CONCLUSIONS FROM PHYSICAL MODEL OF THE COLUMBIA RIVER

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Conclusions Concerning Model Capability and Limitations

1. Roughness in the model as determined from the project grain analyses was verified prior to velocity measurements as sufficiently correct to produce model staging to within 2-1/3 percent of hydraulic radius. The average deviation was three-fourths percent of hydraulic radius. Point gage readings of water surface elevations during transient tests indicated that friction did not change significantly during the earlier velocity measurements.

2. Since friction was accurately reproduced in the model, point velocities, velocity profiles, and secondary flows are expected to scale provided there are no major defects in geometric similitude.

3. Since friction and velocity are properly scaled and boundary shear determined from velocity profiles is expected to scale within the precision of measuring velocity and differences of elevation between the flow boundary and the velocity measuring device.

4. Analysis of the model scaling in terms of entrainment functions, such as Shields', Gessler's, and Lane's, indicates that when sediment simultaneously scales by geometry and by settling velocity, only particles greater than 13-mm model or 5.12-foot prototype would have general movement similarity (Gessler's 85 percent chance of moving). For Lane's critical tractive force (approximately Gessler's 50 percent chance of moving), movement would scale for model diameters equal to and greater than 8-mm model or 3.15-foot prototype. Gessler's 5 percent chance of moving or rare movement would scale for particles equal to and greater than 6.5-mm model or 2.6-ft prototype.

5. Because of difficulty of assessing probability in the model and since design for bank stability is directed toward no movement, the early decision to measure velocity profiles to determine hydraulic boundary shear and then use entrainment or critical tractive force data from other sources is substantiated.

6. Because of surface tension effects, the model cannot scale waves equal to or less than 6-inches prototype. Larger waves caused by kinetic impact from spillway or outlet flows do not scale for other reasons; however, despite wave scaling defect, model measurements can detect sources and location of maximum waves.

7. The height of capillary rise in the model does not scale. Water will saturate relatively much higher in the model; thus, beaching

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action due to oscillating pore pressure fluidizing of the bank will not scale.

8. Bank storage is distorted by the capillary rise and the presence of model containing walls which can act as barriers not present in the prototype. Combinations of defect in bank storage and permeability scaling affect transient tests to some unknown degree and direction.

9. The structural properties of the model riverbank materials do not scale; thus, bank slides in the model would not necessarily be expected to be reproduced in the prototype or vice versa.

Conclusions and Recommendations Concerning Embankment Design

1. Maximum velocities 5 feet above the bed measured in the model were 10.3 ft/s at station 191+00 and 10.0 ft/s at station 74+00.

2. The maximum tractive forces measured in the model for 405,000 ft^3/s flow were 2.64 lb/ft^2 on the bottom at station 191+00, 2.4 lb/ft^2 on the bottom and 2.1 lb/ft^2 on a 1-1/2 to 1 slope at the highway bridge, and about 2.1 lb/ft^2 on the bottom at station 74+00. The maximum sizes of sediment which would be expected to move at these combinations of tractive force and side slopes are 13, 11-1/4, 18, and 10 inches, respectively.

3. Based on tractive force values measured on the river bottom in the model, clay deposits (which were not at the location of maximum tractive force) would be protected with 4-inch-diameter gravel blankets with the exception of station 191+00, which would require a blanket of 12-inch boulders to prevent erosion If for some reason the maximum shear moved to the left side over the clay, then a blanket of 20-inch boulders would be required. It is recommended that the right bank from station 171+00 to 195+00 be alined at least according to the original specifications. After alinement, the maximum tractive force would probably be not greater than 2.1 lb/ft^2. On the river bottom, 10-inch cobbles would be sufficient to protect the clay against 405,000 ft^3/s flow. Locating clay deposits and placing protective boulder and cobble blankets in deep or fast water could be difficult. Articulated mats are a possible alternative.

4. For tractive force values determined with the model or from any other source, figure 2 can be used to determine the combined coefficient that includes Gessler's probability of moving and the effect of gravity due to embankment slopes. Multiplying the tractive force by the coefficient results in the particle size in millimeters. Using the curve for the probability of 0.85 gives the size that would be in general movement, using the probability of 0.5 would result in the size nearest to that which would be obtained from Lane's critical tractive force curve. Using a probability of 0.05 would give the

sizes which would move rarely. It is recommended that 0.05 probability of moving be used in the design for no movement.

5. Inspection of figure 2 indicates that erosion stability deteriorates rapidly as slopes get greater than 2 to 1. Thus, it is recommended that 2 to 1 slopes be considered the maximum allowable. Wave erosion stability deteriorates, similarly.

6. Figure 2 also shows that slopes of 5 to 1 and greater can be considered flat in terms of bank erosion stability.

7. In future embankment construction, more care should be taken in keying or trenching bank toes below scour level. After alinement at station 191+00 and for flows up to 400,000 ft^3/s, no scour is expected in natural bottom bed material 10 inches in diameter or greater.

8. Drill hole logs indicate that bed materials have been active from depths of 3 feet to 20 feet; thus, it is recommended that bank toes be keyed to a depth of 20 feet in sand areas. The keying depth could be decreased as size of the bed material increases, becoming equal to riprap size where the riverbed is of 10-inch cobble size or greater.

9. Field reports indicate that 5-foot breaking waves caused by about 31,400 ft^3/s outlet flow failed 600 feet of the riprap armor on the 1-1/2 to 1 slope of the stabilization fill below the visitors' center. The California Highway Department design for this height of continuous front ocean-type waves (as opposed to choppy waves) would require a 2.8-foot-diameter riprap which approximates the prototype 3.6-foot mean and 5.9-foot maximum diameters specified for the 1-1/2 to 1 armor slope.

10. The maximum tractive force measured during the 31,400 ft^3/s outlet flow on the 1-1/2 to 1 riprap bank below the visitors' center was 0.5 lb/ft^2, sediment with diameters 4 inches and less would be expected to move on the basis of tractive force only. This, together with conclusion 9, indicates that wave action was the main cause of the riprap failure below the visitors' center.

11. The model indicated that for 31,400 ft^3/s outlet flow there is backflow of 5.4 ft/s at the embankment toe about 1,000 feet downstream from the spillway. The surface water is traveling at the same speed downstream. The shear between these flows may have contributed to the failure of the riprap bank point below the visitors' center.

12. The writer does not know how to combine wave design with velocity or tractive force design. Project personnel report that waves are generally dissipated by the time they reach station 86+00 after which tractive force design should be adequate by itself. Analysis should be

made to determine if attenuation of spillway and outlet waves with respect to distance downstream could be determined by computations. This information could be used for making a decision as to whether field observations should be made. The California Highway wave design method is presumed to be forcontinuously breaking ocean type waves. It is recommended that the Bureau search for design methods and/or data more related to waves that occur downstream from spillways and outlets at dams.

13. Model and prototype wave data were found in report No. HYD-336. This report indicates 8-foot waves are to be expected for 400,000 ft^3/s flow over the spillway. For 1,000,000 ft^3/s, 18- to 20-foot waves are to be expected. On the basis of California Highway design for continuously breaking waves, 4.9-foot and 10.5-foot riprap would be needed to protect against these two wave conditions on 1-1/2 to 1 side slopes.

14. An emergency transient test was made dropping flow from 405,000 to 90,000 ft^3/s, simulating overload circuit breaker shutdown of 10 Third Powerplant units with 15-second guard gate closure. Water level versus time was recorded at eight different stations from the powerplant corner block to station 204+00. Time constants (time to reach 63.2 percent of the total change of water level) ranged from 37.4 to 42.2 minutes, averaging 40.3 minutes. The total drop in water level for the eight stations varied from 29.4 to 32.7 feet, averaging 30.9 feet. The rate of change of water surface elevation at the eight stations during the time constant interval varied from 0.47 ft/min to 0.55 ft/min, averaging 0.49 ft/min. The average leading edge velocity of the wave was 60 ft/s between stations 59+50 and 204+00.

15. Another emergency test was made dropping the flow from 185,000 to 90,000 ft^3/s simulating the more likely shutdown of three units. The time constant averaged 46.7 minutes. The total change of water level averaged 12.9 feet. The rate of change of water level during the time constant interval averaged 0.18 ft/min. The leading edge of the wave traveled at 41.2 ft/s.

16. Another emergency test was made dropping the flow from 122,000 to 90,000 ft^3/s, simulating the shutdown of one unit. The time constant averaged 53.8 minutes. The total change of water level averaged 5.17 feet. The rate of change of water level during the time constant interval averaged 0.10 ft/min. The leading edge of the wave traveled at 24.9 ft/s.

17. An operational transient test was made increasing flow from 122,000 to 405,000 ft^3/s, simulating putting 10 units up to maximum in sequence from 10 units with 10 percent no-load. The rate of increase represented 100 kW/min. After the water surface stabilized,

the units were turned off in sequence at a rate simulating 70 kW/min. For the rising part of the transient, the average time constant was 53.5 minutes, the average total rise of the water surface was 26.3 feet, the average rate of rise was 0.31 ft/min, and the velocity of the leading edge was 32.2 ft/s. For the falling part of the transient, the time constant averaged 82.8 minutes, the average total drop of the water surface was 30 feet, the average rate of fall was 0.23 ft/min, and the average velocity of the leading edge of the wave was 37.1 ft/s.

18. Another operational transiet test was made increasing flow from 99,000 to 184,000 ft^3/s, simulating three units going on-line up to maximum in sequence at a rate of 100 kW/min starting at 10 percent no-load. After the water surface stabilized, the units were turned off at a rate of 70 kW/min. For the rising part of the transient, the time constant averaged 44.4 minutes, the average total rise of the water surface was 12.5 feet, the average rate of rise was 0.27 ft/min., and the average velocity of the leading edge of the wave was 24.9 ft/s. For the falling part of the transient, time constant averaged 55.8 minutes, the average total fall was 13.4 feet, the average rate of fall was 0.15 ft/s, and the velocity of the leading edge of the wave was 30.7 ft/s.

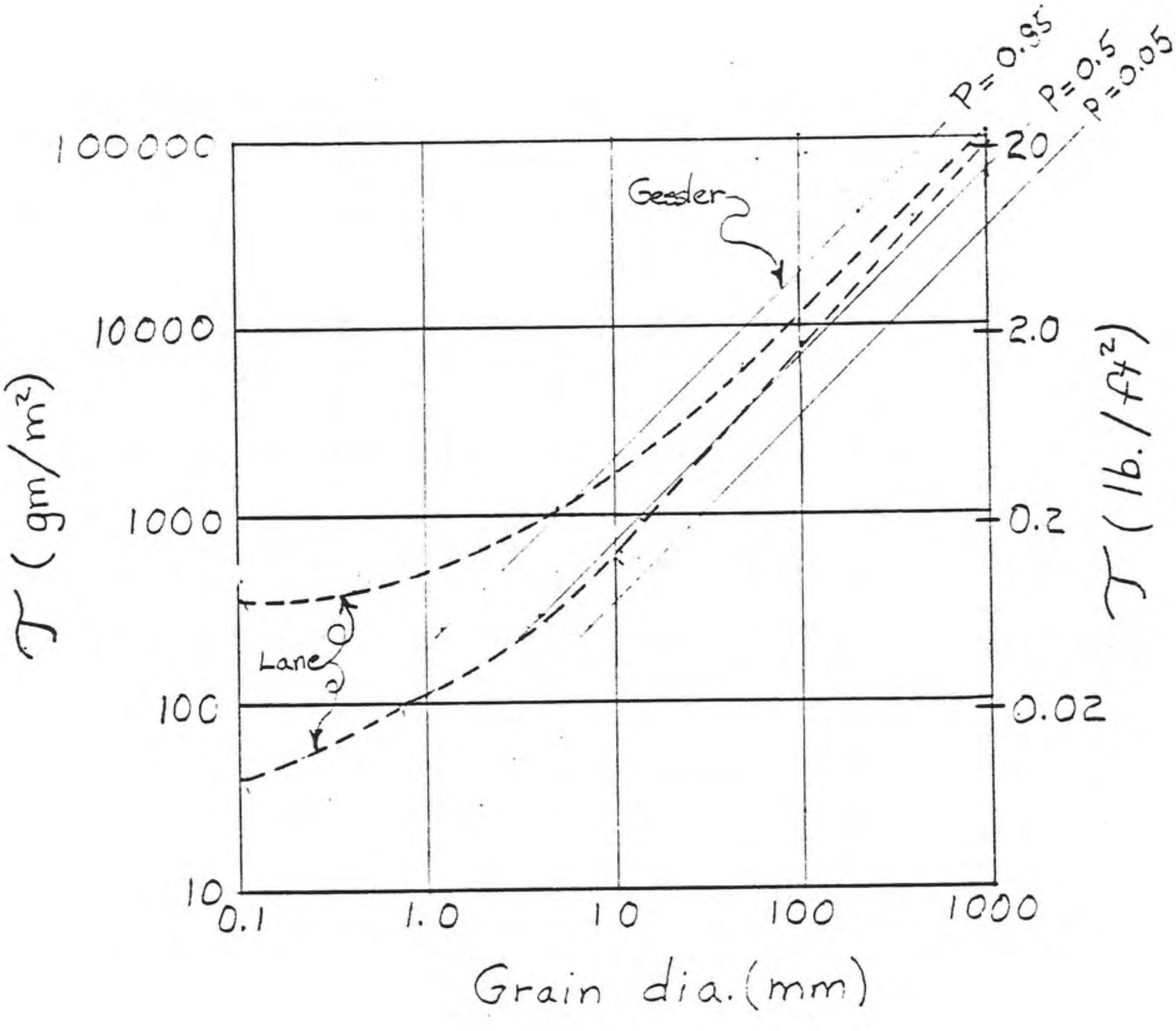
19. Another operational transient test was made increasing flow from 93,000 to 122,000, simulating one unit goin on-line up to maximum at a rate of 100 kW/min starting at 10 percent no-load. After the water surface stabilized, the units were turned off at a rate of 70 kW/min. For the rising part of the transient, the time constant averaged 44.6 minutes, the average total rise of the water surface was 4.94 feet, the average rate of rise was 0.089 ft/min., and the average velocity of the leading edge of the wave was 33.8 ft/s. For the falling part of the transient, time constants averged 56.0 minutes, the average total fall was 4.96 feet, the average rate of fall was 0.056 ft/s, and the velocity of the leading edge of the wave was 27.5 ft/s.

20. The results of the emergency test should be considered in terms of the embankment stability to determine how much compensation needs to be done with outlet and/or spillway flow. Protecting against waves near the dam, due to compensation flow, may be the most critical part of the design and may need to be optimized expensewise with the design for the downstream.. It may be necessary to protect this area with articulated mats or tetrapod types of armor.

21. The transient characteristics of the physical model should be verified. It is recommended that the physical model results be compared with mathematical models if possible. The best parameter for comparing and calibrating the physical model would be the true knowledge of the velocity of the wave leading edge. However, for comparison with mathematical models, this would require small incremental time

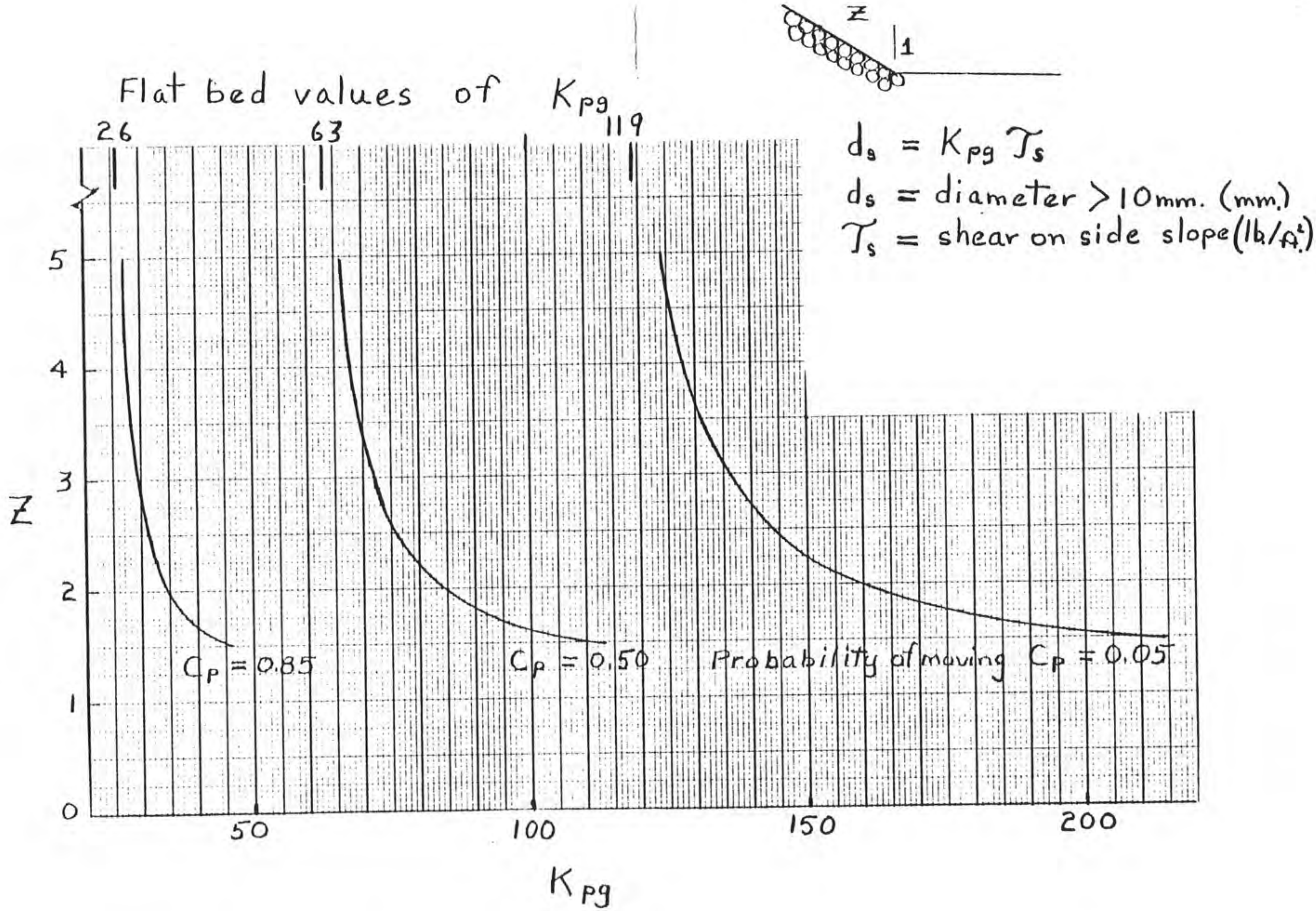
output from computer programs. The transient tests that were performed with one unit could be compared with field data with least risk to the prototype banks.

22. It is recommended that efforts be made to determine the actual risk of having different numbers of units undergo circuit breaker shutdown. This may require hiring a consultant with considerable experience in the field of engineering risk analysis.



P=0.95
P=0.5
P=0.05
100000
10000
1000
100
10
20
2.0
0.2
0.02
Gessler
Lane
0.1
1.0
10
100
1000
Grain dia.(mm)
τ (gm/m²)
τ (lb./ft²)

Figure 8



Flat bed values of Kpg
26
63
119
z
1
ds = Kpg Ts
ds = diameter > 10mm. (mm.)
Ts = shear on side slope (lb/ft.²)
Z
0
1
2
3
4
5
Cp = 0.85
Cp = 0.50
Probability of moving Cp = 0.05
50
100
150
200
Kpg

diameters less than 10 mm because the equation 2 Reynolds number limitation.

Table 2 - Values of $(1/K_pK_g)$ for equation 4a to determine diameter of material (mm) that will move with a probability (p) on side slopes (Z:1) for tractive force (Pa) and for an angle of repose of 42^o, $(1\ lb/ft^2) = 47.88$ Pa)

Side slope (Z)	Probability of moving P = 0.05	P = 0.5	P = 0.85
0.0	∞	∞	∞
1.5	4.51	2.36	0.96
1.75	3.75	1.96	0.79
2.0	3.38	1.77	0.73
2.5	3.03	1.50	0.65
3.0	2.86	1.50	0.61
4.0	2.71	1.42	0.59
5.0	2.63	1.38	0.56
Flat	2.52	1.32	0.54

Table 1. - Station 41+40
River - 405,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
690	6.2	0.69	48
534	7.8	0.48	82
414	6.9	1.16	80
227	7.2	0.88	69
126	3.1	0.63	53
95	2.0	0.07	40
63	0.5	0.008	26

Table 1. - Station 74+00 - continued
River - 405,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
672	6.6	2.08	44
372	10.0	1.25	65
276	8.9	1.36	62
156	8.5	1.32	50
120	8.2	1.18	39

Table 1 - Station 86+00 - continued
River - 405,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
756	3.6	0.46	23
636	8.7	0.56	54
504	9.8	0.54	62
372	8.4	0.54	70
168	5.9	0.61	59
126	4.2	0.53	48
84	3.0	0.39	32

Table 1. - Station 102+00 - continued
River - 405,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
99	4.1	0.02	38
148	4.4	0.42	54
198	5.2	0.41	64
390	6.7	0.76	87
522	7.5	0.82	84
654	6.2	0.64	68
750	3.2	0.38	37

Table 1. - Station 169+00 - continued
River - 405,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
320	7.5	0.82	95
380	6.9	0.53	104
440	5.5	0.62	104
500	4.1	0.57	104
560	4.2	0.20	94
620	2.1	0.04	88

Table 1. - Station 177+00 - continued
River - 405,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
644	7.3	0.29	43
500	8.0	0.74	72
470	8.8	0.22	73
440	8.1	0.57	76
300	8.6	0.41	73
140	8.0	0.19	56
32	4.8	0.02	36

Table 10 - Station 191+00 - continued
River - 405,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
760	7.2	2.15	28
675	8.9	2.27	45
435	10.3	3.64	75
330	9.6	2.79	60
280	5.8	3.48	52
195	6.8	2.70	28

Table 1. - Station 41+40 - continued
River - 240,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
690	3.25	0.49	37.1
534	4.40	1.15	69.4
414	4.95	1.06	66.5
227	4.85	1.15	55.5
126	1.75	0.14	35.7
102	0.45	0.08	26.3

Table 1. - Station 74+00 - continued
River - 240,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
672	5.75	0.75	33.1
492	7.8	1.97	49.0
372	8.6	0.74	50.6
276	6.5	1.82	49.7
156	7.25	0.95	34.9
135	6.20	1.63	28.3
111	4.90	1.71	21.4

Table 1. - Station 86+00 - continued
River - 240,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
636	6.9	0.59	39.3
504	7.5	0.52	48.3
372	7.45	0.25	55.7
168	4.85	0.063	43.3
145	2.9	0.19	34.6

Table 1. - Station 102+00 - continued
River - 240,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
669	4.4	0.23	48.8
595	5.95	0.36	61.3
522	6.5	0.61	69.5
390	5.4	0.58	72.5
198	5.15	0.073	52.0
148	3.8	0.044	43.5

Table 1. - Station 154+00 - continued
River - 240,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
780	4.05	0.10	40.4
732	5.25	0.04	50.0
636	5.5	0.34	50.1
456	7.5	0.14	50.3
312	6.9	0.11	49.0
180	4.25	0.82	42.6
132	4.5	0.61	37.4

Table 1. - Station 169+00 - continued
River - 240,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
620	1.35	0.31	73.2
560	3.7	0.05	82.3
500	4.15	0.39	85.1
436	3.90	0.90	88.6
380	4.7	0.56	88.4
320	5.5	0.64	79.2

Table 1. - Station 177+00 - continued
River - 240,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
644	6.9	0.12	43.6
500	7.1	0.19	61.4
470	6.7	0.33	63.8
440	7.5	0.14	64.0
300	6.6	0.19	59.7
200	4.35	0.70	50.6
132	3.75	0.07	39.0

Table 1. - Station 191+00 - continued
River - 240,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
714	5.25	1.37	27.6
674	5.75	2.04	36.7
554	7.45	1.89	53.4
434	8.60	1.36	60.2
330	6.40	1.87	49.2
279	5.20	1.30	36.6

Table 1. - Station 41+40 - continued
River - 160,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
690	1.43	0.38	27
534	4.45	0.016	61
414	4.40	0.024	59
227	4.52	0.008	49
126	0.50	0.50	32

Table 1. - Station 74+00 - continued
River - 160,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
672	4.21	0.021	22
492	6.27	0.036	39
372	6.46	0.022	44
276	5.46	0.046	41
165	5.98	0.023	29
135	5.90	0.017	22

Table 1. - Station 86+00 - continued
River - 160,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
636	4.85	0.41	33
504	5.95	0.77	40
372	5.16	0.48	49
276	5.00	0.28	46
168	3.50	0.36	38
141	2.20	0.36	32

Table 1. - Station 102+00 - continued
River - 160,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
687	2.55	0.17	40
522	4.27	0.30	62
390	4.12	0.35	65
198	2.20	0.29	42
162	1.25	0.56	37
126	0.79	0.40	27

Table 1. - Station 169+00 - continued
River - 160,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft2)	Depth (ft)
620	0.67	0.068	66
560	3.15	0.018	76
500	2.69	0.069	77
440	3.07	0.054	80
380	3.87	0.016	79
320	3.10	0.064	73

Table 1. - Station 177+00 - continued
River - 160,000 (ft^3/s)

Distance from crest ~~or~~ ~~ro~~ad (ft)	Velocity 5 feet from bed (ft.s)	Tractive force (lb/ft^2)	Depth (ft)
500	5.25	0.22	55
470	5.69	0.10	56
440	5.28	0.37	58
330	5.60	0.06	52
140	3.12	0.04	29
117	2.57	0.13	27

Table 1. - Station 191+00 - continued)
River - 160,000 (ft^3/s)

Distance from crest ~~or road~~ (ft)	Velocity 5 feet from bed (ft/s)	Tractive force (lb/ft^2)	Depth (ft)
670	4.1	1.43	27
450	7.6	1.06	55
324	5.6	1.30	44
285	2.9	0.52	36

Table 1. - Station 37+75 - Continued
River - 839,000 (ft^3/s)

Station	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)
600	1.1	0.174	30.9
500	4.6	0.083	27.5
400	3.7	0.22	47.7
280	1.7	0.30-2.47	43.4

Table 1. - Station 59+50 - continued
River - 82,600 (ft^3/s)

Station	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)
560	3.9	--	--
420	3.6	0.026	
280	2.4	0.06-0.19	

Table 1. - Station 86+00 - continued
River - 85,500 (ft^3/s)

Station	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)
700	0.4	0.038	24.4
410	4.0	1.03-2.43	41.1
250	2.4	0.50	27.1

Table 1. - Station 116+00 - continued
River - 85,900 (ft^3/s)

Station	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)
750	2.2	0.086	27.4
550	2.7	0.82	43.8
350	3.0	0.09-0.35	28.4

Table 1. - Station 169+00 - continued
River - 82,200 (ft^3/s)

Station	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)
646	1.7	0.52	80.4
550	3.0	0.22	80.5
455	1.2	0.0061	73.9

Table 10 - Station 191+00 - continued
River - 86,400 (ft^3/s)

Station	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)
670	1.0	2.39	51.9
560	2.2	1.24	48.4
450	2.6	0.24-1.40	45.7

Table 1. - Station 230+00 - continued
River - 82,200 (ft^3/s)

Station	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)
670	1.0	0.38	66.0
560	2.2	0.65	70.2
440	2.9	0.17	66.2

Table 1. - Station 278+00 - continued
River - 85,700 (ft^3/s)

Station	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)
660	4.2	0.15	36.8
530	3.6	0.17	44.5
400	1.8	0.007-1.0	41.2

Table 2. - Station A*

Spillway - 100,000 ft^3/s
Power - 184,600 ft^3/s
Total 284,600 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)	Diameter (mm)		
				85% chance moving	50% chance moving	5% chance moving
2,382	1.60	0.25	74.3	6.5	15.7	29.9
2,280	1.60	.10	91.6	2.6	6.3	11.9
2,040	2.50	-	100.6	-	-	-
1,800	2.50	-	102.6	-	-	-
1,560	1.50	-	103.2	-	-	-
1,320	0.45	.17	97.6	4.4	10.7	20.3
1,080	-	-	97.9	-	-	-
840	1.65	-	83.3	-	-	-
714	0.35	.26	75.7	6.7	16.4	31.0

* Parallel to and 240 ft downstream from spillway.

Blanks indicate velocity profiles were not logarithmic and did not lend themselves to analysis.

Table 2. - Station B*

Spillway - 100,000 ft^3/s
Power - 184,600 ft^3/s
Total 284,600 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Diameter (mm)			
			Depth (ft)	85% chance moving	50% chance moving	5% chance moving
2,384	1.60	0.25	74.3	6.5	16	30
1,834	1.95	.50	41.3	13	31.5	60
1,774	2.50	-	75.6	-	-	-
1 654	2.6	033	89.4	0.86	2.1	3.9
1,414	2.1	.019	91.1	0.49	1.2	2.6
1,294	2.2	-	90.2	-	-	-
1,174	3.0	.028	78.5	0.73	1.8	3.3
1,114	2.70	.21	66.6	5.5	13	25
934	6.75	.057	50.4	1.5	3.6	6.8
814	5.35	.160	56.5	4.2	10	19

* Parallel to and 1080 ft downstream from spillway.

Table 2. - Station C*

Spillway - 100,000 ft^3/s
Power - 184,600 ft^3/s
Total 284,600 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)	Diameter (mm)		
				85% chance moving	50% chance moving	5% chance moving
2,032	3.95	0.71	36.8	18.4	44.7	84.8
2,000	3.45	0.49	59.3	12.7	30.9	58.8
1,760	5.00	-	82.3	-	-	-
1,640	5.35	0.03	74.4	0.78	1.89	3.58
1,400	5.05	1.68	67.6	43.6	106	201

* Parallel to and 2120 ft downstream from spillway.

Table 2. - Station Highway Bridge

Spillway - 100,000 ft^3/s
Power - 184,600 ft^3/s
Total 284,600 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)	Diameter (mm) 85% chance moving	50% chance moving	5% chance moving
688	2.50	-	51.1	-	-	-
556	5.30	1.30	73.9	33.7	81.9	155
376	7.70	0.87	70.3	22.6	54.8	104
184	4.10	0.84	31.4	21.8	52.9	100
160	1.65	1.40	17.2	36.3	88.2	167

Table 2. - Station A

Spillway - 200,000 ft^3/s
Power - 184,600 ft^3/s
Total 384,600 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Diameter (mm)			
			Depth (ft)	85% chance moving	50% chance moving	5% chance moving
2,382	1.10	0.17	81.2	4.41	10.7	20.3
2,280	0.90	0.097	99.7	2.51	6.11	11.6
2,040	2.50	-	109.0	-	-	-
1,800	2.70	0.18	111.2	4.59	11.1	21.1
1,560	3.00	-	111.0	-	-	-
1,320	0.25	0.88	105.6	22.8	55.4	105
1,080	1.00	0.82	106.2	21.3	63.0	97.9
840	1.30	0.06	92.0	1.56	81.9	7.16
714	1.20	0.21	84.0	5.45	75.6	25.1

Table 2. - Station B

Spillway - 200,000 ft^3/s
Power - 184,600 ft^3/s
Total 384,600 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)	Diameter (mm)		
				85% chance moving	50% chance moving	5% chance moving
1,894	2.35	0.170	75.8	4.41	10.7	20.3
1,834	2.76	0.044	95.5	1.14	2.77	5.25
1,774	3.30	0.160	97.8	4.15	10.1	19.1
1,654	4.00	-	98.8	-	-	-
1,414	2.70	0.078	97.7	2.02	4.91	9.31
1,294	2.44	0.340	87.0	8.82	21.4	40.6
1,174	3.00	0.0095	86.7	0.25	0.60	1.13
1,114	3.90	-	74.0	-	-	-
934	4.30	0.64	59.3	16.6	40.3	112
814	5.13	0.15	61.4	3.79	9.20	17.4

Table 2. - Station C

Spillway - 200,000 ft^3/s
Power - 184,600 ft^3/s
Total 384,600 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Diameter (mm)			
			Depth (ft)	85% chance moving	50% chance moving	5 % chance moving
1,160	0.65	0.078	69.1	2.02	4.91	9.31
1,400	4.10	0.41	75.8	10.6	25.8	48.9
1,640	4.60	-	83.4	-	-	-
1,760	5.00	0.023	91.3	0.60	1.45	2.75
2,000	3.25	0.36	69.1	9.35	22.7	43.0
2,032	3.83	0.72	45.5	18.7	45.4	86.0

Table 2. - Station Highway Bridge

Spillway - 200,000 ft^3/s
Power - 184,600 ft^3/s
Total 384,600 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Diameter (mm)			
			Depth (ft)	85% chance moving	50% chance moving	5% chance moving
160	0.65	0.98	25.9	25.4	61.7	117
184	4.60	0.65	39.4	16.9	40.9	77.6
376	7.70	1.00	78.8	26.0	63.0	117
556	3.70	2.10	82.7	54.5	132	251
688	3.30	0.77	58.7	20.0	48.5	91.9

Table 2. - Station A

Spillway - 415,000 ft^3/s
Power - 185,000 ft^3/s
Total 600,000 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)	Diameter (mm) 85% chance moving	50% chance moving	5% chance moving
2,400	0.90	0.4	96.0	10.0	25.0	48.0
2,280	3.07	0.5	114.0	13.0	32.0	60.0
2,040	7.40	-	122.0	-	-	-
1,800	7.40	-	122.0	-	-	-
1,560	6.35	-	122.0	-	-	-
1,320	6.75	-	119.0	-	-	-
1,080	1.80	-	118.0	-	-	-
840	5.35	-	106.0	-	-	-
714	5.15	-	98.0	-	-	-

Table 2. - Station B

Spillway - 415,000 ft^3/s
Power - 185,000 ft^3/s
Total 600,000 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Diameter (mm)			
			Depth (ft)	85% chance moving	50% chance moving	5% chance moving
1,894	6.52	0.0615	34.6	1.59	3.87	7.34
1,834	3.70	1.33	46.8	34.5	83.8	159
1,714	3.35	1.00	78.4	26.0	63.0	119
1,654	3.80	0.352	112	9.14	22.2	42.0
1,414	3.80	0.310	114	8.05	19.5	37.0
1,294	3.25	0.820	117	21.3	51.6	97.9
1,174	3.45	0.342	108	8.88	21.5	40.8
1,114	2.70	0.224	95.4	5.81	14.1	26.7
934	3.45	0.342	68.4	8.88	21.5	40.8

Table 2. - Station C

Spillway - 415,000 ft^3/s
Power - 185,000 ft^3/s
Total 600,000 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)	Diameter (mm) 85% chance moving	50% chance moving	5% chance moving
1,160	0.52	0.0671	84.1	1.75	4.22	8.01
1,400	4.25	0.174	88.0	4.52	11.0	20.8
1,640	4.90	0.359	97.8	9.32	22.6	42.9
1,760	4.85	0.0629	105.8	1.63	3.96	7.51
2,000	3.50	0.587	62.8	15.2	37.0	70.1
2,032	0.50	2.56	61.3	66.5	161	306

Table 2. - Station Highway Bridge

Spillway - 415,000 ft^3/s
Power - 185,000 ft^3/s
Total 600,000 ft^3/s

Distance from road (ft)	Velocity 5 feet from bed (ft/s)	Tractive force on bed (lb/ft^2)	Depth (ft)	Diameter (mm) 85% chance moving	50% chance moving	5% chance moving
100	1.10	5.48	24.6	142	345	654
184	4.35	4.96	55.4	128	312	592
376	10.10	0.587	92.8	15.2	37.0	70.1
556	8.02	1.57	97.2	40	98.9	188
688	3.80	4.66	76.3	120	293	556
748	0.85	0.0856	46.2	2.22	5.39	10.2

Table 3. - Maximum velocity five feet above bottom (ft/s)

Station	Discharge (ft^3/s)					
	160,000	240,000	284,000	384,600	400,000	600,000
A Parallel to and 240' d.s. spillway	-	-	2.50	3.00	-	7.40
B Parallel to and 1080' d.s. spillway	-	-	6.75	5.13	-	6.52
C Parallel to and 2120' d.s. spillway	-	-	5.35	5.00	-	4.90
Highway Bridge	-	-	7.70	7.70	(8.00)	10.10
41+00	4.52	4.95	-	-	7.8	-
74+00	6.46	8.6	-	-	10.0	-
86+00	5.95	7.5	-	-	9.8	-
102+00	4.27	6.5	-	-	7.5	-
154+00	-	7.5	-	-	-	-
169+00	3.87	5.5	-	-	7.5	-
177+00	5.69	7.5	-	-	8.8	-
191+00	7.6	8.6	-	-	10.3	-

( ) Interpolated.

Columbia River Model Data

Table 4. - Maximum tractive force (lb/ft²)

Station	Discharge (ft^3/s)					
	160,000	240,000	284,000	384,600	400,000	600,000
A Parallel to and 240' d.s. spillway	-	-	0.26	0.88	-	-
B Parallel to and 1080' d.s. spillway	-	-	0.50	0.64	-	1.33
C Parallel to and 2120' d.s. spillway	-	-	1.68	0.72	-	2.56
Highway Bridge	-	-	1.40	2.10	(2.40)	5.48
41+00	0.50	1.15	-	-	1.16	-
74+00	0.046	1.97	-	-	2.08	-
86+00	0.77	0.59	-	-	0.61	-
102+00	0.56	0.61	-	-	0.82	-
154+00	-	0.82	-	-	-	-
169+00	0.069	0.90	-	-	0.82	-
177+00	0.37	0.70	-	-	0.74	-
191+00	1.43	2.04	-	-	3.64	-

( ) Interpolated.

Columbia River Model Data

Table 5. - Maximum diameter with five percent chance of moving (mm)

Station	Discharge (ft^3/s) 160,000	240,000	284,000	384,600	400,000	600,000
A Parallel to and 240' d.s. of spillway	-	-	31.0	105.0	-	-
B Parallel to and 1080' d.s. of spillway	-	-	25.0	112.0	-	159.0
C Parallel to and 2120' d.s. of spillway	-	-	201.0	86.0	-	306.0
Highway Bridge	-	-	167.0	251.0	(286.0)	654.0
41+00	60.0	58.0	-	-	138.0	-
74+00	5.5	90.0	-	-	248.0	-
86+00	92.0	70.0	-	-	73.0	-
102+00	67.0	73.0	-	-	98.0	-
154+00	-	98.0	-	-	-	-
169+00	8.2	107.0	-	-	98.0	-
177+00	26.0	84.0	-	-	88.0	-
191+00	171.0	244.0	-	-	435.0	-

( ) Interpolated.

Columbia River Model Data

Table 6. - Maximum diameter 50 percent chance of moving (mm)

Station	Discharge (ft^3/s) 160,000	240,000	284,000	384,600	400,000	600,000
A Parallel to and 240' d.s. of spillway	-	-	16.0	82.0	-	-
B Parallel to and 1080' d.s. of spillway	-	-	32.0	40.0	-	84.0
C Parallel to and 2120' d.s. of spillway	-	-	106.0	45.0	-	161.0
Highway Bridge	-	-	88.0	132.0	(151.0)	345.0
41+00	32.0	72.0	-	-	73.0	-
74+00	2.9	124.0	-	-	131.0	-
86+00	49.	37.0	-	-	38.0	-
102+00	35.0	38.0	-	-	52.0	-
154+00	-	52.0	-	-	-	-
169+00	4.3	57.0	-	-	52.0	-
177+00	8.2	44.0	-	-	47.0	-
191+00	90.0	129.0	-	-	229.0	-

( ) Interpolated.

Columbia River Model Data

Table 7. - Maximum diameter 85 percent chance of moving (mm)

Station	Discharge (ft^3/s)					
	160,000	240,000	284,000	384,600	400,000	600,000
A Parallel to and 240' d.s. of spillway	-	-	6.7	23.0	-	-
B Parallel to and 1080' d.s. of spillway	-	-	13.0	17.0	-	35.0
C Parallel to and 2120' d.s. of spillway	-	-	44.0	19.0	-	66.0
Highway Bridge	-	-	36.0	54.0	(62.0)	142.0
41+00	13.0	30.0	-	-	23.0	-
74+00	1.2	51.0	-	-	54.0	-
86+00	20.0	15.0	-	-	16.0	-
102+00	15.0	16.0	-	-	21.0	-
154+00		21.0	-	-	-	-
169+00	1.8	23.0	-	-	21.0	-
177+00	9.6	18.0	-	-	15.0	-
191+00	37.0	53.0	-	-	95.0	-

( ) Interpolated.

Columbia River Model Data

Table 8. - Summary of riprap design methods sizing for D_{50} in feet

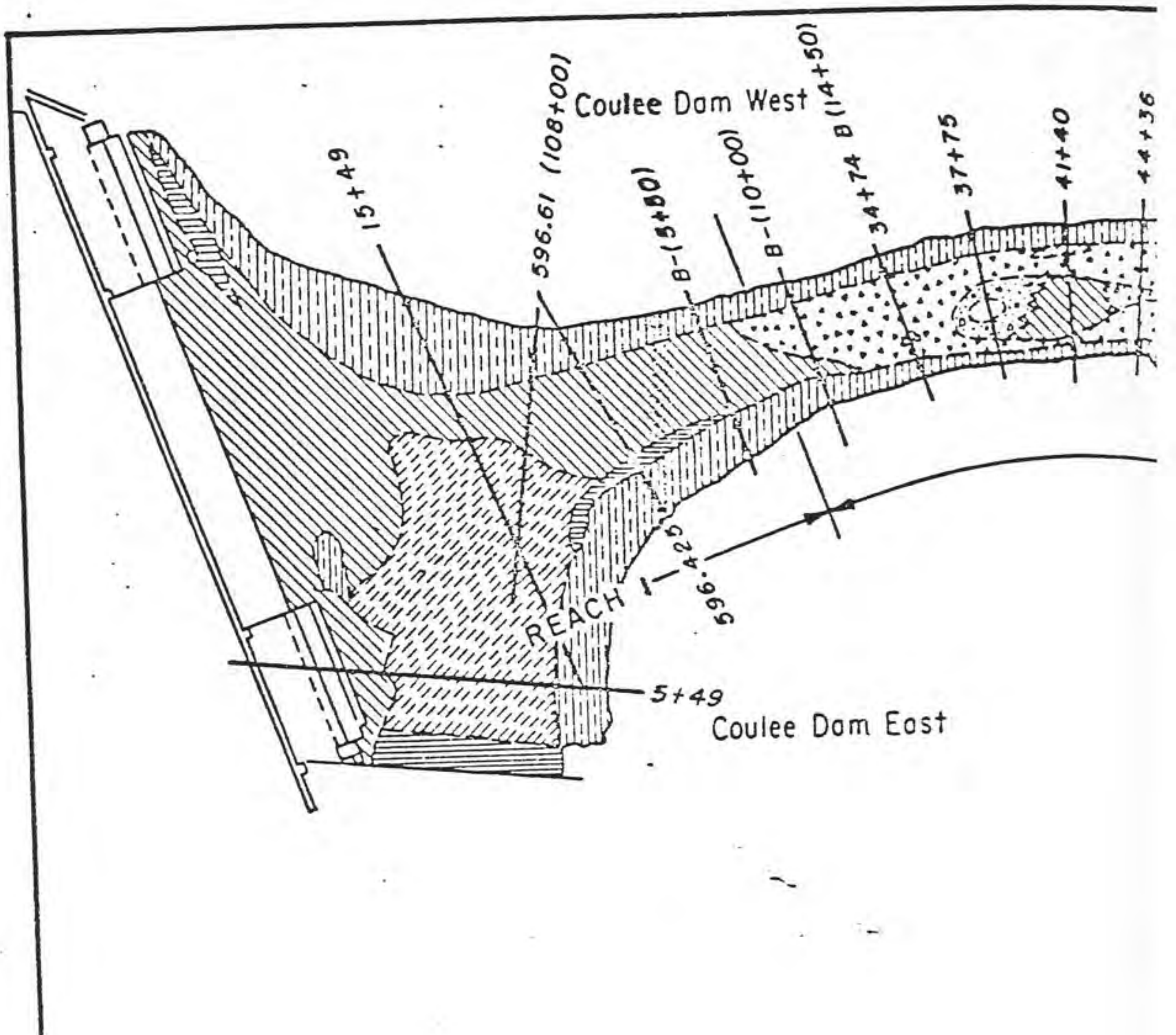
Q = Design Discharge = 400 000 ft^3/s (11 300 m^3/s)

River stabilization area	2 and 3	4	5	6	7	8 and 9
Average velocity* (ft/s)	10.36	10.36	9.77	9.2	9.2	11.3
Tractive shear* (lb/ft^2)	1.70	1.70	1.30	1.86	1.86	2.09
Tractive shear** (lb/ft^2)	1.16	2.08	0.82	0.82	3.64	-
Largest τ above used for designs below						
D_{50} sizes (ft):						
Physical model study	~~1.3~~ 0.9	1.1	0.7	~~1.9~~ 1.0	1.9	~~1.0~~ 1.09
USBR Monograph 25 (Based on $V_b = 0.7 V_m$)	~~1.0~~ 0.8	~~1.3~~ 0.8	0.7	~~1.0~~ 0.6	~~1.4~~ 0.6	~~0.9~~ 1.0
Bureau of Public Roads	0.6	~~0.9~~ 0.6	~~0.6~~ 0.5	~~0.7~~ 0.5	~~1.0~~ 0.5	0.7
California Division of Highways	2.1	2.1	1.9	1.7	1.7	2.5
Army Corps after Campbell	1.6	1.6	1.4	1.4	1.4	1.8
Simons and Senturk	~~2.8~~ 2.3	~~2.8~~ 2.3	1.8	2.5	2.5	2.8
Sedimentation degradation study	1.6	1.6	1.5	1.3	1.3	2.0

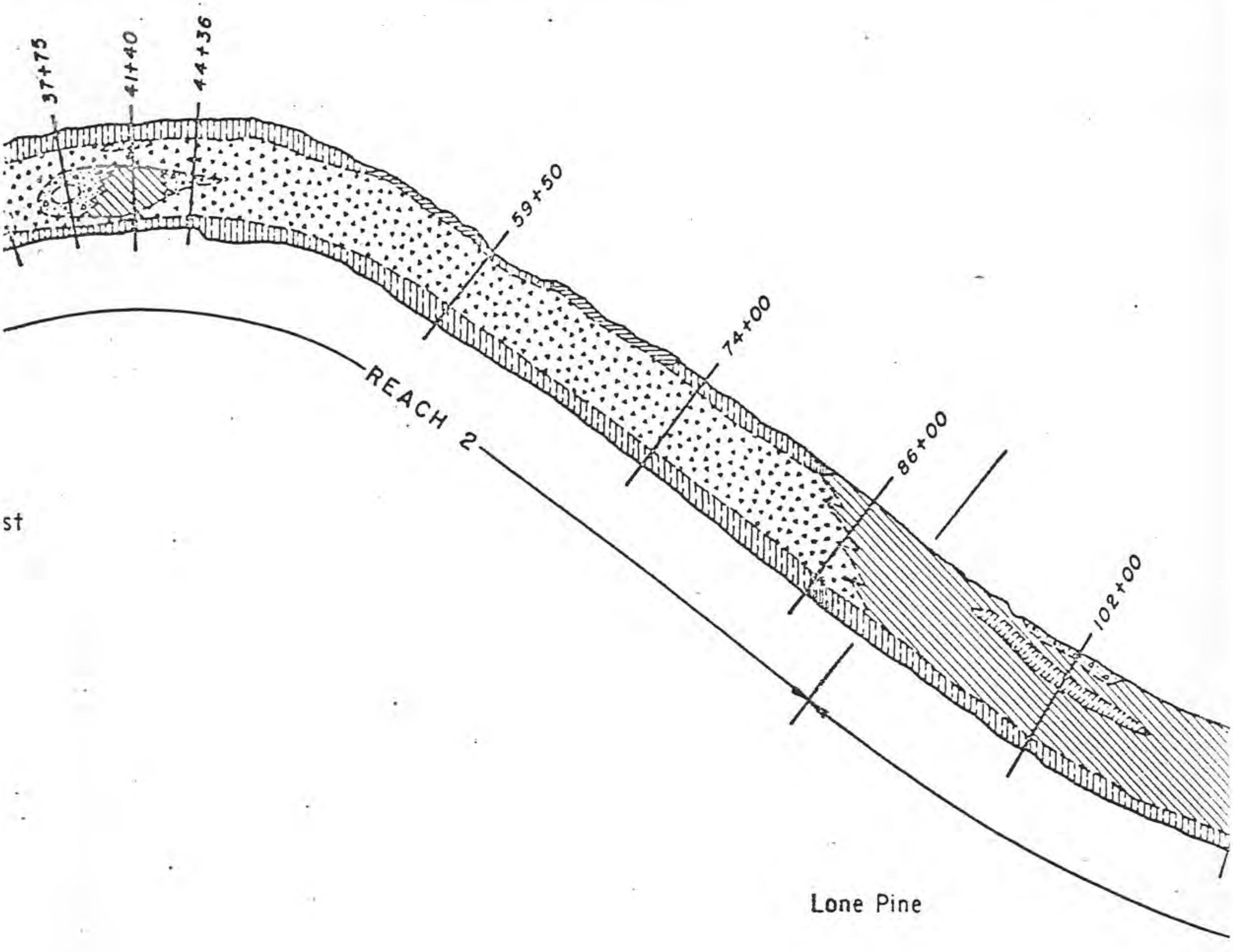
Velocity in ft/s
Tractive force in lb/ft^2

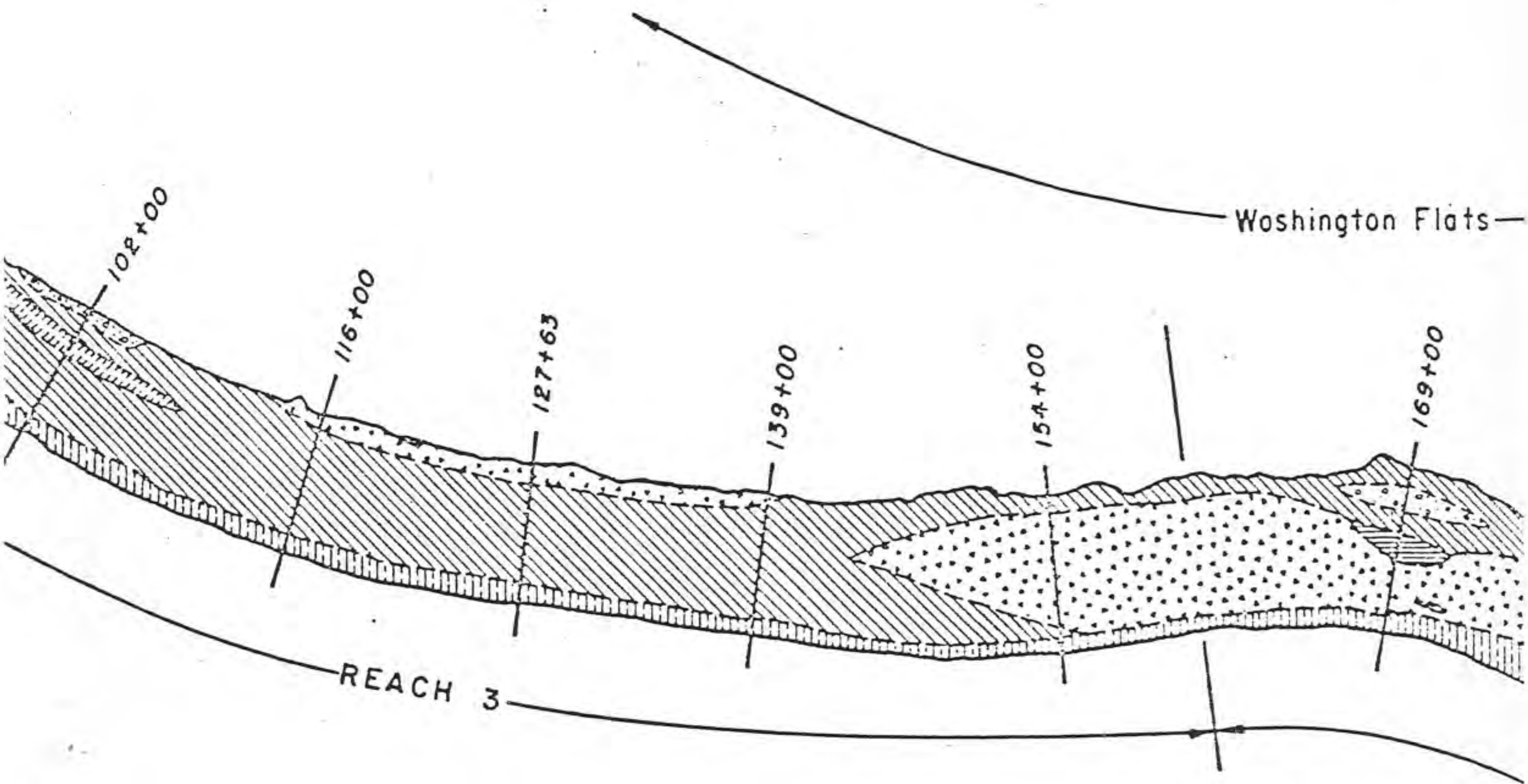
1 ft = 0.305 m
1 ft/s = 0.305 m/s
1 lb/ft^2 = 47.88 Pa

* Values from degradation study.
** Values from physical model study.



Coulee Dam West
15+49
596.61 (108+00)
B-(5+80)
B-(110+00)
34+74 B (14+50)
37+75
41+40
44+36
REACH
596.425
5+49
Coulee Dam East

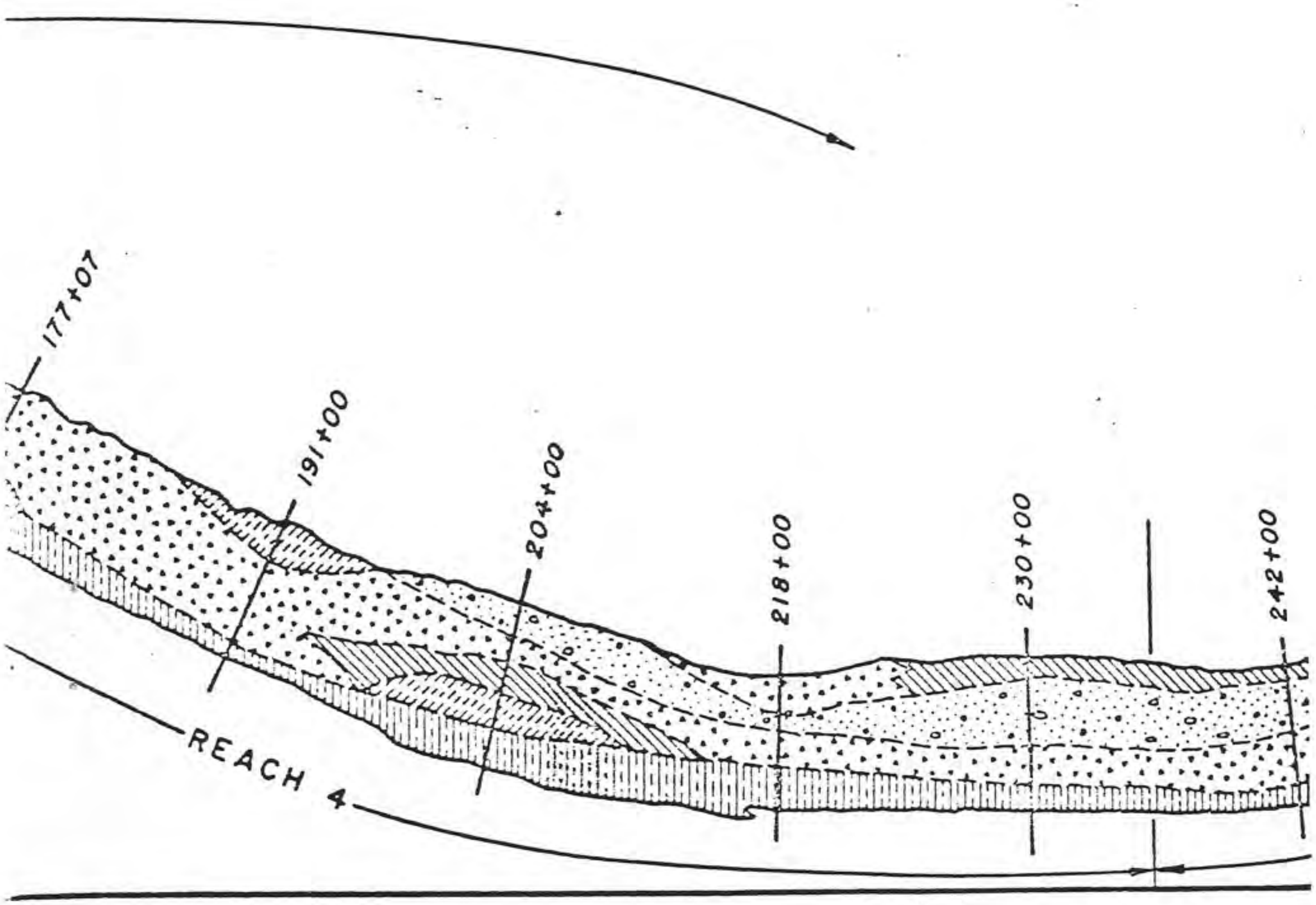

37+75
41+40
44+36
59+50
74+00
86+00
102+00
REACH 2
st
Lone Pine



Washington Flats
102+00
116+00
127+63
139+00
154+00
169+00
REACH 3
Elmer City

EXPLANATION OF SYMBOLS

- CLAY (MASSIVE AND BEDDED)
- SAND AND GRAVEL
- COBBLES AND GRAVEL W/BOULDERS
- BOULDERS AND COBBLES
- RIPRAP
- GRANITE



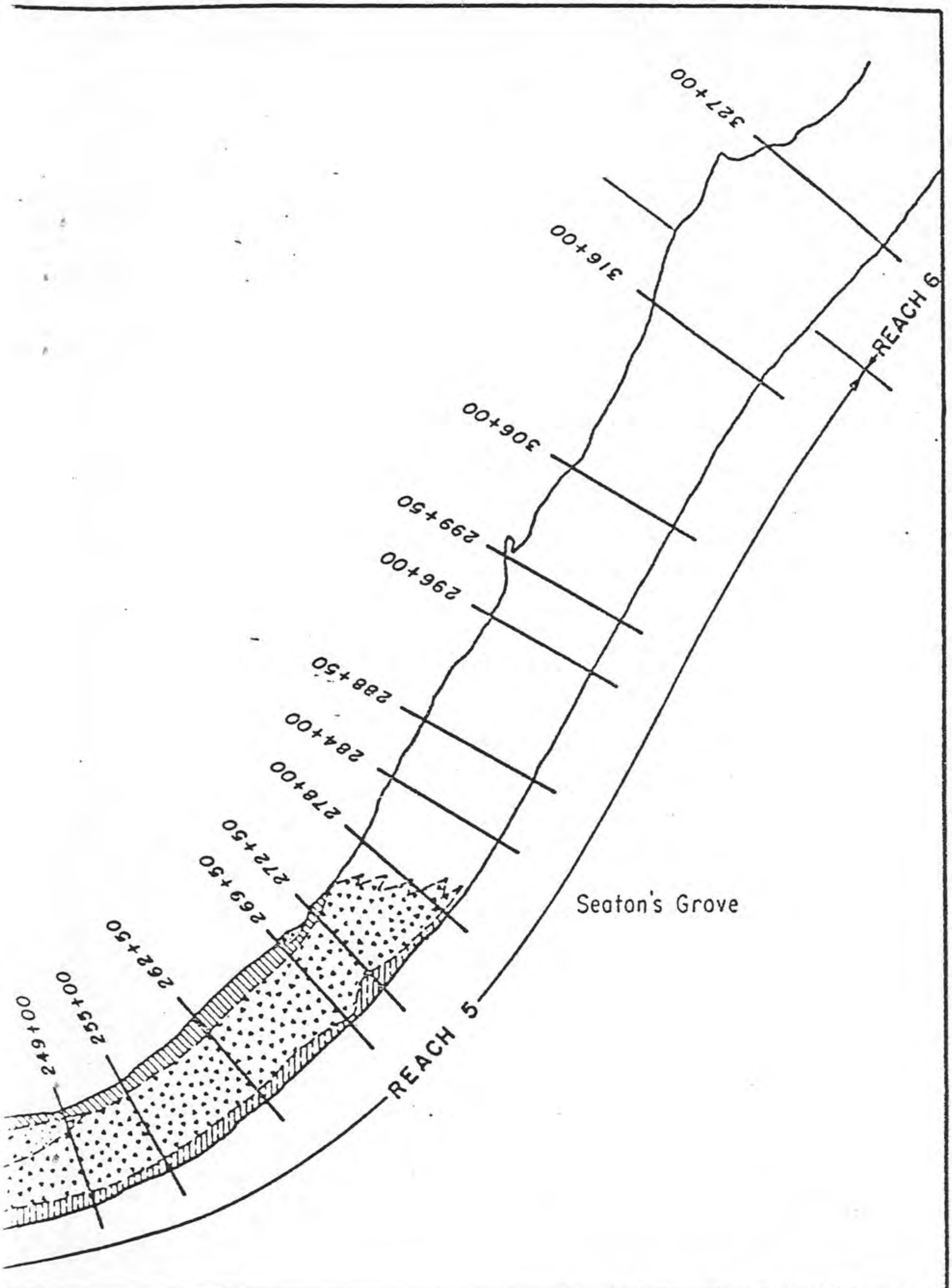


Figure 1. - Location map for river sections and bed material.

OPTIONAL FORM NO. 10 (O/P 4-65) 5010-107
MAY 1962 EDITION
GSA GEN. REG. NO. 27

UNITED STATES GOVERNMENT

Memorandum

Memorandum

TO : Chief, Dams Branch
Attn D-224

Denver, Colorado
DATE: February 2, 1979

THROUGH: Chief, Hydraulics Branch

FROM : R. A. Dodge

SUBJECT: Riverbank Stabilization Program - Results From Physical Hydraulic Model Study of Columbia River

Enclosed are conclusions and recommendations from the draft report concerning physical model studies to help determine the effects of hydraulics on bank stability downstream from the Grand Coulee Third Powerplant extension. The first group of conclusions relates to the capability of the model and its limitations. The second group is conclusions and recommendations more directly related to the embankment design.

Figure 2 is enclosed so that the equation can be applied to the values of tractive force already provided to the designers. This figure includes estimates of probability of moving and correction for bank side slope.

Table 2 gives the results of measurements taken at the highway bridge and upstream. This table lists velocities 5 feet above the bed, tractive force values where they could be determined by velocity distribution, and sediment sizes related to 0.05, 0.50, and 0.85 Gessler probability of moving. Table 3 lists maximum velocities 5 feet above the bed for all measuring stations. Table 4 lists the maximum tractive forces found at all the measuring stations. Tables 5, 6, and 7 give the sizes of sediment related to the three Gessler probabilities of moving for the maximum values of tractive force given in table 4.

If there are any questions or comments concerning these conclusions, recommendations, figures, or tables, please contact me so that my explanations and your thoughts can be incorporated into the final report.

Enclosures
1. Conclusions and recommendations
2. Slope correction curves
3. Tables 2 through 7

Copy to: Chairman Coordinator, Riverbanks Stabilization Program (Carter), PN-230
(with enclosure 1)

Blind to: Project Coordinator, Grand Coulee Project (Bartel)
(with enclosure 1)
D-274 (Orvis)
(with copy of all enclosures)
D-753 (Blanton)
(with copy of all enclosures)
D-1532

RADodge:sda-V

Note Fig 1 & Table 1 diliverd to designers c/o Memo
Fig A & Table 8 from Frisco Paper with Orvis