Demonstration Projects Illustrating Void-Filled Riprap Applications in Stream Restoration

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ABSTRACT

Riffle-pool complexes – rocky chutes alternating with deeper, stiller water -- are commonly found in gravel and cobble bed streams and are nature's way of dissipating energy. Muller Engineering Company re-created riffles as part of a 2003 project to restore a badly eroding reach of Cottonwood Creek in Cherry Creek State Park near Denver, Colorado. In the process, a rock mix was developed that emulates the bed material found in natural riffles. This material, termed "void-filled riprap" was found to possess a number of properties that enable it to perform better than ordinary riprap.

The successful application of void-filled riprap at Cottonwood Creek has led to riffle drop applications for several stream restoration projects along Cherry Creek and other locations around the Denver metropolitan area. Void-filled riprap has also be used as channel lining for several projects on steep headwater streams.

This paper provides an overview of void-filled riprap and its development during the Cottonwood Creek project. Two demonstration projects are also presented. The first, the Cherry Creek Open Space Restoration Project, located near the historic 17-mile House in Arapahoe County, Colorado, discusses the use of riffle drops. The second, a stabilization project on upper Marcy Gulch in Highlands Ranch, Colorado, addresses the use of void-filled riprap for channel lining. Guidance on design and construction is provided and conditions that are favorable or unfavorable for the use of void-filled riprap are discussed.

1.0 INTRODUCTION

Riffle-pool complexes – rocky chutes alternating with deeper, stiller water -- are commonly found in gravel and cobble bed streams and are nature's way of dissipating energy. Even low-gradient sand-bed streams in Colorado's front range exhibit occasional riffles made up of coarser, gravelly material; however, many natural riffles in plains streams are not adequate in frequency or rock size to provide stable stream conditions given the increased runoff and narrowed floodplain channels typical of urban watersheds. Therefore, a concept is discussed for creating riffle drops of a sufficient particle size and frequency to provide stable stream conditions for a given design flow event.

Rock riffles alternating with deeper pools are a common pattern in natural streams

The concept of riffle drops was implemented in the 2003 Cottonwood Creek Reclamation Project in Cherry Creek State Park. In the process, a rock mix was developed that emulates the well-graded matrix of rock, gravel, and sand particles that is characteristic of natural riffles. The rock material, termed "void-filled riprap" was found to possess a number of functional properties that enable it to perform better than ordinary riprap. Although the rock installed in Cottonwood Creek includes fractured granite in addition to riverine material and is larger than the existing gravel riffles evident in the creek (the sizes of the largest rock pieces are more typical of riffles found in steeper-gradient streams), the resulting stream form exhibits a natural appearance and seems to have been accepted as a natural system by the abundance of waterfowl and wildlife frequenting the rehabilitated creek.

A rudimentary form of void-filled riprap has been used by the Urban Drainage and Flood Control District (UDFCD) since 1996 to protect the banks of the South Platte River. Unstable river banks have been graded and armored with fractured riprap and then the voids in between the riprap have been filled by washing natural riverbed material (cobbles, gravels, sands, and silts) into the placed riprap. The District has found that the resulting void-filled riprap has been exceptionally stable and easy to re-vegetate.

The application of void-filled riprap at Cottonwood Creek, which has fared well and appears promising thus far, has led to numerous riffle drop applications in Cherry Creek upstream of Cherry Creek Reservoir and in other locations around the Denver metropolitan area. Void-filled riprap has also been used as channel lining in several rehabilitation projects on steep headwaters streams.

This paper provides an overview of the use of void-filled riprap and its development during the Cottonwood Creek Reclamation Project. Two demonstration projects are presented. One, the Cherry Creek Open Space Restoration Project, located near the historic 17-mile House in Arapahoe County, discusses the use of riffle drops. The other, a stabilization project on upper Marcy Gulch in Highlands Ranch, Colorado, addresses the use of void-filled riprap for channel lining. Guidance for design and construction is provided and conditions that are favorable or unfavorable for the use of void-filled riprap are discussed.

2.0 DEVELOPMENT OF VOID-FILLED RIPRAP FOR GRADE CONTROL DURING COTTONWOOD CREEK RECLAMATION PROJECT

Riffle drops were developed as part of a project to reclaim a severely eroded reach of Cottonwood Creek within Cherry Creek State Park. The goal of the project, funded by the Cherry Creek Basin Water Quality Authority, was to stabilize the creek and reduce phosphorous loading to Cherry Creek Reservoir. Over the years, the Cottonwood Creek channel had eroded to a depth of 6 to 8-feet below the adjacent banks, forming an incised channel with vertical sides, unstable and largely devoid of vegetation. The adjacent overbanks had become “high and dry” and converted from a riparian fringe to an upland area with short grasses. One hundred feet away, it was not even obvious that a creek existed in the area, so low and hidden was the water.

Stream degradation had lowered Cottonwood Creek’s channel invert 6 to 8 feet below its historic elevation

The incision of Cottonwood Creek below its former banks converted the area from a riparian floodplain, subject to overtopping during high flows, to a dried out upland.

2.1 Re-establishing a Healthy Stream System

The concept for restoring Cottonwood Creek was to raise the channel invert back up to its historic elevation and reconnect the channel to the floodplain. Figure 1 illustrates this concept which creates a healthier stream by restoring the hydraulic and ecologic functions of a natural stream system. The raised condition creates a shallow base flow channel that allows storm flows to spill out into the broad adjacent floodplain overbanks during larger events. Widespread, shallow flow conveyed through the overbank vegetation travels much slower than storm flows carried within a confined incised channel.

Raising the incised channel invert in turn raises the ground water table closer to the flood-

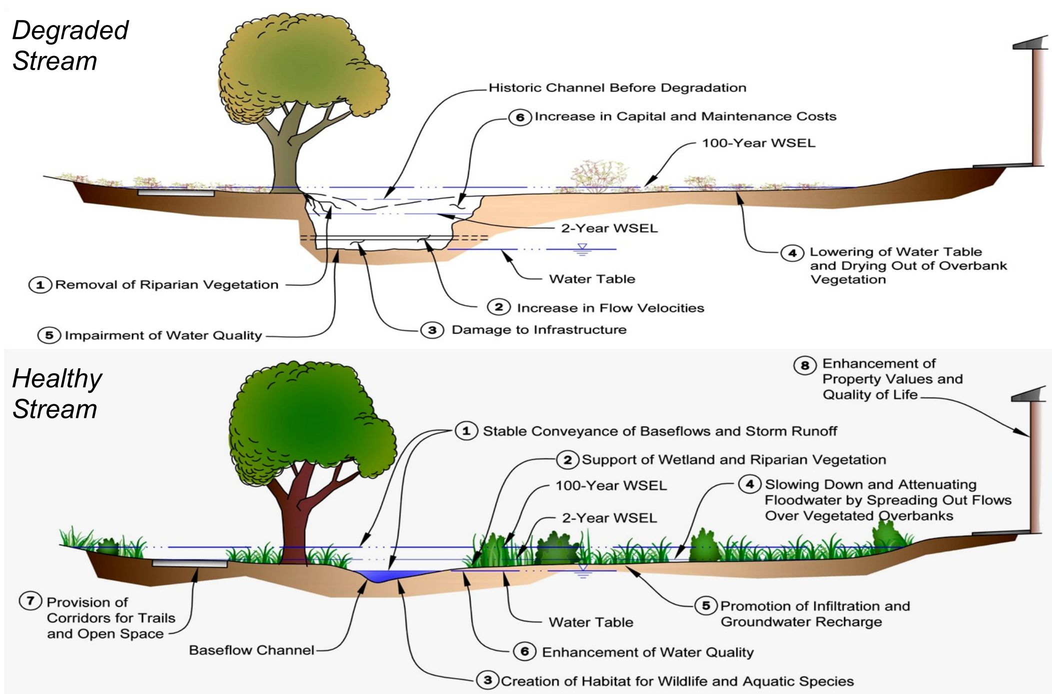


***Figure 1. Degraded Stream Environment in Contrast to Healthy Floodplain** (from Arapahoe County Stormwater Management Manual).*

plain overbanks. Riparian vegetation adjacent to the creek and across the floodplain can tap into the higher groundwater table, in addition to taking advantage of wetting and infiltration during more frequent overbank flows to establish itself as a dense, protective cover across the floodplain. This vegetation reduces erosion by slowing floodwaters, reinforcing the soil matrix with root systems, and providing lay down coverage over the soil surface. In summary, creating widespread, shallow storm flows over vegetated overbanks is essential to promoting healthy riparian vegetation, enhancing water quality through infiltration and vegetative filtering, and maintaining favorable habitat and aesthetics – in short, creating a healthy stream system.

A key element for reclaiming Cottonwood Creek was the implementation of grade control structures, or drop structures, to make up the difference between the design thalweg slope (approximately 0.2 percent) and the steeper overbank slope (approximately 1.0 percent). Historically, the channel slope would have matched the overbank slope; however, streams in urbanizing areas tend to erode to flatter slopes in response to increased runoff, and Cottonwood Creek below a developed portion of Centennial and Douglas County is no exception. To maintain the desired shallow base flow channel that is connected to the floodplain and spills into the floodplain during storms, small height grade control structures are ideal, with vertical drop heights of one-foot or less. Riffle drops seemed to be the perfect fit for this scenario.

2.2 Riffle-Pool Stream Form

Riffle-pool complexes are commonly found in gravel and cobble bed streams and are nature's way of dissipating energy. Figure 2 shows a classic example of a riffle pool complex where there is a meandering channel with scoured out pools in the bends and rock riffles in the straight sections. Riffles are comprised of larger rock that armors the channel at a slightly steeper channel slope. In the Denver Metro area, there are a number of examples of natural riffles along the South Platte River, Bear Creek, and other streams.

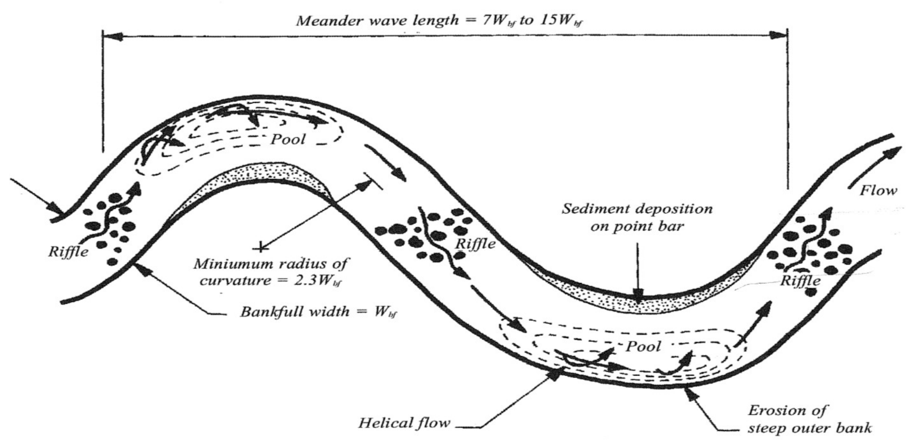
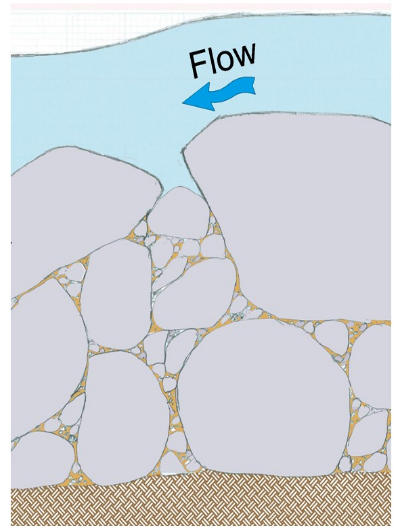


Figure 2. Classic Riffle-pool Stream Pattern *(adapted from Newbury and Gaboury, 1993).*

These photos of the South Platte River in Adams County and Bear Creek downstream of Bear Creek Reservoir illustrate natural riffle-pool stream forms.

Well-graded mix of rock, gravels, and sands in a natural rock riffle.

To gain a better understanding of natural riffle configurations and rock distribution, an existing stream riffle was examined on Bear Creek located downstream of Bear Creek Reservoir. The slope of the existing riffle was measured to be approximately 20H:1V (5-percent). The channel bottom directly under the flowing water consisted of coarse rock ranging in size from several inches to slightly over one foot. Upon removing the top layer of rocks and digging deeper into the channel substrate, it became apparent that the rock mix was very well graded, ranging from silts and sands through fine and coarse gravels to small cobbles and larger rock.



This graphic illustrates how smaller rock becomes "wedged in" under larger rock.

Other than at the surface, where the flow had removed all but the coarse rocks, the material was mixed together in a densely-packed mass. Cobbles were wedged into the spaces between the larger rocks, gravel material wedged into the spaces between the cobbles, sand material wedged into small voids in the gravel, and silts filled in the smaller voids of the sand. The result was an interlocked matrix of material that functioned as a self-contained filter, where smaller size particles were held in place by slightly larger particles. Because there were no voids in the matrix, water flowed on top of the natural riffle material.

The banks along the active channel of Bear Creek were comprised of the same well-graded rocky material, but slightly smaller in size than the material in the channel bottom, and were well vegetated with riparian grasses, willows, and Cottonwood trees. So while the bed and bank material was rocky, it was still able to provide a growing medium that could sustain riparian vegetation.

Thus, several characteristics of natural riffle material give it unique advantages over conventional riprap as a construction material for stream restoration:

1. The well-graded particles in natural riffles are packed together more densely than the individual pieces of standard riprap, providing additional stability and interlocking.

2. Natural riffles have no open voids; therefore, water flows on top and reduces the likelihood that flow will dive down and find a weak spot in the subgrade. This avoids the erosion and piping out of fine material that can occur adjacent to or under conventional riprap. Also, keeping flow on the top of the rock is generally desirable from an aesthetic viewpoint.

Natural riffles consist of a mix of rock, gravels, and sands that is densely-packed and able to support riparian vegetation.

3. Riffles contain an effective internal filter. This allows re-created riffles made of void-filled riprap to be constructed without a separate underlying filter layer, enabling thinner overall installations with reduced subgrade excavation.

4. Riffles provides a growing medium that supports riparian vegetation. Such vegetation not only adds aesthetic and habitat value to a stream environment, but helps to slow flows and reinforce overbanks, reducing erosion and increasing stream stability.

2.3 Development of Void-Filled Riprap to Emulate Natural Riffle Material

The form and properties of natural riffles seemed ideal for raising the eroded invert and providing grade control for the Cottonwood Creek reclamation project. The first step was to locate a source for natural riffle rock material. It was estimated that a median rock (D_{50}) of 12-inches would be needed for the Cottonwood riffles. It was quickly discovered that local gravel pits in the Denver Metro area don't have river bed material this large. The only possible sources for material of this size were found to be a few hours away in the mountains and importing from this distance made it cost prohibitive. Also, the mountain material was not typically marketed or sold in its natural, raw form and thus there were no protocols in place to deliver material of a specific size range.

Therefore, a different approach was taken. It was decided to emulate natural riffles with materials that were readily available at local quarries and gravel pits. The backbone of the mix was standard 12-inch D_{50} riprap. The next size down was desired to wedge into voids that were observed in stockpiles of 12-inch riprap; after several visits to the local quarries and gravel pits, a 7-inch minus crushed rock surge was selected. The 7-inch minus rock consisted of blasted quarry rock processed through a 7-inch crusher sieve, and thus contains rock fragments from an inch or two up to about 6-inches.

Two key ingredients to fill in the gaps between riprap pieces are 7-inch minus crushed surge (left) and 4-inch minus pit run surge (right)

In like manner, 4-inch minus pit run surge (material processed through just one 4-inch screen) was selected to make up the finer portion of the mix. The 4-inch minus pit run surge comes from gravel pits along local rivers and is predominantly a silty-sandy material that includes "pea" gravels and coarse gravels and round river rock up to almost 4-inches in diameter. This material is very effective in wedging into the voids of the 7-inch minus crushed rock and is the "special" ingredient that fills out the mix and provides some cohesion to hold the rock matrix together. This, and some added topsoil, provides the growing medium for vegetation. The resulting mix was termed "void-filled riprap".

After selecting readily-available void-filled riprap ingredients, the next step was to try to determine optimum mix proportions. Small scale pilot mixes were experimented with using a large plastic bin and scale, aiming for the heaviest mix of materials possible in the full bin. **The objective was to fill all the voids of the 12-inch riprap in a manner that created the highest density mix without displacing the riprap pieces away from each other.** Mixes were developed that increased the density from about 90 pounds per cubic foot (pcf) for plain riprap to over 140 pcf for void-filled riprap.

Once an initial trial mix was determined, the first large-scale mixing of void-filled riprap was undertaken out in the field at Cottonwood Creek. Field mixing was accomplished using a loader that mixed the rock up against an excavated hillside and proportions were based on "loader bucket" units. Some tweaking of the proportions was necessary to obtain a material that resembled the natural well-graded riffle material found in streams like Bear Creek. And, because the two surge materials were found to

These photos illustrate the riffle-pool stream form created in the Cottonwood Creek project reach.

be somewhat variable in composition it was necessary to monitor the particle distribution of these materials and sometimes add selected aggregates to fill out the desired mix. Some of the materials that were added included UDFCD Type II Bedding and 2- to 4-inch cobbles.

Control of the void-filled riprap proportions was based on visual inspection in comparison to a suitable reference mix and relied heavily on the judgment and skill of the field engineer.

The riffle drops constructed in Cottonwood Creek have performed well, remaining stable during a large (estimated to be greater than a 2-year) storm event that occurred immediately after the drop installation. Since construction, riparian grasses and willows have become established within the void-filled riprap along the edges of the active channel, adding to the stability of the reclaimed stream.

2.4 Applications of Void-Filled Riprap in the Denver Metro Area

Starting with the use of void-filled riprap on Cottonwood Creek in 2003, a number of void-filled riprap applications have been designed in the Denver metro area. Ten of these projects are described in Appendix A. A location map is also provided so that readers can find these projects in the field.

Two demonstration projects are described in the following sections to further explore the design and construction of riffle drops and void-filled riprap channel lining.

3.0 RIFFLE DROP DEMONSTRATION PROJECT -- CHERRY CREEK OPEN SPACE RESTORATION

The riffle drop principles pioneered in the Cottonwood Creek Reclamation Project were applied on a much larger and more dynamic stream system in the Cherry Creek Open Space Restoration Project, completed in 2006 for UDFCD and Arapahoe County.

3.1 Description of Cherry Creek Watershed and Project Reach

Cherry Creek is a large watershed located southeast of the Denver metro area that drains approximately 420 square miles. The majority of the watershed is undeveloped in the upstream reach and consists of high prairie grasslands and ponderosa pine woodlands. Land uses in the upper watershed include including grazing for cattle and horses and some farmland. As Cherry Creek gets closer to the Denver metro area, residential development becomes more prevalent, especially near the Town of Parker, Colorado.

The Town of Parker has experienced significant growth over the past 20 years. Increased urban runoff in Cherry Creek may be a contributory factor in the instability that is evident within the Cherry Creek channel, showing itself in alternating cycles of degradation and aggradation. The Cherry Creek channel within the Parker area is a wide, sandy corridor that consists of a shallow, 20-foot wide base flow channel and a broad floodplain that varies from 500 to 1000-feet wide. The floodplain corridor is heavily vegetated -- predominantly with willows and Cottonwood trees. Riparian and wetland grasses are found along the edges of the base flow channel.

It has been observed that the Cherry Creek corridor has a “sponge effect”. Several times in recent years significant flood peaks (upwards of 5000 cfs) have been recorded upstream at the Franktown gage, but have attenuated down to almost nothing (under 100 cfs) by the time the peaks reached the northern limits of Parker. It is hypothesized that the wide deposit of sandy alluvial material under the Cherry Creek floodplain infiltrates a lot of these flood flows, especially when the flows spread out into overbank areas.

Because of the watershed size, flood flow estimates are large. At the project reach, the future development 2-year discharge is estimated to be 4000 cfs and the 100-year flow is estimated to be 48,000 cfs according to UDFCD studies. However, stream gages on Cherry Creek indicate that the 2-year storm may be smaller and possibly less than 1000 cfs, due to the “sponge effect”.

Degradation had lowered the project reach approximately 5-feet below the adjacent top of banks, exposing two sanitary sewer crossings.

The Cherry Creek Open Space Restoration Project involved the restoration of 2500 linear feet of Cherry Creek in Arapahoe County, located downstream of the Town of Parker. The base flow channel in this reach had downcut approximately 5-feet, putting infrastructure at risk. Two sanitary sewer crossings had become exposed due to the degradation in the channel.

In addition, the incised condition was bringing about the same unfortunate side effects as were described for Cottonwood Creek. The lowered base flow channel became disconnected from the broad, 1000-foot wide floodplain in the area. The water table followed the channel invert down below the adjacent banks and, as a result, the riparian vegetation in the overbanks was drying out and dying. Large storm flows were being carried in the deep, narrow base flow channel instead of spreading out in the overbank areas, which resulted in high velocities and further erosion of the base flow channel bed and banks. In addition, the "sponge effect" was reduced due to less over-bank flow, reducing the natural infiltration and attenuation of flood peaks provided by the corridor. In summary, the eroded channel in the project reach was jeopardizing the overall health of the stream system – degrading habitat, water quality, and the ability of the floodplain to remain stable in large storm events.

Channel degradation and bank erosion was contributing to water quality concerns in Cherry Creek.

3.2 Project Improvements

Like the Cottonwood Creek improvements, the key element for the restoration of the project reach was to raise the degraded invert back up to maintain a shallow base flow channel that is connected to the floodplain so that flow spills out into the floodplain during storms. And, like Cottonwood Creek, small-height riffle drops were determined to be an ideal type of grade control structure to be implemented within the wide floodplain of Cherry Creek.

Photo showing restored stream with riffle drop just after construction.

A total of five riffle drops were designed for mainstem Cherry Creek in the project reach, each 9-inches high, sloping at 20:1, and reducing the channel gradient to approximately 0.2 percent between drops. The structures were constructed of a 24-inch thick layer of 12-inch D_{50} (Type M) void-filled riprap. Because the void-filled riprap material is relatively impermeable, an additional grout or sheet pile cutoff was not provided, although sheet piling was added to a pedestrian crossing at the upstream end of the project and a tie-in drop at the down-stream end to provide two "hard points" along the project reach. The tie-in drop was several feet high to transition from the restored, raised invert to the downstream incised invert.

The riffle drops were configured with wide, flat bottoms to spread out flows and tied into the two to three foot high banks of what historic mapping showed to be the creek's primary channel in the mid-1970s. This channel was re-created to convey a bank-full event of approximately 1000 cfs. Flood flows in excess of this would spill into a wide vegetated floodplain.

Raising the invert with riffle drops was designed to improve the health of the stream in the following ways:

1. Restore favorable hydraulics and the "sponge effect" associated with spreading storm flows out in a wide vegetated floodplain.

2. Raise groundwater to restore streambank ecology by enhancing riparian vegetation.

3. Improve water quality by filtering runoff through overbank vegetation and promoting infiltration in the sandy floodplain.

4. Reduce the scour effects and hydraulic jump conditions that would be associated with larger drop structures (the riffle drops drown out quickly and are almost imperceptible in larger flows).

Figure 3 shows the cross sectional layout of one of the riffle drops within the Cherry Creek floodplain. The figure illustrates how the incised channel was filled to create a shallow base flow channel, and how larger flood events are allowed to spread out to extend well beyond the width of the riffle drop. This is to keep unit discharges low over the void-filled riprap even during large floods. In this way, there is less hydraulic force exerted on the rock and the average flood velocities are reduced. Some of

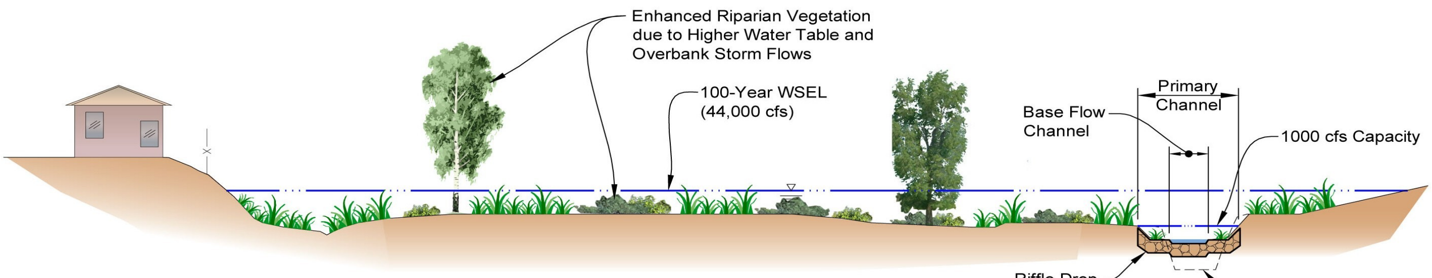


Figure 3. Cross-sectional Layout of Riffle Drop for Cherry Creek Open Space Restoration Project.

the “art” that is associated with designing riffle drops comes in selecting the vertical and horizontal layout of the drops in relation to the adjacent surroundings. Selecting drop locations and spacing along the channel, determining appropriate widths for the drops, and positioning crests “just right” (neither too high nor too low) are critical steps that requires time in the field to develop an understanding of the hydraulic, geomorphologic, hydrologic, and vegetative conditions of the channel. Section 5.1 provides design guidance for locating and configuring riffle drop structures. Figure 4 shows a representative profile layout of the riffle drops used in Cherry Creek.

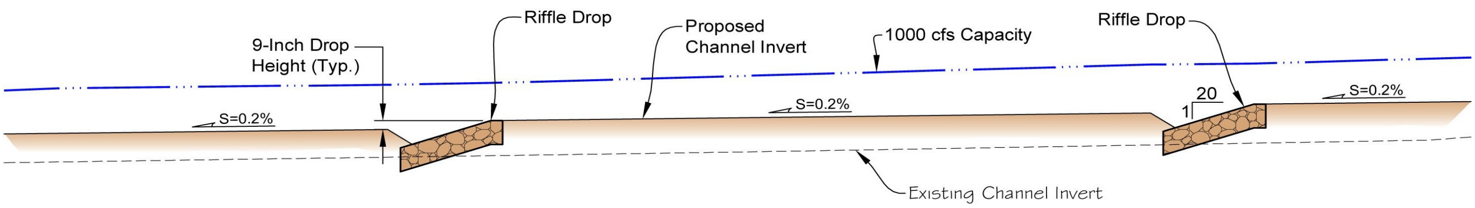


Figure 4. Representative Profile Layout of Riffle Drops.

Restored channel showing riffle drop.

Aerial perspective photo of Cherry Creek Open Space Restoration Project soon after construction showing riffle drops and secondary channel under high Spring flows.

4.0 CHANNEL LINING DEMONSTRATION PROJECT -- UPPER MARCY GULCH RESTORATION

4.1 Project Description

The Upper Marcy Gulch Restoration project was the first project where void-filled riprap was used in a channel lining application. The project was completed in 2005 for the Highlands Ranch Metro District (HRMD) and UDFCD and involved restoring an incised reach of Marcy Gulch in the upper portion of the watershed. The upper watershed is approximately 200 acres in area and drains a residential area and large high school/middle school campus. Approximately 50% of the watershed is preserved as open space. Vegetation in the open space consists predominantly of upland prairie grasses and scattered clusters of gambel oak trees and sumac shrubs.

The Marcy Gulch channel is comprised of sandy soil with native vegetation consisting primarily of upland grasses and clusters of sumac and wild plum shrubs. Because of its close proximity to the headwaters of the watershed, the longitudinal slope of the channel was very steep at 2.4 percent. Historically, it was a “dry gulch” with no base flows. Due to increased runoff from the surrounding residential development and school campus, however, signs of wetter conditions and erosion were evident. A 4-foot deep 8-foot wide incised channel had cut within the valley bottom. It was clear that the steep, sandy channel could not handle the increased runoff conditions and further erosion would occur, damaging the existing vegetation and placing existing sanitary and storm sewer utilities at risk.

This photo shows the degraded condition of the Upper Marcy Gulch channel before the project.

4.2 Alternatives Evaluation

A conventional drop structure approach was initially considered for restoring the project reach and flattening the longitudinal slope from 2.4% to a more stable slope of 0.4%. It was determined that twelve 4-foot high drop structures spaced an average of 170-feet apart would be needed. Incorporating this many large drop structures would result in extensive re-grading of the channel and disturbance to the overbank vegetation.

As an alternative to drop structures, stabilizing the low flow channel by lining it with void-filled riprap was considered. With this channel lining approach, there would be less re-grading and disturbance to the overbank vegetation because the lining could conform more closely to the steep valley slope. It was also determined to be more cost effective than the conventional drop structure approach, with an estimated savings of $100,000 in construction. Based on these advantages, HRMD and UDFCD decided that void-filled riprap lining was the best approach for restoring this reach of channel.

4.3 Project Improvements

The project improvements included lining the low flow channel with void-filled riprap and also incorporating several small step-pool boulder drops to help flatten the channel slope and emulate the appearance of a mountainous stream.

The void-filled riprap lined low flow channel was designed to convey a 2-year event with larger floods spreading out into the vegetated overbanks. The total width of the lining was 25-feet. Void-filled riprap was used to line the 6-foot wide channel bottom, where the most frequent flows would be carried, and soil riprap was used along the side slopes. The soil riprap extended along the side slope to a depth of 1.5-feet above the channel bottom and was buried with topsoil and covered with biodegradable coir blanket. One of the key benefits of the approach was being able to position the void-filled riprap lined channel to match the valley topography and minimize disturbance to the overbank vegetation. This was accomplished by varying the longitudinal slope of the void-filled riprap lined channel from 1.5 to 2.4-percent.

A total of ten small step/pool boulder drop structures were incorporated along strategic locations in the channel to help flatten the slope of the riprap lined portions and allow for flat pools/wetland pockets to be developed at sharp bends in the channel. The step/pool structures varied in drop height from 1 to 2-feet and were constructed of loose 18-inch to 36-inch boulders with grout cutoff walls. Sheet pile cutoff walls were incorporated at four of the structures to help raise the groundwater table and enhance riparian vegetation. The sheet pile cutoffs also served as an insurance measure by providing periodic "hardpoints" that would minimize erosion damage if any of the loose void-filled riprap lining or boulders were to be displaced during a large storm.

Photo showing boulder drop structure and vegetated void-filled riprap lining beyond.

An average rock size (D_{50}) of 9-inches was determined to be appropriate for the void-filled riprap lined low flow channel. The rock was sized using UDFCD and US Army Corps of Engineers (USACE) methods for mild slope channels (this method is further discussed in Section 5.4). A HEC-RAS model of the channel was developed for newly constructed conditions and for established vegetated conditions with n-values of 0.04 and 0.07, respectively. The 9-inch D_{50} size was determined to be sufficient during a 100-year storm (peak flow of 420 to 630 cfs) assuming mature riparian vegetation becomes established within the low flow channel.

This photo attests to the ability of void-filled riprap lining to support wetland and riparian vegetation and keep flows on top of the rock.

Since the stability of the rock was dependent on riparian vegetation to help slow flood flows and reinforce the underlying rock matrix, the design plans focused on establishing a dense stand of vegetation in the channel bottom and sides. Revegetation included native riparian grass seeding and plugs, Cottonwood and Peachleaf willow trees, willow fascines at bends, and native shrub plantings including Sumac and Chokecherry. Wetland grass plugs were planted directly into the void-filled riprap bottom and included Prairie Cordgrass, Baltic Rush, and Creeping Spikerush species.

Today, thick vegetation has established across the valley bottom and has helped to stabilize the channel. The riparian and wetland grasses are so healthy in the channel bottom that it is getting difficult to see the exposed void-filled riprap in many areas. Willows and Cottonwoods are also developing well from both planted material and wind-blown seed.

The Upper Marcy Gulch void-filled riprap lining project has created a stable, well vegetated stream to reclaim the former eroding, incised gulch.

5.0 DESIGN GUIDANCE FOR RIFFLE DROPS AND VOID-FILLED RIPRAP LINING

This section provides general design guidance for riffle drops and void-filled riprap lining. Conditions that are suitable for void-filled riprap are described and the benefits associated with the appropriate use of void-filled riprap are summarized. In addition, conditions that are *not* suitable for void-filled riprap are covered and limitations on the use of void-filled riprap are discussed. General recommendations on hydraulic design, rock sizing methods, and the layout of riffle drops and void-filled riprap lining are provided.

5.1 Riffle Drops

Riffle drops – low height, gently sloping grade control structures built of void-filled riprap – are ideal for certain applications, but are not necessarily the drop type to be selected for every situation.

Conditions that are suitable for riffle drops. Riffle drops are best suited for the following stream conditions:

1. Wide, flat floodplains with shallow active channels (either under existing conditions or after channel improvements are constructed) where generally uniform flow conditions exist across the width of the floodplain. Riffle drops may be used with sandy or clayey subgrade conditions.

2. Low gradient streams where flow depths are great enough to provide high tailwater conditions to help drown out the accelerated flow over the drops.

3. Relatively flat, vegetated overbanks that can handle periodic flooding without significant erosion or flood damage to structures.

4. Locations where only a small drop height is desired (generally one foot or less).

Benefits of riffle drops include:

a. Natural in appearance and easily blended with surrounding environment.
b. Cost effective.
c. Less energy to dissipate due to low drop height, which results in "drowning out" during large storms.
d. Flexible nature allows for riffle to adjust or withstand channel movement.
e. Enables upstream and downstream fish passage.
f. Aerates flows to improve water quality.
g. Allows minimal permanent impacts to wetlands.
h. Acceptance by regulatory agencies.

Conditions that are not suitable for riffle drops. Riffle drops are not suitable for the following stream conditions (the converse of the suitable conditions listed above):

1. Narrow, deeper channels or floodplains where flow can be concentrated over the drop.

2. Steep streams where it is unlikely that high depths or tailwater conditions will exist downstream of the drop.

3. High or steep overbanks that will overtop only infrequently or could erode during overtopping events due to poor vegetation or a steep longitudinal slope.

4. Locations where a drop height greater than about one foot is desired.

In addition, the limitations discussed below need to be understood and addressed if riffle drops are intended to be implemented on a project.

Limitations Regarding the Use of Riffle Drops. Just as riffle drops are not suited for every channel condition, the use of riffle drops is not suited for every type of project. Several of the limitations regarding the use of riffle drops are as follows:

a. The hydraulic design assumptions are critical to sizing the rock appropriately, so it is imperative that good hydraulic modeling techniques be employed and that a broad range of discharges be evaluated to determine the worst-case flow conditions to use for design. If there is not the budget or inclination to undertake a thorough hydraulic analysis, riffle drops are not a good choice.

b. The success or failure of a riffle drop is very installation-sensitive; rock cannot just be ordered from a supplier and dumped in. There is a variance in the particle distribution of void-filled riprap ingredients from local quarries, so the mix needs to be carefully managed and adjusted as necessary in advance of and during construction. Also, segregation of the various sized pieces of rock is a continual challenge during installation, so mixing, hauling, and placement operations all need to be geared to maintain a uniform mix of material. Finally, shaping and compaction of the void-filled riprap needs to take place in a manner that achieves the right thickness the first time with minimal rework. All of this requires a lot of attention by the engineer and contractor during construction, so more construction observation effort is required for a riffle drop installation than for conventional improvements.

c. Riffle drops are normally situated to take advantage of existing stands of durable overbank vegetation. Therefore, it is necessary to implement strict controls on contractor access to prevent critical stands of vegetation from being disturbed. This requires that the engineer think through construction access, show tight limits of construction on the design plans, and see that those limits are enforced in the field.

d. Even if the hydraulic design and the construction installation is undertaken thoroughly, there is still some risk of rock movement due to flow concentrations or major bed movement or some factor that may be beyond the designer's control. This needs to be kept in mind when selecting riffle drops as a structure type. One technique to help mitigate this concern is to plan for a "hard point" periodically – a hardened "anchor drop" or a concrete or sheet piling cutoff -- to provide additional security that major channel erosion will be controlled.

Riffle Drop Layout. After constructing a number of riffle drop projects, several general layout guidelines have been developed, as follows.

1. It is good practice to provide a flat (zero percent or upstream channel slope) approach section of void-filled riprap 10-feet or longer at the upstream end of the drop.
2. It is recommended that the longitudinal slope of the drop be 20:1 (5 percent) or flatter.
3. It is recommended that the net drop height be about 1 foot or less from the upstream channel invert to the stable downstream channel invert elevation and that the drop slope be continued to a depth of at least 1-foot below the stable downstream channel invert elevation (the *total* drop height is then about 2 feet).
4. Drops are to be laid out sequentially based on a conservatively flat estimate of long-term equilibrium slope (Figure 12-4 of the Arapahoe County Stormwater Management Manual provides

guidance for selecting channel design slopes).

5. The drop crest is trapezoidal in section with a bottom width at least as great as the upstream channel bottom width (generally no less than 10 feet), side slopes no steeper than 8:1, and a crest depth and overall width sufficient to carry the primary channel design flow (crest depth is typically 1.5 to as much as 4.0 feet deep) and tie into stable channel banks on both sides.
6. It is recommended that riffle drops be located generally in straight sections of a stream between channel bends.
7. A void-filled riprap thickness at least 2 times the design D_{50} is necessary.
8. Additional void-filled riprap thickness may be provided at the upstream end of the structure to provide a deeper cutoff, or sheet piling or a grout cutoff may be provided.
9. Design conditions that call for average rock sizes (D_{50}) between 6- and 18-inches are typical. Hydraulic conditions that call for a D_{50} greater than 18-inches are generally not recommended, since it is more difficult to avoid flow concentrations in the bigger rock and it is harder to proportion and mix 24-inch void-filled riprap and keep it from segregating in the field.

Hydraulic analysis and rock sizing is addressed in a later section. First, suitable conditions and layout guidelines for void-filled riprap lining installations are discussed.

5.2 Void-Filled Riprap Lining

The conditions that are suitable for void-filled riprap lining of channels are similar to the conditions identified above that are suitable for riffle drops.

Conditions that are suitable for void-filled riprap lining. Void-filled riprap lining is best suited for the following stream conditions:

1. Wide, flat floodplains with shallow base flow channels (either under existing conditions or after channel improvements are constructed) where generally uniform flow conditions exist across the width of the floodplain.

2. Low to moderate gradient streams where flow velocities and unit discharges will result in reasonable rock sizes.

3. Relatively flat, vegetated overbanks that can handle periodic flooding without significant erosion.

Void-filled riprap lining has many of the same benefits as listed above for riffle drops.

Conditions that are not suitable for void-filled riprap lining. Void-filled riprap lining is not suitable for the following stream conditions (the converse of the suitable conditions listed above):

1. Narrow, deeper channels or floodplains where flow can be concentrated over the lining.

2. Very steep streams where flow velocities and unit discharges will result in unreasonably large rock sizes.

3. High or steep overbanks that will overtop only infrequently or could erode during overtopping events due to poor vegetation or a steep longitudinal slope.

In addition, the limitations regarding the use of riffle drops discussed previously need to be considered before void-filled riprap lining is selected as a stabilization technique.

Layout guidelines for void-filled riprap lining. Although not as extensive as the guidelines for riffle drops, the following are recommendations for laying out void-filled riprap lining of channels.

1. The void-filled riprap lining is trapezoidal in section with a bottom width at least as great as the upstream and downstream channel bottom width (generally no less than 5 feet), side slopes 5:1 or flatter, and a rock depth and overall width sufficient to carry the primary channel design flow (crest depth is typically 1.0 to 2.0 feet deep).

2. It is recommended that the longitudinal slope of the lining be 2 percent or flatter, although in minor drainageways with small design flows and wide, shallow flow conditions, steeper slopes may be possible (but it is generally recommended that slopes not exceed 5 percent).

3. It is recommended that the void-filled riprap lining be extended to a depth of at least 1-foot below the stable downstream (unlined) channel invert elevation or terminated at a grade control structure.

4. A void-filled riprap thickness at least 2 times the design D_{50} is necessary.

5. Additional void-filled riprap thickness may be provided at the upstream end of the lining to provide a deeper cutoff, or sheet piling or a grout cutoff may be provided.

6. Design conditions that call for average rock sizes (D_{50}) between 6- and 18-inches are typical. Hydraulic conditions that call for a D_{50} greater than 18-inches are not recommended, since it is more difficult to avoid flow concentrations in the bigger rock and it is harder to proportion and mix 24-inch void-filled riprap and keep it from segregating in the field.

Hydraulic design and rock sizing is addressed in the next section.

5.3 Hydraulic Evaluation of Riffle Drops and Void-Filled Riprap Lining

Once a site has been identified as a good candidate for the use of riffle drops or void-filled riprap lining, the first step in the design typically consists of a hydraulic evaluation to determine flow capacity, depths, velocities, and unit discharges for the proposed installation. These hydraulic results are then used to determine cross sectional geometry of the riffle drop or channel lining and determine the appropriate rock size for the void-filled riprap. Typically, the hydraulic conditions are evaluated or modeled using the HEC-RAS River Analysis program developed by the U.S. Army Corps of Engineers.

Setting up an accurate HEC-RAS model and understanding its results is important in designing riffle drops and void-filled riprap lining. Key factors to consider in the hydraulic evaluation and setup of the HEC-RAS model include:

a. Evaluate a broad range of flows.

b. Strategically locate bank stations.

c. Select proper Manning's n values (channel roughness coefficients).

Evaluate a broad range of flows. It important to evaluate a broad range of storm events, especially for riffle drops, because in some cases low or medium flows can end up being the critical condition when determining rock size. Typical flow conditions to consider in hydraulic modeling include:

1. Low Flow Condition: average annual event, 1-year or 2-year storm, bankfull event for primary channel.

2. Medium Flow Conditions: 5-year or 10-year event

3. High Flow Conditions: 100-year event

In the design of riffle drops, low flow conditions usually represent flows that run parallel to the longitudinal slope face (typically at 5 percent or less) and are usually in a supercritical flow regime. For these conditions, there are special methods that have been developed for sizing rock on steep slopes with supercritical flow. Conversely during medium to high flows, most small height riffle drops will drown-out and transition to a subcritical flow regime where more commonly used subcritical riprap sizing methods can be implemented.

Strategically locate bank stations. The bank station locations are important in examining hydraulic results in various portions of the channel cross section. HEC-RAS computations are based on flow conveyance computations for three areas in a cross section: the left overbank, main channel, and right overbank. Hydraulic results (unit discharge, velocity, area, etc.) for each of these three areas of the cross section are provided in HEC-RAS' standard output tables. The bank station locations delineate the dividing point between the main channel and the two overbanks.

Since rock sizing is based on velocity and unit discharge, it is important to obtain representative hydraulic information where velocities and unit discharges are the highest, meaning in the main channel rather than in the overbanks. The main channel is defined as follows.

a. For riffle drops during low flows, the main channel is typically established as the base flow channel bottom; for perennial streams, this is the width that is relatively smooth because there is no vegetation. On the riffle drops themselves, the main channel is modeled as the bottom width out to the toe of the side slopes.

b. For void-filled riprap lined channels, bank stations are usually set at the channel bottom/toe of slope so that the main channel is delineated as the bottom width of the channel.

It is important to select bank stations to represent the central portion of the channel where flow is deepest and fastest.

In both cases, this designation of bank stations allows hydraulic information to be obtained where flow runs the deepest and fastest.

Roughness Coefficients. Selection of channel roughness coefficients (Manning's n-values) is also very important in HEC-RAS modeling and can have a significant impact on hydraulic results. N-values typically vary over the cross section of a natural stream or open channel. However, n-values also vary with flow conditions. For low flow conditions or widespread shallow flows, n-values are on the higher side because channel surface features (grass, shrubs, trees, or rock) protrude further, relatively speaking, into the flow. When the ratio of the depth of flow to the protruding height becomes small (shallow depth and significant protrusion), this is termed "high relative roughness".

Conversely, n-values will be generally lower during high flow conditions like the 100-year event because channel surface features protrude proportionally less into deeper flows (low relative roughness). In addition, grasses, herbaceous plants, and willows tend to bend over or lay down in the larger flows and, therefore, hydraulic roughness diminishes.

For example, when modeling low flow conditions (1-year event) for the Cherry Creek Open Space project in the primary channel (overall width of approximately 110-feet), an n-value of 0.035 was used to represent the roughness in the main channel (the 20-foot bottom width of the riffle drop and the unvegetated upstream and downstream base flow channel) and a significantly higher n-value of 0.10 was used to represent the willow vegetation in the overbanks. The higher n-values in the overbanks resulted in reduced flow conveyance in the overbanks but forced more flow to be conveyed in the smoother low flow channel bottom. This resulted in higher flow velocities and unit discharges in the low channel bottom (appropriately so), which are the critical parameters in rock sizing. If too high of an n-value was selected in the main channel and too low of a value used in the overbanks, the rock could end up undersized for the actual hydraulic conditions in the central portion of the drop.

Selecting n-values low enough in the main channel and high enough in the overbanks pushes more flow to the center to better represent the higher velocities and unit discharges that should be used for void-filled riprap sizing.

Guidance on n-value selection can be found in numerous open channel flow references including the UDFCD *Storm Drainage Criteria Manual*, Chow's *Open Channel Hydraulics* book, and several USGS references including *Water Supply Paper 1849* (Barnes, 1967) and *Determination of Roughness Coefficients for Streams in Colorado (Water Resources Investigations Report 85-4004)*. In addition, UDFCD has published several studies pertaining to the influence of vegetation on roughness in Cherry Creek. Both the CSU and USDA documents mentioned in the next section (in regard to rock sizing) provide equations for estimating n-values for exposed riprap on steep slopes. Overbank areas with riparian vegetation like willow stands and cottonwood trees can be difficult to estimate n-values for. New research on n-values for riparian vegetation is being conducted at various hydraulic laboratories; these findings will be helpful when published.

5.4 Rock Sizing Methods

Two conditions are to be considered when sizing riprap for riffle drops or void-filled riprap lining. These are categorized as *steep* slope conditions and *mild* slope conditions.

Steep slope conditions. Steep slope rock sizing equations are used for applications where the slope is greater than 2 percent and/or flows are in the supercritical flow regime. For riffle drops, the steep slope equations are typically used for low flow conditions, when flows are supercritical down the 5 percent riffle face slope. The following steep slope rock sizing equations have been used on past projects including the demonstration projects:

1. CSU Equation, *Development of Riprap Design Criteria by Riprap Testing in Flumes: Phase II* (prepared by S.R. Abt, et al, Colorado State University, 1988). This method was developed for steep slopes from 2 to 20 percent.

2. USDA- Agricultural Research Service Equations, *Design of Rock Chutes* (by K.M. Robinson, et al, USDA- ARS, 1998 Transactions of ASAE) and *An Excel Program to Design Rock Chutes for Grade Stabilization*, (K.M. Robinson, et al, USDA- ARS, 2000 ASAE Meeting Presentation). This method is based on laboratory data for slopes from 2 to 40 percent.

3. USACE Steep Slope Riprap Equation, *Hydraulic Design of Flood Control Channels, EM1110-2-1601*, (July 1991). Method is applicable for slopes from 2 to 20 percent.

All three of the steep slope methods are based on two key parameters: unit discharge and channel slope. Flow concentration is one of the main problems that can develop along steep riprap slopes. Both the CSU and USACE references recommend that the design unit discharge be increased by a flow concentration factor. Also, all three methods were developed with relatively uniform rock gradations with a coefficient of uniformity (D_{60}/D_{10}) less than 2.0. Standard UDFCD riprap gradations are not nearly as uniform with coefficients of uniformity near 3.5. Therefore, the rock size computed by the steep slope equations needs to be increased by approximately 30% when specifying standard UDFCD riprap gradations. The CSU reference has an approach for determining this gradation adjustment factor.

Mild slope conditions. When subcritical flow conditions occur and/or slopes are mild (less than 2 percent), the following riprap sizing methods have been used:

1. UDFCD Equation, *Urban Storm Drainage Criteria Manual*, Volume 1, (June 2001). Applicable for Froude numbers less than 0.8.

2. USACE Equation, *Hydraulic Design of Flood Control Channels, EM1110-2-1601*, (July 1991). Applicable for subcritical flow conditions and slopes less than 2 percent.

Design safety factor. A key parameter to consider when estimating (and ultimately specifying) the size of void-filled riprap is what safety factor to use. Many of the methods listed herein mention safety factors but generally leave this up to the designer. Designers need to keep in mind that some of these methods were developed from controlled laboratory conditions and that applications in the field are definitely less controlled.

Field installation of rock is not as precise as in laboratory conditions – it is difficult to grade riprap perfectly flat across a channel bottom or in a manner that provides a uniform slope. Sometimes the riprap delivered from local quarries is a little smaller than specified. Flow conditions on natural streams can be affected by a variety of elements including debris, sedimentation, unexpected vegetation, etc. that can result in unanticipated flow concentrations. The bottom line is that it is important to include some safety factor when sizing riprap because these real-life application issues are difficult to quantify.

It is also important to be somewhat conservative in sizing because void-filled riprap is a loose material that can be moved or dislodged if not properly sized. Once this happens, the structure or lining improvement can become compromised. Even if the rock mix is properly sized based on the methods described above, individual rock particles can still move and shift. Therefore, use of a safety factor is recommended. For most of the projects that have been constructed to date, the safety factor consists of selecting a riprap size that is one size larger than the computed rock size (e.g., if the computed D_{50} is between 6– and 9-inches [where Type L riprap would be used if no safety factor were considered], then a D_{50} of 12-inches [Type M riprap] is recommended). However, the use of void-filled riprap with a D_{50} larger than 18-inches (Type H riprap) is generally not recommended, so if applying a safety factor or increasing the D_{50} size results in rock larger than Type H, the use of void-filled riprap for that hydraulic condition is discouraged.

5.5 Specifying a Void-Filled Riprap Mix

Once a D_{50} rock size has been selected for a specific project or application, the void-filled riprap mix needs to be specified. This involves two things:

1. Specifying all of the individual material components that will make up the mix.

2. Specifying the gradation of each material component by identifying a variety of particle sizes (from large to small) and the range of allowable "passing" percentages for each particle size.

An example mix is shown in the following table. This is the mix that was specified for the Sulphur Gulch project in the Town of Parker. Photos of each of the individual components of this mix are shown in Appendix B.

This is not necessarily the mix to use for every application that calls for an 18-inch D_{50} rock size. However, it is a mix that endeavors to meet the objective of filling all the voids of the riprap in a manner that creates the highest density mix without displacing the riprap pieces away from each other.

Approximate Proportions (loader buckets)	Material Type	Material Description
6	Riprap	D50=18-inch (Type H)
3	Void-fill material	7-inch minus crushed rock surge (100% passing 7-inch sieve, 80-100% passing 6-inch sieve, 35-50% passing 3-inch sieve, 10-20% passing 1.5-inch sieve)
1	Void-fill material	2 to 4-inch cobble (round washed river rock that is well-graded, 100% passing 6-inch sieve, 35-50% passing 3-inch sieve, 5-20% passing 2-inch sieve)
1	Void-fill material	4-inch minus pit run surge (round river rock and sand, well graded, 90-100% passing 4-inch sieve, 70-80% passing 1.5-inch sieve, 40-60% passing 3/8-inch sieve, 10-30% passing #16 sieve).
1	Void-fill material	Type II bedding
½ to 1	Void-fill material	Native topsoil
Top layer	Top dressing	Additional 4 to 12-inch cobbles (round washed river rock that is well graded, 80-100% passing 12-inch sieve, 35-50% passing 6-inch sieve, 5-20% passing 4-inch sieve) shall be mixed in on the surface of the void-filled riprap (covering approximately 30% of the surface) prior to compaction of the void-filled riprap. Cobbles shall be fully embedded into the mass of the void-filled riprap.

Variations to this mix have been specified to meet the needs of different projects. Installations that are desired to appear like natural river rock contain rounded cobbles, such as the mix shown above. Other installations where aesthetics is not seen as important have used more angular rock, although the pit run surge is always retained as a critical ingredient. Mixes have varied in the amount of topsoil that is added; more topsoil may "hide" the rock more and help vegetation become established quicker, but allows more fine material to wash off the surface when runoff occurs.

6.0 GUIDANCE FOR CONSTRUCTION OBSERVATION SERVICES

Riffle drops and void-filled riprap lining are very installation-sensitive, so it is important to provide sufficient oversight by the design engineer and/or a construction inspector during construction. This includes reviewing rock material submittals, field observation during initial mixing, and observation during placement of void-filled riprap. These construction services are described below.

6.1 Material Submittals

Laboratory test certificates and gradations for all materials included in the riffle rock mix need to be submitted to the design engineer/inspector for review. For the less common (and less controlled) materials, such as the 7-minus crushed surge and the 4-inch minus pit run surge materials, it is recommended that samples (in 5-gallon buckets) be submitted for review.

Besides checking to see that all the specified gradation requirements are met, sometimes it is necessary to make adjustments in the mix proportions if individual materials are slanted toward the large or small end of the allowable range. Sometimes a contractor has difficulty finding material that meets the specified gradation for a particular component. Often, this can be resolved by selecting a different supplier for that component.

The submittal process is important, because there can be confusion with the local quarries and gravel pits when ordering these materials. By going through the submittal process, both the design engineer and the contractor can make sure that the proper materials are being ordered.

6.2 Mixing Void-Filled Riprap

This photo shows void-filled riprap being proportioned and mixed with a loader and excavator.

On past projects, the individual void-filled riprap materials have been delivered and unloaded onsite in separate stockpiles. Mixing has then been accomplished using a front end loader to add the proper “loader bucket” proportions of each material into one combined stockpile. Once all the materials have been added, the pile is mixed thoroughly to blend the materials together using the loader or large track hoe excavator. **The goal is to fill the voids of the base riprap material without displacing the riprap. The interlocking nature of riprap in the mixed material needs to remain essentially the same as if the riprap was placed without void-fill material.**

The specified mix proportions are usually noted as approximate because the two surge materials vary somewhat between different suppliers and variations in gravel pits. The surge materials are only processed through one screen size (7-inch minus or 4-inch minus), so the gradations vary. Therefore, it is important that the design engineer is onsite during the first mixing operation to make slight adjustments to the proportions if necessary. The typical adjustment is associated with the 4-inch minus pit run surge material. If it is in lacking in cobbles, then the amount of 2 to 4-inch cobble material can be increased to compensate. Conversely, if the 4-inch minus pit run surge material has a lot of cobble, then the proportion of 2 to 4-inch cobble can be reduced.

6.3 Placing Void-Filled Riprap

Void-filled riprap often needs to be re-mixed in place to maintain a uniform distribution of particle sizes.

Void-filled riprap can be challenging to place because it has a tendency to segregate. The finer sands and gravels tend to separate from the larger riprap. Contractors need to take care to minimize segregation when hauling the mixed material from the stockpile to the installation location.

The loose material needs to be placed in a single lift of sufficient height such that final grade will be achieved upon compaction. In most cases, some additional mixing with a track excavator is needed after the initial placement to make sure that void-filled riprap is thoroughly mixed and that there is no segregation or areas where the void-filled riprap consists primarily of the smaller void-fill materials. Again, the goal is to completely fill the riprap voids without displacing riprap. In some cases, additional void-filling may be necessary after the void-filled riprap has been placed because the fines have a tendency to migrate to the bottom. In these situations, a 50:50 mixture of the pit run and Type II bedding can be sprinkled on the surface and washed in with water using a high pressure hose to fill any small voids that may exist down below the surface. Other than filling voids that may extend down into the void-filled riprap, not much of this material should be left on the surface, as it will wash away during runoff events.

After the void-filled riprap has been loosely placed **(prior to compaction)**, a top dressing of the large cobbles can be mixed in on the surface for a more natural river bed look, if desired. Usually, this is done by sprinkling a few cobbles such that they cover approximately 30-percent of the surface.

The last step is to compact the loosely placed void-filled riprap material by driving over it with a heavy duty track excavator or dozer. Water can be added, if necessary, so that the moisture content of the mixture is at optimum conditions during the compaction process.

Photo showing smooth layout of void-filled riprap after compaction by excavator.

For riffle drop and void-filled riprap lining applications, it is important that the finished top elevation of the void-filled riprap layer closely matches design grades to within a tolerance of 0.10 feet. Having tight elevation tolerances helps to minimize development of flow concentrations. Finally, if for some reason the compacted material ends up below final grade, it is not acceptable to allow placement of only the smaller void-fill material or additional top dressing cobbles to achieve final grade. In such cases it is necessary to add more standard sized void-filled riprap and remix the entire thickness of rock to achieve the design section.

To ensure that mixing and placement of the void-filled riprap gets accomplished properly, it is a good idea to require the contractor to install a test section of the void-filled riprap at the beginning of the project for review and approval by the design engineer. The test section helps to ensure that the contractor fully understands the construction requirements at the beginning and then can make adjustments as necessary during the construction process. Construction observation time is still necessary for the remaining void-filled riprap installation, but the test section allows the process to get off on the “right foot”.

7.0 CONCLUSION

This paper describes the development of a new type of rock mix, termed "void-filled riprap" and shows how this rock can be applied to stream stabilization projects. Several characteristics of void-filled riprap give it unique advantages over conventional riprap as a construction material for stream restoration:

1. The well-graded particles in void-filled riprap are packed together more densely than the individual pieces of standard riprap, providing additional stability and interlocking.

2. Void-filled riprap has no open voids; therefore, water flows on top and reduces the likelihood that flow will dive down and find a weak spot in the subgrade. This avoids the erosion and piping out of fine material that can occur adjacent or under conventional riprap. Also, keeping flow on the top of the rock is generally desirable from an aesthetic viewpoint.

3. Void-filled riprap contains an effective internal filter, so no underlying filter material is necessary. This allows thinner overall installations of rock with reduced subgrade excavation.

4. Void-filled riprap provides a growing medium that supports riparian vegetation. Such vegetation not only adds aesthetic and habitat value to a stream environment, but helps to slow flows and reinforce overbanks, reducing erosion and increasing stream stability.

Void-filled riprap has been used in the construction of riffle drops and channel lining on a number of projects in the Denver metro area. In each of these projects, stream conditions were judged to be suitable for void-filled riprap, a thorough design process was followed to lay out and size the void-filled riprap, and careful inspection was provided during the construction phase. **It is emphasized that void-filled riprap has limitations and is not suitable for every situation. Each potential application must be analyzed to see if the use of void-filled riprap is appropriate.**

Appendix A

Applications of Void-Filled Riprap in the Denver Metro Area

Starting with the use of void-filled riprap on Cottonwood Creek in 2003, a number of void-filled riprap applications have been constructed in the Denver metro area. These projects are described below and locations are shown on the enclosed map.

1. Cottonwood Creek Reclamation Project, Phase 1 (2003).
Project sponsor – Cherry Creek Basin Water Quality Authority.
Eleven riffle drop structures with drop heights of 9-inches were constructed over a reach length of 5200 feet.

2. Upper Marcy Gulch (2005).
Project sponsors – UDFCD and Highlands Ranch Metro District.
In the first application of its kind, void-filled riprap was used to create a continuous cobble-lined stream in a steep 1600-foot reach of Marcy Gulch.

3. Cherry Creek Restoration at 17-mile House (2006).
Project sponsors – UDFCD and Arapahoe County.
To complete this stream restoration project on a 2500-foot long reach, five riffle drop structures with drop heights of 9-inches were constructed on mainstem Cherry Creek. In addition, a riffle drop and a two-foot high riffle-rock chute were installed on a secondary channel that conveys runoff during larger storm events.

4. Backcountry Community (2003-2010).
Project sponsor – SheaHomes.
Void-filled riprap lining was incorporated as a part of a stormwater management system for a new residential community located in Highlands Ranch. The community was designed with an open space theme to reduce runoff volume and preserve water quality. Instead of conventional curb and gutter, inlets, and storm sewers, the stormwater management features consisted primarily of roadside swales, an extensive network of open space drainageways, and numerous detention basins. Because of the site's steep topography, many of the swales and drainageways were lined with void-filled riprap. Void-filled riprap was also incorporated into the multi-purpose water feature/irrigation channels located at the entry and within the central open space.

5. Marcy Gulch at Town Center Drive (2007).
Project sponsors – UDFCD and Highlands Ranch Metro District.
Void-filled riprap was used to create a cobble lined stream in an 800-foot reach of Marcy Gulch.

6. Pine Lane Bridge over Cherry Creek (2007).
Project sponsor – Town of Parker.
To provide stream stabilization for a 1200-foot reach of Cherry Creek upstream and downstream of this new bridge, five riffle drop structures with drop heights of 9-inches were constructed.

7. Cherry Creek Restoration at Stroh Ranch (2007-2008).
Project sponsors – UDFCD and Town of Parker.
To complete this stream restoration project on a 4800-foot long reach, seven riffle drop structures with drop heights of 12-inches were constructed on Cherry Creek.

8. Cottonwood Creek Reclamation Project, Phase 2 (2008).
Project sponsor – Cherry Creek Basin Water Quality Authority.
Ten riffle drop structures with drop heights of 12-inches were constructed on this 8800-foot reach. In addition, eleven riffle-rock chutes 1.5-feet to 2.5-feet high were interspersed with the riffle drops to create varied grade control features.

9. Hess Road Bridge over Cherry Creek (2009).

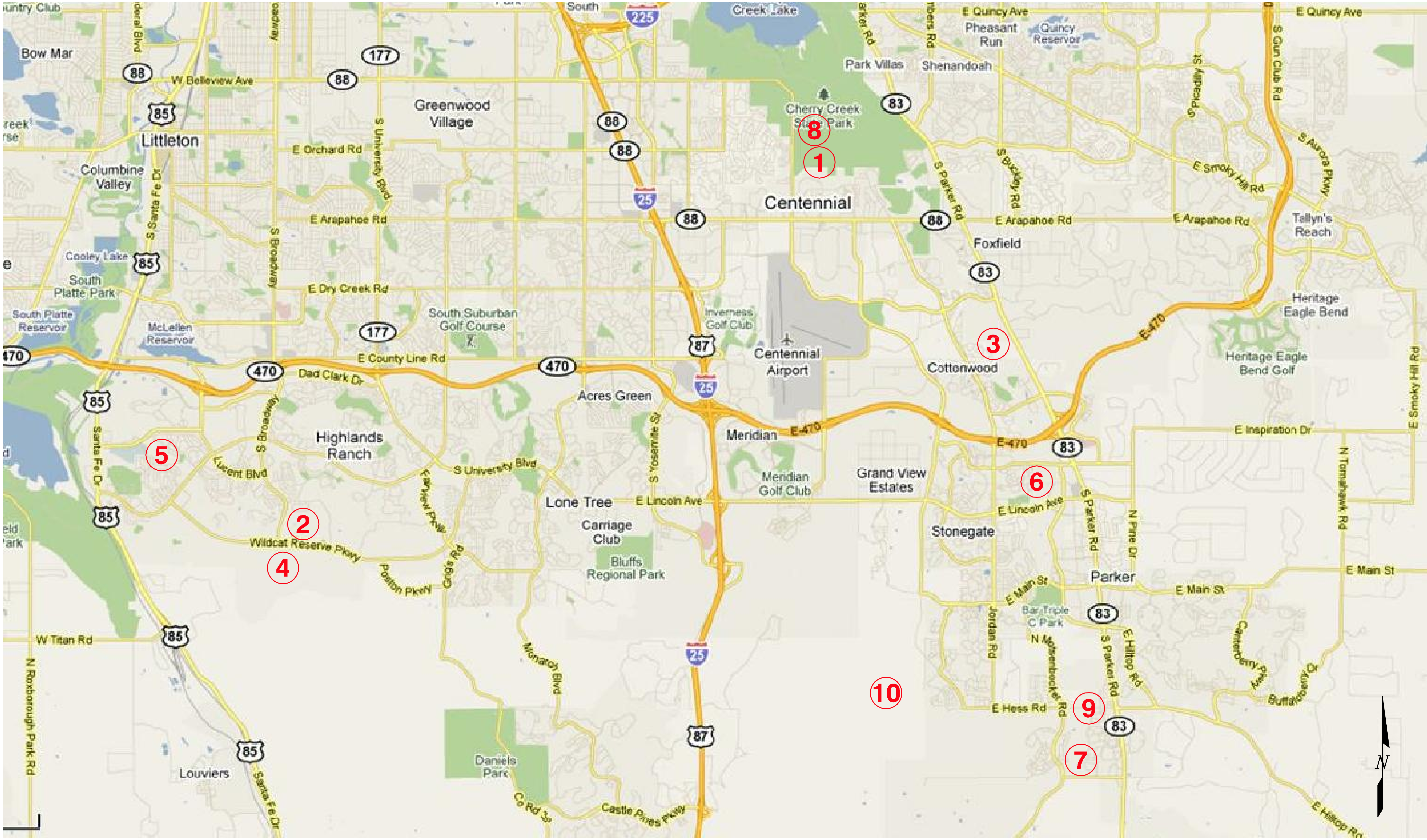
Project sponsor – Town of Parker.

To provide stream stabilization for a 2500-foot reach of Cherry Creek upstream of this new bridge, five riffle drop structures with drop heights ranging from 9-inches to 12-inches were constructed.

10. Hess Road Extension (2009, 2010).

Project sponsor – Douglas County.

In another first-time application, 6.9 miles of steep roadside ditches for this new 5.2-mile long divided highway were lined with void-filled riprap.



1. COTTONWOOD CREEK RECLAMATION PROJECT, PHASE 1
2. UPPER MARCY GULCH
3. CHERRY CREEK RESTORATION AT 17-MILE HOUSE
4. BACKCOUNTRY COMMUNITY
5. MARCY GULCH AT TOWN CENTER DRIVE
6. PINE LANE BRIDGE OVER CHERRY CREEK
7. CHERRY CREEK RESTORATION AT STROH RANCH
8. COTTONWOOD CREEK RECLAMATION PROJECT, PHASE 2
9. HESS ROAD BRIDGE OVER CHERRY CREEK
10. HESS ROAD EXTENSION

APPLICATIONS OF VOID-FILLED RIPRAP IN THE DENVER METRO AREA

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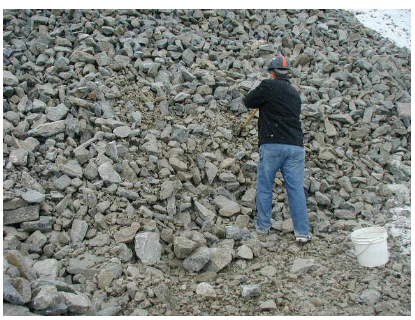
Appendix B
Photos of Void-Filled Riprap Ingredients

For reference, photos of each void-filled riprap ingredient listed in the sample mix in Section 5.5 is shown below.

Stockpiles of the separate void-fill materials.

Type M Riprap (12-inch D50).



7-inch minus crushed surge.

Type II Bedding.

4-inch minus pit run surge.

2 to 4-inch cobble.

4 to 12-inch cobble.

Close-up photographs of mixed void-filled riprap and final placement.

Stockpile of mixed void-filled riprap.

Void-filled riprap after placement and compaction.