Bank Stabilization with Fabric Encapsulated Soil Lifts (FESL)

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Abstract:

Fabric Encapsulated Soil Lifts, commonly referred to as FESL, pronounced (feh-sl or fes-uhl), have begun to increase in popularity as a viable bioengineering bank stabilization technique. Originally designed to replace riprap, FESL provides a softer engineering solution to typical hard-armoring type projects. The usage of native materials and the implementation of live cuttings and geotextile fabrics provides a short-term and long-term solution to reduce and/or prevent bank erosion yet does so in an aesthetically pleasing manner. It’s deformability and flexibility make it a universal technique for a variety of stream types within a wide range of environments and site conditions.

With a history dating back to the 1940’s, but not gaining traction in the United States until the 1990’s, FESL (also referred to as F-E-S or geogrids), was designed to replace hard armoring techniques as river regulators, permitting agencies, and local and state governments sought a softer approach to bank stabilization. The purpose of this study is to provide a comprehensive guide into the concept, design, and construction of FESL to prove its viability as a bank stabilization technique. This study discusses the individual components of FESL and design considerations that must be evaluated during any project involving FESL. The components include native soils, geotextile fabrics, and live cuttings, that when constructed properly are capable of withstanding shear stresses up to 6.0 lb/ft^2 after 3-5 growing seasons. The use of FESL, however, is not appropriate for all sites; therefore, each project should include a detailed evaluation of the site-specific hydrology and hydraulics, as well as the site topography, to determine if a bioengineering approach is acceptable.

Four case studies evaluating four different FESL projects are discussed, which includes design and performance-to-date values for a variety of systems. These case studies indicate that if the general criteria for FESL discussed in this document are implemented into the design and construction, then FESL will be a successful bank stabilization technique if permitted by the site conditions. A project example follows where the reader is stepped through the evaluation, analysis, and design decisions that were made in a real project located along the Boise River in Boise, Idaho.

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1. Introduction

1.1 Summary

The use of fabric encapsulated soil lifts (FESL), pronounced (feh-sl or fes-uhl), has become increasingly popular as restoration practitioners around the country seek to provide a more aesthetically pleasing and natural approach to bank stabilization. FESL is a bioengineering technique in which brushlayering and live fascines are wrapped with geotextile fabrics in tightly packed soil lifts, with live stakes anchored within. First used in the 1940's but not gaining traction until the 1990s (Hoitsma, 1999), FESL (also referred to as F-E-S or geogrids), was designed to replace riprap as river regulators, permitting agencies, and county and state governments sought a softer approach to bank stabilization.

Projects with the U.S. Army Corps of Engineers (USACE), as well as other federal, state, and municipal agencies, are often restricted from using hard armoring techniques, such as riprap or concrete-lined channels for environmental reasons, leading to an increase in the popularity of bioengineering techniques such as FESL. It has quickly become a viable solution for most bank stabilization projects. The combination of biological, mechanical, ecological elements creates a bank stabilization technique that utilizes both living and nonliving engineering materials (USACE- Allen, H.H. & Leech, J.R.).

Compared to other bioengineering techniques that rely entirely on vegetation for bank stability, FESL provides both short term and long-term stabilization. The FESL provides immediate stabilization without vegetation growth as the geotextile maintains slope stability until the vegetation can become established. Over time, the blankets will naturally biodegrade, while the root systems of the live cuttings expand and bind the soil particles together and ultimately increase the overall stability of the bank. The exposed vegetation increases surface roughness and reduces local flow velocities close to the bank, thus reducing the transport capacity and shear stress near the bank. Photographs of recently installed FESL are presented below.

Photographs 1 and 2
Recently constructed FESL along the Boise River (looking upstream). Photos taken March 2019 (left) and August 2020 (right).

In addition to providing a natural approach to bank stabilization, FESL is flexible and deformable, meaning it can be constructed to meet site specific conditions. Common design parameters that may vary include the bank slope angle, number and thickness of lifts, and the top and bottom elevation of lifts and vegetation with respect to anticipated flow depths. Common FESL bank slopes range between 1H:1V and 2H:1V, with typically 3 -4 lifts. Standard construction practice varies, but each lift commonly varies in thickness between 8”-18” resulting in typical FESL heights of 3 -6 ft.

1.2 Purpose

The purpose of this document is to present a comprehensive guide for Engineers/Scientists, Contractor’s, and Clients, into the purpose, design, and construction of Fabric Encapsulated Soil Lifts. As a relatively new and uncommon (to-date) bank stabilization technique, FESL often appears to be a difficult construction technique for those who are new to the approach. To date, a comprehensive guide such as this document has not been available, forcing engineers and contractors alike to piece together the various components and design considerations required for a successful FESL project. This document discusses the concept of FESL, the design elements and considerations incorporated into any FESL project, and a guide for construction.

Case studies for a few project examples designed by Jacobs Engineering Group, Inc. are also included, as is an ongoing design (as of Spring 2021), where the author will walk the reader through the design decisions that were made based on a real-world project scenario. The goal of this document is to demonstrate FESL’s legitimacy as a viable solution for bank stabilization projects and to provide insight into the process required for proper FESL construction.

1.3 History of FESL

Living and inert materials have been recorded as viable alternatives for stream erosion protection in Europe since the eighteenth and nineteenth centuries (Evette et al, 2009). Records indicate that the term “biological engineering” or “ingenieurbiologie” was first used by V. Kruedener in 1951, when referring to projects that utilized the biological attributes of live vegetation to solve the physical laws of “hard” armoring. From there, the term bioengineering (or biotechnical engineering) was born and continues to evolve to this day.

The use of live stakes to secure banks and slopes has been referenced dating back to the sixteenth century, mainly after Leonardo da Vinci recommended it to prevent bank erosion (Labonne et al, 2019). Similarly, King Frederick William I of Prussia ordered willows to be planted in order to stabilize the riverbanks of his territory and to slow water flow. It was not until the eighteenth century, however, when books on bank stabilization with live cuttings began to be published by French, German, and Italian scientists. The scientists quickly saw what hydrologists, geomorphologists, and hydraulic engineers are seeing today, that live materials produce a living bank that is capable of withstanding erosional forces that otherwise would have resulted in bank failure.

The use of bioengineering principles in the United States did not begin as early as the projects in Western Europe. The earliest record of the use of bioengineering in the United States was in 1934, when the Forest Service began implementing bioengineering techniques when trees, brush, live fascine, brush layering, and rock were used to stop erosion. John E. Hughes, a Junior Forester with the Forest Service, describes that bioengineering, then simply referred to as “erosion control structures”, should be considered “only as temporary expedients to hold the soil in place until vegetation can become established and stabilize a [bank] permanently” (USDA, 2003). It wasn’t until the 1990’s, based on recorded information available to the author, that FESL (then called terraced geocells) was introduced. Hoitsma and Miller (1999) discuss the need for a technique that could withstand higher shear forces that would otherwise exceed the stability of traditional bioengineering designs. By combining the vegetation element of bioengineering techniques with synthetic materials, the geocells were constructed and were determined to be able to withstand shear stresses of nearly 115 Pa (2.4 lb/ft^2).

Since the 1990s, the use of FESL has only grown in popularity. There are numerous other project examples around the country, not mentioned in this report, that are responsible for the implementation of this bank stabilization technique. Credit for the introduction of FESL into the United States cannot be given to any one individual nor any single entity, as it's implementation and design are very rarely ever the exact same.

2. Fabric Encapsulated Soil Lifts

2.1 Uses and Benefits

A primary benefit of FESL is it's ability to provide immediate stabilization in advance of vegetation establishment. The geotextile reinforcement of each lift along the bank and the incorporation of live cuttings decreases hydraulic forces along the bank and holds the newly constructed soil lifts together until the vegetation can provide stability for the bank for the long term. Over time (typically 3-5 years), the geotextile will gradually biodegrade as it is made of woven coir and jute fibers, while the root system of the live cuttings within the FESL will bind the soil particles together and increase the overall stability of the bank. Additional benefits of FESL and other bioengineering techniques include:

- Emphasizes native vegetation
- Provides immediate resistance to hydraulic forces
- Self-sustaining with deep-binding root mass that is resistant to erosion
- Deformable and less likely for entire treatment to fail structurally if a portion fails
- Cost-effective in the long-term due to less maintenance
- Aesthetically pleasing.

The typical section in Figure 1 consists of three lifts of FESL and an upper section graded at a stable slope, vegetated, and covered with geotextile fabric. While the elevations and constituent species may change, this typical section is often constructed in the splash zone and bank zone (see Section 2.2) of a FESL installation project: the splash zone that includes a vegetation reinforced slope that is well-suited for greater erosive forces along streams and the upper bank zone that provides long-term erosion protection while incorporating native riparian species suitable for restoration. Commonly used riprap or native streambed alluvium at the toe (within the toe zone) is not shown in Figure 1.

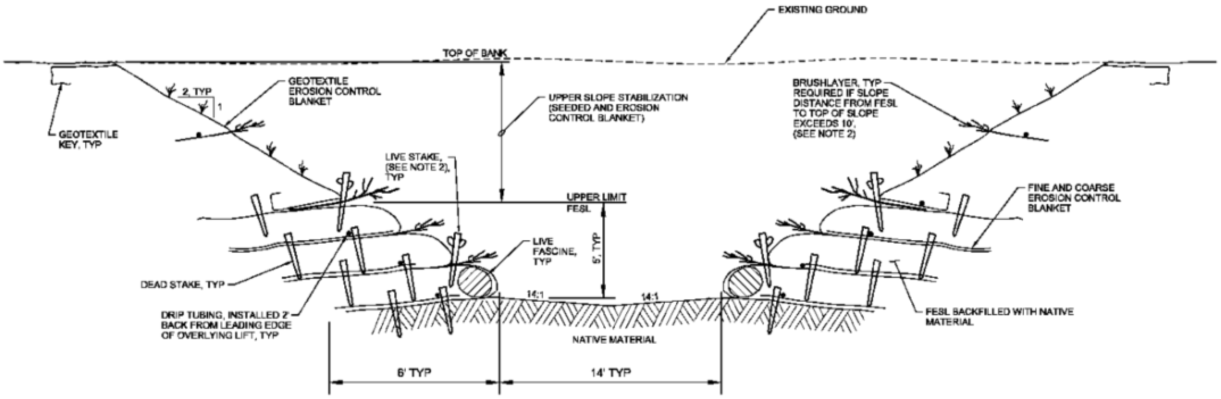


Figure 1. Typical FESL Section

2.2 Bank Zones

The design of FESL is based on a zonal approach in terms of river hydrology (i.e. river stage), as represented by the typical channel section incorporating FESL illustrated in **Figure 1.** As described by Lyn and Newton (2015), a zonal approach can be used to differentiate between a lower bank region and an upper bank region along the streambank. A schematic of the zonal approach concept, separating a typical riverbank into four different zones, is presented in Figure 2.

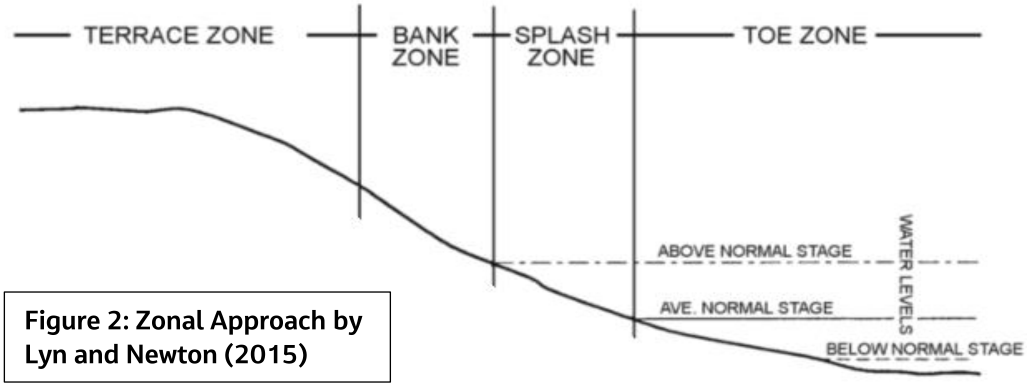


Figure 2: Zonal Approach by Lyn and Newton (2015)

This zonal approach provides a practical method for assigning reliable streambank protection materials based on the frequency of inundation and the typical hydraulics experienced in each zone. The separating stages, as identified in Figure 2, include the normal baseflow (i.e. average normal stage), and the typical ordinary high-water mark (OHWM), commonly assigned a 1.5-year recurrence interval (i.e. above normal stage). The difference between the terrace zone and the bank zone is delineated by a change in bank slope, as the terrace zone is defined by the overbank areas which are very rarely inundated. It is important to note that these zones are not precise, and vary seasonally, and even daily. A description of each zone and the appropriate type of typical streambank protection materials is given below.

2.2.1 Toe Zone

The toe zone is expected to experience the largest shear stresses and would therefore have the highest erosion potential and be the most at risk for failure. With respect to the design of FESL, this zone extends from below the channel invert up to the ordinary baseflow water level and is best suited for hard armoring elements such as rock riprap or equivalent. Toe slope failure is one of the primary failure mechanisms of FESL, as failure of the toe leads to failure and collapse of the overlying bank. To counteract these high shear stresses, toe slope protection should be designed to extend to the maximum scour depth for the design event of choice, and should follow typical riprap guidance for the size and thickness of the material. It is commonly recommended that the riprap that is installed below the water surface is increased in thickness by up to 50%, compared to the riprap above the OHWM.

2.2.2 Splash Zone

The splash zone, as defined by Lyn and Newton (2015), is delineated as the area of the bank between the baseflow WSE and the OHWM. This splash zone is subject to shear stresses higher than the bank zone, but less than those in the toe zone, thus creating an area where additional protection beyond vegetation is likely required, but hard armoring like riprap may not be necessary. Commonly used stability thresholds which can serve as guidance in deciding the proper stabilization technique are described in Section 3.1. The splash zone is the area in which FESL is most commonly installed.

FESL can extend above the OHWM elevation, if additional bank protection is justified, but it is not recommended to install FESL below the splash zone at an elevation within the toe zone. A detailed look at the vegetation specified for each FESL application will be required to ensure the selected species are capable of tolerating an increased frequency of flooding and higher shear stresses and channel velocities.

2.2.3 Bank Zone

Above the splash zone is the upper bank zone, which extends from the ordinary high-water mark (OHWM), up to the terrace zone where the bank slopes flatten. This upper bank zone often requires less stringent streambank protection material design compared to the toe zone, resulting in it commonly being vegetated without the use of a hard-armoring technique. Because of the frequency of inundation (>1.5-year recurrence interval), supplemental irrigation may be required if FESL is to be constructed in the bank zone. Plants should be positioned in their correct zone based on their ability to tolerate certain frequencies and durations of flooding, and should include a detailed look into their abilities to dissipate stream energy.

2.2.4 Terrace Zone

The terrace zone is the portion of the bank inland from the bank zone. It is usually not subjected to erosive action from streamflow, except during extremely high flows, but can be easily eroded when flooded if vegetation is not present. Vegetation in this zone is extremely important for intercepting floodwater from overbank flooding, but also for increasing the strength of the soil by reducing its moisture content (Allen & Leech, 1997). Similar to the bank zone, selection of the species of this zone must consider the flood (and drought) tolerance of each species.

2.3 FESL Components

The key to success for any FESL project is the proper installation of high-quality materials. There are five key components to a complete installation of FESL: geotextile fabric, soil, live cuttings, a keyway to protect the ends of each lift, and a rock toe. There have been numerous instances where incorrect installation of just one of the components described below has resulted in failure of the entire FESL.

2.3.1 Geotextile Fabrics

Each lift of FESL construction consists of geotextile fabric which provides two functions: to retain soil particles and provide sufficient pullout resistance to satisfy slope stability requirements. This often requires two products: a coarse outer layer and a fine inner layer (Figure 3), but may also be accomplished with a single geotextile. Some products (e.g. Nedia KoirWrap1000 or equivalent) provide both fabrics combined into 1 roll, which is acceptable if the following material properties are met:

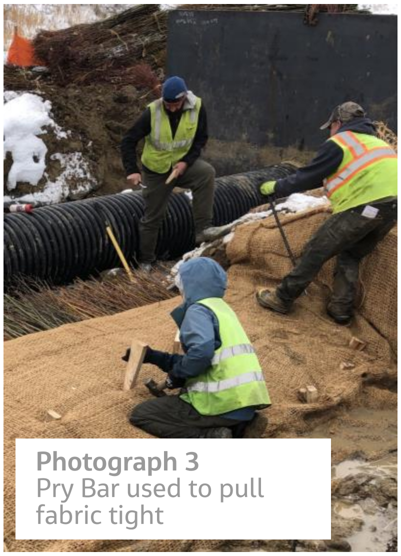
Table 1: Required Geotextile Fabric Material Properties

Geotextile Property	Test Method	Minimum Average Roll Values	
		Fine Geotextile	Coarse Geotextile
Mass per Unit Area (oz/yd^2)	ASTM D6475	10	26
Dry Tensile Strength (lb/ft)	ASTM D6818	200	1,250
Thickness (in.)	ASTM D6525	0.23	0.56

The outer geotextile layer is a coir matting (i.e. coconut fiber) product used to provide strength and rigidity to the soil lift. This outer geotextile is responsible for providing pullout resistance against lateral earth pressures in the slope by retaining the soil mass, and for withstanding the shear stresses and velocities within the channel. The coir fibers are slow to degrade, providing between 3 and 5 years of stability for the vegetation to establish. The inner geotextile layer is a coir, jute, or straw netting product used to provide an additional layer of protection, but also to encourage root establishment. This fine geotextile product better holds the soil particles in place, but cannot withstand the higher hydraulic forces, thus requiring the two layers. On streams where ice damage may occur, outer fabrics (coarse geotextile) with greater tensile strength and abrasion resistance should be evaluated (Karle, 2003).

Figure 3: Examples of Coarse (left) and Fine (right) Biodegradable Geotextiles

The geotextiles should be placed to ensure the largest tensile strength direction of the fabric is oriented perpendicular to the bank. This approach typically requires joining of the fabric, which is completed by overlapping a minimum of 18-inches in the downstream direction (i.e. direction of flow) and securing the joint into the underlying material. The fabric should be neatly and tightly wrapped to prevent drag forces from high flow events from acting on loose fabric (Baird et al., 2015). To keep the fabric tight, dead and live stakes are used to stake the fabric down into the compacted soil below. The objective is to minimize rolls/wrinkles in the fabric and construct a tight, snug finished product that has some “spring” in the fabric. Until the vegetation is established, rolls and wrinkles will increase the near-bank drag forces and could reduce the long-term effectiveness of the fabric. Large pry bars (Photograph 3) or even a contractor-made apparatus (i.e. lumber and C-clamps or equivalent) to utilize the excavator bucket have been used successfully to achieve the optimal tightness of the fabric.



Photograph 3
Pry Bar used to pull fabric tight

2.3.2 Native Soil

FESL projects consist of soil lifts built one on top of another, set back from the one below at the desired average slope angle resulting in a sloped geotextile retaining wall. The number of lifts may vary based on site conditions, but most FESL applications consist of 3-4 lifts. FESL lifts commonly vary from 8”- 18” in thickness, with 12”-18” being ideal for the most protection. Lifts larger than 18” in thickness can erode more readily and are not recommended (Baird et al., 2015). The selected thickness of each lift must balance the site hydraulics and the cost of the project as thicker lifts are generally less expensive due to a decrease in the total required quantity of lifts.

Backfill material for the lifts should be clean, native material, free from rocks larger than 6 inches, from roots and other organic matter, ashes, cinders, trash, debris, and other deleterious materials. The soil should serve as a suitable growth medium, while also offering resistance to grain detachment and transport (Miller & Hoitsma, 1998). If native material is inadequate, fill materials should consist of organic silts and clays, or soils that will support the selected vegetation. Because the long-term success of all bioengineering techniques rests on the success of the vegetation establishment, the selected soil is of the utmost importance. In most cases, restoration projects involving FESL commonly occur at project sites where vegetation is already established, meaning native soils are typically appropriate. It is not uncommon, however, for soil amendments to be required to optimize the soil conditions for vegetation growth. If soil chemistry issues may be present, soil samples should be collected and evaluated by a soil scientist or geotechnical engineer.

Each soil lift should be compacted prior to stretching of the top section of fabric, but care should be taken to prevent over-compaction which may hinder root establishment. The percent or degree of compaction should be evaluated on a case-by-case basis (typically 80-85%) but should never exceed 95% Standard Proctor. In most FESL installation applications, light compaction with the bucket of an excavator has proven to be adequate in achieving an appropriate level of compaction.

2.3.3 FESL Keyway

Perhaps as important to the overall success of FESL as the soil and vegetation, FESL keyways prevent failure by anchoring the lifts into the bank at the ends of each lift. Similar in concept to rock keyways that “lock” the structure into the bank, FESL keyways are constructed into the bank to prevent unraveling at the ends of the lifts where the geotextile wraps are most vulnerable. It is vital for the upstream and downstream ends of the FESL to be anchored sufficiently to minimize the impacts from erosion and scour that could otherwise cause the geotextile fabric to unravel. Especially at the upstream end, channel flows could erode unreinforced portions of adjacent streambank, or undermine the FESL and get inside of the fabric if not properly secured. Ultimately, this could cause failure of the entire FESL section as the fabric could continue to be “pulled” into the channel, resulting in complete bank failure if vegetation has not yet been established.

To prevent this phenomenon, each FESL lift should extend into the bank a minimum of 10 feet at the ends, perpendicular to the exposed FESL face. While a 90-degree angle (between the keyway wraps and the direction of streamflow) is not an absolute requirement, the FESL should extend back at an angle that can effectively dissipate the perpendicular flows of the channel. Figure 4 presents a schematic of how the keyways should be constructed, indicating what is exposed and how much of the lift is buried within the bank.

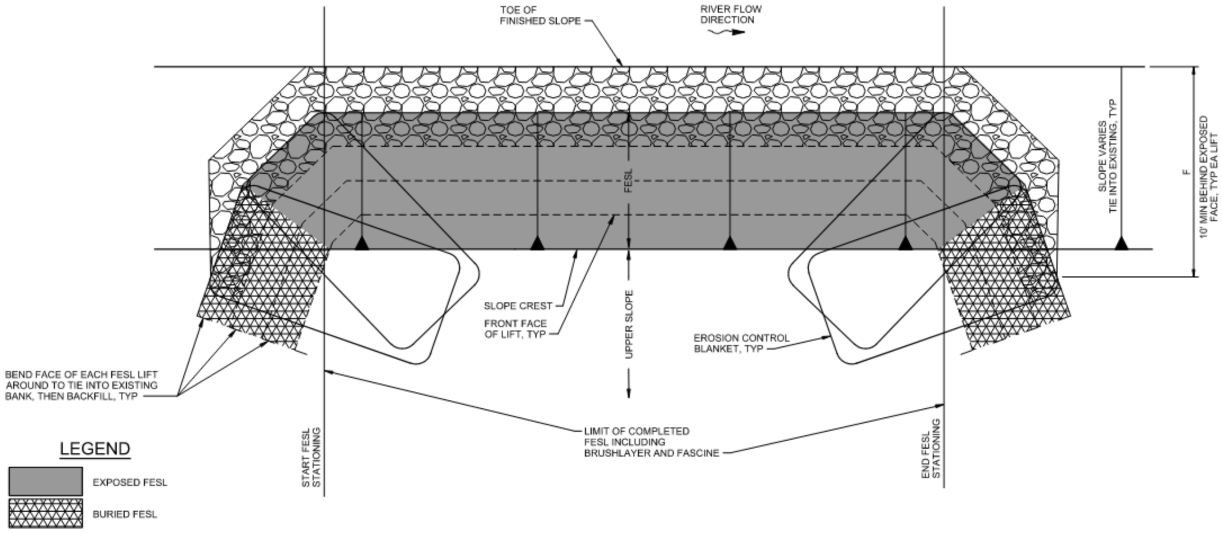


Figure 4: FESL Keyway schematic

2.3.4 Vegetation - Live Cuttings

Biostabilization treatments are most effective when they are constructed using dormant vegetation (i.e., live cuttings that are collected during the winter season) and irrigated for the first growing season as needed. For much of the United States, the dormant season is at least November 15 through February 15, meaning most FESL construction projects occur in the winter. Once buds begin to swell and leaves begin to appear, the plant is no longer dormant. It’s important to use dormant cuttings, as they are prone to first grow roots when planted, and are better able to resist environmental stresses (Luna et al., 2006).

This dormant season and the species of cuttings to be used vary by geography and should be determined by a biologist or landscape architect. Within the Western United States, dogwood (*Cornus sericea*), cottonwood (*Populus* species), and willow (*Salix* species) are the most commonly used species for FESL applications. Hoag et al. (2008) provides a Riparian Plants Use Guide for the Intermountain West and Pacific Northwest Regions, however numerous species identified within the Guide can also be used within the Midwest, Northeast, and Southern states.

Because of construction sequencing, it is common for cuttings to be harvested (or imported) and stored on site for a period of days prior to installation. Local harvesting of native species is preferred to importing species from a supplier, however various project constraints may make importing live cuttings the preferred alternative. If possible, local harvesting should be completed within 1 week of installation and should follow direction provided in a Guide published by the United States Forest Service (USFS) entitled “Collecting Dormant Hardwood Cuttings for Western Riparian Restoration Projects”.

Cuttings are highly perishable, meaning they must be protected from drying out immediately after harvesting. When properly harvested and stored, cuttings can survive for weeks prior to installation. When improperly stored, or harvested outside of the dormancy period, the cuttings should be installed no later than 1 week following harvesting for a higher probability of success. When harvesting cuttings during freezing weather, the bundles should be kept as cool as possible and out of the direct sunlight, with minimum exposure to wind.

Direct sunlight and wind can accelerate the dehydration process of harvested cuttings, especially in low humidity environments. To keep them moist, soaking the stored cuttings in moist soil, or in a wet burlap bag or equivalent can drastically improve the probability of success. Within 24 to 48 hours of planting, soaking the butt (i.e. cut) end of the cuttings in water (e.g. pond, river’s edge, etc.) will also improve their chance of survival, especially if the dormancy period is ending.

FESL installation projects typically involve thousands of live cuttings, as they are used in three forms within the FESL: live fascine, brushlayer, and live stakes. Each application serves a different purpose, but all increase the probability of a successful vegetation establishment following construction. Each of these components are discussed in detail below.

2.3.4.1 Live Fascine

A fascine is a bundle of four to six-foot-long live cuttings tied together (Figure 5) and installed at the toe of slope as discussed in Section 4 and shown in Attachment 1. This bundle of cuttings is installed parallel to flow, providing additional protection to the toe of the FESL slope where shear stresses are highest. As the fascine grows roots, it’s erosion control function improves, but also improves the riparian zone function and the fisheries habitat within the channel. While acceptable to install fascine in more than the bottom lift, standard construction practice only involves the installation at the toe of the FESL slope.

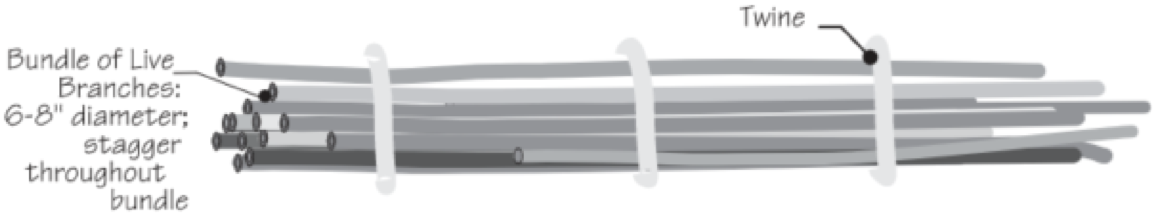


Figure 5: Schematic of Live Fascine
[Photo Source: USDA (2003) - A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization)]

2.3.4.2 Brushlayer

Brushlayering is the technique of laying live cuttings along horizontal benches, oriented perpendicular to flow with the top end of the cutting exposed outside the bank slope. Within FESL, a brushlayer is installed between each lift with the cuttings protruding from the slope face to assist with retarding runoff and reducing surface erosion (Figure 6). Once the brushlayer becomes established, the roots add significant resistance to sliding and shear displacement, while the exposed vegetation increases surface roughness along the bank. No more than 20 percent of the length of each cutting should be left exposed on the completed slope.

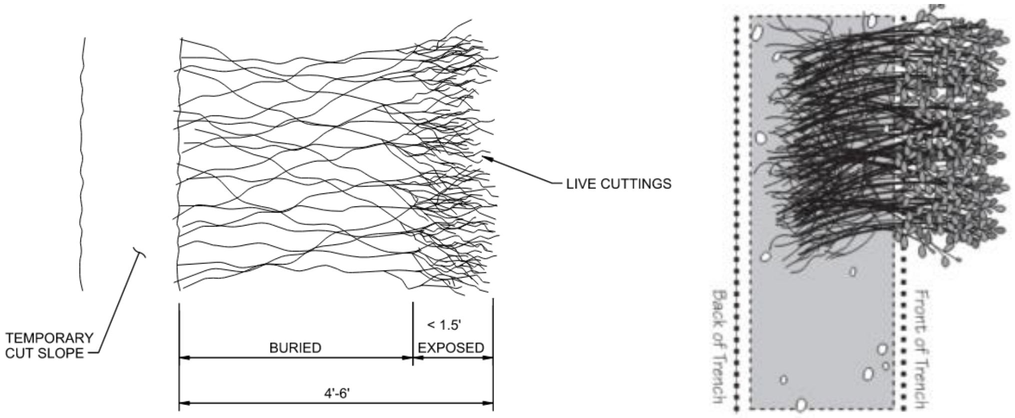


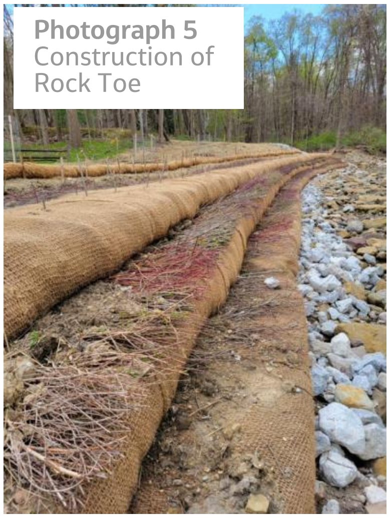
Figure 6: Detail and Schematic of Brushlayering
[Photo Source: USDA (2003) - A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization]

2.3.4.3 Live Stakes

Live stakes are 1 to 2 inches in diameter and approximately 2-3 feet long cuttings used to stake the geotextile fabric and aid in vegetation establishment. Used in conjunction with dead stakes, the stakes are also responsible for holding the geotextile fabric in place and ensuring the fabric is tight for enhanced performance. Live stakes are inserted throughout the FESL at a specified density dependent on bank slope, environmental conditions, and soil conditions to create the root mass required to bind the soil particles together. Live stakes perform best when installed within the wetted zone of the bank, but may require supplemental irrigation during the first two growing seasons for optimal success. Photograph 4 shows a typical live stake installed in an overbank area to aid in vegetation establishment.


Photograph 4
Typical Live Stake

2.3.5 Rock toe


Photograph 5
Construction of Rock Toe

As the maximum shear stresses within the channel are experienced along the lower part of the bank (i.e. toe zone), and then decrease to zero near the free surface, a rock toe is commonly implemented below FESL (Photograph 5). As stated by Fischenich (2003), “A combination of riprap in the toe section and woody vegetation on the upper banks often affords the best combination of stabilization and environmental benefits”. This rock toe slope protection is capable of withstanding shear stresses of nearly 10 lb/ft^2 (when properly installed), with the gradation for toe slope protection sized based on the site-specific hydraulics. The primary benefit for the rock toe is that it provides protection that is not impacted by the channel hydrology which may otherwise “drown” establishing vegetation along the FESL. Typical rock toe designs extend below the channel thalweg and the predicted scour depth, and up to the baseflow water surface elevation. Figure 7 below presents a typical FESL detail with a rock toe included.

3. Design Considerations

As shown in Figure 7, all the individual FESL components discussed above are included within each section of FESL. The decision to include or not include various components is dependent on the site conditions, emphasizing the importance of evaluating the site-specific hydraulics for each individual project.

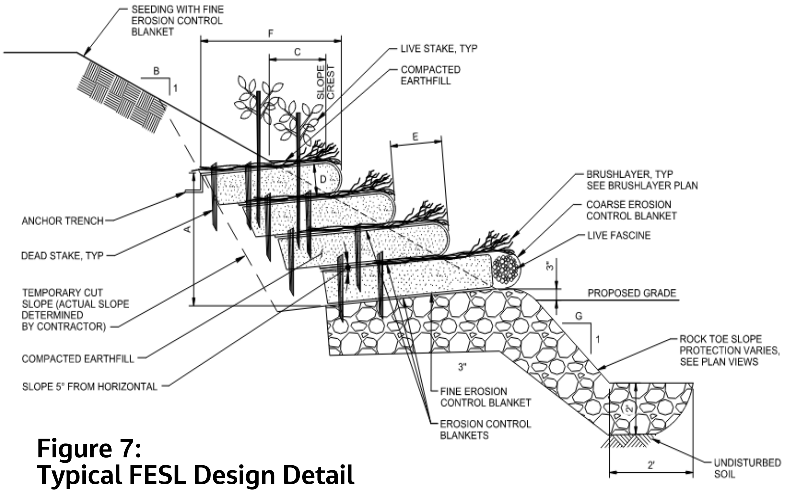


Figure 7:
Typical FESL Design Detail

When determining if FESL is a viable approach for a specific project, the design engineer must evaluate the following parameters:

- Existing and Proposed Site and Channel Geometry
- Soil Conditions (i.e. Soil Types, Soil Chemistry, etc.)
- Environmental Conditions
- Proposed Hydrology and Hydraulic Conditions

Proposed channel geometry is often influenced by various site constraints, especially the existing channel geometry. When feasible, steep channel banks should be graded back to a more stable side slope, such as 2H:1V, or whatever the soil type stability analysis deems stable. It is recommended that FESL is not installed on side slopes steeper than 1H:1V, with the ideal range of side slopes being between 1:1 – 2:1 (H:V). Flatter than 2H:1V is possible but may not justify additional bank stabilization measures.

Environmental conditions must also be evaluated and considered for any FESL design project. The stream orientation, elevation, and latitude, all affect the vegetation success. For example, on a stream oriented east-west, the north-facing slope will not get nearly as much sunlight as the south-facing bank. Similarly, for higher latitudes and steeper banks, this effect is more extreme and has a legitimate detrimental effect on the timing until vegetation is fully established. Similar effects occur from shade from overlying structures (i.e. bridges) or large overstory canopy in mature forested areas.

The most important parameters that must be considered when determining if FESL is a viable stabilization method are the proposed hydrologic and hydraulic conditions. As a bioengineering solution, FESL cannot withstand the same shear stresses and velocities that a hard-armoring technique can dissipate (see Section 3.1), nor can it handle frequent abrupt changes to the hydrology. Care must be taken when designing FESL that the frequency of inundation is consistent with the requirements of the selected species to ensure the highest probability of success. If the water level is too low or too high for an extended duration, the probability of success could diminish. The installation of FESL is not recommended below the baseflow water level, nor is it preferred significantly above the OHWM unless supplemental irrigation is included during the first few growing seasons.

3.1 Stability Thresholds

To date, little research has been completed on the maximum permissible hydraulic forces that a finished FESL project is capable of withstanding. This is the result of numerous design variations and highly variable site conditions (soil type, environment, channel geometry) that are present in any FESL construction project. The U.S. Bureau of Reclamation published “Bank Stabilization Design Guidelines” (Baird et al., 2015) which presents the maximum permissible velocities and shear stresses for various material types, which can be used as guidance for most design projects. The relevant resistance values for FESL components are presented in Table 2, in addition to some common hard-armoring techniques for comparison.

Table 2: Maximum Permissible Values for FESL Components

Material	Maximum Permissible Velocity (ft/s)		Maximum Permissible Shear Stress (lb/ft^2)	
	Low	**High**	**Low**	**High**
Erosion Control Fabric				
Coarse	3	4	0	2.25
Fine	1	3	1.5	1.65
Brushlayer (Initial vs. Grown)	12		0.4	6.25
Fascine	6	8	1.25	3.1
Live Stakes	3	10	2.1	3.1
Hard Armoring				
Riprap Rock Toe[1]	10	13	5.1	
Gabions	14	19	10	
Concrete	> 18		12.5	
1. Riprap gradation assumes d50 = 12"				

Source: U.S. Bureau of Reclamation (Baird et al., 2015)

While not explicitly stated, it is assumed that a properly constructed FESL project is capable of withstanding velocities up to 10 ft/s and shear stresses up to 6 lb/ft^2. Documentation proving these values through laboratory or real-world studies could not be found, but these values are a general rule of thumb used in industry. Li and Eddleman (2002) did evaluate numerous biotechnical streambank stabilization techniques, including vegetated geogrids (e.g. FESL) and assigned it a “Medium to High” Strength classification in their cost-strength matrix. This classification is based on the assumed strength of the technique after 3-4 growing seasons and equates to a value of approximately 290 Pascals (6.05 lb/ft^2) according to their documentation.

It is recommended that detailed site-specific hydraulic analysis is completed for any FESL design project to evaluate the maximum anticipated hydraulic forces. It is also important to note, that every material is subject to failure for large enough flooding events, therefore it is up to the discretion of the design engineer to decide at what recurrence interval failure of FESL may be acceptable. As with any project, the design must balance design constraints, project goals, and cost implications. FESL is relatively labor intensive (similar to the labor input required for other types of slope reinforcement), therefore it may not be the most cost-effective alternative for all bank stabilization projects.

3.2 Bank Slope Sensitivity

The design bank slope of most FESL projects is highly dependent on the existing topography of the site and other project constraints. Often times, the proposed FESL bank slope (i.e. side slope) is very similar to pre-project conditions or pre-erosion conditions if the project bank has experienced significant erosion. Excavation volumes, and the resulting impacts to project costs, are always a factor within any FESL project and may hinder the design from using an optimal bank slope.

When possible, however, the design bank slope can be optimized based on site-specific parameters. Billingsley (2020) evaluated different FESL scenarios using 2-Dimensional modeling software to identify what bank slope (1:1 or 2:1 H:V) was optimal for the construction of FESL. The results of the study indicated that there was a threshold for bank slope sensitivity in relation to the channel slope, where a 1H:1V bank slope may be preferred over an assumed more stable 2H:1V FESL bank slope. Although a 1.5:1 (H:V) bank slope was not evaluated, there is a small range where neither a 1H:1V nor a 2H:1V FESL bank slope is ideal, therefore it is assumed that 1.5H:1V FESL bank slope would result in optimal hydraulics for increased stability. A summary of the results, assuming a well-vegetated FESL reach, are presented in Table 3.

Table 3: FESL Bank Slope Recommendations Based on Channel Slope

Channel Slope	Recommended FESL Bank Slope (H:V)
S < 2.7%	2:1
2.7% < S < 3.0%	1.5:1
S > 3.0%	1:1

Although the results above are based off a high roughness coefficient assumption (well-established vegetation), the same recommendations can be made for recently installed FESL projects. As the vegetation becomes established and the roots bind the soil particles together, FESL is capable of providing the same level of stability within steeper channels. The results also indicated that, in general, FESL provides the most benefit to channel slopes (i.e. longitudinal profile) that exceed 1.8%, although slopes above 5.0% were not evaluated. Below 1.8%, FESL provided benefit by decreasing the near bank velocities and shear stresses, however the bank protection benefit was especially evident in steeper system simulations as opposed to flat channel reaches.

3.3 Failure Mechanisms

FESL failure is not only an expensive issue, but also a potentially catastrophic issue with respect to the bank. When bank protection fails, including hard armoring techniques, it leaves an exposed bank that is (likely) much more susceptible to erosion than it was pre-construction. One benefit of FESL is that it is extremely deformable, in that very rarely does it fail catastrophically and rather deforms to the eroded channel. Nonetheless, failure of the entire lift is possible if the FESL is “flanked” from behind or if the channel migrates entirely around it. To prevent this, it is especially important for the Contractor and Designer (e.g. Engineer) to be actively communicating to ensure the design intent is correct and understood by both parties, the FESL materials are appropriate, and the construction methods follow the design goals. The primary failure mechanisms for FESL revolve around improper construction, improper design, or factors out of the control of either the contractor or engineer (force majeure). Common examples of these categories resulting in failure are listed below and should be carefully considered during the design and construction stages of the project.

Improper Construction

- FESL keyways not constructed or not adequately anchored
- Improper materials (incorrect plant species, wrong geotextile fabric, etc.)
- Improper installation of materials (geotextile, density of cuttings, rock toe)
- Sharp angular fill or geotextile stretched too tightly resulting in fabric tear
- Inadequate site preparation.

Inadequate Design

- Failure to evaluate channel hydrology to determine optimal FESL lift thickness and total height
- Failure to evaluate soil chemistry
- Improper vegetation species selection based on frequency of inundation, geography, site conditions
- Failure to include toe slope protection.

Other Factors

- High Flows (> 2-yr recurrence interval) immediately after construction
- Major Flooding (> 10-yr recurrence interval) within 1-2 growing seasons
- No channel flows or rain to aid in vegetation establishment (supplemental irrigation often times recommended)
- Large Woody Material transport and bank impact during flooding
- Unexpected Livestock or Beaver Grazing
- Plant Disease or soil toxicity

As with any stream restoration or bank stabilization project, the concept of risk must be considered and accepted. Most projects are not designed to withstand 100-year (or greater) recurrence intervals, meaning failure is possible and likely in the long-term. Risk from failure from some of the mechanisms listed above can be mitigated or minimized but can typically not be eliminated completed. This is especially true for the channel hydrology, where a 10-year recurrence interval only has a 10% chance of occurring within a given year, but nonetheless can wash out a newly constructed FESL project within a week of project completion (see Section 5.) The project design and construction should include as much protection as feasible to reduce the risk associated with the items listed above, thus increasing the probability for success.

4. Construction Guidance

The following section explains some of the key steps of construction and clarifies the intent of important design elements for typical FESL installations project. Construction of the bank stabilization technique typically proceeds in the following primary stages:

1) Cofferdam and Dewatering and/or Diversion of Water
2) Selective Clearing and Grubbing
3) Construction of Rock Toe
4) Harvest of live cuttings and supply to project sites concurrent with FESL construction
5) Construction of FESL Lifts
6) Final Grading, Permanent Erosion Control, Seeding, and Secondary Planting

4.1 Cofferdam and Dewatering

Diversion of stream flow (or cofferdam construction) or dewatering is typically required prior to commencing project work. While the rock toe can be constructed in the wet, the soil lifts must be constructed under controlled conditions. Dewatering efforts for all projects must adhere to State and Federal permit requirements, but it is important to note that it is not necessary to construct the rock toe in the dry. In other words, complete dewatering so that the bank work can be done in the dry is not necessary unless required by permit and the dewatering effort may only consist of diverting active flow around the bank toe zone where excavation may occur, and for a short period of time (e.g., excavation and placement of rock toe should take no more than five working days at each project area). Once the rock toe is constructed, all subsequent work for most projects could take place above the water surface and coffering may no longer be required.

The cofferdam and/or diversion of water should consider the channel hydrology and whether or not the system is flashy in nature. It is recommended that the Contractor has secondary plans and emergency bank protection measures in place in anticipation of a large storm event that could occur during construction. Monitoring of daily weather forecasts is always recommended, as an incomplete FESL lift should never be exposed to high flows.

When possible or when information is available, piezometric data in the area should be evaluated to determine if seepage may be encountered during excavation. In the event that seepage is encountered, the contractor should manage groundwater flow in the area during lift construction. This could include staging excavation quantities and timing to allow the seepage to dissipate, or other means of passive seepage control using temporary trenches and rock backfill.

4.2 Selective Clearing and Grubbing

Selective clearing and grubbing of the bank should proceed once the rock toe work area is isolated from surface waters by constructing a cofferdam. Clearing and grubbing over overbank areas can occur prior to diversion of water. If salvageable material is within the clearing and grubbing zones, those materials should be selectively removed to be used in the FESL installation as live cuttings. Existing mature (8-inch+ diameter at breast height) trees (including root zones) should be maintained and protected for use with the FESL. The zone designated for construction of FESL on the typical section will also be excavated at this stage. The contractor should not excavate more than necessary and should stage excavation such that only the least amount necessary is left undisturbed prior to construction of FESL. This selective clearing and grubbing task will require close coordination and communication between the operator and on-site representative. All suitable topsoil should be salvaged and stockpiled and all excavated soils will be temporarily stockpiled onsite and used as backfill for constructing FESL.

4.3 Construction of Rock Toe

If sufficient coarse stone is encountered at the position of the rock toe or if valuable root mass already exists at the specified location, total excavation and replacement of material shown on the project drawings (within the FESL and/or rock toe zones) may not be required at the discretion of the on-site representative. Where necessary, the contractor should excavate and replace with imported riprap, relying on judgment of the on-site engineer and design riprap particle size. The rock toe must be keyed-in a minimum 2 feet into the existing streambed (or at the appropriate scour depth) wherever imported riprap is installed. All suitable excavated soils will be temporarily stockpiled onsite and used as backfill for construction of the FESL lifts.

4.4 Construction of Fabric Encapsulated Soil Lifts

The timing of the harvest of live cuttings is critical to FESL construction. As previously mentioned, typical FESL projects require thousands of live cuttings that must be harvested in dormancy (at least November 15 through February 15) and stored near the project site in a wet location, protected from the wind and from freezing temperatures. If harvesting locally, it is recommended that the harvest be conducted to maintain 1 to 2 days of lead time on the FESL construction activities onsite and that live cuttings are not left un-installed for more than 7 days following harvest.

The geotextiles for FESL construction will be fully degradable natural coir/jute fabric products. The sourcing and onsite storage of live cuttings and geotextiles should be coordinated with the engineer and should follow the recommendations presented above. When construction of the lifts is ready to begin, the photographs in **Attachment 1** can be used as guidance. The photos present a typical construction sequence for Fabric Encapsulated Soil Lifts, including live fascine and a brushlayer on a Jacobs' (formerly CH2M HILL) project located in the state of Washington.

4.5 Final Grading and Site Restoration

Final grading following lift construction will consist of filling and grading the upper slope between the topmost FESL lift and the top of slope, and will include placement of erosion control geotextile. All additional live cuttings not placed within the FESL lifts can be planted in cleared areas around the FESL and up the bank. The remainder of the disturbed area should be seeded with the approved seed mix and covered with an erosion control fabric. Especially in dry climates, irrigation of live cuttings and re-seeded areas should occur a minimum of three times weekly for up to 8 weeks following installation and seeding operations. Additional irrigation may be required during long stretches of hot temperatures or after 8 weeks if required, based on the cutting viability. Specifications for harvest, delivery, storage, planting and irrigation should be followed for all live staking on the stream bank.

5. Case Studies

Four case studies are presented below, representing Jacobs' projects constructed between 2012 – 2021 on variable sized channels. These case studies serve to inform the reader of various design decisions that were made, and how the FESL has performed since project completion. A summary of the four sites and limited design information, as well as their performance to-date, is presented in Table 4. While three of the projects are all currently performing as expected, each project provides insight into opportunities to improve FESL Design and Construction methodology.

To maintain anonymity, the client names for the projects below are not included and will herein simply be referred to as "Client". The four sites below are described based on the river system in which the project was completed.

Table 4: Summary of Four FESL Project Case Studies

River	State	Year Built	Design Event	Lift Information[1]			Performance (to-date)		
				No.	**Height (ft)**	**Slope (H:V)**	**Q (cfs)**	**Return Interval**	**Success**
Jarvis Creek	TX	2018[3]	2470 cfs (10-YR)	3	4.5	2:1	>2470[2]	>10-YR[2]	Fail
Tributary to Jarvis Creek	TX	2017	10-YR	4-5	4-5	2:1 – 2.5:1	N/A[2]	N/A[2]	Success
Yankee Fork	ID	2012	210 cfs (10-YR)	2	2	2:1	>210[2]	~50-YR[2]	Success
Boise River	ID	2019	9500 cfs (25-YR)	4	6	1.5:1 – 2:1	7340	~10-YR	Success

1. Indicates Design Values
2. Exact Data Unavailable (Ungaged or Unverified)
3. Initial Date of Project Completion

5.1 Jarvis Creek – Texas

Initial FESL construction along Jarvis Creek, a tributary to the Lower Colorado River in Southeast Texas, was completed on December 1, 2018. Jarvis Creek is located in Southeast Texas and is a very flashy system with very erodible soils along the banks. Within 10 days of initial project construction (December 10th), a high-flow storm event (>10-YR recurrence interval) completely washed out the right bank and partially damaged the left bank. Based on project modeling results, the maximum average velocity along the FESL for the 10-year event was 6.1 ft/s.

Photograph 6
Jarvis Creek – looking downstream. January 2019.

Based on observations and field measurements completed during post-failure site visits, it was determined that there were numerous failure mechanisms that contributed to the failure of the FESL. Certainly, the largest was the storm that swept through the area within 10 days of project completion, however numerous construction-related items that did not follow the design details were also identified. While the right bank completely failed (Photograph 6), evaluation of the left bank showed that the following construction deficiencies also contributed to the failure:

- *FESL ends not adequately anchored / improper keyway.* The complete failure of the FESL along the right bank was the result of an inadequate upstream keyway, that allowed the water to "flank" the FESL and erode the bank behind

- *Inadequate FESL height.* The design drawings called for 5-feet (vertically) of FESL (5 lifts) to protect the bank from larger events, however only 2.5 to 3 feet of FESL (3 lifts) were constructed. The >10-YR event overtopped the FESL and eroded the un-vegetated bench above the top lift.

- *Improper Compaction of Fill Material.* It was noted that the soil was very uncompacted, much less than the recommended 85% relative compaction, which likely led to increased erosion.

- *Bank slope was non-uniform and steeper than designed.* The project design called for a 2H:1V FESL bank slope, however field measurements indicate that the FESL was installed at ~1.25:1 (H:V). In certain systems, 1.25:1 (H:V) is adequate, however given the soil material in Southeast Texas, flatter slopes were recommended.

- *Improper brushlayer geometry.* Live cuttings were installed with 3-4 ft of length exposed beyond the completed face (50 percent or greater compared to their length). This resulted in higher drag forces on the live cuttings, and less resistance to pullout.

Construction oversight was not provided (or required) during the initial phases of construction and no on-site representative with qualified FESL experience was present during the construction of these lifts. For inexperienced contractor's, it is important for an experienced individual to be on site through the entirety of construction to identify and correct vulnerable mechanisms of failure during construction. It is anticipated that the impacts of the storm could have been minimized if the FESL lifts were constructed correctly.

Photograph 7
Jarvis Creek – Left Bank. Fall 2020.

Approximately 18 months after the storm destroyed the FESL on the right bank and damaged the left bank, the banks have completely failed (Photograph 7) as a result of channel migration. The failure of FESL prior to vegetation establishment leaves the recently disturbed banks very exposed and susceptible to erosion. This risk after failure should be accounted for in the design process, especially in the sizing of the upstream keyways.

The redesign effort for this project (completed December 2020) incorporates a similar design approach but was modified to account for the new topography caused by the severe bed and bank erosion that has resulted from the FESL failure. Construction oversight throughout the entirety of the construction process will be required, which should prevent the same mistakes from occurring again.

Project Summary: *Failure*

Lessons Learned: Importance of On-Site Representative (for inexperienced contractors)
Importance of Keyway & Rock Toe
Risks after Failure

5.2 Unnamed Tributary to Jarvis Creek – Texas

A separate project along an unnamed tributary to Jarvis Creek for the same Client was constructed in March 2018, prior to the project above. Erosion of the banks resulted in nearly vertical slopes with significant aggradation downstream of the reach, resulting in localized flooding during large rainfall events. Because of USACE permitting implications, FESL was proposed and was installed for 200 feet along both banks. The restored section included 4 to 5 feet of vegetated-reinforced FESL slope (2:1 H:V or flatter) installed at the mapped OHWM, which was delineated by a wetland scientist. Hydrology for the tributary was calculated through a hydrologic analysis, however no gage data was available or has been available since project completion. Proposed conditions HEC-RAS modeling results indicated that maximum design event (10-YR) velocities were 4 ft/s, significantly less than the maximum permissible velocity of FESL. Because of USACE requirements, alternative toe slope protection within the toe zone was implemented, as riprap could not be installed below the OHWM. Photograph 8 presents the FESL reach immediately after construction, while Photograph 9 presents the reach in the Summer of 2020 after nearly 3 growing seasons. While no post-project hydrology or hydraulic monitoring data are available, the reach remained stable after the large storm event in December 2018 as discussed above.

Photograph 8 (Left)
Recently constructed FESL along the Jarvis Creek tributary (looking upstream) – Spring 2018

Photograph 9 (Below)

Vegetated FESL along the Jarvis Creek tributary (looking downstream) – Summer 2020

Project Summary: *Success (Based on short-term Results)*

Lessons Learned: Supplemental Irrigation may not be required in humid regions
Flatter than 2H:1V may not justify cost of FESL; other techniques may be acceptable
Importance of Proper Vegetation Selection (Varies by Geography)

5.3 Yankee Fork – Idaho

In 2012, FESL was designed to protect the banks of a side channel off of the Yankee Fork of the Salmon River in the mountains of Central Idaho. Because of the high elevation and a shorter growing season, the Yankee Fork side channel project was completed in the Fall before the snow arrived for the winter. Because of weather and access concerns, winter and spring construction would likely not have been possible, let alone successful.

The FESL was designed for the 10-year event, corresponding to a design discharge of 210 cfs and a velocity of 7.6 ft/s. The mainstem 10-year discharge was approximately 2,340 cfs. The bottom lift of FESL was installed at the baseflow elevation of the side channel and extended up 2 feet vertically (2 lifts) at a 2H:1V slope to the 10-year WSE. While there is no gage located within the side channel, hydrologic data from a gage (USGS 13296000) in the mainstem indicates that flows exceeded the 50-year event (3304 cfs) in 2017. It was assumed that the flows in the side channel also exceeded the 10-year design values. Photographs 10 and 11 show the FESL within the Yankee Fork side channel in April 2013 (left) and again in June 2020 (right). As shown, the geotextile fabrics have disintegrated, and the vegetation is wholly responsible for the stability of the bank which has remained stable for nearly 8 years.

Photograph 10
Yankee Fork Side Channel – April 2013

Photograph 11
Yankee Fork Side Channel – June 2020

Project Summary: *Success (Based on long-term Results)*

Lessons Learned: Difficulty of construction at high elevation in Fall when ground is freezing
Local harvesting is a big advantage
Importance of Site-Specific Hydrology and Hydraulic Evaluations

5.4 Boise River – Idaho

Heron Park is a park located along the Boise River greenbelt in Boise, Idaho. In 2017, high water (9590 cfs) from the Boise River partially inundated the greenbelt, damaging approximately 200 feet of the existing riverbank and the asphalt trail at the top of the bank. Although dam-controlled, this correlates to a ~25-year recurrence interval based on the Boise River Flood Insurance Study (FIS) published by FEMA. Rather than adding riprap to stabilize the damaged section, the Client requested a stabilization technique that provided structural protection for the nearby infrastructure, respected the natural conditions of the Boise River, and met local landowner's aesthetic expectations. Another project goal was to implement a bank stabilization technique that is cost effective over the life of the project (balancing construction and maintenance costs).

The FESL toe was set at the summer irrigation flow WSE (~750 cfs) and extended up 6 feet (vertically) to approximately the 25-year WSE at variable slopes (1.5 – 2:1 H:V). Supplemental irrigation was available to aid in vegetation establishment, thus the decision to install the lifts higher along the bank. Since construction completed in March 2019, 7340 cfs (~10-Year Recurrence Interval) has been released (May 2019) and tested the FESL within two months of project completion. This flow resulted in velocities exceeding 5 ft/s and shear stresses exceeding 1.1 lb/ft^2. Photograph 12 shows the FESL in August 2019, with Photograph 13 showing the FESL in July 2020. Photographs 1 and 2 in Section 1.0 show the same reach of FESL installed at Heron Park looking upstream.

Photograph 12
Boise River – looking downstream. August 2019.

Photograph 13
Boise River – looking downstream. July 2020.

Project Summary: *Success (Based on short-term Results)*

Lessons Learned: Supplemental Irrigation Required in Dry Climates above OHWM.

5.5 Discussion

While comprehensive post-construction monitoring data is not available for any of the sites discussed above, all indications point to FESL being a viable stabilization technique if constructed properly. The three successful projects have shown good vegetation survival rates (~80%) and have each successfully withstood a 10-year event or greater since project completion. The Jarvis Creek example indicates the importance of proper construction and the necessity for construction oversight, especially in flashy systems and/or with inexperienced contractors. While project goals and constraints vary based on site location, each project described above provides valuable insight for future FESL projects.

6. Cottonwood Creek Design and Hydraulic Evaluation

Located just north of Downtown Boise, the Cottonwood Creek watershed encompasses nearly 8,000 acres of the Boise Front, with elevations ranging from 5,600 AMSL down to approximately 3,000 AMSL at The Military Reserve on the north side of Boise. The daylighting of Cottonwood Creek has been a project long-desired by numerous stakeholders, as a once well-connected tributary to the Boise River is now confined with a degrading concrete and sandstone flume running through (and below) downtown Boise.

This section aims to walk the reader through the design process completed as part of the Cottonwood Creek Daylighting Project. We will walk through the site hydrology, the hydraulic analysis, and the design decisions that were made to place FESL along both the Boise River banks as well as the banks of the new daylighted channel. To understand why certain decisions were made, it is important to first understand the history of the project and the design objectives identified by the Client.

6.1 Project Introduction

The Cottonwood Creek Daylighting Project is a unique opportunity to restore riparian and aquatic habitat in Julia Davis Park near downtown Boise, by removing the existing underground flume and creating an open channel. Currently, a buried 6' x 4.5' sandstone box flume approximately 400' long (exact length unknown) conveys Cottonwood Creek to the Boise River. The proposed project will abandon the existing flume and create a small channel that will provide not only aesthetic benefits to Julia Davis Park, but also hydraulic and ecological benefits to Cottonwood Creek as well as the Boise River (see rendering – Figure 8).

Photograph 14
Existing Flume Outlet into Boise River

This project will add significant value to the habitat for fish spawning and rearing, increase the ecological visibility of the Boise River, and connect a part of Boise's history to the community via interaction within Julia Davis Park. With a new daylighted channel into the Boise River, it was quickly determined that bank protection measures were justified to prevent erosion at the confluence. FESL has been installed along other regions of the Boise River (i.e. Heron Park) and has been successful and extremely well received because of its natural aesthetics. As such, FESL was immediately identified as a potential solution to stabilize the banks of the Boise River and the daylighted channel in the vicinity of the confluence. The sections below discuss the analyses completed to determine if FESL was a viable solution and then walks through the design decisions that were made based on the hydraulic results. This methodology is consistent with other FESL design projects; however, it is important to remember that each project is unique and should undergo similar analyses to ensure FESL is an appropriate bank stabilization technique.

Figure 8: Cottonwood Creek Proposed Rendering

6.2 Hydrology and Hydraulics

As a FEMA mapped river, the Boise River hydrology is well defined, with the larger flows included in the Flood Insurance Study (FIS). The Boise River hydrology and the resulting Water Surface Elevations at the Cottonwood Creek confluence based on HEC-RAS modeling results are presented in Table 5.

Table 5: Boise River Hydrology

Boise River (At Lucky Peak Dam)	Design Event						
	Baseflow	**OHWM**	**5-year**	**10-year**	**50-year**	**100-year**	**500-year**
Peak Discharge (cfs)	750[1]	3,000[1]	6,100[1]	7,200[2]	11,000[2]	16,600[2]	34,800[2]
Water Surface Elevation @ Cottonwood Creek Confluence (ft AMSL)	2692.6	2694.1	2695.4	2697.0	2698.6	2700.7	2703.5
1. Indicates approximate value based on hydrologic analysis *2. Effective hydrology published in FIS*							

Unlike the Boise River hydrology, the Cottonwood Creek hydrology is not well defined, especially as it has been significantly changed in recent years due to the construction of flood control facilities upstream of the project site. These flood control facilities collect sediment, attenuate flood flows, and decrease the baseflow through the flume to approximately 2 cfs. Based on the existing maximum capacity of the flume, there is potential for approximately 300 cfs to be conveyed down the new daylighted channel, therefore this flow is considered the maximum design event for the project.

Based on the hydrology, four 1-Dimensional HEC-RAS model scenarios were developed to analyze the hydraulics in both the Boise River and in Cottonwood Creek. These four scenarios are as follows:

1. High Cottonwood Flows (300 cfs), Low Tailwater in Boise (750 cfs)
2. High Cottonwood Flows (300 cfs), High Tailwater in Boise (6100 cfs)
3. Low Cottonwood Flows (2 cfs), Low Tailwater in Boise (750 cfs)
4. Low Cottonwood Flows (2 cfs), High Tailwater in Boise (6100 cfs)

Figure 9 presents a profile cut along the alignment of the daylighted Cottonwood Creek, also showing the water surface elevations of the Boise River for the various recurrence intervals.

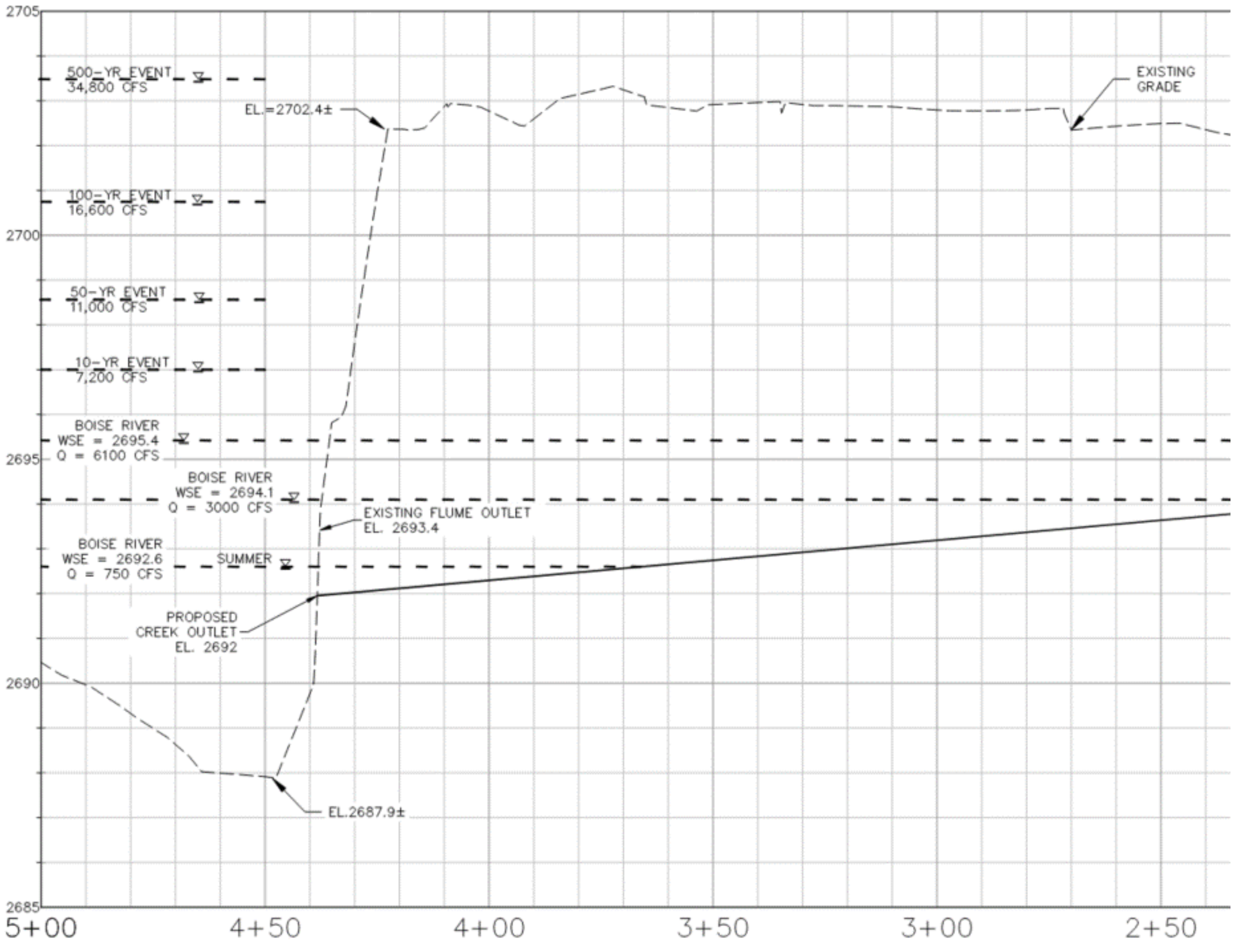


Figure 9: Cottonwood Creek Proposed Profile

Hydraulic results from the 1-Dimensional Boise River Effective Model (from FEMA) indicate that the maximum velocity (5.32 ft/s) and shear stress values (0.89 lb/ft^2) in the project vicinity for the 10-year event (7,200 cfs) are both well below the threshold for FESL stability. While 2-Dimensional models would provide more accurate velocities and shear stresses along the bank compared to the cross-sectionally averaged values computed by a 1D HEC-RAS model, even the addition of a Factor of Safety (FS) of 1.5 to account for the cross-sectionally averaged values yields results that are below the thresholds for FESL stability. The Factor of Safety varies based on the site-specific conditions and should be selected using professional engineering judgement but can be valuable when added to 1-Dimensional model results to more closely compare the expected local conditions at the bank. When possible, however, 2-Dimensional modeling software should be used for bank stabilization projects to determine more accurate near-bank velocities and shear stresses.

As such, FESL stability is not a concern along the banks of the Boise River, however elevation needs to be carefully evaluated to ensure the frequency of inundation is consistent with the needs of the selected plant species.

For FESL in Cottonwood Creek, the highest velocities and shear stresses would be experienced when there is minimal backwater from the Boise River, but high flows (300 cfs) coming out of the flume outlet (Alternative 1). Conversely, high backwater from the Boise River would dissipate energy from flows coming down Cottonwood Creek and could cause localized scour, meaning the upstream extent of the FESL should be carefully considered. The four scenarios above were modeled in HEC-RAS using either WSE = 2692.6 or WSE = 2695.4 as downstream boundary conditions to represent the baseflow and the 5-year water surface elevations in the Boise River. The results of the analyses are presented in Table 6.

Table 6: Cottonwood Creek Model Results

Alternative	Boise River		Cottonwood Creek (50' Upstream of Confluence)		
	Discharge (cfs)	WSE	Discharge (cfs)	Max Velocity (ft/s)	Max Shear Stress (lb/ft^2)
1 (High CW, Low Boise)	750	2692.6	300	8.19	2.49
2 (High CW, High Boise)	6100	2695.4	300	5.37	0.99
3 (Low CW, Low Boise)	750	2692.6	2	1.70	0.25
4 (Low CW, High Boise)	6100	2695.4	2	0.04	0.00

Based on the results above, the FESL stability threshold is not exceeded for any of the model scenarios, even if a FS = 1.5 was applied to the results. Due to the proposed low sinuosity of Cottonwood Creek and the location of the daylighted creek confluence within the Boise River, a Factor of Safety of 1.5 was deemed to be conservative for comparing the HEC-RAS results. Even with this additional Factor of Safety, the maximum permissible shear stress of FESL is not exceeded, making it a viable option for stabilization of the banks along the Boise River and the proposed daylighted channel.

6.3 FESL Design

With FESL being the preferred option for bank stabilization for the new confluence, the following design decisions must be made to finalize the design:

- Plant species for Live Cuttings (Brushlayer(s), Fascine, Live Stakes)
- Total Height/Quantity of Lifts
- Thickness of Lifts
- FESL Bank Slope

Selection of a plant species mix should always include input from a botanist, wetland scientist, or landscape architect. Based on the success of past Boise River stabilization projects, a species mix was easily determined and is presented below:

Table 7: Live Cuttings Species Mix

Scientific Name	Common Name	Approximate %
Salix exigua	Coyote Willow	55-65
Salix bebbiana	Bebb Willow	25
C sericea	Red Osier Dogwood	up to 10
P trichocarpa	Black Cottonwood	up to 10

The design of the lifts begins with evaluation of the proposed and existing ground bank slopes. Based on site constraints and in an effort to more closely match the existing bank slope of the Boise River, a FESL slope of 2H:1V was selected. From there, the starting elevation and the total height of the FESL is determined by the water surface elevations presented in Tables 5 and 6. Since Cottonwood Creek (near the river) will primarily be inundated by backwater as opposed to flows from the flume (Figure 9), the frequency of inundation should be based on the Boise River WSEs and not the results from the Cottonwood Creek flows. Within the last 10 years, flows in Cottonwood Creek have not exceed 2 cfs, therefore it is unlikely that these flows will adequately inundate the FESL for optimal vegetative success.

As discussed above, the ideal location for FESL installation is within the Splash Zone, beginning at the baseflow WSE and extending up to the OHWM (or slightly above). For the Boise River, in the vicinity of Cottonwood Creek, the baseflow WSE is 2692.6 ft AMSL. With an OHWM elevation at 2694.1, and a 5-year WSE at 2695.4 ft AMSL, it was determined that three 12-inch lifts of FESL would be the most appropriate. Supplemental irrigation was also readily available, thus allowing the design to extend above the OHWM and further up the bank. Above the top lift, a small 3’ - 6’ bench which is typically constructed to aid in vegetation establishment was added and will be planted with live stakes. From the bench, the banks (i.e. bank zone) are sloped to match the proposed grading plan to where they intersect with the terrace zone, approximately 10 feet above the channel thalweg. A detail of the proposed FESL design is presented in Figure 10.

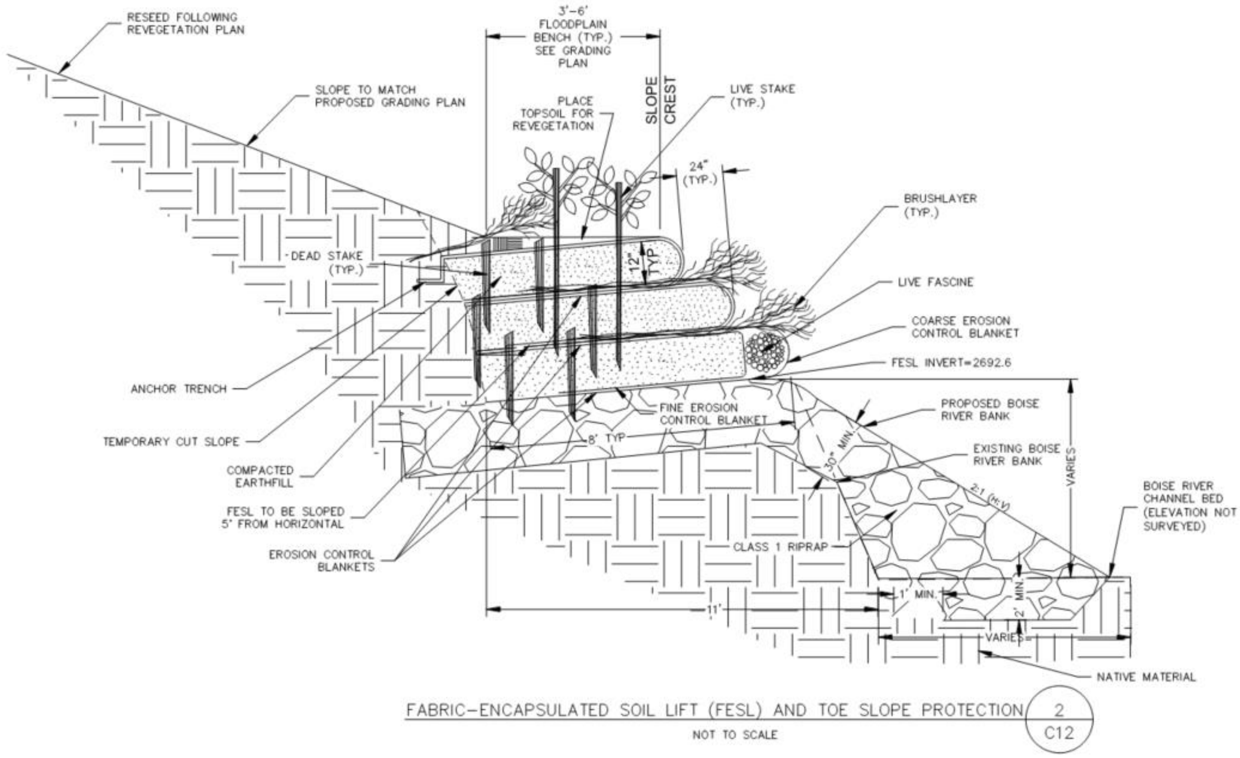


Figure 10: Proposed FESL Design Detail for Cottonwood Creek

For this project, root wads were readily available and were able to be incorporated into the FESL design. These rootwads will be installed during the installation of the rock toe and will be buried a sufficient distance into the bank to eliminate potential for displacement.

Figure 11 shows a plan view of the design, showing the approximate FESL extents including the rock toe and the keyway. Note that the upstream keyways are not included in the figure but will be constructed and keyed into the abutments of the proposed bridge crossing over the creek. While not represented in either Figure 10 or 11, the FESL will be sloped longitudinally with the banks (parallel to channel thalweg). The toe design elevation in Figure 11 presents the elevation along the Boise River, however the FESL will slope up as it extends up into Cottonwood Creek. This emphasizes the importance of having on-site representation during construction to ensure details such as this are included in the construction.

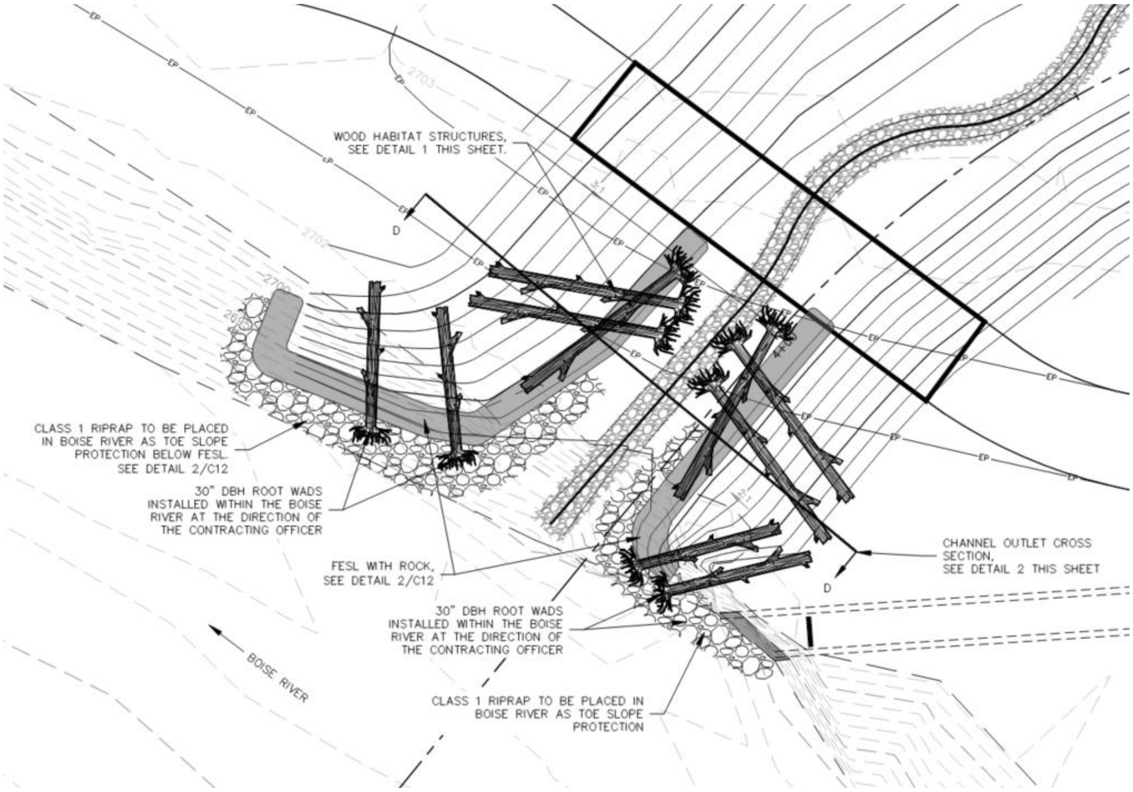


Figure 11: Plan View of Cottonwood Creek Design

While this Cottonwood Creek example is simplified, it emphasizes the importance of evaluating the hydrology and hydraulics of the system in which FESL will be installed. It is extremely important to ensure the FESL is installed in the right bank zone (splash zone) and is designed to maximize the bank protection and reduce failure potential.

7. Conclusion

Selection of a streambank stabilization method is becoming increasingly difficult as new and improved techniques are implemented. While this document has served to inform the reader of the viability of fabric encapsulated soil lifts for bank stabilization, the author also recognizes that FESL has limitations. As a bioengineering technique, FESL is not capable of withstanding the same hydraulic forces as traditional riprap or other hard-armoring techniques, however few (or none) laboratory test results are available to identify a closer range for FESL stability. To-date, it is believed that FESL is capable of withstanding velocities up to 10 ft/s and shear stresses up to 6.0 lb/ft^2 when fully vegetated, however long-term laboratory data would be beneficial to confirm these values. The case studies presented within this document indicate that properly constructed FESL is capable of withstanding velocities exceeding 7.6 ft/s and shear stresses up to 1.1 lb/ft^2 (in the absence of additional post-project data) immediately after construction and prior to vegetation establishment, however this is a limited dataset and could be confirmed with additional project examples. It is believed that these values continue to increase after each growing season as the vegetation becomes more established.

As with any bank stabilization project, the project success is dependent on the hydrology and the channel flows. As a bioengineering technique, FESL is more susceptible to failure immediately after construction, so care must be taken to minimize the risk of failure from high flows before the vegetation is established. The addition of a rock toe, in conjunction with tight, compacted soil lifts drastically improves the probability of success, emphasizing the importance of proper construction (which may require on-site representation). The selection and implementation of the appropriate vegetation species throughout the lifts will be wholly responsible for the long-term stability of the FESL and should consider site specific hydrologic and hydraulic conditions, geography, and a variety of additional factors as described in this document.

Any bank stabilization project requires recognition of a certain level of risk, as very rarely do the project constraints (funding, topography, hydraulics, etc.) allow a bank stabilization design to protect against extremely high (50 to 100-YR or greater) recurrence intervals. For projects with the goal of protection against these extremely high events, FESL likely isn’t the best solution; however, it is an excellent option for those projects where aesthetics and minimal maintenance requirements are most desirable. Regardless, FESL shows promise as a viable short term and long-term stabilization method that blends in with the landscape through its use of native vegetation and natural materials. As an evolving method, the guidance and lessons learned in past projects provide insight allowing the design of the technique to be constantly evolving into an even better bank stabilization solution.

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Attachment 1

The photos (taken by and courtesy of Frank Gariglio) present a typical construction sequence for Fabric Encapsulated Soil Lifts, including live fascine and brushlayers. These photos are from Jacobs' (formerly CH2M) Tyee project located on the Entiat River near the unincorporated town of Brief, WA in Chelan County. Brief is located approximately 23 miles northwest of Entiat, WA on Highway 19 (Entiat River Rd.).

Photograph 1
Preparing FESL lift for backfill. Note the compacted bench below the fabric where the coarse matting is laid down first, followed by the fine erosion control matting inner layer

Photograph 2
Preparation of the Live Fascine. When harvesting locally, cuttings should be alive (but preferably dormant) and bound together tightly. Fascines can also be provided already bound when delivered to the site by a supplier.

Photograph 3
Backfill of the first lift. Note the two layers of fabric and the Live Fascine bundle at the toe. The backfill should consist of clean native (or imported) backfill material.

Photograph 4
Construction of the first FESL lift. Forms, such as the wood form in the background, are a common method used to ensure proper construction.

Photograph 5
Continuing construction of the first lift. Backfill of first lift to be compacted to ~85% standard compaction and wrapped with fabric

Photograph 6
Completion of the first lift and installation of brushlayer. Note the keyway constructed on the right side of the photo (upstream), with the fabric pulled back as the lift terminates and the fold in the fabric oriented downstream.

Photograph 7
Construction of Second lift. Note how the excavator is being used for compaction of the soil material.

Photograph 8
Completion of second lift and live stakes installed in first lift. Note the soil "sprinkled" on top of brushlayer between the second lift – this aids in root establishment of the brushlayer cuttings.

Photograph 9
Preparation of fascine and fabric for the first lift on the opposite (left) bank

Photograph 10
Completion of first lift on the left bank. Note the method for creating the forms and the stakes (live and dead) installed within the fabric throughout the length of the lift.

Photograph 11
Completion of first two lifts along left bank with brushlayer and live stake. Additional fabric used for upper slope stabilization above the second lift.

Photograph 12
Completed installation of FESL looking downstream