EVALUATION OF RIPRAP SIZING AND GRADATION FOR THE PETROTOMICS TAILINGS RECLAMATION PLAN

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1.0 INTRODUCTION

The three rock sizes that have been specified for riprap and rock mulch (rock armor) for the Petrotomics Tailings Reclamation include: Dam Outslope Rock Armor, 5:1 Slope Rock Armor and Channel Riprap. The preceding listing is in order of smallest to largest rock size. Each of the rock sizes requires an underlying filter material, and the channel riprap will also require what is essentially a two stage filter. The lower (fine) filter material for the channel riprap is required to bridge the gap between a large channel riprap and a soil base material.

2.0 ROCK RIPRAP GRADATIONS

The present rock and filter specifications are presented in Table 1. The optimum gradation listed is for riprap with a specific weight of 165 lbs/cubic feet. The gradation of the riprap was determined using the method described in Army Corps of Engineers (ACOE), Engineering Manual (EM) 1110-2-1601, page 42. The gradation listed is for riprap with a specific weight of 165 lbs/cubic feet.

The criteria used are given below. Note that a number prefixed with a "W" is the weight of stones less than or equal to the percentage given. Likewise, a number prefixed by a "D" is the maximum diameter of a stone of that percentage.

1) The weight of the W_{50} stone is greater than or equal to the W_{50} stone predicted using the chosen rock sizing method.

2) The diameter of the D_{50} stone is less than or equal to 0.67 thickness of riprap placement.

3) The weight of W_{100} stone is greater than or equal to two (2) times the lower limit of W_{50} stone.

4) The weight of W_{100} stone is less than or equal to five (5) times the lower limit of the W_{50} stone.

5) The diameter of the D_{100} stone is less than or equal to the riprap thickness.

6) The weight of the W_{15} stone is greater than or equal to 0.063 of the upper weight limit of the W_{100} stone.

7) The weight of the W_{15} stone is less than the upper limit of the W_{50} or equal to the filter requirements.

The above criteria also allow the substitution of the D_0 or D_{25} in the D_{15} criteria if better suited to the prescribed rock source. The criteria were developed for riprap revetments in areas where there will be a relatively large stress on the rock bed, such as under continuous flows or in beach areas subject to wave action. In the proposed mine reclamation application, the rock will be used in highly ephemeral channels or as rock armoring on overland flow areas where actual submergence of the rock will be extremely rare. Hence, the rock gradation criteria are overly restrictive for the given application and a minor adjustment of many of the criteria can be tolerated without any detriment to the erosion protection. In fact, NRC personnel have indicated that rock used for rock mulch armoring should be as uniform as possible in size to allow easier placement and to prevent segregation. If a rock mulch is produced that is more uniformly sized than the criteria allow, the criteria will be waived with the exception of the minimum D_{50}.

The rock gradation criterion of greatest importance is #1. Riprap sizing methods typically yield a minimum W_{50} or D_{50} necessary to withstand the design flows. Thus, this rock D_{50} represents a minimum allowable and reduction of this size is not possible without some adjustment of design constraints. Rock gradation criterion #2 is also very important in that it establishes the minimum thickness of the rock layer as a function of the D_{50}. The maximum rock D_{50} in Table 1 is controlled by criterion #2. There are generally no design constraints that will disallow increasing the D_{50} beyond the maximum in Table 1 if the rock thickness is increased accordingly. The obvious disadvantage to increasing the rock D_{50} above the maximum in Table 1 is that the required increase in thickness will require additional rock volume. Criterion #5 can also affect the required rock layer thickness, but with careful placement techniques and efforts to push protruding rocks down into the filter,

some minor relaxation of criterion #5 can be allowed. The remainder of the criteria are intended to produce a gradation that will result in a dense rock layer with interlocking of individual stones and limited void space.

The application of these criteria have produced the minimum and maximum rock sizes in Table 1. As stated in the previous paragraph, the maximum D_{50} in the table is a function of the rock thickness and can be increased if the rock thickness is also increased. There are some obvious rock sizing constraints in Table 1 that can be adjusted for available rock processing equipment and methods. As an example, a maximum rock D_{100} of 22.82 inches for the channel riprap can likely be achieved by screening on a 24 inch screen.

An alternate recommended rock gradation is presented by Simons and Senturk (1977). An adapted set of the criteria is presented below.

1) $D_{100} = 2.0 * D_{50}$

2) $D_{85} = 1.7 * D_{50}$

3) $D_{20} = 0.5 * D_{50}$

4) $D_{15} = 0.42 * D_{50}$

This recommended gradation produces a slightly broader distribution than the ACOE method.

Figures 1 through 3 present rock gradations for the three rock sizes. The small numerical differences in rock sizes between tabulations on the figures and Table 1 are the result of minor computational differences and rounding errors. It is desirable that each rock gradation fall between the lower and upper bound curves as shown on Figures 1 through

4. Each curve is defined by three points (D_{100}, D_{50}, and D_{15} or D_{25} or D_0), and there are no prescribed criteria for intermediate points. Hence, screening processes can be adapted to limit maximum sizes for some point between the lower and upper bounds. As an example, the minimum and maximum D_{100}'s for the 5:1 Slope Rock are 4.19 inches and 5.68 inches, respectively. If the material is screened to limit the maximum rock diameter to 5 inches, and there is a measurable portion of the rock that is greater than 4.19 inches in diameter, these criteria are met. As discussed above, some minor relaxation of the ACOE criteria can be tolerated to allow use of conventional screens and processing methods. Likewise, it is generally acceptable to substitute larger rock for smaller rock with a corresponding adjustment in thickness.

3.0 FILTER GRADATIONS

The present filter specifications are presented in Table 1. The filter material gradation criteria is taken from Barfield et al. (1981) and is as follows:

(1) $\frac{D_{50}\text{ (riprap)}}{D_{50}\text{ (filter)}} < 40$ and $\frac{D_{50}\text{ (filter)}}{D_{50}\text{ (base)}} < 40$

(2) $5 < \frac{D_{15}\text{ (riprap)}}{D_{15}\text{ (filter)}} < 40$ and $5 < \frac{D_{15}\text{ (filter)}}{D_{15}\text{ (base)}} < 40$

(3) $\frac{D_{15}\text{ (riprap)}}{D_{85}\text{ (filter)}} < 5$ and $\frac{D_{15}\text{ (filter)}}{D_{85}\text{ (base)}} < 5$

Note: Base material is material over which filter is placed.

These criteria were originally developed for filters around drains or in emergent seepage conditions and were applied to filters for riprap as a conservative design for this much less critical condition. Sherard et al. (1984a) and Sherard et al. (1984b) present a discussion of the application of and conservatism in filter criteria for seepage through embankments or dams. Their conclusions were: many of the criteria are not particularly useful, the useful criteria are generally conservative for even the most critical situations, and there are some less critical situations where filter criteria are not necessary. The use of a filter material to prevent erosion of the base material beneath the rock riprap is obviously much less critical than emergent seepage.

The criteria basically create bounds based on the size of the rock and the size of the base material. There is presumably an intersection of the bounds dictated by the overlying rock and the underlying base material which is the acceptable filter gradation. Unfortunately, in cases where the base material is relatively fine, the intersection representing the acceptable filter gradation is very narrow or may not exist at all. The problem is exacerbated by increasing rock size and in this situation it would seem to be necessary to use a staged filter design. This is called for in the case of the Channel Riprap and Figure 4 presents an example where the lower bound for the filter is greater than the upper bound for the filter for the Dam Outslope Rock, leading to consideration of a two-stage filter. However, in the case of small to moderate rock sizes, the added complexity of a multiple stage filter dictated by the overly restrictive filter criteria would introduce placement difficulties, where a single stage filter with some relaxation of the filter criteria would be more than adequate. This is particularly the case for the rock mulch or rock armor, where saturation of the rock and filter will be extremely rare.

Figure 5 presents the filter bounds for the various rock sizes as indicated in Table 1. With the exception of the Channel Riprap, the filter requirements for the rock sizes are very similar. For this reason, it is proposed that a single material be specified for use as the filter for the 5:1 Slope Rock and the Dam Outslope Rock, as well as for the fine (lower) filter for the Channel Riprap. The proposed gradation for this filter is presented in Figures 1 and 2 (Figure 1 has a slightly different lower bound), with the required filter gradation criteria tabulated at the bottom of the figure. The assumed base material for all but the Dam Outslope was a sample of silty sand that will be used as cover for the tailings area. This represents a fairly common material for the area. With the exception of the Dam

Outslope, where the base material will be a clay, the required relaxation of the filter gradation criteria is minimal. The proposed limits for the filter are: 0.02 in. $< D_{15} <$ 0.25 in., 0.06 in. $< D_{50} <$ 0.75 in., and $D_{85} >$ 0.25 inch. The relaxed filter ratios in Figure 2 and Figure 3 are based on rock gradations that meet the ACOE criteria.

The adjustment of the filter criteria is very large for the Dam Outslope due to the large difference between the base material size and the rock size. However, this is a decidedly non-critical filter situation with potential overland flow resulting only from direct precipitation on the outslope, and the base material is a cohesive clay. The potential for erosion of the base material through a 8.5 inch thick layer of filter and rock mulch is virtually nil, and thus usage of the general filter is considered appropriate.

The general filter can also be used as the fine filter material for the Channel Riprap. Figure 3 presents a combination where the fine filter is the base material for the Channel Riprap to allow sizing of the upper filter. The gradation of the fine filter was assumed to fall in the middle of the bounds presented in Figure 2. In Figure 3, one filter ratio was relaxed from 5 to 4 to produce the filter constraints. This very minor relaxation allows the use of the Dam Outslope Rock as the upper filter for the Channel Riprap. Given that the filter gradation is based on ratios for an assumed lower filter gradation and an assumed rock gradation, slight adjustments in the ratios will not have an adverse impact on filter performance.

4.0 SUMMARY

Although the rock gradation and filter gradation criteria provide guidelines for the production of the materials, the preceding discussion indicates that many of the criteria can be modified for some situations. For the rock gradations, the key criteria are the minimum D_{50} and the maximum D_{50}, which insure the rock is large enough and that the rock is placed to an appropriate thickness, respectively. NRC personnel have indicated that these are also key issues in the rock gradation, along with production of a material that can be placed to give a uniform surface with minimal segregation. Larger rock can be substituted for smaller rock, as long as an appropriate adjustment in rock thickness is made and the additional thickness does not result in flow diversion. Flow diversion can be avoided by a tapering of rock and/or filter thickness or by an adjustment in the subgrade. NRC personnel have also indicated that flexibility in the secondary rock gradation criteria based on D_{15} and D_{100} can be incorporated in the interest of producing a more uniform rock size.

The filter gradation criteria are overly restrictive and can incorporate substantial flexibility. The intent of using a filter in this application is to prevent erosion of the base through the rock riprap or rock mulch and the use of sand to gravel filter as specified will achieve that goal. Velocities within the filter will be very low, and saturation of the filter beneath the rock mulch will be infrequent. As such, the specified filter configuration(s) will be more than adequate.

A summary listing of the noted changes in rock or filter design is as follows:

- A single filter material can be used as the filter for the Dam Outslope Rock, the 5:1 Slope Rock, and the fine filter for the Channel Riprap. Specifically, the modified filter gradation proposed is:

% passing	Upper Limit (inches)	Lower Limit (inches)
D_{85}	---	0.25
D_{50}	0.75	0.06
D_{15}	0.25	0.02

This filter material would be used for items 3, 5 and 7 shown in the **Riprap and Filter Material Specifications**.

- The Dam Outslope Rock can be used as the upper (coarse) filter for the Channel Riprap. Specifically, the item 6 Dam Outslope Rock would be used as item 2 coarse filter shown in the **Riprap and Filter Material Specifications**

- The D_{15} and D_{100} rock gradation criteria can be waived to produce a more uniform rock size distribution for rock with a D_{50} of less than 6 inches.

5.0 REFERENCES

Army Corps of Engineers (ACOE), 1970, Hydraulic Design of Flood Control Channels, EM 1110-2-1601.

Barfield, B.J., R.C. Warner and C.T. Haan, 1981. Applied Hydrology and Sedimentology of Disturbed Lands, Oklahoma Technical Press, Stillwater, Oklahoma, 74074.

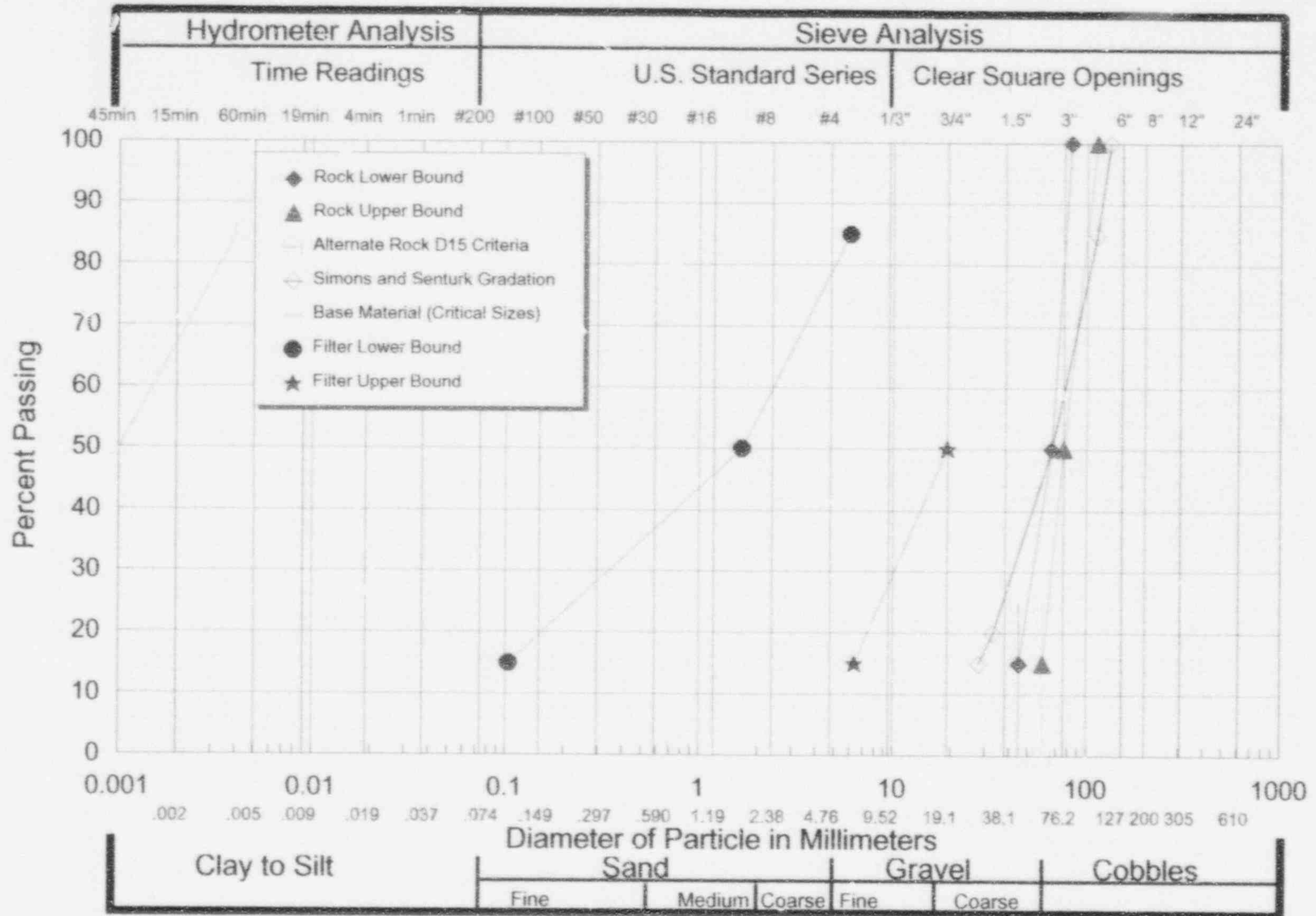
Sherard, J.L, L.P. Dunnigan and J.R. Talbot, 1984a. "Basic Properties of Sand and Gravel Filters", Journal of Geotechnical Engineering, ASCE, Volume 110, No. 6, June, 1984.

Sherard, J.L, L.P. Dunnigan and J.R. Talbot, 1984b. "Filters for Silts and Clays", Journal of Geotechnical Engineering, ASCE, Volume 110, No. 6, June, 1984.

Simons, D.B. and F. Senturk, 1977. Sediment Transport Technology, Water Resources Publications, Fort Collins, Colorado.

Table 1. Petrotomics Rock and Filter Sizing Summary

Section		RIPRAP D15 Range (inches)	RIPRAP D15 Range (feet)	RIPRAP D50 Range (inches)	RIPRAP D50 Range (feet)	RIPRAP D100 Range (inches)	RIPRAP D100 Range (feet)	FILTER D15 Range (inches)	FILTER D15 Range (feet)	FILTER D50 Range (inches)	FILTER D50 Range (feet)	FILTER D85 Range (inches)	FILTER D85 Range (feet)
Channel Riprap	(minimum)	9	0.75	13.35	1.11	16.82	1.40	0.263	0.022	0.354	0.030	2.1	0.175
Thickness = 1.9'	(maximum)	12	1.00	15.28	1.27	22.82	1.90	1.57	0.131	4.25	0.354		
5:1 Rock Armor	(minimum)	2.27	0.19	3.32	0.28	4.19	0.35	0.06	0.005	0.087	0.007	0.528	0.044
Thickness = 5.75"	(maximum)	3	0.25	3.79	0.32	5.68	0.47	0.19	0.016	0.6	0.050		
Dam Outslope Armor	(minimum)	1.78	0.15	2.6	0.22	3.28	0.27	0.052	0.004	0.069	0.006	0.417	0.035
Thickness = 4.5"	(maximum)	2.4	0.20	2.96	0.25	4.45	0.37	0.083	0.007	0.614	0.051		



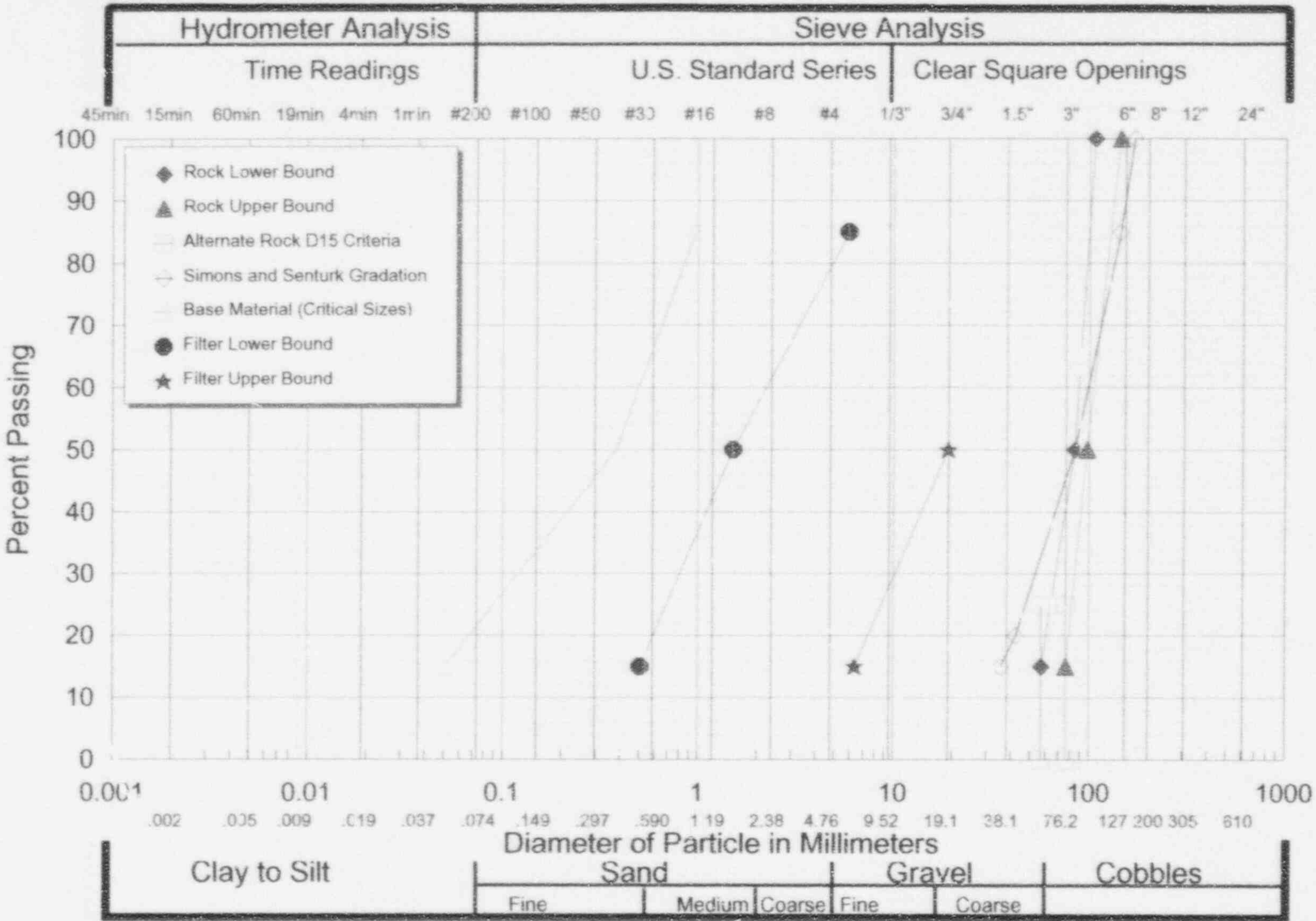
	D15 (inch)	D20 (inch)	D50 (inch)	D85 (inch)	D100 (inch)
ACOE Rock Upper Bound	2.35		3.00		4.45
ACOE Rock Lower Bound	1.76		2.60		3.28
Simons and Senturk Rock	1.09	1.30	2.60	4.42	5.20
Filter Upper Bound	0.2496		0.7500		
Filter Lower Bound	0.0041		0.0650	0.2363	
Base Material	0.0000		0.0000	0.0002	

Filter Ratios

D50 Rock / D50 Filter < 40
D50 Filter / D50 Base < 18750
5 < D15 Rock/ D15 Filter < 40
5 < D15 Filter/ D15 Base < 12480
D15 Rock / D85 Filter < 8.3
D15 Filter / D85 Base < 1560

Rock Thickness (inch) - 4.50

Figure 1. Dam Outslope Rock and Filter Gradation With Revised Filter Ratios

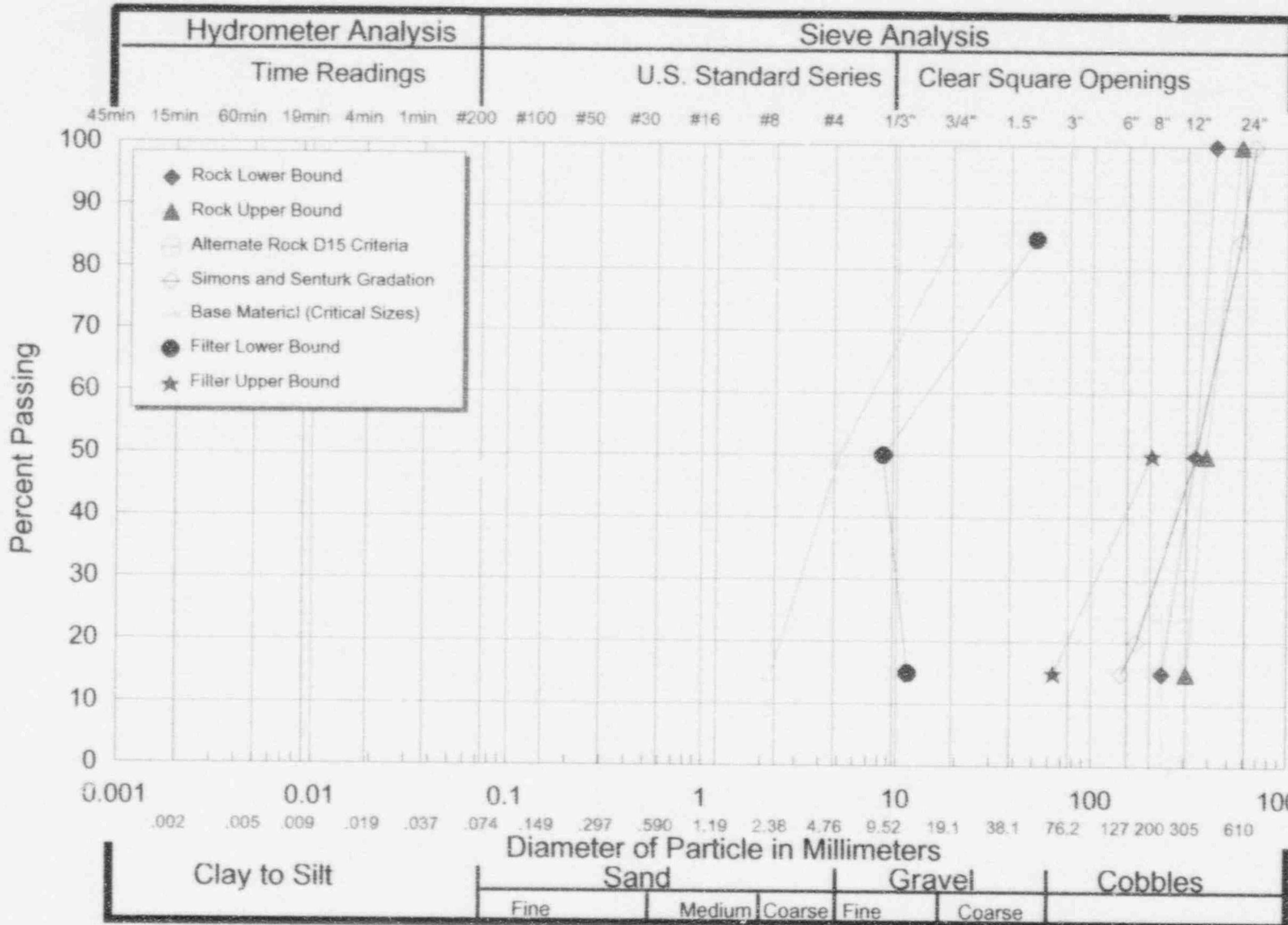


	D15 (inch)	D20 (inch)	D50 (inch)	D85 (inch)	D100 (inch)
ACOE Rock Upper Bound	3.00		3.83		5.68
ACOE Rock Lower Bound	2.25		3.32		4.18
Simons and Senturk Rock	1.39	1.66	3.32	5.64	6.64
Filter Upper Bound	0.2500		0.7500		
Filter Lower Bound	0.0200		0.0593	0.2318	
Base Material	0.0020		0.0150	0.0380	

Filter Ratios

D50 Rock / D50 Filter <	56		
D50 Filter / D50 Base <	50		
	5	< D15 Rock/ D15 Filter <	40
	10	< D15 Filter/ D15 Base <	125
D15 Rock / D85 Filter <	10.8		
D15 Filter / D85 Base <	6.6	Rock Thickness (inch) -	5.75

Figure 2. 5:1 Slope Rock and Filter Gradation With Revised Filter Ratios



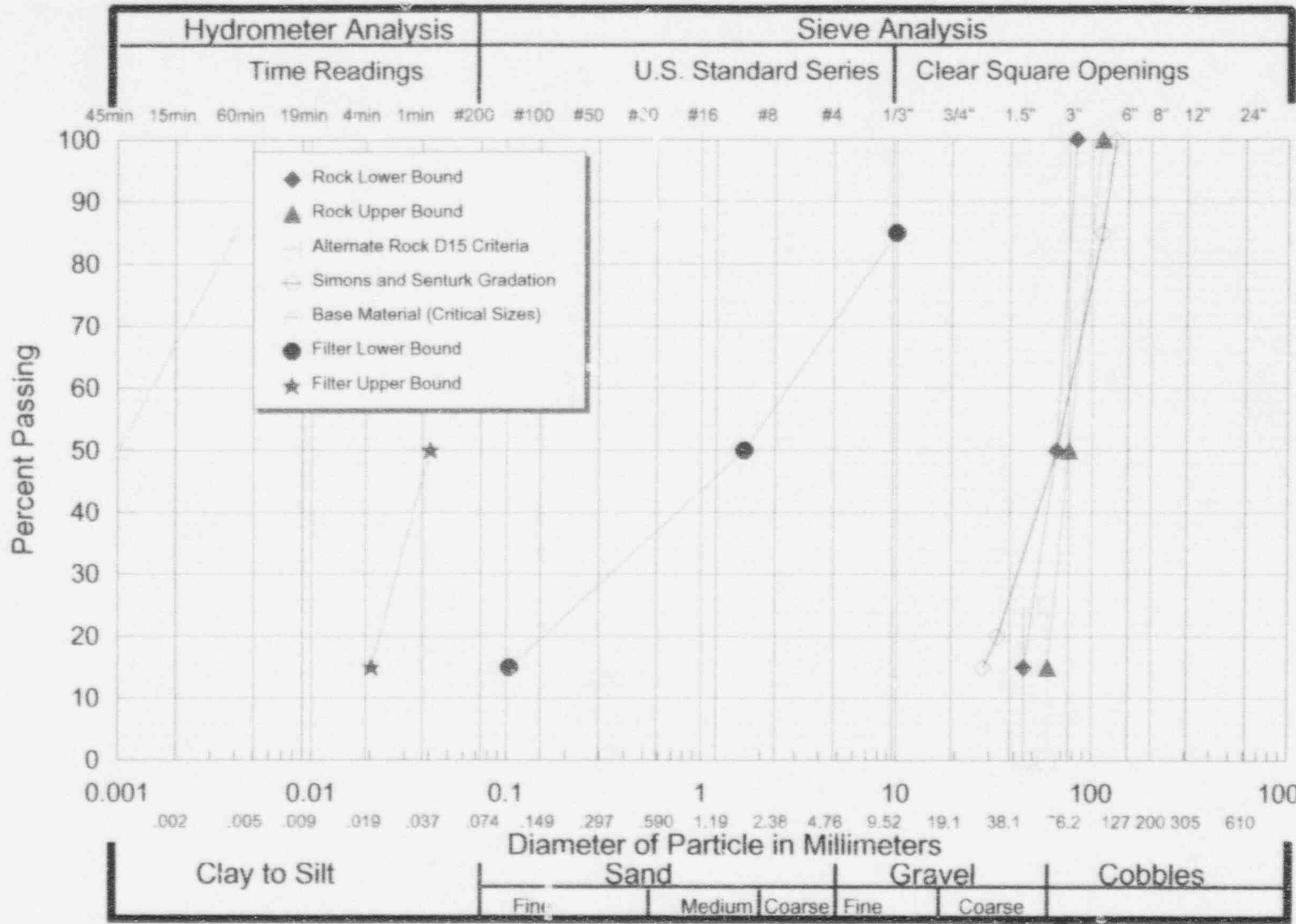
	D15 (inch)	D20 (inch)	D50 (inch)	D85 (inch)	D100 (inch)
ACOE Rock Upper Bound	12.08		15.21		22.83
ACOE Rock Lower Bound	9.06		13.35		16.82
Simons and Senturk Rock	5.61	6.68	13.35	22.70	26.70
Filter Upper Bound	2.5167		8.0000		
Filter Lower Bound	0.4500		0.3338	2.0134	
Base Material	0.0900		0.2000	0.7500	

Filter Ratios

D50 Rock / D50 Filter < 40
D50 Filter / D50 Base < 40
4 < D15 Rock/ D15 Filter < 40
5 < D15 Filter/ D15 Base < 125
D15 Rock / D85 Filter < 5
D15 Filter / D85 Base < 5

Rock Thickness (inch) - 22.82

Figure 3. Channel Riprap Rock and Filter Gradation With General Filter Base



	D15 (inch)	D20 (inch)	D50 (inch)	D85 (inch)	D100 (inch)
ACOE Rock Upper Bound	2.35		3.00		4.45
ACOE Rock Lower Bound	1.76		2.60		3.28
Simons and Senturk Rock	1.09	1.30	2.60	4.42	5.20
Filter Upper Bound	0.0008		0.0016		
Filter Lower Bound	0.0041		0.0650	0.3922	
Base Material	0.0000		0.0000	0.0002	

Filter Ratios

D50 Rock / D50 Filter < 40

D50 Filter / D50 Base < 40

5 < D15 Rock/ D15 Filter < 40

5 < D15 Filter/ D15 Base < 40

D15 Rock / D85 Filter < 5

D15 Filter / D85 Base < 5

Rock Thickness (inch) - 4.50

Figure 4. Dam Outslope Rock and Filter Gradation With Clay Dam Base

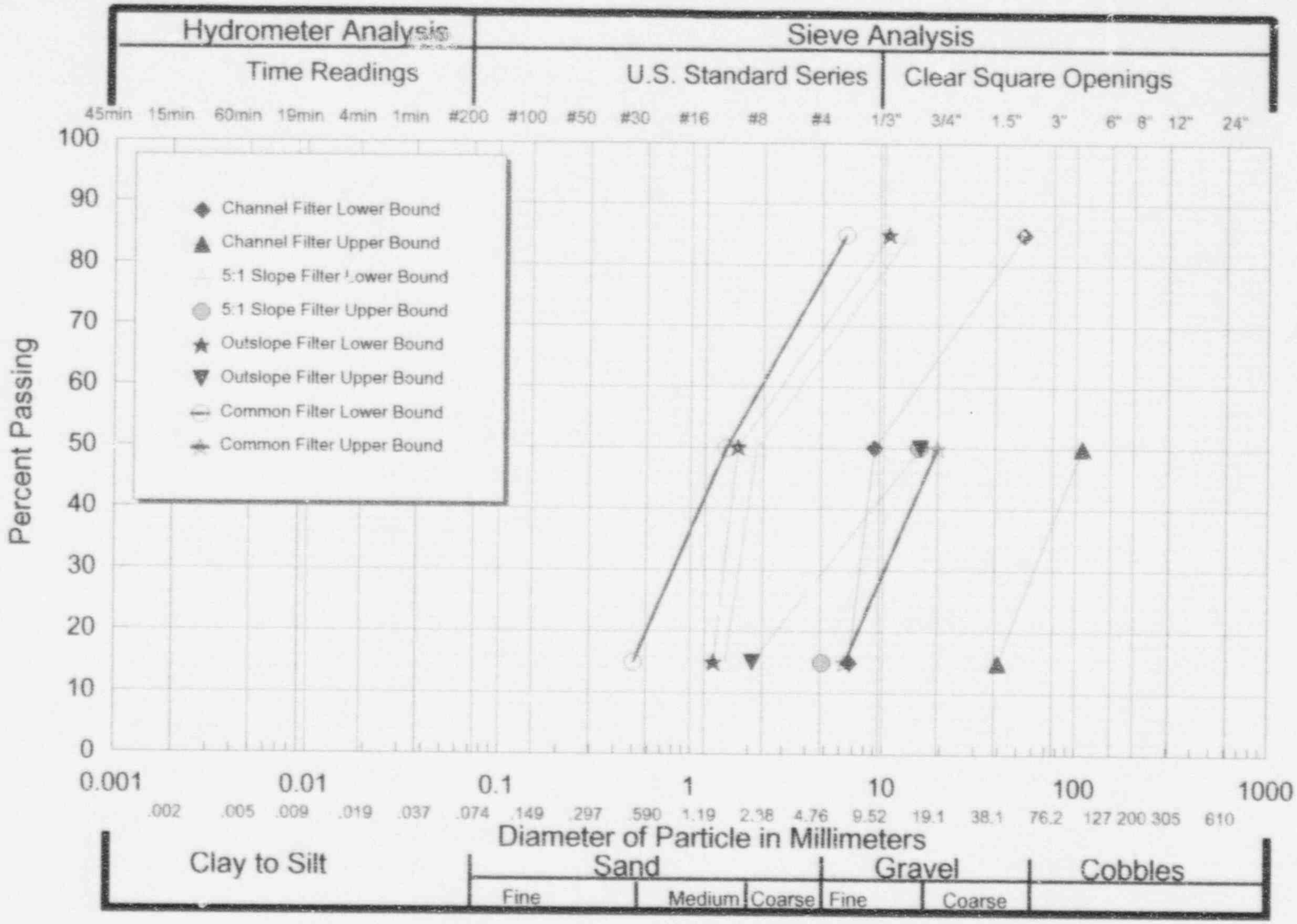


Figure 5. Filter Gradations for Rock Mulch and Rock Riprap