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Effects of Rock Riprap Design Parameters on Flood Protection Costs for Uranium Tailings Impoundments

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ABSTRACT

This report examines the costs of rock riprap flood protection for design flood events at two uranium tailings impoundments in western Colorado. The two sites are the Grand Junction impoundment located along the Colorado River and the Slickrock impoundment located along the Dolores River. The sensitivity of rock type, embankment side slope, and various safety factors is evaluated for six design flood events at Grand Junction and one flood event at Slickrock. The safety factor method of riprap design is used for the cost comparison.

SUMMARY

The Pacific Northwest Laboratory (PNL) is studying the problem of long-term protection of earthen covers on decommissioned uranium tailings impoundments. The major erosive forces acting on these covers will be river flooding and overland flow from rainfall-runoff. For impoundments adjacent to rivers, overbank flooding presents the greater potential for significant erosion. To protect the earthen covers against flood erosion, rock riprap armoring will be placed over the cover surface. Because of the large size rock usually required for riprap, the quarrying, transport, and placement of the rock could be a significant part of the decommissioning cost.

This report examines the sensitivity of riprap protection costs to certain design parameters at tailings impoundments. The parameters include flood discharge, riprap materials, impoundment side slopes, and an added safety factor. Two decommissioned tailings impoundments are used as case studies for the evaluation. These are the Grand Junction, Colorado, impoundment located adjacent to the Colorado River and the Slickrock, Colorado, impoundment located adjacent to the Dolores River. The evaluation considers only the cost of riprap protection against flood erosion.

The study results show that embankment side slope and rock specific gravity can have optimum values or ranges at a specific site. For both case study sites the optimum side slope is about 5H:1V. Of the rock sources considered at Grand Junction, the optimum specific gravity would be about 2.50; however, an optimum rock specific gravity for the Slickrock site could not be determined. Other results indicate that the arbitrary safety factor usually added in riprap design can lead to large increases in protection costs.

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1.0 INTRODUCTION

Many decommissioned uranium tailings sites are located within major river flood plains, requiring that site reclamation measures include protection against flooding. Armoring slopes with riprap is one of the most common methods for flood erosion protection and is considered a principal alternative for protection of uranium tailings impoundments against soil erosion. A U.S. Nuclear Regulatory Commission (NRC) objective in the siting and design of tailings impoundments is to eliminate or reduce disruption by natural forces to the extent reasonable (Scarano and Lineham 1978). To accomplish this objective, tailings impoundments situated within major flood plains are designed to withstand very large flood events (e.g., the probable maximum flood or PMF).

The purpose of this report is to evaluate the sensitivity of flood protection costs to rock riprap design parameters at tailings impoundments situated within flood plains. Two case studies of decommissioned sites located within flood plains are the basis for this evaluation. These are the Grand Junction, Colorado, impoundment located within the flood plain of the Colorado River, and the Union Carbide Corporation's Slickrock, Colorado, impoundment located within the flood plain of the Dolores River.

This report is a companion to two other reports. These reports present the results of two case studies of decommissioned uranium tailings impoundments that evaluate rock riprap protection requirements for long-term stabilization of the earthen covers:

1. The Selection and Testing of Rock Riprap for Uranium Tailings Impoundments. NUREG/CR-3747 (PNL-5064) (M. G. Foley, C. S. Kimball, D. A. Myers and J. M. Doesburg, 1984)

2. Effects of Hydrologic Variables on Rock Riprap Design for Uranium Tailings Impoundments. NUREG/CR-3752 (PNL-5069) (W. H. Walters and R. L. Skaggs, 1984).

In this report, riprap protection designs are based on the Safety Factor Method, which is discussed in only enough detail to develop and evaluate costs associated with different design factors. The riprap protection designs presented for the two case studies are preliminary and should be considered as working estimates for study purposes. The final designs for the two sites would require a much more detailed engineering study. A detailed discussion of riprap design methods has been given by Walters (1982). This report is not concerned with flood protection measures other than riprap, nor is an evaluation of the level of risk of failure made relative to the design parameters. Nelson et al. (1983) discuss alternative reclamation measures and risks of failure.

Sections 1 and 2 of this report are the introduction and conclusions. Section 3 discusses design parameters used in the analysis of costs for riprap protecion. The design parameters include the design flood hydraulics; riprap materials; and embankment side slopes. Section 4 is concerned with the Grand Junction impoundment. An evaluation is made of the required rock sizes, area of impoundment requiring flood protection, volume of riprap, and filter material requirements. Section 5 deals with the Union Carbide Corporation's Slickrock impoundment where a similar evaluation is performed. Cost estimates for the Grand Junction and Slickrock tailings impoundments are developed in Section 6; the sensitivity to changes in the design parameters is discussed.

2.0 CONCLUSIONS

The results of this study demonstrate that riprap design parameters such as side slope angle and rock specific gravity can have optimum values or ranges for a specific impoundment site. An added safety factor will increase costs significantly, but this increase is less site-specific than other variables.

The safety factor is normally added to the median diameter of the riprap and, therefore, has a direct effect on the overall gradation and cover thickness. The increase in rock size for a constant value of safety factor becomes larger as the design shear stress increases, which corresponds to an increase in design flood discharge. Thus, the higher the design flood discharge, the more the safety factor increases the final median diameter. The design flood used for tailings impoundment riprap protection will likely be limited to the PMF event. The actual selection of the value of safety factor will have more of an impact on the design economics because it is selected based on engineering judgment and usually varies from 1.5 to 2.0. Using a safety factor of 2.0 at the Grand Junction and Slickrock impoundments could result in cost increases of as much as 60%.

By using the Safety Factor Method for riprap design, an optimum embankment side slope in terms of costs can be determined for the design flood conditions. At both the Grand Junction and Slickrock impoundments the optimum side slope is about 5H:1V. Above this value the rock size requirement increases significantly. For side slope values flatter than 6H:1V, the rock size requirement decreases very little, but the amount of earthwork and area to be protected become increasingly larger. This can significantly increase the costs of the riprap cover.

For the Grand Junction site the optimum specific gravity of the available rock sources considered was about 2.50 based on the PMF flood event, side slopes of 6H:1V, and a safety factor of 1.5. Above this approximate value an increase in rock density had little effect on the median diameter. For the Slickrock site there was no clearly defined optimum value of specific gravity.

The cost analysis indicated that the use of local rock, even though it had a lower specific gravity, could be more economical than using denser rock located farther from the site. In the case of the Grand Junction site, it was found that a cost savings of up to 45% could be realized by using local Dakota sandstone (specific gravity = 2.25) instead of the nearest limestones (specific gravity = 2.70), which are about 80 miles from the site. However, the use of basalts from the Grand Mesa (specific gravity = 2.65 to 2.75), about 40 miles from the site, would be comparable in cost to using local Dakota sandstone. The increase in costs would be about 5% for the basalt. The results point out the need to consider all sources of rock available in the area and, after determining if its durability is acceptable, to perform a sensitivity analysis using the various specific gravities.

3.0 DESIGN PARAMETERS AFFECTING COSTS FOR RIPRAP PROTECTION

Numerous procedures are available to the engineer in designing riprap covers for protection against the erosive forces of flowing water. The design procedures normally specify the size or weight of rock for given flow velocities or shear stresses and require the use of certain input parameters whose selection is based on either institutional constraints or best engineering judgment (i.e., the design flood hydraulics, physical properties of riprap materials and embankment side slopes).

3.1 SELECTION OF RIPRAP DESIGN METHOD

Design methods have been developed around the concept of the initiation of motion of a single particle. The Safety Factor Method for riprap design, developed by Stevens and Simons (1971) and Stevens, Simons and Lewis (1976), was identified by Walters (1982) as the preferable choice for designing riprap protective covers for uranium tailings impoundments. The Safety Factor Method provides a greater degree of control in estimating the size and weight of rock to be placed on the uranium tailings impoundment. The safety factor can be more accurately utilized to account for such uncertainties as magnitude of the design flood, localized scour, and durability of rock. This method is used to estimate the size of rock required for riprap protection of the Grand Junction and Slickrock uranium tailings impoundments.

The safety factor (SF) in this method is defined as:

$$SF = \frac{\text{moments of forces resisting rotation}}{\text{moments of forces tending to dislodge stone}} .$$

A safety factor equaling unity indicates critical conditions where incipient motion begins for the design flood conditions. A safety factor greater than unity indicates the riprap is considered safe from failure for the design flood conditions. A safety factor less than unity indicates instability with likely failure for the design flood conditions. Some margin of safety (SF>1) is normally included in the riprap design because of the assumptions in the development of the design method and the possibility that the actual local tractive forces on the riprap will exceed those used in the design.

Selection of the safety factor value in the riprap design can significantly affect riprap protection costs. The larger the safety factor used, the larger will be the required rock for the riprap protection. Since the protective cover thickness is dependent on rock size, a larger safety factor value will require a greater protective cover thickness and a correspondingly larger quantity of riprap.

3.2 SELECTION OF DESIGN FLOOD

Design flood analyses for conventional water resource projects are based on either a statistical analysis of historical data or maximization of hydrologic and meteorologic data to determine a PMF. Statistical analysis of historical floods is based on data seldom extending back in time more than 100 years with any continuity of record and, therefore, will not normally be sufficient for designing riprap protective covers for tailings impoundments. The PMF analysis, on the other hand, involves a much more detailed approach where the hydrologic and meteorologic processes are maximized to produce a flood that is considered to be the most severe reasonably possible (American Nuclear Society 1981). Where public safety is not involved, the 100-year flood, standard project flood (SPF), or 500-year flood is often used as the design flood for conventional water resource projects. In cases where public safety or nuclear projects are involved, the PMF has been used as the design flood (U.S. Nuclear Regulatory Commission 1982).

Although it is likely that the design of riprap protection of uranium tailings impoundments will be based on a conservative PMF analysis, this report also evaluates the costs for riprap protection using other statistical and empirical flood events for comparative purposes. Hydraulic data for rock riprap design have been computed for both the Grand Junction and Slickrock sites for several flood events. At the Grand Junction site the 100- and 500-year events, the Corps of Engineers SPF, and the PMF were used to develop design flood data (Walters and Skaggs 1984).

The only PMF estimate available for the Colorado River near Grand Junction was that prepared by R. W. Beck and Associates (1982) for the Una Reservoir site located about 40 miles upstream. The Una Reservoir PMF, developed on a feasibility level basis, was estimated at 130,000 cfs for a 7,370 mi^2 area. The Grand Junction PMF was determined by adjusting the Una Reservoir PMF to account for the greater drainage area at Grand Junction. The resultant PMF discharge for a drainage area of 8,900 mi^2 is 146,000 cfs.

As a rough check on the PMF calculations, the upper and lower limits of the Grand Junction PMF were estimated using the SPF (U.S. Army Corps of Engineers 1976). The Grand Junction SPF peak discharge was set at 70,000 cfs based on available peak discharge data and a selected exceedance frequency of 250 years. A Corps of Engineers empirical relationship indicates that the SPF is from 40 to 60% of the PMF (U.S. Army Corps of Engineers 1965). On the basis of this relationship, the upper and lower PMF limits were estimated to be 175,000 cfs (upper PMF) and 117,000 cfs (lower PMF). These two discharges were included in the hydraulic analyses.

Only the PMF discharge was considered for a design flood event at the Slickrock site. It was estimated using a procedure similar to the one used for the Grand Junction site. The Slickrock PMF was determined by adjusting the PMF for the McPhee Dam site (809 mi^2) based on the increased drainage area (1430 mi^2) at the Slickrock site. The McPhee Dam site PMF had been previously determined by a U.S. Bureau of Reclamation study (1974). The PMF peak discharges for the McPhee Dam and the Slickrock sites are 46,100 cfs and 54,700 cfs, respectively.

The hydraulic data for all flood events were computed using HEC-2 water surface profiles (U.S. Army Corps of Engineers 1979). The data are presented in Sections 4 and 5 of this report.

3.3 SELECTION OF RIPRAP MATERIALS

Rock for use as riprap should be highly durable and should produce fragments in suitable sizes and weights to resist the design forces on the protective cover layer. Lack of durability of the selected rock may allow mechanical and/or chemical weathering to reduce the rock sizes below acceptable design limits. Lack of suitable rock within reasonable haul distances of the tailings impoundment may require the use of less durable local rock in either larger size fragments or greater protective cover thicknesses to offset the weathering process. Costs associated with the use of less durable rock could be higher because of the larger quantity of rock required to provide the same protection as highly durable rock.

The specific gravity of the rock can also have an effect on the costs. The size of rock for a given safety factor increases with decreasing specific gravity so that larger volumes of less dense rock will be required to provide the same degree of protection as that of higher density rock.

Preliminary suitability evaluations of potential riprap materials in the vicinity of the Grand Junction and Slickrock tailings impoundments have been performed by Foley et al. (1984). Twenty-seven samples were collected and simple field tests were performed on potential sources of riprap. This report assumes that the durability of the sampled rock is adequate for providing long-term protection.

3.4 SELECTION OF SIDE SLOPES

The selection of embankment side slopes for riprap protection will have a direct bearing on construction costs. For a given design flood, flatter side slopes will require riprap protection of a larger area with associated higher costs. The side slopes, in part, determine the required rock size and thickness of the protective cover. With steeper side slopes the rock size must be larger and the protective cover layer thicker. However, the decrease in area using steeper side slopes may offset the increased quantity of rock needed to achieve the greater protective cover thickness.

The Final Generic Environmental Impact Statement (FGEIS) on Uranium Milling (U.S. Nuclear Regulatory Commission 1980) recommends the use of reduced slope gradients on tailings impoundments to minimize potential erosion. Although slope gradients of 10H (horizontal):1V (vertical) are specified, it is noted in the FGEIS that these specified slope gradients may be impractical due to site-specific factors. The side slopes of the decommissioned aboveground uranium tailings impoundments are often steeper than 10H:1V, requiring extensive slope cutback or fill to be used to reduce the slope gradients. In some cases, such as the Grand Junction and Slickrock tailings impoundments where rivers front portions of the impoundment, slope cutback will be required to achieve 10H:1V slopes. This will greatly increase construction costs due to excavating, handling, and relocating the tailings.

4.0 GRAND JUNCTION URANIUM TAILINGS IMPOUNDMENT

4.1 DESCRIPTION OF SITE

The Grand Junction tailings impoundment is a 65-acre tract located on the south side of the city of Grand Junction, Colorado. The mill site, including the tailings impoundment, is situated on the north bank of the Colorado River and is adjacent to the industrial center of the city. Uranium milling began in 1951 and was shut down in 1970.

The tailings impoundment shown in Figure 4.1 is about 59 acres in size and was stabilized in 1972 with a 6-in.-thick earth cover, vegetated with grass. The long axis of the impoundment runs east-west, paralleling the Colorado River, and at its longest point is about 2500 ft long. At its widest point at the eastern end of the impoundment, it is about 950 ft wide. An earthen dike was constructed along the south, east, and west sides of the impoundment to contain the tailings. Some riprap flood protection has been placed along the south side of the impoundment adjacent to the Colorado River. The toe of the tailings impoundment varies between 4569 and 4578 ft, mean sea level (MSL) along the northern, eastern and western sides of the impoundment. The river bed elevation on the south side of the impoundment is between 4552 and 4558 ft, MSL. The highest elevations are found along the eastern half of the impoundment, reaching an elevation of about 4612 ft, MSL. Existing embankment side slopes vary significantly along the impoundment. Side slopes of that portion of the impoundment fronting the Colorado River are generally steeper than 4H:1V and, in some cases, are steeper than 2H:1V. The side slopes on the north and east sides of the impoundment are generally flatter than 6H:1V. The side slopes on the west side of the impoundment are about 4H:1V.

4.2 GRAND JUNCTION FLOOD ANALYSIS

Hydraulic analysis of flood flows on the Colorado River at the Grand Junction impoundment has been performed by Walters and Skaggs (1984). Summaries of the hydraulic analysis, giving the discharge, flood stage, current velocity, hydraulic radius, energy slope, and shear stress for each of the flood events, are shown in Tables 4.1 and 4.2. Cross sections of the impoundment showing the flood stages are shown in Figure 4.2. The hydraulic characteristics at river mile (RM) 387.86 on the upstream end of the impoundment are more severe and will be used in this report for designing the riprap cover. The hydraulic characteristics in Tables 4.1 and 4.2 were computed along the south side of the impoundment, which fronts the Colorado River. The hydraulic analysis does not apply to the north and west sides of impoundment, which are not directly exposed to the flood flows. For estimating purposes it has been assumed that the flood stage and energy slope on the north and west sides of the impoundment are the same as on the south side of the impoundment, but because the flow

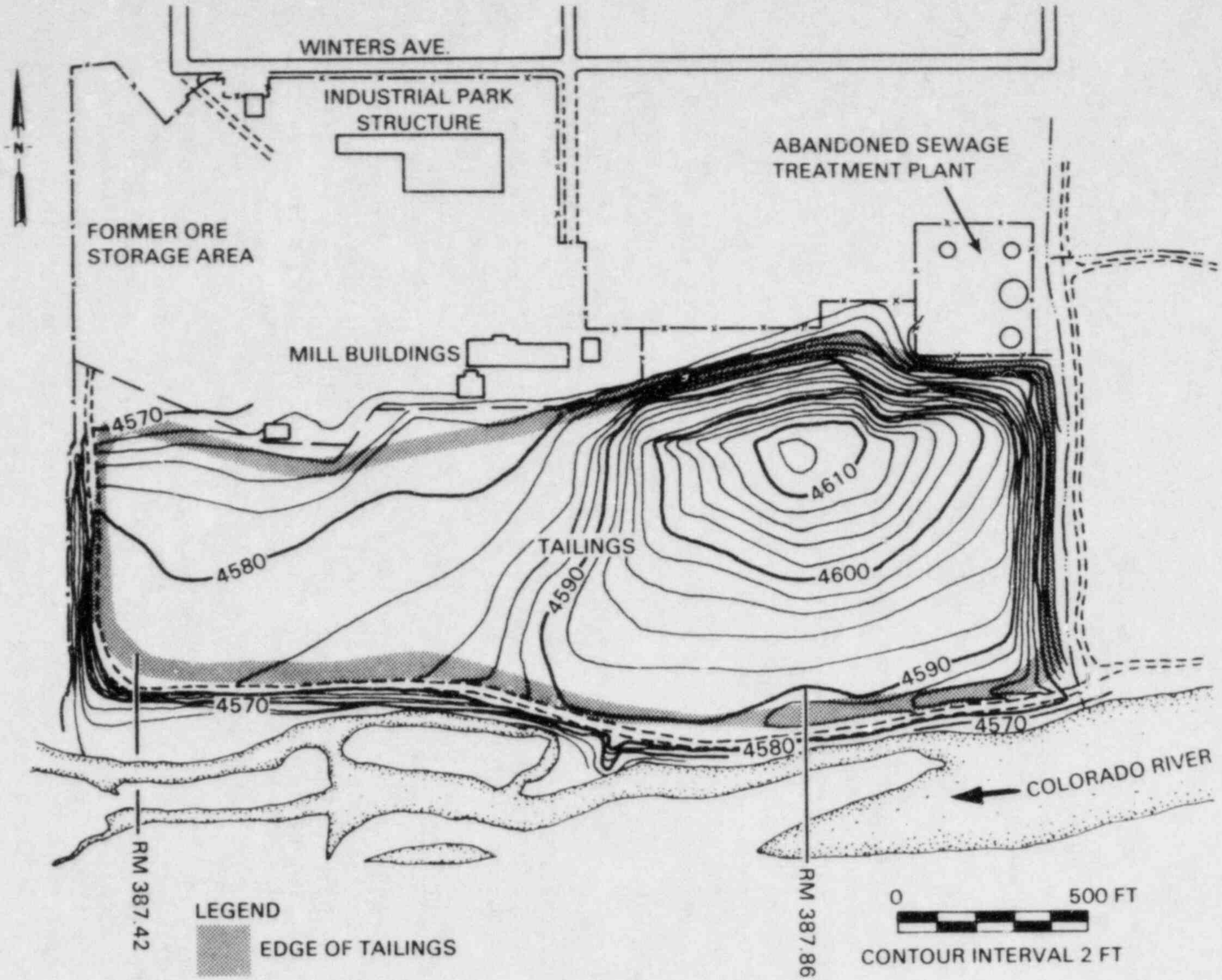

FIGURE 4.1. Grand Junction Uranium Tailings Impoundment (from Ford, Bacon and Davis Utah Inc. 1977)

TABLE 4.1. Hydraulic Characteristics of Various Flood Events at Colorado River Mile 387.86

Flood Event	Discharge[a] (cfs)	Stage (ft, MSL)	Velocity (fps)	Hydraulic Radius (ft)	Energy Slope (ft/ft)	Shear Stress (lb/ft^2)
Upper Limit PMF	175,000	4579.6	23.5	16.8	0.00419	4.40
Grand Junction PMF	146,000	4578.3	21.1	15.6	0.00373	3.64
Lower Limit PMF	117,000	4577.3	18.1	14.9	0.00344	3.20
500-yr Flood	82,000	4575.3	14.6	13.5	0.00283	2.38
SPF	70,000	4574.5	13.3	12.5	0.00260	2.03
100-yr Flood	63,000	4573.9	12.9	12.0	0.00245	1.83

(a) Main channel only.

TABLE 4.2. Hydraulic Characteristics of Various Flood Events at Colorado River Mile 387.42

Flood Event	Discharge[a] (cfs)	Stage (ft, MSL)	Velocity (fps)	Hydraulic Radius (ft)	Energy Slope (ft/ft)	Shear Stress (lb/ft^2)
Upper Limit PMF	175,000	4576.3	10.9	14.2	0.00410	3.64
Grand Junction PMF	146,000	4575.1	9.9	12.9	0.00356	2.87
Lower Limit PMF	117,000	4573.2	9.3	11.1	0.00327	2.27
500-yr Flood	82,000	4571.[illegible]	7.9	9.3	0.00269	1.56
SPF	70,000	4570.5	7.3	8.6	0.00248	1.33
100-yr Flood	63,000	4570.0	7.0	8.2	0.00235	1.20

(a) Main channel only.

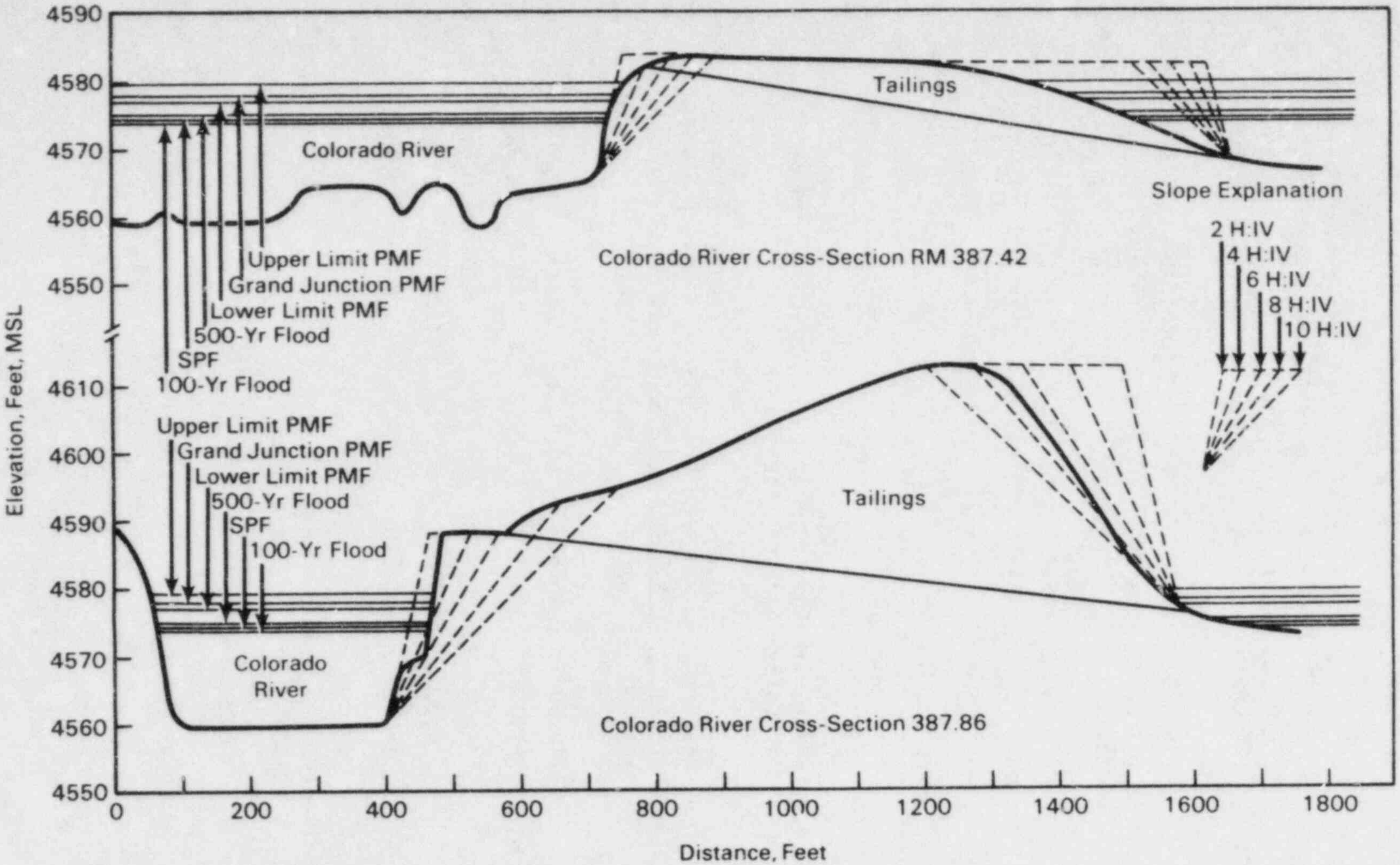

FIGURE 4.2. Grand Junction Impoundment - Median Rock Diameter of Riprap as a Function of Flood Flows and Side Slopes

depth is less, the corresponding shear stress on the riprapped slope is less. Approximate shear stresses for the various flood events based on the depth of flow on the north and west sides of the impoundment are shown in Table 4.3.

TABLE 4.3. Approximate Shear Stress on North and West Sides of Impoundment for Various Flood Events

Flood Event	Discharge[a] (cfs)	Flow Depth (ft)	Energy Slope (ft/ft)	Shear Stress (lb/ft^2)
Upper Limit PMF	175,000	7	0.00425	1.86
Grand Junction PMF	146,000	5	0.00373	1.16
Lower Limit PMF	117,000	4	0.00344	0.86
500-yr Flood	82,000	2	0.00283	0.35
SPF	70,000	2	0.00260	0.32
100-yr Flood	63,000	1	0.00245	0.15

(a) Main channel only.

4.3 EARTHWORK

The existing embankment side slopes of the Grand Junction impoundment fronting the Colorado River are too steep for the direct placement of riprap (Figure 4.2). Slope cutback is required along the south side of the impoundment because of its proximity to the Colorado River, but the use of fill is possible on the north, east, and west sides to obtain the desired side slopes. Estimated volumes of cut and fill material to achieve the different side slopes are shown in Table 4.4. About 257,000 yd^3 of material would have to be excavated for side slopes of 10H:1V. The volume of excavated material increases with decreasing side slopes. For side slopes of 4H:1V there is a fourfold decrease in the volume of excavated material to 55,000 yd^3.

Depending on the desired side slopes of the impoundment, some or all of the excavated material from the south side can be used to achieve the desired slopes on the north, east, and west sides of the impoundment. Except for side slopes of 4H:1V, the volume of excavated material on the south exceeds the volume fill on the other sides. This excess material can conceivably be used to make the slopes on top of the pile more uniform. For the purposes of this report, the excavated material obtained from cutting back the slope on the south side will be placed on the impoundment so excess material does not need to be hauled to an offsite disposal area.

4.4 ROCK RIPRAP SIZE

The required rock size for riprap protection below the design flood elevation is dependent on the design flood characteristics, the embankment side

TABLE 4.4. Cut and Fill Volumes to Obtain Indicated Side Slopes - Grand Junction Impoundment

Side Slopes	Cut Volume[a] (yd^3)	Fill Volume,[b] (yd^3)
10H:1V	256,700	124,700
8H:1V	186,000	97,800
6H:1V	121,300	88,500
4H:1V	55,000	131,700

(a) All the cut is on the south side of the impoundment. Values are rounded to nearest 100 yd^3.
(b) All the fill is on the north, east, and west sides of the impoundment.

slopes, the safety factor used, and the characteristics of the source rock. Tables A.1 through A.4 (Appendix A) summarize the required median diameter of rock at the Grand Junction tailings impoundment for specific gravities from 2.00 to 2.75, six different flood events, side slopes from 2H:1V to 10H:1V, and safety factors from 1.00 to 2.00. The median size of rock increases with decreasing specific gravity, and increasing flood flows, side slopes, and safety factor. Use of embankment side slopes of 2H:1V or greater does not appear to be technically feasible in many cases due to the large rock required for the higher flood events and safety factors greater than 1.0. As an example, the median rock diameter on the south and east sides of the impoundment for embankment side slopes of 2H:1V, the upper limit of the PMF, and a safety factor of 1.5 is 8.2 ft for rock with a specific gravity of 2.00.

4.4.1 Effect of Design Flood Characteristics on Rock Riprap Size

Figure 4.3 illustrates how the median rock diameter varies for each of the six flood events for the north and west sides and the south and east sides of the impoundment. A safety factor of 1.5, side slopes of 6H:1V, and specific gravity of 2.50 were used in computing the median rock diameter. For the south and east sides of the impoundment the median diameter increases from 0.7 ft for the 100-yr flood to 1.6 ft for the upper limit of the PMF. For the north and west sides of the impoundment the median diameter ranges from about 0.5 in. for the 100-yr flood to 0.8 ft for the upper limit of the PMF.

The median diameter of rock for protection against the SPF (70,000 cfs) on the south and east sides of the impoundment roughly corresponds to the median diameter of rock for protection against the upper limit of the PMF (175,000 cfs) on the north and west sides of the impoundment. Larger rock is required on the south and east sides of the impoundment because the flow

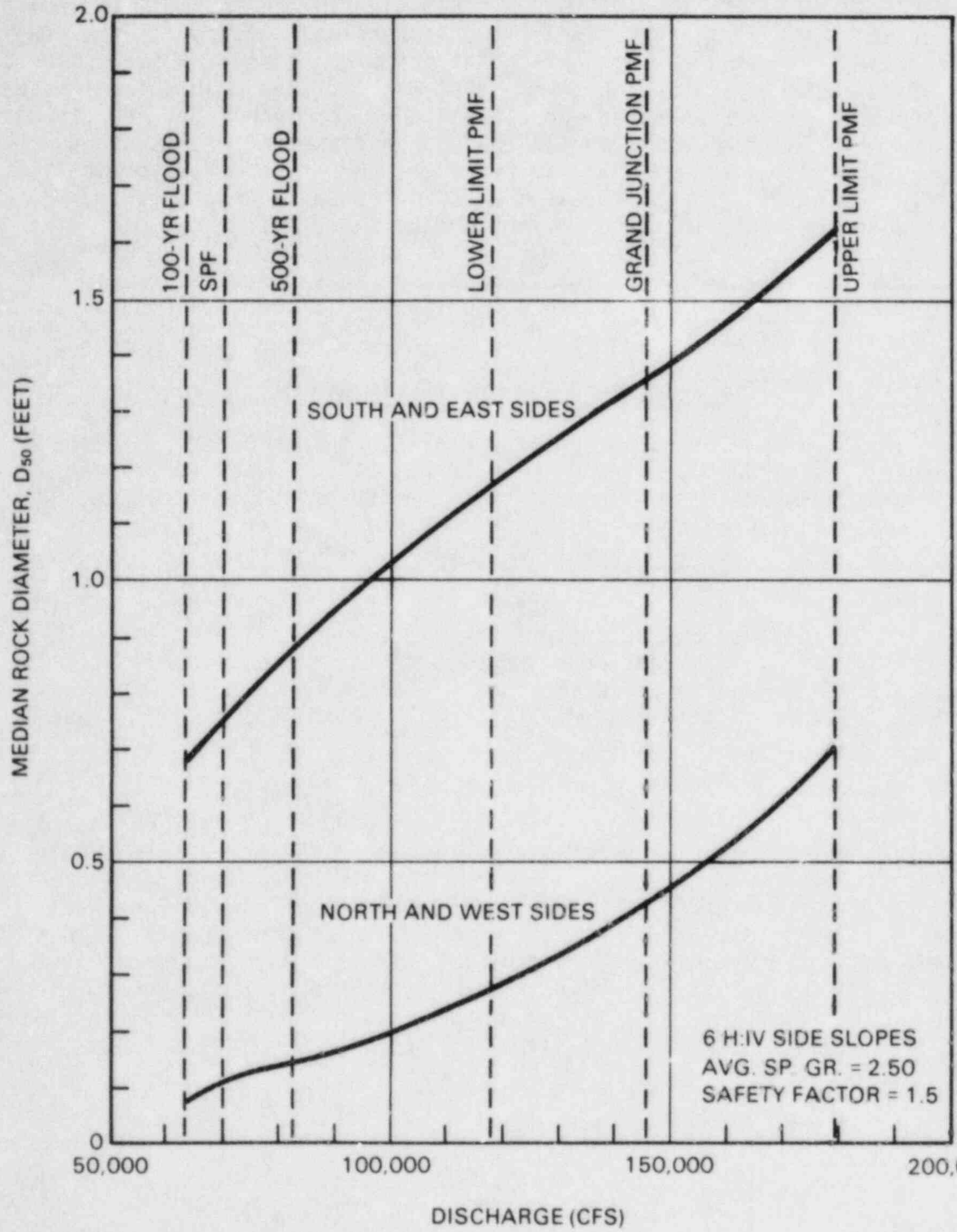

FIGURE 4.3. Grand Junction Impoundment - Median Rock Diameter of Riprap as a Function of Flood Flow

depths, velocities and shear stresses are higher on the side of the impoundment exposed directly to flood flows of the Colorado River. The increase in median diameter of rock with increasing flood flows is nonlinear because of the nonlinear increase in shear stress and energy slopes with increasing flood flows. The rate of increase of the median diameter of rock on the north and west sides of the impoundment is much greater for flows higher than about 150,000 cfs for the same reason. The range of size for the median diameter rock (south and east sides) for the lower and upper limits of the PMF is from 1.2 to 1.6 ft. The lower and upper PMF events represent a 50% increase in discharge and correspond to about a 33% increase in median rock size.

The sharp increase in the median diameter (north and west sides) from about 150,000 cfs up to 175,000 cfs is due primarily to the significant percentage increase in overbank flow depth.

4.4.2 Effect of Specific Gravity on Rock Riprap Size

There is a wide variation in specific gravity of rock outcrops in the general vicinity of Grand Junction that could possibly be used for riprap protection of the impoundment. The specific gravity of samples collected by Foley et al. (1984) varied from about 1.80 to 2.65. Figure 4.4 illustrates how the median diameter varies with specific gravity of the rock. Side slopes of 6H:1V, safety factor of 1.5, and the flow characteristics associated with the Grand Junction PMF are used in this example. The median diameter of riprap increases from 1.2 ft for a specific gravity of 2.75 up to 1.9 ft for a specific gravity of 2.00 on the south and east sides of the impoundment. The median diameter on the north and west sides of the impoundment is much smaller, varying from 5 in. for a specific gravity of 2.75 to about 7 in. for a specific gravity of 2.00.

At the Grand Junction impoundment the median rock diameter decreases significantly for specific gravity values between 2.00 and 2.50. For specific gravities greater than 2.50, the decrease in diameter is very small. Under the design criteria of Figure 4.4, the use of rock with a specific gravity greater than 2.50 would not appear to be cost effective, especially over long haul distances, since the increase in stone weight would be of no benefit. On the other hand, rock with a specific gravity much less than 2.50 would require much larger sizes and may not be cost effective depending on haul distances. The curves of Figure 4.4 point out that for several sources of rock with varying specific gravities an optimum source could be determined by several design iterations.

4.4.3 Effect of Side Slopes on Rock Riprap Size

The variation of median rock diameter with embankment side slope is shown in Figure 4.5 for the Grand Junction PMF, a safety factor of 1.5, and an average specific gravity of 2.50. For the south and east sides of the impoundment the median rock diameter varies from 1.3 ft for side slopes of 10H:1V to 4.5 ft for side slopes of 2H:1V.

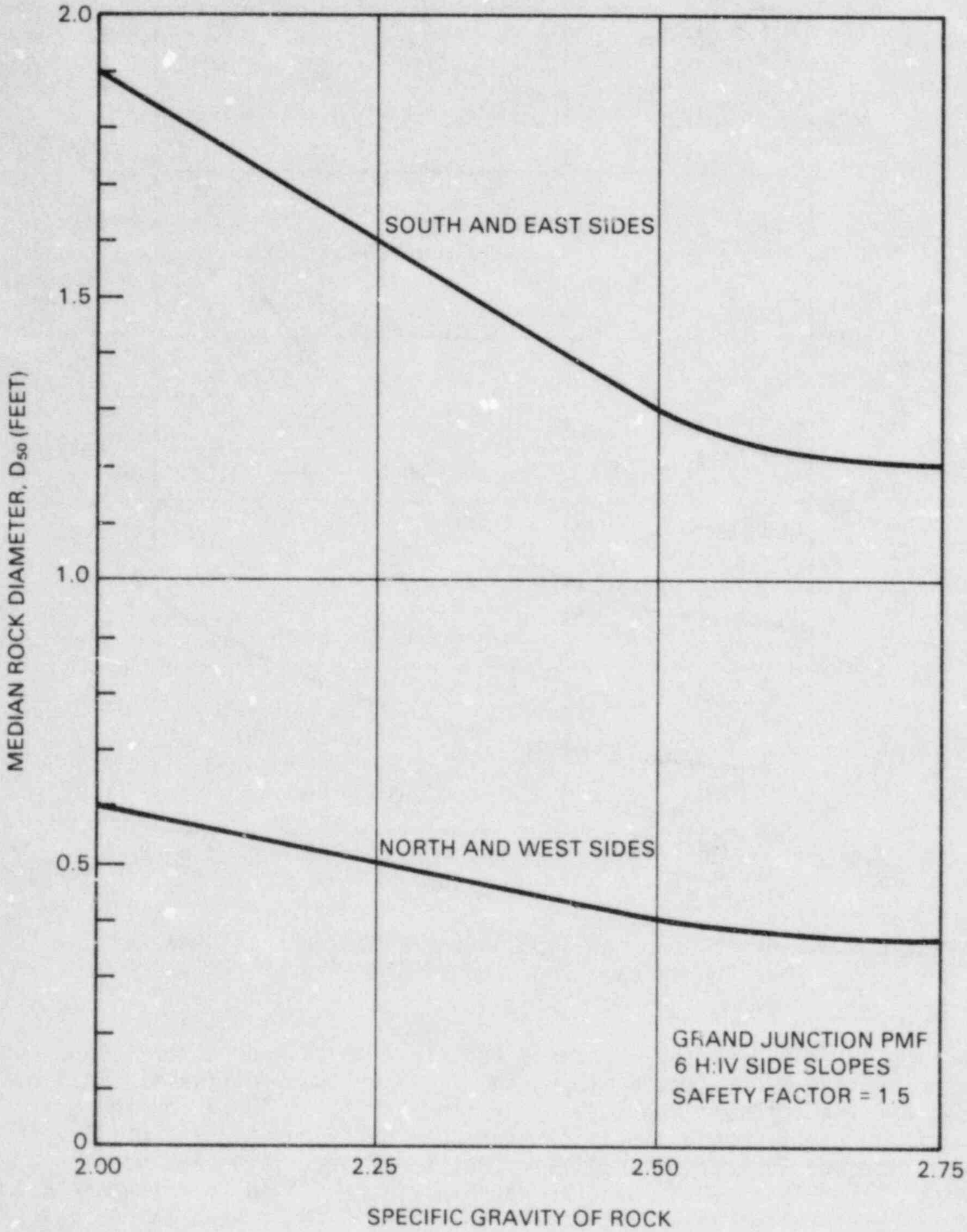

FIGURE 4.4. Grand Junction Impoundment - Median Rock Diameter of Riprap as a Function of Specific Gravity of Rock

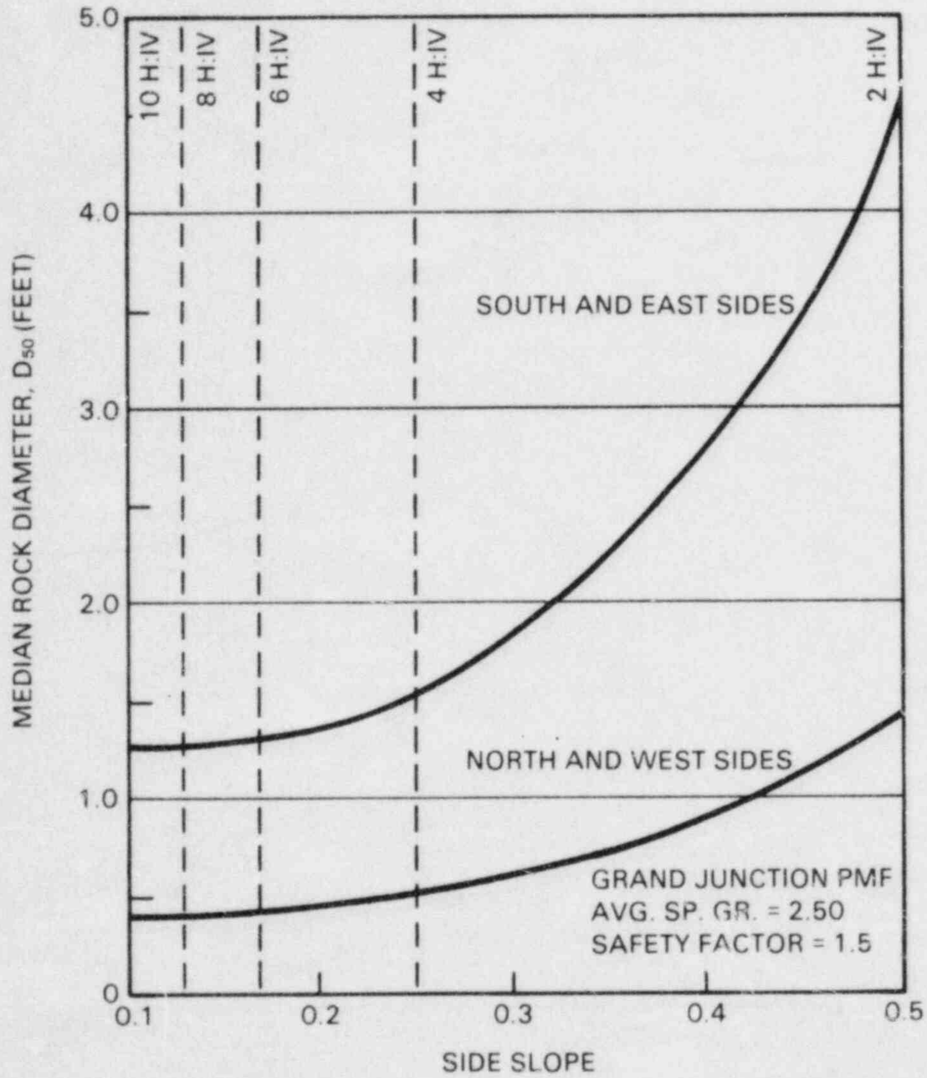

FIGURE 4.5. Grand Junction Impoundment - Median Rock Diameter of Riprap as a Function of Side Slopes

The median rock diameter increases by only a small amount for side slopes up to about 4H:1V. For steeper slopes the increase is significant. This would indicate that the optimum embankment side slope is about 4H:1V for the Grand Junction impoundment. Side slopes flatter than 6H:1V require essentially the same rock size and would provide little additional protection against flood erosion. Although curves such as the ones in Figure 4.5 do indicate an optimum slope for the specified conditions, any final design would need to be evaluated for the amount of cut and fill earthwork necessary.

4.4.4 Effect of Safety Factor on Rock Riprap Size

The variation of median rock diameter with an added safety factor is shown in Figure 4.6 for the Grand Junction PMF, a side slope of 6H:1V, and an average specific gravity of 2.50. The median rock diameter increases with increasing safety factor. The rate of increase is only slightly nonlinear. Since the selection of a safety factor is based primarily on engineering judgment, its value should be weighed carefully against economic considerations. For a more detailed discussion of safety factors, the reader is referred to the companion report by Walters and Skaggs (1984).

4.5 RIPRAP GRADATION AND THICKNESS

Lack of proper gradation is one of the most common causes of riprap failure. Riprap gradation guidelines are normally based on the median rock diameter (D_{50}) where the maximum rock size (D_{max}) and the 10 to 20 percentile (D_{10-20}) are defined as a percentage of the D_{50} size. Recommended values for the D_{max} size range from 1.3 to 2.0 times the D_{50} size, with 2.0 being the most commonly used. The value for the D_{10} to D_{20} size ranges from 0.20 to 0.30

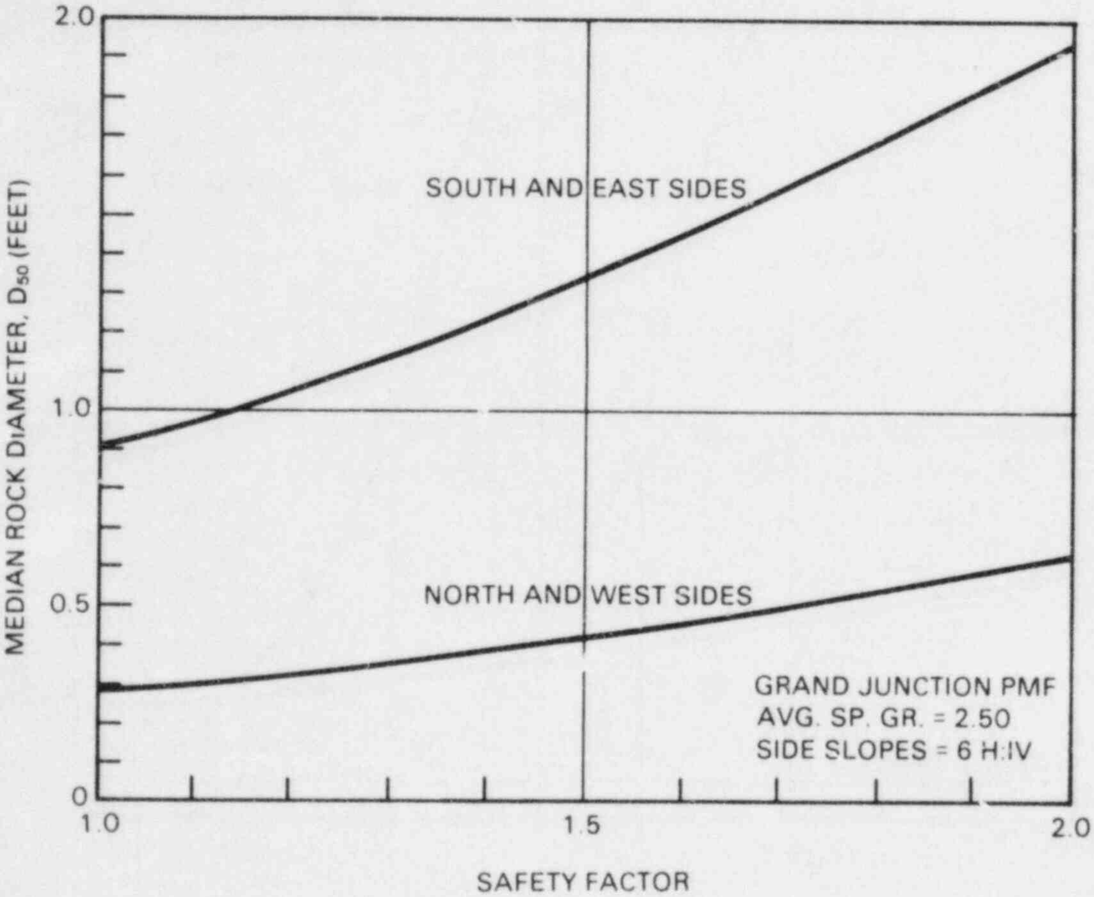

FIGURE 4.6. Grand Junction Impoundment - Median Rock Diameter as a Function of Safety Factor

times the D_{50} size (Simons, Li and Associates 1982). Figure 4.7 illustrates the size gradation of rock for a riprap cover on the south and east sides (D_{50} = 1.3 ft), and north and west sides (D_{50} = 0.4 ft) of the Grand Junction impoundment corresponding to the Grand Junction PMF, embankment side slopes of 6H:1V, rock specific gravity of 2.50, and safety factor of 1.5. The maximum rock size (D_{100}) is 2.6 ft and the D_{15} size is 0.4 ft on the south and east sides of the impoundment.

The thickness of the riprap cover should be sufficient to accommodate the largest rock in the riprap material. Oversize rock protruding above the riprap layer can reduce the stability by creating local turbulence that removes the smaller rock, provide large voids that expose filter material or may reduce

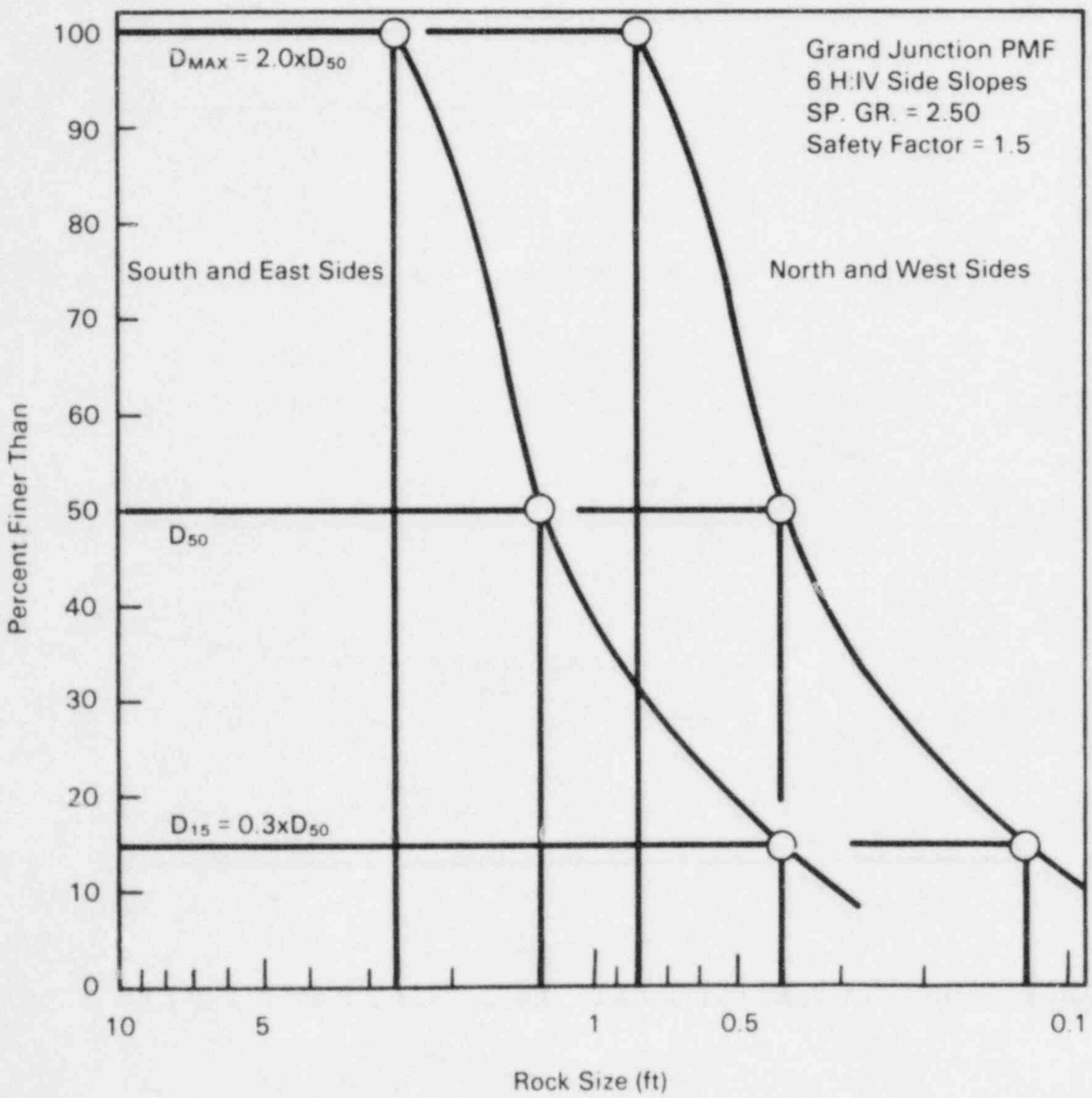

FIGURE 4.7. Grand Junction Impoundment - Size Gradation Curves of Riprap

support between individual rocks. Similar to gradation specifications, recommendations for the cover thickness vary from 1.3 to 2.0 times the median rock diameter (D_{50}) to accommodate the maximum rock size in the riprap material (Simons, Li and Associates 1982). The riprap cover thickness in the above example is 2.6 ft for the south and east sides of the impoundment and 0.8 ft for the north and west sides.

4.6 AREA OF IMPOUNDMENT TO BE COVERED WITH RIPRAP

The area of the Grand Junction impoundment to be covered by riprap depends on the selection of the design flood and side slopes. A summary of the area requiring riprap protection for each of the six flood events and indicated side slopes is shown in Table 4.5. Figure 4.8 is a plan view and cross section of the riprap cover for protection against the Grand Junction PMF and 6H:1V side slopes. The riprap cover is about 6500 ft long and surrounds the entire impoundment. The riprap cover on the south and east sides of the impoundment requires much larger rock than on the north and west sides, because of the much higher flow velocities and shear stresses. The top elevation of the riprap cover is 4578 ft, MSL (no freeboard), corresponding to the flood stage of the Grand Junction PMF. The toe elevation varies. At RM 387.86, the side of the impoundment fronting the Colorado River, the toe elevation is 4555 ft, MSL. At this location the vertical height of the riprap cover is 23 ft. On the side of the impoundment facing away from the Colorado River (north side) the vertical height of the riprap cover is from 5 to 8 ft.

TABLE 4.5. Grand Junction Impoundment - Area Requiring Riprap for Different Flood Events and Side Slopes

Side Slope	Upper PMF	Grand Junction PMF	Lower PMF	500-yr Flood	SPF	100-yr Flood
	Area of Impoundment Requiring Riprap (ft^2)					
2H:1V						
N/W	56,000	41,500	34,200	19,600	19,600	12,400
S/E	124,500	109,100	101,400	86,000	86,000	78,300
4H:1V						
N/W	103,300	76,500	63,100	36,200	36,200	22,800
S/E	229,700	201,200	187,000	158,500	158,500	144,300
6H:1V						
N/W	152,400	112,800	93,000	53,400	53,400	33,600
S/E	338,800	296,800	275,900	233,900	233,900	212,900
8H:1V						
N/W	202,000	149,500	123,300	70,800	70,800	44,500
S/E	449,100	393,400	365,600	310,000	310,000	282,200
10H:1V						
N/W	251,800	186,400	153,700	88,200	88,200	55,500
S/E	559,800	490,400	455,800	386,400	386,400	351,700

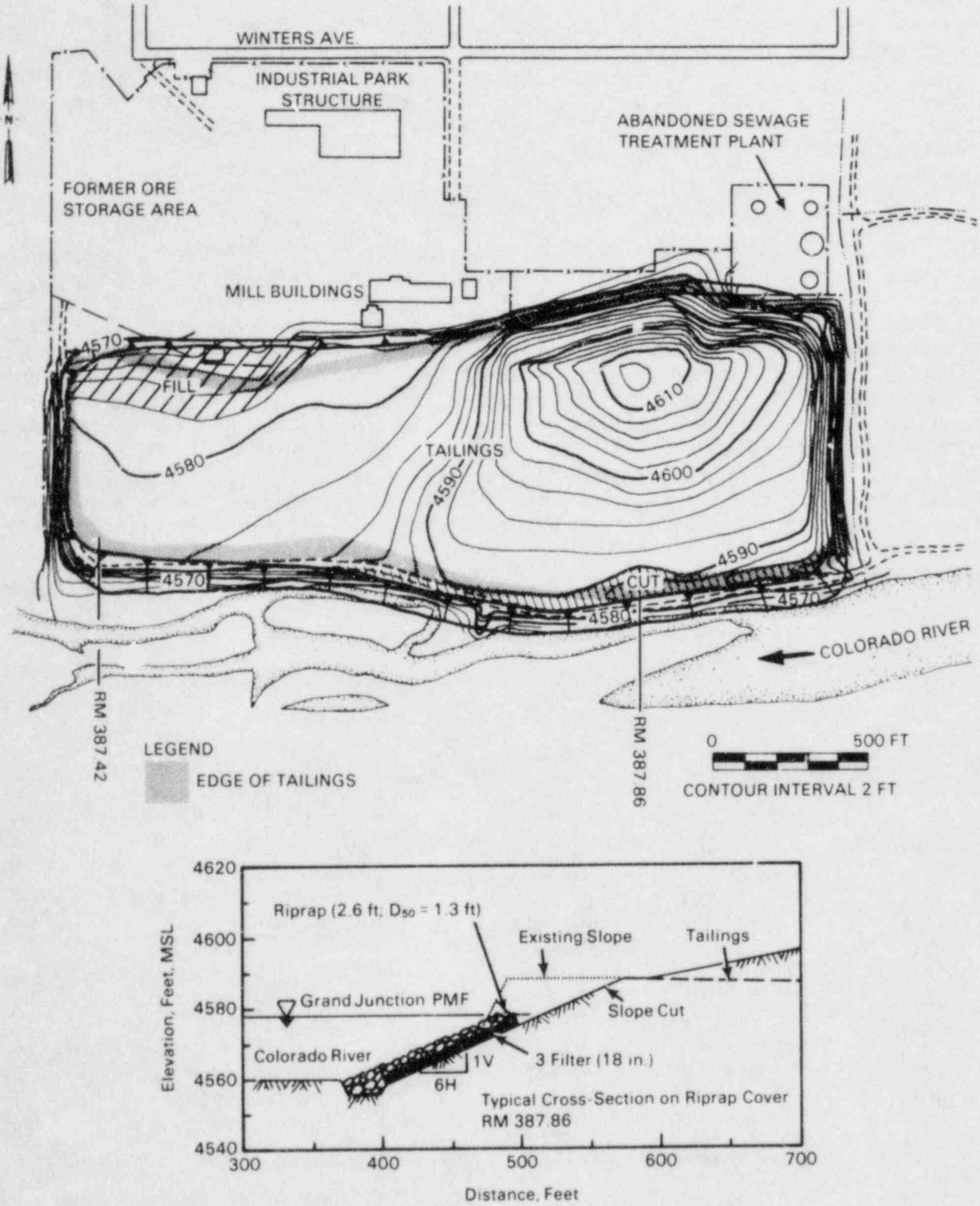

FIGURE 4.8. Grand Junction Impoundment - Plan View and Typical Cross Section of Riprap Cover

The area is divided into the north and west (N/W) sides and the south and east (S/E) sides of the impoundment because of the different rock size requirements. Depending on the selected flood event and side slopes, the area of the impoundment requiring riprap varies from about 2.1 acres (100-yr flood and 2H:1V side slopes) to 18.6 acres (upper limit PMF and 10H:1V side slopes). In some cases it may be desirable to extend the riprap above the design flood elevation to provide an additional freeboard to account for runup from waves or uncertainties in the computed water surface elevation. Adding 2 ft of freeboard above the design flood stage increases the riprapped area by about 25%.

4.7 VOLUME OF RIPRAP FOR FLOOD PROTECTION

The volume of riprap for flood protection of the Grand Junction tailings impoundment can be determined by multiplying the area of the impoundment to be covered (Table 4.5) by twice the corresponding median rock diameter (Tables A.1 through A.4) and by a factor to account for the voids between individual rocks. The following expression is used to estimate the volume of solids (riprap) for flood protection of the impoundment:

$$V_s = \frac{V_A}{\rho + 1}$$

where

V_s is the volume of solids (riprap)
V_A is the absolute volume equal to the area multiplied by 2 D_{50}
ρ is the void ratio of dumped rock (in this case $\rho + 1 = 1.36$).

Tables B.1 through B.4 of Appendix B summarize the required volume of riprap at the Grand Junction impoundment for different rock specific gravities, side slopes, safety factors, and flood events. The volumes in these tables do not include freeboard allowance. Adding 2 ft of freeboard above the design flood stage increases the volume of riprap by about 18%.

The estimated volumes of riprap have been computed for four different cases of specific gravity of the source rock available at the Grand Junction impoundment. Although it is desirable to use rock with a specific gravity of 2.50 or greater, the exposed rock formations in the Grand Junction area that are possible sources for riprap are sandstone with specific gravities generally less than 2.50. The Dakota sandstone deposits along the Gunnison River and the south side of the Colorado River flood plain are the most readily available source of rock. Haul distances to the impoundment are 5 miles or less. The specific gravity of the sandstone, as determined by Foley et al. (1984), ranges from 2.06 to 2.46 for weathered samples with the average being 2.25. The required volume of riprap is 29,000 yd^3 (Table B.2) using Dakota sandstone as the source, the Grand Junction PMF, side slopes of 6H:1V, and a safety factor of 1.5. The volume of riprap required for the same design flood event, side slopes and safety factor, but with a rock specific gravity of 2.50 is 23,500 yd^3 (Table B.3). For a rock specific gravity of 2.75, the required volume of rock would be 21,900 yd^3 (Table B.4).

4.8 FILTER LAYER REQUIREMENTS

The existing soil cover of the Grand Junction impoundment is very fine, requiring the placement of gravel or crushed rock filters between the riprap and soil cover to prevent the cover from being washed out through the riprap voids. Suggested specifications for gravel filters, including size gradation and thickness, have been summarized by Simons and Senturk (1977). The suggested specifications are based on the size properties of the riprap and base material (soil cover). The suggested specifications are:

$$\frac{D_{50}\ \text{(filter)}}{D_{50}\ \text{(base)}} < 40 \tag{4.1}$$

$$5 < \frac{D_{15}\ \text{(filter)}}{D_{15}\ \text{(base)}} < 40 \tag{4.2}$$

$$\frac{D_{15}\ \text{(filter)}}{D_{85}\ \text{(base)}} < 5\ . \tag{4.3}$$

In some cases, two or three filters of different size gradations may be required because the size difference between the riprap and underlying base material is very large. In the case of the Grand Junction impoundment, three different filter layers are required.

The suggested thickness of each filter layer is 6 to 9 in. Using the 6-in. value and three filter layers, the total filter thickness is 18 in. Based on the total filter-layer thickness and the areas in Table 4.5, the volume of filter material for different flood events and side slopes is summarized in Table 4.6.

TABLE 4.6. Grand Junction Impoundment - Volume of Filter Material Required for Indicated Flood Event and Side Slopes

Side Slope	Volume of Filter (yd^3)					
	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
2H:1V	7,400	6,200	5,500	4,300	4,300	3,700
4H:1V	13,600	11,300	10,200	8,000	8,000	6,800
6H:1V	20,100	16,700	15,100	11,700	11,700	10,100
8H:1V	26,600	22,200	20,000	15,600	15,600	13,300
10H:1V	33,200	27,600	24,900	19,400	19,400	16,600

5.0 SLICKROCK URANIUM TAILINGS IMPOUNDMENT

5.1 DESCRIPTION OF SITE

The Union Carbide Corporation's Slickrock uranium tailings impoundment is located about 3 miles northwest of Slickrock, Colorado, 9 miles east of the Colorado-Utah border, and 25 miles north of Dove Creek, Colorado. The impoundment is bordered on the north and east sides by the Dolores River. The Slickrock mill site became operational in 1957 and was closed in 1961. The mill was an upgrade plant capable of handling 500 tons of ore per day. The upgraded material was then shipped to Rifle, Colorado, for further processing.

The tailings impoundment shown in Figure 5.1 contains about 350,000 tons of sandy tailings covering an area of about 19 acres. The base of the impoundment is about 10 ft above the Dolores River during low water conditions and the top of pile is about 60 ft above the river. The impoundment is located within the Dolores River flood plain. A small rock dike has been constructed along the north and east sides of the impoundment to protect the base of the impoundment from direct attack by Dolores River overflows. A diversion ditch and rock material have been placed on some areas of the impoundment surface to redirect runoff and protect against erosion.

The tailings impoundment is about 1900 ft long and at its widest point is about 650 ft wide. The impoundment side slopes are quite variable, ranging from 4H:1V to 7H:1V along the east side of the impoundment and from 6H:1V to 8H:1V on the south side of the impoundment. The north and west sides of the impoundment abut Dolores River terrace deposits or bedrock.

5.2 SLICKROCK FLOOD ANALYSIS

The Slickrock flood protection analysis is based on the hydraulic characteristics of the PMF because this is the flood event that will normally be the design basis for flood protection of uranium tailings impoundments located in flood plains.

The hydraulic characteristics of the PMF at various locations along the Slickrock tailings impoundment are summarized in Tables 5.1 and 5.2. The characteristics are given for both the main channel (Table 5.1) and overbank area (Table 5.2). Figure 5.1 shows the locations of the cross sections where the characteristics were computed. Figures 5.2a and 5.2b are cross sections of the impoundment showing the PMF water surface elevation.

The hydraulic characteristics of the PMF vary considerably along the impoundment, especially between areas where the main river channel flows against the side slopes and where there is a wide overbank area. The asterisks in Tables 5.1 and 5.2 indicate those values used in the design of the riprap flood protection for the Slickrock impoundment. The highest shear stress of

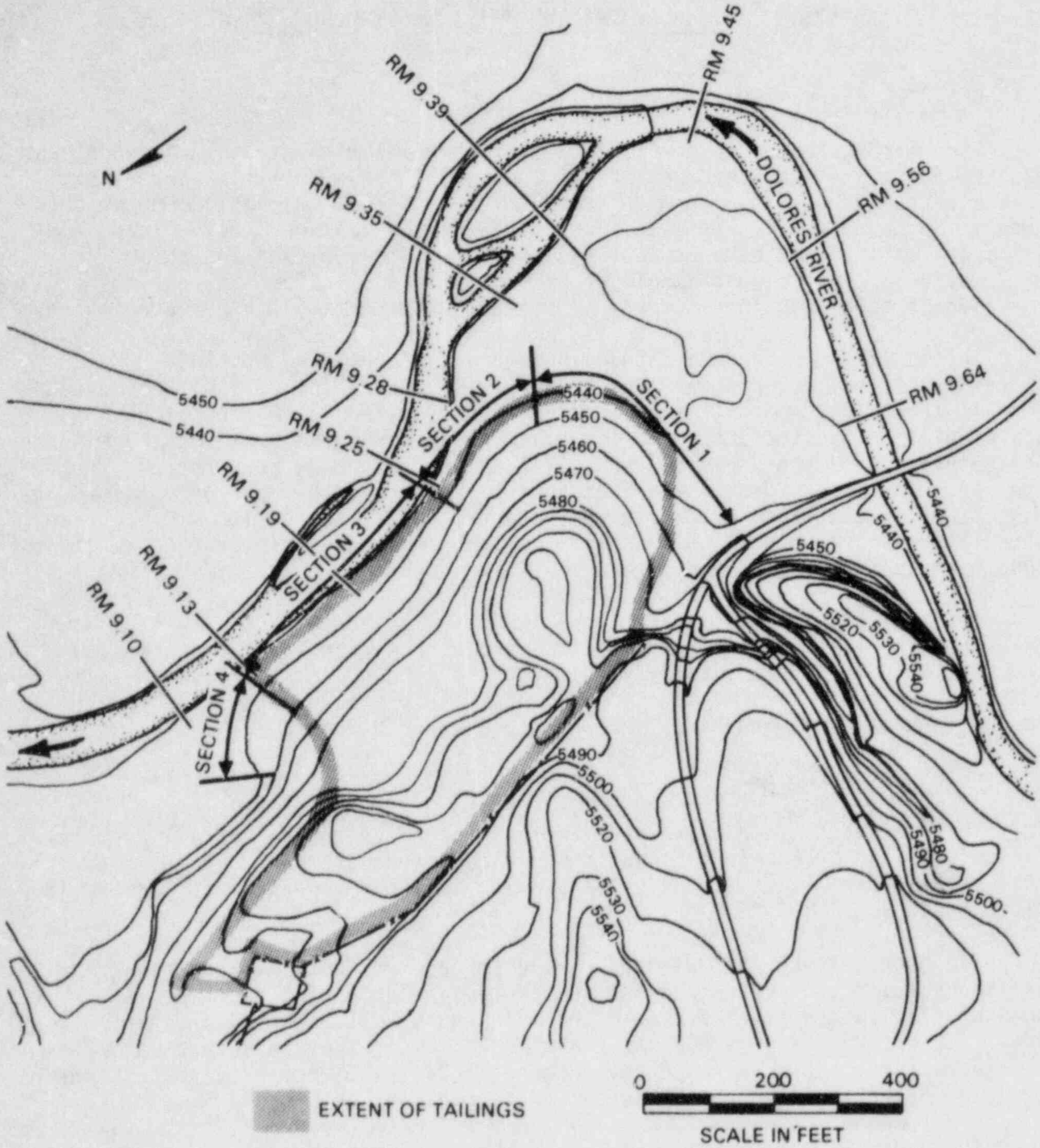

FIGURE 5.1. Union Carbide Corporation's Slickrock Impoundment

TABLE 5.1. Hydraulic Characteristics in Main Channel of Dolores River Along the Slickrock Impoundment for the Probable Maximum Flood (46,100 cfs)

Cross Section	Stage (ft, MSL)	Velocity (fps)	Average Hydraulic Radius (ft)[a]	Energy Slope, (ft/ft)[a]	Average Shear Stress (lb/ft^2)[a]
RM 9.64	5452.4	11.47			
			21.24	2.05×10^{-4}	0.271
RM 9.56	5452.6	10.63			
			22.36	1.02×10^{-3}	1.42
RM 9.45	5452.4	9.20			
			21.28	1.08×10^{-3}	1.44
RM 9.39	5452.1	6.98			
			22.18	9.20×10^{-4}	1.27
RM 9.35	5451.6	8.21			
			22.07	1.61×10^{-3}	2.21
RM 9.28	5448.8	16.50			
			21.12	5.74×10^{-3}	7.56[b]
RM 9.25	5449.3	10.71			
			21.10	1.13×10^{-3}	1.49
RM 9.19	5449.4	9.80			
			22.76	1.30×10^{-3}	1.85[b]
RM 9.13	5449.6	7.80			
			24.23	1.06×10^{-3}	1.60
RM 9.10	5449.5	7.85			
			23.34	6.15×10^{-4}	0.896
RM 9.05	5449.5	5.64			

(a) The data in these columns are computed for channel segments between cross sections.
(b) Indicates values used in computing rock sizes.

TABLE 5.2. Hydraulic Characteristics in Overbank Area of Dolores River Adjacent to the Slickrock Impoundment for the Probable Maximum Flood (46,100 cfs)

Cross Section	Stage (ft, MSL)	Velocity (fps)	Average Hydraulic Radius (ft)[a]	Energy Slope (ft/ft)[a]	Average Shear Stress (lb/ft^2)[a]
RM 9.64	5452.4	3.41			
			9.37	3.91×10^{-4}	0.229
RM 9.56	5452.6	2.74			
			12.21	4.07×10^{-3}	3.10[b]
RM 9.45	5452.4	3.13			
			12.45	2.67×10^{-3}	2.07
RM 9.39	5452.1	2.07			
			12.01	2.09×10^{-3}	1.57
RM 9.35	5451.6	2.29			
			10.07	4.42×10^{-3}	2.78
RM 9.28	5448.8	6.65			
			7.45	9.91×10^{-3}	4.61
RM 9.25	5449.3	3.05			
			7.52	1.00×10^{-3}	0.469
RM 9.19	5449.4	4.62			
			8.93	1.20×10^{-3}	0.669
RM 9.13	5449.6	3.31			
			11.31	8.26×10^{-4}	0.583[b]
RM 9.10	5449.5	2.27			
			12.92	3.81×10^{-4}	0.307
RM 9.05	5449.5	1.88			

(a) The data in these columns are computed for channel segments between cross sections.
(b) Indicates values used in computing rock sizes.

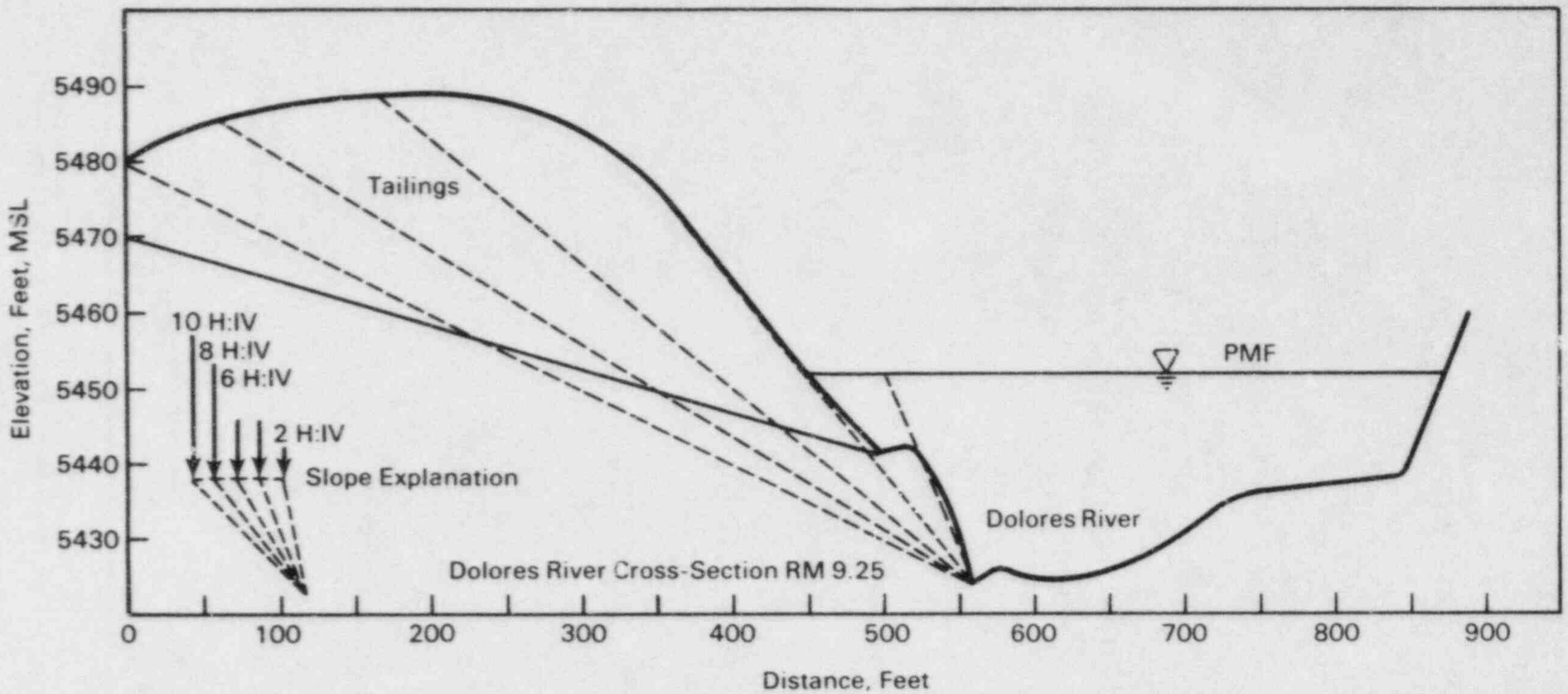

FIGURE 5.2a. Slickrock Impoundment - Cross Sections of Impoundment Showing PMF Stage

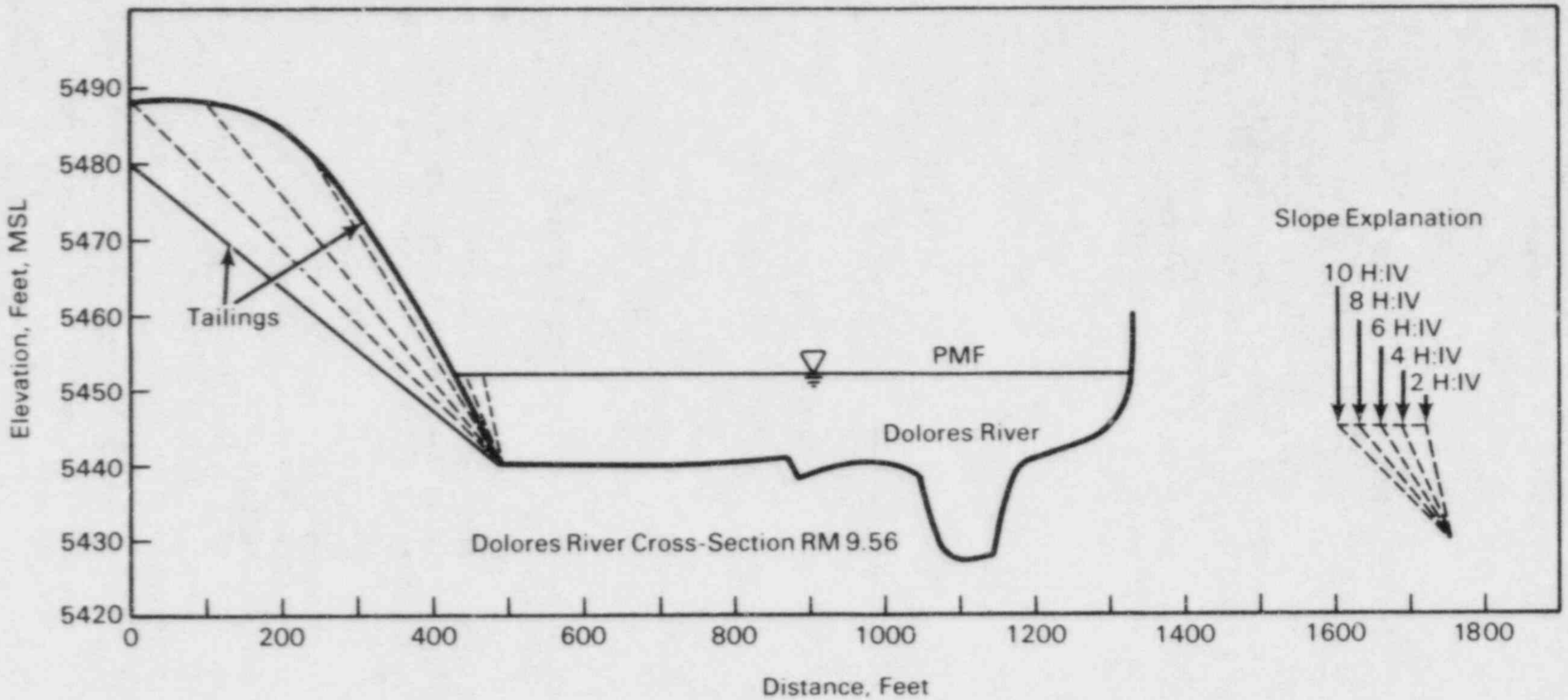

FIGURE 5.2b. Slickrock Impoundment - Cross Sections of Impoundment Showing PMF Stage

7.56 lb/ft^2 occurs between RM 9.28 and 9.25, which coincides with a bend and constriction of the river and where the impoundment base is very near the riverbank.

5.3 EARTHWORK

Depending on the desired side slopes for riprap placement, either cut or fill is required at the Slickrock impoundment (Figure 5.2). Table 5.3 is a summary of the volume of material to be excavated or placed to achieve side slopes of 10H:1V, 8H:1V, 6H:1V and 4H:1V. Side slopes of 10H:1V and 8H:1V would require the removal of the major portion of the uranium tailings. Use of side slopes of 6H:1V requires about the same volume of cut material as fill material. Existing side slopes of the impoundment are flatter than 4H:1V requiring that fill be hauled in and placed on the existing slopes to steepen them if riprap is placed on side slopes steeper than 6H:1V.

TABLE 5.3. Slickrock Impoundment - Cut and Fill Volume to Obtain Indicated Side Slopes

Side Slope	Cut Volume (yd^3)	Fill Volume (yd^3)
10H:1V	297,000	0
8H:1V	164,800	0
6H:1V	28,900	20,400
4H:1V	0	24,500

5.4 ROCK RIPRAP SIZE

Required size of rock below the design flood elevation at the Slickrock tailings impoundment was evaluated using the Safety Factor Method. Various specific gravities, embankment side slopes, and safety factors are used in the evaluation. As mentioned previously, the evaluation is confined to the flow characteristics of the PMF. The impoundment is divided into four sections based on the different shear stresses, which could occur along the impoundment as a result of the PMF. The sections are shown in Figure 5.1.

Tables A.5 through A.8 (Appendix A) summarize the median diameter of rock at the Slickrock impoundment for the PMF flow conditions and for different rock specific gravities, side slopes and safety factors. Median rock diameters are summarized for the four sections of the impoundment delineated in Figure 5.1. The median rock diameter of riprap increases with decreasing specific gravity of rock, and increases with steeper side slopes and increasing safety factor. Section 2 of the Slickrock impoundment is the most critical because of the high shear stress that could occur there during the PMF. The median rock diameter at Section 2 is more than twice that required at the other three sections.

5.4.1 Effect of Specific Gravity on Rock Riprap Size

Figure 5.3 illustrates how the median diameter of riprap varies with specific gravity of the rock. Riprap cover with side slopes of 6H:1V, safety factor of 1.5, and flow characteristics associated with the PMF are used in this example. The median diameter of riprap at Section 2 is quite large and is very sensitive to differences in specific gravity. The required median rock diameter at Section 2 increases from 2.4 ft for rock with a specific gravity of 2.75 up to 4.2 ft for rock with a specific gravity of 2.00. The large rock size at Section 2 is due to the high design shear stresses occurring at this section as a result of the flood channel restrictions and bend in the Dolores River at this location. The design shear stresses at Sections 1, 3, and 4 are substantially less than at Section 2. As a result of the lower shear stresses, the required median rock diameter is less and the sensitivity to specific gravity of the rock is less. At Section 3, for instance, the required median rock size varies from 0.6 ft for rock with a specific gravity of 2.75 to 1.0 ft for rock with a specific gravity of 2.00.

5.4.2 Effect of Side Slopes on Riprap Size

The dependency of the size of riprap on embankment side slopes at the Slickrock impoundment is illustrated in Figure 5.4. The median diameter of riprap is sensitive to side slopes for those steeper than 4H:1V.

At Section 2, for side slopes steeper than about 6H:1V the required diameter of rock increases very rapidly, from about 2.8 ft for side slopes of 6H:1V up to 9.3 ft for side slopes of 2H:1V. For side slopes flatter than 6H:1V the required rock diameter at Section 2 is not nearly as sensitive. The required median rock diameter at Section 2 increases only from 2.6 ft to 2.8 ft for side slopes between 10H:1V and 6H:1V. Although sections 1, 3, and 4 experience the same trends as does Section 2, the sensitivity to side slopes steeper than 6H:1V is not nearly as great because the shear stresses at these sections under the PMF flow conditions are much smaller and the required median rock diameter is correspondingly smaller. At Section 1, for example, the required median rock diameter increases from 1.1 ft for side slopes of 10H:1V to 3.8 ft for side slopes of 2H:1V.

As with the Grand Junction impoundment the increase in median rock diameter is sensitive to increasing the embankment side slopes for slopes steeper than about 4H:1V, indicating that the optimum embankment side slopes are about 4H:1V for placement of riprap.

Embankment side slopes flatter than 6H:1V provide little additional protection against flood flows and side slopes steeper than 4H:1V require increasingly larger rock to provide the same degree of protection.

5.4.3 Safety Factor

The variation of median rock with an added safety factor is shown in Figure 5.5 for the Slickrock PMF event, a side slope of 6H:1V, and an average specific gravity of 2.50. The curves for sections 1 through 4 indicate that

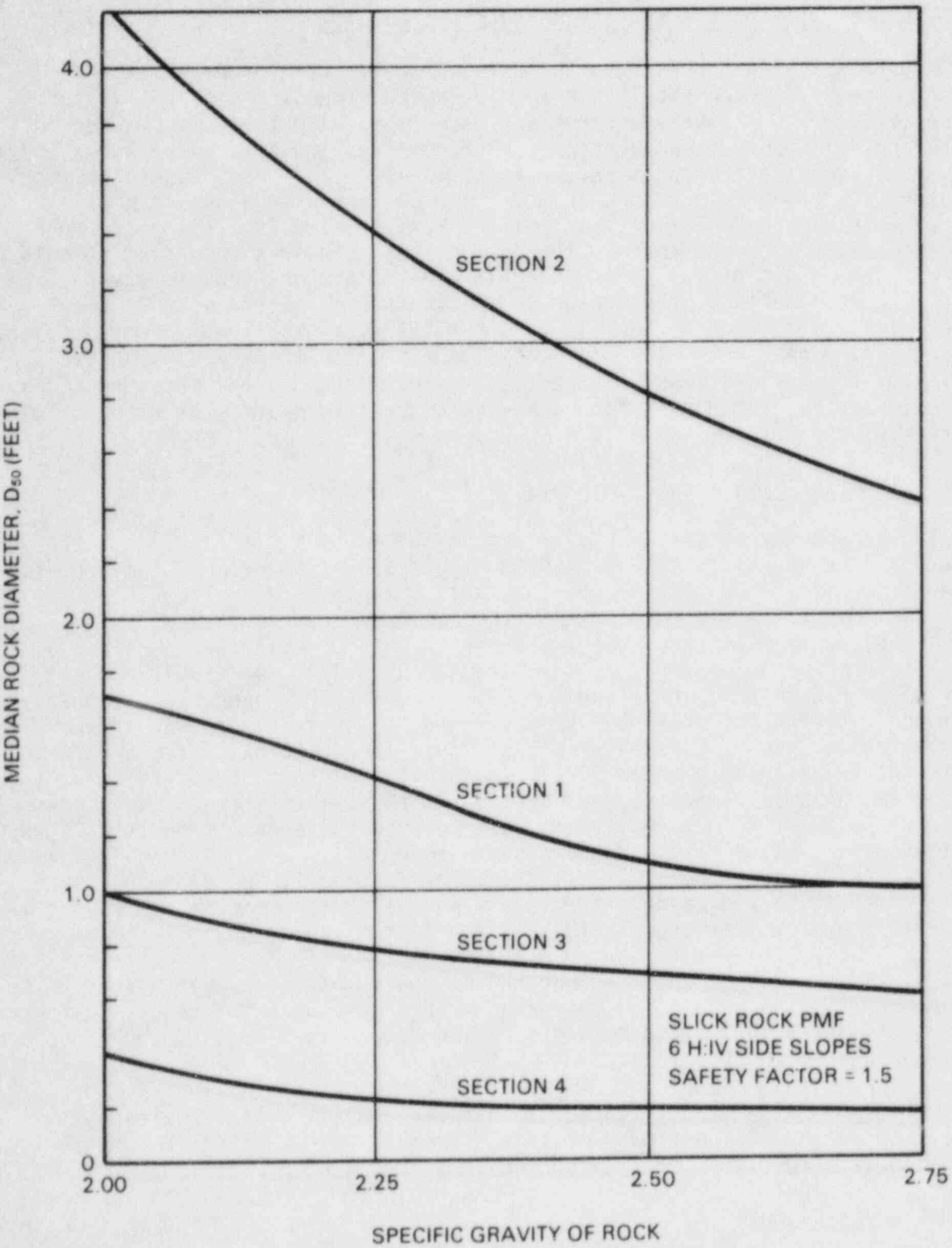

FIGURE 5.3. Slickrock Impoundment - Median Rock Diameter of Riprap as a Function of Specific Gravity of Rock

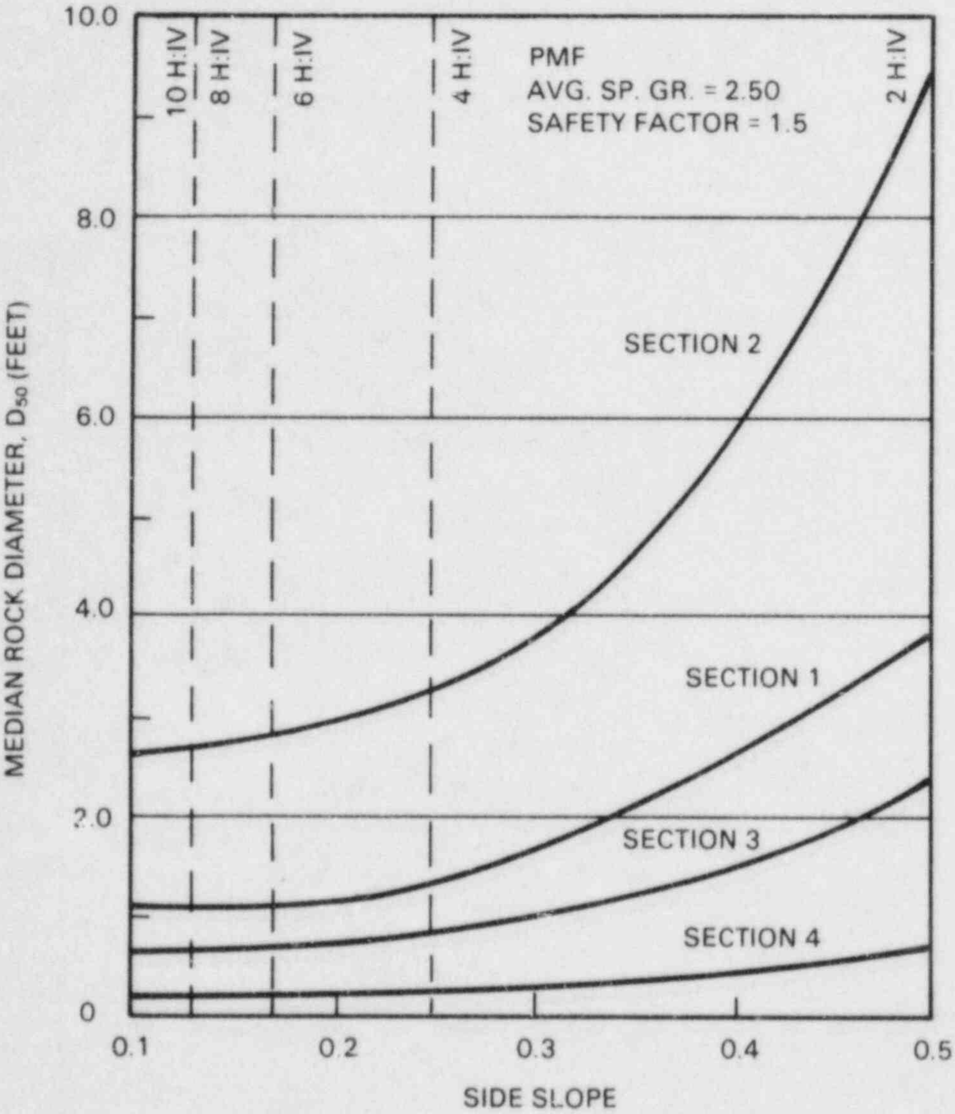

FIGURE 5.4. Slickrock Impoundment - Median Rock Diameter of Riprap as a Function of Side Slopes

the rate of increase of median rock diameter with safety factor is greater as the shear stress increases. This would indicate that adding a safety factor will be more costly than for the lesser values of shear stress. For a more detailed discussion of safety factors the reader is referred to the companion report by Walters and Skaggs (1984).

5.5 RIPRAP GRADATION AND THICKNESS

Riprap gradation and thickness guidelines have been previously discussed in Section 4.5. Figure 5.6 illustrates the size gradation of rock for a riprap cover on each of the four sections shown on Figure 5.1. The flow conditions of the Slickrock PMF, rock specific gravity of 2.50, embankment side slopes of

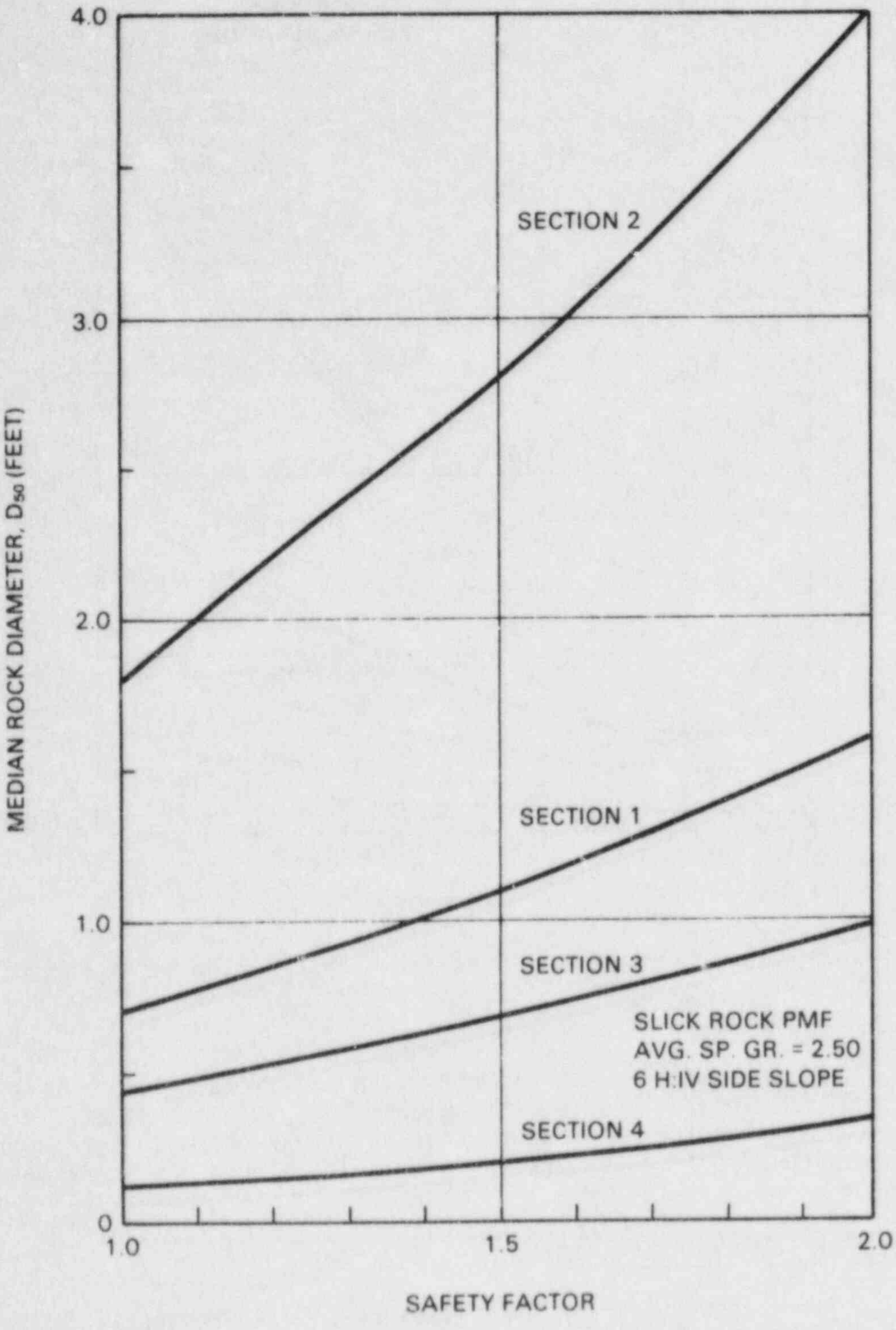

FIGURE 5.5. Slickrock Impoundment - Median Rock Diameter of Riprap as a Function of Safety Factor (τ = shear stress in lb/ft^2)

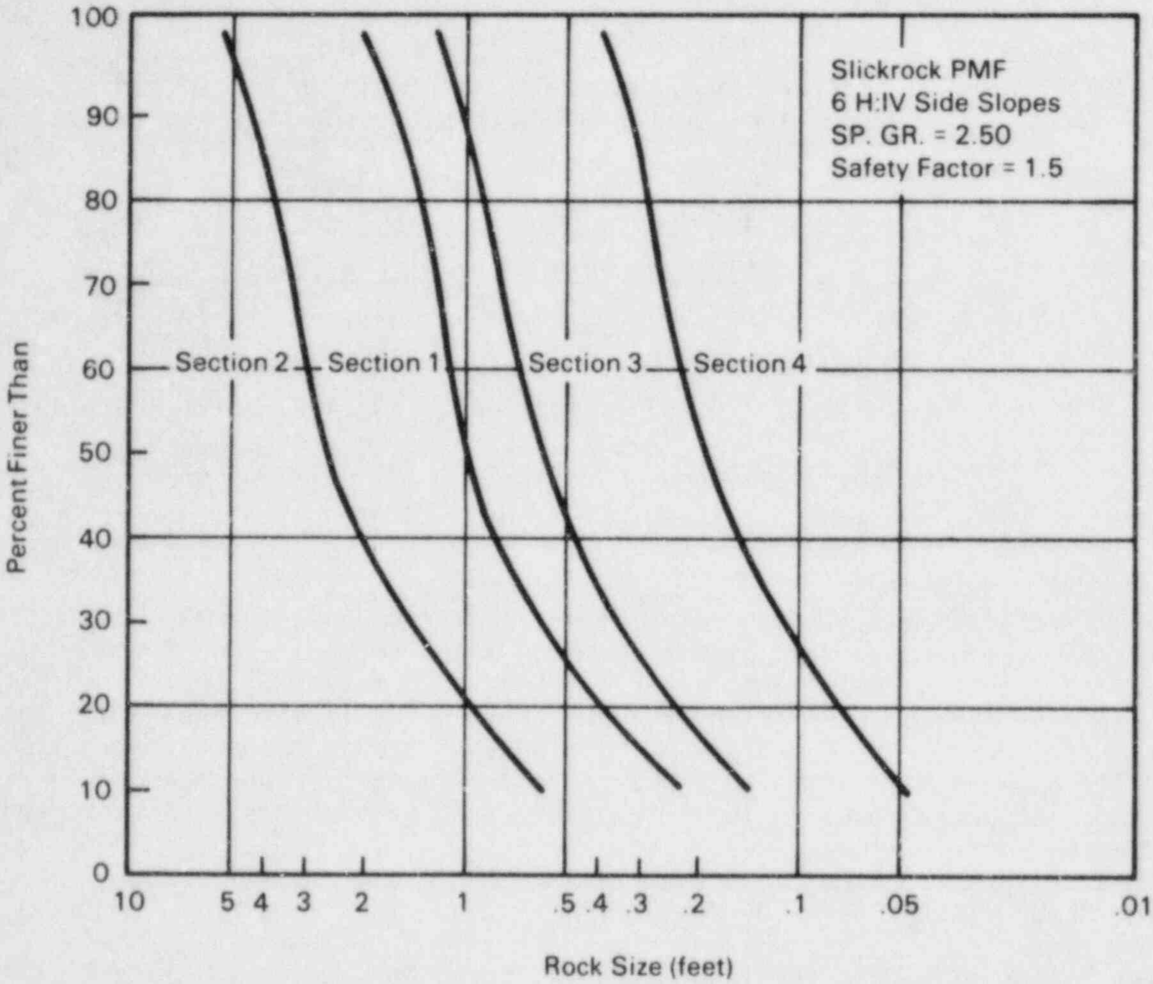

FIGURE 5.6. Slickrock Impoundment - Size Gradation of Riprap

6H:1V, and safety factor of 1.5 were used to compute the median rock diameter. The maximum and D_{15} rock sizes for section 2 are 5.2 ft and 0.8 ft, respectively. The riprap cover thickness roughly corresponds to the maximum rock size, D_{max}, for each of the sections of the impoundment. The cover layer for section 2 of the impoundment is 5.2 ft for the design parameters in Figure 5.6.

5.6 AREA OF IMPOUNDMENT TO BE COVERED WITH RIPRAP

A summary of the area of the Slickrock impoundment requiring riprap protection against the PMF for various side slopes is given in Table 5.4 for each of the four sections of the impoundment shown in Figure 5.1. The total area to be covered for side slopes of 2H:1V is about 2.0 acres and increases to 9.1 acres for side slopes of 10H:1V.

Figure 5.7 is a plan view and typical cross section of the riprap cover for protection against the PMF with embankment side slopes of 6H:1V. The top elevation of the riprap cover is 5453 ft, MSL (no freeboard), corresponding

TABLE 5.4. Slickrock Impoundment - Area Requiring Riprap for Protection Against PMF with Different Side Slopes

Section	Side Slopes				
	2H:1V	4H:1V	4H:1V	8H:1V	10H:1V
	Area to be Covered by Riprap (ft^2)				
1	18,600	34,600	50,600	67,200	83,800
2	23,000	42,400	62,400	83,000	103,300
3	38,200	70,400	103,900	138,100	171,700
4	8,700	16,200	23,700	31,500	39,300
Total	88,500	163,600	240,600	319,800	398,100

to the PMF flood stage. The toe elevation varies from 5440 ft, MSL, to 5427 ft, MSL, with the lowest elevation being along that portion of the impoundment fronting the Dolores River. The maximum height of the riprap cover is 26 ft. The riprap cover is about 2,000 ft long and is tied into old Dolores River terrace deposits and bedrock at both ends of the impoundment. Two 150-ft wing walls have been incorporated into the cover along that portion of the impoundment directly fronting the Dolores River to protect the embankment from scour during normal high flows.

5.7 VOLUME OF RIPRAP FOR FLOOD PROTECTION

The volume of riprap for flood protection can be determined by multiplying the area of the impoundment that must be covered for the specified side slopes (Table 5.4) by twice the corresponding median rock diameter (Tables A.5 through A.8), and by a factor to account for the voids between individual rock pieces. The relationship has been discussed in Section 4.7.

Table 5.5 is a summary of the required volume of riprap for protection against the PMF for different rock specific gravities, side slopes, and safety factors. Exposed rock formations in the vicinity of the Slickrock are exclusively sandstones with specific gravities ranging from slightly less than 2.00 to about 2.50. Sandstones of the Dakota, Morrison or Entrada formations are the most likely to yield adequately durable rock for riprap protection (Foley et al. 1984). Possible quarry sites can be found within 5 miles of the impoundment. The required volume of riprap for flood protection using rock with a specific gravity of 2.50, side slopes of 6H:1V, and safety factor of 1.50 is 16,800 yd^3. With a specific gravity of 2.00, the required volume of riprap increases to 25,000 yd^3.

5.8 FILTER LAYER REQUIREMENTS

A gravel or crushed rock filter between the riprap and soil cover is required at the Slickrock impoundment to prevent the soil cover from being washed out through the voids in the riprap. Suggested specifications for

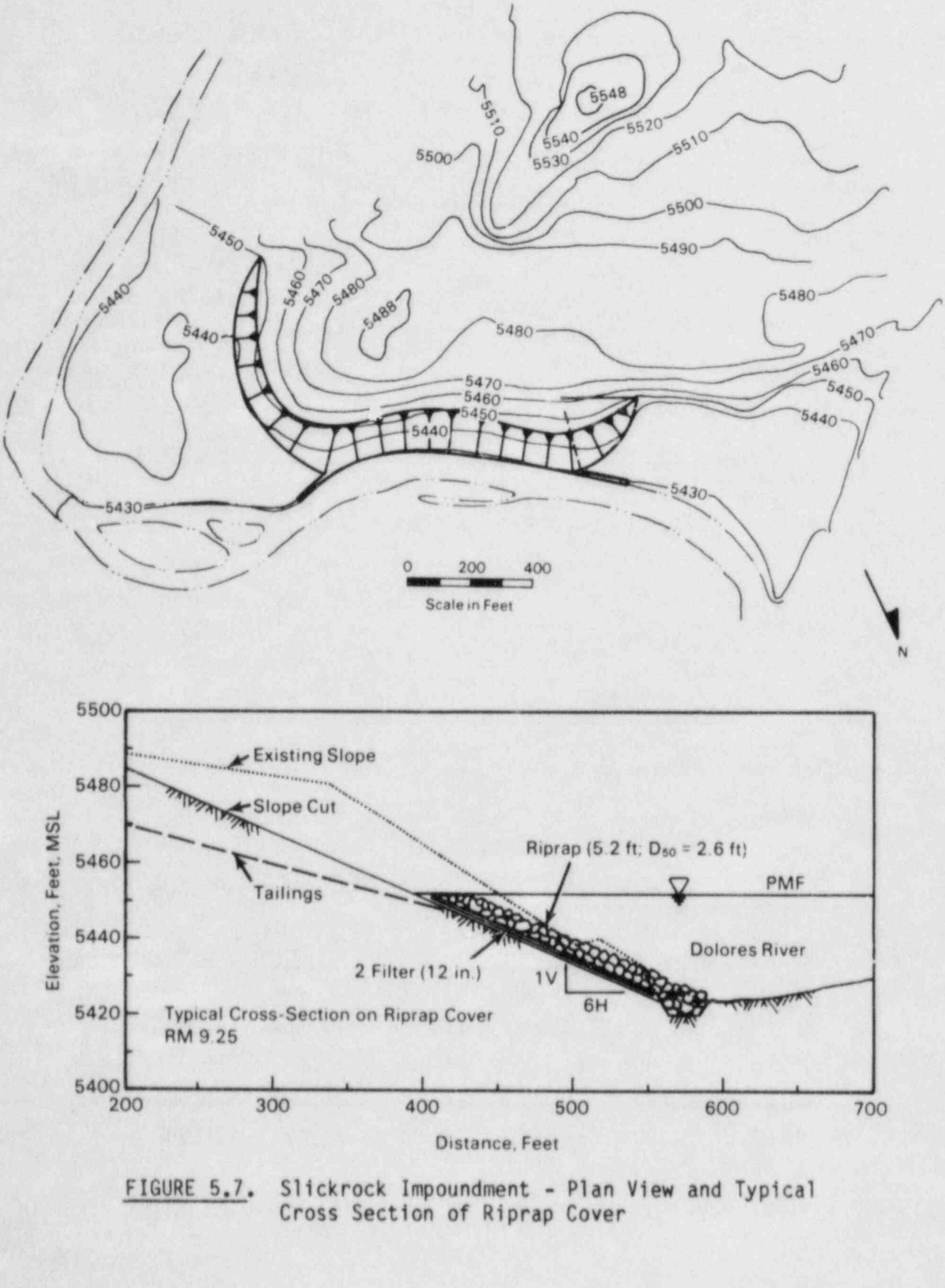

FIGURE 5.7. Slickrock Impoundment - Plan View and Typical Cross Section of Riprap Cover

TABLE 5.5. Slickrock Impoundment - Vclume of Riprap for Flood Protection Against the PMF for Different Rock Specific Gravities, Side Slopes and Safety Factors

Side Slopes	SF=1.0	SF=1.25	SF=1.50	SF=1.75	SF=2.00
	Required Volume of Riprap for sp gr = 2.00 (yd^3)				
2H:1V	9,100	15,253	---	---	---
4H:1V	11,600	15,100	19,800	24,800	31,200
6H:1V	16,400	20,300	25,000	30,400	36,400
8H:1V	20,600	26,600	32,300	38,700	45,000
10H:1V	25,700	32,600	39,200	46,300	53,400
	Required Volume of Riprap for sp gr = 2.25 (yd^3)				
2H:1V	7,400	12,100	---	---	---
4H:1V	9,500	12,200	15,500	19,800	25,000
6H:1V	12,700	16,400	20,200	24,300	29,000
8H:1V	16,800	20,600	25,600	30,300	35,700
10H:1V	20,500	25,700	31,800	36,700	43,300
	Required Volume of Riprap for sp gr = 2.50 (yd^3)				
2H:1V	6,200	10,200	20,600	---	---
4H:1V	7,900	10,100	13,100	16,400	20,700
6H:1V	10,500	13,900	16,800	20,300	24,100
8H:1V	13,500	17,300	21,800	25,600	29,500
10H:1V	16,800	21,500	25,700	31,300	36,200
	Required Volume of Riprap for sp gr = 2.75 (yd^3)				
2H:1V	5,400	8,700	17,800	---	---
4H:1V	6,700	8,800	11,200	13,800	17,800
6H:1V	9,200	11,700	14,500	17,400	20,300
8H:1V	12,200	15,500	18,500	21,800	25,600
10H:1V	15,200	19,300	23,000	27,200	31,300

gravel filters are summarized in Section 4.8. Two filter layers with a minimum thickness of 6 in. each will be required. Based on a total filter layer thickness of 12 in. and the areas in Table 5.4, the volume of filter material for different side slopes is summarized in Table 5.6.

TABLE 5.6. Slickrock Impoundment - Volume of Filter Material Required for Indicated Side Slopes

Side Slopes	Volume of Filter Material (yd^3)
2H:1V	2,400
4H:1V	4,500
6H:1V	6,600
8H:1V	8,700
10H:1V	10,800

6.0 EVALUATION OF COSTS FOR FLOOD PROTECTION

Cost estimates for providing flood protection at the Grand Junction and Slickrock impoundments using riprap are developed in this section. The purpose for developing an estimate of costs is to evaluate the effects of varying design parameters such as side slopes, safety factor, specific gravity of rock, and flood flows. The unit costs for developing estimates have been obtained from recent publications and from agencies with considerable experience in similar projects, such as the U.S. Bureau of Reclamation and the State of Colorado Conservation Board. The costs have been updated where necessary to 1983 price levels. Escalation and/or discount factors have not been included to account for construction taking place over a number of years. Engineering and contingency costs have been included in the cost estimates, but no costs for short- or long-term maintenance are incorporated. Annual maintenance costs amounting to upwards of 1% of the construction costs could be incurred initially as the riprap cover settles and becomes stabilized. A value of 6% of the construction cost is used as the engineering cost, and 15% of the construction and engineering costs are used for contingencies.

Construction costs include those associated only with the construction of the riprap cover and do not represent other possible reclamation costs such as additional soil for the radon suppression cover or protection against localized runoff erosion above the design flood elevation. Construction costs do include earthwork of the tailings impoundment embankments in preparation for placement of riprap, and costs associated with mining, hauling, and placing rock filter and riprap material on the impoundment embankments. Table 6.1 is a summary of unit costs in cubic yards (yd^3) and cubic yard-miles (yd^3-mi) used in development of the estimates for flood protection at the Grand Junction and Slickrock impoundments.

The costs for flood protection using riprap can vary significantly according to the selection of design parameters. In some cases, the selection of these design parameters may be limited by circumstances such as available sources of rock or side slope restrictions imposed by the geometry of the impoundment. The following paragraphs discuss the effects of varying these design parameters on the costs for flood protection of the Grand Junction and Slickrock impoundments.

6.1 GRAND JUNCTION IMPOUNDMENT

Costs for flood protection of the Grand Junction impoundment are developed from estimates of the required earthwork given in Table 4.4, the volume of riprap in Tables B.1 through B.4, the volume of filter material in Table 4.6, and the unit costs in Table 6.1.

TABLE 6.1. Unit Costs for Flood Protection

Item	Unit Cost
Earthwork	
Grading (recontouring)	\$ 1.15/yd^3
Hauling (≤5 mi)	\$ 0.25/yd^3-mi
Excavate, load, dump (fill) (<5 mi)	\$ 1.25/yd^3
Riprap and Filter Rock	
Mining, sorting, loading (1 ft to 4 ft diameter)	\$12.50/yd^3
Mining, screening, loading (2 in. to 12 in. diameter)	7.50/yd^3
Hauling (≤5 mi)	\$ 0.25/yd^3-mi
Dumping, spreading	\$ 1.25/yd^3

Tables C.1 through C.4 (Appendix C) summarize costs for constructing a riprap cover at the Grand Junction impoundment for the different flood events, embankment side slopes, rock specific gravities and safety factors. Construction costs range from slightly less than \$400,000 for protection against the 100-yr flood, using rock with a specific gravity of 2.75, embankment side slopes of 6H:1V, and a safety factor of 1.0, to \$2.7 million for protection against the upper PMF, using rock with a specific gravity of 2.00, embankment side slopes of 10H:1V, and a safety factor of 2.0.

6.1.1 Effects of Selection of Design Flood and Safety Factor on Costs

Six flood events were evaluated at the Grand Junction impoundment. These include the 100-yr flood (63,000 cfs), SPF (70,000 cfs), 500-yr flood (82,000 cfs), lower limit of the PMF (117,000 cfs), Grand Junction PMF (146,000 cfs), and the upper limit of the PMF (175,000 cfs).

Estimated costs for construction of riprap cover with side slopes of 6H:1V using rock with an average specific gravity of 2.25 are shown in Figure 6.1 for safety factors of 1.0, 1.5, and 2.0. An average rock specific gravity of 2.25 corresponds to Dakota sandstone that is readily available in the vicinity of the Grand Junction site.

The estimated costs for construction of a riprap cover with 6H:1V side slopes using rock with an average specific gravity of 2.25 range from about \$400,000 for the 100-yr flood and safety factor of 1.0 to \$1,460,000 for the upper limit of the PMF and safety factor of 2.0. Use of the 500-yr flood as the design flood with a safety factor of 2.0 is about equivalent to the use of the Grand Junction PMF with a safety factor of 1.0. The corresponding cost is

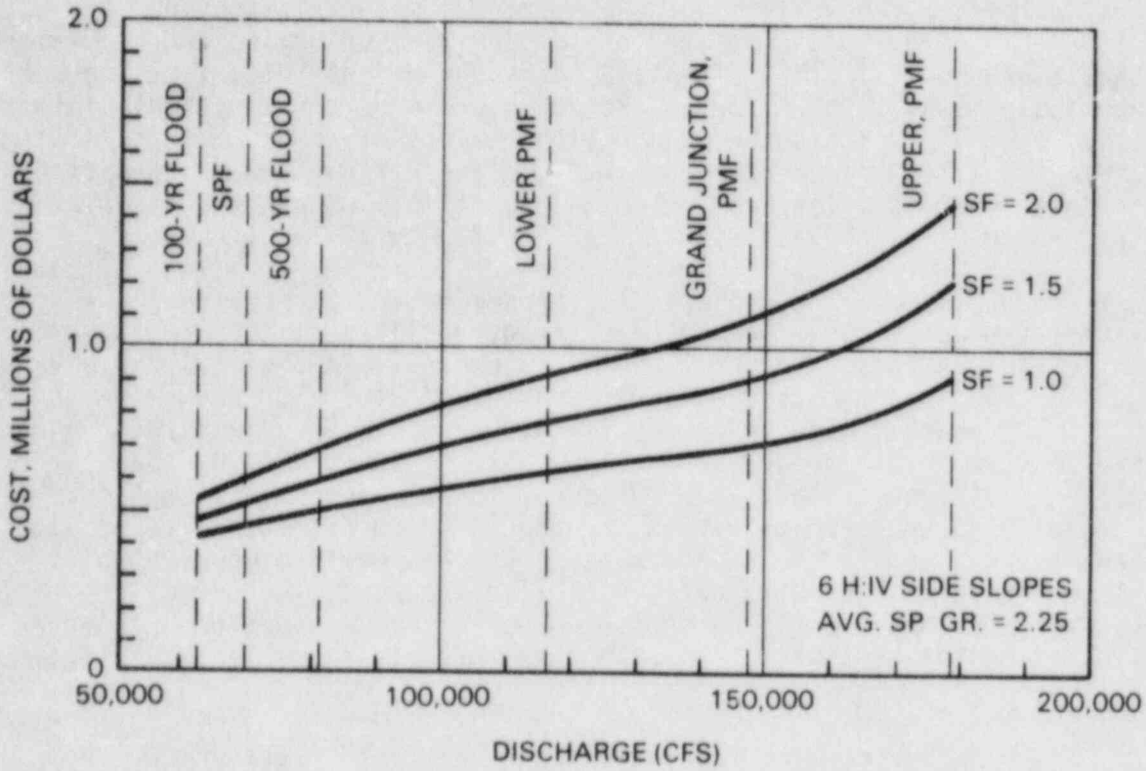

FIGURE 6.1. Grand Junction Impoundment - Effect of Selection of Design Flood and Safety Factor on Costs for Flood Protection

about $700,000. With a safety factor of 1.5 the increase in costs using the 100-yr flood versus the Grand Junction PMF is slightly greater than 90%, increasing from $460,000 for the 100-yr flood to $904,000 for the Grand Junction PMF. There is an increase in costs of about 57% between the 500-yr flood and the Grand Junction PMF. Cost trends using other rock specific gravities and embankment side slopes are similar to those in Figure 6.1. The costs would be less using rock with a higher specific gravity. If only flatter embankment side slopes are considered the costs are higher. The costs using other rock specific gravities and side slopes are summarized in Tables C.1 through C.4 of Appendix C.

Selection of the safety factor used in the design of the riprap cover has a significant effect on the costs, as illustrated in Figure 6.1. For the Grand Junction PMF, the costs for a riprap cover would increase from $703,000 for a safety factor of 1.0 to $1,104,000 for a safety factor of 2.0. This represents an increase in costs of about 57%.

6.1.2 Effects of Specific Gravity of Source Rock on Costs

Potential riprap materials in the vicinity of the Grand Junction impoundment are composed almost exclusively of sandstone with specific gravities ranging from slightly less than 2.00 to about 2.50. Sandstones such as the

Dakota sandstone are exposed within 5 miles of the site. The nearest limestones, which are generally high quality riprap material with specific gravities around 2.70, are located north of Rifle, Colorado, about 80 miles northeast of the mill site. In-place costs for use of these limestones as riprap could be as high as \$30 to \$35/yd^3 because of the long haul distances involved. Basalt can also be an excellent source of riprap materials with specific gravities between 2.60 and 2.80. Basalt flows are exposed on top of Grand Mesa about 40 miles from the Grand Junction impoundment. In-place costs for use of these basalts as riprap are from \$20 to \$25/yd^3.

Table 6.2 summarizes the cost of riprap protection considering specific gravities typical of the rock sources in the vicinity of the Grand Junction site for various safety factors. The most expensive option (\$1,214,000) would be a sandstone source with a specific gravity of about 2.00 and a safety factor of 2.0. The least expensive option (\$673,000) would be a sandstone source with a specific gravity of about 2.50 using a safety factor of 1.0. Sandstones with specific gravities of about 2.25 would provide the next least expensive option. Sandstones with specific gravities of about 2.00 do not appear to be viable alternatives since limestones and basalts can be obtained more cheaply. The final selection of the rock source will also depend on the durability of the rock, which has not been taken into account in this evaluation. Limestone or basalt may be the best choice because these materials are very durable.

TABLE 6.2. Summary of Dollar Cost of Riprap Protection for the Grand Junction PMF (side slope = 6H:1V)

Safety Factor	Specific Gravity: Sandstones 2.00	Sandstones 2.25	Sandstones 2.50	Limestones or Basalts 2.75
1.0	805,000	703,000	(673,000)	736,000
1.25	934,000	834,000	746,000	895,000
1.50	1,003,000	904,000	805,000	1,008,000
1.75	1,104,000	1,003,000	904,000	1,055,000
2.00	(1,214,000)	1,104,000	974,000	1,165,000

The volume of rock for construction of the riprap cover using limestone or basalt with specific gravities greater than 2.50 would be less than the volume using local sandstone. The increase in haul distances, however, will significantly increase the unit costs for the riprap and offset the decrease due to the lesser volume. Using limestone for riprap material, the costs for construction of the riprap cover would range from about \$1,175,000 to \$1,308,000. This represents an increase of 30% to 45% over the costs for using local sandstone. Likewise, the costs for construction using basalt would be higher than using local sandstone, but the cost increase would not be as great as that for limestone due to the shorter haul distance. The construction costs for the riprap cover (6H:1V side slopes) using basalt from Grand Mesa would range from $736,000 (SF = 1.0) to $1.2 million (SF = 2.0) representing an increase of about 5% over that for using local sandstone.

6.1.3 Effects of Selection of Side Slopes on Costs

Side slopes of 2H:1V, 4H:1V, 6H:1V, 8H:1V, and 10H:1V were evaluated in terms of the volume of riprap required for flood protection of the Grand Junction impoundment. It was found that side slopes of 2H:1V were not technically feasible because of the extremely large rock that would be required using the PMF as the design flood and safety factors higher than 1.0. The costs for riprap using 2H:1V side slope, therefore, will not be evaluated. Figure 6.2 illustrates the costs for riprap protection of the Grand Junction impoundment as a function of side slopes. The optimum side slopes, in terms of costs, are slightly steeper than 6H:1V. Although steeper side slopes require a smaller area to be covered by riprap, the rock size increases. For slopes steeper than 6H:1V, the decrease in area is more than offset by the increase in rock size. The corresponding volume of riprap and costs will be slightly greater for these steeper slopes.

The costs for the riprap cover using side slopes of 6H:1V are significantly less than those using side slopes of 10H:1V, as illustrated in Figure 6.3. The costs for the riprap cover with side slopes of 6H:1V using the

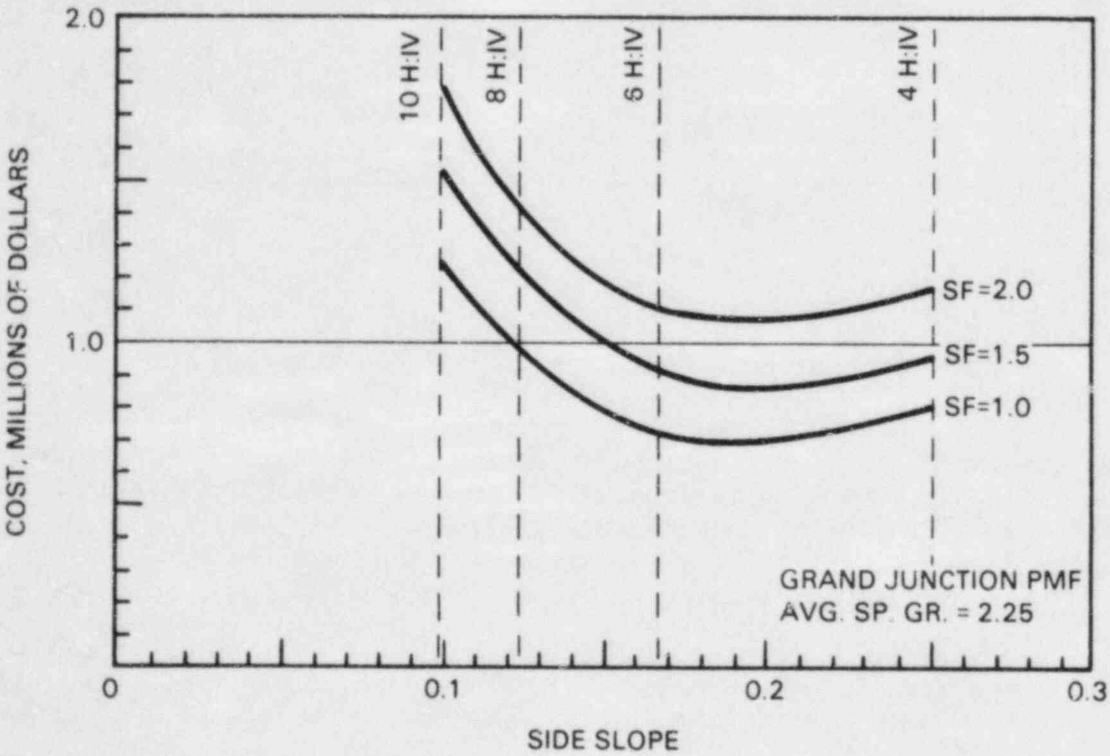

FIGURE 6.2. Grand Junction Impoundment - Cost Optimization of Side Slopes

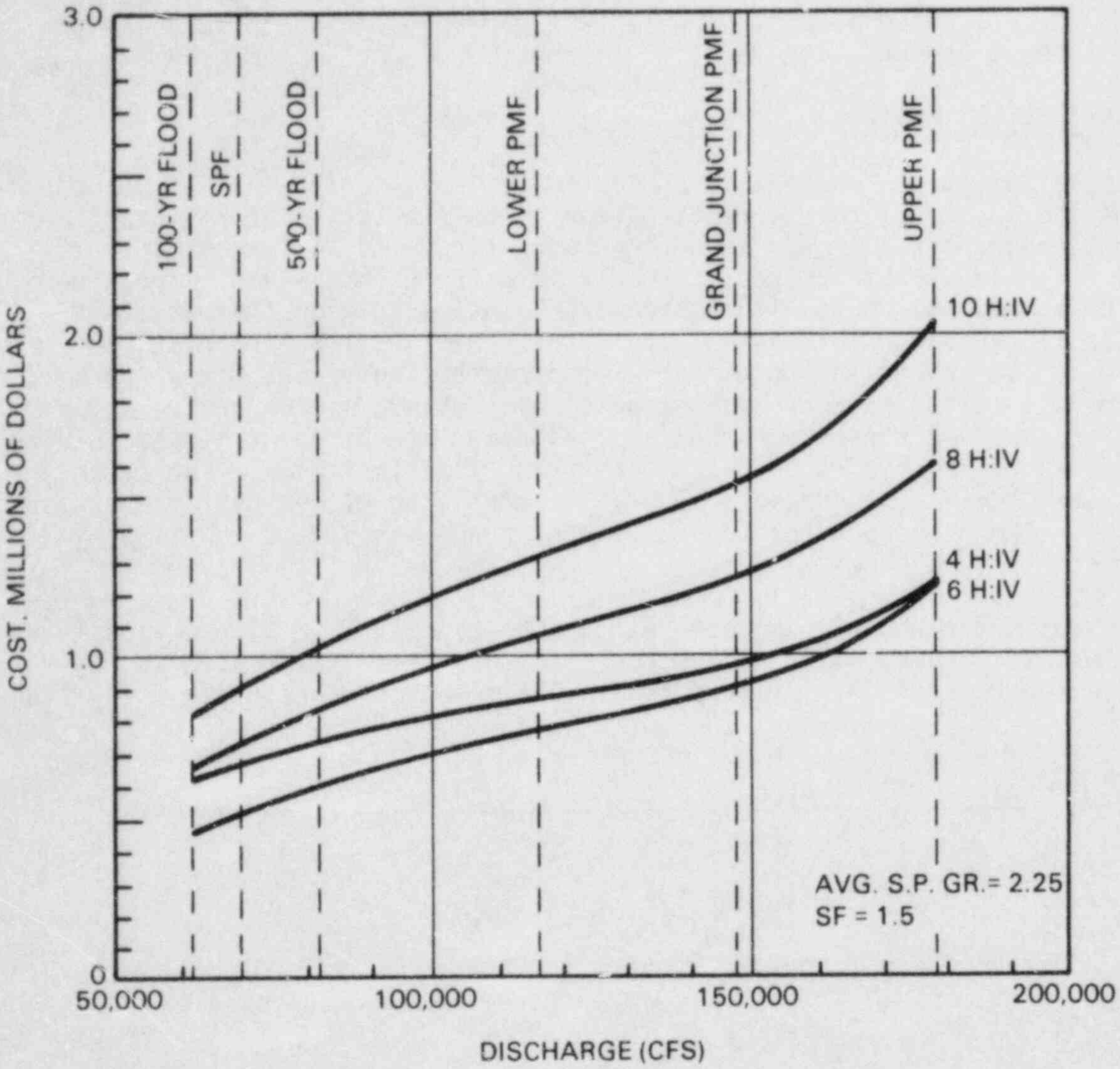

FIGURE 6.3. Grand Junction Impoundment - Effect of Selection of Side Slopes on Costs for Flood Protection

Grand Junction PMF as the design flood, a safety factor of 1.5, and average rock specific gravity of 2.25 is $904,000. The cost using side slopes of 10H:1V is $1,523,000, an increase of about 70%.

6.2 SLICKROCK IMPOUNDMENT

Costs for flood protection of the Slickrock impoundment using riprap are developed from estimates of earthwork given in Table 5.3, the volume of riprap in Table 5.5, the volume of filter material in Table 5.6, and the unit costs given in Table 6.1.

Table C.5 (Appendix C) summarizes costs for constructing a riprap cover at the Slickrock impoundment using different embankment side slopes, rock specific gravities, and safety factors. The costs are based on the PMF as the design flood. Construction costs range from about $290,000 using embankment side slopes of 6H:1V, rock with a specific gravity of 2.75, and a safety factor of 1.0 to about $2.4 million using embankment side slopes of 10H:1V, rock with a specific gravity of 2.00, and a safety factor of 2.0.

6.2.1 Effects of Specific Gravity of Source Rock on Costs

Table 6.3 summarizes the cost of riprap protection for the sandstone specific gravities typical of the Slickrock site for various values of safety factor. Rock with a specific gravity of about 2.50 provides the least expensive option. The cost increases from $312,000 (sp gr = 2.50, SF = 1.0) up to $786,000 (sp gr = 2.00, SF = 2.00). For the frequently used safety factor of 1.50, the cost increases from $427,000 up to $577,000 or about 35%.

TABLE 6.3. Summary of Dollar Cost of Riprap Protection for the Slickrock PMF (side slope = 6H:1V)

Safety Factor	Specific Gravity Sandstones 2.00	2.25	2.50
1.00	421,000	352,000	(312,000)
1.25	492,000	421,000	375,000
1.50	577,000	489,000	427,000
1.75	677,000	565,000	492,000
2.00	(786,000)	650,000	560,000

6.2.2 Effects of Selection of Side Slopes on Costs

The relationship of riprap cover costs at the Slickrock impoundment as a function of embankment side slopes is shown in Figure 6.4 for rock with a specific gravity of 2.25 (Dakota sandstone). Side slopes steeper than 4H:1V are not technically feasible because of the large rock that would be required for the riprap cover, and are excluded from the evaluation.

The costs for a riprap cover increase significantly for embankment side slopes steeper than 6H:1V because of the large amount of earthwork required to decrease the existing embankment side slopes. Embankment side slopes of 6H:1V, therefore, appear to be the most cost effective. Riprap cover costs for a safety factor of 1.5 and a rock specific gravity of 2.25 increase from $489,000 for 6H:1V side slopes to $2.0 million for 10H:1V side slopes. This represents a 310% increase in costs, even though the degree of flood protection is theoretically the same.

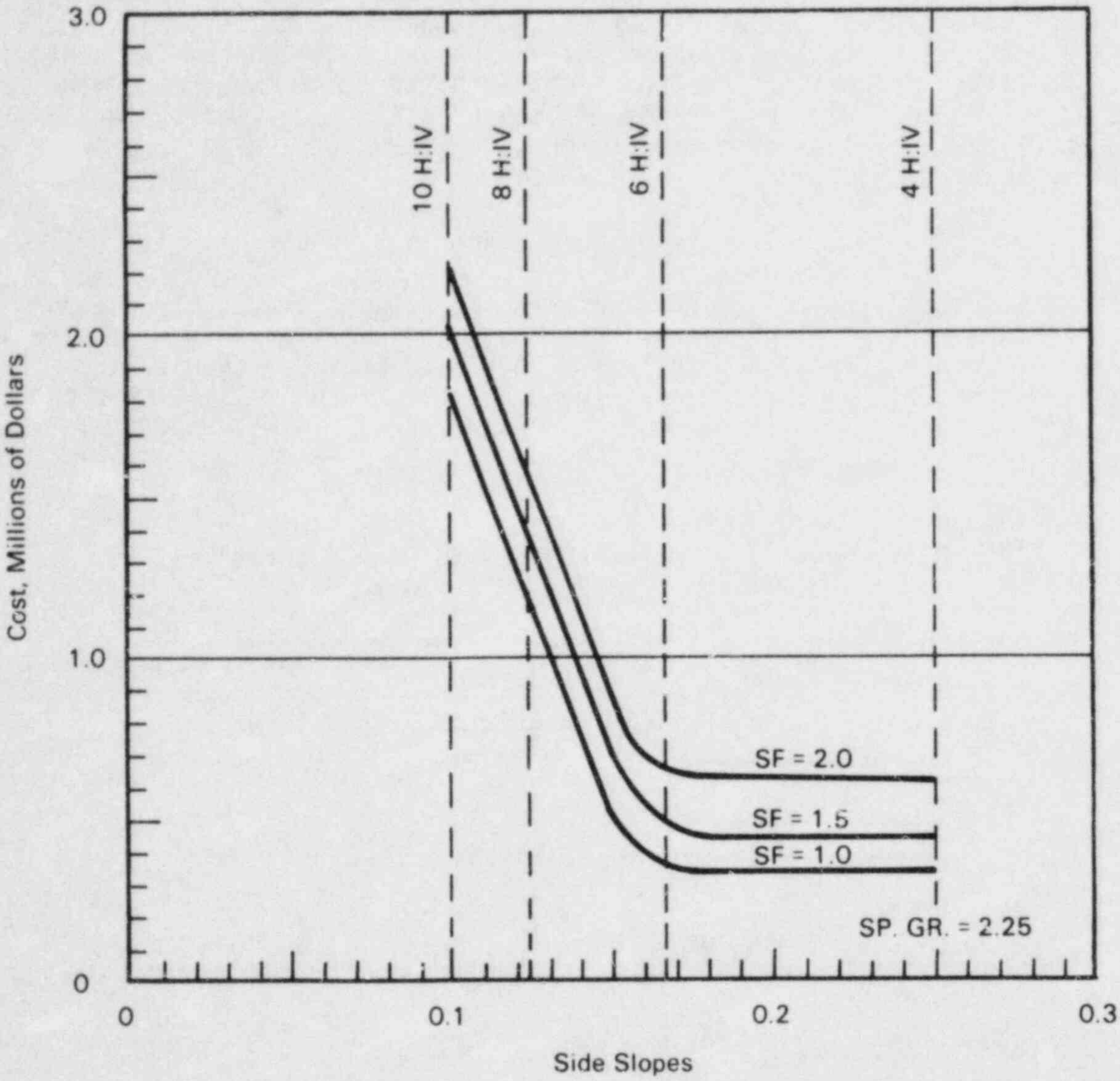

FIGURE 6.4. Slickrock Impoundment - Effect of Selection of Side Slopes on Costs for Flood Protection

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APPENDIX A

MEDIAN DIAMETER OF RIPRAP - GRAND JUNCTION AND SLICKROCK IMPOUNDMENTS

APPENDIX A

MEDIAN DIAMETER OF RIPRAP - GRAND JUNCTION AND SLICKROCK IMPOUNDMENTS

TABLE A.1. Median Diameter of Riprap for Rock with a Specific Gravity of 2.00, Different Flood Events, Side Slopes, and Safety Factors - Grand Junction Impoundment

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 1.0					
2H:1V						
N/W	1.0	0.6	0.5	0.2	0.17	0.08
S/E	2.4	2.0	1.7	1.3	1.1	1.0
4H:1V						
N/W	0.7	0.4	0.3	0.13	0.12	0.06
S/E	1.7	1.4	1.2	0.9	0.8	0.7
6H:1V						
N/W	0.7	0.4	0.3	0.12	0.11	0.05
S/E	1.6	1.3	1.1	0.8	0.7	0.6
8H:1V						
N/W	0.6	0.4	0.3	0.12	0.11	0.05
S/E	1.5	1.3	1.1	0.8	0.7	0.6
10H:1V						
N/E	0.6	0.4	0.3	0.12	0.11	0.05
S/E	1.5	1.2	1.1	0.8	0.7	0.6
	Required D_{50} (ft) for SF = 1.25					
2H:1V						
N/W	1.9	1.2	0.9	0.4	0.3	0.15
S/E	4.6	3.7	3.3	2.4	2.1	1.9
4H:1V						
N/W	1.0	0.6	0.4	0.18	0.17	0.08
S/E	2.3	1.9	1.7	1.2	1.1	0.9
6H:1V						
N/W	0.9	0.5	0.4	0.17	0.15	0.07
S/E	2.1	1.7	1.5	1.1	1.0	0.9
8H:1V						
N/W	0.8	0.5	0.4	0.16	0.15	0.07
S/E	2.0	1.7	1.5	1.1	0.9	0.8
10H:1V						
N/E	0.8	0.5	0.4	0.16	0.14	0.07
S/E	2.0	1.6	1.4	1.1	0.9	0.8

TABLE A.1. (contd)

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 1.5					
2H:1V						
N/W	3.4	2.1	1.6	0.6	0.6	0.3
S/E	8.2	6.7	5.9	4.4	3.7	3.4
4H:1V						
N/W	1.2	0.7	0.5	0.2	0.2	0.09
S/E	2.8	2.3	2.0	1.5	1.3	1.2
6H:1V						
N/W	1.0	0.6	0.5	0.19	0.18	0.08
S/E	2.5	1.9	1.8	1.3	1.1	1.0
8H:1V						
N/W	1.0	0.6	0.5	0.19	0.17	0.08
S/E	2.4	1.9	1.7	1.3	1.1	1.0
10H:1V						
N/E	1.0	0.6	0.4	0.18	0.17	0.08
S/E	2.4	1.9	1.7	1.2	1.1	1.0
	Required D_{50} (ft) for SF = 1.75					
2H:1V						
N/W	>10	6.6	4.9	2.0	1.8	0.9
S/E	>10	>10	>10	>10	>10	>10
4H:1V						
N/W	1.4	0.9	0.7	0.3	0.2	0.11
S/E	3.4	2.8	2.4	1.8	1.5	1.4
6H:1V						
N/W	1.2	0.7	0.6	0.2	0.2	0.10
S/E	2.9	2.2	2.1	1.5	1.3	1.2
8H:1V						
N/W	1.1	0.7	0.5	0.2	0.2	0.09
S/E	2.3	2.2	2.0	1.5	1.2	1.1
10H:1V						
N/E	1.1	0.7	0.5	0.2	0.19	0.09
S/E	2.7	2.2	1.9	1.4	1.2	1.1

TABLE A.1. (contd)

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 2.0					
2H:1V						
N/W	>10	>10	>10	>10	>10	>10
S/E	>10	>10	>10	>10	>10	>10
4H:1V						
N/W	1.7	1.1	0.8	0.3	0.3	0.14
S/E	4.1	3.3	2.9	2.2	1.9	1.7
6H:1V						
N/W	1.4	0.9	0.6	0.3	0.2	0.11
S/E	3.3	2.5	2.4	1.8	1.5	1.4
8H:1V						
N/W	1.3	0.8	0.6	0.2	0.2	0.10
S/E	3.1	2.5	2.2	1.6	1.4	1.3
10H:1V						
N/E	1.2	0.8	0.6	0.2	0.2	0.10
S/E	3.0	2.4	2.1	1.6	1.4	1.2

TABLE A.2. Median Diameter of Riprap for Rock with a Specific Gravity of 2.25, Different Flood Events, Side Slopes, and Safety Factors - Grand Junction Impoundment

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 1.0					
2H:1V						
N/W	0.8	0.5	0.4	0.2	0.14	0.07
S/E	1.9	1.6	1.4	1.0	0.9	0.8
4H:1V						
N/W	0.6	0.3	0.3	0.10	0.10	0.05
S/E	1.3	1.1	1.0	0.7	0.6	0.5
6H:1V						
N/W	0.5	0.3	0.3	0.10	0.09	0.04
S/E	1.3	1.0	0.9	0.7	0.6	0.5
8H:1V						
N/W	0.5	0.3	0.2	0.10	0.09	0.04
S/E	1.2	1.0	0.9	0.7	0.6	0.5
10H:1V						
N/E	0.5	0.3	0.2	0.10	0.09	0.04
S/E	1.2	1.0	0.9	0.7	0.6	0.5

TABLE A.2. (contd)

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 1.25					
2H:1V						
N/W	1.5	1.0	0.7	0.3	0.3	0.12
S/E	3.7	3.0	2.6	1.9	1.7	1.5
4H:1V						
N/W	0.8	0.5	0.4	0.15	0.13	0.06
S/E	1.8	1.5	1.3	1.0	0.8	0.8
6H:1V						
N/W	0.7	0.4	0.4	0.13	0.12	0.06
S/E	1.7	1.4	1.2	0.9	0.8	0.7
8H:1V						
N/W	0.7	0.4	0.3	0.13	0.12	0.05
S/E	1.6	1.3	1.1	0.9	0.7	0.7
10H:1V						
N/E	0.7	0.4	0.3	0.13	0.11	0.05
S/E	1.6	1.3	1.1	0.9	0.7	0.7
	Required D_{50} (ft) for SF = 1.5					
2H:1V						
N/W	2.7	1.7	1.3	0.5	0.5	0.2
S/E	6.5	5.3	4.7	3.5	3.0	2.7
4H:1V						
N/W	0.9	0.6	0.5	0.18	0.16	0.08
S/E	2.3	1.8	1.6	1.2	1.0	0.9
6H:1V						
N/W	0.8	0.5	0.4	0.15	0.14	0.07
S/E	2.0	1.6	1.4	1.1	0.9	0.8
8H:1V						
N/W	0.8	0.5	0.4	0.15	0.14	0.06
S/E	1.9	1.6	1.4	1.1	0.9	0.8
10H:1V						
N/E	0.8	0.5	0.4	0.15	0.13	0.06
S/E	1.9	1.5	1.3	1.0	0.8	0.8

TABLE A.2. (contd)

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 1.75					
2H:1V						
N/W	8.5	5.4	4.2	1.6	1.5	0.7
S/E	>10	>10	10.0	9.0	8.5	7.5
4H:1V						
N/W	1.1	0.7	0.5	0.2	0.2	0.09
S/E	2.7	2.2	1.9	1.4	1.2	1.1
6H:1V						
N/W	1.0	0.6	0.4	0.18	0.16	0.08
S/E	2.3	1.9	1.6	1.2	1.0	0.9
8H:1V						
N/W	0.9	0.6	0.4	0.17	0.16	0.07
S/E	2.2	1.8	1.6	1.2	1.0	0.9
10H:1V						
N/E	0.9	0.6	0.4	0.17	0.15	0.07
S/E	2.1	1.7	1.5	1.1	1.0	0.9
	Required D_{50} (ft) for SF = 2.0					
2H:1V						
N/W	>10	>10	>10	>10	>10	>10
S/E	>10	>10	>10	>10	>10	>10
4H:1V						
N/W	1.4	0.9	0.6	0.3	0.2	0.11
S/E	3.3	2.7	2.3	1.8	1.5	1.3
6H:1V						
N/W	1.1	0.7	0.5	0.2	0.19	0.09
S/E	2.6	2.2	1.9	1.4	1.2	1.1
8H:1V						
N/W	1.0	0.6	0.5	0.19	0.18	0.08
S/E	2.5	2.0	1.8	1.3	1.1	1.0
10H:1V						
N/E	1.0	0.6	0.4	0.19	0.17	0.08
S/E	2.4	2.0	1.7	1.3	1.1	1.0

TABLE A.3. Median Diameter of Riprap for Rock with a Specific Gravity of 2.50, Different Flood Events, Side Slopes, and Safety Factors - Grand Junction Impoundment

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 1.0					
2H:1V						
N/W	0.7	0.4	0.3	0.13	0.12	0.05
S/E	1.6	1.3	1.2	0.9	0.7	0.7
4H:1V						
N/W	0.5	0.3	0.2	0.09	0.08	0.04
S/E	1.1	0.9	0.8	0.6	0.5	0.5
6H:1V						
N/W	0.4	0.3	0.2	0.08	0.08	0.04
S/E	1.1	0.9	0.8	0.6	0.5	0.4
8H:1V						
N/W	0.4	0.3	0.2	0.08	0.07	0.04
S/E	1.0	0.8	0.7	0.5	0.5	0.4
10H:1V						
N/W	0.4	0.3	0.2	0.08	0.07	0.04
S/E	1.0	0.8	0.7	0.5	0.5	0.4
	Required D_{50} (ft) for SF = 1.25					
2H:1V						
N/W	1.3	0.8	0.6	0.2	0.2	0.10
S/E	3.0	2.5	2.2	1.6	1.4	1.3
4H:1V						
N/W	0.7	0.4	0.3	0.12	0.11	0.05
S/E	1.5	1.3	1.1	0.8	0.7	0.6
6H:1V						
N/W	0.7	0.4	0.3	0.11	0.10	0.05
S/E	1.4	1.1	1.0	0.7	0.6	0.6
8H:1V						
N/W	0.6	0.4	0.3	0.11	0.10	0.05
S/E	1.4	1.1	1.0	0.7	0.6	0.5
10H:1V						
N/W	0.6	0.3	0.3	0.10	0.10	0.05
S/E	1.3	1.1	1.0	0.7	0.6	0.5

TABLE A.3. (contd)

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 1.5					
2H:1V						
N/W	2.3	1.4	1.1	0.4	0.4	0.18
S/E	5.5	4.5	4.0	2.9	2.5	2.3
4H:1V						
N/W	0.8	0.5	0.4	0.15	0.13	0.06
S/E	1.9	1.5	1.3	1.0	0.9	0.8
6H:1V						
N/W	0.8	0.4	0.3	0.13	0.12	0.06
S/E	1.6	1.3	1.2	0.9	0.8	0.7
8H:1V						
N/W	0.7	0.4	0.3	0.12	0.11	0.05
S/E	1.6	1.3	1.1	0.8	0.7	0.6
10H:1V						
N/W	0.6	0.4	0.3	0.12	0.11	0.05
S/E	1.6	1.3	1.1	0.8	0.7	0.6
	Required D_{50} (ft) for SF = 1.75					
2H:1V						
N/W	7.0	4.4	3.3	1.4	1.3	0.6
S/E	>10	>10	>10	8.9	7.6	6.9
4H:1V						
N/W	0.9	0.6	0.4	0.18	0.16	0.08
S/E	2.3	1.8	1.6	1.2	1.0	0.9
6H:1V						
N/W	0.9	0.5	0.4	0.15	0.14	0.06
S/E	1.9	1.6	1.4	1.0	0.9	0.8
8H:1V						
N/W	0.8	0.5	0.4	0.14	0.13	0.06
S/E	1.8	1.5	1.3	1.0	0.8	0.7
10H:1V						
N/W	0.7	0.5	0.3	0.14	0.13	0.06
S/E	1.8	1.4	1.3	0.9	0.8	0.7

TABLE A.3. (contd)

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 2.0					
2H:1V						
N/W	>10	>10	>10	>10	>10	>10
S/E	>10	>10	>10	>10	>10	>10
4H:1V						
N/W	1.1	0.7	0.5	0.2	0.19	0.09
S/E	2.7	2.2	1.9	1.4	1.2	1.1
6H:1V						
N/W	0.9	0.6	0.4	0.18	0.16	0.07
S/E	2.2	1.8	1.6	1.2	1.0	0.9
8H:1V						
N/W	0.9	0.5	0.4	0.16	0.15	0.07
S/E	2.1	1.7	1.5	1.1	0.9	0.8
10H:1V						
N/W	0.8	0.5	0.4	0.16	0.14	0.07
S/E	2.0	1.6	1.4	1.1	0.9	0.8

TABLE A.4. Median Diameter of Riprap for Rock with a Specific Gravity of 2.75, Different Flood Events, Side Slopes, and Safety Factors - Grand Junction Impoundment

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 1.0					
2H:1V						
N/W	0.6	0.4	0.3	0.11	0.10	0.05
S/E	1.4	1.1	1.0	0.7	0.6	0.6
4H:1V						
N/W	0.4	0.2	0.18	0.08	0.07	0.03
S/E	1.0	0.8	0.7	0.5	0.4	0.4
6H:1V						
N/W	0.4	0.2	0.17	0.07	0.06	0.03
S/E	0.9	0.7	0.6	0.5	0.4	0.4
8H:1V						
N/W	0.4	0.2	0.17	0.07	0.06	0.03
S/E	0.9	0.7	0.6	0.5	0.4	0.4
10H:1V						
N/W	0.4	0.2	0.17	0.07	0.06	0.03
S/E	0.9	0.7	0.6	0.5	0.4	0.4
	Required D_{50} (ft) for SF = 1.25					
2H:1V						
N/W	1.1	0.7	0.5	0.2	0.19	0.09
S/E	2.6	2.2	1.9	1.4	1.2	1.1
4H:1V						
N/W	0.6	0.3	0.2	0.10	0.09	0.04
S/E	1.3	1.1	0.9	0.7	0.6	0.5
6H:1V						
N/W	0.5	0.3	0.2	0.09	0.09	0.04
S/E	1.2	1.0	0.9	0.6	0.5	0.5
8H:1V						
N/W	0.5	0.3	0.2	0.09	0.09	0.04
S/E	1.2	0.9	0.8	0.6	0.5	0.5
10H:1V						
N/W	0.5	0.3	0.2	0.09	0.08	0.04
S/E	1.1	0.9	0.8	0.6	0.5	0.5

TABLE A.4. (contd)

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
			Required D_{50} (ft) for SF = 1.5			
2H:1V						
N/W	2.0	1.2	0.9	0.4	0.3	0.16
S/E	4.7	3.8	3.4	2.5	2.1	1.9
4H:1V						
N/W	0.7	0.4	0.3	0.13	0.12	0.05
S/E	1.6	1.3	1.2	0.9	0.7	0.7
6H:1V						
N/W	0.6	0.4	0.3	0.11	0.10	0.05
S/E	1.4	1.2	1.0	0.8	0.7	0.6
8H:1V						
N/W	0.6	0.4	0.3	0.11	0.10	0.05
S/E	1.4	1.1	1.0	0.7	0.6	0.6
10H:1V1						
N/W	0.6	0.3	0.3	0.10	0.10	0.04
S/E	1.3	1.1	1.0	0.7	0.6	0.5
			Required D_{50} (ft) for SF = 1.75			
2H:1V						
N/W	6.0	3.8	2.8	1.2	1.1	0.5
S/E	>10	>10	>10	7.1	6.6	5.9
4H:1V						
N/W	0.8	0.5	0.4	0.15	0.14	0.07
S/E	1.9	1.6	1.4	1.0	0.9	0.8
6H:1V						
N/W	0.7	0.4	0.3	0.13	0.12	0.06
S/E	1.6	1.3	1.2	0.9	0.7	0.7
8H:1V						
N/W	0.7	0.4	0.3	0.12	0.11	0.05
S/E	1.6	1.3	1.1	0.8	0.7	0.6
10H:1V						
N/W	0.6	0.4	0.3	0.12	0.11	0.05
S/E	1.5	1.2	1.1	0.8	0.7	0.6

TABLE A.4. (contd)

Side Slope	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
	Required D_{50} (ft) for SF = 2.0					
2H:1V						
N/W	>10	>10	>10	>10	>10	>10
S/E	>10	>10	>10	>10	>10	>10
4H:1V						
N/W	1.0	0.6	0.5	0.18	0.17	0.08
S/E	2.3	1.9	1.7	1.2	1.1	0.9
6H:1V						
N/W	0.8	0.5	0.4	0.15	0.14	0.06
S/E	1.9	1.5	1.4	1.0	0.9	0.8
8H:1V						
N/W	0.7	0.5	0.3	0.14	0.13	0.06
S/E	1.8	1.4	1.3	0.9	0.8	0.7
10H:1V						
N/W	0.7	0.4	0.3	0.13	0.12	0.06
S/E	1.7	1.4	1.2	0.9	0.8	0.7

TABLE A.5. Median Diameter of Riprap at Section 1 for PMF and Different Rock Specific Gravities, Side Slopes, and Safety Factors - Slickrock Impoundment

Side Slopes	SF=1.0	SF=1.25	SF=1.50	SF=1.75	SF=2.00
	Required D_{50} (ft) for sp gr = 2.00				
2H:1V	1.7	2.8	5.7	>10	>10
4H:1V	1.2	1.5	2.0	2.5	3.1
6H:1V	1.1	1.4	1.7	2.1	2.5
8H:1V	1.1	1.4	1.7	2.0	2.3
10H:1V	1.1	1.3	1.6	1.9	2.2
	Required D_{50} (ft) for sp gr = 2.25				
2H:1V	1.4	2.3	4.6	>10	>10
4H:1V	0.9	1.3	1.6	2.0	2.5
6H:1V	0.9	1.1	1.4	1.7	2.0
8H:1V	0.9	1.1	1.3	1.6	1.8
10H:1V	0.8	1.1	1.3	1.5	1.8
	Required D_{50} (ft) for sp gr = 2.50				
2H:1V	1.1	1.9	3.8	>10	>10
4H:1V	0.8	1.0	1.3	1.6	2.1
6H:1V	0.7	0.9	1.1	1.4	1.6
8H:1V	0.7	0.9	1.1	1.3	1.5
10H:1V	0.7	0.9	1.1	1.3	1.5
	Required D_{50} (ft) for sp gr = 2.75				
2H:1V	1.0	1.6	3.3	>10	>10
4H:1V	0.7	0.9	1.1	1.4	1.8
6H:1V	0.6	0.8	1.0	1.2	1.4
8H:1V	0.6	0.8	0.9	1.1	1.3
10H:1V	0.6	0.8	0.9	1.1	1.3

TABLE A.6. Median Diameter of Riprap at Section 2 for PMF and Different Rock Specific Gravities, Side Slopes, and Safety Factors - Slickrock Impoundment

Side Slopes	SF=1.0	SF=1.25	SF=1.50	SF=1.75	SF=2.00
	Required D_{50} (ft) for sp gr = 2.00				
2H:1V	4.1	6.9	>10	>10	>10
4H:1V	2.8	3.7	4.8	6.0	7.6
6H:1V	2.7	3.4	4.2	5.1	6.0
8H:1V	2.6	3.3	4.0	4.8	5.6
10H:1V	2.6	3.3	3.9	4.7	5.4
	Required D_{50} (ft) for sp gr = 2.25				
2H:1V	3.3	5.5	>10	>10	>10
4H:1V	2.3	3.0	3.8	4.8	6.1
6H:1V	2.1	2.7	3.4	4.0	4.8
8H:1V	2.1	2.6	3.2	3.8	4.5
10H:1V	2.1	2.6	3.2	3.7	4.3
	Required D_{50} (ft) for sp gr = 2.50				
2H:1V	2.8	4.6	9.3	>10	>10
4H:1V	1.9	2.5	3.2	4.0	5.1
6H:1V	1.8	2.3	2.8	3.4	4.0
8H:1V	1.7	2.2	2.7	3.2	3.7
10H:1V	1.7	2.2	2.6	3.1	3.6
	Required D_{50} (ft) for sp gr = 2.75				
2H:1V	2.4	3.9	8.0	>10	>10
4H:1V	1.6	2.2	2.7	3.4	4.3
6H:1V	1.5	1.9	2.4	2.9	3.4
8H:1V	1.5	1.9	2.3	2.7	3.2
10H:1V	1.5	1.9	2.3	2.7	3.1

TABLE A.7. Median Diameter of Riprap at Section 3 for PMF and Different Rock Specific Gravities, Side Slopes, and Safety Factors - Slickrock Impoundment

Side Slopes	SF=1.0	SF=1.25	SF=1.50	SF=1.75	SF=2.00
	Required D_{50} (ft) for sp gr = 2.00				
2H:1V	1.0	1.7	3.4	>10	>10
4H:1V	0.7	0.9	1.2	1.5	1.9
6H:1V	0.7	0.8	1.0	1.2	1.5
8H:1V	0.6	0.8	1.0	1.2	1.4
10H:1V	0.6	0.8	1.0	1.1	1.3
	Required D_{50} (ft) for sp gr = 2.25				
2H:1V	0.8	1.3	2.7	>10	>10
4H:1V	0.6	0.7	0.9	1.2	1.5
6H:1V	0.5	0.7	0.8	1.0	1.2
8H:1V	0.5	0.6	0.8	0.9	1.1
10H:1V	0.5	0.6	0.8	0.9	1.1
	Required D_{50} (ft) for sp gr = 2.50				
2H:1V	0.7	1.1	2.3	>10	>10
4H:1V	0.5	0.6	0.8	1.0	1.2
6H:1V	0.4	0.6	0.7	0.8	1.0
8H:1V	0.4	0.5	0.7	0.8	0.9
10H:1V	0.4	0.5	0.6	0.8	0.9
	Required D_{50} (ft) for sp gr = 2.75				
2H:1V	0.6	1.0	2.0	>10	>10
4H:1V	0.4	0.5	0.7	0.8	1.1
6H:1V	0.4	0.5	0.6	0.7	0.8
8H:1V	0.4	0.5	0.6	0.7	0.8
10H:1V	0.4	0.5	0.6	0.7	0.8

TABLE A.8. Median Diameter of Riprap at Section 4 for PMF and Different Rock Specific Gravities, Side Slopes, and Safety Factors - Slickrock Impoundment

Side Slopes	SF=1.0	SF=1.25	SF=1.50	SF=1.75	SF=2.00
	Required D_{50} (ft) for sp gr = 2.00				
2H:1V	0.3	0.5	1.1	6.9	>10
4H:1V	0.2	0.3	0.4	0.5	0.6
6H:1V	0.2	0.3	0.3	0.4	0.5
8H:1V	0.2	0.3	0.3	0.4	0.4
10H:1V	0.2	0.3	0.3	0.4	0.4
	Required D_{50} (ft) for sp gr = 2.25				
2H:1V	0.3	0.4	0.9	5.5	>10
4H:1V	0.18	0.2	0.3	0.4	0.5
6H:1V	0.16	0.2	0.2	0.3	0.3
8H:1V	0.16	0.2	0.2	0.3	0.3
10H:1V	0.16	0.2	0.2	0.3	0.3
	Required D_{50} (ft) for sp gr = 2.50				
2H:1V	0.2	0.4	0.7	4.6	>10
4H:1V	0.15	0.19	0.2	0.3	0.4
6H:1V	0.14	0.18	0.2	0.3	0.3
8H:1V	0.13	0.17	0.2	0.2	0.3
10H:1V	0.13	0.17	0.2	0.2	0.3
	Required D_{50} (ft) for sp gr = 2.75				
2H:1V	0.19	0.3	0.6	4.0	>10
4H:1V	0.13	0.16	0.2	0.3	0.3
6H:1V	0.12	0.15	0.18	0.2	0.3
8H:1V	0.12	0.15	0.18	0.2	0.2
10H:1V	0.11	0.14	0.17	0.2	0.2

APPENDIX B

VOLUMES OF RIPRAP REQUIRED AT THE GRAND JUNCTION IMPOUNDMENT

TABLE B.1. Volume of Riprap with a Specific Gravity of 2.00 Required to Protect Against Indicated Flood Events, Different Side Slopes, and Safety Factors - Grand Junction Impoundment

Side Slope Safety Factor	Required Volume of Riprap (sp gr = 2.00), yd^3					
	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
2H:1V						
SF=1.0	19,400	13,300	10,300	6,300	5,400	4,400
SF=1.25	37,000	24,700	19,900	11,600	10,100	8,200
SF=1.5	66,000	44,600	35,600	21,200	17,900	14,700
SF=1.75	---	---	---	---	---	---
SF=2.0	---	---	---	---	---	---
4H:1V						
SF=1.0	25,200	17,000	13,300	8,100	7,100	5,600
SF=1.25	34,400	23,300	18,700	10,800	9,800	7,200
SF=1.5	41,800	28,100	22,100	13,300	11,600	9,500
SF=1.75	50,400	34,500	26,800	16,100	13,300	11,100
SF=2.0	60,900	40,800	32,300	19,600	17,000	13,600
6H:1V						
SF=1.0	35,300	23,500	18,000	10,500	9,200	7,000
SF=1.25	46,300	30,600	24,500	14,500	13,100	10,500
SF=1.5	54,400	34,400	29,500	17,200	14,500	11,700
SF=1.75	63,500	39,900	34,600	19,700	17,200	14,100
SF=2.0	72,500	45,900	39,100	23,800	19,700	16,400
8H:1V						
SF=1.0	43,300	31,200	23,900	14,000	12,200	9,300
SF=1.25	57,700	40,500	32,600	19,200	15,800	12,500
SF=1.5	69,700	45,600	36,400	22,600	19,300	15,600
SF=1.7	80,600	52,800	43,200	26,100	21,100	17,100
SF=2.0	89,000	60,100	47,800	27,800	24,400	20,200
10H:1V						
SF=1.0	53,900	36,200	29,800	17,400	15,200	11,700
SF=1.25	72,000	47,800	38,200	24,000	19,600	15,500
SF=1.5	86,900	56,800	45,600	26,200	24,000	19,400
SF=1.75	97,400	65,900	51,400	30,500	26,200	21,400
SF=2.0	108,000	72,200	57,100	34,700	30,500	23,300

TABLE B.2. Volume of Riprap with a Specific Gravity of 2.25 Required to Protect Against Indicated Flood Events, Different Side Slopes, and Safety Factors - Grand Junction Impoundment

Side Slope Safety Factor	Required Volume of Riprap (sp gr = 2.25), yd^3					
	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
2H:1V						
SF=1.0	15,300	10,600	8,400	4,900	4,300	3,500
SF=1.25	29,700	20,100	15,700	9,200	8,300	6,500
SF=1.5	52,300	35,300	28,400	16,900	14,600	11,600
SF=1.75	---	---	63,000	43,900	41,400	32,500
SF=2.0	---	---	---	---	---	---
4H:1V						
SF=1.0	19,700	13,400	11,200	6,200	5,400	4,000
SF=2.5	27,000	18,500	14,600	8,900	7,200	6,400
SF=1.5	33,900	22,200	18,000	10,800	8,900	7,200
SF=1.75	40,000	27,000	21,100	12,500	10,800	8,800
SF=2.0	49,200	33,400	25,500	15,900	13,300	10,300
6H:1V						
SF=1.0	28,200	18,000	15,000	9,200	7,900	5,900
SF=1.25	37,200	25,100	20,000	11,900	10,600	8,200
SF=1.5	43,500	29,000	23,000	14,400	11,900	9,400
SF=1.75	50,700	34,400	26,000	15,800	13,200	10,500
SF=2.0	57,100	39,900	31,100	18,400	15,900	13,000
8H:1V						
SF=1.0	34,900	23,800	19,200	12,200	10,500	7,800
SF=1.25	46,800	31,200	23,900	15,700	12,300	10,900
SF=1.5	55,300	38,400	30,600	19,200	15,700	12,400
SF=1.75	63,700	43,500	34,600	21,000	17,500	14,000
SF=2.0	72,200	47,800	39,200	22,600	19,300	15,600
10H:1V						
SF=1.0	43,500	29,800	24,000	15,200	13,000	9,700
SF=1.25	58,400	38,800	29,800	19,500	15,200	13,600
SF=1.5	68,900	45,200	35,700	21,700	17,400	15,500
SF=1.75	76,300	51,500	40,600	24,000	21,700	17,400
SF=2.0	86,900	59,500	45,600	28,300	24,000	19,400

TABLE A.6. Median Diameter of Riprap at Section 2 for PMF and Different Rock Specific Gravities, Side Slopes, and Safety Factors - Slickrock Impoundment

Side Slopes	SF=1.0	SF=1.25	SF=1.50	SF=1.75	SF=2.00
	Required D_{50} (ft) for sp gr = 2.00				
2H:1V	4.1	6.9	>10	>10	>10
4H:1V	2.8	3.7	4.8	6.0	7.6
6H:1V	2.7	3.4	4.2	5.1	6.0
8H:1V	2.6	3.3	4.0	4.8	5.6
10H:1V	2.6	3.3	3.9	4.7	5.4
	Required D_{50} (ft) for sp gr = 2.25				
2H:1V	3.3	5.5	>10	>10	>10
4H:1V	2.3	3.0	3.8	4.8	6.1
6H:1V	2.1	2.7	3.4	4.0	4.8
8H:1V	2.1	2.6	3.2	3.8	4.5
10H:1V	2.1	2.6	3.2	3.7	4.3
	Required D_{50} (ft) for sp gr = 2.50				
2H:1V	2.8	4.6	9.3	>10	>10
4H:1V	1.9	2.5	3.2	4.0	5.1
6H:1V	1.8	2.3	2.8	3.4	4.0
8H:1V	1.7	2.2	2.7	3.2	3.7
10H:1V	1.7	2.2	2.6	3.1	3.6
	Required D_{50} (ft) for sp gr = 2.75				
2H:1V	2.4	3.9	8.0	>10	>10
4H:1V	1.6	2.2	2.7	3.4	4.3
6H:1V	1.5	1.9	2.4	2.9	3.4
8H:1V	1.5	1.9	2.3	2.7	3.2
10H:1V	1.5	1.9	2.3	2.7	3.1

TABLE A.7. Median Diameter of Riprap at Section 3 for PMF and Different Rock Specific Gravities, Side Slopes, and Safety Factors - Slickrock Impoundment

Side Slopes	SF=1.0	SF=1.25	SF=1.50	SF=1.75	SF=2.00
	Required D_{50} (ft) for sp gr = 2.00				
2H:1V	1.0	1.7	3.4	>10	>10
4H:1V	0.7	0.9	1.2	1.5	1.9
6H:1V	0.7	0.8	1.0	1.2	1.5
8H:1V	0.6	0.8	1.0	1.2	1.4
10H:1V	0.6	0.8	1.0	1.1	1.3
	Required D_{50} (ft) for sp gr = 2.25				
2H:1V	0.8	1.3	2.7	>10	>10
4H:1V	0.6	0.7	0.9	1.2	1.5
6H:1V	0.5	0.7	0.8	1.0	1.2
8H:1V	0.5	0.6	0.8	0.9	1.1
10H:1V	0.5	0.6	0.8	0.9	1.1
	Required D_{50} (ft) for sp gr = 2.50				
2H:1V	0.7	1.1	2.3	>10	>10
4H:1V	0.5	0.6	0.8	1.0	1.2
6H:1V	0.4	0.6	0.7	0.8	1.0
8H:1V	0.4	0.5	0.7	0.8	0.9
10H:1V	0.4	0.5	0.6	0.8	0.9
	Required D_{50} (ft) for sp gr = 2.75				
2H:1V	0.6	1.0	2.0	>10	>10
4H:1V	0.4	0.5	0.7	0.8	1.1
6H:1V	0.4	0.5	0.6	0.7	0.8
8H:1V	0.4	0.5	0.6	0.7	0.8
10H:1V	0.4	0.5	0.6	0.7	0.8

TABLE A.8. Median Diameter of Riprap at Section 4 for PMF and Different Rock Specific Gravities, Side Slopes, and Safety Factors - Slickrock Impoundment

Side Slopes	SF=1.0	SF=1.25	SF=1.50	SF=1.75	SF=2.00
	Required D_{50} (ft) for sp gr = 2.00				
2H:1V	0.3	0.5	1.1	6.9	>10
4H:1V	0.2	0.3	0.4	0.5	0.6
6H:1V	0.2	0.3	0.3	0.4	0.5
8H:1V	0.2	0.3	0.3	0.4	0.4
10H:1V	0.2	0.3	0.3	0.4	0.4
	Required D_{50} (ft) for sp gr = 2.25				
2H:1V	0.3	0.4	0.9	5.5	>10
4H:1V	0.18	0.2	0.3	0.4	0.5
6H:1V	0.16	0.2	0.2	0.3	0.3
8H:1V	0.16	0.2	0.2	0.3	0.3
10H:1V	0.16	0.2	0.2	0.3	0.3
	Required D_{50} (ft) for sp gr = 2.50				
2H:1V	0.2	0.4	0.7	4.6	>10
4H:1V	0.15	0.19	0.2	0.3	0.4
6H:1V	0.14	0.18	0.2	0.3	0.3
8H:1V	0.13	0.17	0.2	0.2	0.3
10H:1V	0.13	0.17	0.2	0.2	0.3
	Required D_{50} (ft) for sp gr = 2.75				
2H:1V	0.19	0.3	0.6	4.0	>10
4H:1V	0.13	0.16	0.2	0.3	0.3
6H:1V	0.12	0.15	0.18	0.2	0.3
8H:1V	0.12	0.15	0.18	0.2	0.2
10H:1V	0.11	0.14	0.17	0.2	0.2

APPENDIX B

VOLUMES OF RIPRAP REQUIRED AT THE GRAND JUNCTION IMPOUNDMENT

TABLE B.1. Volume of Riprap with a Specific Gravity of 2.00 Required to Protect Against Indicated Flood Events, Different Side Slopes, and Safety Factors - Grand Junction Impoundment

	Required Volume of Riprap (sp gr = 2.00), yd^3					
Side Slope Safety Factor	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
2H:1V						
SF=1.0	19,400	13,300	10,300	6,300	5,400	4,400
SF=1.25	37,000	24,700	19,900	11,600	10,100	8,200
SF=1.5	66,000	44,600	35,600	21,200	17,900	14,700
SF=1.75	---	---	---	---	---	---
SF=2.0	---	---	---	---	---	---
4H:1V						
SF=1.0	25,200	17,000	13,300	8,100	7,100	5,600
SF=1.25	34,400	23,300	18,700	10,800	9,800	7,200
SF=1.5	41,800	28,100	22,100	13,300	11,600	9,500
SF=1.75	50,400	34,500	26,800	16,100	13,300	11,100
SF=2.0	60,900	40,800	32,300	19,600	17,000	13,600
6H:1V						
SF=1.0	35,300	23,500	18,000	10,500	9,200	7,000
SF=1.25	46,300	30,600	24,500	14,500	13,100	10,500
SF=1.5	54,400	34,400	29,500	17,200	14,500	11,700
SF=1.75	63,500	39,900	34,600	19,700	17,200	14,100
SF=2.0	72,500	45,900	39,100	23,800	19,700	16,400
8H:1V						
SF=1.0	43,300	31,200	23,900	14,000	12,200	9,300
SF=1.25	57,700	40,500	32,600	19,200	15,800	12,500
SF=1.5	69,700	45,600	36,400	22,600	19,300	15,600
SF=1.7	80,600	52,800	43,200	26,100	21,100	17,100
SF=2.0	89,000	60,100	47,800	27,800	24,400	20,200
10H:1V						
SF=1.0	53,900	36,200	29,800	17,400	15,200	11,700
SF=1.25	72,000	47,600	38,200	24,000	19,600	15,500
SF=1.5	86,900	56,800	45,600	26,200	24,000	19,400
SF=1.75	97,400	65,900	51,400	30,500	26,200	21,400
SF=2.0	108,000	72,200	57,100	34,700	30,500	23,300

TABLE B.2. Volume of Riprap with a Specific Gravity of 2.25 Required to Protect Against Indicated Flood Events, Different Side Slopes, and Safety Factors - Grand Junction Impoundment

Side Slope Safety Factor	Required Volume of Riprap (sp gr = 2.25), yd^3 Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
2H:1V						
SF=1.0	15,300	10,600	8,400	4,900	4,300	3,500
SF=1.25	29,700	20,100	15,700	9,200	8,300	6,500
SF=1.5	52,300	35,300	28,400	16,900	14,600	11,600
SF=1.75	---	---	63,000	43,900	41,400	32,500
SF=2.0	---	---	---	---	---	---
4H:1V						
SF=1.0	19,700	13,400	11,200	6,200	5,400	4,000
SF=2.5	27,000	18,500	14,600	8,900	7,200	6,400
SF=1.5	33,900	22,200	18,000	10,800	8,900	7,200
SF=1.75	40,000	27,000	21,100	12,500	10,800	8,800
SF=2.0	49,200	33,400	25,500	15,900	13,300	10,300
6H:1V						
SF=1.0	28,200	18,000	15,000	9,200	7,900	5,900
SF=1.25	37,200	25,100	20,000	11,900	10,600	8,200
SF=1.5	43,500	29,000	23,000	14,400	11,900	9,400
SF=1.75	50,700	34,400	26,000	15,800	13,200	10,500
SF=2.0	57,100	39,900	31,100	18,400	15,900	13,000
8H:1V						
SF=1.0	34,900	23,800	19,200	12,200	10,500	7,800
SF=1.25	46,800	31,200	23,900	15,700	12,300	10,900
SF=1.5	55,300	38,400	30,600	19,200	15,700	12,400
SF=1.75	63,700	43,500	34,600	21,000	17,500	14,000
SF=2.0	72,200	47,800	39,200	22,600	19,300	15,600
10H:1V						
SF=1.0	43,500	29,800	24,000	15,200	13,000	9,700
SF=1.25	58,400	38,800	29,800	19,500	15,200	13,600
SF=1.5	68,900	45,200	35,700	21,700	17,400	15,500
SF=1.75	76,300	51,500	40,600	24,000	21,700	17,400
SF=2.0	86,900	59,500	45,600	28,300	24,000	19,400

TABLE B.3. Volume of Riprap with a Specific Gravity of 2.50 Required to Protect Against Indicated Flood Events, Different Side Slopes, and Safety Factors - Grand Junction Impoundment

Side Slope Safety Factor	Required Volume of Riprap (sp gr = 2.50), yd^3 Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
2H:1V						
SF=1.0	12,900	8,600	7,200	4,300	3,400	3,100
SF=1.25	24,300	16,700	13,300	7,700	6,800	5,600
SF=1.5	44,300	29,900	24,200	14,000	12,100	9,900
SF=1.75	---	---	---	43,200	37,000	29,800
SF=2.0	---	---	---	---	---	---
4H:1V						
SF=1.0	16,600	11,200	8,900	5,400	4,500	4,000
SF=1.25	22,700	15,900	12,200	7,100	6,200	4,800
SF=1.5	28,300	18,500	14,600	8,900	8,100	6,400
SF=1.75	33,900	22,200	17,700	10,800	8,900	7,200
SF=2.0	40,000	27,000	21,000	12,500	10,800	8,800
6H:1V						
SF=1.0	23,600	16,300	13,000	7,800	6,600	4,700
SF=1.25	31,600	20,300	16,500	9,200	7,900	7,100
SF=1.5	36,100	23,500	19,500	11,900	10,500	8,200
SF=1.75	42,600	29,000	23,000	13,100	11,900	9,400
SF=2.0	48,100	32,800	26,000	15,800	13,200	10,500
8H:1V						
SF=1.0	28,900	19,500	15,200	8,700	8,700	6,300
SF=1.25	40,800	26,900	21,900	12,200	10,500	7,800
SF=1.5	46,800	31,200	23,900	14,000	12,200	9,300
SF=1.75	52,800	36,200	28,600	17,400	14,000	10,900
SF=2.0	61,300	40,500	32,600	19,200	15,800	12,500
10H:1V						
SF=1.0	36,000	24,500	19,100	10,900	10,800	7,800
SF=1.25	47,800	32,500	27,300	15,200	13,100	9,700
SF=1.5	57,000	38,800	29,800	17,400	15,200	11,700
SF=1.75	64,500	42,500	34,800	19,600	17,400	13,600
SF=2.0	72,000	47,800	38,200	24,000	19,700	15,500

TABLE B.4. Volume of Riprap with a Specific Gravity of 2.75 Required to Protect Against Indicated Flood Events, Different Side Slopes. and Safety Factors - Grand Junction Impoundment

Side Slope Safety Factor	Required Volume of Riprap (sp gr = 2.75), yd^3					
	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
2H:1V						
SF=1.0	11,300	7,400	6,100	3,400	2,900	2,700
SF=1.25	21,000	14,700	11,400	6,800	5,800	4,800
SF=1.5	38,000	25,300	20,500	12,100	10,100	8,200
SF=1.75	---	---	---	34,600	32,100	25,500
SF=2.0	---	---	---	---	---	---
4H:1V						
SF=1.0	14,800	9,600	7,700	4,500	3,600	3,200
SF=1.25	19,700	13,400	9,900	6,200	5,400	4,000
SF=1.5	23,900	15,900	13,200	8,100	6,200	6,000
SF=1.75	28,300	19,600	15,700	8,900	8,100	6,400
SF=2.0	34,400	23,300	19,000	10,800	9,800	7,200
6H:1V						
SF=1.0	19,900	12,500	9,900	6,600	5,300	4,700
SF=1.25	26,300	18,000	14,500	7,900	6,700	5,900
SF=1.5	30,800	21,900	16,500	10,500	9,200	7,100
SF=1.75	35,300	23,500	19,500	11,900	9,200	8,200
SF=2.0	41,700	27,300	23,000	13,100	11,900	9.400
8H:1V						
SF=1.0	26,400	16,600	13,000	8,700	7,000	6,300
SF=1.25	34,900	21,700	17,200	10,400	8,700	7,800
SF=1.5	40,800	26,900	21,900	12,200	10,500	9,300
SF=1.75	46,800	31,200	23,900	14,000	12,200	9,300
SF=2.0	51,700	34,100	27,900	15,700	14,000	10,900
10H:1V						
SF=1.0	32,900	20,700	16,300	10,800	8,700	7,800
SF=1.25	40,400	27,100	21,600	13,000	10,900	9,700
SF=1.5	47,800	32,500	27,300	15,200	13,100	9,700
SF=1.75	53,900	36,200	29,800	17,400	15,200	11,700
SF=2.0	61,400	41,500	32,300	19,500	17,400	13,600

APPENDIX C

CONSTRUCTION COSTS - GRAND JUNCTION AND SLICKROCK IMPOUNDMENTS

TABLE C.1. Construction Costs for Flood Protection Including Engineering and Contingencies for Rock with Specific Gravity of 2.00 - Grand Junction Impoundment

Side Slope Safety Factor	Construction Costs, Millions of Dollars					
	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
4H:1V						
SF=1.00	1.046	0.868	0.787	0.666	0.647	0.605
SF=1.25	1.214	0.984	0.886	0.714	0.696	0.634
SF=1.50	1.349	1.112	0.948	0.761	0.729	0.677
SF=1.75	1.507	1.189	1.034	0.812	0.761	0.706
SF=2.00	1.699	1.312	1.135	0.875	0.828	0.751
6H:1.						
SF=1.00	1.062	0.805	0.684	0.506	0.482	0.422
SF=1.25	1.263	0.934	0.803	0.579	0.553	0.486
SF=1.50	1.410	1.003	0.895	0.628	0.579	0.508
SF=1.75	1.577	1.104	0.989	0.674	0.628	0.552
SF=2.00	1.742	1.214	1.070	0.748	0.674	0.594
8H:1V						
SF=1.00	1.377	1.120	0.942	0.707	0.674	0.594
SF=1.25	1.641	1.237	1.101	0.802	0.740	0.652
SF=1.50	1.860	1.365	1.170	0.864	0.805	0.708
SF=1.75	2.059	1.497	1.295	0.929	0.837	0.736
SF=2.00	2.212	1.631	1.379	0.959	0.897	0.792
10H:1V						
SF=1.00	1.750	1.358	1.208	0.914	0.874	0.777
SF=1.25	2.081	1.507	1.362	1.035	0.954	0.846
SF=1.50	2.354	1.735	1.497	1.075	1.035	0.880
SF=1.75	2.545	1.902	1.603	1.154	1.075	0.935
SF=2.00	2.739	2.016	1.708	1.231	1.154	0.989

TABLE C.2. Construction Costs for Flood Protection Including Engineering and Contingencies for Rock with Specific Gravity of 2.25 - Grand Junction Impoundment

Side Slope Safety Factor	Construction Costs, Millions of Dollars					
	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
4H:1V						
SF=1.00	0.946	0.802	0.748	0.630	0.616	0.575
SF=1.25	1.079	0.896	0.811	0.680	0.649	0.619
SF=1.50	1.206	0.963	0.873	0.714	0.680	0.634
SF=1.75	1.317	1.051	0.930	0.746	0.714	0.663
SF=2.00	1.485	1.168	1.011	0.808	0.761	0.691
6H:1V						
SF=1.00	0.931	0.703	0.629	0.482	0.458	0.402
SF=1.25	1.096	0.834	0.720	0.531	0.507	0.444
SF=1.50	1.212	0.904	0.775	0.577	0.531	0.466
SF=1.75	1.343	1.003	0.830	0.602	0.555	0.486
SF=2.00	1.460	1.104	0.924	0.650	0.605	0.531
8H:1V						
SF=1.00	1.224	0.967	0.856	0.674	0.644	0.566
SF=1.25	1.441	1.102	0.942	0.739	0.677	0.623
SF=1.50	1.597	1.234	1.064	0.802	0.739	0.650
SF=1.75	1.750	1.327	1.137	0.835	0.772	0.679
SF=2.00	1.905	1.406	1.221	0.864	0.805	0.708
10H:1V						
SF=1.00	1.560	1.241	1.102	0.874	0.834	0.740
SF=1.25	1.832	1.406	1.208	0.953	0.874	0.811
SF=1.50	2.025	1.523	1.317	0.993	0.914	0.846
SF=1.75	2.160	1.638	1.406	1.035	0.993	0.880
SF=2.00	2.354	1.785	1.497	1.114	1.035	0.917

TABLE C.3. Construction Costs for Flood Protection Including Engineering and Contingencies for Rock with Specific Gravity of 2.50 - Grand Junction Impoundment

Side Slope Safety Factor	Construction Costs, Millions of Dollars					
	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
4H:1V						
SF=1.00	0.889	0.762	0.707	0.616	0.600	0.575
SF=1.25	1.001	0.848	0.767	0.647	0.630	0.590
SF=1.50	1.103	0.896	0.811	0.680	0.666	0.619
SF=1.75	1.206	0.963	0.868	0.714	0.680	0.634
SF=2.00	1.317	1.058	0.930	0.746	0.714	0.663
6H:1V						
SF=1.00	0.847	0.673	0.592	0.456	0.434	0.380
SF=1.25	0.993	0.746	0.657	0.482	0.458	0.424
SF=1.50	1.076	0.805	0.712	0.531	0.506	0.444
SF=1.75	1.195	0.904	0.775	0.553	0.531	0.466
SF=2.00	1.296	0.974	0.830	0.602	0.555	0.486
8H:1V						
SF=1.00	1.114	0.889	0.783	0.611	0.611	0.539
SF=1.25	1.331	1.024	0.906	0.674	0.644	0.566
SF=1.50	1.441	1.102	0.942	0.707	0.674	0.594
SF=1.75	1.551	1.193	1.028	0.769	0.707	0.623
SF=2.00	1.707	1.273	1.101	0.802	0.740	0.652
10H:1V						
SF=1.00	1.423	1.145	1.013	0.796	0.794	0.705
SF=1.25	1.638	1.291	1.163	0.874	0.836	0.740
SF=1.50	1.807	1.406	1.208	0.914	0.874	0.772
SF=1.75	1.944	1.474	1.299	0.954	0.914	0.811
SF=2.00	2.081	1.570	1.362	1.035	0.957	0.846

TABLE C.4. Construction Costs for Flood Protection Including Engineering and Contingencies for Rock with Specific Gravity of 2.75[(a)] - Grand Junction Impoundment

Side Slope Safety Factor	Construction Costs, Millions of Dollars					
	Upper Limit PMF	Grand Junction PMF	Lower Limit PMF	500-yr Flood	SPF	100-yr Flood
4H:1V						
SF=1.00	1.014	0.835	0.764	0.647	0.621	0.595
SF=1.25	1.155	0.945	0.830	0.696	0.673	0.618
SF=1.50	1.277	1.017	0.926	0.751	0.696	0.676
SF=1.75	1.404	1.125	0.998	0.775	0.751	0.688
SF=2.00	1.581	1.232	1.094	0.830	0.801	0.711
6H:1V						
SF=1.00	0.992	0.736	0.641	0.504	0.467	0.430
SF=1.25	1.177	0.895	0.775	0.542	0.507	0.465
SF=1.50	1.307	1.008	0.832	0.617	0.580	0.499
SF=1.75	1.438	1.055	0.919	0.658	0.580	0.531
SF=2.00	1.623	1.165	1.021	0.693	0.658	0.566
8H:1V						
SF=1.00	1.349	1.012	0.881	0.703	0.654	0.605
SF=1.25	1.596	1.160	1.003	0.752	0.703	0.649
SF=1.50	1.766	1.310	1.139	0.804	0.755	0.692
SF=1.75	1.940	1.435	1.197	0.856	0.804	0.692
SF=2.00	2.082	1.519	1.312	0.906	0.856	0.739
10H:1V						
SF=1.00	1.717	1.295	1.135	0.909	0.848	0.788
SF=1.25	1.934	1.481	1.288	0.972	0.912	0.843
SF=1.50	2.148	1.637	1.454	1.036	0.975	0.843
SF=1.75	2.325	1.744	1.526	1.100	1.036	0.901
SF=2.00	2.542	1.898	1.598	1.161	1.100	0.956

(a) Nearest source of rock with a specific gravity of greater than 2.50 is Grand Mesa basalt about 40 miles from Grand Junction Impoundment

TABLE C.5. Construction Costs For Flood Protection Against PMF Including Engineering and Contingencies - Slickrock Impoundment

Specific Gravity Side Slope	Construction Costs, Millions of Dollars				
	SF=1.00	SF=1.25	SF=1.50	SF=1.75	SF=2.00
sp gr = 2.00					
4H:1V	0.375	0.439	0.525	0.616	0.733
6H:1V	0.421	0.492	0.577	0.677	0.786
8H:1V	1.217	1.326	1.431	1.548	1.662
10H:1V	1.924	2.051	2.172	2.301	2.432
sp gr = 2.25					
4H:1V	0.336	0.387	0.446	0.525	0.620
6H:1V	0.352	0.421	0.489	0.565	0.640
8H:1V	1.148	1.217	1.308	1.394	1.493
10H:1V	1.829	1.924	2.037	2.126	2.247
sp gr = 2.50					
4H:1V	0.308	0.348	0.402	0.462	0.541
6H:1V	0.312	0.375	0.427	0.492	0.560
8H:1V	1.086	1.156	1.239	1.308	1.379
10H:1V	1.762	1.848	1.924	2.027	2.116

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16. ABSTRACT (200 words or less)

This report examines the costs of rock riprap flood protection for design flood events at two uranium tailings impoundments in western Colorado. The two sites are the Grand Junction impoundment located along the Colorado River and the Slickrock impoundment located along the Dolores River. The sensitivity of rock type, embankment side slope, and various safety factors is evaluated for six design flood events at Grand Junction and one flood event at Slickrock. The safety factor method of riprap design is used for the cost comparison.

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EFFECTS OF ROCK RIPRAP DESIGN PARAMETERS ON FLOOD PROTECTION COSTS FOR URANIUM TAILINGS IMPOUNDMENTS

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