Relief Well Rehabilitation Options in Chief Joseph Dam Right Abutment Drainage Tunnel

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EXECUTIVE SUMMARY

This report summarizes the data, observations, methods, assumptions, and decisions for the design of the Relief Well Rehabilitation Project in the Right Abutment Drainage Tunnel at Chief Joseph Dam. Geologists from the U.S. Army Corps of Engineers (USACE) led the design effort. This project began in 2012 with Jeff Powers as the technical lead. I became technical lead in late 2013. The design for this project was completed in March 2015, the contract was awarded April 30, 2015, and construction will occur in September 2015. After rehabilitation is completed, a copy of this report should be attached to the final construction report as an appendix.

Chief Joseph Dam (CJD) is a dam on the Columbia River and is owned and operated by the USACE. It is the second only to Grand Coulee dam as the largest producer of hydropower in the United States. The right abutment drainage tunnel contains wooden stave relief wells. Water flows from these wells which reduces the hydrostatic pressure in the right abutment of the dam. The 22 wells in the floor of the tunnel are 60 years old and are in need of rehabilitation.

The objective of this project is to control the groundwater gradient, prevent the movement of sediment, stop total screen collapse, and prevent initiation of backwards erosion and piping in the abutment. The rehabilitation solution is to install new stainless steel screens into the existing wells, backfill the annular space between the old wooden screen and the new stainless steel screens with a 3/8-inch pea gravel filter pack, and install a new top cap to hold the new screen in place.

This report documents the data, observations, and methods used to complete the final design. During tunnel inspections USACE geologists observed dislodged end plugs and evidence of sediment movement out of the formation. The relief wells have historically high flows between 6,000 gallons per minute (gpm) to 9,000 gpm. Mr. Powers and I designed the new screens based on as-built data and historic tunnel flow. The new screens are 8-in diameter, 100 slot (0.10-inch) screens. We found that screen diameter and slot size would provide adequate transmitting capacity for most of the relief wells. The filter pack gradation is based on descriptions from foundation construction reports. I found that 3/8-inch pea gravel is appropriate for the abutment material. During design, I also considered an option to install the screens into the relief wells without filter pack. I eliminated this option because it did not meet our rehabilitation objective to prevent total failure of the wooden screens.

TABLE OF CONTENTS

EXECUTIVE SUMMARY .... **I**

TABLE OF CONTENTS .... **II**

LIST OF FIGURES .... **III**

LIST OF TABLES .... **IV**

ACKNOWLEDGEMENTS .... **IV**

1. INTRODUCTION **1**

2. BACKGROUND **3**

2-1. CJD Geologic Setting 3
2-1. Purpose of Relief Wells and Drainage Tunnels 4
2-2. CJD Relief Tunnel Description 5
2-3. Rehabilitation Objectives 7
2-4. Rehabilitation Alternatives 7
2-5. Selected Rehabilitation Method 8

3. RELIEF WELL CONDITION **11**

3-1. Methods and Data Sources 11
3-2. Relief Well Data Findings and Observations 12
3-3. Relief Well Flow Analysis 12

4. HISTORICAL FLOWS AND CAPACITY ANALYSIS **17**

4-1. Methods and Data Sources 17
4-2. Historic Flow Data Findings 18
4-3. Capacity Calculation Methods 18
4-4. Capacity Calculation Results 19
4-5. Capacity Analysis 19

5. FILTER PACK DESIGN **25**

5-1. Methods and Data Sources 25

5-2. FILTER PACK DATA INPUTS AND METHODS 26
5-3. SELECTED FILTER PACK 28
5-4. SELECTED FILTER PACK RATIONALE 28

6. NOT-SELECTED REHABILITATION OPTION EVALUATION 29

6-1. NO-FILTER PACK DESIGN EVALUATION 31

7. ASSUMPTIONS FOR THE DESIGN 35

8. CONCLUSION 37

REFERENCES 38

APPENDIX: TABLES, FIGURES AND TERMS 39

APPENDIX TABLES 39

APPENDIX FIGURES 39

TERMS 40

LIST OF FIGURES

Figure 1-1: Relief Tunnel at Chief Joseph Dam. 1
Figure 2-1: Chief Joseph Dam Location. 3
Figure 2-3: Annotated aerial photograph of Chief Joseph Dam Features. 5
Figure 2-4: Generalized Cross Section of the Relief Tunnel, looking upstream. 7
Figure 2-5: Relief Well Problem Definition. 10
Figure 2-6: Relief Well Proposed Rehabilitation Design. 10
Figure 3-1: USACE Geologists using a downhole camera to record the condition of the relief wells in the 6-ft high section of the tunnel. 11
Figure 3-2: Well 6. Obstruction, possibly part of dislodged end plug at ~ 21.7 ft depth. 15
Figure 3-3: Well 8 Teleview: Screen was knocked down the well when the top cap was removed in 2013, sediment on the screen accumulated between 2013 and 2015. 15
Figure 3-4: Well 8 side-camera view of existing well, sediment can be seen behind the screen slots. 16

Figure 3-5: Sediment accumulating below stairs. 16
Figure 4-1: Monthly Flow Reading. 17
Figure 4-2: Example Plot from Instrumentation Web Site with Flow at Wells 16 to 20A. 21
Figure 4-3: Historic Relief Tunnel Flow 1980 to 2013. 22
Figure 4-4: Historical Maximum and Mean Flow in the Relief Tunnel for each Well. 23
Figure 4-5: Historic Max and Mean Flow in each Relief Well Compared to the Calculated New Screen Capacity. 24
Figure 5-1: Relief Tunnel Excavation Units from CJP-08M-288. 26
Figure 5-2: Description of Openwork Gravels from the 1957 CJD Foundation Report. 27
Figure 6-1: The Potential Issue with Option 7 is Forming Voids Under the Tunnel Floor. 32
Figure 6-2: Volume of Filter Material for Each Well in the CJD Relief Tunnel. 33

LIST OF TABLES

Table 3-1: Relief Well As-Built Data and Recent Depth Measurements. 14
Table 5-1: GP-GM Base Material Used in the Filter Analysis. 27
Table 5-2: Filter Specification: 3/8-in Pea Gravel. 28
Table 6-1: Comparison of Rehabilitation Options 6 and 7. 30
Table 6-2: Calculated Volume of Filter Pack 34

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The entire geology section helped at some point with this project. Jeff Powers began the design and much of my work was reviewing and updating his design. Kerri Swanson drew and printed many versions of the plans. Amy Ebnet and Sharon Gelinas sat in a room with me one morning and walked through the filter pack analysis. Dave Sullivan, Matt Brookshier, Jon Moen, and Dave Chapman helped with field work in the tunnel. Andrejs Dimbirs plotted instrumentation data. Laura Boerner, Ellen Engberg, and Richard Smith all provided guidance, motivation, and review. The rest of the relief well rehab project delivery team worked hard getting this project ready for contracting. You all contributed to this report, thank you! And last, thank you David Garon, I wouldn't have been able to do this without your support. Let's get this constructed!

1. INTRODUCTION

Figure 1-1: Relief Tunnel at Chief Joseph Dam.

Chief Joseph Dam (CJD) is a hydroelectric dam on the Columbia River that is the second only to Grand Coulee Dam as the largest producer of hydropower in the United States. The dam is owned and operated by the U.S. Army Corps of Engineers (USACE), Seattle District (NWS). The right abutment drainage tunnel contains 22 relief wells in the floor of the tunnel that reduce the hydrostatic pressure in the right abutment. Figure 1-1 shows a former USACE District Commander in the 4.5-ft high section of the drainage tunnel. A 250-ft long earthen embankment was placed between the concrete spillway of the dam and the abutment. Seepage erosion through dam abutments and earthen embankments is historically the most common type of failure mode for dams. Thus, it is critical at CJD to control the water gradient and filter the discharge water to prevent piping and erosion or soil heave. The 22 wells at CJD are 60 years old and are in need of repair. They are made of wood and they may already be allowing sediment from the formation to exit the abutment uncontrolled. A sudden collapse of the wooden staves in one of the wells could lead to a more rapid removal of embankment material from the abutment and lead to failure of the earth embankment dam. The purpose of the rehabilitation project is to prevent sudden collapse of one of these screens and prevent the movement of sediment out of the abutment while continuing to control the hydrostatic pressure in the abutment. The rehabilitation solution (Option 6) is to install new stainless steel screens into the existing wells, backfill the annular space between the old wooden screen and the new stainless steel screens with a pea gravel filter pack, and install a new top cap to hold the new screen in place.

This project began in 2012 after the Periodic Assessment that recommended that the drains be rehabilitated within ten years. Jeff Powers was the first design lead. He started the initial design, performed an alternatives analysis, inspected the wells, calculated the screen capacities, and outlined the needed contract specifications. Mr. Powers left the U. S. Army Corps of Engineers in early 2014, and I transitioned to become the lead designer in late 2013. As technical lead, my contributions to the project include reviewing and finishing the design, documenting methods and data, preparing plans and specifications for contracting, and coordinating construction. I considered and rejected an additional rehabilitation alternative, conducted additional well inspections, updated the design including the capacity calculations, flow frequency analysis on certain wells, and the final filter pack design. I wrote the contract specifications, edited design drawings, scheduled construction, evaluated construction techniques, and facilitated coordination with others including: CADD technician, cost estimator, construction staff, Chief Joseph Dam operations staff, the downstream Douglas County PUD dam, Bonneville Power Administration (BPA), and Native American Tribes.

Installing new screen and filter pack into the existing wells is the best method to rehabilitate the relief wells at CJD because it meets our design objectives to control the groundwater gradient, prevent the movement of sediment, stop total screen collapse, and prevent initiation of backwards erosion and piping. This option is constructible within the 8-ft by 5-ft tunnel without machinery or drill rigs and has a reasonable cost. The design for this project was completed in March 2015, the contract was awarded April 30, 2015, and construction will occur in September 2015.

This report documents the data we used for the design of Option 6 including as-built data and historical relief well data, calculations used to determine screen length and slot sizes, and my contribution to the project which include the final filter pack design and the consideration of option 7. Option 7 was eliminated because it did not meet the design objectives, but it is included in this report for completeness. After rehabilitation is completed, this report should be attached to the final construction report as an appendix.

2. BACKGROUND

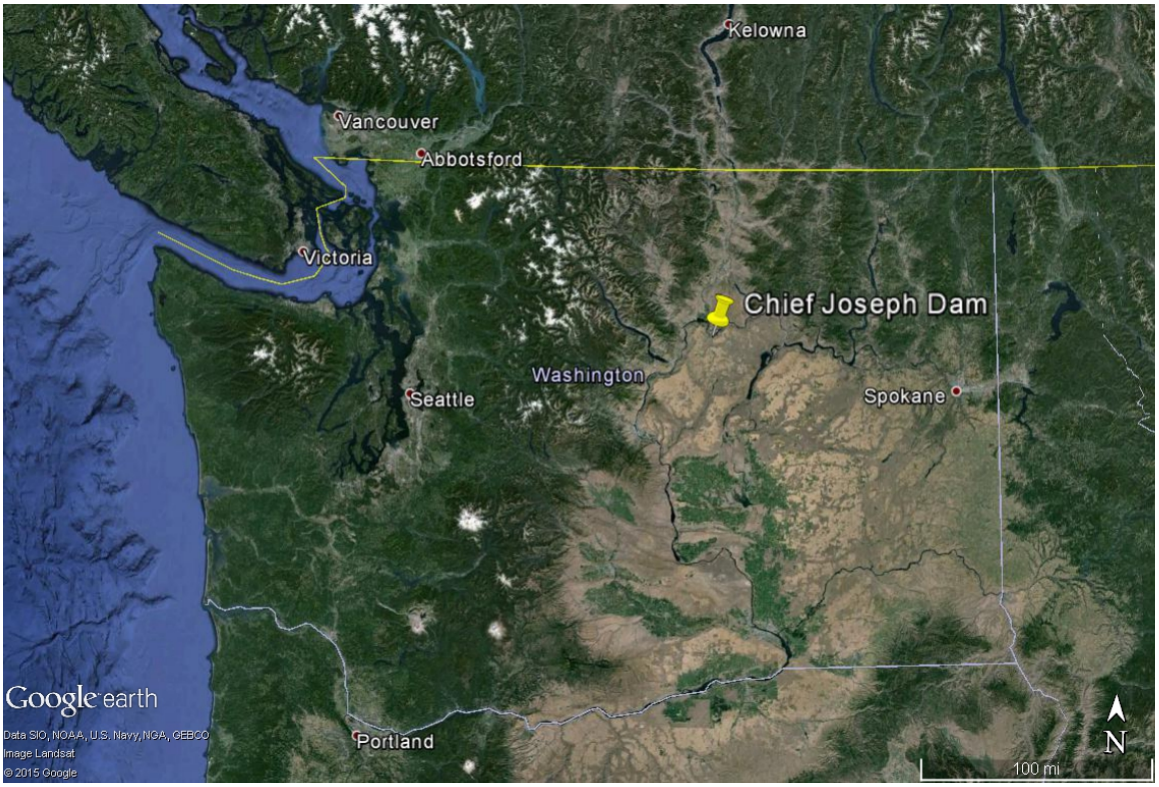

Figure 2-1: Chief Joseph Dam Location.

2-1. CJD Geologic Setting

CJD is located near Bridgeport Washington on the Columbia River (Figure 2-1). The dam is located between two geologic provinces with the Okanogan Highlands to the North, and the Columbia Plateau to the South (Eckerlin and Galster, 1989).

The dam site is located within the Columbia River valley where Pleistocene glacial sediments form glacial terraces within the valley. The right bank is a 250 foot (ft) high glacial terrace. The left bank of the dam is capped by Columbia River Flood Basalts. The main river channel is about 800 ft wide at the project site. Beneath the river channel, foundation of the dam is composed of Mesozoic crystalline rocks including granodiorite.

According to the 1957 foundation report (USACE, 1957), the right abutment is composed of glacial sediments including outwash sands and glacial till. The outwash sands are located over bedrock and are about 100 ft thick. The unit includes open work gravels with some clay infilling and sand lenses. This unit has high permeability. Above the outwash is about 10 ft of a silty “dump moraine”. Glacial till caps these sediments and is about 155 ft thick and has a low permeability.

2-1. Purpose of Relief Wells and Drainage Tunnels

Relief wells are frequently used to reduce subsurface hydrostatic pressures in the downstream foundations of dams and levees. Dams and levees are structures that retain water behind them in a reservoir. Because of the head difference between the reservoir and the tailwater (water elevation downstream of the structure) water flows through the foundation and abutment (native material adjacent to the structure). This flow is called seepage. The gradient between the reservoir and tailwater may be steep especially at high head projects like CJD and causes high hydrostatic pressures in the foundation and abutment. High hydrostatic pressure has the potential to cause the removal of sediment from foundation and abutment (piping) or uplift of sediments (heave). Relief wells act like artificial springs and flow with artesian pressure (so they are generally not pumped). Some relief wells are installed in tunnels that collect and direct the water discharged from the relief wells (EM 1110-2-1914).

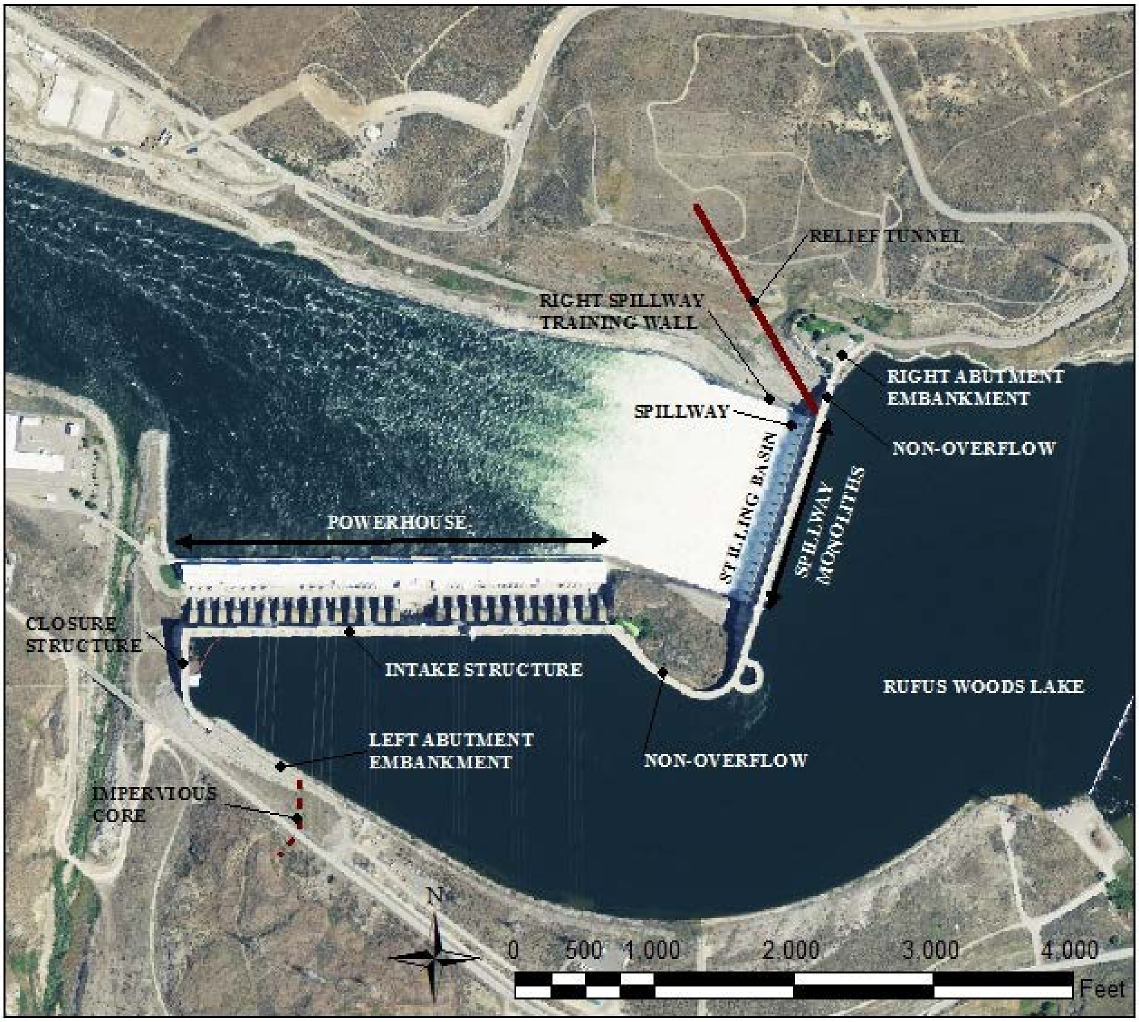

Figure 2-2: Annotated aerial photograph of Chief Joseph Dam Features.

2-2. CJD Relief Tunnel Description

The relief tunnel is located in the right abutment of CJD. The tunnel is accessed through the spillway monoliths of the dam (Figure 2-2). The tunnel is 1,020 ft long, 8 ft tall and 5 ft wide (Figure 2-3). The bottom of the tunnel floor rises with a 1% slope from the drainage sump to the distal end within the abutment. A two-foot high catwalk runs along the length of the tunnel. The drainage sump and drain to the river are at the southeast end of tunnel. There are 22 wells along the length of the floor of the tunnel, 20 of which are spaced every 50 ft along the tunnel. The first well is 45 ft from the entrance of the tunnel. Two wells (19A and 20A) are located 15 ft offset on either side of Well 20, which is the last well in the tunnel.

The relief tunnel was constructed as CJD was being built and before the reservoir was filled (USACE, 1957). This means it was constructed in dry conditions because the reservoir did not exist and water did not flow at a high gradient through the abutment. The first 120 ft of the tunnel was constructed in the open cut between the monolith and the right abutment. The materials around the tunnel in this section include embankment material: impervious fill, pervious fill, and random fill. The back 900 ft of the tunnel was bored through the abutment. The native materials around the tunnel in this section include mostly open work gravel with clay and a sand unit in the back of the tunnel. Wells 1 and 2 are located in the embankment fill, and the other wells are in the in-situ geological materials.

The relief wells were hand dug to bedrock in 3-ft diameter borings to depths of approximately 30 ft. Twelve-inch (in) diameter slotted wooden stave screens were installed into the borings and backfilled with ¾-in minus gravel between the wood and the surrounding formation within a 1 foot annulus (Figure 2-4). Two additional wells (19A and 20A) were drilled in October 1954 (USACE, 1955). Water enters the screens through rectangular slots cut into the wood staves (Figure 3-4).

Water has flowed from the wells since the reservoir was raised in 1954. The total average discharge from the tunnel varies seasonally between 6,000 gallons per minute (gpm) to 9,000 gpm. The water that comes up from the relief wells flows from the back of the tunnel on the NW end down towards the dam on the SE end. Water drains into a sump drain in the tunnel floor (Figure 2-3). This sump is connected hydrologically to the river on the downstream side of the dam (the tailwater). Because of this connection, water from the river will flood back into the tunnel when the river elevation increases, increasing the water level in the tunnel and making it unsafe for staff to access the tunnel. Flooding of the tunnel occurs when CJD passes high flows by generating power or spilling water over the spillway.

These relief wells are now over 60 years old. The wooden staves are always under water and are in relatively good condition. However, video inspection revealed that some wells have bacteria accumulation, offset joints, and the end plugs are dislodged. The dislodged end plugs may allow sediment from the formation to enter the well and then exit through the tunnel thus initiating a backwards erosion and piping failure mode.

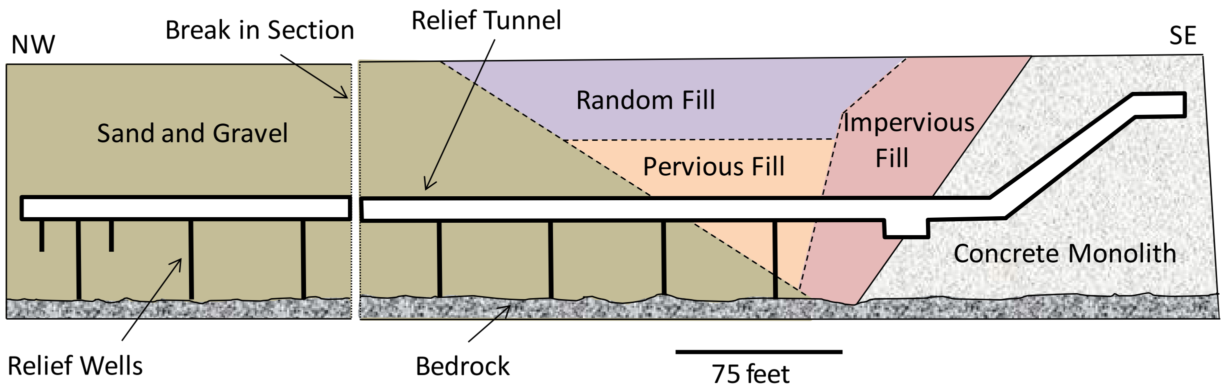

Figure 2-3: Generalized Cross Section of the Relief Tunnel, looking upstream.

2-3. Rehabilitation Objectives

The rehabilitation objectives are to: 1) continue to allow drainage of the right abutment with no reduction in drainage capacity; 2) prevent the movement of sediment out of the existing wells; 3) prevent a sudden collapse of the wooden relief wells; and 4) stop initiation of backwards erosion and piping in the abutment.

Design constraints include working within the existing tunnel that: 1) is 8-ft tall by 5-ft wide; 2) is 200 ft underground; 3) always has 6,000 to 9,000 gpm of water flowing through it; and 4) has existing wells that are 12-in diameter and 30 ft deep. This means the rehabilitation must be performed without machinery or drill rigs. Material may be carted down stairs, but they must be hand carried into the tunnel. The entire 1000 ft tunnel has a 2-ft high catwalk, with a clearance of 6 ft, and the first 60 ft has the catwalk raised an additional 1.5ft with a clearance of 4.5 ft (Figure 1-1). Additionally, the project must be completed within a 2-week work window to minimize impacts to power production at the next downstream dam and be completed within a previously specified budget. A design was successfully developed to meet these objectives and overcome the project limitations.

2-4. Rehabilitation Alternatives

During the first stages of design by Jeff Powers, he considered six options to meet the design objectives. These alternatives are:

- Option 1. Installation of new wells mid-way between existing wells, and decommissioning of existing wells.

- Option 2. Remove existing wells and replace with new wells in same locations as existing wells.
- Option 3. Redevelopment of existing wells.
- Option 4. Line existing wells with pre-pack well screens and no sand and gravel backfill between pre-pack and existing well.
- Option 5. Line existing wells with pre-pack well screens, and sand and gravel filter backfill between pre-pack and existing well.

Options 1-3 were eliminated because they did not meet the rehabilitation objects. Please see Table A- 1 in the Appendix for advantages and disadvantages associated with each option. Options 4 and 5 considered pre-pack screens which contain plastic beads built into the screen that act as the filter. The pre-pack screens options were not selected because the screens are too heavy to carry by hand, which meant the methods were too difficult to construct, and the options had a much higher cost than traditional screens and filter pack. Option 6 with traditional screens was the selected option.

- Option 6. Line existing wells with standard well screen and sand and gravel backfill.

During the next phase of design, option 6 was further evaluated by also considering option 7.

- Option 7. Line existing wells with standard well screens with no sand and gravel backfill. This option was not selected, please see section 6 Not-Selected Rehabilitation Option Evaluation for discussion of this option.

2-5. Selected Rehabilitation Method

The selected option is Option 6, which is to line the existing wells with standard well screen with sand and gravel backfill between the screen and the existing wood staves (Figure 2-5). This option consists of lining the existing wooden stave wells with rod-based wire-wrapped stainless steel well screens. Following steel screen liner installation, sand and gravel backfill graded to prevent native formation materials from passing through the filter will be installed as a filter pack material between the old and new well screens. The diameter of the stainless steel screen will be sized so that it fits inside the existing wooden screen, with approximately 1.5-in open area between the steel screen and the wooden stave. The stainless steel screen will have sufficient open area to pass flows in excess of the maximum observed historical flow at each well. Screen segments will be installed in 5-foot increments that will be threaded together so that installation is rapid compared to other well rehabilitation options. The filter backfill, composed predominantly of a pre-designed sand and gravel mixture, will serve two purposes, 1) to provide stability for the new screen liner, and 2) to reduce movement of fine sediments that flow toward the new well screen. One disadvantage of adding sand and gravel backfill is that the steel screen will then be firmly fixed in place and will not be removable for maintenance or repair. A second disadvantage is that it may be difficult to install the filter pack due to the hydraulic pressure of the drains where high flow volumes will act against the gravity placement of the sand. It is estimated this method of rehabilitation will take 14 field work days to complete. The weight of each 5-ft screen segment is only 40 pounds, making manual installation of wells utilizing this design easier than for the pre-packed screens which weigh 175 pounds per 5-ft segment. Option 6 is recommended for all wells due to its relative low cost, relative ease and speed of installation, and because it is the least restrictive on passing maximum historical flows due to the ability to adjust screen slot size equivalent and filter gradation. This option is constructible within the 8-ft by 5-ft tunnel without machinery or drill rigs and has a reasonable cost.

Option 6 is the best method to rehabilitate the relief wells at CJD. It meets our design objectives to control the groundwater gradient, prevent the movement of sediment, stop total screen collapse, and prevent initiation of backwards erosion and piping.

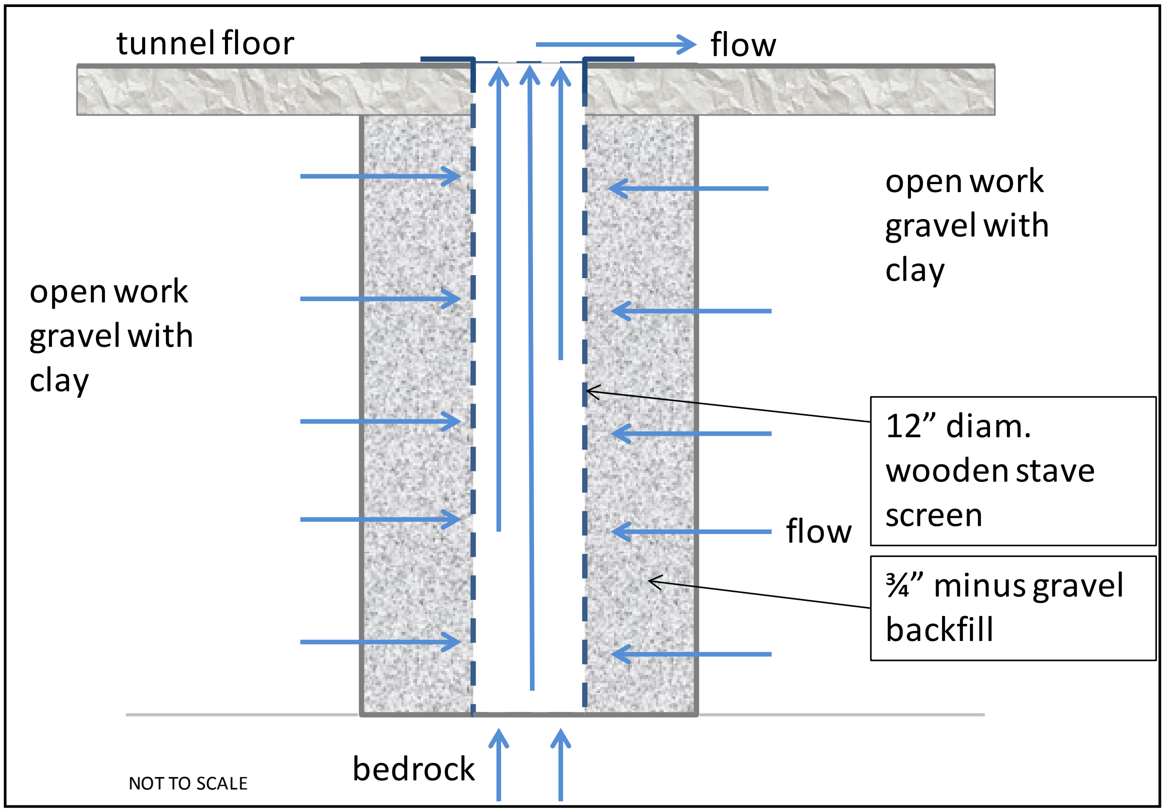

Figure 2-4: Relief Well Problem Definition.

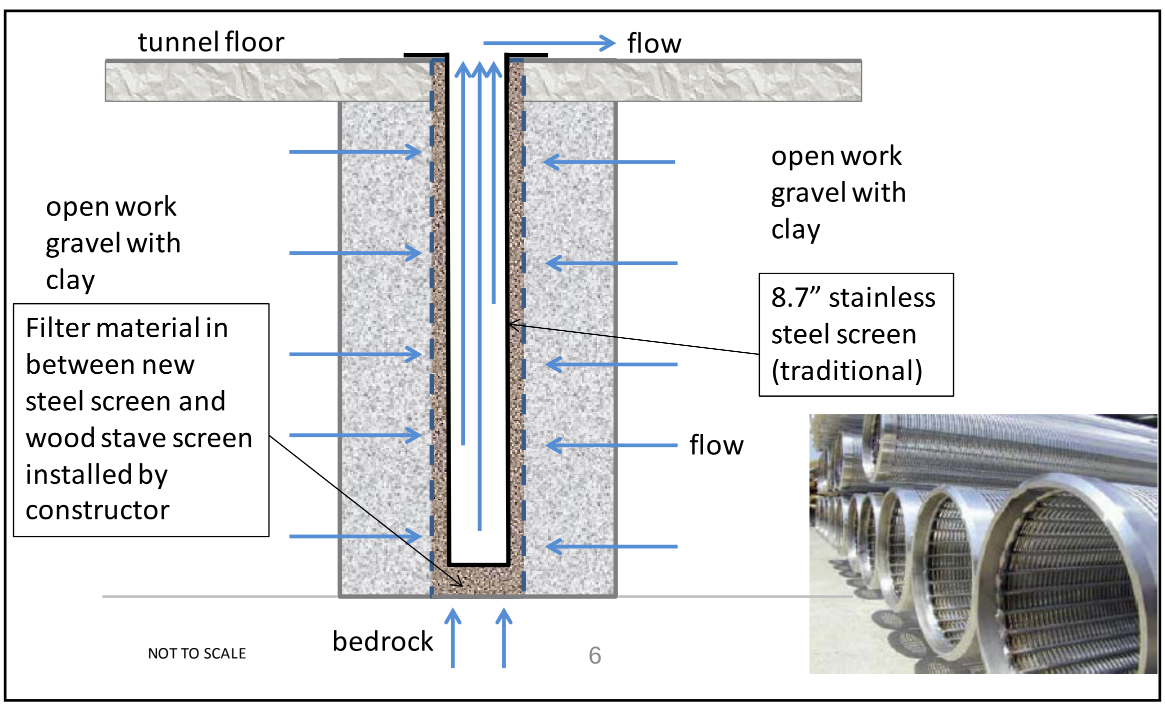

Figure 2-5: Relief Well Proposed Rehabilitation Design.

3. RELIEF WELL CONDITION

3-1. Methods and Data Sources

Figure 3-1: USACE Geologists using a downhole camera to record the condition of the relief wells in the 6-ft high section of the tunnel.

Tunnel construction details were recorded on two as-built drawings. Mr. Powers used theses drawings to calculate the total depth of the relief wells, and I used them to review his calculations. One drawing is a geologic cross-section of the material recorded during the excavation of the tunnel (USACE, 1976). The drawing includes: the distance excavated and the dates they reached each distance, geologic descriptions of the units, and bottom elevation of each relief well boring. The second drawing shows the concrete tunnel construction condition (USACE, 1950). This drawing includes spacing of each relief well and the tunnel position in relation to the rest of the dam. We calculated the top elevation of each well using the tunnel floor elevations, and we subtracted the elevation listed on the geologic section of the tunnel.

Geologists, engineers, and maintenance staff monitor and inspect the condition of the relief wells. Monitoring methods include monthly tunnel inspections where CJD staff measures the flow out of each well, periodic inspections (which occur every five years), and other inspections (which occur as-needed). Inspections include dropping a weighted tape down the wells to determine the total depth. The wells have recently been inspected using a downhole camera to observe and record the condition of the wooden staves, the amount of material on the bottom of the wells, and any other features (Figure 3-1). The first visual inspection of the relief wells with a downhole camera occurred in 2010. Additional inspections occurred in 2011, 2013, 2014, and 2015. Field notes are taken during inspections.

3-2. Relief Well Data Findings and Observations

As-built construction details are summarized in Table 3-1 and inspection findings are summarized in the Appendix in Table A- 2. Other data collected include videos of each well and field notes. Figure 3-2, Figure 3-3, and Figure 3-4 are the type of images captured in the videos.

During the inspections, Geology Section staff found that overall the wooden screens are in fairly good condition. Four wells have wooden obstructions in the middle of the screens, these are dislodged end plugs (Figure 3-2). The wooden stave wells were completed with wooden end plugs at the bottom of the wells, so in these four wells the end plugs have popped up and wedged partially up the well. In-place end plugs were not observed in the other wells because most wells have sand and gravel covering the bottom of the wells. This sand material has two possible sources, see 3-3 for explanation. Sand has also accumulated on the joints between screen sections (Figure 3-3). Many wells have a few feet of difference between the as-built design depth and the current measured depth. Sand particles can be seen through the screen slots (Figure 3-4). Some wells have offset joints between screen segments and some have small amounts of damage to the screens. Some of the wells are fouled with white substance on the wooden screens. This material is mineral or bacteria. See the Appendix, Table A- 2 for complete description of inspection findings. In the videos we observed sand particles picked up by the flow of water. Sediment is accumulating at the bottom of the stairs to the tunnel (Figure 3-5).

3-3. Relief Well Flow Analysis

These observations including: dislodged end plugs, sand and gravel at the bottom of the wells, shallower measured depths compared to as-built conditions, and sediment accumulating at the bottom of the stairs, support the idea that sediment from the abutment could be exiting the formation through the wells and out to the river. If the wells were constructed correctly, there shouldn't be any sediment in the bottom of the wells. One potential source of the sand and gravel is from the incorrect construction of wells 19A and 20A. When wells 19A and 20A were drilled, the perforated tile pipe in the gravel drain was drilled through and gravel from the drain was released into the tunnel. This gravel drain is 2 to 3 ft thick underneath the concrete floor of the tunnel. In addition, we did not observed in-place end plugs in the other wells because they were covered with sand, so we assume that some of them could have dislodged end plugs that floated out of the wells and did not become wedged in the wells. This means an unknown number of wells, in addition to the four with dislodged end plugs, are open to the formation at the bottom of the wells.

Based on these observations, the wells are deteriorating, and could eventually fail, and lead to total collapse. In addition, the wells could be open to the formation, and sediment may be coming into the wells through the screen slots. One of the metal screens from a temporary cap over the well was knocked down to the bottom of the well in 2013. When we inspected the well in 2015, we observed that sand and small gravels had fallen onto the screen. The sand around the screens is one source of the sediment at the bottom of the wells, and the other source is the sediment that came out of the gravel drain when wells 20A and 19A were drilled in 1955 (USACE, 1955). This material would not explain the additional material that had fallen on the metal top cap screen between 2013 and 2015. The amount of material that accumulated between 2013 and 2015 could cause the approximately 1-ft difference in depth in the 60 years since the wells were constructed (Table A- 2). The base of the stairs are at the same elevation of the tunnel, and when tailwater from CJD rises above the elevation of the tunnel drain, the tunnel fills with river water. This is likely the time when sand from the relief wells is transported to the base of the stairs and deposited there. During this time, the wells are not monitored and the total volume of sediment being removed is unknown.

The current wooden screens are ineffective at preventing the movement of sediment and could allow backwards erosion and piping in the right abutment to occur. The dislodged end plugs are a sign the wells are deteriorating and need to be repaired. New stainless steel screens with the appropriate filter pack will prevent the movement of material and prevent a sudden failure if one of the screens were to collapse. An appropriate filter pack would prevent the movement of sediment into the wells and out of the abutment.

For the design of the rehabilitation method we used the total depth of the wells and the obstruction depths to calculate the length of screen and volume of filter pack to be placed. The screens were designed to end above the obstructions in the four wells with dislodged end plugs and with enough filter pack to fill the space below the broken end plugs and the new screen. The screen lengths were designed to be light enough to be carried into the tunnel, and short enough to fit within the limited height of the tunnel, yet as long as possible to limit the number of sections that have to be placed. Ten-foot sections would be too tall, 3-foot sections would require too many trips, threads, and effort to install, and so 5-foot sections were the right length for this project. The total length of the screen was maximized while keeping the end at least 0.5 ft above the bottom of the well and above the obstructions.

Table 3-1: Relief Well As-Built Data and Recent Depth Measurements.

Relief Well ID	Distance within Tunnel (ft)	As-built Completion Depth (ft)	Measured Depth (ft)[1]
1	45	N/A*	21.5
2	95	32.9	28.4
3	145	34.0	32.5
4	195	31.9	31.0
5	245	36.3	34.5
6	295	38.0	33.8
7	345	32.5	28.0
8	395	30.3	28.1
9	445	31.1	30.4
10	495	33.1	21.7
11	545	33.3	22.6
12	595	25.8	23.9
13	645	28.7	27.3
14	695	32.5	30.5
15	745	31.0	30.1
16	795	29.0	28.2
17	845	32.3	30.3
18	895	33.7	32.1
19	945	28.5	28.0
19A	960	14.9	5.6[2]
20	995	31.0	31.0
20A	1010	14.9	4.5[2]

Notes:
*N/A – Not available. No information on well 1.
Data calculated from Drawing E-51-11-15, 1950 and Drawing #CJP-O&M-288, 1976.
1 – Measured during 2013 and 2014 inspections
2 – Filled with cobbles and gravel to six ft below tunnel floor in 1955.

Figure 3-2: Well 6. Obstruction, possibly part of dislodged end plug at ~ 21.7 ft depth.

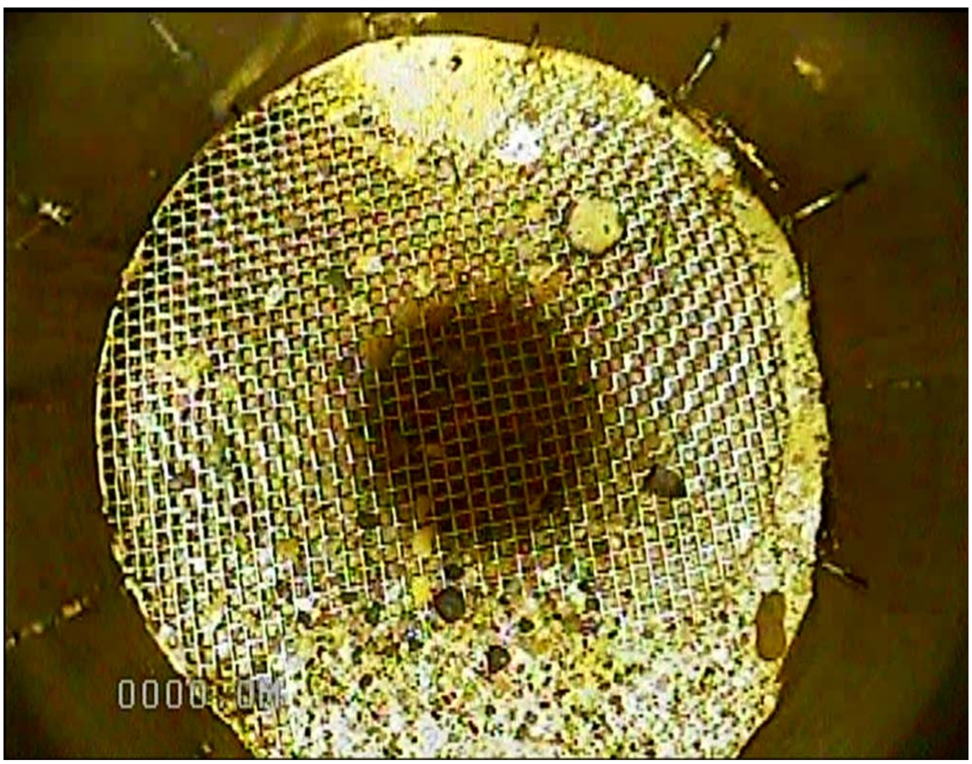

Figure 3-3: Well 8 Teleview: Screen was knocked down the well when the top cap was removed in 2013, sediment on the screen accumulated between 2013 and 2015.

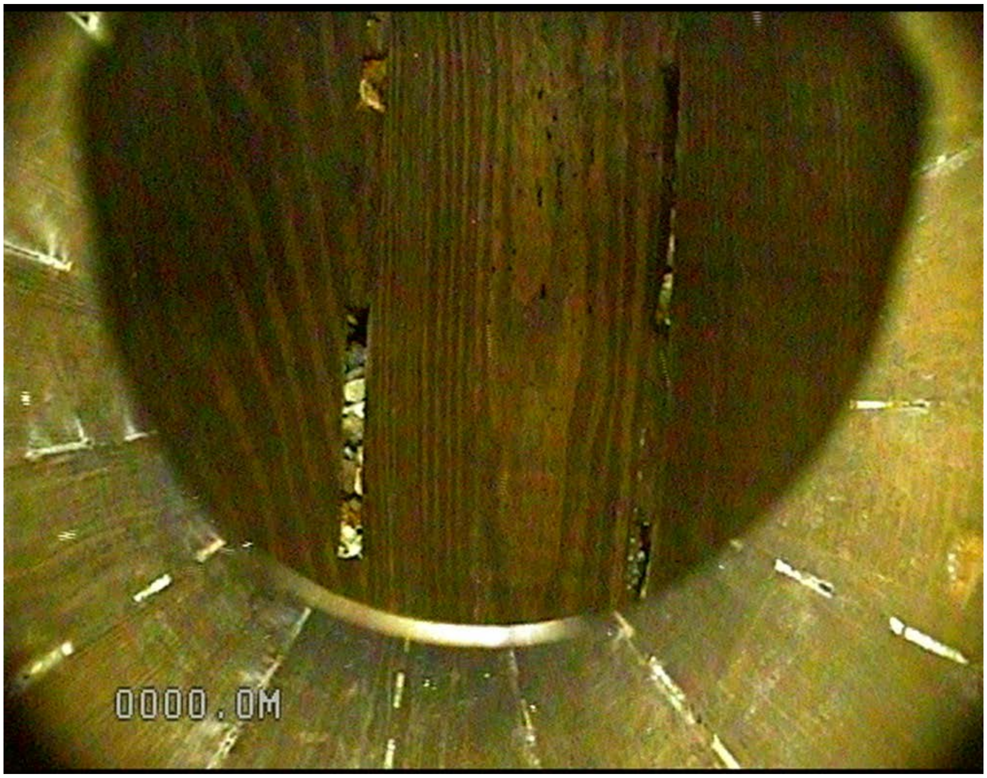

Figure 3-4: Well 8 side-camera view of existing well, sediment can be seen behind the screen slots.

Figure 3-5: Sediment accumulating below stairs.

4. HISTORICAL FLOWS AND CAPACITY ANALYSIS

4-1. Methods and Data Sources

Flow from the tunnel is manually monitored during monthly tunnel inspections. Once a month, CJD staff access the relief tunnel and use a flow meter to measure the flow from each well. Each well had a temporary top cap installed in 1979. The mesh screen of the cap is about 1.5 ft below the tunnel floor, which allows the monthly flow measurements to be made with the flow meter in the well as shown in Figure 4-1. These monthly readings have occurred since 1980.

Figure 4-1: Monthly Flow Reading.

After the manual readings, data are entered into an Excel spread sheet, emailed to the Geology and Instrumentation staff and entered into our database. Intermittently from 1980 to 2013 an automated sensor recorded data on the total flow from the tunnel including flow (cubic feet per second [cfs]), level (ft), and velocity (feet per second [ft/s]). This sensor also recorded when tailwater flooded the tunnel.

4-2. Historic Flow Data Findings

Figure 4-2 is an example of the data that is taken by CJD and monitored by NWS Geologists. The data are kept in a database that goes back to 1980. Data before then are recorded in paper records and periodic inspection (PI) reports. According to the 2012 PI report (USACE, 2012), average flow in the tunnel decreased from 90 cfs in 1953 to 25 cfs in 1977. From 1977 to 2010, the total tunnel flow rate remained relatively constant between 20 and 25 cfs. There was no apparent increase in tunnel flows that could be attributed to the pool raise in February 1981 when the normal full pool was raised from elevation 946 feet to elevation 956 feet. From 2010 to 2012 the total tunnel flow increased an average of a few cfs due to increasing trends in flow from wells 16, 17, 18, 19, and 20. The increase is most evident in well 20 with an increase from ~3.5 cfs to approximately 4.5 cfs (Figure 4-3). The flows then dropped again, so more time will be required to determine if that increase was a one-time event or part of a larger pattern. The historic flow in the relief tunnel is shown in Figure 4-3. Figure 4-4 shows the maximum and mean flow from 1980 until 2013. The upstream wells have the highest flow, and well 20 has consistently higher flow than the other wells.

- Well 20 averages 3.54 cfs.
- Three wells (Well 16, 17, 19) average less than 2 cfs.
- Two wells (Well 02 and Well 18) average less than 1 cfs.
- Seventeen wells average less than 0.5 cfs.

4-3. Capacity Calculation Methods

The historic flow data were the inputs used for the new screen capacity calculations. The new stainless steel screens will need to pass the maximum discharge from each well while keeping the entrance velocity below 0.1 ft/s. An entrance velocity over 0.1 ft/s can cause head loss through the well and can cause incrustation of the screen, which further reduces a screen's intake area and transmitting capacity. To determine if the selected screen met this requirement we compared the total transmitting capacity of the new screen to the maximum and mean historic discharge. The diameter of the screen had to be small enough (8-in) to fit into the existing wells (12 in diameter) with enough room to allow filter pack to be tremied into the annular space around the screen. The capacity calculations informed the design, but we prioritized installing only 8-in diameter screens so we can install filter pack in the annular space. With 10-in screen we could not fit a tremie pipe into the annular space and fill it with filter pack. Because we do not want to install new wells, but only rehabilitate the existing wells, the new screen diameter and lengths are limited by the existing wells dimensions. Therefore, to provide sufficient transmitting capacity we chose a well screen slot size that had the most open area that was also compatible with the coarse sediment in the abutment. The selected screen was 100 slot (0.100-in). Transmitting capacity for a 1-foot section was calculated from the screen manufacturer sheets that list the screen types and intake area. Transmitting capacity is intake area * 0.31 (Driscoll, 1986), and for the screen we selected, this is 171 square-inch (sq-in) * 0.31 = 53.01 gallons per minute per foot (gpm/ft). Next we multiplied the transmitting capacity times the total length of new screen. This gave us the total new screen transmitting capacity for each well. Next we divided the total transmitting capacity by the maximum flow and then the mean flow to find the factor of safety for each well. Mr. Powers set up the spreadsheet, and I used his template to re-calculate the lengths and transmitting capacity as the team made design decisions.

4-4. Capacity Calculation Results

Appendix, Table A- 3 gives the results of these calculations. Figure 4-5 shows the results in a chart. For most wells, the new screens have enough transmitting capacity to pass the maximum flow out of the well. Wells 16, 20, and 20A have a factor of safety below one, and could not pass the maximum discharge. Figure A- 1, Figure A- 2, and Figure A- 3 show frequency histograms of the flow measurements from 1980 to 2013. The red bins are the discharge that the wells would not be able to fully pass. These wells can pass the mean flow, only well 20A has a factor of safety below one for mean flow. The 100 slot screen with an 8-in diameter and about 30 ft in length is sufficient to pass maximum flow in most wells.

4-5. Capacity Analysis

The 100 slot, 8-in diameter screen allows most wells to pass their historic discharge. Two of the three wells that can't pass the maximum discharge, can pass the mean discharge. Well 20A has a factor of safety below one for both maximum and mean discharge, but because this well is only 3-ft deep, and does not pass much flow, we decided preventing failure of the screen and installing a filter pack is more important than keeping the entrance velocity below 0.1 ft/s. Another factor is that the relief tunnel has a gravel drain below the tunnel floor. This drain contains a perforated tile pipe. It is unknown how much flow out of the wells actually flows through the gravel drain. Based on our experience with a similar relief tunnel in western Washington (Howard Hanson Dam), we assume some of the discharge through the wells is from the gravel drain in to the well. We found that at Howard Hanson Dam the gravel drain was transmitting a higher percentage of the total discharge than the relief wells. This means the CJD relief wells don’t necessarily need to transmit all of the historic flow, and being able to transmit the mean flow is sufficient. The transmitting capacity calculations give us a good estimate for how long each screen needs to be, but we decided to weigh that calculation lower than the priority to install filter pack and new screens in each well.

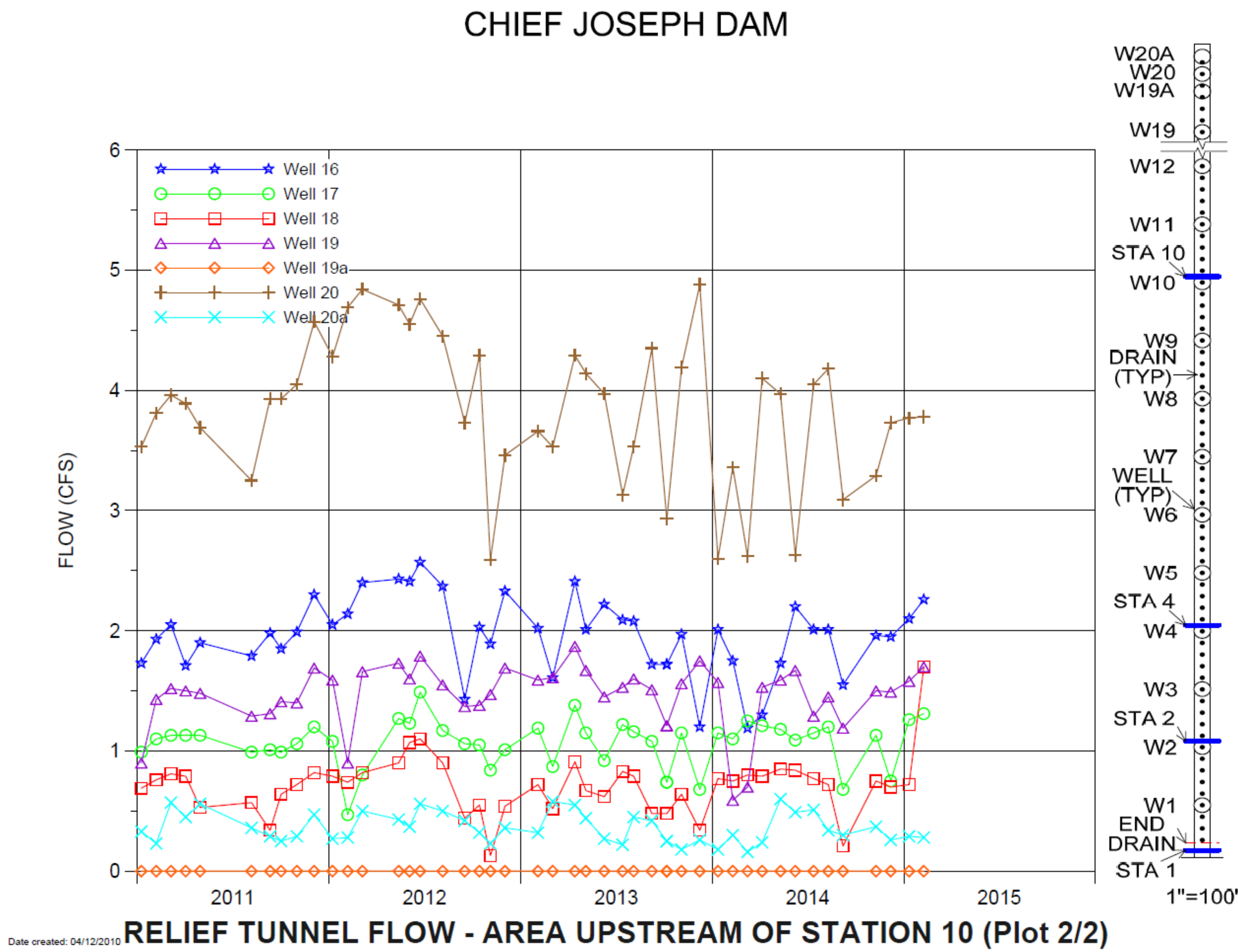

Figure 4-2: Example Plot from Instrumentation Web Site with Flow at Wells 16 to 20A.

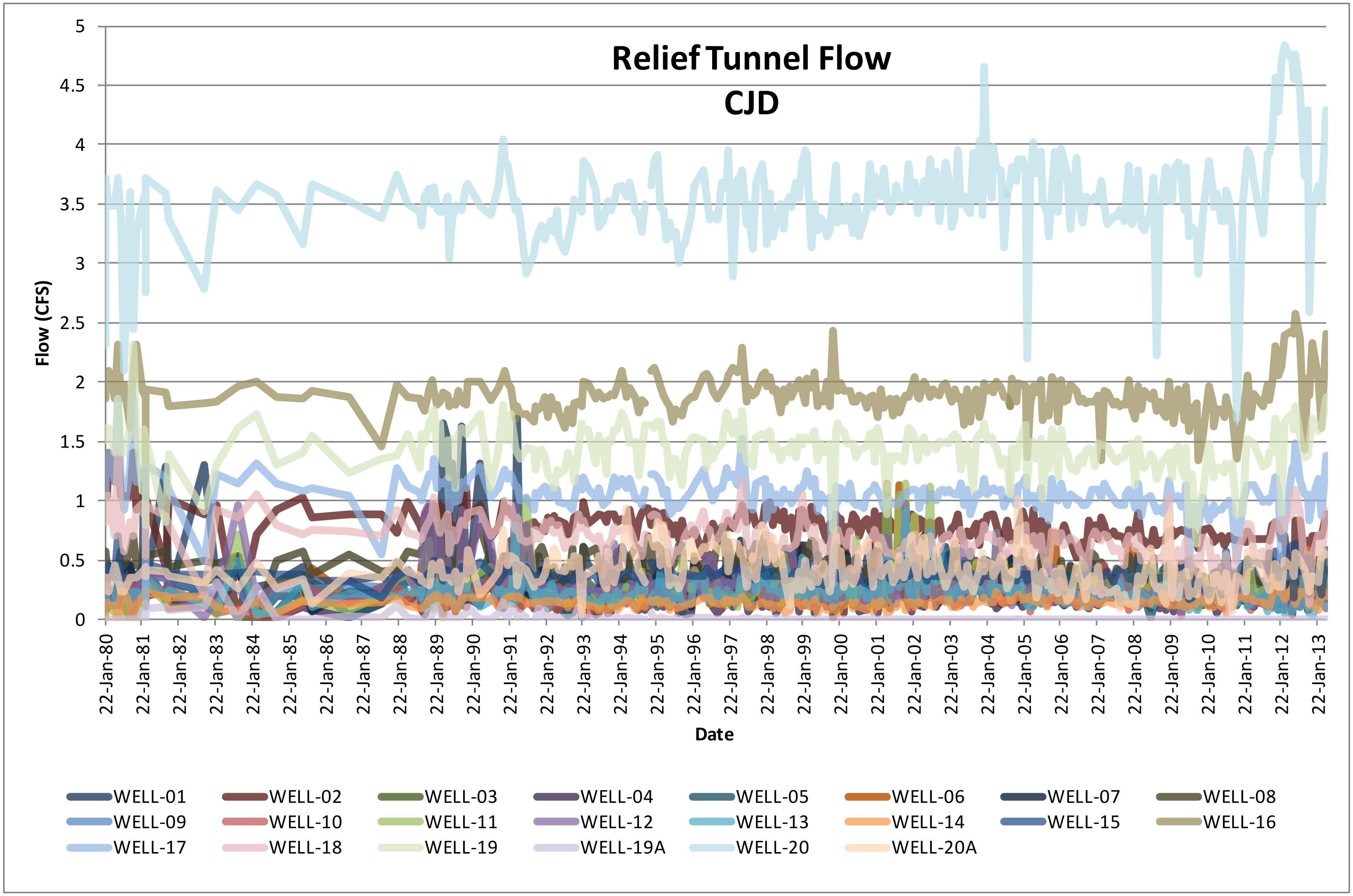

Figure 4-3: Historic Relief Tunnel Flow 1980 to 2013.

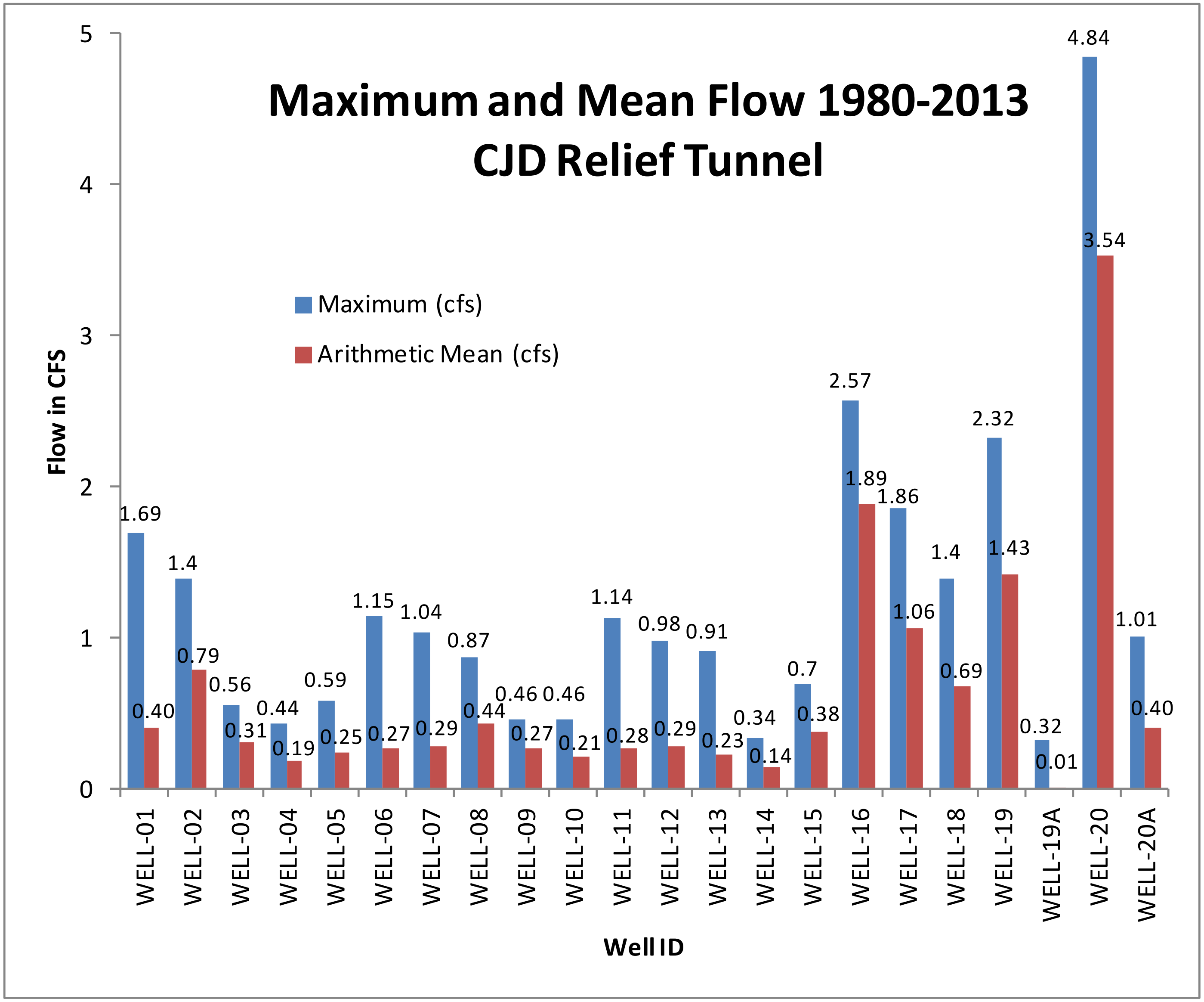

Figure 4-4: Historical Maximum and Mean Flow in the Relief Tunnel for each Well.

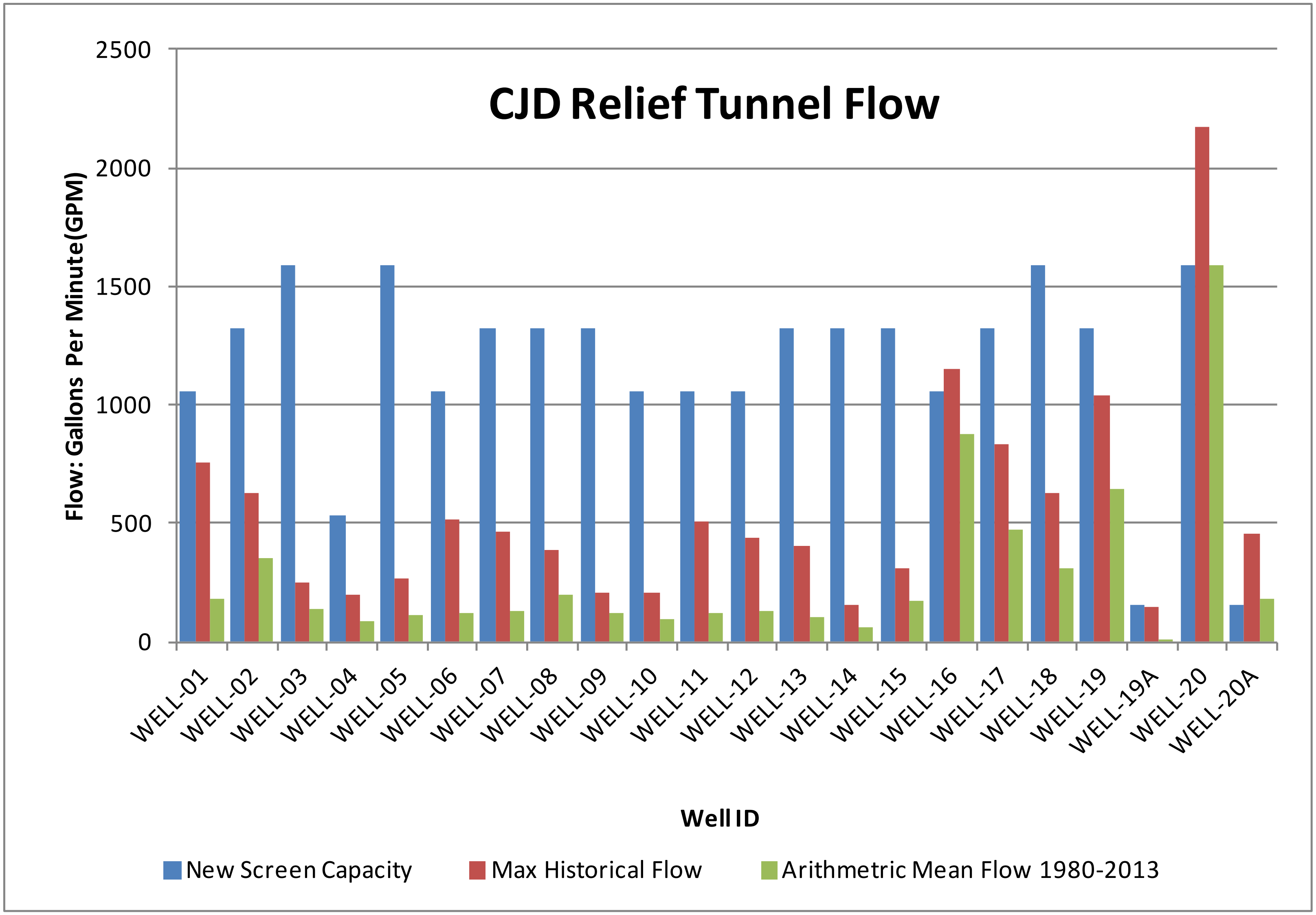

Figure 4-5: Historic Max and Mean Flow in each Relief Well Compared to the Calculated New Screen Capacity.

5. FILTER PACK DESIGN

5-1. Methods and Data Sources

To determine the appropriate filter pack I used the spread sheet in Figure A- 4 and Figure A- 5 to calculate the gradation of an appropriate filter for the base material. The spreadsheet helps us design a filter pack that is coarser than base soil, is uniform (not gap graded), and fits within a max and min grain size related to the base soil. The spreadsheet is based on the methods described in USACE Engineering Manual documents EM 1110-2-2300 and EM 1110-2-1901 for designing a filter pack.

Goals for the filter pack include:

- Prevent backwards erosion and piping in right abutment. To do this we need to ensure that when the current wooden screens collapse, material cannot exit the formation.
- Filter needs to prevent movement of sediment from entering the wells (reduce inlet velocity). Sand accumulating at the bottom of the stairs shows us material is moving out of the wells.
- Slot size needs to be large enough to maintain current capacity of the wells.
- Filter needs to be more permeable than the base material to pass water into the relief well.
- Filter needs to be small enough to fit down 1-in tremie pipe so that we can prevent bridging and segregation while installing the filter pack.
- Filter and Slot size needs to be compatible.

Some constraints and assumptions on the filter pack design:

1. We don’t have gradation information for the openwork gravel with silt that the wells are built in. For the gradation of the base material we used a Unified Soil Classification System (USCS) poorly graded gravel with silt and sand (GP-GM) based on prior descriptions of the formation (Figure 5-1 and Figure 5-2).
2. We don’t know if the measured flows are only from groundwater entering the wells, or if some of the water is from the gravel drain. Based on the measuring method, the flows could include flow from the gravel drain. In addition, we prioritized installing filter pack over keeping the inlet velocity below 0.1 ft/s.

3. There's a concern with the high upward velocity out of the wells that fine grained filter material would be unable to overcome the hydraulic pressures and fall to the bottom of the well during installation. We accommodated this concern by using the coarsest grain size distribution that can also fit into the 1-in tremie pipe. We assume larger particles will be more likely to overcome these hydraulic pressures. These construction limitations were taken into consideration in addition to the gradation calculated using the spreadsheet in Figure A- 4 and Figure A- 5. In addition, we've informed the contractor of our concern and suggest that the contractor use water while installing the filter pack. This will allow the particles to flow down the tremie pipe and should help the filter overcome hydraulic pressure.

5-2. Filter Pack Data Inputs and Methods

The first step of a filter pack analysis is to enter the base soil gradation. There are no site specific gradation analyses for the abutment material. We used a theoretical poorly graded gravel with silt and sand (GP-GM) gradation based on the description of the abutment materials (Table 5-1). The front part of the tunnel from Well 2 until just before Well 12 is described as the gravel with clay (Figure 5-1). The tunnel from Well 12 to the back of the tunnel and Well 20A is bedded gravel, sand, and openwork gravel with clay. Figure 5-2 shows the description of the openwork gravel from the Foundation Report for CJD (USACE, 1957).

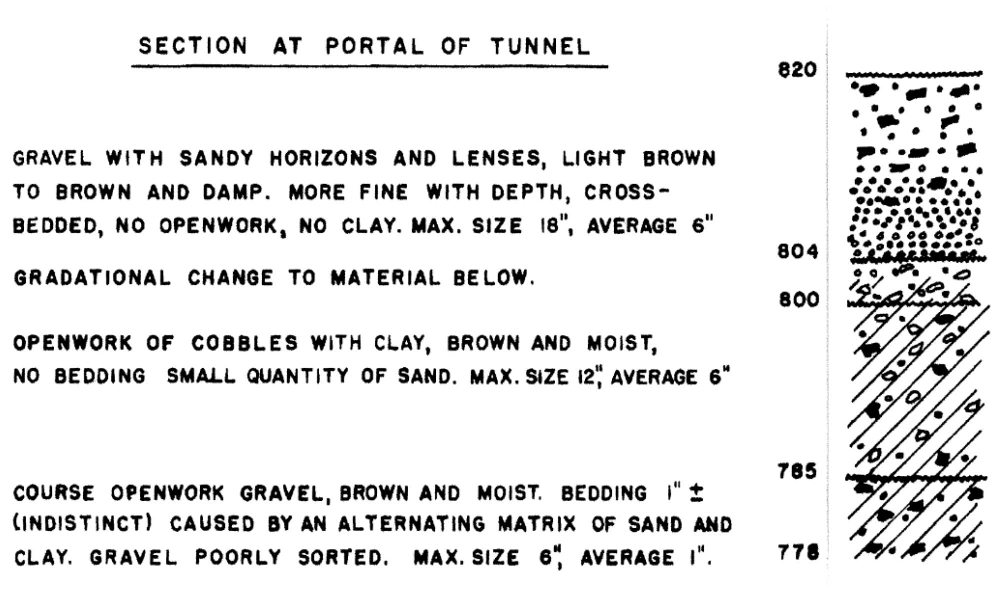

Figure 5-1: Relief Tunnel Excavation Units from CJP-08M-288.

(5) Openwork Gravel. The horizon which lies below the dump moraine and the disturbed gravel above, has been described as openwork gravel because a large proportion is lacking in sand and has open interstices, partially filled with brown clay. Sizes range from boulder to sand with the material placed in lenses which show stratification within themselves. Clean, well graded sand and gravel lenses are found throughout the mass. A. S. Cary *(1950) described deposits of openwork gravel and presented information on origin and engineering importance.

Figure 5-2: Description of Openwork Gravels from the 1957 CJD Foundation Report.

Table 5-1: GP-GM Base Material Used in the Filter Analysis.

Particle Size (mm)	Sieve #	Base Soil, % Passing
19	-	100%
12.7	-	77%
9.5	-	61%
4.75	4	41%
2.0	10	29%
1.18	16	25%
0.6	30	21%
0.425	40	19%
0.15	100	13%
0.75	200	10.4%
0.001	-	0.0%

The spreadsheet plots the base gradation curve in red (Figure A- 4). When the base soil contains gravel sized particles (greater than the No. 4 sieve, or 4.75 mm), then the base soil is adjusted so that only particles less than the No. 4 sieve are plotted. The percent passing total includes all particles less than the No. 4 sieve, this is plotted in blue.

Next I selected candidate filters from a list of options in the spreadsheet. This showed me how the candidate filter compared to the adjusted filter. The candidate filter is plotted in orange.

1. Adjusted down so that no particles are larger than ½-in to fit into the tremie
2. Compatible with slot size (0.100 in)
3. Permeability is based on the base soil before regrading, and is 3 to 5 times the d_{15} of the base soil.

5-3. Selected Filter Pack

The selected filter pack is 3/8-in pea gravel (Table 5-2). The standard specifications for concrete aggregates, ASTM C33: 02a, Table 2: grading requirements for coarse aggregates, Size # 8, matches this specification. This filter pack should be easy to find and is fairly consistent across different manufacturers and suppliers of gravel.

Table 5-2: Filter Specification: 3/8-in Pea Gravel.

Standard sieve size	Equivalent grain size (mm)	Coarse band limit – percent finer	Fine band limit – percent finer
1/2-inch	12.70	100	100
3/8-inch	9.51	80	100
#4	4.76	10	30
#8	2.36	0	10
#16	1.19	0	5
#200	0.074	0	2

Permeability Criterion is the measure that seepage will flow more quickly through the filter than through the base soil. This ensures water will drain into the relief well. The calculation for this is the 15 percent of the filter material divided by the 15 percent of the unadjusted base material should be ≥ 3 to 5 (EM 1110-2-1901, appendix D).

For this candidate filter pack and base soil: D_{15} Base (unadjusted) = 0.2123 mm, D_{15} Candidate = 4.99 mm for the upper bound, and 2.81 mm for the lower bound. This gives permeability criterion range of 23.5 to 13.25. These values are greater than 3 to 5, so the candidate filter is more permeable than the base soil.

5-4. Selected Filter Pack Rationale

The selected filter pack meets our objectives. It is compatible with a 100 slot screen, it is uniform, has the largest diameter grain at 3/8-in and less which will fit into a 1-in tremie pipe, is large enough to fall against the water flow up the well, and is more permeable than the base soil. 3/8-in pea gravel is a common size for gravel suppliers, so the contractor would not need to have the filter material specifically sieved. Additional specifications were included to clarify that for the filter pack must consist of a hard, clean/washed, and rounded to sub-rounded gravel.

6. NOT-SELECTED REHABILITATION OPTION EVALUATION

During design, I considered an additional option. The team was concerned that Option 6 would take too long to construct and that the cost for labor would be too high. Option 7 is to: Line existing wells with standard well screens and no sand and gravel backfill, but this option was not selected.

This option would consist of lining the existing wooden stave wells with rod-based wire-wrapped stainless steel well screen. The diameter of the stainless steel screen would be such that it fits inside the existing wooden screen, with about 1.5-in open area between the steel screen and the wooden stave. A larger diameter screen with a larger capacity could be installed in certain wells because the annular space for filter material and a tremie pipe is not needed. The stainless steel screen would have sufficient open area to pass flows in excess of the maximum observed historical flow at each well. Screen segments would be in 5-foot increments that could be threaded together and could be installed relatively easily and quickly with respect to other well rehabilitation options. The annular space between the old and new well screens would not be filled with filter backfill. Not installing filter backfill cuts down on cost of materials, decreases labor for moving and installing, and avoids any difficulties with installing the filter pack due to the hydraulic pressure of the drains with higher flow volumes acting against gravity. The steel screen could be removed for inspection, maintenance, or repair. This would allow us to view the wooden stave pipe condition. The disadvantages of not adding sand and gravel backfill is that the new screens would be unstable without the stability provided by the filter backfill. Also, the new screens could become clogged because the new screens alone do not reduce all movement of fine sediments toward the new well screen. The annular space between the old and new screens would provide room for the 12-in diameter screen to collapse into, potentially allowing void space to develop under the tunnel floor. It is estimated this method of rehabilitation would take 8 field work days to complete. The weight of each 5-foot screen segment is only 49 pounds, making manual installation of wells utilizing this design easier than for the pre-packed screens. This option is not recommended for all wells because it does not ensure the long-term stability against wooden stave pipe collapse, and it does not prevent future piping of sediments through the wells.

Table 6-1 compares rehabilitation options 6 and 7.

Table 6-1: Comparison of Rehabilitation Options 6 and 7.

Rehabilitation Option	Advantages	Disadvantages
6. Line existing wells with standard continuous-slot well screen and filter backfill between new and old wells	• Relatively low cost • Design is least restrictive on passing of maximum flows • Relatively quick to install • Relatively light and easy to handle 5-ft screen segments compared to pre-pack screen. • Filter material stabilizes screen in the borehole • Provides filtering protection against erosion. • Filter designed specifically for the formation. • Less annular space between new and existing screen means wooden screen collapse is less likely to lead to void space or movement of material into the well.	• Screen liners are not removable • Potential difficulty overcoming hydraulic pressure to install filter
7. Line existing wells with standard well screens and no sand and gravel backfill. (8” diameter screen or 10” diameter screen)	• Screen liners would be removable for inspection and maintenance. • Relatively quick to install • Relatively low cost • No potential difficulty overcoming hydraulic pressure to install filter • 10” screen has an annular space too small for filter material, and the annular space is smaller than with an 8” screen.	• Does not ensure new screen stability nor prevent collapse of the wooden screens • Allows movement of fine sediment , which could clog the screen • 8” screen leaves a larger annular space which could lead to larger void spaces around screen and under the tunnel floor • 10” screen has an annular space too small for filter material; the top caps wouldn’t have a filter port. This option doesn’t allow for inspection of the filter level which could indicate the condition of the wooden screen, could not monitor the wooden screen without removing the entire screen assembly. • Well collapse could mean the gravel drain would fall into the annular space, leaving a void under the tunnel floor. • Installation of the 10” screen is more likely to damage the existing wood screen or the new screen when it’s installed.

6-1. No-Filter Pack Design Evaluation

Option 7 leaves empty annular space around the screen in between the old and new casing (Figure 6-1). I assumed the wooden stave screens will eventually collapse. The collapse will likely be at one defined section of the cylinder screen, and some of the 1-foot radius cylinder of pea gravel will fall into the annular space. The pea gravel will fill in the annular space volume while dropping the surface height of the pea gravel under the tunnel floor around the well (Figure 6-1).

The likelihood of all well screens collapsing at once is low, but the wood screens in all the wells will eventually collapse. The likelihood of a screen collapsing all the way around the well is moderate because if part of a screen breaks, then the rest of the screen is more likely to collapse. We want to avoid an open area below the tunnel that could increase the risk of seepage and piping or internal erosion initiation within the right abutment.

I calculated the needed volume of fill between the old and new screens to determine the potential void volume. The calculation is based on the formula for a cylinder:

$$v=\pi * r^2 * h$$

To account for the difference between the depth of screen (measured depth) and the depth of the new screen (screen length) I subtracted the cylinder volume of the new screen from the cylinder volume of the current wells. This calculation includes the radii of the old wells and the new screens: 12-in (0.5-foot radius) diameter minus volume of outer diameter (OD) of new 8-in screen (0.3625-foot radius). The 8-in screen was used because that allows filter material to be installed at a later time.

$$v= (\pi * 0.5\text{ft}^2 * \text{measured depth ft}) – (\pi * 0.3625\text{ ft}^2 * \text{screen length ft})$$

This gives us the volume in cubic feet (ft^3) as seen in Table 6-2 and Figure 6-2. Table 6-2 and Figure 6-2 both include the volume around the screen, the volume under the screen (below the lower limit of the proposed stainless-steel screens, and the total volume of filter required for each well. This calculated volume equals the potential void space around each well. I calculated the void space for all wells.

The fill volume around the screen length is dependent on the length of the screen. It ranges from 7.7 ft^3 to 11.4 ft^3; with most wells at 9.5 ft^3. Well 4 and Well 19A have the shortest screen lengths and the lowest volume around each well at 4.0 ft^3 and 1.4 ft^3, respectively. For most wells, the volume around the screen is greater than the volume under the screen. This means that most of the potential void volume is from an absence of filter material around the length of the screen, not the volume under the screens. Only putting filter below the screens would not prevent void collapse for most wells, so filter pack should be installed both under and around the screens to prevent void space from forming.

The two exceptions are Wells 4 and 6 that have end plugs obstructing the bottom of the wells. These two wells have volumes below the screens that exceed the volume around the screens. The obstructions prevent the installation of longer screen and leave a larger void space below the new screens. Because the end plugs are dislodged, this means it is even more important to install filter pack into these wells to prevent the movement of sediment. These two wells will require extra attention to ensure filter pack is tremied around the obstructions.

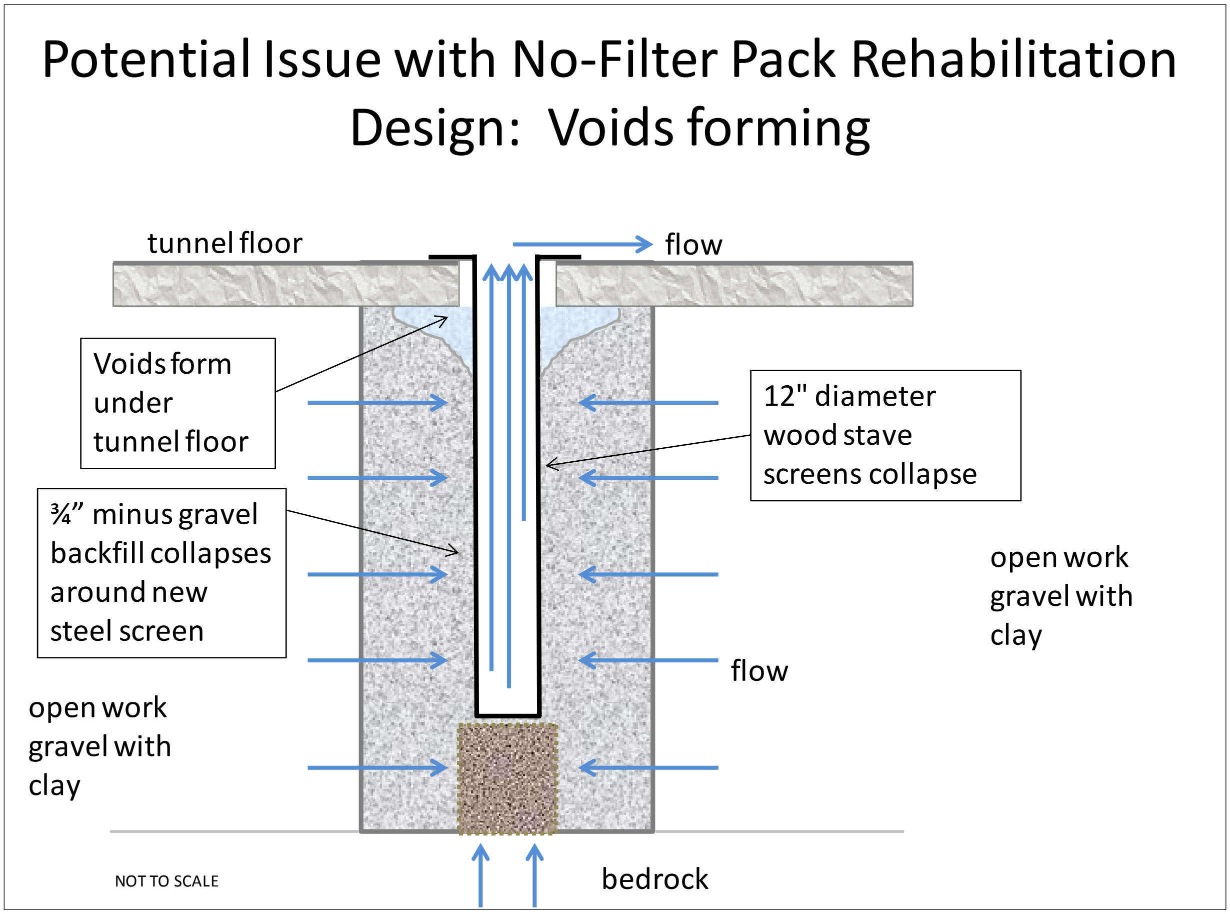

Figure 6-1: The Potential Issue with Option 7 is Forming Voids Under the Tunnel Floor.

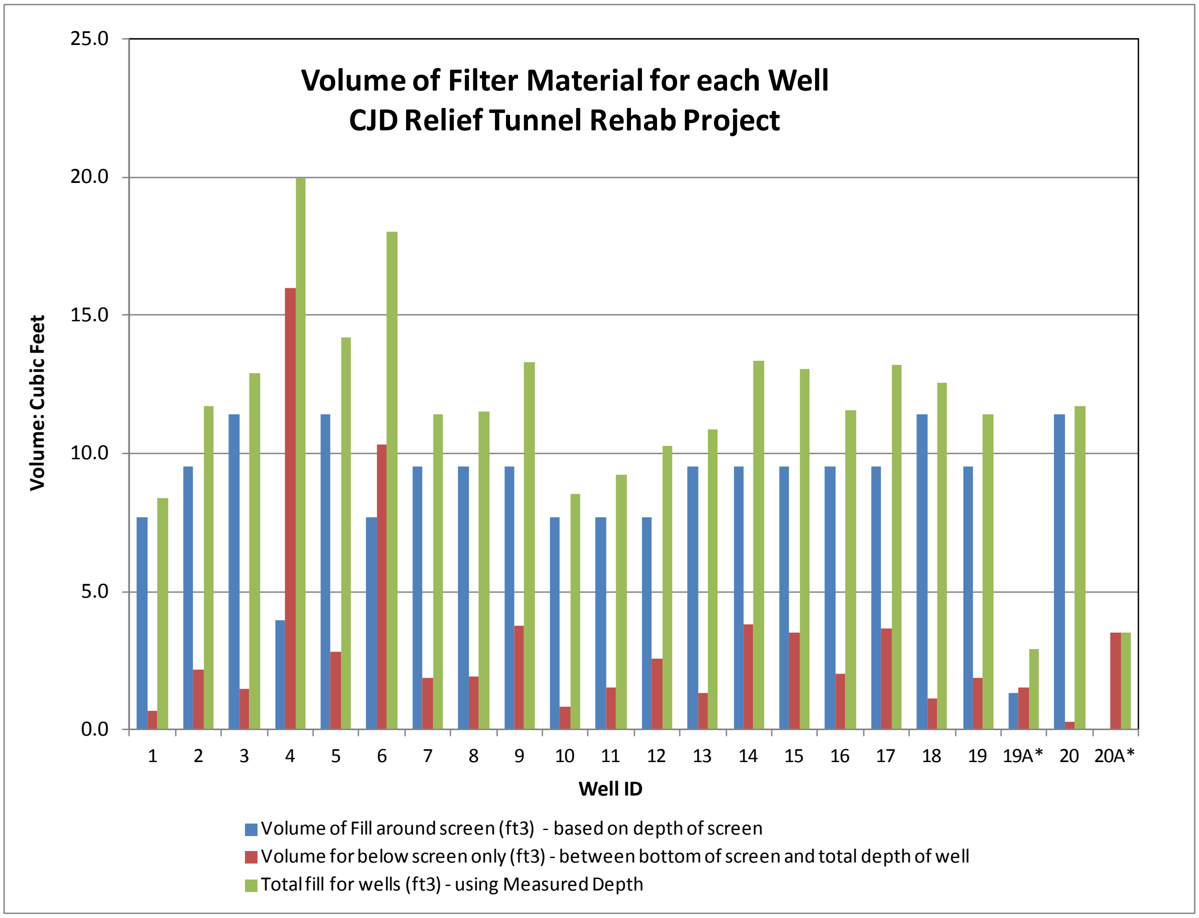

Figure 6-2: Volume of Filter Material for Each Well in the CJD Relief Tunnel.

Table 6-2: Calculated Volume of Filter Pack

Well	Measured Depth of Well (ft) - Depth to be filled with Filter	Screen Length (ft)	Volume of Fill around screen (ft^3) - based on depth of screen	Volume for below screen only (ft^3) - between bottom of screen and total depth of well	Total fill for wells (ft^3) - using Measured Depth	Notes for End Plug Obstructions That impact length of screen in the well.
1	21.5	20.625	7.7	0.7	8.4	
2	28.4	25.625	9.5	2.2	11.7	
3	32.5	30.625	11.4	1.5	12.9	
4	31.0	10.625	4.0	16.0	20.0	End plug at 12.6 ft.
5	34.2	30.625	11.4	2.8	14.2	
6	33.8	20.625	7.7	10.3	18.0	End plug at 21.7 ft.
7	28.0	25.625	9.5	1.9	11.4	
8	28.1	25.625	9.5	1.9	11.5	
9	30.4	25.625	9.5	3.8	13.3	
10	21.7	20.625	7.7	0.8	8.5	
11	22.6	20.625	7.7	1.6	9.2	End plug at 22 ft.
12	23.9	20.625	7.7	2.6	10.3	
13	27.3	25.625	9.5	1.3	10.9	
14	30.5	25.625	9.5	3.8	13.4	
15	30.1	25.625	9.5	3.5	13.1	
16	28.2	25.625	9.5	2.0	11.6	End plug at 24 ft.
17	30.3	25.625	9.5	3.7	13.2	
18	32.1	30.625	11.4	1.2	12.6	
19	28.0	25.625	9.5	1.9	11.4	
19A*	5.6	3.625	1.4	1.6	2.9	Difference between as-built and measured depth due to cobble fill.
20	31.0	30.625	11.4	0.3	11.7	Large diameter screens - no fill required
20A*	4.5	0.0	0.0	3.5	3.5	Difference between as-built and measured depth due to cobble fill. No Fill.
Total (ft^3):			**184.8**	**68.8**	**253.6**	

7. ASSUMPTIONS FOR THE DESIGN

We based the current design on the following assumptions:

The first is that the wooden staves will eventually fail. It appears the wood itself is in good condition and is not rotting or decomposing because it is always underwater and never exposed to air. However, concerns are raised because the wooden end plugs are in the middle of some of the wells, and no longer close off the formation from the well. We've assumed this is a sign the wells are deteriorating and will require repair. The dislodged end plugs allow the possibility of movement of sediment into the well, and out of the drainage tunnel.

Another concern is the white substance on the wells (likely mineral or bacteria). If this substance fills in the slots in the wooden screens it could reduce flow into the wells. When the wells are lined with the new stainless steel screens we will lose the ability to inspect the wooden staves and the slots. Ideally we would remove the wooden staves when we insert the new screens. However, it appears the wells were drilled before the pool at CJD was filled, and there was no water in the tunnel at that time. It would be very difficult to remove the wooden staves or even re-drill additional wells in the current wet conditions. It'd be difficult to fit a drill rig that'd be required to over-drill the current wells. The time to remove the wood staves and replace them would be on the order of months, which would require a lengthy tailwater restriction, which would be very costly in lost hydropower for Wells Dam downstream of CJD.

a) Removing the wooden staves would likely require a drill rig.

b) It would be difficult to fit the appropriate drill rig in the drainage tunnel.

c) The head of the reservoir and the rate of flow from the wells could make drilling and installing new wells difficult.

d) It would be expensive to drill from above the tunnel or within the tunnel.

The best solution is to install the new screens into the existing wells, and then monitor the piezometers above the drainage tunnel. Currently, the flow out of the wells and drainage tunnel is slightly decreasing, likely due to reservoir rim silting and sedimentation. We assume the flows from the drainage tunnel will continue to decrease due to the silting of the reservoir rim, reducing flow from the pool into the right abutment. Our assumption is that if the white substance does fill in the slots on the wooden staves we will notice reduced flows from the wells and drainage tunnel, but increased piezometer levels in the right abutment. Increased piezometers and decreased flow will mean the wells are not passing the flow necessary to lower water pressure in the right abutment. At that point a new measure will be required; this could include more relief wells in the drainage tunnel or rehabilitation of the current wells.

8. CONCLUSION

During inspections USACE geologists found the current wooden stave wells were in need of repair, and the 2012 Periodic Assessment report recommended the relief wells be repaired within 10 years. Our rehabilitation objectives are to continue to control the groundwater gradient in the right abutment, prevent the movement of sediment into the wells, stop total screen collapse, and prevent initiation of backwards erosion and piping. We selected option 6, line the existing wells with standard well screen with sand and gravel backfill between the screen and the existing wood staves. Options 1-5 and 7 were excluded because they did not meet the rehabilitation objectives. We used historical relief flow data and the as-built drawings to calculate the new screen capacities. Using these capacities and an informed estimate of the base soil in the right abutment, I determined the appropriate filter pack of a 3/8-in pea gravel. During the filter pack analysis we considered the option of not placing filter pack in the well around the screen, and found that this option would not meet our rehabilitation goals. Any potential void spaces that could occur under the tunnel floor were large enough to exclude that option. The final method is to place new 8-in diameter, 100 slot stainless steel screens into the existing wells and fill the annular space with 3/8-in pea gravel and install a new top cap to hold the system in place. The 5-foot screen lengths can be carried by hand down the stairs and will fit in the short height of the tunnel. This rehabilitation method meets our requirements. After the project is complete, we will continue to monitor the piezometers in the right abutment. This project will be constructed in September 2015, and this report should be attached as an appendix to the final construction report.

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APPENDIX: TABLES, FIGURES AND TERMS

Appendix Tables

Table A- 1: Advantages and Disadvantages of Rehabilitation Options 1-5. 41
Table A- 2: Relief Well Observation Summary. 42
Table A- 3: Screen Capacity Calculations. 44

Appendix Figures

Figure A- 1: Frequency of flow out of Well 16 limited by new screen design. 45
Figure A- 2: Frequency of flow out of Well 20 limited by new screen design. 45
Figure A- 3: Frequency of flow out of Well 20A limited by new screen design. 45
Figure A- 4: Filter Pack Analysis Worksheet pt 1. 46
Figure A- 5: Filter Pack Analysis Worksheet pt 2. 47

Terms

From ER 1110- 2-1156, Safety of Dam.

Abutment: That part of the valley side against which the dam is constructed. The left and right abutments of dams are defined with the observer viewing the dam looking in the downstream direction.

Dam: An artificial barrier, including appurtenant works, constructed for the purpose of storage, control, or diversion of water.

Embankment: A raised structure of earth, rocks, or gravel, usually intended to retain water or carry a roadway.

Filter: One or more layers of granular material graded (either naturally or by selection) so as to allow seepage through or within the layers while preventing the migration of material from adjacent zones.

Periodic Assessment: The periodic assessment consists of a periodic inspection, a potential failure modes analysis, and a risk assessment based on existing data and a minimum development of limited consequence data.

Relief Well: A vertically installed well consisting of a well screen surrounded by an annulus of filter material, commonly attached to a riser pipe with discharge control. Relief wells are installed for the purpose of relieving seepage or excess groundwater pressures from beneath a confining layer or structure (From ER 1110-2-1942).

Tremie (Tremie Pipe): A method where a pipe (or the pipe that) is used to place filter material around a screen. Placing the filter pack through a tremie pipe prevents segregation of the particles and bridging around the screen.

Table A- 1: Advantages and Disadvantages of Rehabilitation Options 1-5.

Rehabilitation Option	Advantages	Disadvantages
1. Install new wells & decommission old wells	• Use of larger mechanized equipment means less manual labor	• Required installation from top of right abutment, necessitating 1,000's of ft of extra drilling • Drill sites on severe slope with limited access • High cost • Prolonged tailwater restrictions
2. Overdrill old wells & install new wells in their place	• Use of larger mechanized equipment means less manual labor • Decommissioning of existing wells not required	• Required installation from top of right abutment, necessitating 1,000's of ft of extra drilling • Drill sites on severe slope with limited access • High cost • Prolonged tailwater restrictions
3. Redevelop existing wells	• Lowest cost • Relatively quick	• Does not accomplish main rehabilitation objective
4. Install pre-pack screen liners in existing wells, no additional filter between pre-pack and wood stave	• Screen liners would be removable should servicing be required • Relatively quick	• Relatively high cost • Heavy screens difficult to maneuver • Wells with high flows cannot use this design
5. Install pre-pack screen liners in existing wells, with additional filter between pre-pack and wood stave	• Highest level of filtering protection against erosion/piping	• Relatively high cost • Heavy screens difficult to maneuver • Screen liners are not removable • Wells with high flows cannot use this design • Potential difficulty overcoming hydraulic pressure to install filter

Table A- 2: Relief Well Observation Summary.

Relief Well ID	Distance within tunnel (ft)	Floor Elevation (ft)	As-built Bottom Elevation (ft)	As-built Depth (ft)	9/11/11 Measured Depth (ft)	4/14/13 Depth (ft)	3/09/14 Measured Depth (ft)	Observations
1	45	783.45	NA	NA	-	-	21.5	Wires at about 4 ft bgs and 20 ft bgs. There is a lot of orange debris/fouling. The material accumulates on the joints between stave sections and in the screen openings. A thin layer of sand and fine gravels accumulated on top of this orange material. Sand and sediment at the bottom of the well. Wood appears to be in fair condition.
2	95	783.95	751.1	32.85	29.2	28.4	-	Slots look partially blocked by a white substance. A slat in the wood stave pipe is damaged below the joint at about 12 feet. A screwdriver, wood debris, gravel and white substance are at the bottom of the well.
3	145	784.45	750.5	33.95	-	-	32.5	Wire across well at 25 ft bgs. Top 10 ft of the well has more white hair-like (fibrous) material in the screen openings. Movement of the material shows flow into the well. Some sand and sediment at the bottom of the well. Wood appears to be in fair-good condition.
4	195	784.95	753.1	31.85	31	12.6	-	A piece of wire was stretched across the well at about 12 feet. The camera broke it off as it was lowered down the well. The camera only made it down to an approximate depth of 12.6 feet because of an obstruction blocking half of the diameter of the well. The obstruction could be part of the end plug of the well that got forced up. The wood stave pipe above this depth is in good condition. Obstruction at 12.6 ft. 2011 video showed wire and part of end plug partially obstructing at 12.6 ft.
5	245	785.45	749.2	36.25	35	34.2	-	The slots are partially blocked by a white substance. There was fine gravel and a wire mesh screen sitting on the bottom of the well.
6	295	785.95	748	37.95	21.7	33.8	-	A piece of wire was stretched across the well at about 10 feet. The camera broke it off. There was an obstruction at approximately 21.7 feet that prevented the camera to pass. The obstruction was likely the end plug of the well that got forced up. The open depth of the well below the obstruction is unknown. Tape initially caught on partial obstruction at 26.0 ft. Partial obstruction in 2011 reported at 21.7 ft. (video showed to be end plug vertically aligned).
7	345	786.45	754	32.45	-	-	28	Sand and sediment at the bottom, not much flow out of this one. Staves appear to be in good shape. Less white and orange material than the other wells inspected today. However, this well has small gravels on the joints between sections, and some hard white material in the screen openings. Wood appears to be in very good condition.
8	395	786.95	756.7	30.25	-	28.1	-	Top cap screen could not be removed in 2011, Measured in 2013, televiewed 01/11/15. No obstructions. Top cap screen is on the bottom of the well, with a few gravels on it. Appears that the gravels sank to bottom of well in the past two years since the top cap was removed. Side-view camera shows large sand, small gravel particles in the slots of the wooden casing. Wood appears to be in good condition.
9	445	787.45	756.4	31.05	29.7	30.4	-	Slots are partially blocked by white substance. Pipe joints are offset at about 21 feet. Sand and fine gravel at bottom of well.
10	495	787.95	754.9	33.05	22.6	21.7	-	Slots are partially blocked by a white substance. Fine gravel in the bottom of the well

Relief Well ID	Distance within tunnel (ft)	Floor Elevation (ft)	As-built Bottom Elevation (ft)	As-built Depth (ft)	9/11/11 Measured Depth (ft)	4/14/13 Depth (ft)	3/09/14 Measured Depth (ft)	Observations
11	545	788.45	755.2	33.25	22	22.6	-	Slots are partially blocked by a white substance. Wood is obstructing the well at about 22 feet. It appears to be the end plug of the well that got forced up. Fine gravel and debris in the bottom of the well below the wood obstruction.
12	595	788.95	763.2	25.75	24.7	23.9	-	Slots are partially blocked by a white substance. Fine gravel in the bottom of the well.
13	645	789.45	760.8	28.65	28.1	27.3	-	Slots are partially blocked by a white substance. Gravel in the bottom of the well.
14	695	789.95	757.5	32.45	-	-	30.5	No obstructions, wooden staves appear to be in good condition. Sediment at joints between sections, and some hard white material in screen openings. Sand and sediment at the bottom of the well. Wood appears to be in good condition.
15	745	790.45	759.5	30.95	31	30.1	-	Slots appear to be clogged with a white substance near the top of the screen. Gravel was sitting in the joint at about 21 feet. Wood stave pipe appeared to have grind marks on the inside of it. Gravel and blue glass in the bottom of the well. High flows through slot could be detected by movement of white substance in slots.
16	795	790.95	762	28.95	28	28.2	-	At 24 ft wood obstructed the well preventing the camera to pass. The wood may be the end plug for the screen at the bottom of the well.
17	845	791.45	759.2	32.25	30.7	30.3	-	Wood, glass, glove, and sand and gravel at the bottom of the well. Wood stave pipe is slightly offset at the joint at about 12 feet below the tunnel floor.
18	895	791.95	758.3	33.65	32.3	32.1	-	Medium to coarse sand and broken light bulbs at the bottom of the well. The as-builts show the formation at the bottom of this well is sand.
19	945	792.45	764	28.45	28.5	28	-	Slots appear partially clogged with white substance. Fine to coarse gravel at the bottom of the well. Flow up through the gravel was observed.
19-A	980	792.8	777.9	14.9	-	-	5.6	Half of the screen was broken to allow insertion of the downhole camera. The second half of the screen is at the bottom of the hole. The well is only 5.6' deep, there are cobbles filling the well. Small gravels sit in the horizontal joints between staves. Wood appears to be in good condition.
20	995	792.95	762	30.95	31.3	31	-	Upper half of screen had gray/white substance growing on or attached to it. Medium to coarse sand, fine gravel and a few cobbles at the bottom of the well. Flow through sand could be detected.
20-A	1010	793.1	778.2	14.9	5.5	4.5	-	Cobbles and broken steel screen at bottom of well.

Table A- 3: Screen Capacity Calculations.

	WELL-01	WELL-02	WELL-03	WELL-04	WELL-05	WELL-06	WELL-07	WELL-08	WELL-09	WELL-10	WELL-11	WELL-12	WELL-13	WELL-14	WELL-15	WELL-16	WELL-17	WELL-18	WELL-19	WELL-19A	WELL-20	WELL-20A
As-built depth (ft)	?	32.9	34	31.9	36.3	38	32.5	30.3	31.1	33.1	33.3	25.8	28.7	32.5	31	29	32.3	33.7	28.5	14.9	31	14.9
Measured depth (ft)	21.5	28.4	32.5	12.6	34.2	33.8	28	28.1	30.4	21.7	22.6	23.9	27.3	30.5	30.1	28.2	30.3	32.1	28	5.6	31	4.5
Total new screen length (ft)	20	25	30	10	30	20	25	25	25	20	20	20	25	25	25	20	25	30	25	3	30	3
Screen nominal diameter (in)	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Screen continuous slot size	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Screen-compatible filter emplaced?	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	Yes	Yes
Transmitting capacity new screen (gpm/ft)[1]	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01	53.01
Total transm. cap. new screen (gpm)	1060.2	1325.25	1590.3	530.1	1590.3	1060.2	1325.25	1325.25	1325.25	1060.2	1060.2	1060.2	1325.25	1325.25	1325.25	1060.2	1325.25	1590.3	1325.25	159.03	1590.3	159.03
Max historical flow (gpm)	758	628	251	197	265	516	467	390	206	206	512	440	408	153	314	1153	835	628	1041	144	2172	453
Arithmetic mean flow 1980-2013 (gpm)	180	353	139	86	112	121	130	198	122	94	124	128	101	64	172	874	476	308	641	5	1587	181
Is total transm. cap. new screen > max historical flow?	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	NO	NO
Factor of safety avail (tot trans cap/max hist flow)	1.4	2.1	6.3	2.7	6.0	2.1	2.8	3.4	6.4	5.1	2.1	2.4	3.2	8.7	4.2	0.9	1.6	2.5	1.3	1.1	0.7	0.4
Factor of safety (mean)	5.9	3.8	11.4	6.2	14.2	8.8	10.2	6.7	10.9	11.3	8.6	8.3	13.1	20.7	7.7	1.2	2.8	5.2	2.1	31.8	1.0	0.9

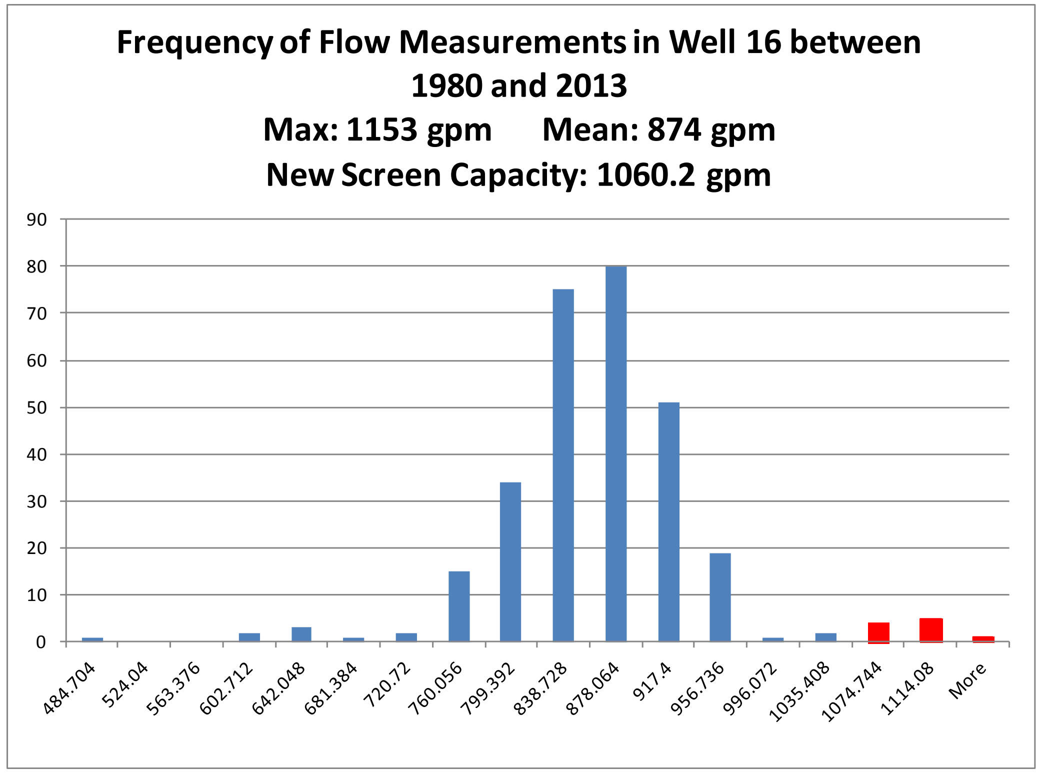


Figure A- 1: Frequency of flow out of Well 16 limited by new screen design.

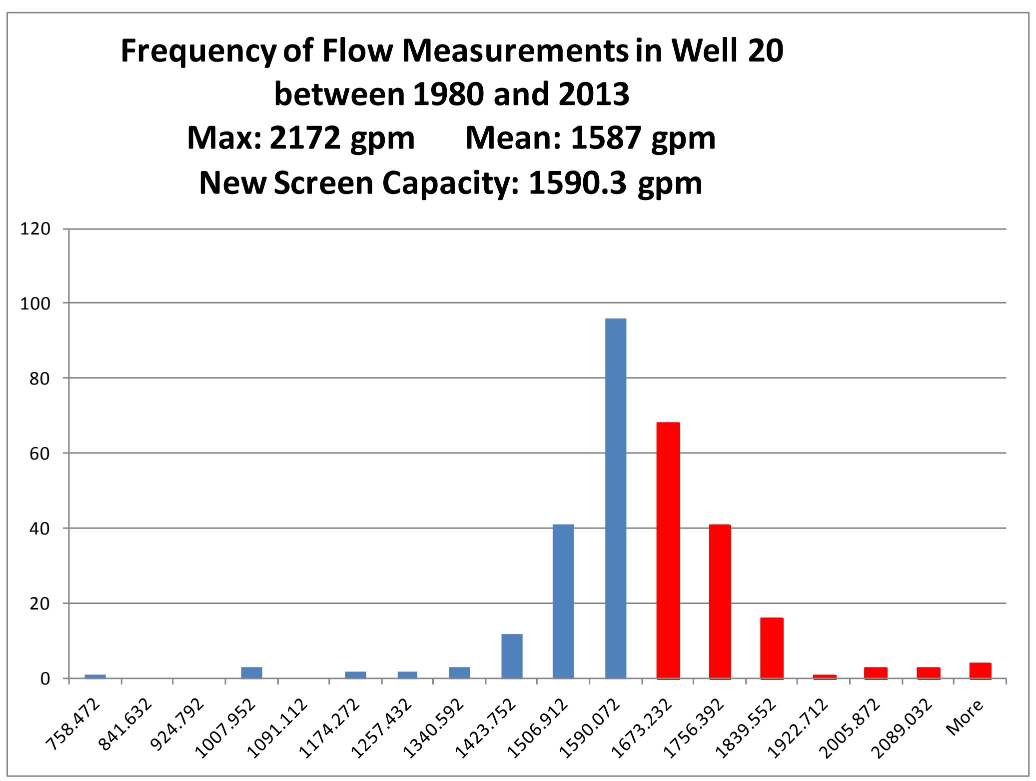


Figure A- 2: Frequency of flow out of Well 20 limited by new screen design.

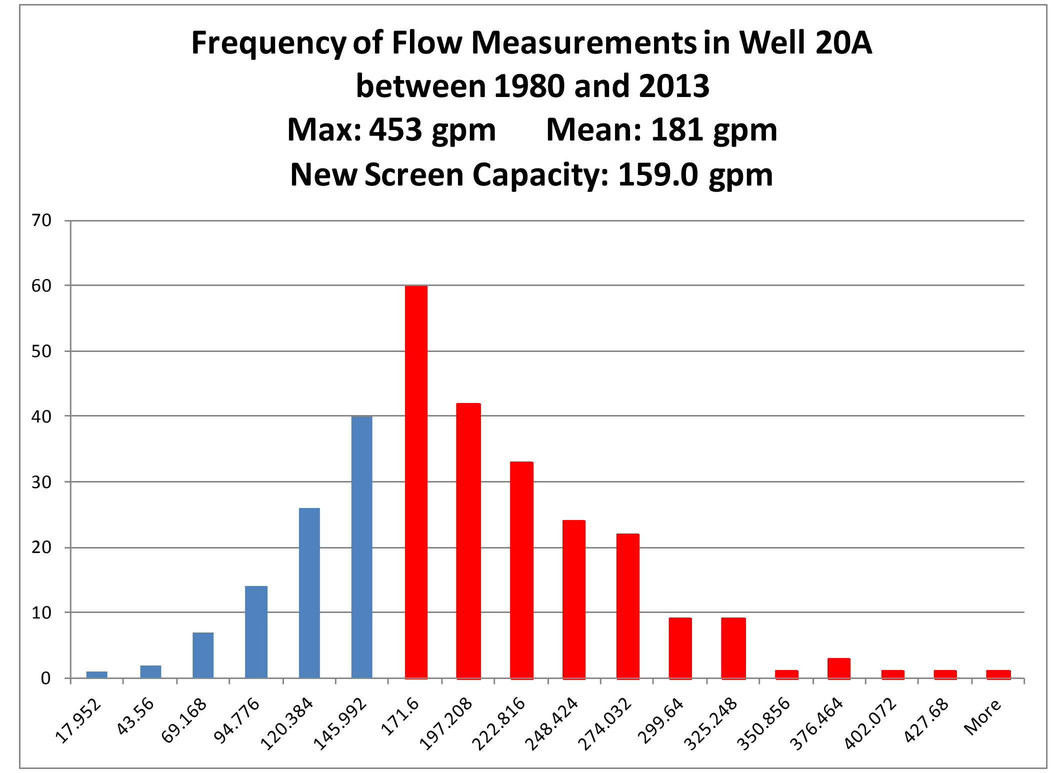


Figure A- 3: Frequency of flow out of Well 20A limited by new screen design.

Base Material

Determine the gradation curves of the base soil. Use enough samples to define the range of grain size for the base soil. Design the filter gradation based on the base soil that requires the smallest D_{15F} size. If soil has particles larger than the #4 sieve, an adjusted gradation is calculated. Input values below for the base soil (original) gradation (in red):

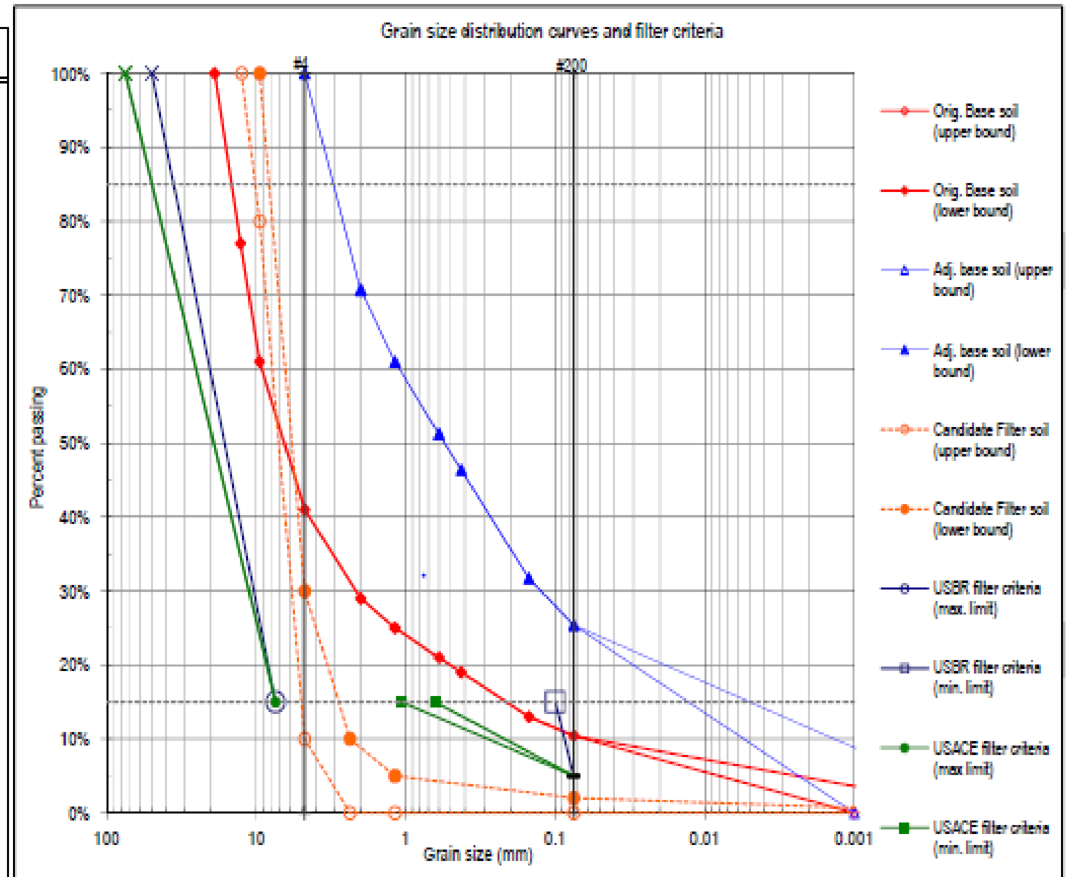
Project: CJD Relief Tunnel Well Rehab
GP-GM

Name: KAG
Date: 02/25/15

Particle size (mm)	Sieve #	Base soil (original), % passing (upper bound)	(lower bound)	Adjusted gradation, % passing upper bound	lower bound
25	-				
19	-	100.0%	100.0%		
12.7	-	77.0%	77.0%		
9.5	-	61.0%	61.0%		
4.75	4	41.0%	41.0%	100.0%	100.0%
4.00	5				
3.35	6				
2.80	7				
2.36	8				
2.00	10	29.0%	29.0%	70.7%	70.7%
1.70	12				
1.40	14				
1.18	16	25.0%	25.0%	61.0%	61.0%
1.00	18				
0.850	20				
0.710	25				
0.600	30	21.0%	21.0%	51.2%	51.2%
0.500	35				
0.425	40	19.0%	19.0%	46.3%	46.3%
0.300	50				
0.250	60				
0.212	70				
0.180	80				
0.150	100	13.0%	13.0%	31.7%	31.7%
0.125	120				
0.106	140				
0.090	170				
0.075	200	10.4%	10.4%	25.4%	25.4%
0.053	270				
0.037	-				
0.019	-				
0.009	-				
0.005	-				
0.002	-				
0.001	-	0.0%		0.0%	
0.0001	-	0.0%	0.0%	0.0%	0.0%

Required entry values are defined below. *

Average % passing #200 after regarding (if any) = A = 25.4%



Properties of base soil	Upper bound	Lower bound
D_{85B} of original base soil =	14.610 mm	14.610 mm
D_{85B} of adjusted base soil =	3.049 mm	3.049 mm
D_{15B} of original base soil =	0.2123 mm	0.2123 mm
D_{15B} of adjusted base soil =	0.0128 mm	0.0050 mm
D_{60B} of adjusted base soil =	1.103 mm	1.103 mm
D_{10B} of adjusted base soil =	0.0055 mm	0.0014 mm
C_u of adjusted base soil =	201.0	811.1

Fixed points on graph:
- ▬ <5% passing #200
- x 50mm max. grain size (USBR)
- x 75mm max. grain size (USACE)

Filter Material

Filter criteria required by the USBR as published in *Design Standards - Embankment Dams No. 13 (1994)*:

*Required entry values for base soil & candidate filter gradations:

Candidate filter soil gradation. Values shown in red in the left column, and all values in the two right columns, can be changed.

Acceptibility of candidate filter (CF) soil:

Figure A- 4: Filter Pack Analysis Worksheet pt 1.

D_{85B} used in filter design	3.049
Average Passing #200 sieve of base soil (from adjusted gradation)	25.4%
Base soil category	3
Base soil description	Silty and clayey sands and gravels
Filter criteria (mm)	Maximum: $D_{15F} \leq$ 7.43 To ensure sufficient permeability: Minimum: $D_{15F} \geq$ 0.10
Maximum particle size of filter (mm)	**50**
Maximum % passing # 200 sieve	5%
PI of material passing #40	0 when tested in accordace with USBR 5360, Earth Manual, on material passing #40

Filter criteria required by the US Army Corps of Engineers as published in EM 1110-2-2300 (31 Jul 94):

D_{85B} used in filter design	3.049
Average Passing #200 sieve of base soil (from adjusted gradation)	25.4%
Base soil category	3
Filter criteria (mm)	Maximum: $D_{15F} \leq$ 7.43 to 7.43 To ensure sufficient permeability: Minimum: $D_{15F} \geq$ 0.64 to 1.06
Maximum particle size of filter (mm)	75
Maximum % passing # 200 sieve	5%
PI of material passing #40	0 when tested in accordance with EM 1110-2-1906

**If the base soil is in category 4, use the lower of the two 'max. D_{15F}' values when the filter is beneath riprap subject to wave action or beneath drains which may be subject to violent surging and/or vibration.

1. Particle size for 100% passing.
2. % Passing the #4 sieve.
3. % Passing the #200 sieve.
4. One point in the 85% - 90% range and another point in the 80% - 85% range, or the 85% point.
5. One point in the 15% - 20% range and another point in the 10% - 15% range, or the 15% point.
6. No duplicate entries; if D100<#4, enter 101% for #4 and 100% for appropriate size.

USBR filter gradation limits:

Maximum limit	
Grain size (mm)	% Passing
50.00	100.0%
7.43	15.0%

Minimum limit	
Grain size (mm)	% Passing
0.10	15.0%
0.075	5.0%

USACE filter gradation limits:

Maximum limit	
Grain size (mm)	% Passing
75.00	100.0%
7.43	15.0%
7.43	15.0%

Minimum limit	
Grain size (mm)	% Passing
0.64	15.0%
1.06	15.0%
0.075	5.0%

Particle size *mm*	Sieve #	% Passing (upper bound)	% Passing (lower bound)
150.0	-		
100.0	-		
90.0	-		
75.0	-		
63.0	-		
50.0	-		
37.5	-		
25.0	-		
19.0	-		
12.5	-	100.0%	
9.5	-	80.0%	100.0%
4.75	4	10.0%	30.0%
3.35	6		
2.36	8	0.0%	10.0%
2.00	10		
1.70	12		
1.40	14		
1.18	16	0.0%	5.0%
0.850	20		
0.600	30		
0.425	40		
0.300	50		
0.250	60		
0.212	70		
0.180	80		
0.150	100		
0.125	120		
0.106	140		
0.090	170		
0.075	200	(0.0%)	(2.0%)
0.053	270		
0.037	-		
0.019	-		
0.009	-		
0.0001	-	0.0%	0.0%

Required entry values are defined above. *

Properties of candidate filter soil (CF). D sizes are in mm:					
	D_{85CF}	D_{15CF}	D_{60CF}	D_{10CF}	C_U
upper bound	10.17	4.99	7.79	4.75	1.64
lower bound	8.19	2.81	6.39	2.36	2.71

USBR criteria	Upper bound	Lower bound
Max % passing #200:	OK	OK
Max particle size (mm):	OK	OK
Maximum D_{15CF}:	OK	OK
Minimum D_{15CF}:	OK	OK
To minimize segregation (from *Table 2*)***		
Max allowable D_{90CF} =	40	OK
Max D_{90CF} =	10.90	

USACE criteria	Upper bound	Lower bound
Max % passing #200:	OK	OK
Max particle size (mm):	OK	OK
Maximum D_{15CF}:	OK	OK
Minimum D_{15CF} ($3 \times D_{15B}$):	OK	OK
Minimum D_{15CF} ($5 \times D_{15B}$):	OK	OK
To minimize segregation (from *Table B-3*)***		
Max allowable D_{90CF} =	40	OK
Max D_{90CF} =	10.90	

Filters should be relatively uniform (see the C_U value of the candidate filter soil.). Also, filters should not be gap-graded.

*** Generally, this requirement is only necessary for coarse filters and gravel zones that serve as both filters and drains. For sand filters with D_{90} < ~20mm, these limitations are usually not necessary.

Figure A- 5: Filter Pack Analysis Worksheet pt 2.