A Case History of Highwater Shore Erosion and Bank Stabilization via Tree Roots

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ABSTRACT

Extreme highwater pool elevations in Pactola Reservoir, South Dakota in 2015 and 2019 resulted in massive shoreline erosion along the southern banks. This shoreline erosion occurred despite the geologic material being highly fractured rock with fracture dip angles approximately parallel to that of the subject hillside. The shale and siltstone in the upper 30 meters of the geology had weathered into silt and clay, leaving a matrix of 70% to 90% rock and 10% to 30% fine-grained soil. When highwater occurred, the silty portion of the shore materials eroded, while the remaining small amounts of highly plastic clay were insufficient to bind the weak and thinly bedded rock together, and rock slipped along the 15 to 30-degree fracture dip angle into the water. The shore erosion was arrested by a line of pine trees, and the erosion patterns show the effectiveness of tree roots to resist erosion in highly fractured rock. The erosion case history is presented with descriptions of several individual root systems that were effective in shore stabilization, as well as descriptions of several individual tree root systems that were ineffective in shore stabilization and the trees perished in the highwater evens and toppled.

INTRODUCTION

When thinking of soil erosion, the mind quickly focuses on scour-type erosion problems wherein wind or water at moderate to high fluid velocity are brought over a soil. The moving fluid imparts a shear stress, that, if greater than the critical shear stress of the soil, particles are lifted and mobilize. That critical shear stress is a function of particle size, weight, adhesion, and shape. The phenomena of scour-type erosion are very well studied for both wind and water. However, other erosion pathways do commonly occur. Examples of alternative erosion pathways include wave action (where an orbital shear stress from waves may exceed the critical shear stress), or internal piping erosion of dams or other earth structures (where fluid flow gradients may exceed the critical shear stress). One of the least common erosion pathways is high-water erosion of lakes, reservoirs, or backwater channels wherein a free hydrostatic condition never encountered by the soil occurs, as water at low velocity sits against the previously unsaturated soil for prolonged periods. This changes the effective stresses within the soil, and as effects of capillary action and matric suction dissipate over time, the soil matrix may loose significant strength via reductions in apparent cohesion. The loss of apparent cohesion leads to sluffing of near surface material at the soil-water interface even at low fluid velocities. This type of erosion is seen most commonly during initial filling of reservoirs. The sluffing is surficial and does not meet the criteria of slope instability but may still be a significant loss of soil material into the water.

In 2015 and 2019, high water events at Pactola Reservoir in the Black Hills of South Dakota resulted in high-water erosion of a hillside that is documented in this case history. This case history is of interest for 5 reasons: 1) the erosion occurred in a high water event rather than a scour event, 2) the erosion occurred in a rock-dominated geologic material rather than a soil, a material that should be erosion resistant per conventional assessment techniques, 3) erosion was localized to a single hillside of specific geology, 4) the erosion of the shoreline was arrested by the roots of Ponderosa Pines (*P. ponderosa*) that were below the high water surface elevation in several areas, and 5) not all woody root structures were effective at arresting the loss of material into the water from the bank. Thus, this case history provides a unique examination of how the woody roots of trees may or may not provide erosion protection in rocky geologic materials.

Bio-inspired engineering research that carefully examines tree roots has tended to focus on the strength of a root reinforced soil (Liang et al. 2017), using root banks as an analogy for retaining walls (Pollen and Simon 2005), or in shallow slope stabilization (Gray and Sotir 1996, Cohen and Schwartz 2017). Studies on these aspects of root mechanics show that root reinforcement strengthens soils and slopes, while reducing erosion. Recent work by Liang et al. (2017) is notable as they used 3D-printed fine root structures of herbaceous shrubs in geotechnical centrifuge modeling for understanding shallow slope reinforcement. Their experiments show that the root structures can be more efficient than typical anthropogenic slope stability mitigation techniques. Other significant research is the work of Wu (Wu et al. 1988a, b, Wu et al. 2005) who performed excavations of small tree root systems. Exhumed roots were placed in a small chamber where pull-out tests were performed. However, the work to date on the biomimetics of roots as an erosion arresting technology has not examined the morphology or topology as key parameters. In this paper, the morphology and topology of the woody root structures are highlighted, and indeed, play critical role in the erosion resistance of the bank.

SITE CHARACTERISTICS AND HIGH-WATER EVENTS

The hillside in question that experienced high-water erosion is mapped in Figure 1 as shale. This hillside dips at approximately 8° to 25° towards the pool, with the shale bedding layers dipping at approximately 30° preferentially towards the pool. Thus, the rock bedding planes are slightly steeper than the hillside itself in the area of the erosion. The rock itself tends to be mostly grey to dark grey siliceous biotite phyllite and schist with some shale and chert, and minor amounts of siltstone. The rock at the location of the erosion event is highly anisotropic, with the rock being weaker in the direction of the bedding planes.

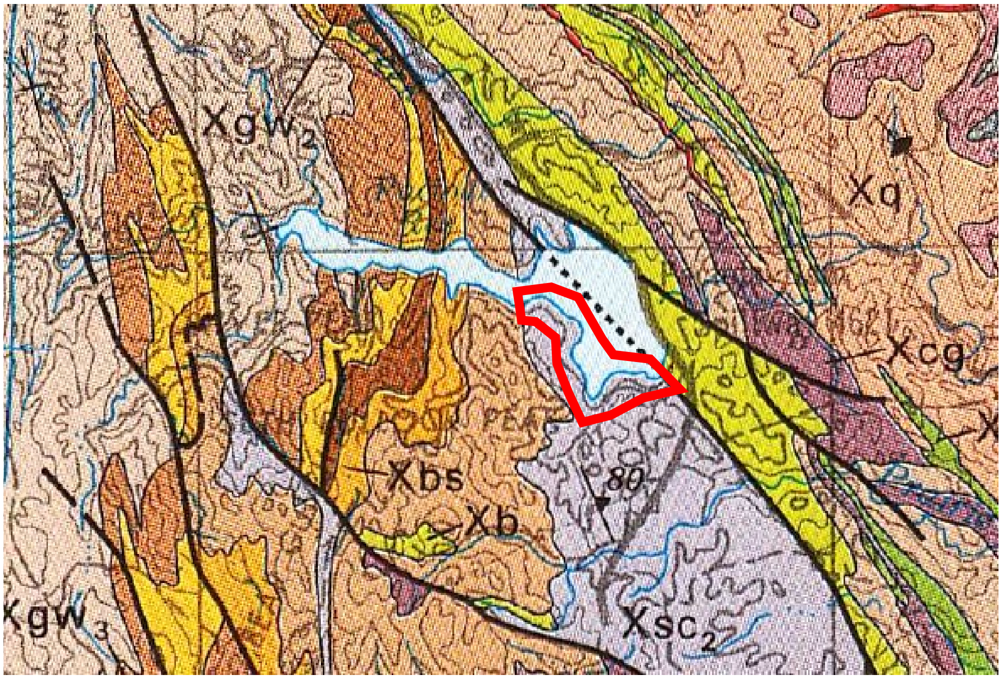

Figure 1. Geology map of Pactola. Shore erosion area outlined in red. Base-map from DeWitt et al. (1989). Formation Xcs_2 in which shore erosion is entirely located is metamorphosed carbonaceous shale (early Proterozoic).

The rock is highly fractured, with an RQD of 20% or less. Discontinuities are spaced at 50 to 100-mm, are smooth, and infilled with soft silty to clayey soil. Discontinuity thickness ranges from 2 to 10-mm. The intact rock has uniaxial compressive strength of 10 to 40-MPa and may be broken by hand or by a single blow from a geologic hammer. There are occasional inclusions of harder granitic cobbles and boulders at the west edge of the erosion area. The Rock Mass Rating is 20 or less. The infilling of the wide discontinuities accounts for 10% to 30% of the formation by mass. The infilling is silty in nature, with low to moderate plasticity. Grains size distributions show that the material has 15% clay by mass or less, with fine sand content of 20 to 30%. When wet, the soil infill has shear strength of 40 to 80-kPa, but when dry the soil infill has shear strength of 140 to 190-kPa, as measured by pocket penetrometer. A slaking test of oven-dried infill material shows full slake at 4 minutes inundation, while slaking does not occur in the rock after 96 hours. Therefore, the soil infill material loses 100-kPa or more shear strength when saturated, and near surface dry soils will break apart within a few moments of inundation whereas the rock is stable.

Overtop of the rock, there is a thin topsoil overburden of approximately 30-cm thickness. The topsoil is the same in composition and geotechnical properties as the infill material below, but with high amounts of organic material such as rootlets, woody debris, and pine needles. Figure 2 shows an aerial view of the area studied in this paper, indicating the heavy timber cover over the hillside.

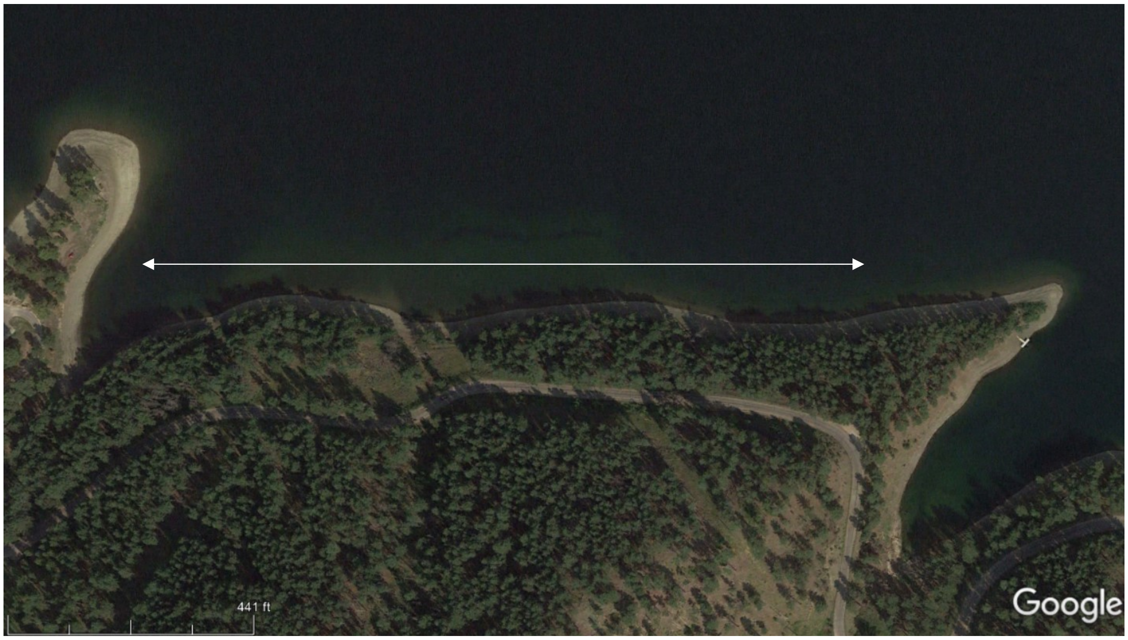

Figure 2. Extents of case history observations and measurements. Base satellite imagery courtesy of Google Earth™ .

EROSION DURING HIGH-WATER EVENTS

The shoreline at Pactola tends to be a gentle slope of width that varies seasonally with the water surface elevation (WSE) of the pool. Between the native hillsides and the shoreline is a steep bank that varies from 45° to vertical. This bank is the location of the high-water erosion phenomena each time a new maximum WSE is reached. The bank varies between 1 to 1.5-m in height. Figure 3 shows the shoreline, bank and hillside looking to the west along the study area. Note in Figure 3 the shape and characteristics of the rock that has produced a talus from the 2019 erosion event. The gentle shoreline is evident in Figure 3, with the talus from the 2015 erosion event having weathered and degraded via ice and wave action into smaller sand and gravel sized particles in just 4 years. The width of the erosion losses in 2015 and 2019 were approximately 1.2 to 1.5-m across the length of the study area. Figure 4 shows the post-event shoreline in late 2019 looking to the east. Sketches indicate the pre-2019 bank from the 2015 erosion event. Several trees that were not able to stabilize the bank in the 2015 erosion event can be seen fallen to the ground and stripped of their bark in the photographs taken in late 2019.

Documentation of the high WSE in 2015 and 2019 are shown in Figure 4 from the United States Geologic Survey (USGS) gauge station at Pactola, located across the lake from the erosion site. The records for the pool begin at initial filling in the early 1930s, but the USGS gauge station was only installed in the 1960s. Bureau of Reclamation records show that the WSE pre-USGS gauge never exceeded the data shown in Figure 4.

Figure 3. Bank as pictured after the 2019 erosion event. Note the talus of rock fragments from the high-water erosion event earlier that year. Talus from the 2015 high-water erosion event is to the right and has weathered into smaller fragments and gravels.

Figure 4. View of the erosion area to the east after then 2019 erosion event. The yellow lines show the approximate slope and bank after the 2015 erosion event.

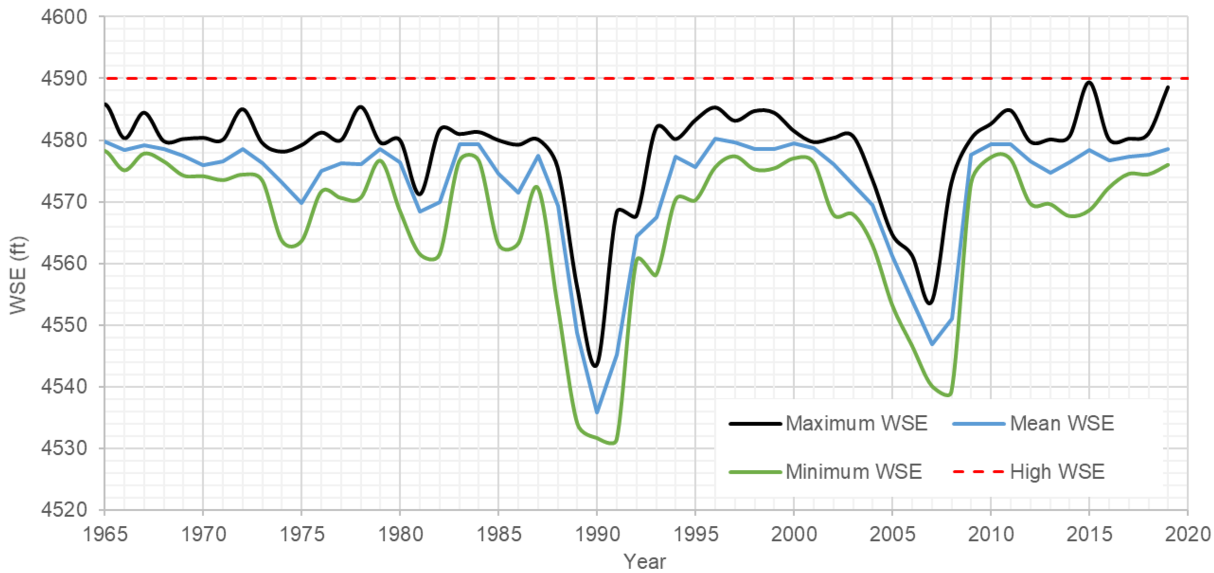

Figure 5. Water level record for Pactola Reservoir. Source: USGS gauge station on site.

Figures 3 and 4 show that the new bank that formed in the 2019 erosion event formed along the root structures of the large coniferous *P. ponderosa* trees that grown plentifully on the hillside. These trees have provided surface erosion protection to the slope for millennia, and in this new erosion paradigm have stabilized the slope and arrested the high-water erosion event of the bank. The woody roots of the trees are of particular interest. Although the “first order” (i.e. very small rootlets) rootlets certainly play a large role in surface erosion mitigation, for the purposes of this deep-seated bank erosion during high-water events, the woody roots appear to be performing most of the stabilization while the rootlets do not.

ROOT STRUCTURES OF LARGE CONIFERS

The woody roots of large conifers can be described as having multiple orders. There are several classification systems in use amongst biologists, but the system proposed by Danjon et al. (2005 and 2008) is used here. In the Danjon et al. system, the woody roots are ranked from taproots through 4 orders plus a specialty root type, the “sinker”. Figure 6 presents one description of the woody roots of a conifer from Danjon et al. In Figure 6 the black taproot is apparent. The taproot serves critical function in the early stages of root establishment and growth. In early years, the taproot provides most of the stability for the tree and is the location from which most of the 1st order rootlets emerge the bring water and nutrients into the organism. However, as the tree matures and its foliage crown becomes more extended, the water availability at the taproot diminishes. This is due to the foliage of the crown blocking precipitation from falling on or around the bole. This is an advantageous situation for the tree but results in the woody roots having to spread out. In the Danjon et al. system, Figure 6 shows the woody roots that spread out in light blue. From these spreading roots, sinkers begin to grow which descend deeper into the subsurface and act in similar manner to what the taproot did in earlier stages of development.

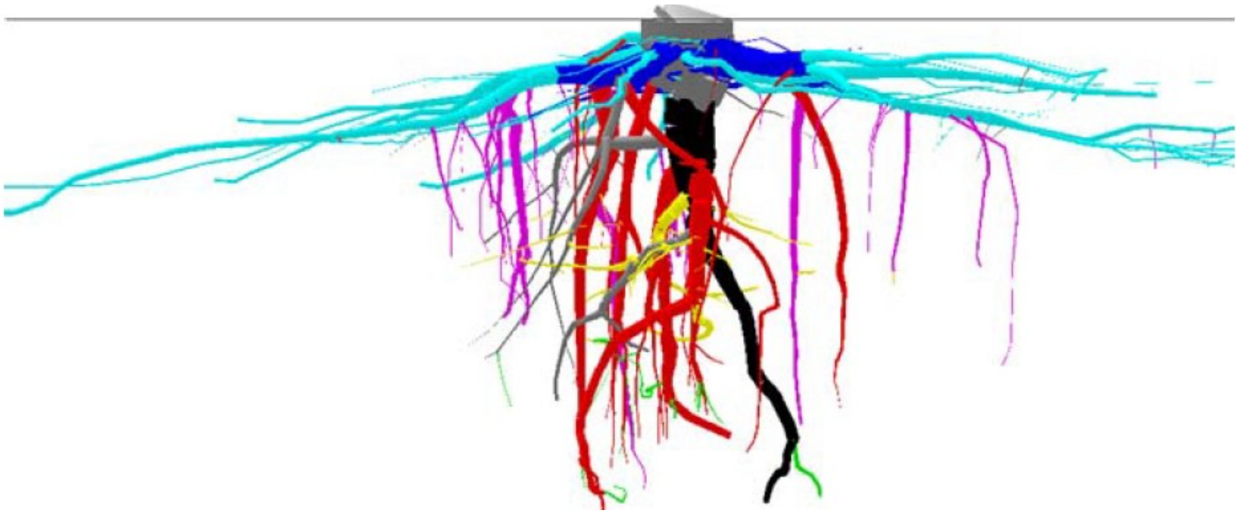

Figure 6. Digital rendering of the root structure of a 27-years-old *P. pinaster* tree from the south of France in a sandy spodosol. Colors represent the orders of the roots from taproot (black) through 4th order and sinkers. Typical of large conifers in deep thick sandy soils. Depth of penetration is 2/3 radius of spread. Modified after Danjon et al. (2005 and 2008).

The woody root structure of Figure 6 is generalized, and not all large conifer specimens will have a woody root structure with that number of sinkers. The tree in Figure 6 was growing in a deep and loose sand deposit, and thus may be an idealization. Figure 7 presents a classic case of a different large conifer growing in thin soil cover over hard competent rock. In the case of Figure 7, the taproot is limited due to the extreme hard growing conditions beneath the bole, few sinkers have developed, and the tree is forced to use the spreading woody roots for most of its stability. The mapping of Figure 7 shows more of the 1st order rootlets in addition to the thick woody roots. These rootlets were omitted from Figure 6. In order to understand the specific species at Pactola, a young specimen growing in an area of thick, loose, sandy soil was exposed and the woody roots are presented in Figure 8. Note that this specimen has a small taproot.

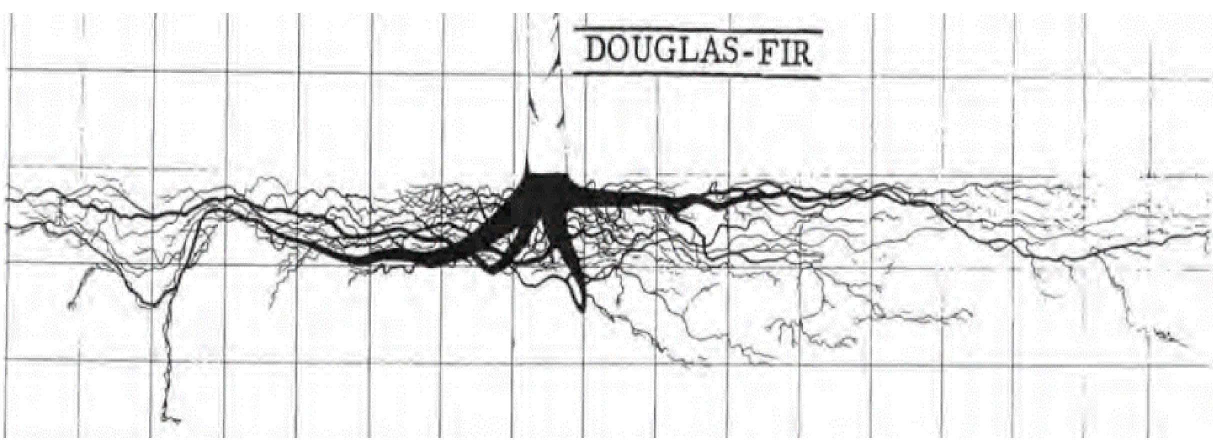

Figure 7. Rendering of the root structure of a Douglas Fir in the western United States growing in thin surficial soils over top of rock. (from Berndt and Gibbons 1958). Maximum penetration is less than 1/4 radius of spread. No sinkers on this specimen.

Figure 8. Woody root structure of a *P. ponderosa* local to Pactola away from any water courses that grew on a gentle slope in thick sandy soil. Taproot depth is approximately 1/3 of the radius of spread of the woody root mat. Note: no sinkers on this specimen.

WOODY ROOT STRUCTURES THAT STABILIZED THE BANK

Five individual specimens were mapped in detail in the study area. Three of these trees had woody roots that stabilized the bank at their locations and are typical of the structures of the many specimens all along the new bank formed in the 2019 erosion event. Most of these trees had partial root exposure in the 2015 erosion event. Trees that had been growing downslope of the high-water mark in 2015 had previously fallen in preceding decades from prolonged submergence, and account for frequent submerged logs just offshore.

The three individual specimens mapped in detail are typical of that seen in Figure 9. In these specimens, the taproot is not dominant. The woody roots spread out far from the bole (see the turquoise roots in Figure 6). The trees have many sinker roots (see the red roots in Figure 6). The root structures often interlock with those of adjacent or nearby trees. Exposed woody roots can be seen along the new bank, where the bank has stabilized at approximately the midline of the trees, meaning about half of the woody roots of the trees have been exposed in the erosion event. This does not bode well for the long-term survivability of the trees, and it is anticipated that, consistent with previous high-water events, that these specimens will die off over the next decade. Their roots will rot away, and when a new high-water event occurs, another erosion event will occur. However, the focus of this paper is on the role that the existing woody root structures play in bank stabilization in the subject high-water events. Table 1 lists the 5 specimens mapped in detail and shows the relative spread of the woody roots compared to the diameter of the foliage crown and the bole.

Figure 9. Root structure that stabilized the bank (newer exposures from the 2019 event to the left and right of the bole). The bleached roots at the front middle of the image were exposed in the 2015 high-water erosion event. Note large root spread and frequent sinkers.

All trees mapped leaned into or towards the slope, rather than away from the slope, indicating that there was no general slope instability underlying the vegetated root mat. All 5 trees had maximum heights exceeding 16 meters, and all specimens are estimated to be at least 50-years old or older. Common amongst all tree woody root structures that performed will in stabilization were: 1) large spread of the woody roots in the upper 1-m of the ground, 2) less reliance on a single large taproot, 3) a higher concentration of sinkers, and 4) high degree of interlock with the woody roots spreading out from adjacent specimens.

WOODY ROOT STRUCTURES THAT DID NOT STABILIZE THE BANK

Figure 10 shows an example of the two specimens mapped in detail that performed poorly at bank stabilization. These two specimens had erosion mass losses of at least 80% around the taproot. Common to the poor performing specimens were 1) a single, large, dominant taproot, 2) few (if any) sinkers, 3) less spread of the woody roots relative to the foliage crown, and 4) less interlock with the spreading roots of neighboring specimens. Figure 10's specimen was only saved from toppling due to the interlock of roots on its upslope side.

Figure 10. Specimen "E", typical of root structures that did not stabilize the bank. Note that erosion occurred on 80% of the base of the tree. This specimen had a deep taproot but had very few of the spreading woody roots or sinkers. Interlock only in the area not eroded.

Table 1. Individual tree stabilization.

Tree	Crown Diam (m)	Bole Diam (cm)	Max Height (m)	Lean (deg, + is upslope)	Woody Root Spread (m)	Root Interlock?	Predominant Tap Root?	Sinkers?	Did the Roots Stabilize?
A	2.4	25	16.8	0	5.5	N	N	Y	Yes, except for an area with no sinkers or interlock
B	3.0	36	18.3	15	5.6	N	Y	N	No
C	4.9	36	16.8	15	7.3	Y	N	Y	Yes
D	4.9	56	19.8	5	7.3	Y	N	Y	Yes
E	3.7	46	18.3	15	4.3	Y	Y	N	No, Only in the root interlock area

CONCLUSIONS

Extreme highwater pool elevations in Pactola Reservoir, South Dakota in 2015 and 2019 that exceeded the previous highwater elevations by 1.2-meters resulted in massive shoreline erosion along the southern banks of the lake. This shoreline erosion occurred despite the geologic material being largely highly fractured rock (siliceous biotite phyllite and schist with minor amounts of siltstone, and carbonaceous shale) with fracture dip angles approximately parallel to that of the subject hillside. The shale and siltstone in the upper meters of the geology had weathered into silt and clay, leaving a matrix of 70% to 90% RQD < 20 rock and 10% to 30% fine-grained soil. When highwater occurred in 2015 and 2019, the silty portion of the shore materials eroded, while the remaining small amounts of highly plastic clay were insufficient to bind the weak and thinly bedded rock together, and rock slipped along the 15 to 30-degree fracture dip angle into the water. The shore erosion was arrested by a line of pine trees, and the erosion patterns show the effectiveness of tree woody roots to resist erosion in highly fractured rock. The erosion case history is presented in this paper along with descriptions of several individual tree root systems with significant differences in morphology that all were effective in shore stabilization, as well as descriptions of several individual tree root systems that were ineffective in shore stabilization and the trees perished in the highwater evens and toppled. Lessons learned are derived from the successful versus unsuccessful root stabilization morphologies with implications to anthropogenic bio-inspired erosion prevention systems. The primary lessons for bio-inspired engineering design and biomimicry are that the idea of a large number of vertical elements such as taproot (i.e. a pile) or other discrete vertical element is ineffective at high-water erosion mitigation in highly fractured rock and silty soils. However, use of horizontal elements with occasional vertical elements appears to be far more effective.

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