California Levee Vegetation Research Program

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

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Also published in the Proceedings of the Annual Conference of the Association of the State Dam Safety Officials; 2011, September 25-29, Washington D.C.

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INVESTIGATION OF TREE ROOT PENETRATION INTO A LEVEE SOIL-CEMENT-BENTONITE SLURRY CUTOFF WALL – PART II

Leslie F. Harder, Jr., PhD, PE, GE,[1] Roy Kroll, CEG,[2]
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Abstract:

In October 2009, a trenching investigation of tree root penetration into an 18-year-old soil-cement-bentonite (SCB) wall within a Sacramento levee was carried out. That investigation revealed that roots from a large black walnut tree 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 cut 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. The new root extensions also penetrated the wall through small, regularly spaced vertical cracks in the wall. This research was carried out as part of the California Levee Vegetation Research Program and was published last year at the 2010 ASDSO Annual Conference.

A year later, additional trenching investigations were completed in September through November 2010 along different sections of the same SCB wall opposite valley oak and cottonwood trees. In these more recent investigations, root travel from the oak trees was observed to be relatively limited. On the other hand, roots from the cottonwood trees were found to have penetrated extensively into the levee and at great distances from the trees themselves, sometimes as much as 50 to 100 feet away. As found in the prior year trenching investigation of the black walnut tree roots, the roots from the cottonwood trees were found to have been cut during the original excavation of the SCB wall, and then to have grown new root extensions that traveled along and into the wall through small vertical cracks in the wall. However, the new extensions from the broken cottonwood roots were much larger, typically $1^1/_2$ to $2^1/_2$ inches in diameter versus $^1/_4$ to $^3/_4$ inch in diameter for the black walnut tree. They also travelled further along the SCB wall than did those from the black walnut tree. In addition, burrows from ground squirrels were found 4 to $5^1/_2$ feet deep into the levee, and even in the SCB wall itself.

This paper presents some of the observations made during the 2010 trenching investigations, laboratory test results for samples of the levee fill and the SCB wall, and information on root characteristics and animal burrows 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. These legacy levees 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 riparian areas is considered to be essential by resources agencies for maintaining a number of threatened and endangered species (see Figure 1), but this presence is often in conflict with various levee vegetation management guidelines.

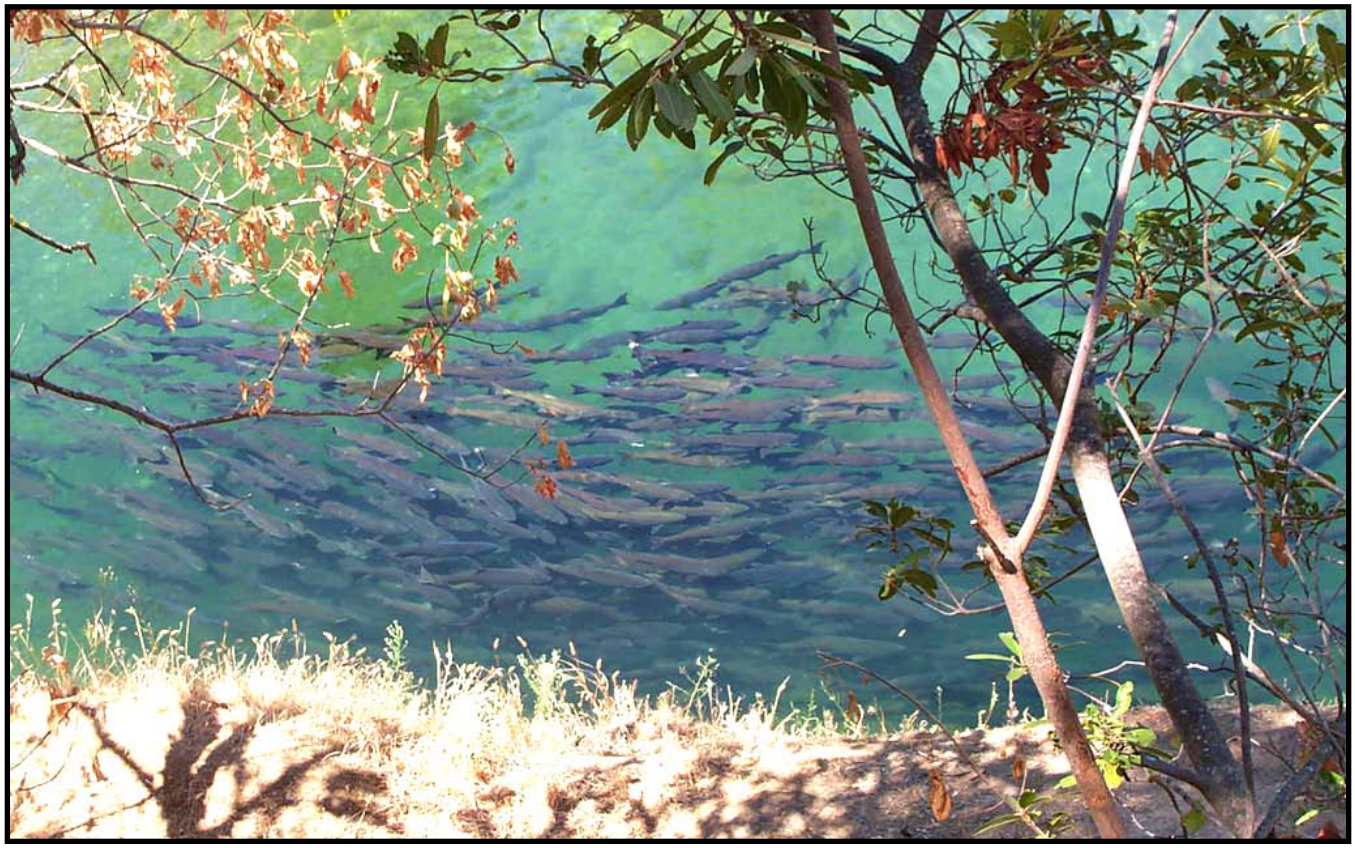


Figure 1: Photograph of salmon seeking shaded riverine habitat (from California Department of Fish and Game)

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 a vegetation-free zone with no woody vegetation on the levees or within 15 feet of the levee toes on either side of the levees (see Figure 2).

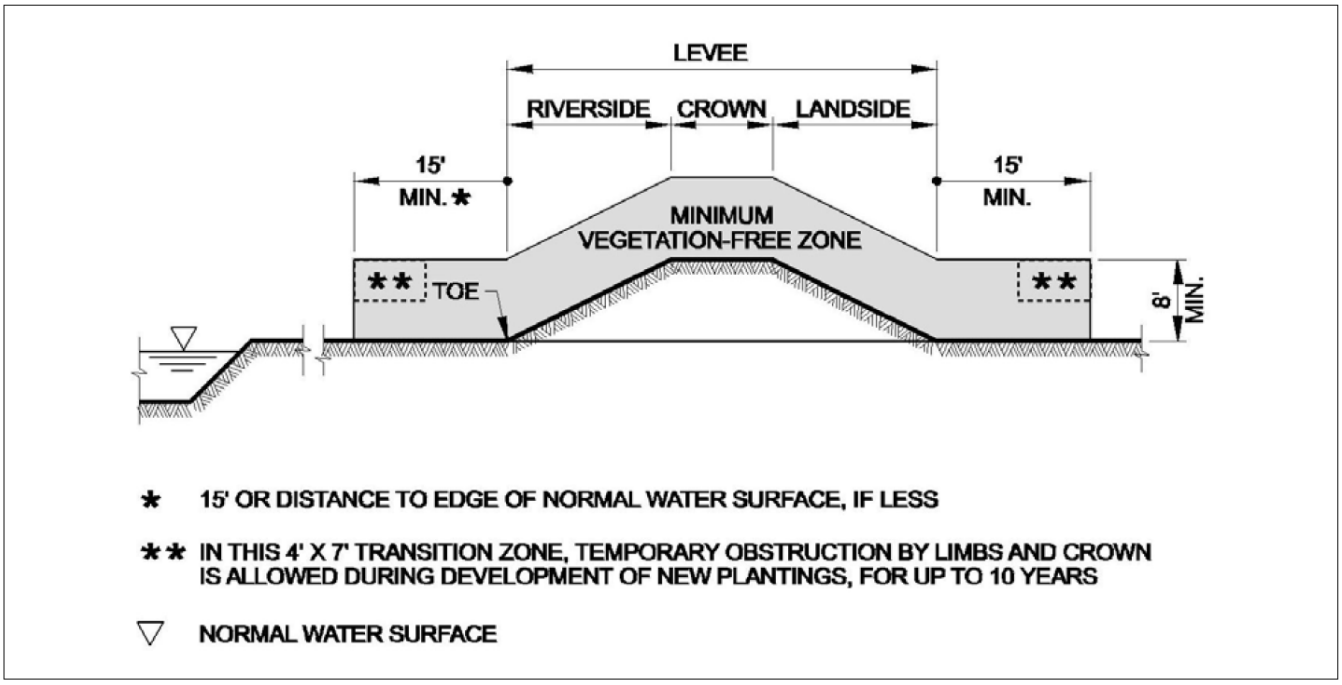


Figure 2: Minimum vegetation-free zone for federal levees (from Corps of Engineers, ETL 1110-2-571, April 10, 2009)

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 maintaining organizations 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 several billion dollars. However, this woody vegetation also represents the last remnant of a once vast riparian forest that provides critical habitat to a number of endangered species. Thus, it is unclear if resource agencies responsible for the enforcement of environmental regulations would ever allow the large-scale removal of woody vegetation along the levee system since it comprises critical habitat for endangered species. This is because there may be no acceptable way to mitigate for this loss. Vegetation removal also creates significant impacts to recreation and neighborhood aesthetics that need to be considered.

As a result, many levee owners and maintaining agencies are hoping that they may be able to retain at least some woody vegetation along the existing legacy levee system 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.

California Levee Vegetation Research Program

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 completing 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 complementary 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.

2009 Investigation of Pocket Area Site F

In October 2009, the CLVRP sponsored an investigation of an existing soil-cement-bentonite (SCB) slurry cutoff wall that had been constructed as a seepage barrier 18 years earlier in a tree-covered levee. The purpose of this investigation had been to determine if the wall had been 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, SCB slurry cutoff walls were installed through the 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.

The 2009 investigation was carried out at CLVRP's Research Site F in Sacramento's Pocket Area opposite a large black walnut tree (see Figure 3). The investigation consisted of excavating a trench on both sides of the SCB wall down to a depth of approximately 6 feet and documenting the roots present and their interactions with the wall. The results of that investigation were reported by Harder et al. (2010) and are summarized as follows:

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, located 35 feet from the wall. These cut roots were generally between about $^{1}/_{4}$ and $1^{1}/_{4}$ inches in diameter.

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

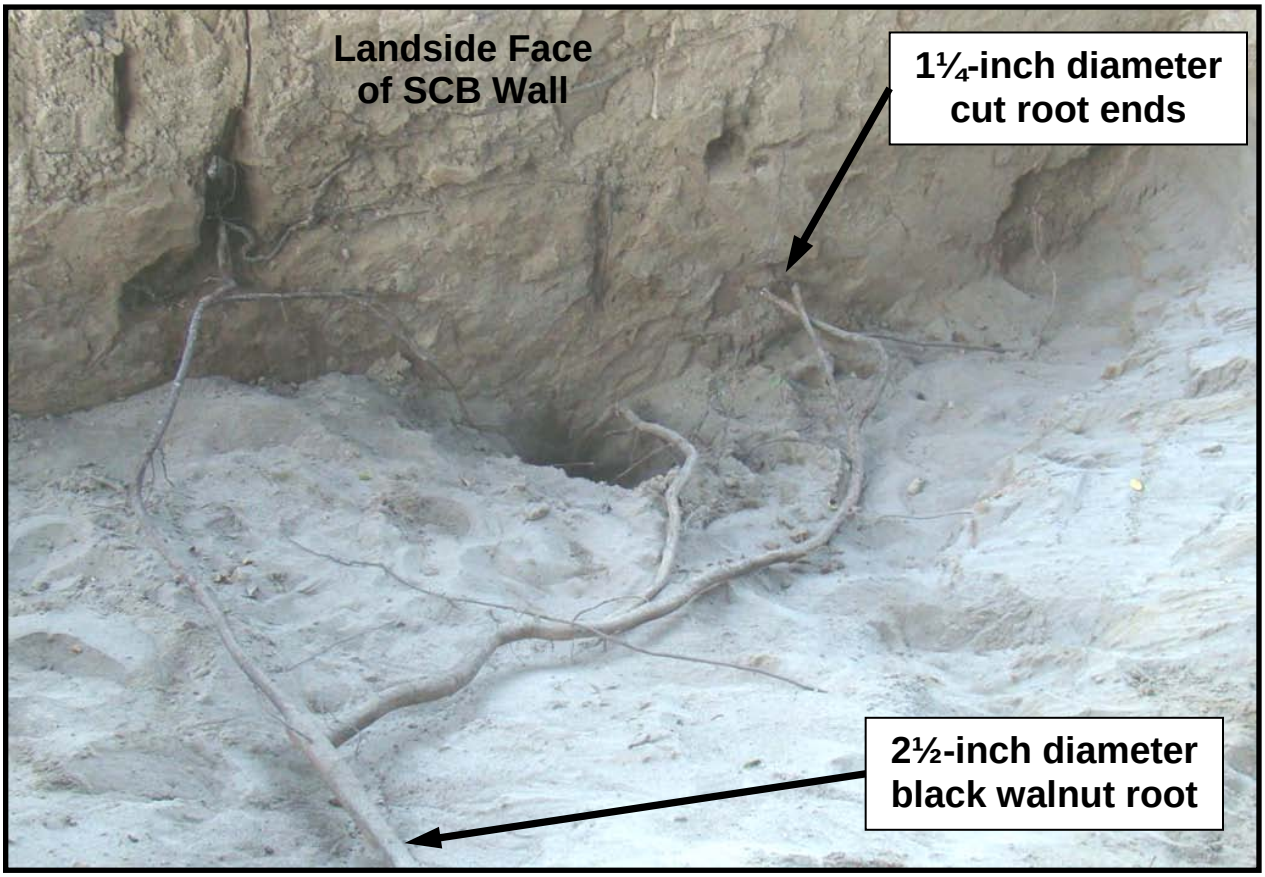


Figure 3: Views of 2009 trench excavation along SCB slurry cutoff wall at Pocket Area Site F opposite large black walnut tree (October 2009)

3. It was evident that the ends of the roots cut during the initial construction of the SCB cutoff wall largely died and rotted, but also commonly regenerated new smaller branch roots at, or near, the cut ends. These new root extensions were typically $^{1}/_{4}$ to $^{3}/_{4}$ inch in diameter.

4. 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 the outside and within the outer 1 to 6 inches of the 18-inch-thick 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 SCB wall's outside edge.

5. 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.

6. Where the roots encountered the near-vertical cracks, the roots exploited the openings and traveled up and down 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 the wall's cracks.

7. In the 2009 investigation, 6 separate branch roots were found to have penetrated completely through the 18-inch thick SCB wall within transverse cracks along an exposed wall length of about 12 feet. With the exception of one $^{5}/_{8}$-inch branch root, these penetrations were by branch roots approximately $^{1}/_{16}$ to $^{3}/_{16}$ inches in diameter.

8. 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 encountered 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 roots of some tree species can extend large distances.

Purpose of 2010 Investigations

In September through November 2010, another round of trench investigations was conducted in Sacramento's Pocket Area. The purpose of these investigations was to again investigate root interactions and potential penetrations with the SCB wall. However, the focus this time was to examine this root behavior from different tree species, namely valley oak and cottonwood. The results of these investigations are described in the following sections.

POCKET AREA INVESTIGATION SITES

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 4). 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, together with silt and clay lenses. Over the years, river water has seeped through and beneath the levee at high flood stages.

Figure 4: Aerial photograph of Sacramento's Pocket Area illustrating the locations of the 2009 and 2010 trenching investigations (modified from Google Earth, 2009)

In 1991, the Corps constructed a shallow SCB slurry cutoff wall through the approximate center of the Pocket Area levee in an effort to cut off through-levee seepage. Figure 5 presents cross-sections from the design drawings showing the general location and dimensions of the SCB wall. 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 slurry forward towards 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). During the 2009-2010 excavations, this trapezoidal backfill was found to have variable dimensions and to have included bentonite in its mix.

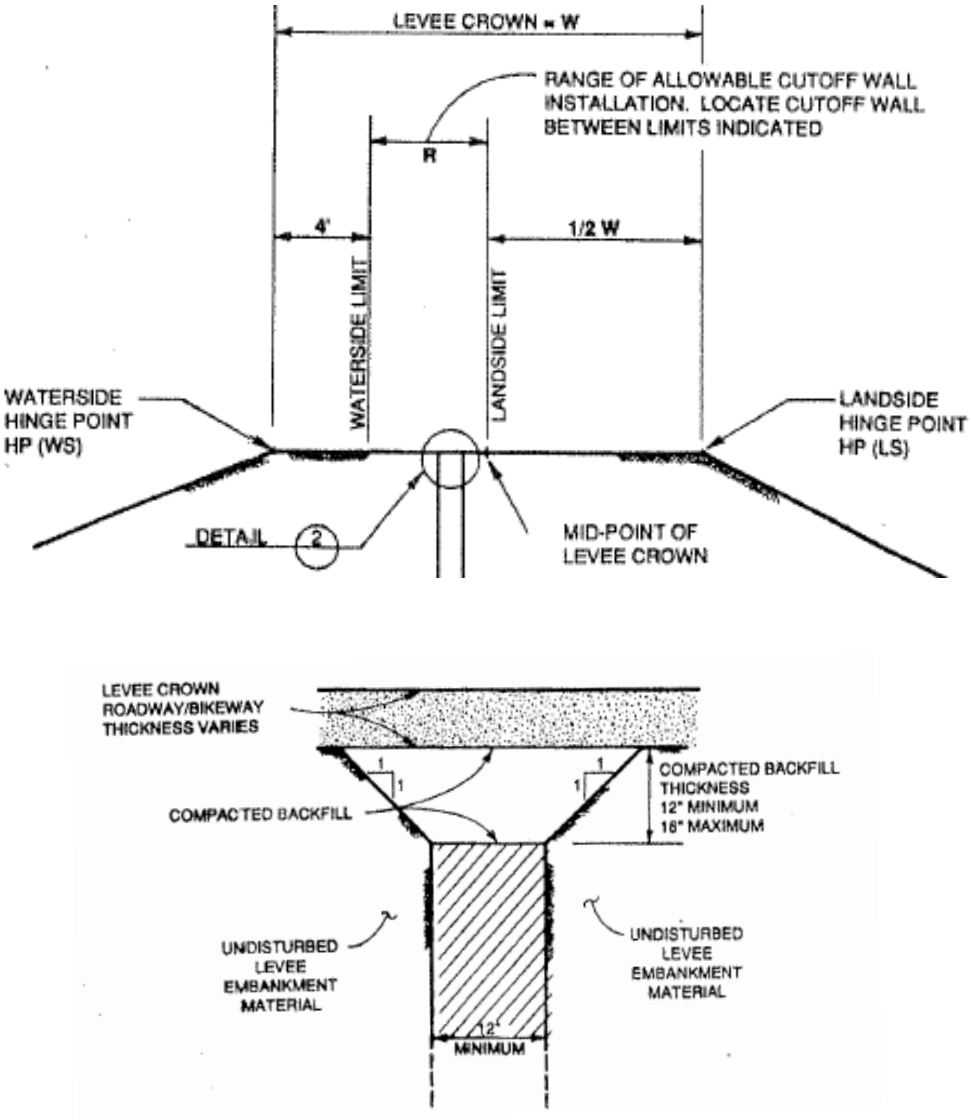


Figure 5: Design details for 1991 SCB slurry cutoff wall (from Corps of Engineers, 1991)

Figure 6: Views of recent SCB Wall construction along Sacramento River levee (November 2009)

2010 Site Locations

Two CLVRP Research sites in the Pocket area were trenched in the fall of 2010:

Site B

Site B was located near Levee Mile 5.6 (N38.4889°, N121.5513°). At this location, two valley oak trees (*Quercus lobata*) were growing on the landside slope of the levee approximately 4 feet below the levee crown. The site had previously been studied by an ERDC research team that had conducted ground penetrating radar surveys of tree roots and had made shallow excavations downslope below the two trees to look at tree root architecture.

Site G

Site G was located near Levee Mile 4.8 (N38.4995°, N121.5579°). Site G had previously been investigated by researchers from the University of California, Davis as part of the CLVRP to fully excavate and examine tree root architecture of two valley oak trees situated approximately 8 feet waterward of the waterside levee toe. During the course of those investigations of the two valley oak trees, relatively large roots from cottonwood trees (*Populus fremonti*) were encountered that appeared to be travelling into the waterside levee slope

towards the levee crown. This area appeared to have very high potential for finding root interactions with the SCB wall.

SITE B EXCAVATION

Excavation Plan

The plan at Site B had been to excavate the SCB wall opposite two valley oak trees located on the landside slope of the levee approximately 4 feet below the levee crown. One of the trees had a trunk diameter of approximately 24 inches; the other tree had two trunks with approximately 12- and 16-inch diameters. The two valley oak trees were located about 28 feet apart. In 2009, the ERDC team had found significant tree roots (2 to 3 inches in diameter) extending downslope from the larger tree (see Figure 7).

(a)

(b)

Figure 7: (a) View of valley oak trees near levee crown at Site B (May 31, 2009) and (b) View of tree roots exposed downslope of larger valley oak in ERDC excavation (October 2009)

Prior to excavating the SCB wall at this location, an initial backhoe trench was completed along the levee crown approximately 15 feet away from the two oak trees. The purpose of this initial trench was to verify that large roots were actually extending towards the SCB wall and that a larger trench excavation of the wall would be worthwhile. This initial trench was 60 feet long and typically ranged between 8 and 9½ feet in depth (see Figure 8). It was located approximately 5 to 7 feet landward of the alignment of the SCB wall.

Figure 8: View of initial backhoe trench excavation opposite valley oak trees at Site B (September 9, 2010)

Small Tree Roots Found in Initial Backhoe Trench Excavation at Site B

The initial trench failed to encounter roots of any significant size (i.e. $^{1}/_{2}$ inch in diameter or greater), even though the trench was commonly 9 feet deep opposite the two oak trees. However, at a depth of 4 feet in the trench, comparable to the elevation that trees were situated on the slope, small roots were found. These small roots were about $^{1}/_{16}$ inch to $^{1}/_{4}$ inch in diameter and were extending waterward towards the river (see Figure 9). The levee material encountered in the trench was a fine, poorly graded sand with silt (SP-SM). A sample of this levee material was tested and found to have the following grain size characteristics:

D_{50} = 0.30 mm
Fines Content = 11.7 percent
Coefficient of Uniformity, C_u = 7

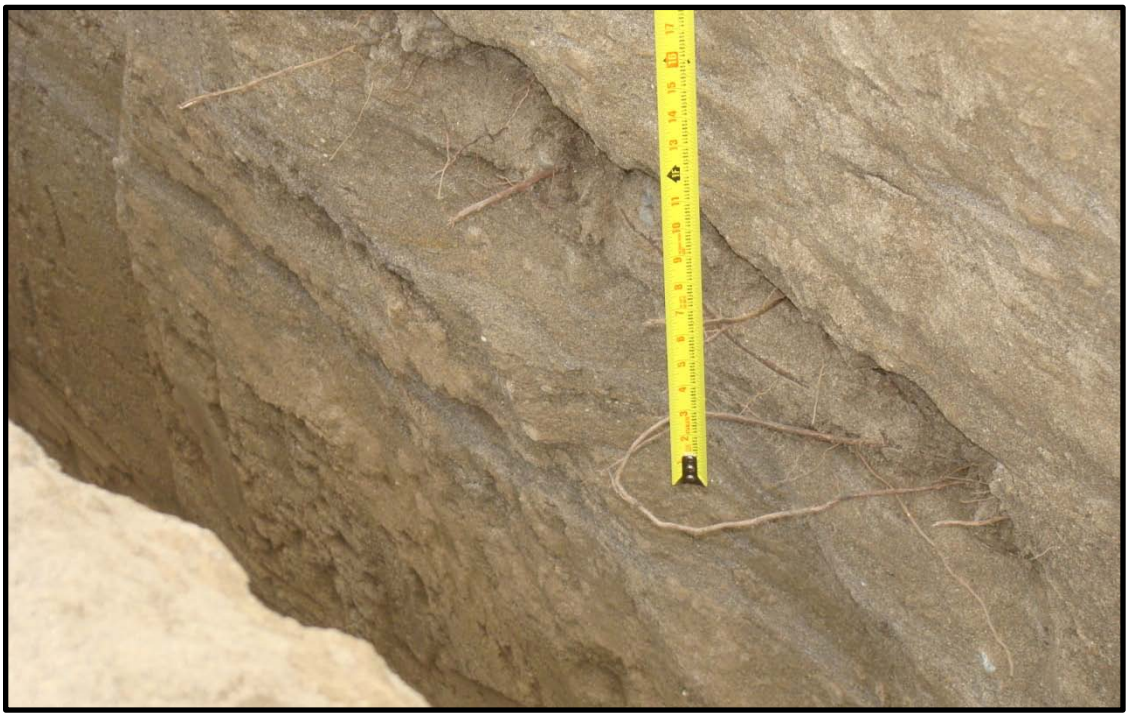


Figure 9: Views of small roots found in initial backhoe trench excavation opposite valley oak trees at Site B (September 9, 2010)

Grouted Animal Burrow Found in Initial Backhoe Excavation at Site B

While large roots were not found in the initial backhoe excavation at Site B, pieces of cement grout were encountered. These pieces of grout were found opposite the more southern, or downstream, oak tree that had two trunks. The grout pieces were located at a depth of 4 feet, at the same elevation that the small roots were found and at the same elevation that the two valley oaks were situated on the levee slope 15 feet away horizontally (see Figure 10).

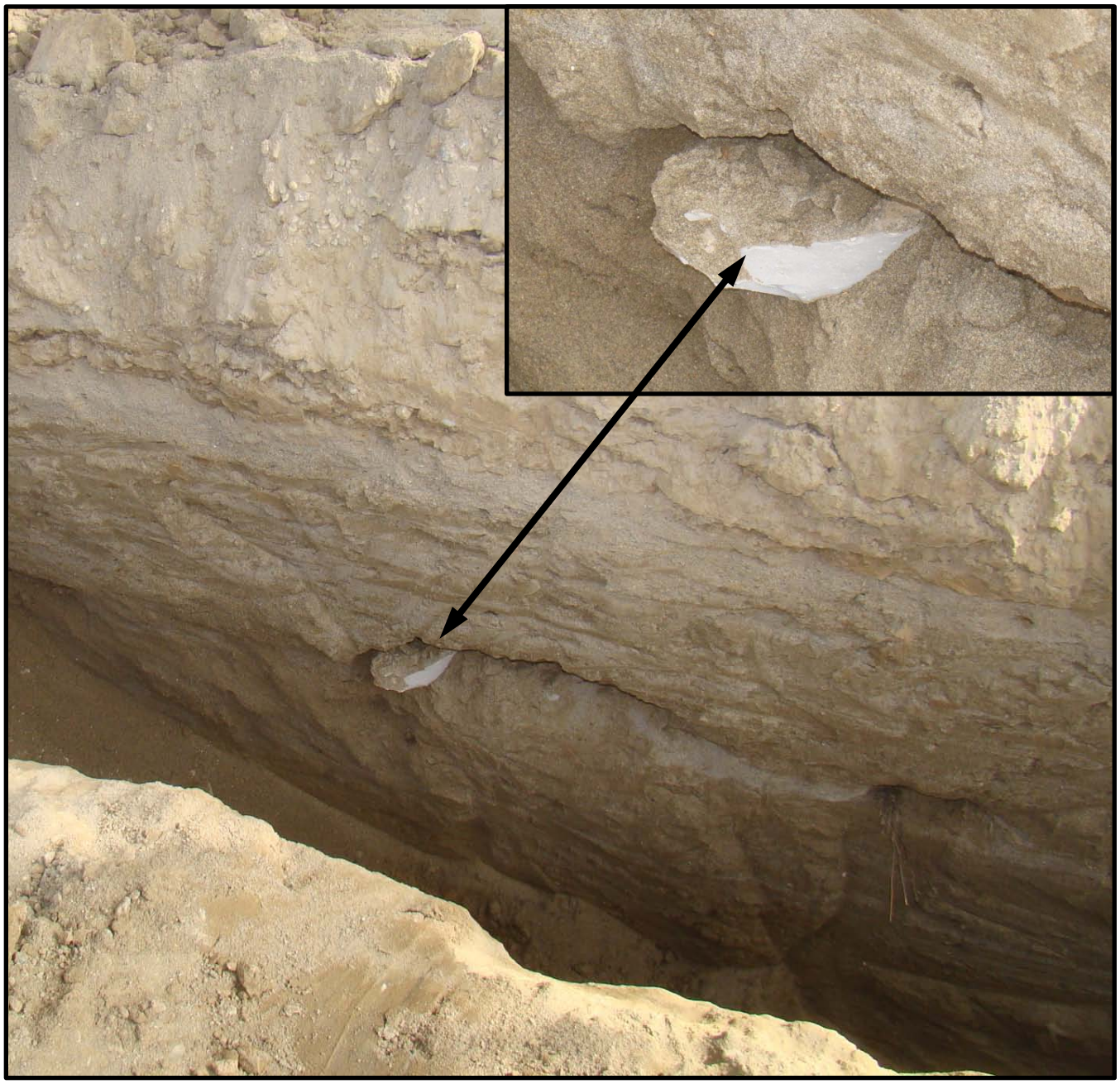


Figure 10: View of grouted animal burrows found in initial backhoe trench excavation opposite valley oak trees at Site B (September 9, 2010)

At first, it was difficult to understand how the grout had gotten into the levee at this depth and several feet away from the SCB cutoff wall. After broken walnut shells were found in the upper surfaces of some of the grout pieces and discussing this with CDWR personnel, it became clear that CDWR had previously grouted animal burrows in this area a few years before. Chunks of grout brought up from the trench indicated that the burrows were at least 2½ to 4 inches high (assuming that the grout filled the tunnels to their tops), and generally 4 to 12 inches in width. The geometry of the grout pieces suggested that different burrow tunnels/branches sometimes merged together into larger openings (see Figures 11 and 12). The size of the grouted burrows and the presence of the walnut shells indicated that this was the grouted burrow of a ground squirrel or family of ground squirrels.

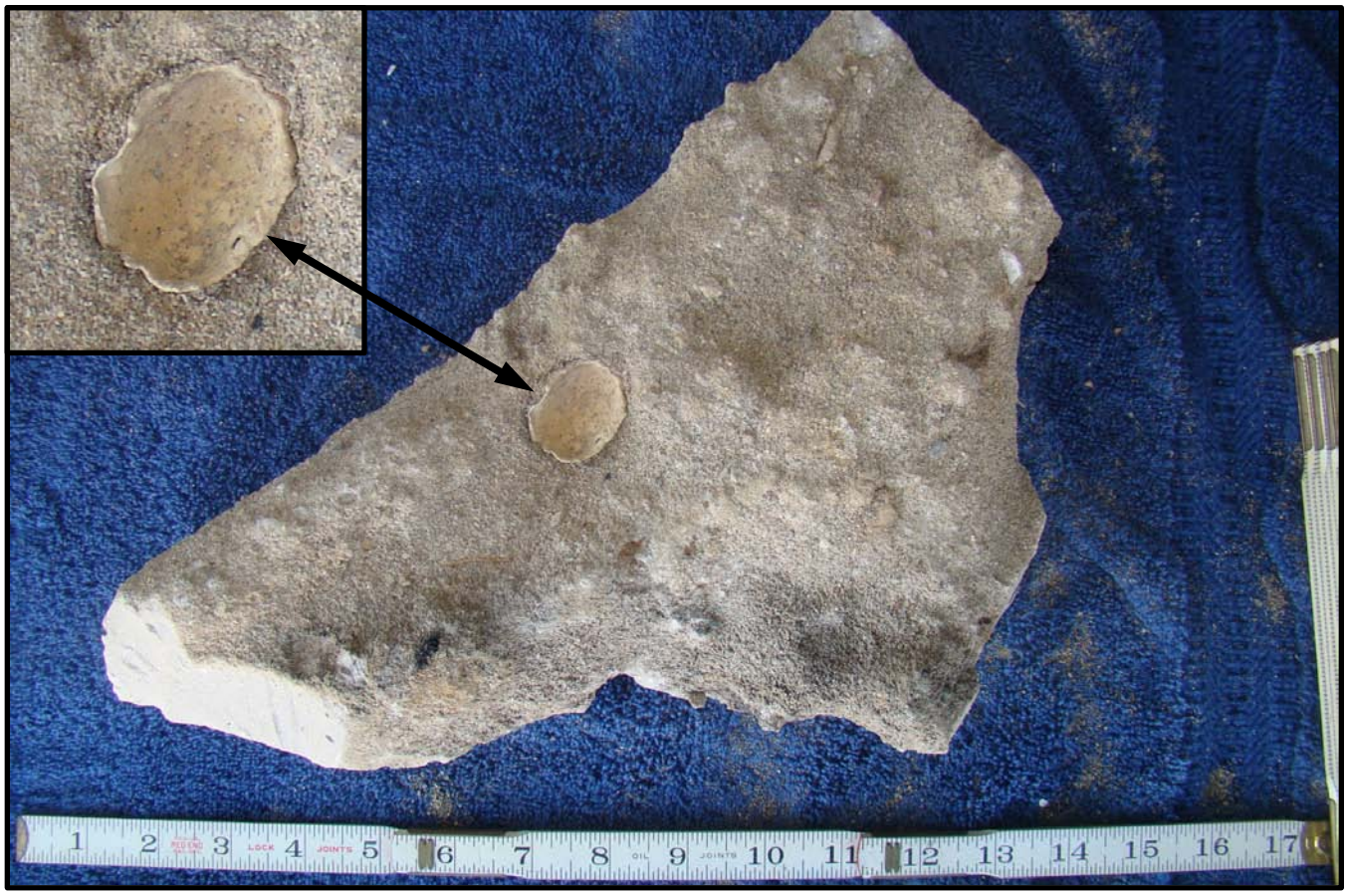


Figure 11: View (looking down) of piece of grouted animal burrow with walnut shell half found in initial backhoe trench excavation at Site B (September 9, 2010)

Because only small roots were found travelling waterward towards the SCB wall from the two valley oak trees, it was concluded that a larger trench excavation of the SCB wall was not worthwhile and the initial backhoe trench was backfilled with no more work done at this site.

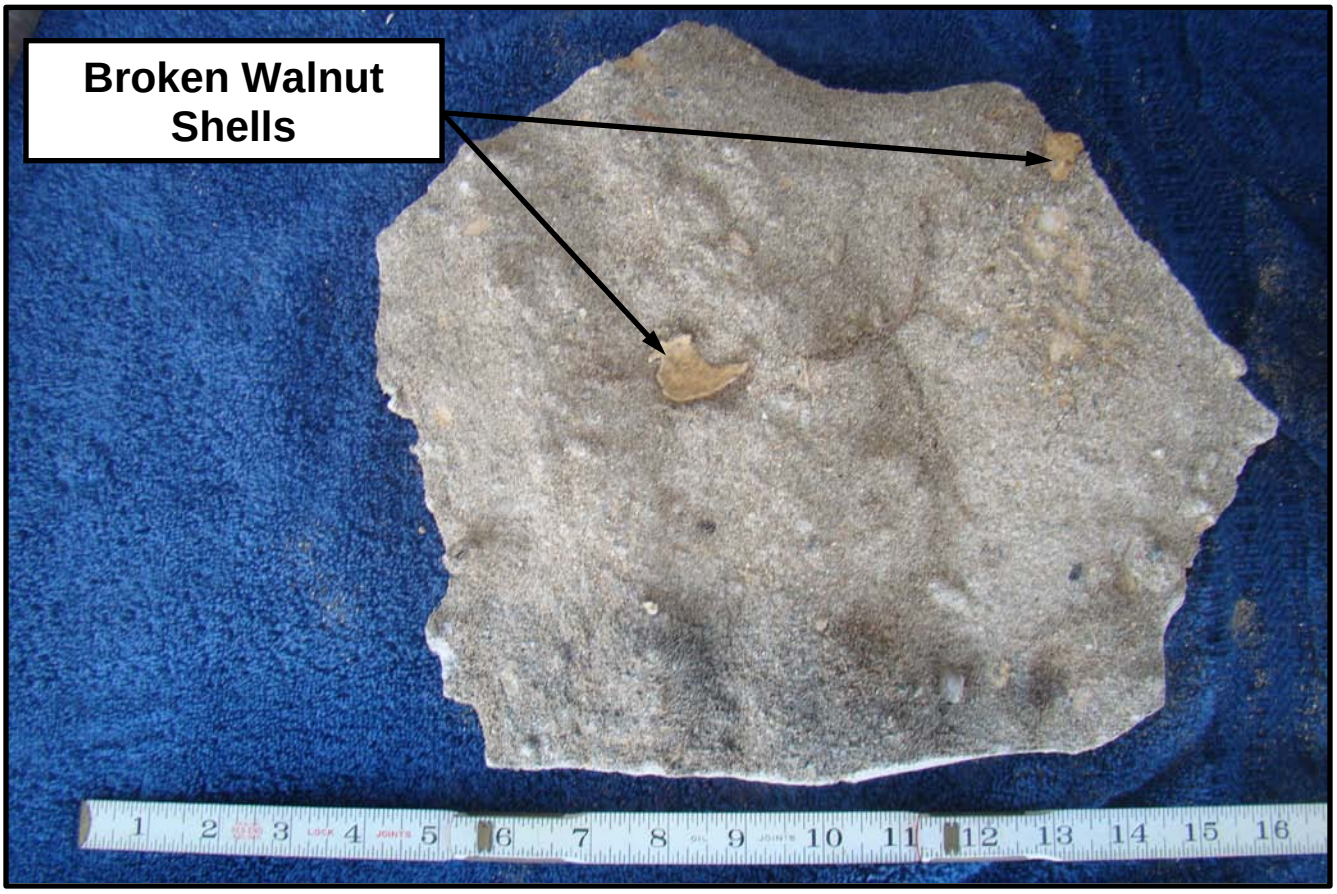


Figure 12: View (looking down) of piece of grouted animal burrow with broken walnut shells found in initial backhoe trench excavation at Site B (September 9, 2010)

SITE G CUTOFF WALL EXCAVATION

Site G Valley Oak Root Characterization

CLVRP researchers from the University of California, Davis, had previously made excavations around two valley oak trees located approximately 8 feet waterward of the waterside levee toe at Site G. These excavations were carried out as part of the CLVRP to characterize the root systems of these two trees. The excavations were generally done using a pneumatic excavation technique (air knife) in order to remove soil without disturbing the roots of the two valley oak trees (see Figure 13). During the course of these excavations, it was found that both of the oak trees had relatively deep vertical tap roots extending directly beneath the trunks and extensive horizontal root systems. However, neither valley oak tree had roots of any significant size (> 1 inch) penetrating very far into the levee (see Figure 14).

Figure 13: View of U C Davis researcher using an air knife to excavate roots around Valley Oak #2 at Site G (August 25, 2010)

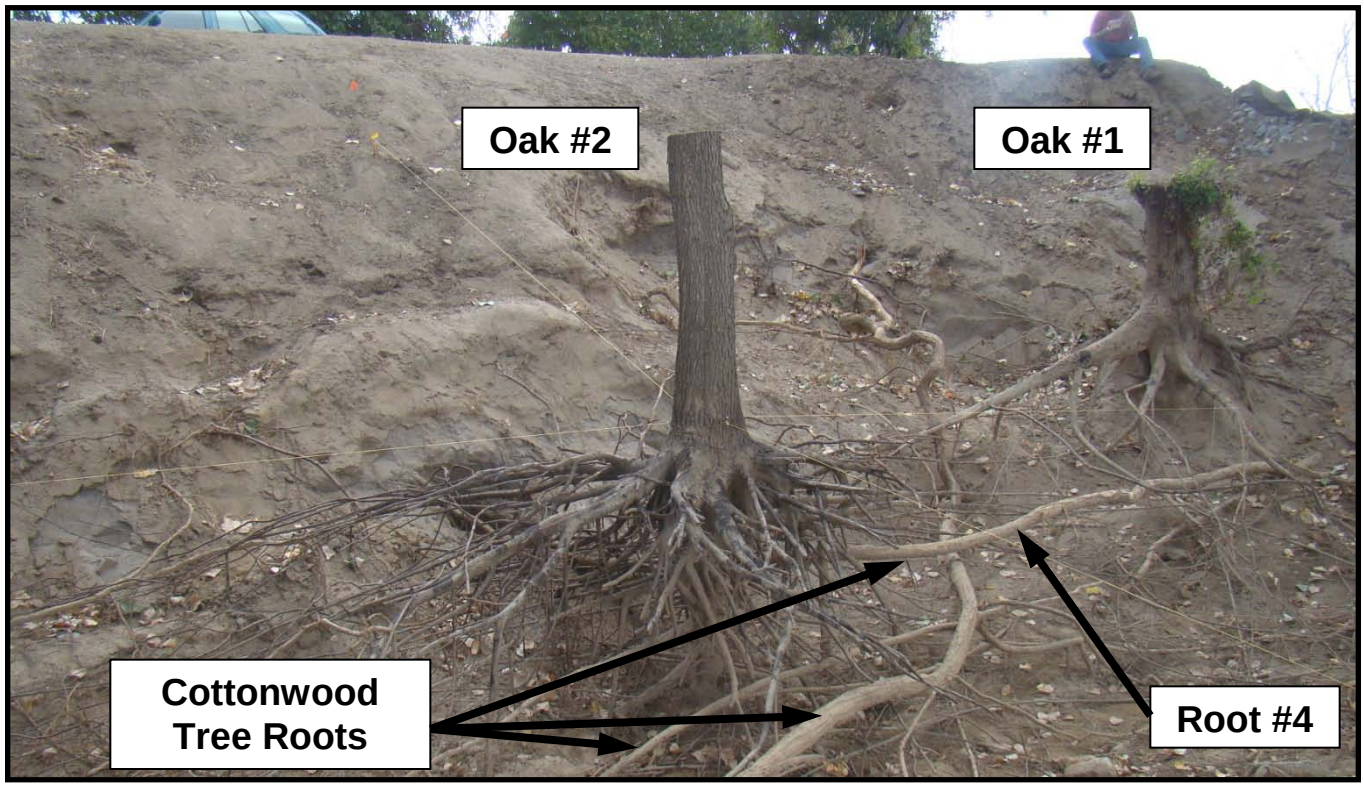


Figure 14: View of cottonwood roots running through valley oak roots and into waterside levee slope at Site G (September 27, 2010)

Purpose of Excavation at Site G

During the course of the tree root characterization for the two valley oak trees, several large roots from nearby cottonwood trees were also encountered traveling through the root systems of the oak trees and up into the levee slope (see Figures 14 and 15). These cottonwood roots were approximately 3 to 4 inches in diameter and appeared to be traveling at about a 3-foot depth near the waterside levee toe. It was decided to excavate and expose one of these cottonwood roots (Root #4) as it ran up and into the levee from the waterside toe. At the same time, the SCB cutoff wall would be excavated to determine if cottonwood roots had encountered and interacted with the wall. The presence of English walnut trees (grafted onto black walnut trunks) near the top of the landside levee slope also made this a very promising site to excavate.

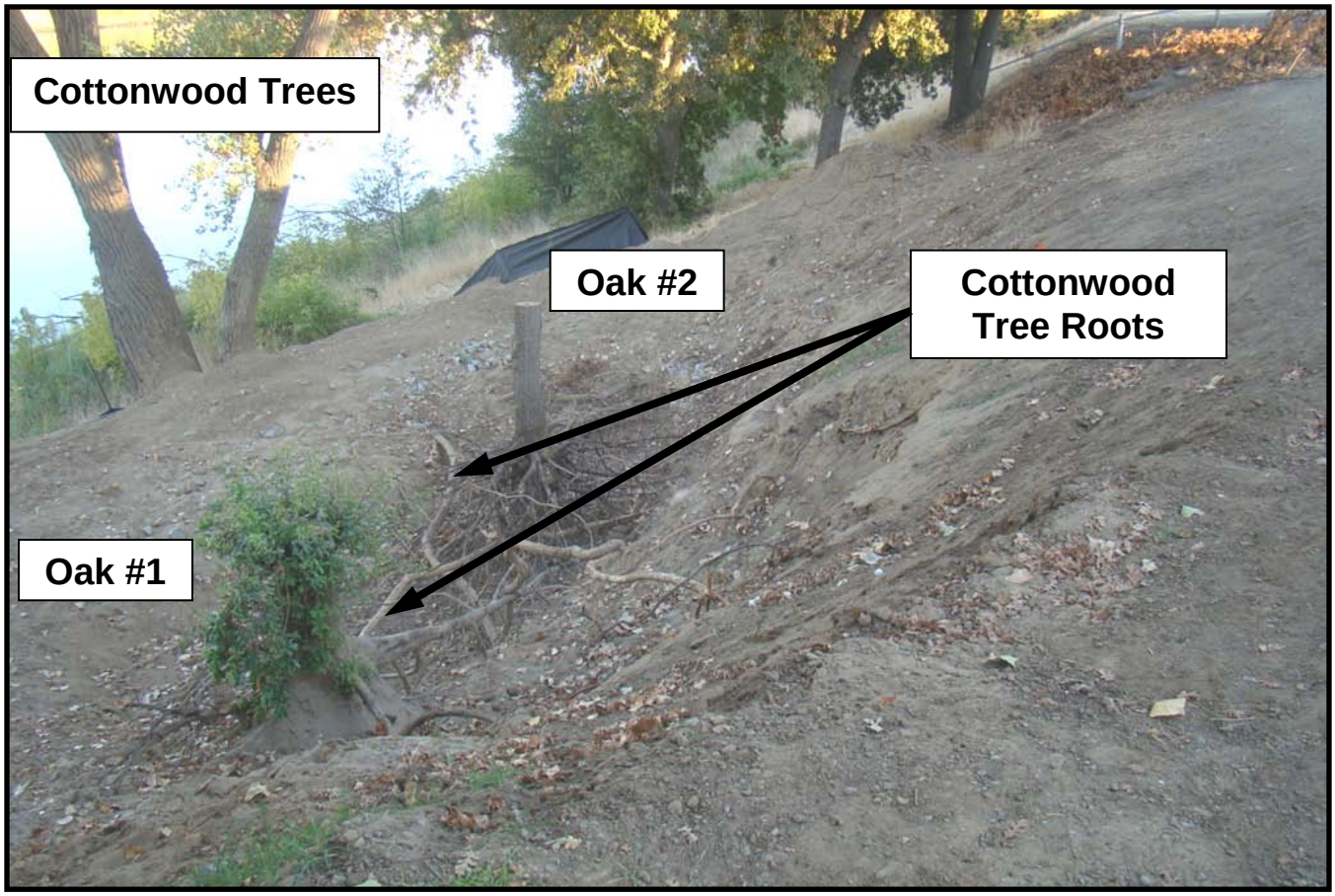


Figure 15: View of cottonwood roots running through valley oak roots and into waterside levee slope at Site G (September 27, 2010)

Excavation Process at Site G

The excavation of the cottonwood tree roots and of the SCB cutoff wall at Site G began on September 20, 2010 and was concluded on November 13, 2010. In general, there were two parallel sets of activities. Near the waterside levee toe, a 3-inch-diameter root from an unknown cottonwood tree (Root #4) was excavated and followed up and into the waterside levee slope. This root originated from a cluster of cottonwood trees on the riverbank south (downstream) of Site G (see Figure 16). Most of this excavation work was carried out by hand labor using shovels, together with the use of a vacuum truck to remove the excavated soil (see Figure 17). At the same time, the SCB wall along the levee crown was also being excavated. The initial phase of the SCB wall excavation was carried out using a backhoe. Later, hand labor using shovels and the vacuum truck were used to uncover both sides of the SCB wall (see Figure 18). The excavation of Root #4 eventually extended all the way to the SCB wall making it basically the stem of an inverted "T"-shaped excavation (see Figure 16). The maximum depths of the excavations were approximately 10 feet, although they were typically only about 5 to 6 feet deep along most of their lengths. Figure 19 presents an aerial Google Earth view of the initial excavation of the SCB wall.

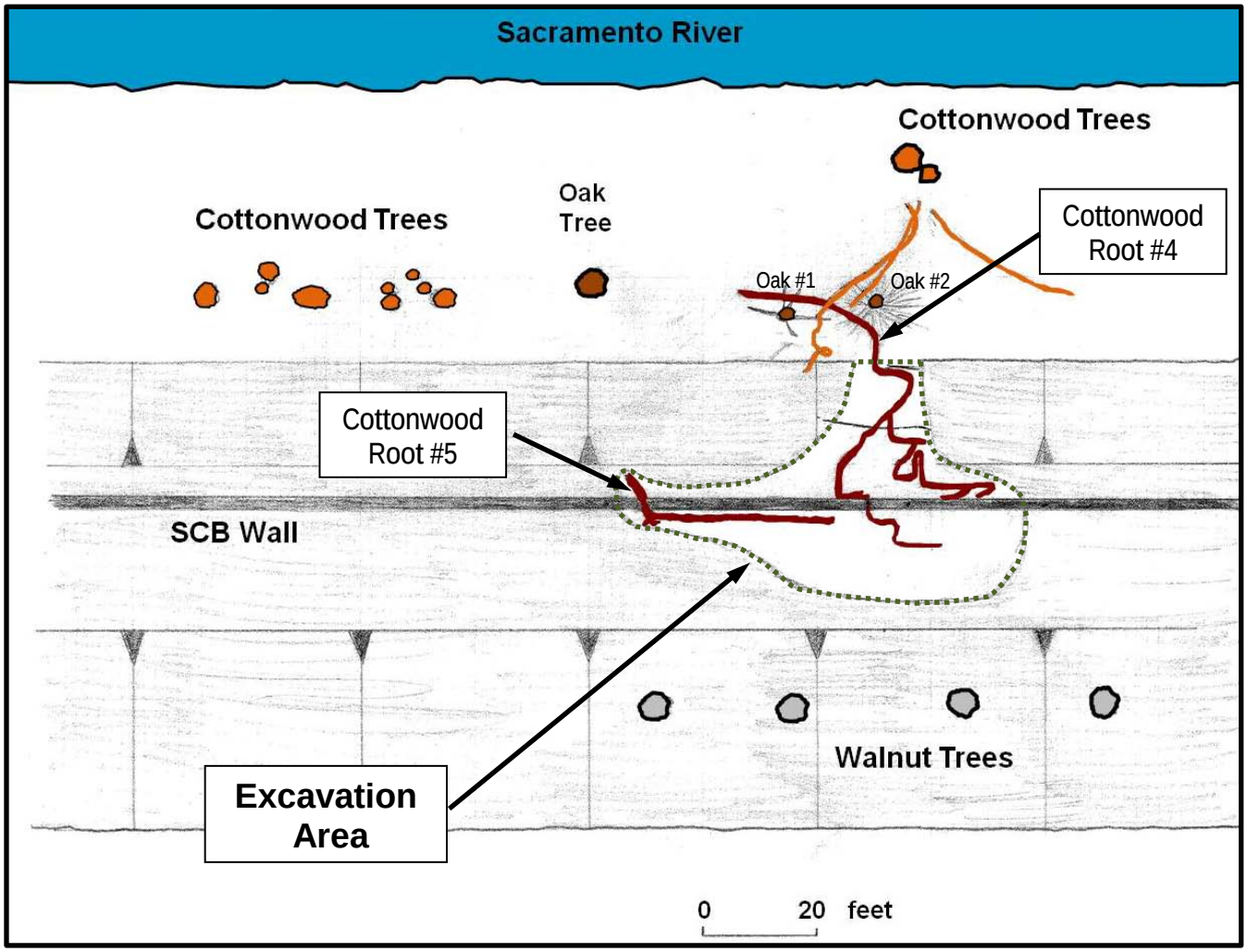


Figure 16: Sketch of Site G excavation area

Figure 17: View of Cottonwood Root #4 excavated near waterside levee toe at Site G (September 30, 2010)

Figure 18: View of SCB wall being excavated with shovels and vacuum truck at Site G (October 11, 2010)

Figure 19: Aerial view of initial excavation of SCB wall at Site G (from Google Earth, September 20, 2010)

The levee embankment soil that was excavated at Site G represented an interbedded series of lenses of brown silt (ML) and gray poorly graded sand (SP). Figure 20 presents a photograph of some of these lenses which typically ranged between 6 and 18 inches in thickness. A sample of one of the silt lenses was tested and found to have the following characteristics:

Fines Content = 97 percent
Liquid Limit = 44 percent
Plasticity Index = 17 percent

A sample of an adjoining sand lens was tested and found to have the following grain size characteristics:

D_{50} = 0.31 mm
Fines Content = 1.5 percent
Coefficient of Uniformity, C_u = 2.6

Digging with shovels and using the vacuum truck to remove the sandy material was relatively easy and efficient. However, it was much more difficult to excavate the silt lenses because the silt tended to clog the vacuum hoses, resulting in significant interruptions in the work to clear the hoses. After the excavation and documentation was complete, the excavations were backfilled during the week of November 15, 2010 with compacted soil by personnel of CDWR's Sacramento Maintenance Yard using the soil that had been excavated.

Figure 20: View of interbedded brown silt and gray sand lenses in levee at Site G (October 12, 2010)

Condition of SCB Slurry Cutoff Wall at Site G

The SCB Slurry Cutoff Wall at Site G was markedly different than the wall exposed at Site F the previous year. As at Site F, the compacted bentonite-soil trapezoidal cap at the top of the wall began about 13 inches below the levee crown. However, at Site G, the bentonite-soil cap extended much deeper down to approximately 42 inches below the top of the levee where it transitioned into the SCB wall material (see Figure 21). In addition, while the wall at Site F was approximately 18 inches wide, the wall at Site G was only about 13 inches in width. Attempts were made to obtain block samples of the SCB wall material at Site G but it was more friable than the wall material at Site F and intact samples could not be obtained. Material properties of the wall at Site F tested the previous year are presented in Table 1:

Table 1: Summary of 2009 Laboratory Tests of Recovered Levee Fill Soils at Site F

Block Sample	Depth Below Top of Levee (feet)	Moist Unit Weight (pcf)	Dry Unit Weight (pcf)	Water Content (%)	Porosity n (%)	Unconfined Compressive Strength (psi)
1	4.3 – 5.6	81.5	42.5	91.8	74	25.4
2	3.4 – 4.3	74.7	41.2	81.4	75	15.0

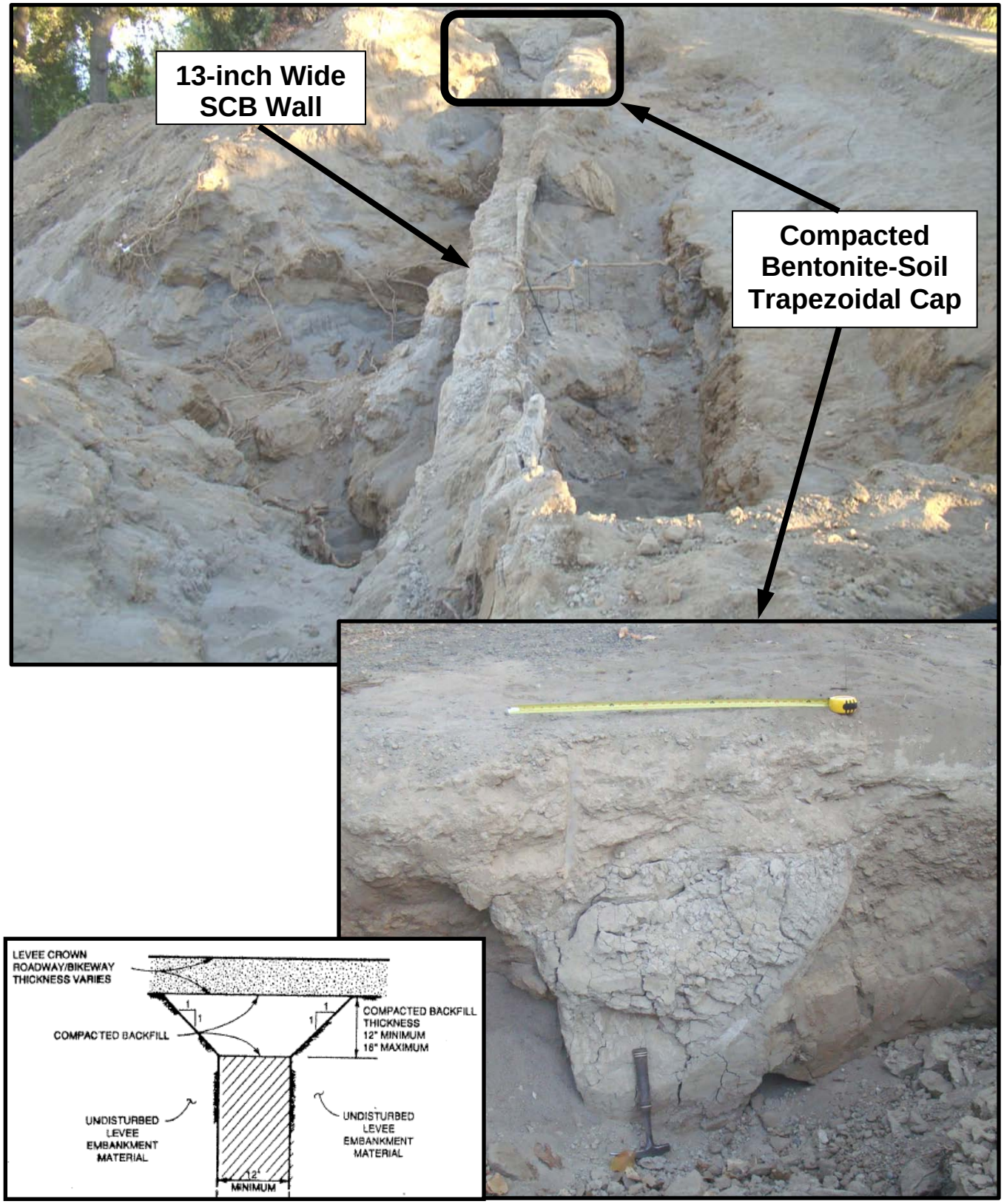


Figure 21: View looking upstream of compacted bentonite-soil trapezoidal cap at top of SCB wall exposed at Site G (October 7, 2010)

Cracks were also found in the SCB wall at Site G. However, as illustrated with orange spray paint in Figure 22, they were spaced irregularly. The spacing of the cracks at Site G was also generally larger (typically 3 to 5 feet) than the more uniform 10- to 20-inch spacing at Site F. Together with the inability to obtain intact specimens at Site G, this may suggest that the cement content of the SCB wall at Site G was lower than that at Site F.

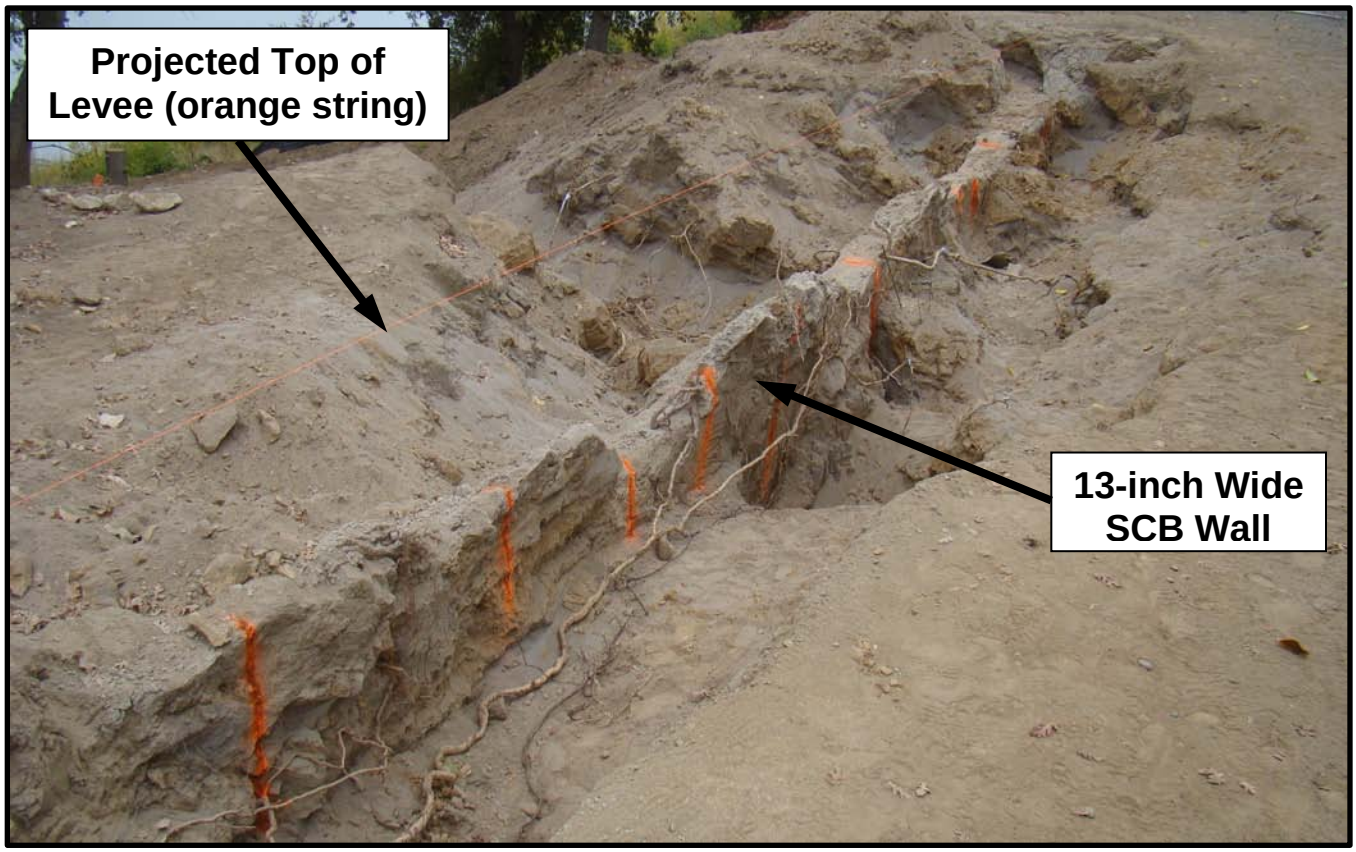


Figure 22: View looking upstream of cracks (painted orange) in SCB wall and overlying cap exposed at Site G (November 13, 2010)

ROOT OBSERVATIONS AT SITE G

General Observations

The following general observations were made of the tree roots exposed at Site G:

1. Cottonwood Root #4 travelling up from the waterside levee toe split into two smaller root branches, Root #4A ($1^3/_4$ inches in diameter) and Root #4B ($1^1/_4$ inches), a few feet upslope of the levee toe. Both of these root branches eventually reached the wall at a depth of approximately 9 to 10 feet where they appear to have been cut by the 1991 SCB wall trench excavation wall (see Figure 23). Both of these two root branches also developed new root extensions which traveled along the outside of the waterside edge of the wall, and then exploited small cracks in the wall or the cap at shallower depths to travel all of the way through the wall.

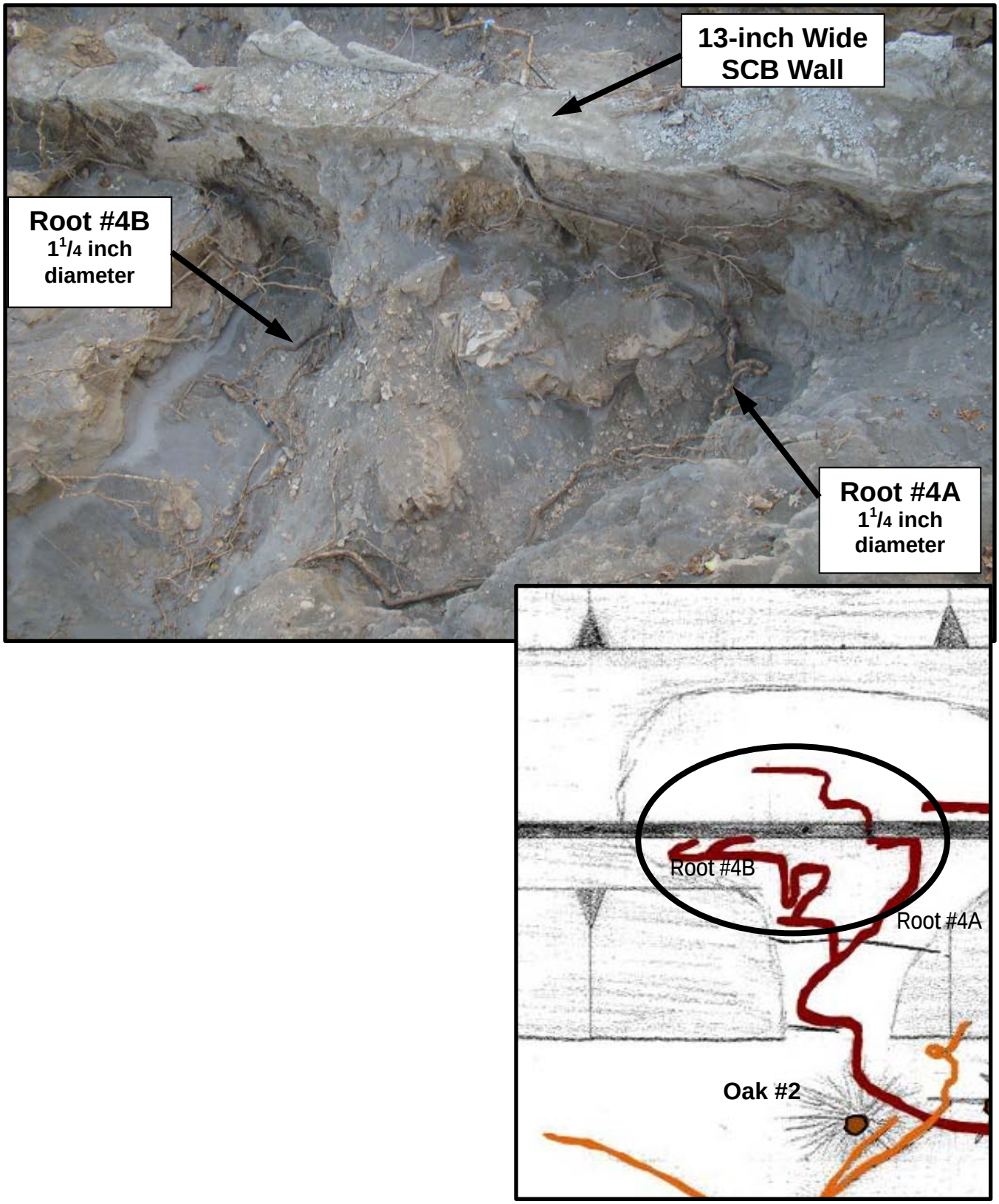


Figure 23: View of cottonwood roots #4A and #4B at waterside edge of SCB wall at Site G (November 13, 2010)

2. On the landside edge of the SCB wall, small cottonwood roots approximately $^{1}/_{2}$ inches in diameter were found which did not originate from Root #4. Instead, these came from a 4-inch diameter parent root, Root #5, located approximately 40 feet to the south of where Root #4A and Root #4B had encountered the SCB wall. Root #5 is believed to have originated from the same cluster of cottonwood trees located to the south of Site G.

3. We did not encounter any major roots near the SCB wall that extended from the walnut trees located near the top of the landside slope. However, small roots (~$^{1}/_{4}$ inch to $^{1}/_{2}$ inches in diameter) apparently originating from the walnut trees were found in the trench excavation.

4. A California ground squirrel burrow was found in the SCB wall extending as far down as 5½ feet below the crown of the levee

More details about the root observations are presented in the following sections.

Root #4A

Root #4A was approximately $1^{1}/_{4}$ inches in diameter where it encountered the waterside edge of the SCB wall at a depth of approximately 9 feet. As shown in Figure 24, the root appears to have been damaged at this location, perhaps cut by the 1991 excavation for the SCB wall. From this point, Root #4A then traveled vertically up along the outside of the wall for a distance of about 26 inches where it took a 90 degree turn to the horizontal (upstream). It then ran about 41 inches before again going vertical up the outside edge of the wall along a crack in the wall. It then penetrated through a crack in the trapezoidal bentonite-soil cap above the SCB wall at a depth of approximately 40 inches below the top of the levee (see Figure 25).

A small root branch from Root #4A approximately $^{3}/_{8}$ of an inch in diameter extended to and down the same crack in the SCB wall along the waterside edge of the wall before it penetrated through the wall at a depth of about 7 feet below the top of the levee. The diameter of the root branch that penetrated through the crack was approximately $^{1}/_{8}$ of an inch in diameter (see Figure 26).

Root #4B

Root #4B was approximately $1^{1}/_{4}$ inches in diameter where a damaged, twisted end was found about 1 foot away from the waterside edge of the SCB wall at a depth of approximately 10 feet below the top of the levee. As shown in Figure 27, this root also appeared to have been torn by the 1991 excavation for the SCB wall and this torn, damaged root also appeared to have generated a new root extension. This new extension of Root #4B took a series of turns along and away from the wall and even traveled away from the wall as much as 4 feet before it reversed direction back to the wall where it traveled upstream along the wall for a distance of about 7 feet. At this location, Root #4B divided into several branches which traveled along the waterside edge of the wall. One branch from Root #4B approximately $^{3}/_{8}$ of an inch in diameter penetrated through a crack in the wall at a depth of approximately 5 feet below the top of the levee. Two other branches from Root #4B approximately $^{1}/_{2}$ of an inch in diameter penetrated through the trapezoidal bentonite-soil cap above the SCB wall at a depth of approximately 4 feet below the top of the levee (see Figure 28).

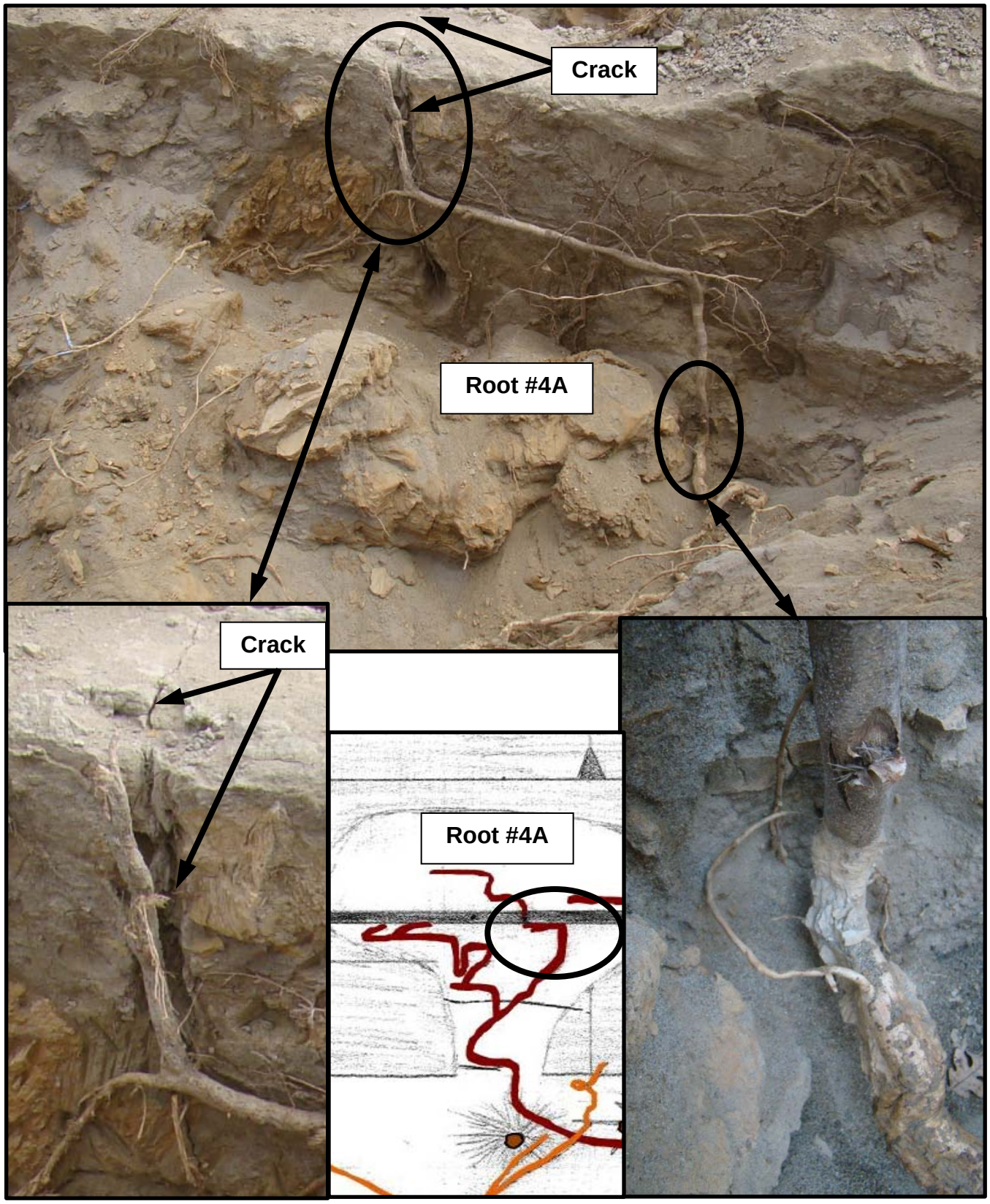


Figure 24: Views of Root #4A along waterside edge of SCB wall at Site G (October/November 2010)

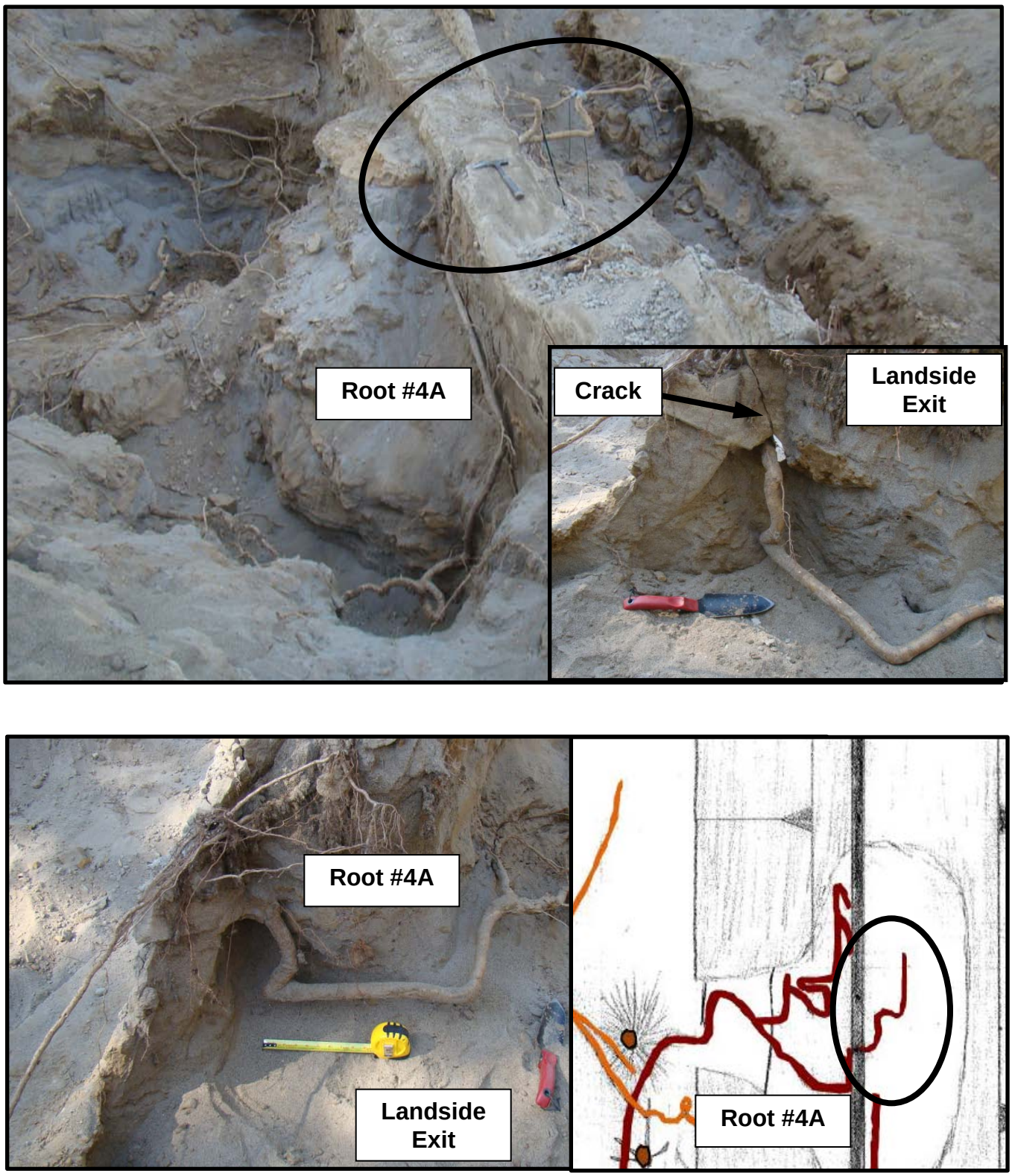


Figure 25: Views of Root #4A travelling up waterside edge of SCB wall and penetrating through crack in bentonite-soil cap to landside at Site G (October/November 2010)

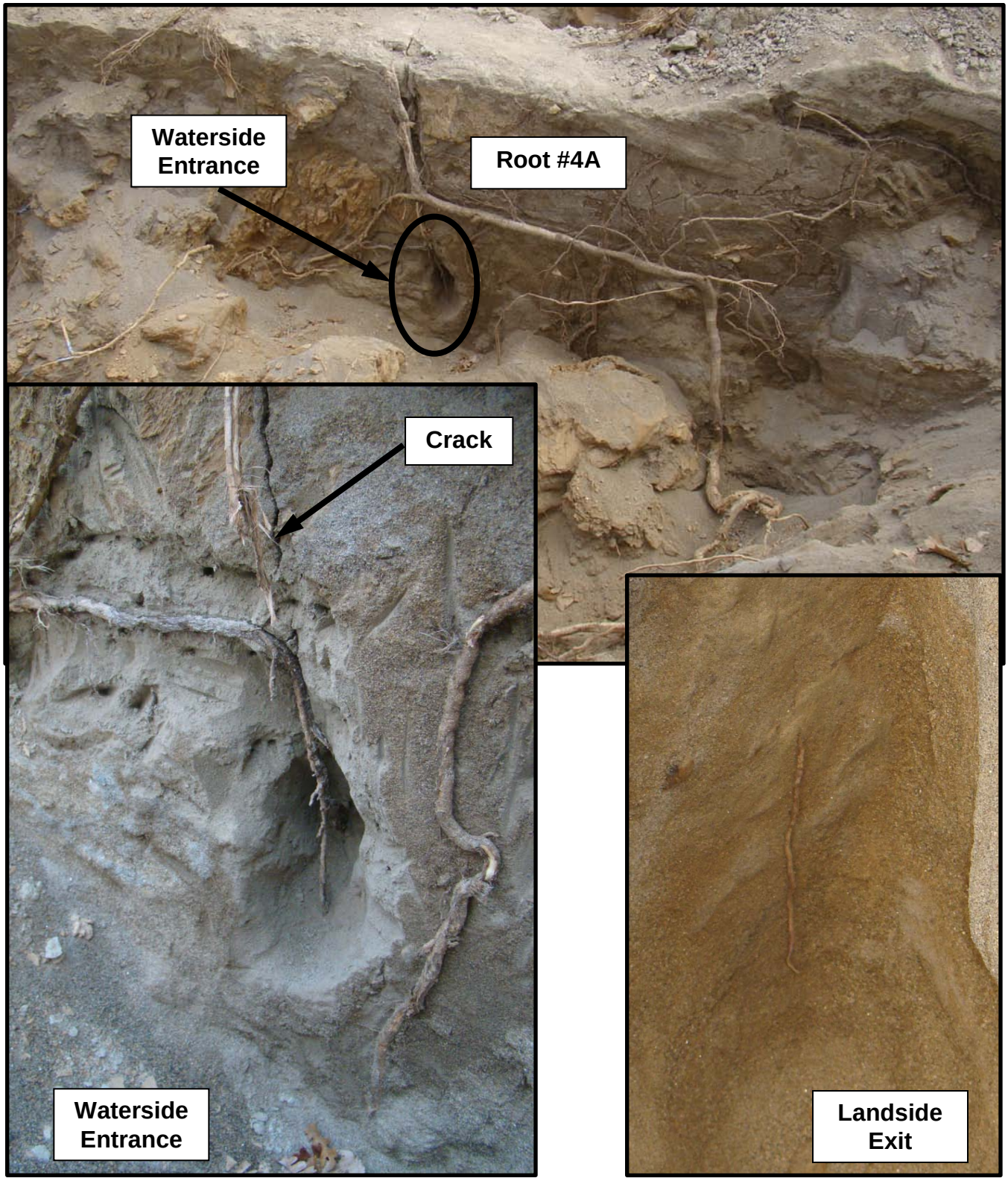


Figure 26: Views of small (~$^{1}/_{8}$ inch diameter) root extension from Root #4A penetrating through SCB Wall along small crack at Site G (October/November 2010)

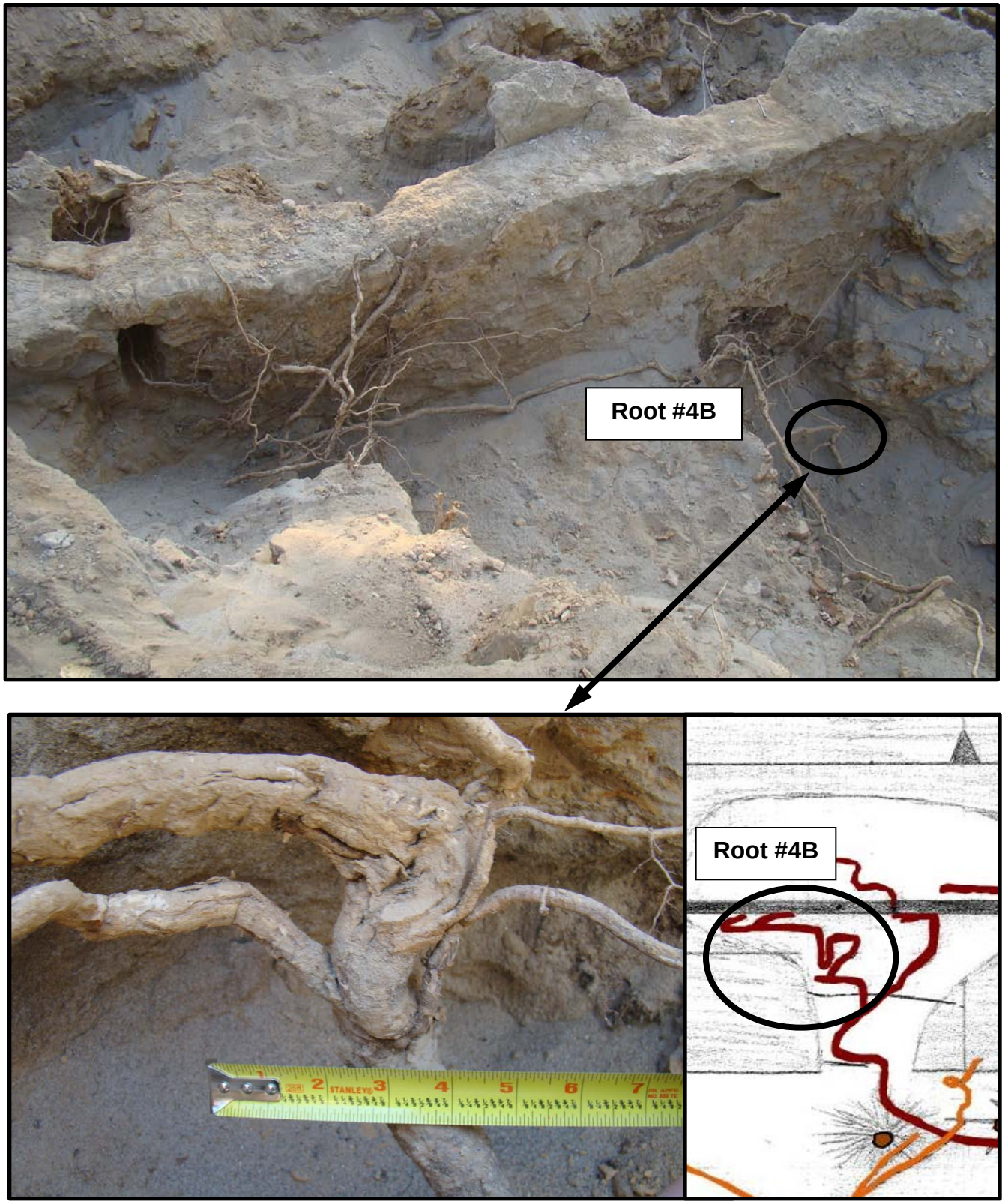


Figure 27: Views of Root #4B along waterside edge of SCB wall at Site G (October/November 2010)

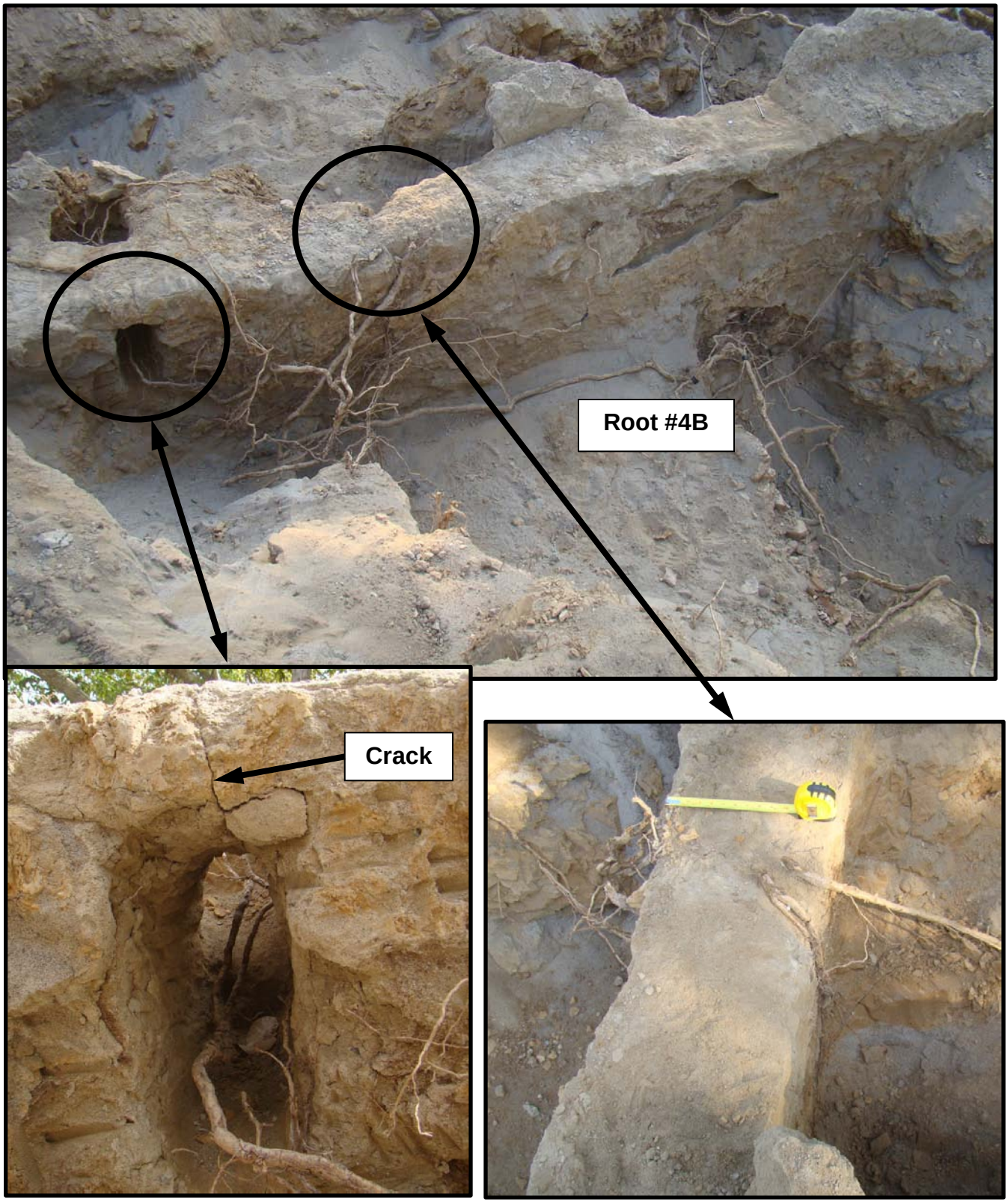


Figure 28: Views of Root #4B branches penetrating through crack in SCB wall and through trapezoidal bentonite-soil cap above SCB wall at Site G (October/November 2010)

Cottonwood Roots #4A and #4B were found to have traveled relatively deep below the waterside levee slope, ranging from about 3 feet deep below the ground surface at the waterside toe to as much as 10 feet below the top of the levee at the SCB wall. Figure 29 illustrates the paths of these two root branches.

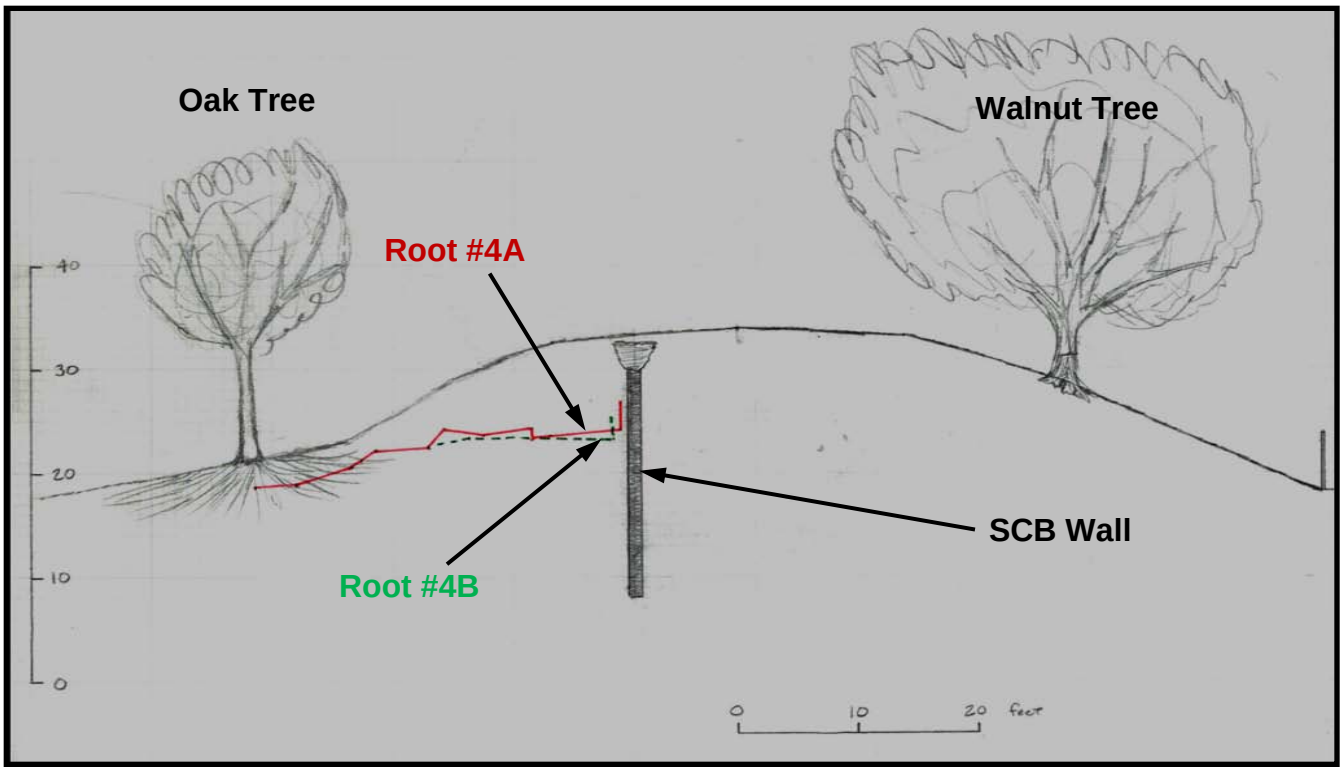


Figure 29: Cross section sketch illustrating travel paths of Cottonwood Roots #4A and #4B traveling up waterside slope of levee at Site G

Root #5

The approximate $^{1}/_{2}$–inch diameter tips of two cottonwood roots, Roots #5A and #5B, were found traveling along the landside edge of the SCB wall a few feet south (downstream) of the location where Root #4A had penetrated through the trapezoidal bentonite-soil cap above the SCB wall (see Figure 30). However, it was clear that these two cottonwood roots did not come from Root #4. Instead, they were coming from another cottonwood root that had penetrated the SCB wall further to the south. Root #5A was excavated to a depth of 10 feet below the top of the levee when it became too deep to excavate any further along the wall. Root #5B was then excavated and found to have traveled a significant distance along the wall at a depth of about 4 to 5 feet before its source was discovered. Approximately 40 feet downstream from where Root #5B was first encountered, a large cottonwood parent root was found to have penetrated through the wall from the waterside at a depth of approximately 5 feet (see Figures 31 through 33). It appeared that this 4-inch diameter root had been cut during the 1991 construction of the SCB wall and had regenerated new root extensions which either grew in a crack in the wall, or induced the crack. Features suggesting that this particular root may have induced the crack in the SCB wall at this location include the fact that the crack was found right

where the parent root encountered the wall, the fact that the crack was wider at depth at the location of the parent root and narrower at the top of the wall, and the extensive vertical growth of the newer root extensions coming from the 4-inch parent root within the wall itself.

Landward of the wall, Root #5 divided into several different branches. In addition to branch Root #5B which had been traced along the wall, a 2-inch diameter root extension also was found to extend upstream. There was not enough time to follow this 2-inch root, but it is believed that it connects up with the Root #5A extension shown in Figure 30.

Small Walnut Tree Roots

Small walnut tree roots approximately $^{1}/_{4}$ inch to $^{1}/_{2}$ inches in diameter were found in the trench excavation on the landward side of the SCB wall. In general, the roots were either black or light gray. The locations of some of these small roots are shown in Figure 31. Typical depths for these walnut roots were between 3 and 4 feet below the top of the levee, about the same elevation as the walnut trees located near the top of the landside levee slope.

Perhaps the most interesting observation regarding these small walnut roots involved a pair of roots traveling almost in a straight line waterward towards the landside edge of the SCB wall (see Figure 34). These two roots, one black and one light gray, were so straight and parallel that they resembled electrical cables within a conduit. It is theorized that they may have been traveling in an abandoned squirrel burrow approximately 3 feet below the top of the levee.

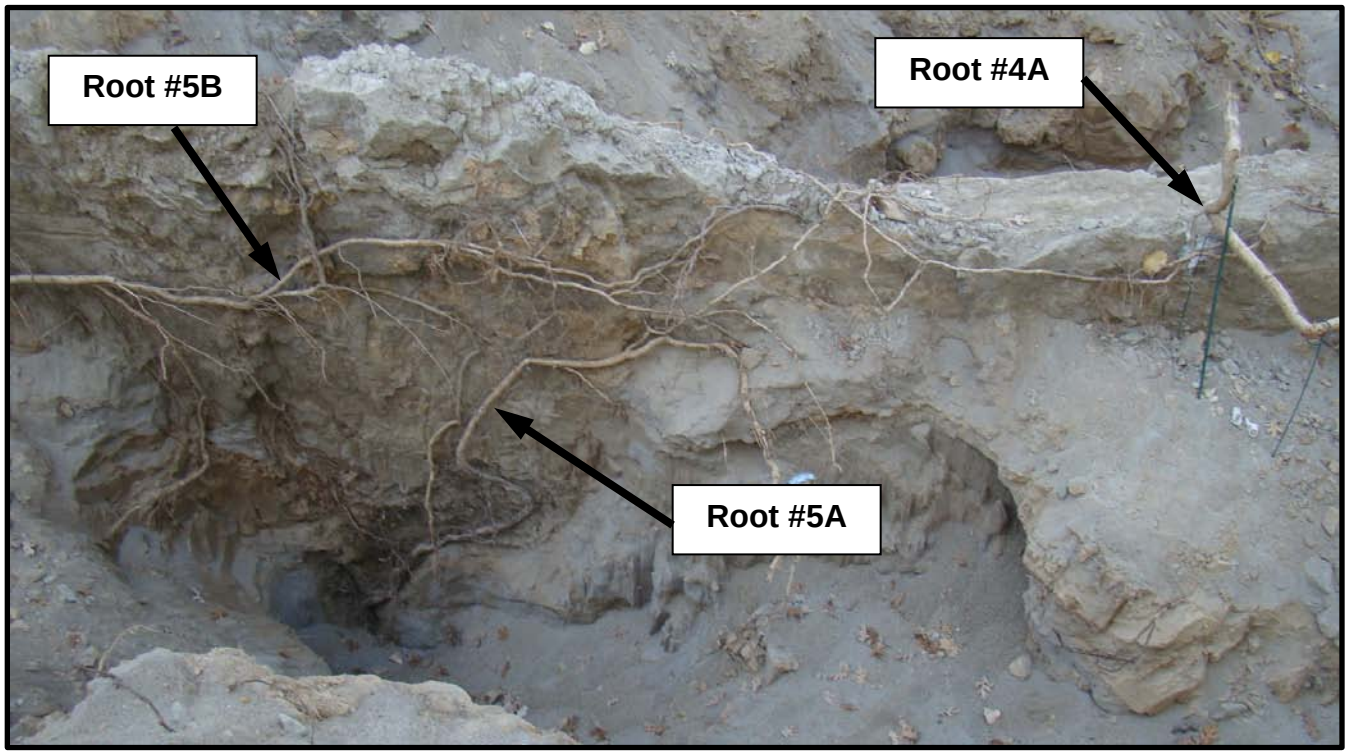
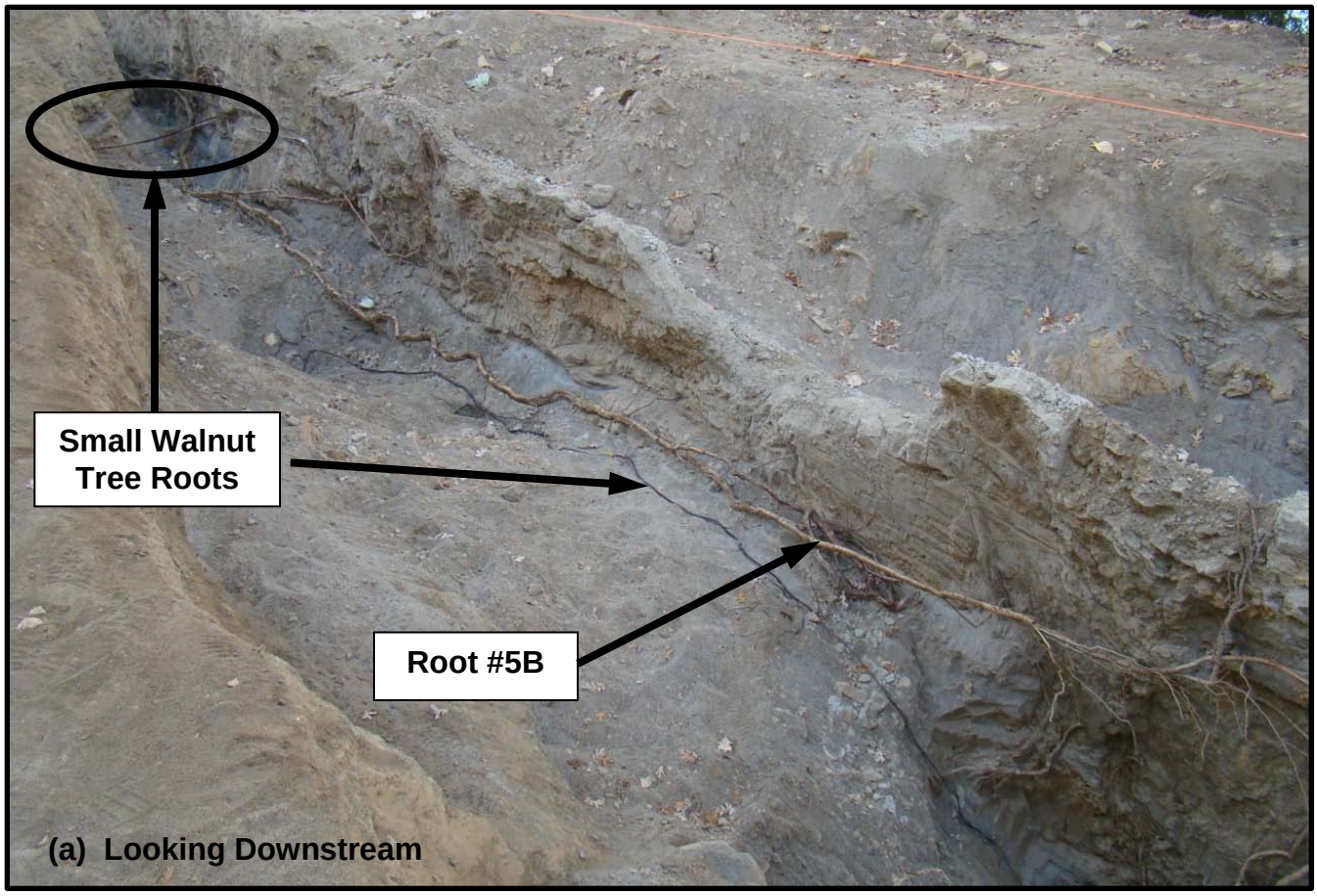


Figure 30: Views of Roots #5A and #5B along landside edge of SCB wall at Site G (October 18, 2010)



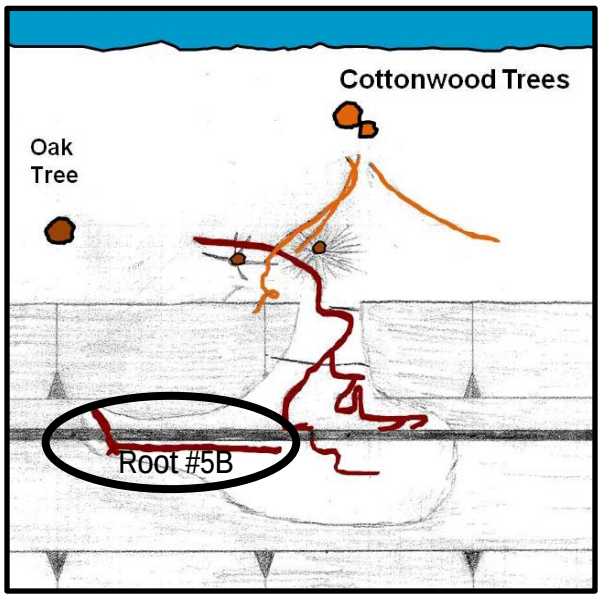


Figure 31: Views of Root #5B extending along landside edge of SCB wall at Site G looking (a) Downstream and (b) Upstream (October 18, 2010)

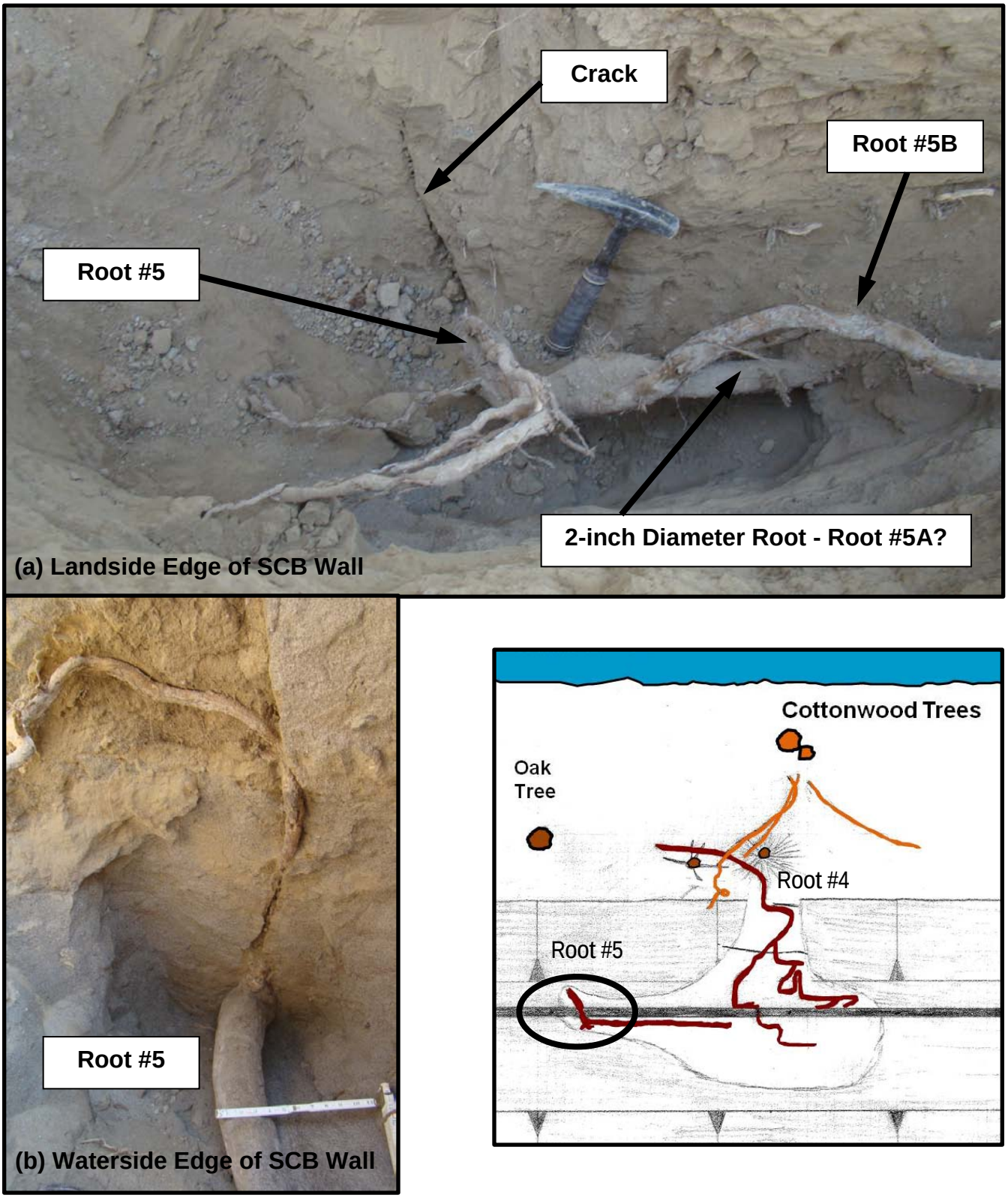


Figure 32: (a) View of Root #5 penetrating through crack in SCB wall and exiting landward and (b) View looking at 4-inch Root #5 at waterside edge of SCB wall (October 20, 2010)

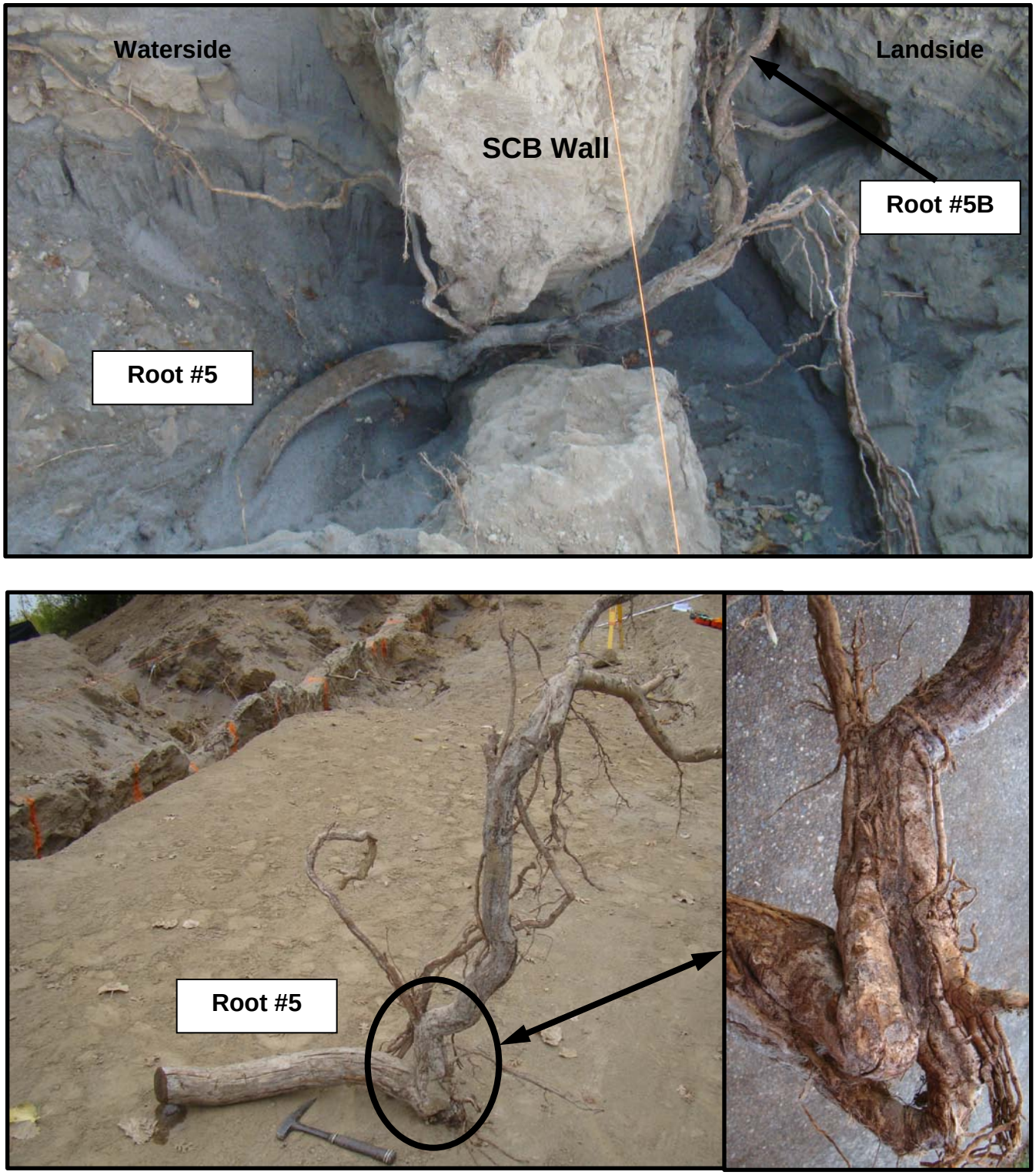


Figure 33: Views of Root #5 extensions that had regenerated within crack in SCB wall at Site G (November 2010)

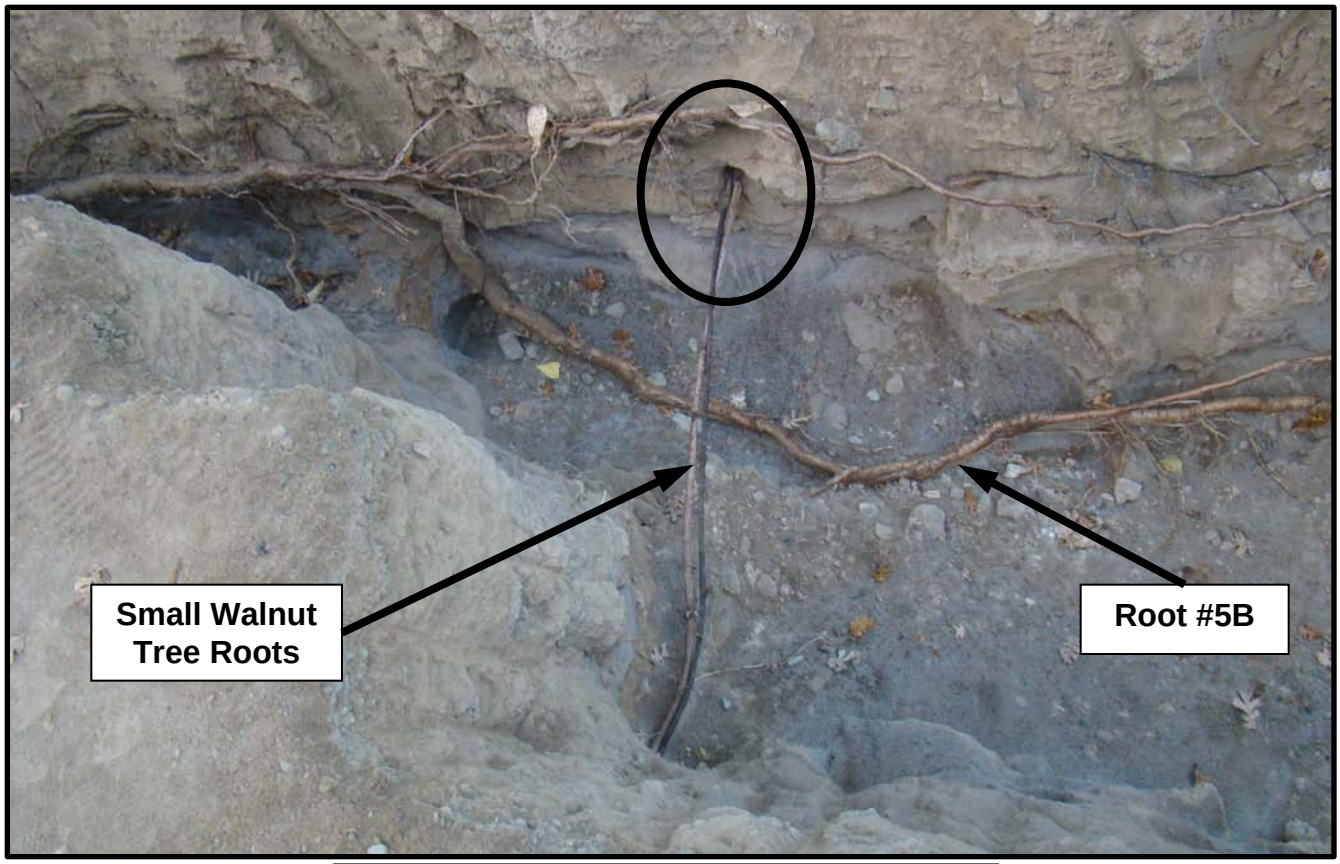


Figure 34: Views of a pair of small walnut tree roots traveling in a presumed abandoned squirrel burrow landward of the SCB wall at Site G (November 2010)

Cottonwood Tree Root Travel

Previous CLVRP investigations have shown that tree roots from cottonwood trees can travel relatively long distances. Cottonwood Roots #4 and #5 originated from a cluster of large cottonwood trees located south (downstream) of the Site G investigations. It was not feasible to identify which of the cottonwood trees was the source of either root. However, if we take the cottonwood trees from this cluster that are located closest to Site G, the root travel distances would range up to 100 feet or more. The cottonwood trees located immediately waterward of the Site G investigations are located 60 feet from the SCB wall (see Figure 35).

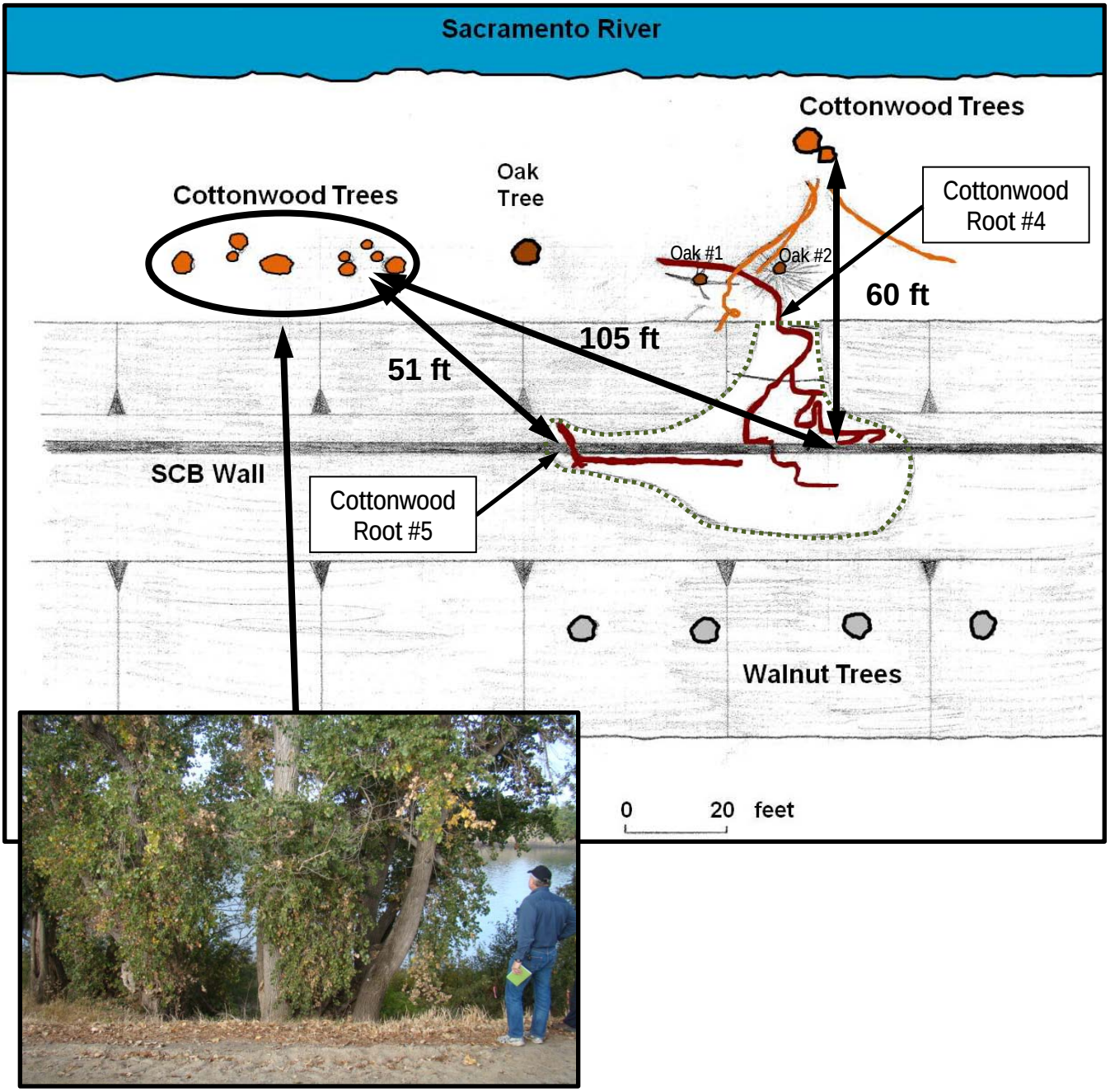


Figure 35: Estimated root travel distances of Cottonwood Tree Roots #4 and #5

Ground Squirrel Burrow Hole in SCB Wall

During the course of excavating the waterside edge of the SCB wall near Root #4B, a ground squirrel burrow hole was discovered within the wall near its waterside edge. After cleaning out the burrow hole of loose debris, it was found that the ground squirrel had tunneled down into the wall from above, and had zigzagged about 3 feet into the SCB wall material (see Figures 36 and 37). The maximum depth of this burrow within the SCB wall was approximately 5½ feet below the top of the levee.

Figure 36: Ground squirrel burrow discovered in SCB wall near Root #4B at Site G (October 2010)

Figure 37: Views of ground squirrel burrow discovered in SCB wall at Site G (October 2010)

The fact that the ground squirrel tunneled into the SCB wall and stayed within the wall despite it being only 13 inches wide suggests that the squirrel may have actually preferred digging in the wall material rather than in the levee sands and silts. It is not known why the SCB wall material may have been a preferred burrowing medium other than the burrow, once created in this stronger material, would probably have more of a tendency to stay open rather than collapse over time.

Summary of Findings and Conclusions

The September through November 2010 trench investigations at Sites B and G revealed significant new information regarding the travel of tree roots and their interactions with a 19-year-old SCB cutoff wall. These findings extend those developed from the excavation at Site F opposite a large black walnut tree the previous year. In addition, the excavations at Sites B and G documented valuable new information regarding the burrowing characteristics of the California ground squirrel in levee materials. The findings and conclusions from this investigation include the following:

1. The tree roots from valley oak trees at Sites B and G did not appear to extend very far or to penetrate deep into the levee.

2. The tree roots from the black walnut tree at Site F (excavated in 2009) were found to have extended 35 feet to SCB wall, and to reach depths of approximately 5 to 6 feet.

3. The tree roots from cottonwood trees were particularly aggressive with large roots found to reach 50 to 100 feet away from the trees at both Sites F and G, with depths reaching as much as 10 feet below the levee crown at Site G.

4. Construction of the 1991 SCB cutoff wall cut or broke several roots that had grown from the black walnut tree at Site F and from cottonwood trees at Site G. These cut roots ranged from $^{1}/_{4}$ of an inch to 4 inches in diameter. The cut ends of the roots at the SCB cutoff wall intersection were, of course, damaged extensively and sometimes were partially dead and rotted. However, they commonly developed new live branch roots at, or near, the cut ends.

5. New root growth appeared to be attracted to the wall, presumably because of available moisture. Laboratory tests from samples obtained at Site F in 2009 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 the outside and within the outer 1 to 6 inches of the wall. In general, this lateral root growth did not penetrate deeply into the wall.

6. The SCB wall was also found to have several near vertical cracks. At Site F, 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. The cracking in the wall at Site G was more irregular and had a larger spacing. This larger spacing and the friability of the SCB wall material at Site G (which prevented rigorous sampling of the SCB wall material) suggests that the cement content of the wall at Site G was less than at Site F.

7. Where roots encountered the near vertical cracks in the SCB walls at both Sites F and G, 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 was true at both Sites F and G. Except in one case, it appeared that the cracks existed prior to the roots penetrating into them. This seems to be the case because several roots were found to have traveled along the cracks on the outside of the SCB wall before entering them. However, the pattern of the SCB wall crack into which large new root branches grew from the 4-inch diameter cut end of Root #5 at Site G suggests that this particular crack may have been created by the growth of the new root extensions from this cottonwood root.

8. Cottonwood Roots #4A and #4B were found to have traveled relatively deeply below the waterside levee slope, ranging from about 3 feet deep below the ground surface at the waterside toe to as much as 10 feet below the top of the levee at the SCB wall. This is significantly deeper than the depths that have been documented elsewhere for other trees and may be indicative that root travel paths, depths, and extents are very much dependent on tree species, soil conditions, and/or climate.

9. Even though Cottonwood Roots #4A and #4B encountered the waterside edge of the SCB wall at a depth of about 10 feet at Site G, they did not penetrate the SCB wall at this depth. Root extensions from both of these damaged roots then traveled significant distances both vertically and horizontally along the outside edge of the wall before they eventually penetrated the wall through cracks at shallower depths. The maximum depth where a root has penetrated the SCB wall was at a depth of 7 feet. The root diameter at this depth was approximately $^{1}/_{8}$ inch. It may be that the propagation of cracks in the wall, which allows for root penetration, may not extend significantly beyond this depth.

10. While this study was principally intended to investigate the rooting patterns of different tree species and the interactions of roots with a SCB cutoff wall, burrows from the California ground squirrel were found at both Sites B and G. The depths of the burrows were 4 feet below the levee crown at Site B and up to 5½ feet below the levee crown at Site G. Both burrows were about 15 to 20 feet horizontally from the surface of a levee slope. At Site G, the burrow was actually within the SCB wall material itself, with indications that the SCB wall material might have been a preferred burrowing medium. The presence of these animal burrows so deep within the levee reinforces the serious threats that burrowing animals present for the integrity of levee systems.

Final Conclusion

While this study provides important new information regarding the interactions of roots and SCB cutoff walls, it is premature to draw final conclusions regarding the efficacy of SCB cutoff walls to act as barriers to tree roots within levees. This particular SCB wall appeared to both attract root growth for moisture and to partially retard root growth laterally through the levee. The old, relatively thin SCB wall in Sacramento's Pocket Area appears to provide only a partial, imperfect barrier to roots. Further studies involving different tree and levee conditions are needed, together with investigations that examine whether cracking occurs in more modern cutoff walls that have larger widths and higher strengths.

Acknowledgements

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The excavations were principally carried out by crews provided by URS, Inc. and the University of California, Davis. These crews were supported by Maintenance Crew II of the CDWR Sacramento Maintenance Yard, which also backfilled the trenches after the excavations were completed. The hard work of John Williams, Gregg Ahlers, James Hughey and Iris Flores are very much appreciated. Laboratory soils testing of the levee fill, and of the SCB wall material at Site F in 2009, was completed by Kleinfelder, Inc.

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[6] CLVRP sponsoring agencies include CDWR, SAFCA, California Department of Fish & Game, U. S. Fish & Wildlife Service, California Central Valley Flood Protection Board, National Marine Fisheries Service, and the California Central Valley Flood Control Association.

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