

## 6. DISCUSSION OF MITIGATION OPTIONS

### 6.1 General

Based on the proposed decommissioning of Reservoir 4, the landslide above Reservoirs 3 and 4 can be viewed in two pieces; the portion of the landslide above Reservoir 3 where mitigation measures must accommodate new reservoir construction, and the portion of the landslide above Reservoir 4. It is not necessary to implement the same mitigation measure across the entire width of the landslide; however, it is necessary to stabilize the entire landslide width to a similar factor of safety (FS). Treating only half of the width would allow the untreated portion to continue moving, which would tend to drag the stabilized mass downhill and could overstress the mitigation measures.

Brief descriptions of the mitigation options evaluated in this study were presented in Section 5. The following sections provide more detailed discussions of the costs, advantages, and disadvantages of each mitigation option. Comparative construction cost estimates were prepared for each mitigation option. The quantities of significant geotechnical work items and unit costs are based on the mitigation geometries shown in Figures 6 to 12 and on our experience with costs for similar work. The cost estimates include work related to mitigating the landslide and geotechnical aspects of reservoir construction such as excavation shoring and foundations. Costs associated with construction of the reservoir, piping and appurtenant structures, final design, preparation of plans and specifications, and services during construction are not included.

Several of the mitigation options could negatively impact the existing drainage tunnels at the site. Results of stability analyses show that the drainage tunnels are important to maintaining and/or improving the stability of the landslide. The locations and elevations of the drainage tunnels are not well documented. Appendix B contains a plan view of the site with locations of drainage tunnels. The plan was produced by Landslide Technology in 1986. The original drawings used to develop the map could not be located during a recent search of the PWB archives. The accuracy of the tunnel locations shown on the map is not readily apparent.

### 6.2 Reservoir 3 Option 1 – Accommodate Slide Movements

Option 1 involves constructing the new reservoir east of the existing landslide toe and placing a compressible inclusion between the landslide mass and replacement reservoir. Fill material placed on the west side of the new reservoir would slightly increase stability of the landslide.

*Shoring.* Since Option 1 involves excavating into the eastern slope of the existing reservoir, excavation shoring required for the new reservoir footprint will be extensive. Temporary shoring walls would be needed on three sides of the new reservoir. We anticipate that soldier pile and tieback shoring walls would be implemented to hold vertical cuts for reservoir construction. It appears that the ground on the west side of the structure would not require shoring; however, care should be taken not to undermine the landslide toe. Undermining the landslide toe will lower the FS and increase rate of landslide movement.

*Foundations.* As discussed in Section 8.2, shallow foundations are not feasible for the new reservoir due to settlement concerns related to backfilling the existing open reservoir west of the

proposed buried reservoir. We anticipate that micropiles would be used to support the new reservoir since conventional pile driving equipment would be difficult to operate in the constricted work area. Piles would need to compensate for downdrag loading due to settlement of the Reworked Portland Hills Silt/Alluvium deposit. This soil was reworked by Tanner Creek and deposited in its current location. Slab-on-grade and/or shallow foundations are expected to be adequate for the reflecting pool. A flexible joint would be required in the reflecting pool because the landslide would continue to move after construction.

*Settlement.* Provided deep foundations are used to support the new reservoir, settlements are expected to range from ½ to 1 inch. About half of the settlement would be due to elastic compression of the piles, and would therefore be uniform between columns. The remaining half of the settlement would be due to bond development of the micropiles and would vary depending on ground conditions in the bond zone, the amount of overbreak experienced during drilling, and the method of grouting. Settlement induced by backfilling between the new structure and the existing reservoir slope could induce settlements of 6 to 12 inches in the Reworked Portland Hills Silt/Alluvium deposit. Settlement of this magnitude would cause downdrag on pile foundations if they are installed before fill is placed. Downdrag would reduce the allowable load on piles (see Section 8.2).

*Subdrainage.* A subdrain system would be necessary to maintain groundwater at or below the base of the new reservoir. This would prevent buoyant uplift on the structure when it is empty. The subdrain system could be designed to fit around the proposed reservoir and piping. For planning purposes, we anticipate that the subdrain would consist of at least 2 feet of free-draining granular material wrapped in nonwoven geotextile extending across the base of the developed site and up the west wall of the existing reservoir. The subdrain should include perforated pipe to collect and drain water to a low point where it can be collected and discharged to the storm sewer. A section view of the proposed subdrain for Reservoir 3 is shown in Figure 13. The slope of the subdrainage layer will have to be constructed steeper than planned final slope to account for settlement that will occur due to backfilling between the proposed reservoir and the reservoir slope.

*Fill.* Fill material used to backfill around the proposed reservoir should be placed as structural fill. The compacted fill should be designed to prevent hydrostatic loading on the structure and minimize settlement. Due to the large volume of fill required, free-draining zones could be defined once reservoir design is further developed such that these objectives are achieved at the minimum cost possible. For planning purposes, we anticipate that a 1-foot-thick layer of free-draining, granular backfill would be placed adjacent to the compressible inclusion. Free draining backfill should be hydraulically connected to the subdrainage system and should be separated from structural fill with a non-woven geotextile as shown in Figure 13.

*Impacts to Tunnels.* Option 1 would have little or no impact on the existing drainage tunnels. Historic plans indicate that the drainage tunnels outlet along the west slope and northern end of Reservoir 3. One option would be to leave the existing reservoir liner in place and let the tunnel

outlets continue to function as they have for the past century. Another option would be to remove the concrete liner to expose the tunnel outlets and hydraulically connect them to the proposed subdrain system. One difficulty with this option is that the historic maps are approximate and the actual locations of the tunnel outlets are not known.

*Seismic Performance.* The compressible inclusion against the new reservoir would act as a plastic element during seismic shaking. As the landslide moves downslope, the EPS would crush when the landslide exerts load higher than its crush strength. Any deformation of the EPS would be unrecoverable. Test data shows that once EPS is loaded to its crush strength, it continues to deform without strain-hardening up to strains on the order of 90 to 95 percent.

*Comparative Cost Estimate for Reservoir 3 Option 1.*

Work Item	Quantity	Unit Price	Cost
Mob/Demob	1	LS	\$400,000
Excavate & Dispose Soil Offsite <sup>(1)</sup>	43,000 cy	\$25/cy	\$1,075,000
Temporary Soldier Pile Wall Shoring	34,500 ft <sup>2</sup>	\$75/ft <sup>2</sup>	\$2,587,500
Drain Rock	10,000 cy	\$35/cy	\$350,000
Compressible Inclusion (3-Ft. Thick)	2,100 cy	\$150/cy	\$315,000
Import Structural Fill	42,000 cy	\$30/cy	\$1,260,000
810 Micropiles (250-k allow. 70-ft avg.)	56,700 ft	\$125/ft	\$7,087,500
Contingency 25%			\$3,269,000
<b>TOTAL COST</b>			<b>\$16,344,000</b>

(1) Includes cut to reach base of subgrade drain elevation 256 feet

(2) Costs for reservoir, piping, and other features not included

*Advantages.*

- Relatively inexpensive
- Conventional construction techniques
- Accommodates static and seismic displacements

*Disadvantages.*

- Lower mitigated FS than other options
- Mitigation may be insufficient to stop creep movements, but should reduce present creep rate
- Construction outside current reservoir footprint
- Extensive excavation shoring
- Settlement induced by backfilling reservoir may impact historic structures

### **6.3 Reservoir 3 Option 2 – Anchor Block Wall**

Option 2 involves resisting landslide forces using post-tensioned ground anchors with bearing pads near the ground surface. Option 2 would maintain the west slope of the existing reservoir at its current slope and grade to avoid destabilizing the existing landslide. Construction of the new

reservoir would require excavating into the east slope of the current reservoir similar to Option 1.

*Shoring.* Excavation shoring for Option 2 would be very similar to that described for Option 1 above.

*Foundations.* Option 2 would require foundations for the reservoir and reflecting pool as described above for Option 1. Piles would need to compensate for downdrag loading due to settlement of the Reworked Portland Hills Silt/Alluvium deposit.

*Settlement.* Settlements with Option 2 would be similar to that described above for Option 1.

*Subdrainage.* A subdrain system similar to that described above for Option 1 would be required for Option 2.

*Fill.* Fill material for Option 2 should be as described above for Option 1.

*Impacts to Tunnels.* There is a high likelihood that existing drainage tunnels would be intercepted by anchor drilling operations. If this occurs, grout injected for the proposed anchors would likely flow into the drainage tunnel and impede drainage. One method to prevent grout from entering the tunnels would be to install permanent casing in the portion of the hole between the surface and a point beyond the tunnel. The amount of casing required to complete the work would be difficult to predict and would increase the cost of the mitigation work. Horizontal drains may be required to mitigate any tunnels impacted by anchor construction.

Historic plans indicate that the drainage tunnels outlet along the west slope and northern end of Reservoir 3. One option would be to leave the existing reservoir liner in place and let the tunnel outlets continue to function as they have for the past century. Another option would be to remove the concrete liner to expose the tunnel outlets and hydraulically connect them to the proposed subdrain system. One difficulty with this option is that the historic maps are approximate and the actual locations of the tunnel outlets are not known.

*Seismic Performance.* Ground anchors have historically performed very well in seismic events; however, most anchored walls have not supported a large landslide mass. The anchors proposed for Option 2 would span a narrow landslide shear zone and bond into bedrock below. The seismic performance of the anchors would be highly dependent on the amount of shear displacement that occurs along the shear zone. Predicted landslide displacements for the 475-year earthquake are low enough that the anchors probably would be undamaged, but predicted displacements for the 2,475-year earthquake are expected to damage the anchor tendons at or near the shear zone. If the anchor tendons are damaged, the landslide could resume moving at a slow creep rate.

*Comparative Cost Estimate for Reservoir 3 Option 2.*

Work Item	Quantity	Unit Price	Cost
Mob/Demob	1	LS	\$700,000
Excavate Bearing Pads & Dispose Soil	10,000 cy	\$25/cy	\$250,000
310 Anchors (9-strand, 185-ft. avg.)	57,350 ft	\$80/ft	\$4,588,000
Excavate & Dispose Soil Offsite <sup>(1)</sup>	43,000 cy	\$25/cy	\$1,075,000
Temporary Soldier Pile Wall Shoring	34,500 ft <sup>2</sup>	\$75/ft <sup>2</sup>	\$2,587,500
Drain Rock	10,000 cy	\$35/cy	\$350,000
Compressible Inclusion (3-ft. thick)	2,100 cy	\$150/cy	\$315,000
Import Structural Fill (incl. drill bench)	52,000 cy	\$30/cy	\$1,560,000
810 Micropiles (250-k allow. 70-ft avg.)	56,700 ft	\$125/ft	\$7,087,500
Contingency (25%)			\$4,628,000
<b>TOTAL COST</b>			<b>\$23,141,000</b>

(1) Includes cut to reach base of subgrade drain elevation 256 feet

(2) Costs for reservoir, piping, and other features not included

*Advantages.*

- Provides active landslide stabilization
- Keeps option for existing reservoir footprint i.e. no new tank

*Disadvantages.*

- Anchors are expected to be damaged during 2,475-year earthquake event
- Possible construction outside current reservoir footprint
- Specialty contractor required
- Extensive excavation shoring
- High likelihood of damaging drainage tunnels
- Measures to prevent tunnel damage would add cost to construction
- Impacts to historic structures from drill bench excavation
- Settlement from backfilling reservoir may impact historic structures

**6.4 Reservoir 3 Option 3 – Landslide Shoring Wall**

Option 3 is similar to Option 2 in that it involves resisting landslide forces with post-tensioned ground anchors. The primary difference is that anchors would react against a vertical wall installed near the existing Reservoir 3 western parapet wall. Option 3 would require less temporary shoring on the east side of the reservoir than Options 1 or 2 because the toe of the landslide would be excavated to create space to construct the reservoir. Stability resistance that is lost by excavating the landslide toe would be made up with higher capacity ground anchors.

*Shoring.* Option 3 would locate more of the new reservoir within the existing reservoir footprint than Options 1 or 2. For this reason, less excavation shoring will be required for Option 3 than

for Options 1 or 2. However, excavation of the western slope will decrease the stability of the landslide and there would be less redundancy with this option if the anchors were damaged. Shoring walls would be required around the perimeter of the existing reservoir, but the average height would be less than in Options 1 or 2. Conventional soldier pile and tieback shoring walls are anticipated to be used.

*Foundations.* Option 3 would require foundations for the reservoir and reflecting pool as described above for Option 1. Piles would need to compensate for downdrag loading due to settlement of the Reworked Portland Hills Silt/Alluvium deposit.

*Settlement.* Settlement of pile foundations for the new reservoir with Option 3 would be similar to that described above for Option 1.

*Subdrainage.* A subdrain system similar to that described above for Option 1 would be required for Option 3. Existing drainage tunnels exposed during excavation should be hydraulically connected to the drainage system next to the shoring walls.

*Fill.* Fill material for Option 3 should be as described above for Option 1.

*Impacts to Tunnels.* There is a high likelihood that existing drainage tunnels would be adversely impacted by ground anchor construction. Grout placed around the anchor would likely flow into the drainage tunnel if intercepted by the anchor. One method to prevent grouting the tunnels would be to install permanent casing in the portion of the hole between the surface and a point beyond the tunnel. The amount of casing required to complete the work would be difficult to predict and would increase the cost of the mitigation work. Horizontal drains would likely be required to mitigate any tunnels impacted by anchor construction.

*Seismic Performance.* The seismic performance of ground anchors used for Option 3 is the same as described under Option 2.