads to other failures. Any of these failure modes can lead to a silt fence installation being ineffective in preventing uncontrolled sediment-laden stormwater runoff from leaving a construction site [14]. Another takeaway is that consistent maintenance is required to ensure that structural failures are prevented or fixed after occurring. However, maintenance issues and variable stormwater runoff events due to different drainage areas, cover, infiltration, and storm intensity can lead to inconsistent and difficult comparisons of results in field monitoring.

1.1.3. Large-Scale Laboratory Testing

Large-scale testing combines the ability to evaluate an entire installation for water quality, sediment retention, and structural performance while subjecting the installation to selected conditions (i.e., flow and sediment introduction rates) in a controlled environment. One large-scale sediment barrier testing method employs a lifted test bed subjected to rainfall simulation to generate simulated sediment-laden stormwater runoff. Gogo-Abite and Chopra [25] used this method on sandy soil slopes of 10, 25, and 33% under three increasing rainfall intensities to test a woven and a nonwoven silt fence installation. The nonwoven fabric silt fence installations tested reduced turbidity by 52%, while the woven installations only reduced turbidity by 18%. Testing also found that when the slope was increased, more structural performance issues, such as overtopping and other failures, occurred due to the increased sediment load experienced [25]. However, due to the drainage area for silt fences on construction projects typically being larger than the rainfall simulation test beds, the testing of sediment barriers in this manner does not fully facilitate the replication of filed conditions.

To improve the methodology for sediment barrier testing, Bugg et al. [19] developed a large-scale sediment barrier testing apparatus at the Auburn University—Stormwater Research Facility (AU-SRF) that is able to simulate a stormwater runoff event by introducing a calibrated amount of water and sediment. Flow is mixed in with a trough and converted into sheet flow using slotted diversion veins on a 3H:1V impervious slope; the sheet flow then runs into a 6.1 m (20 ft) earthen section, where a sediment barrier can be installed. A plan and profile view of the testing apparatus used in the study is shown in Figure 2. Flow and sediment introduction can be calibrated, and these processes are typically based on the runoff produced by a local 2 yr, 24 h storm for a representative drainage area found from sediment barrier standards.



(a)

(b)

Figure 2. Schematic of testing apparatus used by Bugg et al. and Whitman et al. [19]: (**a**) plan view; (**b**) profile view.

Each installation evaluated by Bugg et al. was subjected to three back-to-back simulated stormwater runoff events to evaluate the longevity of the installations [19]. The Alabama DOT nonwoven standard silt fence installation was tested using this apparatus and methodology. Water quality, sediment retention, and structural performance data were collected and used to develop modifications that were then tested to determine whether improvements could be made. The modifications included increasing T-post weight from 1.4 kg/m (0.95 lb/ft) to 1.9 kg/m (1.25 lb/ft), decreasing post spacing from 3.0 m (10 ft) to

1.5 m (5 ft), decreasing fence height from 81.3 cm (32 in.) to 61.0 cm (24 in.), and an offset trench. All modifications aimed to decrease the possibility of structural failures such as undermining and excessive post deflection, which can lead to overtopping and complete installation failure. Using multiple linear regression analysis, the modifications were found to decrease post deflection from 0.22 m (0.72 ft) to as low as 0.01 m (0.03 ft) for the installation with a 15.2 cm (6 in.) offset trench, 1.5 m (5 ft) post spacing, and a height of 61.0 cm (24 in.). The installations that did not overtop or experience other failure modes retained 95% of sediment upstream, while the installations that overtopped retained 83% [7]. Manufactured sediment barrier products (i.e., straw wattles, compost logs, and excelsior blocks) were tested with the same method and were found to have lower impoundments on average, under 0.24 m (0.8 ft), than silt fences, which were able to form impoundments over 0.46 m (1.5 ft) in depth. If a tested practice was able to repeatedly facilitate an impoundment of greater than 0.3 m (1 ft), a sediment capture of over 90% was facilitated. Additionally, sediment capture did not improve with increased impoundment over 0.46 m (1.5 ft) in depth [8]. Due to past testing finding that the clogging of geotextile pores, leading to excessive impoundment and impoundments being able to remain behind installations for long periods of time, can potentially cause structural failure, a silt fence installation with a dewatering board and V-notched overflow weir was tested. The weir, with a splash pad installed downstream to prevent scour, was designed to serve as an emergency spillway at 0.46 m (1.5 ft) to prevent uncontrollable overtopping leading to other structural failures. The dewatering board also had orifices every 7.6 cm (3 in.) to dewater the installation more effectively after a storm event. The installations tested with the dewatering board were able to dewater fully in 4 h, far less than the 24 h for the control installation. There was no loss in sediment retention or water quality performance experienced by the installations tested with the dewatering board [15].

1.1.4. Literature Review Summary

Past research on sediment barriers can be divided into three categories, each providing insight into performance: field monitoring, small-scale laboratory testing, and large-scale performance evaluations. Table 1 summarizes the testing efforts analyzed. Small-scale testing was instrumental in determining that any treatment by silt fences is due to sedimentation within the impoundment formed and not filtration through geotextile fabric. The critical finding of past field monitoring efforts is that proper installation and maintenance are necessary for proper performance. Large-scale testing, specifically the methodology outlined by Bugg et al., can allow for the development of modifications to improve the performance of silt fence installations and prevent structural failures [19].

Table 1. Literature review summary.

Author	Date	Type	Location/ Conditions	Key Conclusions
Wyant [20]	1980	Small-Scale	-	Damming leading to the formation of impoundment leads to sediment removal. Led to development of ASTM D5141.
Barrett et al. [22]	1998	Small-Scale	-	Sediment removal was due to sedimentation and not filtration. Increased detention time and reduced flow-through rates led to increased sediment removal.
Henry and Hunnewell [23]	1995	Small-Scale	-	Smaller soil particles are unable to be removed by sedimentation alone.
Whitman et al. [18]	2019	Small-Scale	-	Replicates more realistic conditions. Turbidity improvement was due to sedimentation.

Table 1. *Cont.*

Author	Date	Type	Location/ Conditions	Key Conclusions
Barrett et al. [22]	1998	Field Monitoring	Texas, USA	Lack of proper maintenance and installation can lead to structural failures and lower treatment efficiency.
Schussler et al. [24]	2020	Field Monitoring	Iowa, USA	Structural performance can be increased through modifications such as an offset trench, decreasing post spacing, and wire backing.
Zech et al. [14]	2009	Field Monitoring	Alabama, USA	Five common failure modes of silt fence installations can lead to uncontrolled sediment-laden discharge: overtopping, undercutting, bypass, improper installation, and the excessive accumulation of material. Proper installation and maintenance can prevent failure.
Gogo-Abite and Chopra [25]	2013	Large-Scale	Rainfall Simulation	Increased sediment load led to structural performance issues. Structural failures lead to uncontrolled sediment discharge.
Bugg et al. [19]	2017	Large-Scale	Alabama, USA	Developed large-scale testing apparatus that subjects 6.1 m (20 ft) section of sediment barrier to chosen conditions.
Whitman et al. [7]	2018	Large-Scale	Alabama, USA	Used Bugg et al.'s methodology. Modified installations, including reducing post spacing, decreasing fence height, increasing post weight, and adding an offset trench to reduce the possibility of structural failures.
Whitman et al. [8]	2019	Large-Scale	Alabama, USA	Used Bugg et al.'s methodology. Evaluated manufactured sediment barriers. Found that repeatedly being able to facilitate 0.3 m (1 ft) of impoundment led to a sediment capture of at least 90%.
Whitman et al. [15]	2021	Large-Scale	Alabama, USA	Used Bugg et al.'s methodology. Developed a dewatering board with an overflow weir to protect installations from excessive impoundment and to effectively dewater and prevent structural failures.

1.2. Research Objective

Due to the lack of large-scale testing on woven silt fence installations and installations under Midwestern United States conditions, the main objective of this study was to determine the structural inefficiencies in the Nebraska DOT standard silt fence. From the structural inefficiencies found, modifications were tested to determine whether improvement is possible under both Nebraska standard conditions and increased, substantial impoundment conditions, and these modifications will be recommended herein. Additionally, across all testing, the mechanisms of water quality treatment in turbidity and total suspended solids (TSS) and, subsequently, sediment capture by woven silt fence installations were determined.

2. Materials and Methods

To determine the effectiveness of Nebraska DOT standard sediment barriers and modifications, the testing method and apparatus outlined in Bugg et al. were used and adjusted to conditions local to Nebraska highway construction projects [19]. The development of the testing methodology took place in three stages: (1) determining the flow and sediment introduction conditions, (2) selecting the sampling locations, and (3) choosing the installations to test, which was an ongoing process as testing occurred and observations were made.

2.1. Determination of Test Conditions

To determine a testing flow rate and sediment introduction rate, a representative drainage area was developed based on the guidance of 0.2 ha (0.5 ac) per 30.5 m (100 ft) of sediment barrier, a design criterion that has been used for silt fences in certain jurisdictions [19]. The testing apparatus at the AU-SRF has a test bed with a width of 6.1 m (20 ft), resulting in a representative drainage area for the testing of 0.04 ha (0.1 ac).

Using Geographic Information System (GIS) analysis from National Oceanic and Atmospheric Administration (NOAA) Atlas 14 data, an average rainfall depth in Nebraska of 5.94 cm (2.34 in.), which represents the amount of rainfall occurring uniformly over an area, was found to ensure that the testing was representative of conditions local to Nebraska DOT highway construction projects [26,27]. The average weighted Curve Number (CN), representing the runoff capability of an area, across the state was found to be 83.76. The values were used in the method outlined in USDA's TR55: Urban Hydrology for Small Watersheds to determine the runoff produced by the representative drainage area [28]. The peak flow and runoff volume calculated by the TR-55 are used in the Modified Universal Soil Loss Equation (MUSLE), which uses site-specific conditions, including stormwater runoff rates, the erosivity of the soil, the steepness and length of the slope, and any erosion or sediment control practices in place, to calculate the estimated soil loss due to a single storm event. The conditions used in calculating soil loss were the average rainfall erosivity and soil erodibility conditions of Nebraska found through a GIS analysis of the state, a bare slope with no erosion control practices installed, and the length–slope factor of the representative drainage area.

The hydrological analysis resulted in total flow introduction conditions of 4.368 m^3 (1154 gal) across a 30 min period, leading to an average flow rate of 0.0024 m^3/s (0.086 ft^3/s) for each simulated stormwater runoff event. MUSLE calculations led to a total soil loss over the representative drainage area of 362 kg (798 lb), which led to a consistent sediment introduction rate of 12.1 kg/min (26.6 lb/min).

2.2. Experimental Design

Under the calculated simulated stormwater runoff conditions, each installed sediment barrier was subjected to three identical back-to-back stormwater runoff events with a 30 min introduction period. Before flow introduction, the sediment barrier was installed according to field standards in the 6.1 m (20 ft) wide soil test bed. The soil used for test bed preparation and sediment introduction was locally sourced from on-site, AU-SRF stockpiles; the soil was classified as a sandy loam with 59% sand, 26% silt, and 13% clay. Plastic sheeting was laid down upstream of the sediment barrier to facilitate the removal of deposited sediment after testing for the measurement of sediment retention.

Water was introduced from a supply pond into a 1135 L (300 gal) tank before passing through a calibrated weir that allowed for the monitoring of flow rates. Flow then passed into a mixing trough, where sediment was manually introduced at a consistent rate through the 30 min testing period. The sediment-laden flow travelled down the 3H:1V impervious slope with slotted diversion veins facilitating sheet flow into the installed sediment barrier. Figure 2 outlines the testing apparatus.

During each 30 min simulated runoff event, water grab samples were taken at 5 min intervals. During the 90 min dewatering period, samples were taken at 5 min intervals through the first 15 min and at 30, 60, and 90 min after flow stoppage. Samples were taken from the impervious slope for influent water quality (S1), at the water surface (S2) and the bottom of the impoundment created (S3), and immediately downstream of the sediment barrier (S4), as shown in Figure 3. These sampling locations were selected to determine the manner of treatment by comparing samples taken at the top and bottom of the impoundment to the discharge. The water samples were tested for turbidity and TSS to determine any water quality improvements. Water depth and length of impoundment were measured upstream of the barrier at the same time intervals as water sampling to determine impoundment potential; water depth in the discharge basin was monitored using a Solinst Leveloger to determine flow-through rates. After the third simulated stormwater runoff event, sediment deposited upstream of the barrier was removed and measured to determine the sediment deposition that each silt fence installation facilitated. After sediment removal, an extreme-case storm event was run without sediment being introduced and increased flow rates, typically around 0.0057 m^3/s (0.20 ft^3/s), which is the highest flow rate the introduction system allows for, to facilitate maximum impoundment to determine whether structural failure (e.g., overtopping, ripping, undermining, etc.) occurred and what impoundment depth caused the failure for each installation.

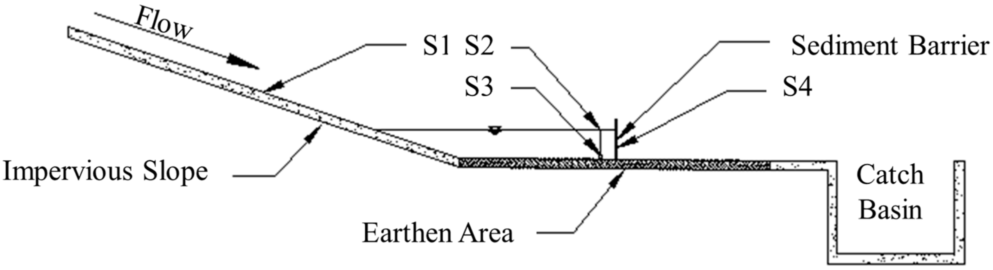
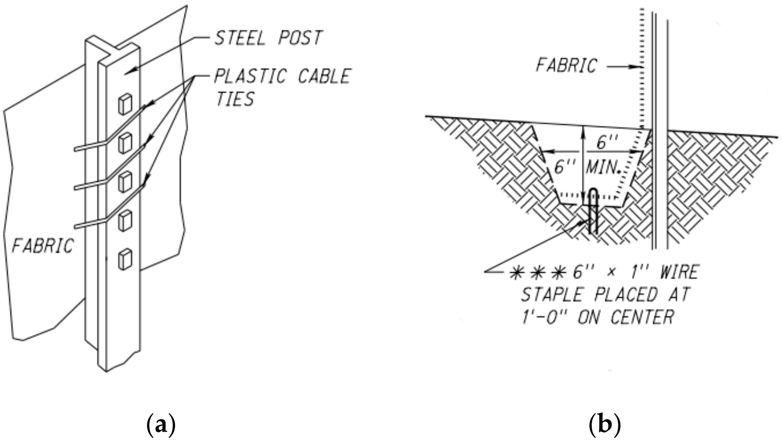


Figure 3. Testing sampling locations.

2.3. Testing Installations

The selected testing regime included three tests of the Nebraska DOT standard silt fence installation to be used as a baseline and the determination of modifications for improving performance. The standard Nebraska DOT silt fence was composed of a single-weave geotextile fabric with an apparent opening size of 600 µm (0.0234 in.) and attached to a 1.7 m (5.5 ft) steel t-post with a minimum weight of 37 kg/m (1.25 lb/ft) spaced 2 m (6 ft) apart with three plastic cable ties at the top of the post securing the fabric to the posts. A 15.2 cm by 15.2 cm (6 in. by 6 in.) trench was dug along the bottom of the posts; a wire staple was used to attach the fabric to the ground within the trench before it was buried and compacted to ensure that the fabric was secured in the ground [12,13]. Figure 4 shows drawings of the standard Nebraska DOT standard silt fence installation; the asterisks in the trenching detail indicate that the installation can also be sliced into the ground and does not require a sod staple in those installations.



(**a**) (**b**)

Figure 4. Nebraska DOT standard silt fence [12]: (**a**) anchoring detail; (**b**) trench detail.

After testing the Nebraska DOT standard silt fence installation, modifications that could improve performance were evaluated. Each modification had a single installation tested under the three simulated stormwater runoff events. A final most feasible and effective installation (MFE-I) was selected from the evaluated modifications; two additional installations of the MFE-I were tested.

3. Results and Discussion

Based on the results of past sediment barrier testing, structural performance and the repeated ability to impound runoff is the most critical factor in ensuring consistent performance and the protection of off-site areas. Structural performance deficiencies were identified and used to develop modifications. Additionally, water quality and sediment capture were evaluated for all silt fence installations.

3.1. Structural Performance

The initial results of the Nebraska DOT standard silt fence installations suggested a need for improvements to ensure structural performance. During testing, excessive sagging under standard test conditions was apparent, which lowered the effective height of the fence by up to 15.2 cm (6 in.); under excessive impoundment conditions, at about 50.8 cm (20 in.) of depth, the zip-ties completely tore through the fabric due to the hydrostatic pressure of the impoundment and caused complete installation failure. Additionally, one installation of the Nebraska DOT standard silt fence was subjected to severe undermining, leading to the immediate loss of impoundment. The sagging and the undermining experienced are shown in Figure 5.

(**a**) (**b**)

Figure 5. Structural performance of Nebraska DOT standard silt fence: (**a**) sagging and undermining of silt fence; (**b**) trench failure of silt fence.

To improve upon the structural deficiencies experienced by the Nebraska DOT standard silt fence installations in testing, a modified installation with a 15.2 cm (6 in.) offset trench from the base of the posts was tested. The offset trench allowed for improved compaction of the soil of the trench and also reduced the height of the silt fence to 45.7 cm (18 in.) from 61.0 cm (24 in.); impoundment during testing under Nebraska conditions never exceeded 33 cm (13 in.) in depth. Prior testing on Alabama DOT silt fences showed that the 15.2 cm (6 in.) offset trench allows for compaction to be completed more reliably and lowers the risk of undermining [7]. The same results were shown under Nebraska conditions, as undermining did not occur, and there was less observed flow passing underneath the fence. Under extreme-case testing with increased impoundment, the offset trench installation did not experience catastrophic failure and instead overtopped. Due to the improvements shown, the offset trench was adopted for testing in all other modifications.

Especially at higher impoundment levels, the silt fence fabric experienced excessive sagging, leading to the zip-ties partially tearing through the fabric at the posts and reducing the installation's effective height. The zip-ties were only attached to the fabrics at the top of the posts, and the hydrostatic pressure of the impoundment led to excessive sagging. To combat sagging, an installation with 5.1 cm by 5.1 cm (2 in. by 2 in.) wooden posts identical to the offset trench installation in every other form was tested; the fabric was stapled to the wooden posts along the entire height of the post. Under tests involving both Nebraska conditions and extreme-case storm event conditions, sagging was reduced but still occurred.

Another common structural issue experienced by silt fences that can be detrimental to the performance of the installation is slow dewatering, caused by pores in the silt fence becoming clogged by sediment. Impoundment remaining behind a silt fence installation for prolonged periods can lead to overtopping after subsequent storm events and increases the risk of other structural failures. In the testing of the Nebraska DOT standard, offset trench, and wooden post silt fence installations, impoundment only receded to less than 7.6 cm (3 in.) during the 90 min dewatering period after the conclusion of flow introduction. It took up to three days for the installation to completely dewater. To aid in the dewatering process, an adjusted version of an installation with a dewatering board with an overflow weir designed by Whitman et al. was tested. A V-notched overflow weir was designed at 30.5 cm (12 in.) above the ground; this height was chosen based on research showing that 30.5 cm (12 in.) of impoundment facilitated 90% of sediment retention under Alabama conditions [8]. The height of 30.5 cm (12 in.) rather than the 45.7 cm (18 in.) used by Whitman et al. [15] was employed due to the Nebraska conditions used in testing rarely resulting in 30.5 cm (12 in.) of impoundment and never reaching 45.7 cm (18 in.) in depth. The difference in impoundment created was due to the flow and sediment introduction rates used in the testing under Nebraska conditions, 0.0024 m^3/s (0.086 ft^3/s) and 12.1 kg/min (26.6 lb/min), respectively, which were less than those used in the testing under Alabama conditions, 0.03 m^3/s (0.22 ft^3/s) and 17 kg/min (37.6 lb/min), respectively [15]. Three 1.9 cm (0.75 in.) diameter orifices were spaced 7.6 cm (3 in.) apart below the weir to allow for the steady dewatering of the impoundment formed. An energy-dissipating splash pad of an excelsior blanket and wattle was installed to prevent downstream scour from the dewatering holes and overflow weir. Figure 6 shows the dewatering board silt fence installation. The dewatering board improved dewatering time, as complete dewatering was achieved in less than 8 h. Impoundment never reached the height of the overflow weir during testing under Nebraska conditions or extreme-case storm event conditions. Excessive sagging led to the effective height of the fence falling below the overflow weir, leading to overtopping, which has the potential to cause scour in areas unprotected by an energy-dissipating device such as a wattle. To ensure that excessive impoundment goes through the overflow weir and does not overtop at other locations, a final installation with a reduction in post spacing from 1.8 m (6 ft) to 1.2 m (4 ft) around the dewatering board was tested. In practice, the adjusted post spacing would only need to be in areas around the dewatering board which would be installed at areas of increased impoundment, such as the lowest point of a run of silt fence experiencing the highest level of impoundment.

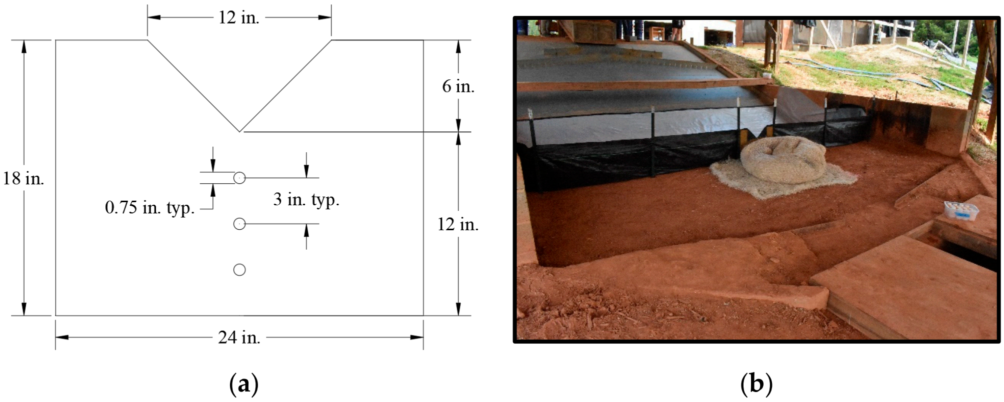


Figure 6. Silt fence installation with dewatering board with overflow weir: (**a**) schematic of dewatering board; (**b**) final installation with splash pad. Note: 1 in. = 2.54 cm.

Under extreme-case storm event testing, the impoundment was able to reach the height of the weir; excessive impoundment and downstream scour were prevented as the flow was unable to overtop at other locations along the installation due to the reduced sagging.

Table 2 shows a summary of the structural performance deficiencies found during testing. Undermining was reduced by the installations with the 15.2 cm (6 in.) offset trench. Only one installation of the six with the 15.2 cm (6 in.) offset trench saw undermining occur, showing a reduced risk of failure compared to the installations without the offset trench. Prolonged dewatering occurred in all installations that did not have a dewatering board. Sagging was only able to be reduced by reducing the post spacing. Excessive sagging in the installation with the dewatering board and overflow weir led to flow bypassing the overflow weir due to the reduced effective height of the installation. The installation with the dewatering board and overflow weir and a reduction in post spacing to 1.2 m (4 ft) reduced the occurrence of all failure modes and was selected as the MFE-I.

Table 2. Summary of the structural deficiencies observed.

Installation Parameters	Standard Testing	Extreme-Case Testing
M0: Nebraska DOT Standard	Sagging, Undermining, Slow Dewatering	Complete Failure
M1: 15.2 cm (6 in.) Offset Trench	Sagging, Slow Dewatering	Sagging, Overtopping, Slow Dewatering
M2: Wooden Posts w/15.2 cm (6 in.) Offset Trench	Sagging, Slow Dewatering	Sagging (less than standard), Overtopping
M3: Dewatering Board w/Overflow Weir, and 15.2 cm (6 in.) Offset Trench	Sagging	Sagging, Overtopping (bypassing weir)
M4: Dewatering Board w/Overflow Weir, 1.2 m (4 ft) Post Spacing, and 15.2 cm (6 in.) Offset Trench (MFE-I)	Undermining	None

3.2. Sediment Retention

The sediment retention percentage was calculated by comparing the weight and moisture content of total deposited sediment to the weight and moisture content of the introduced soil. Equation (1) shows the process used to determine sediment capture for each set of the three simulated stormwater runoff events:

$$\%SC = \frac{\frac{W_d}{1+MC_d}}{\frac{W_I}{1+MC_I}} \tag{1}$$

where

$\%SC$ = percent sediment capture (%);
W_d = weight of deposited sediment (kg [lb]);
MC_d = moisture content of deposited sediment (%);
W_I = weight of introduced sediment (kg [lb]);
MC_I = moisture content of introduced sediment (%).

Capture facilitated by installations that did not fail ranged from 79 to 95%, with an average capture of 83% across the three installations of the Nebraska DOT standard and four modified installations.

3.3. Water Quality

The samples tested for turbidity and TSS were analyzed at the four sampling locations (S1 through S4) to determine overall treatment and the differences in water quality between sampling locations; these water quality parameters were chosen due to the fact that they are indicators of the amount of sediment in water, which is what sediment control practices aim to treat. Table 3 shows a summary of the water quality data across the sampling locations. The impoundment's surface (S2) having lower turbidity and suspended solids values than the lowest depth of impoundment (S3) and the discharge (S4) indicates that water treatment occurred due to soil particles continually falling out of the suspension, while there was little to no treatment occurring through the fabric of the silt fence.

Table 3. Water quality data across all tests.

Sample Location	Turbidity	TSS
Water surface of impoundment (S2)	1753 NTU	1345 mg/L
Lowest depth of impoundment (S3)	2866 NTU	2605 mg/L
Discharge (S4)	1907 NTU	1644 mg/L
Difference between S3 and S2	−38.8%	−48.4%
Difference between S2 and S4	−8.08%	−18.2%
Difference between S3 and S4	50.3%	58.5%

Figure 7 displays the average turbidity over the course of the tests and through the dewatering monitoring period, showing that the average turbidity at the impoundment's surface (S2) was lower than that at both the discharge (S4) and the lowest depth of the impoundment (S3) during the test period, while all three of the sampling locations flattened out to similar values during the dewatering period.

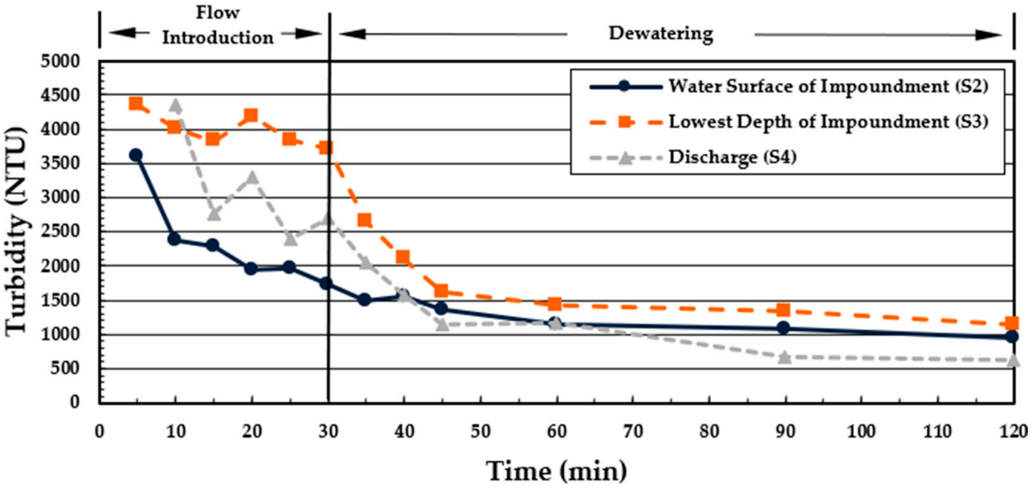


Figure 7. Average turbidity over time for woven silt fence installations.

An unpaired t-test at a 95% confidence interval was used between samples taken at the same time during the same test to determine whether statistically significant turbidity treatment occurred through the installation and within the impoundment. The results of this analysis are shown in Table 4. There was a statistically significant difference between the turbidity at the top of the impoundment and the bottom of the impoundment due to the calculated p-value being far less than the significance level; this difference indicates that water quality at the top of the impoundment is significantly lower in turbidity than at the bottom of the impoundment formed by the practice. However, there was not a statistically significant difference between the turbidity at the top of the impoundment and the discharge flowing through the fabric of the silt fence. This suggests that there no filtration occurs through the woven fabric of the silt fence installation and that water treatment occurs through the process of sedimentation as soil particles fall out of the suspension.

Table 4. Statistical analysis of impoundment and discharge turbidity.

	Mean Diff. (NTU)	df	T-calc	*p*-Value
S2–S3	−1113	416	−7.179	<0.0001
S2–S4	−154.1	237	−0.938	0.3492

4. Conclusions

Due to silt fence installations not having adequately been scientifically tested, especially under conditions local to areas outside of the Southeastern United States, large-scale testing at the AU-SRF was conducted on the current design for Nebraska DOT standard silt fence installations and four modifications. Conditions local to Nebraska highway construction projects were tested to determine water quality treatment, sediment retention, and structural performance; extreme simulated stormwater runoff event conditions were tested to determine structural performance under increased impoundment conditions. Initial testing of the Nebraska DOT standard silt fence indicated a need for improvement in structural performance due to sagging, undermining, long dewatering periods, and complete failure under substantial impoundment; modifications including a 15.2 cm (6 in.) offset trench, wooden posts, and a dewatering board with an overflow weir were tested to determine if improvements were made. From the testing results, the most feasible and effective installation, consisting of a dewatering board with an overflow weir, a 15.2 cm (6 in.) offset trench, and 1.2 m (4 ft) post spacing around the dewatering board, is recommended as the optimal installation due to its increased structural performance and lack of greatly increased installation and material costs. Sediment retention averaged 83% across all modifications, with a maximum of 95%. There was not a clear improvement across the modifications in sediment retention under the standard Nebraska testing conditions; however, the modifications made would allow for repeated sediment retention if properly maintained by preventing structural failures. Additionally, water quality treatment and, subsequently, sediment retention was found to be due to sedimentation within impoundment formed due to there being a statistically significant difference in turbidity between the water's surface and the bottom of the impoundment; there was not a statistically significant difference in turbidity between the water's surface of the impoundment and the discharge.

The results of the sediment barrier testing completed at the AU-SRF can be used to improve the design and implementation of silt fence sediment barriers, especially in the state of Nebraska and surrounding areas, and fill the knowledge gap on sediment barrier testing outside of the Southeastern United States. The results of this study are intended to be used for the development of applicable guidance for silt fence designs and installations for Nebraska highway construction projects, as well as projects in surrounding areas with similar hydraulic and soil conditions and other jurisdictions that outline the use of silt fence installations with woven geotextiles attached to posts using plastic cable ties. The limitations of this study include its limited number of tests, which led to some modifications that could be used to further increase performance not being able to be tested; imperfections in the silt fence fabric causing potential variability between tests; and the fact that long-term performance and material degradation were not evaluated. Additionally, similar testing could be completed on other silt fence alternatives to determine other feasible sediment barrier installations. The testing methodology outlined herein could also be used to test sediment barriers under conditions local to other areas of the country.

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