California Levee Vegetation Research Program

Investigation of Tree Root Penetration Into A
Levee Soil-Cement-Bentonite Slurry Cutoff Wall

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Investigation of Tree Root Penetration into a Levee Soil-Cement-Bentonite Slurry Cutoff Wall

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Abstract:

Regulatory policies have been recently promulgated calling for the removal of all woody vegetation and trees that have grown and matured on or near levees. Due to the significant financial and environmental impacts of removing this mature vegetation, many levee owners and maintaining agencies are looking to retain at least some woody vegetation and are interested in exploring whether structural components such as steel sheetpiles or slurry cutoff walls installed through the top of the levee could act as effective root barriers. To investigate the feasibility of using a soil-cement-bentonite (SCB) wall as a potential root barrier, an 18-year-old SCB wall installed in a Sacramento River levee in Sacramento’s Pocket Area was partially excavated in October 2009. Trench excavations were completed opposite a large black walnut tree growing at the landside edge of the levee crown. The purpose of the trenching was to determine if roots from this tree had penetrated into or through the 18-inch-wide SCB wall during the 18 years following wall construction. Trenching excavations revealed that roots up to 1 3/8 inches in diameter had been encountered during the original construction of the wall and had apparently been cut or broken at the edge of the wall by construction equipment. However, over time, many of the broken ends of the roots had regenerated new branch roots. These new root extensions were found to have penetrated into the SCB wall a few inches, and then to have divided into smaller branches that travelled laterally within the outer few inches of the wall, perhaps absorbing moisture from the wall which still retained a high water content. Some root branches were found to have travelled more than 10 feet laterally within the outer few inches of the wall. The SCB wall was also found to have numerous, small vertical cracks that were regularly spaced about 10 to 20 inches apart, presumably caused by shrinkage of the wall over time. Where the roots encountered the cracks, small branch roots sometimes exploited the cracks and travelled through the wall. An important finding was that the tree roots were not observed to penetrate the wall except through the small cracks. This paper presents some of the observations made during the trenching investigations, laboratory test results for samples from the levee fill and the SCB wall, and information on root characteristics encountered.

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Introduction

Background

The vast majority of our nation’s levees represent legacy systems that were originally constructed decades and generations ago. They commonly share the same space as do critical riparian habitats along our rivers and, over time, woody vegetation has been allowed to grow on or near them. The presence of woody vegetation in these areas is essential for maintaining many threatened and endangered species, but is often in conflict with various levee vegetation management guidelines (see Figure 1).

![Figure 1: Photograph of Salmon Seeking Shaded Riverine Habitat (from California Department of Fish and Game)](image)

In the years following the disastrous 2005 flooding of New Orleans as a result of Hurricane Katrina, the United States Army Corps of Engineers (Corps) has made new efforts to review and strengthen its policies intended to ensure levee safety and integrity, including stricter enforcement of vegetation management guidelines for federal levees. In April 2007, the Corps released a draft white paper, “Treatment of Vegetation within Local Flood Damage Reduction Systems,” that called for the removal of wild growth, trees, and other encroachments which might impair levee integrity or flood-fighting access. In April 2009, the Corps published final guidelines for vegetation plantings and management on levees (see ETL 1110-2-571). These guidelines called for no woody vegetation on the levees or within 15 feet of the levee toes on either side of the levees (see Figure 2).
The Corps has notified local levee sponsors and maintaining organizations that levees which fail to meet these standards will be rated as unacceptable, with the consequence that they could lose eligibility for federal assistance through Public Law 84-99 for post-flood levee rehabilitation. An unacceptable rating could also lead to potential loss of accreditation under the Federal Emergency Management Agency’s (FEMA) National Flood Insurance Program.

The enforcement of well-intentioned Corps policies on levee vegetation has placed local sponsors in a difficult position as the construction and environmental impact costs associated with vegetation removal are often very large, and such efforts divert limited local funding from other higher priority levee safety improvements. The California Department of Water Resources (CDWR) has estimated that removing all of the woody vegetation from federal levees in California’s Central Valley may cost at least $7.5 billion. However, this woody vegetation represents the last remnant of a once vast riparian forest that provides critical habitat to a number of endangered species. Thus, the CDWR estimate may be significantly underestimating the true costs. Moreover, it is unclear if resource agencies responsible for enforcement of environmental regulations would allow the removal of woody vegetation that comprises critical habitat for endangered species along the entire levee system, as there may be no acceptable way to mitigate the loss. There are also significant impacts to recreation and neighborhood aesthetics that need to be considered.

As a result, many levee owners and maintaining agencies are hoping they may be able to retain at least some woody vegetation and are exploring whether structural components such as steel sheetpiles or slurry cutoff walls installed through the top of the levee might be effective root barriers. Such barriers, if shown to be effective, may alleviate the need to remove woody vegetation on some levees and be acceptable to the Corps.
Most levee experts will acknowledge that scientific research is relatively limited with regard to the benefits and disadvantages of woody vegetation on levee integrity. These limitations were noted by the 2008 Battelle Independent Peer Review of the Corps’ vegetation management policies when it concluded that the “existing policies and guidance lack scientific foundation” (see Battelle IPR Comment 4). The Corps’ Engineer Research and Development Center (ERDC) is currently conducting research on the effects of woody vegetation on levees. In addition, through an ongoing policy forum know as the California Levees Roundtable, local and State agencies in California have collaborated to sponsor and implement a complimentary research program entitled the California Levee Vegetation Research Program (CLVRP). The purpose of the CLVRP is to help resolve gaps in knowledge associated with woody vegetation on levees and to better understand the effects that woody vegetation growing on or near levees has on the safety, structural integrity, and functionality of a levee system. The research is also intended to inform policies suitable for the unique climatic, ecological and hydro-geomorphic conditions in California and to provide information to the State of California FloodSAFE Levee Evaluations Program, which is currently evaluating and prioritizing all geotechnical factors that impact the safety and performance of Central Valley levees.

**Purpose of Investigation**

In October 2009, the CLVRP sponsored an investigation of an existing soil-cement-bentonite (SCB) slurry cutoff wall, constructed as a seepage barrier 18 years earlier in a tree-covered levee, to determine if the wall would be an effective root barrier. The investigation was centered along the east levee of the Sacramento River in the Pocket Area of Sacramento, California where several different types of trees have grown for decades on the levee slopes. In this area, soil-bentonite-cement (SCB) slurry cutoff walls were installed through a generally sandy levee in 1991. This investigation provided an opportunity to determine if tree root growth during the intervening 18 years extended to the cutoff wall and what effect the cutoff wall had on any roots that were cut during construction and on any new root growth. Of particular interest was to determine whether the cutoff wall acts as a barrier to tree root penetration and forces the roots to grow laterally along instead of through the wall.

**POCKET AREA SITE**

**General**

The Pocket Area of Sacramento is a residential community located on the east side of a large bend in the Sacramento River about 5 miles south of the State Capitol (see Figure 3). In this area, a relatively large state-federal Project levee (approximately 15 to 20 feet high) was built during the early part of the twentieth century. Since that time, the Pocket Area has grown to an estimated 50,000 residents. Constructed largely of dredged material from the river, the levee itself is largely composed of sands and silty sands. Over the years, river water has seeped through and beneath the levee at high flood stages.
In 1991, the Corps constructed a shallow soil-cement-bentonite (SCB) slurry cutoff wall through the approximate center of the Pocket Area levee in an effort to cut off through-levee seepage. Figure 4 presents a cross-section from the design drawings showing the general location of the SCB wall. Figure 5 presents some of the top-of-wall details and dimensions intended by the design engineers. The design called for a minimum 12-inch-wide SCB wall extending to depths ranging between 17 and 30 feet.

This Pocket Area SCB wall was one of the first slurry cutoff walls constructed in a levee by the Corps’ Sacramento District. To build the wall, the top 1 to 2 feet of the crown roadway material and levee fill was first removed to have a wider, level working platform. A trench was then excavated in the levee and held open by a bentonite-water slurry. Once the trench reached its intended depth and extended sufficiently along the levee, the SCB backfill was pushed into the trench, displacing the bentonite-water mud forward toward the advancing end of the trench. The trench was then excavated along the levee and progressively backfilled as the trench was excavated. Figure 6 presents two photographs of a modern SCB wall under construction along the Sacramento River in 2009.

At the top of the 1991 SCB wall, a 12- to 16-inch thick trapezoidal thickness of compacted backfill was to be constructed above the wall, and the roadway gravel base was to be restored above the compacted backfill (see Figure 5).
Figure 4: General Range of Allowable Limits for 1991 SCB Slurry Cutoff Wall
(from Corps of Engineers, 1991)

Figure 5: Design Details for Top of Wall for 1991 SCB Slurry Cutoff Wall
(from Corps of Engineers, 1991)
Site F Location

The 18-year-old SCB wall constructed in the Pocket Area is one of the oldest such walls constructed in a levee in California. Because it was built within a levee where extensive woody vegetation has been allowed to grow for decades, this wall represented a unique opportunity to evaluate the interaction between tree roots and a SCB wall.

Site selection in the Pocket Area began in spring 2009. The levee was visually inspected on foot, and mapped to pinpoint sites with large trees growing on or near the bases of the levee. Approximately 16 candidate sites for excavation were identified for this study. At these sites, large sycamore, valley oak, black walnut, English walnut, cottonwood, or pine trees were present on or near the levee. At six of the more promising sites where one or more large trees were located near the top of the levee, initial pilot excavations using a backhoe were made in October 2009. The purpose of these pilot excavations was to establish if roots extended from the tree towards the wall within the upper 6 feet of the levee, which was the maximum depth we planned to investigate in this study. If no significant roots were found near the tree in the pilot excavation, the site was abandoned in favor of other more promising sites. In the end, Site F, located near Levee Mile 4.5, was selected for the cutoff wall excavation. The reasons for selecting this site were as follows:
• There was a very large and healthy black walnut (*Juglans nigra*) tree located at the top of a widened levee crown near the landside hinge point (see Figure 7). This tree was approximately 7 feet in diameter a few feet above the ground surface, and approximately 35 feet away from the cutoff wall. The drip line of the tree extended past the centerline of the cutoff wall.

• The initial pilot backhoe excavation near the tree (between the tree and the wall) encountered roots approximately 1½ to 2 inches in diameter at a depth of approximately 5 feet, indicating that roots might extend all the way to the wall.

**SITE F CUTOFF WALL EXCAVATION**

**General Approach**

The excavation of the cutoff wall proceeded in phases. The overall plan was to excavate a large pit with 1:1 side slopes to a maximum depth of about 6 feet to avoid the need for shoring and to provide a sufficient area for the investigation. To avoid damaging the cutoff wall or creating an unsafe working condition, both sides of the wall were excavated concurrently to keep the wall from being laterally loaded (see excavation layout in Figure 8).

**Excavation Process**

The excavation of the cutoff wall at Site F began on October 19, 2009 and was completed by November 2, 2009 when backfilling of the study site began. The initial phases of the excavation were carried out using a backhoe. The upper 14 inches of gravel road base and compacted fill were removed from the footprint of the planned excavation to pinpoint the location of the cutoff wall. Beneath these layers, the older sandy dredged levee fill was exposed and excavated using a backhoe away from the wall. This method avoided inadvertent damage to the wall. As operations approached the SCB wall, a combination of hand excavation methods utilizing shovels and an air knife, which blasts compressed air through a pipe, was employed to expose any roots encountered. While the air knife was an efficient way to remove the soil from the roots and the wall without damaging them, it was still necessary to use the backhoe to remove any spoils away and out of the excavation. The use of the backhoe for this purpose was not an effective approach as it broke a few of the roots at the southern, or downstream, edge of the excavation (Root #4 and branch roots). Towards the latter phase of the excavation, a large vacuum pipe, together with hand shovels, became available and was used to both excavate the sandy soil away from the wall and roots, and to remove it out of the excavation. The vacuum approach was very effective for this purpose and is highly recommended for similar excavations in the future. Figure 9 presents photographs illustrating the different phases and types of excavation.

There was also a considerable amount of hand-excavation near the wall and in the wall to follow root penetrations. Most of this was accomplished using hand shovels and small trowels. Digging into the relatively stiff wall to follow root paths was most effectively done using flat-bladed screwdrivers. Two block samples of the wall were obtained by hand sawing sections of the wall. These block samples, wrapped in cloth and coated in wax, were later taken to a laboratory for testing.
Figure 7: Photographs of Large Black Walnut Tree at Pocket Area Site F (April 29, 2009)
Figure 8: Schematic Layout of Site F Cutoff Wall Excavation

Roots encountered in the excavation were assigned numbers for accounting purposes (see Table 3).
Soils Encountered

The upper part of the levee was covered with approximately 3½ inches of gravel road base. This was underlain by approximately 10 inches of compacted clayey fill which was placed in 1991 to rebuild the levee back to its previous crown elevation after the cutoff wall was completed.

Below the 1991 compacted clayey fill, most of the soils encountered during this excavation were relatively dry gray clean sands and silty sands that were presumably part of the original dredged levee fill. However, within the sandy fill there were also lenses of yellow-brown silty clay, presumably also dredged fill. Most of these lenses were about 1 to 8 inches in thickness. However, one rounded clay mass was about 2 feet in diameter (see Figure 10). Laboratory test results for these two are presented in Table 1:
Figure 10: Photographs of Silty Clay Lenses within Sandy Dredged Levee Fill (October 22-23, 2009)
Table 1: Summary of Laboratory Tests of Recovered Levee Fill Soils at Site F

<table>
<thead>
<tr>
<th>Levee Soil</th>
<th>D50 (mm)</th>
<th>Gravel Content (%)</th>
<th>Sand Content (%)</th>
<th>Fines Content (%)</th>
<th>Liquid Limit (%)</th>
<th>Plasticity Index (%)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray Brown Silty Sand</td>
<td>0.19</td>
<td>1.4</td>
<td>69.6</td>
<td>29.0</td>
<td></td>
<td>NP</td>
<td>7.0</td>
</tr>
<tr>
<td>Yellow-Brown Clay</td>
<td>0.014</td>
<td>0.0</td>
<td>1.2</td>
<td>98.8</td>
<td>45</td>
<td>19</td>
<td>7.0</td>
</tr>
</tbody>
</table>

SCB Cutoff Wall Exposed

The SCB cutoff wall exposed in the Site F excavation was generally configured as described in the design drawings. However, there were two physical dimension differences that were unexpected:

1. The cutoff wall was found to be approximately 18 inches wide, somewhat wider than the minimum 12-inch width called for in the engineering drawings.

2. Instead of having a trapezoidal cap at the top of the wall composed of compacted backfill, a trapezoidal zone of bentonite-cement (and perhaps soil) was placed at the top and along the outside of the wall. This zone widened the wall from a nominal 18 inches up to a top width of about 39 inches, tapering down to the nominal 18 inches at a depth of about 36 inches below the top of the wall. It is theorized that this trapezoidal cementitious cap was placed outside of the completed SCB cutoff wall after it had developed an initial set. This trapezoidal cap was shaved off the 18-inch wall in the later stages of this study’s excavation for the safety of the researchers.

Laboratory test results for the two block samples of the SCB cutoff wall are summarized in Table 2.

Table 2: Summary of Laboratory Tests of SCB Cutoff Wall Block Samples from Site F

<table>
<thead>
<tr>
<th>Block Sample</th>
<th>Depth Below Top of Levee (feet)</th>
<th>Moist Unit Weight (pcf)</th>
<th>Dry Unit Weight (pcf)</th>
<th>Water Content (%)</th>
<th>Porosity (%)</th>
<th>Unconfined Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.3 – 5.6</td>
<td>81.5</td>
<td>42.5</td>
<td>91.8</td>
<td>74</td>
<td>25.4</td>
</tr>
<tr>
<td>2</td>
<td>3.4 – 4.3</td>
<td>74.7</td>
<td>41.2</td>
<td>81.4</td>
<td>75</td>
<td>15.0</td>
</tr>
</tbody>
</table>

It was noteworthy that, even after 18 years within a relatively dry levee fill, the SCB cutoff wall still retained moisture contents as high as 92 percent. In digging in this material and physically handling it, it was apparent that there was moisture in the SCB wall material, as well as in the yellow-brown silty clay lenses. This relatively high moisture was in stark contrast with
the sands and silty sands which felt almost bone dry in comparison. The low dry density of the SCB material means that its porosity, \( n \), is about 75 percent, a relatively high value.

**Cracking in SCB Cutoff Wall**

One of the more significant observations was that the SCB cutoff wall had regularly spaced small near-vertical cracks. The cracks, when first exposed, were very small, generally on the order of a hairline to \( \frac{1}{16} \) of an inch in width. These cracks were presumably due to tensile stresses that built up in the wall as the SCB material gave up moisture over time. As the days passed and the wall was exposed to the dry air, the cracks opened up to as much as \( \frac{3}{8} \) of an inch near the top of the wall. The cracks were spaced at about 10 to 20 inches along the wall (see Figure 11). The cracks tended to decrease in width towards the bottom of the wall. Many of the cracks were observed to traverse the entire 18-inch width of the wall. Given the low density and high porosity of this material, it may not have been surprising that a material containing bentonite and cement developed cracks over time.

**ROOT OBSERVATIONS AT SITE F**

**General Observations**

Several roots from the black walnut tree, and one from a cottonwood tree, were found along the edges of the SCB cutoff wall. The following was generally noted:

1. Construction of the trench to create the SCB wall in 1991 appeared to have cut or broken several roots that had grown from the black walnut tree. These cut roots were generally between about \( \frac{1}{4} \) and \( 1\frac{1}{4} \) inches in diameter.

2. Roots appeared to have grown towards and within the yellow-brown silty clay lenses in the sandy levee fill, presumably due to the relatively greater availability of moisture.

3. It was evident that the cut ends of the roots at the SCB cutoff wall largely died and rotted, but commonly regenerated new smaller branch roots at, or near, the cut ends.

4. In other places away from the cut ends, new or extended branch roots also grew towards the wall.

5. New branch roots appeared to have grown towards the wall, presumably along a moisture gradient. Once at the wall, the roots tended to divide into smaller branches and travel for several feet laterally along and within the outer 1 to 6 inches of the wall. This lateral root growth did not generally penetrate any deeper into the wall; instead the roots appeared to grow principally along and within the wall’s outside edge.

6. Where the roots encountered cracks, the roots exploited the openings and traveled along the cracks. Some roots grew along the outside edge of the cracks for several inches without penetrating deeply into the wall. However, in other locations, small roots grew deep into wall’s cracks.
Figure 11: Photographs of SCB Cutoff Wall Cracking Exposed at Site F
– Looking West at Upper 3 feet of Exposed Landward Side of Wall
(October 26, 2009)
7. In this investigation, 6 separate branch roots were found to have penetrated completely through the SCB wall within transverse cracks along an exposed wall length of about 12 feet.

More details about the root observations are presented in the following sections and summarized in Table 3.

**Root #1**

The tip of Root #1 was first encountered near the top of the landward edge of the SCB wall/wall cap approximately 6.3 feet downstream (southward) from the center point of the black walnut tree. Near the surface it was only about $\frac{1}{16}$ inch in diameter and had a reddish color. In tracing the origin of the root, we excavated the small root along a stair-step pattern of cracks largely downward until we reached a depth of about 36 inches below the top of the levee on the landside portion of the wall (about 23 inches below the top of the SCB wall). At this point the root had several branches, some up to about $\frac{3}{16}$ inch in diameter. Upon further investigation, it was found that this small reddish root originated through a vertical crack from the **waterside** of the SCB wall. Excavations along the root and on the waterside portion of the wall revealed this root had branched off from a $\frac{3}{8}$-inch root growing laterally along the waterside edge of the cutoff wall at a depth of about 46 inches from the top of the levee (see Figure 12).

The specific tree origin of Root #1 remains unclear. The reddish color of Root #1 did not match the dark gray color of the roots from the black walnut tree, and it seemed to be coming from a tree on the waterside half of the levee. However, there were no nearby trees on the waterside. Yet this was not a dead root as it had moisture and was definitely alive. Genetic testing performed at the University of California, Davis, based on a conservative DNA sequence (rbcL) later revealed the root to be part of a cottonwood tree. The nearest cottonwood trees to this study site were found approximately 120 feet upstream and 160 feet downstream, both near the waterside toe of the levee. Given the direction of root growth observed in the trench, that it is likely that the downstream cottonwood is the most likely source for this root.

**Root #2**

Root #2 was approximately $\frac{1}{2}$ inch in diameter and was observed growing from the black walnut tree towards the SCB cutoff wall just downstream of Root #1. Root #2 seemed to favor the yellow-brown silty clay soil lenses within the levee fill and intersected the wall approximately 4 feet below the top of the levee. Root #2 did not appear to have been cut by the 1991 wall construction, but seemed to be new root growth that, after intersecting the SCB wall, appeared to divide into several branch roots traveling upward and laterally downstream along and within the outer 2 to 6 inches of the SCB material. The largest of these branch roots appeared to be about $\frac{1}{4}$ inch in diameter (see Figure 13).

Another branch root from Root #2, approximately $\frac{1}{8}$ inch in diameter, split from Root #2 about 1 foot away from the wall and also grew to the wall where, after intersecting the wall, it divided into smaller branches. Some of these smaller branch roots partially grew into a
<table>
<thead>
<tr>
<th>Root</th>
<th>Diameter</th>
<th>Dist.</th>
<th>Depth</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{3}{16}$</td>
<td>6.3 DS</td>
<td>3.0 LS 3.8 WS</td>
<td>Small reddish roots penetrating cutoff wall through crack, originating from <em>cottonwood tree</em> on waterside of tree.</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{1}{2}$</td>
<td>7.6 DS</td>
<td>4.0 LS</td>
<td>Root from black walnut tree (probably <em>not</em> cut by wall construction) divided into several smaller branches ($\frac{1}{16}$ to $\frac{3}{16}$ inches) at wall and grew up and DS within outer 2 to 6 inches of wall; another separate $\frac{1}{8}$-inch branch from root partially penetrates crack in wall near Root #1 with $\frac{1}{16}$-inch branches.</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{3}{8}$</td>
<td>8.1 DS</td>
<td>4.0 LS</td>
<td>Root from black walnut tree with cut/rotted end - likely cut by wall construction, new $\frac{1}{8}$-inch branch at rotted end partially penetrates wall.</td>
</tr>
<tr>
<td>4</td>
<td>$2\frac{7}{8}$</td>
<td>12. DS</td>
<td>$\sim 4.5$ LS</td>
<td>Root from black walnut tree broken during investigation, splits into three branch roots.</td>
</tr>
<tr>
<td>4A</td>
<td>$1\frac{3}{16}$</td>
<td>12.5 DS</td>
<td>$\sim 4.5$ LS</td>
<td>Root with cut/rotted end – likely cut by wall construction – no new growth.</td>
</tr>
<tr>
<td>4B</td>
<td>$\frac{3}{4}$</td>
<td>12. DS</td>
<td>$\sim 4.5$ LS</td>
<td>Root with cut/rotted end – likely cut by wall construction, several $\sim \frac{3}{16}$-inch new live root extensions.</td>
</tr>
<tr>
<td>4C</td>
<td>$1\frac{1}{8}$</td>
<td>10. DS</td>
<td>$\sim 4.5$ LS</td>
<td>Root with cut/rotted end – likely cut by wall construction – no new growth.</td>
</tr>
<tr>
<td>5</td>
<td>$2\frac{3}{2}$</td>
<td>2. DS</td>
<td>4.5 LS</td>
<td>Large live root from black walnut tree.</td>
</tr>
<tr>
<td>5A</td>
<td>$1\frac{1}{4}$</td>
<td>N/A</td>
<td>N/A</td>
<td>Branching root from Root #5.</td>
</tr>
<tr>
<td>5A1</td>
<td>$1\frac{3}{16}$</td>
<td>N/A</td>
<td>N/A</td>
<td>Branching root from Root #5A.</td>
</tr>
<tr>
<td>5A1A</td>
<td>$1/2$</td>
<td>3.5 US</td>
<td>5.0 LS</td>
<td>Live root with another smaller branch running along wall – main branch with $\frac{1}{2}$ -inch cut/rotted end – likely cut by wall construction – no new growth.</td>
</tr>
<tr>
<td>5A2</td>
<td>$\frac{3}{4}$</td>
<td>1.3 DS</td>
<td>4.5 LS</td>
<td>Major root system – $\frac{3}{4}$-inch new live root branching away from Root #5A1 to run up and into vertical crack in SCB wall. Once in crack, splits into several branches. Main branch, Root #5A2A, is about $\frac{5}{8}$ inches and grew through crack to waterside levee fill. Second major branch, Root #5A2B, grew laterally US along outside 4 inches of SCB wall where it splits several times and enters other cracks.</td>
</tr>
</tbody>
</table>

**Notes:**
1. Approximate root diameter at edge of cutoff wall
2. Horizontal distance measured along cutoff wall opposite center of black walnut tree; US denotes upstream; DS denotes downstream of tree.
3. Depth below top of levee where root meets SCB cutoff wall; LS denotes landside edge of Wall; WS denotes waterside edge of wall.
* Approximate diameter or location before root divides into smaller branches.
Table 3: Summary of Root Observations Near SCB Cutoff Wall at Site F  
(continued)

<table>
<thead>
<tr>
<th>Root</th>
<th>Diameter $^1$</th>
<th>Dist. $^2$</th>
<th>Depth $^3$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>5A2A</td>
<td>5/8</td>
<td>1.3 DS</td>
<td>4.2 LS</td>
<td>Root grew through vertical crack to waterside levee fill – largest root found to penetrate wall</td>
</tr>
<tr>
<td>5A2B</td>
<td>3/8</td>
<td>Varies</td>
<td>Varies</td>
<td>Root grew US along outer edge of SCB wall (~ 3 to 4 inches deep) at least 9 feet US of Root #5A2</td>
</tr>
<tr>
<td>5B</td>
<td>5/8*</td>
<td>N/A</td>
<td>N/A</td>
<td>Branching root from Root #5</td>
</tr>
<tr>
<td>5B1</td>
<td>1/4</td>
<td>5.5 US</td>
<td>5.4 LS</td>
<td>Root from black walnut tree with cut/rotted end – likely cut by wall construction, new 1/8- to 3/8-inch root extensions from end grew into SCB wall</td>
</tr>
<tr>
<td>5B1A</td>
<td>7/8*</td>
<td>5.5 US</td>
<td>&gt; 6. LS</td>
<td>Live vertical root extension grew vertically downward – no end found within 6-foot-depth of trench excavation</td>
</tr>
<tr>
<td>5B1B</td>
<td>7/8</td>
<td>10. US</td>
<td>5.0 LS</td>
<td>Root grew laterally 10 feet upstream where root was damaged – likely cut by wall construction, new 1/4-inch live root extension grew laterally US within outer 3 inches of SCB wall</td>
</tr>
<tr>
<td>5B2</td>
<td>1/4</td>
<td>5.8 US</td>
<td>5.6 LS</td>
<td>Root from black walnut tree with cut/rotted end – likely cut by wall construction, new 1/8- to 3/8-inch root extensions grew into SCB wall</td>
</tr>
<tr>
<td>5C</td>
<td>3/8</td>
<td>3.8 US</td>
<td>&gt; 7. LS</td>
<td>Root from black walnut tree, bent down near landside edge of SCB wall – bending down possibly caused by construction of wall, no end found at 7-foot-depth. Root grew through axle hole for old, rusted pedal from motorized equipment; discarded in levee fill</td>
</tr>
</tbody>
</table>

Notes:  
1 Approximate root diameter at edge of cutoff wall  
2 Horizontal distance measured along cutoff wall opposite center of black walnut tree; US denotes upstream; DS denotes downstream of tree.  
3 Depth below top of levee where root meets SCB cutoff wall; LS denotes landside edge of Wall; WS denotes waterside edge of wall.  
* Approximate diameter or location before root divides into smaller branches

vertical crack near Root #1 at a depth of approximately 36 inches below the top of the levee (see Figure 13). None of the Root #2 branch roots appeared to penetrate into the SCB wall any deeper than 8 inches.

**Root #3**

Root #3 was a 3/8-inch-diameter root which grew from the black walnut tree towards the SCB wall near Root #2. This root appeared to have been cut by the 1991 wall construction as evidenced by the mostly dead and rotted end of the root at the edge of the SCB wall material. However, a newer live root extension approximately 1/8 inch in diameter had grown from the cut end into the wall (see Figure 14). This small root extension was not excavated further due to time constraints.
Figure 12: Photographs of Root #1 along SCB Cutoff Wall at Site F (October 19, 2009)
1/2-inch Root #2 Splitting Into Several Branches in Outer Few Inches of SCB Wall

1/16-inch Branch Root from Root #2 Partially Penetrating Vertical Crack in SCB Wall

Figure 13: Photographs of Root #2 along Landside Face of SCB Cutoff Wall at Site F (October 20-22, 2009)
Figure 14: Photographs of Root #3 along Landside Face of SCB Cutoff Wall at Site F (October 20-22, 2009)
Root #4

Root #4 was discovered accidentally near the downstream end of the trench during routine removal of excavation spoil material when it was snagged and broken by the backhoe. Root #4 was a live root approximately $2^{1/8}$ inches in diameter and grew from the black walnut tree at a depth of approximately 4.5 feet below the top of levee. Root #4 had also divided into 3 branch roots approximately 1 foot away from the edge of the cutoff wall. The three branch roots (Roots #4A, #4B, and #4C) had diameters ranging from $3/4$ to $1^{1/8}$ inches. All three had dead, rotted ends at their intersections with the SCB wall where they were likely severed by the 1991 SCB wall construction. However, the middle branch (Root #4B) had new live $3/16$-inch root extensions that appeared to have grown into the wall before it was snagged by the backhoe (see Figure 15). The alignment of Root #4C at the edge of the SCB wall suggests that it was bent in the upstream direction before being cut during the construction of the wall.

Root #5

Root #5 was the largest and most significant root system found in this investigation at Site F. It was approximately $2^{1/2}$ inches in diameter and found at a depth of approximately 4.5 feet below the top of the levee. This root originated from the black walnut tree, and approximately 6 feet landward of the SCB cutoff wall, it split into three branch roots (Roots #5A, #5B, and #5C) which spread out further away from the tree towards the river (see Figure 16).

Root #5A

Root #5A was by far the most noteworthy of the root branch systems encountered. This root divided into several branches with some ending in dead ends, likely cut by the 1991 SCB wall construction. Other new growth branch roots grew from into the wall and then divided into smaller branch roots which grew laterally along the outer edges of the wall. Some of these latter branch roots exploited vertical cracks in the wall which allowed small roots to grow through the wall. These different branches are summarized as follows:

Root #5A1

Root #5A1 was approximately $1^{3/16}$ inches in diameter where it branched off from Root #5A. It later divided into two main branch roots: Root #5A1A and Root #5A1B (see Figure 17).

Root #5A1A was a $3/4$-inch branch root that ran laterally upstream along the landside edge of the SCB wall for about 4 feet. This root had been cut, likely by the wall construction, and was about $1/2$ inch in diameter at its rotted end. No new growth was present at the severed end of this branch root (see Figure 17).

Root #5A1B was a $1/4$-inch root branch that also ran laterally upstream along the landside edge of the SCB wall roughly parallel with Root #5A1A. It also had a cut/rotted end with no new growth. It may be that the 1991 wall construction cut Roots #5A1A and #5A1B at locations beyond the landside edge of the wall and then bent the outer few...
Figure 15: Photographs of Root #4 along Landslide Face of SCB Cutoff Wall at Site F (October 21-22, 2009)
Figure 16: Photographs of Root #5 System Landside of SCB Cutoff Wall at Site F (October 31, 2009)
Figure 17: Photographs of Root #5A System Landside of SCB Cutoff Wall at Site F (October 29, 2009)
feet of the root ends over to the landside edge of the wall. This may explain the presence of branch roots with dead/severed ends running parallel to the wall for a few feet.

**Root #5A2**

Root #5A2 appeared to be a relatively new branch root growing from Root #5A. This 3/4-inch-diameter live root grew to the SCB wall where it exploited a vertical crack. After initially growing a few inches vertically up the crack, it divided into several smaller branch roots. The two largest of these branch roots were Roots #5A2A and #5A2B (see Figure 18).

Root #5A2A was a 5/8-inch-diameter branch root originating from Root #5A2 which grew through the crack in the SCB wall to the waterside portion of the levee. This branch root extended at least another 8 feet beyond the waterside edge of the wall (see Figure 18). This was the largest complete penetration of a root through the wall found in this study.

Root #5A2B also originated from Root #5A2 and was approximately 3/8 inch in diameter. It grew laterally upstream within the outer 3 to 4 inches of the SCB wall. It eventually extended over 9 feet upstream of where Root #5A2 entered the crack (see Figures 18 and 19). Along the way, it divided into several smaller branch roots. In two cases, smaller branch roots grew across other vertical cracks in the SCB wall and downward along the cracks on the outside edge of the wall before entering the cracks to penetrate further into the wall (see Figure 19).

**Root #5B**

Root #5B was a 1 5/8-inch diameter branch root originating from Root #5. It split into Roots #5B1 and #5B2 (see Figures 16 and 20). Root #5B1 was a 1 1/4-inch-diameter root with a cut/rotted end at the face of the SCB wall, likely severed by the 1991 construction of the wall. However, several live 1/8- to 3/8-inch branch roots grew from the cut end into the SCB wall. A smaller root branch from this root, Root #5B1A, was a 7/8-inch live root that grew down vertically near the edge of the wall (see Figure 20). No end was found for this root within the 6-foot-depth of the trench excavation. Root #5B1B, another 7/8-inch-diameter branch root, extended laterally near the edge of the wall for about 5 feet from Root #5B1. At this location, the root was up against the edge of the wall and had been severed, likely by the 1991 SCB wall construction. However, it had grown a new 1/2-inch-diameter live branch root from the cut end. This new root growth then divided into several smaller branch roots which grew laterally upstream several feet within the outer few inches of the SCB wall (see Figure 21).

Root #5B2 was another 1 1/4-inch-diameter root branching off from Root #5B (see Figures 16 and 20). Its end was also found to be cut and rotted at the landside edge of the SCB wall very close to the similar end of Root #5B1 (see Figure 20). As with Root #5B1, several live 1/8- to 3/8-inch branch roots grew from the cut end into the SCB wall.
Figure 18: Photographs of Root #5A2 System on Both Sides of SCB Cutoff Wall at Site F (October 30, 2009)
Figure 19: Photographs of Root #5A2B System Landside of SCB Cutoff Wall at Site F (October 30 to November 2, 2009)
Figure 20: Photographs of Root #5B System Landside of SCB Cutoff Wall at Site F (October 31, 2009)
Figure 21: Photograph of Root #5B1B Extension Along Landside Edge of SCB Cutoff Wall at Site F (October 29, 2009)

Figure 22: Photograph of Root #5C at Landside Edge of SCB Cutoff Wall at Site F (October 31, 2009)
**Root #5C**

Root #5C was a 1 3/8-inch-diameter root that appeared to have been bent downward near the landside edge of the SCB wall. This orientation might have been caused by the 1991 construction of the SCB wall. No end was found within a depth of 7 feet, measure below the top of the levee. It was also observed that Root #5C had grown through the axle hole of an old, rusted pedal, presumably discarded into the levee fill from some type of vehicle or mechanical equipment.

**Cutoff Wall Penetration By Tree Roots at Site F**

**General**

There were six complete penetrations of the SCB cutoff wall by tree roots observed at Site F. One penetration was a branch root from a cottonwood tree on the waterside, and the other five penetrations were from the black walnut tree on the landside. All six penetrations occurred where relatively small roots exploited vertical cracks in the SCB wall. Table 4 summarizes the six penetrations:

**Table 4: Summary of SCB Cutoff Wall Penetrations by Tree Roots at Site F**

<table>
<thead>
<tr>
<th>Wall Penetration</th>
<th>Side of SCB Wall that Root Exited</th>
<th>Depth(^1) at Exit Point (ft.)</th>
<th>Distance(^2) at Exit Point (ft.)</th>
<th>Root Diameter(^3) at Exit Point (in.)</th>
<th>Tip Distance of Root Beyond Exit Point (ft.)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LS</td>
<td>3.0</td>
<td>6.3 DS</td>
<td>(3/16)</td>
<td>2</td>
<td>From Cottonwood Tree</td>
</tr>
<tr>
<td>2</td>
<td>WS</td>
<td>4.3</td>
<td>1.3 DS</td>
<td>(5/8)</td>
<td>&gt; 8</td>
<td>Root #5A2A</td>
</tr>
<tr>
<td>3</td>
<td>WS</td>
<td>5.8</td>
<td>1.7 US</td>
<td>(3/16)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>WS</td>
<td>5.5</td>
<td>3.8 US</td>
<td>(1/16 - 1/8)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>WS</td>
<td>2.0</td>
<td>5.4 US</td>
<td>(1/16 - 1/8)</td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>WS</td>
<td>4.9</td>
<td>8.5 US</td>
<td>(1/16)</td>
<td>&lt;1</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

1. Depth below top of levee where root exits SCB cutoff wall; LS denotes landside edge of Wall; WS denotes waterside edge of wall.
2. Horizontal distance measured along cutoff wall opposite center of black walnut tree; US denotes upstream; DS denotes downstream of tree.
3. Approximate root diameter at exit point at edge of cutoff wall

Figures 23 and 24 present photographs of the small root penetrations exiting cracks on the waterside face of the SCB cutoff wall.
Figure 23: Photographs of Smaller Root Penetrations Nos. 3 and 4 Exiting on Waterside Face of SCB Cutoff Wall at Site F (November 2, 2009)
Figure 24: Photographs of Small Root Penetrations Nos. 5 and 6 Exiting on Waterside Face of SCB Cutoff Wall at Site F (November 2, 2009)
Backfilling of Trench Excavation

Backfilling of the trench began on November 2, 2009 and was completed 4 days later. All exposed roots were removed from the excavation for further study and to facilitate placement and compaction of the backfill. Any damage to, or samples removed from, the SCB wall as a result of the trench excavations were replaced/repaired with a mix of bentonite-sand-cement grout. After the loose excavation slopes were moistened, loose material was removed and the slopes trimmed. Soil previously excavated from the trench was used to backfill the excavation. The backfill was placed in 6-inch vertical lifts to fill the trench. The placed fill lifts were compacted with a roller attached to the end of a backhoe and by hand-compactors.

Summary of Findings

The October 2009 trench investigations at Site F revealed significant new information regarding the interaction of tree roots from a large black walnut tree and an 18-year-old SCB cutoff wall. While the trench was only 6 feet deep, several roots had intersected the wall approximately 3 to 5½ feet below the top of the levee. The findings and conclusions from this investigation include the following:

1. Construction of the 1991 SCB cutoff wall cut or broke several roots that had grown from the black walnut tree, located approximately 35 feet from the wall. These cut roots ranged between \(\frac{1}{4}\) and \(1\frac{1}{4}\) inches in diameter. The cut ends of the roots at the SCB cutoff wall intersection largely died and rotted, but commonly developed new live branch roots at, or near, the cut ends.

2. New root growth appeared to be attracted to the wall, presumably because of available moisture. Laboratory tests revealed that the SCB backfill had a moisture content of about 80-90 percent even after 18 years in a relatively dry levee fill. Once at the wall, the roots tended to divide into smaller branches and grow for several feet along and within the outer 1 to 6 inches of the wall. In general, this lateral root growth did not penetrate deeply into the wall.

3. The SCB wall was also found to have several near vertical cracks. These cracks were somewhat uniform in spacing, ranging between 10 and 20 inches apart. It is theorized that these cracks were a result of tensile stresses that built up in the SCB material as it gave up moisture over the 18 years following initial construction. This theory is supported by the observed widening of these cracks in the exposed wall during the course of field operations. The relatively low unit weight and high porosity of 75 percent determined for the SCB material may also have facilitated the development of cracking.

4. Where roots encountered the near vertical cracks, they commonly exploited the openings and grew into and along the cracks. Some roots grew along the outside edge of the cracks for a distance without penetrating deeply into the wall. However, in other locations, small roots grew through the wall. This investigation documented 6 complete penetrations of the SCB wall by small roots growing through cracks. With the exception of one \(\frac{5}{8}\)-inch branch root, these penetrations were by branch roots approximately \(\frac{1}{16}\) to \(\frac{3}{16}\) inches in diameter.
5. While this study was intended to investigate the rooting patterns and interactions of roots originating from a black walnut tree located 35 feet landward from the SCB cutoff wall, we also documented a small reddish branch root originating from a cottonwood tree on the waterside portion of the levee. The nearest cottonwood trees are approximately 120 and 160 feet away, and it appears that the small branch root may have originated from the farther, downstream cottonwood as the branch root seemed to be growing along the wall in an upstream direction. This illustrates that tree roots can extend large distances.

**Summary of Conclusions**

While this study provides important new information regarding the interactions of roots and SCB cutoff walls, it is premature to draw conclusions regarding the efficacy of SCB cutoff walls to act as barriers to tree roots within levees. However, the results of this study suggest that SCB cutoff walls may be at least partially effective in creating barriers and root-free zones within levees. The reasoning for this is as follows:

- The method of SCB wall construction utilized at the Pocket Area Site F site employed a large excavator, or backhoe, to excavate the SCB cutoff wall trench. This method effectively cuts, removes and kills most of the existing roots along the alignment of the wall at the time of construction. A certain percentage of these severed roots developed new, but much smaller, branch roots at their cut ends.

- While new roots appear to be attracted to the moisture contained in the SCB wall, most of the new roots observed in this investigation tended to penetrate only a few inches into the SCB wall before dividing into smaller branch roots and growing laterally without further penetration.

- Root penetrations documented through the SCB wall were only through near vertical cracks in the wall. It is unclear if more modern, thicker walls constructed with higher densities and stricter quality control requirements would experience the same cracking patterns.

- Even if all SCB walls have vertical cracks in the upper portions of the wall, it should be noted that the roots that penetrated the wall were relatively small, between 1/16 and 5/8 inches in diameter. Such root sizes are commonly left in place in clearing and grubbing earthwork construction for levees and small dams and not considered a significant issue (see CDWR guide specifications for the construction of small dams).

This study showed very little root penetration through the levee compared to the condition that could be presumed had the wall not been installed, based on the evidence of cut roots encountered in this investigation. It is acknowledged that even small roots can grow to a large size. However, further study is needed to understand the circumstances and the relationships of tree growing conditions to rate of root growth in soils adjacent to slurry walls and the implications to slurry wall performance.

Similar studies involving a variety of tree species, slurry wall designs and methods will help determine if these preliminary conclusions are appropriate. Further research to ascertain what caused the relatively uniform near vertical cracking observed in the Pocket Levee SCB wall would also be advantageous to prevent not only root penetration, but also any degradation.
of the intended purpose of the SCB wall. Future investigations examining whether such cracks occur in more modern SCB walls, and if so, to what depths, would be extremely valuable.

Acknowledgements

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