MADISON RIVER, MONTANA
REPORT ON

FLOOD EMERGENCY
MADISON RIVER SLIDE

VOLUME I
MAIN REPORT

U. S. ARMY ENGINEER DISTRICT, OMAHA
CORPS OF ENGINEERS
OMAHA, NEBRASKA
SEPTEMBER 1960

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MADISON RIVER SLIDE

VOLUME I

SEPTEMBER 1960

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VOLUME I - MAIN REPORT

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(Volume II contains appendixes consisting of detailed technical reports.)

Photo 1. About 20 August 1959. Aerial view of Madison River slide about 2 days following earthquake. USDA - Forest Service photo.

1. The Earthquake. On 17 August 1959, at about 11:38 p.m., one of the most severe earthquakes in the history of the United States struck the Rocky Mountain region in the vicinity of Yellowstone National Park. The shock was recorded at the University of California Seismological Station at Berkeley, California, with a magnitude of 7.5 to 7.75 on the Richter scale. Several after-shocks, ranging in magnitude from 5.5 to 6.75 on the Richter scale, were recorded at Berkeley in the next 24 hours. Many more shocks and tremors of lesser and decreasing magnitude were felt in the area for weeks afterward. The epicenter was estimated to be in the southwestern part of Yellowstone National Park. Damage was particularly heavy in the upper Madison River valley in Montana. Nine lives are known to have been lost and nineteen other persons known or thought to have been in the area have not been accounted for, and are presumed to have perished under the slide at the mouth of the Madison Canyon.

2. This report covers the activities of the Corps of Engineers, under the authority of Public Law 99, 84th Congress, 1st Session, in appraising the situation and in removing the hazard to life and the threat of flood damage caused by the earthquake.

3. Madison River Valley. The Madison River heads in Yellowstone National Park and flows northwest, then northward to the vicinity of Three Forks, Montana, where it joins the Gallatin River on the east and the Jefferson River on the west to form the Missouri River. See the general map Plate 1. Hebgen Dam, a water storage project of the Montana Power Company, is located at the entrance to Madison Canyon in the Madison Mountain Range. From the dam, the river flows west about eight miles to the mouth of the canyon, where it begins curving northward into a broad, open valley. Hebgen Lake formed by Hebgen Dam in a wide valley above the canyon, has a capacity of 345,000 acre-feet. The area from the west boundary of Yellowstone National Park to and including the mouth of Madison Canyon is within the boundaries of the Gallatin National Forest.

4. Hebgen Lake and the Madison River valley have been very popular with vacationers. The Madison River has been known for many years as one of the best trout-fishing streams in the nation. Montana Highway 287 extends from its junction with U. S. 191 about eight miles north of West Yellowstone, Montana, along the north shore of Hebgen Lake, through Madison Canyon and generally down the Madison River to a junction with U. S. 10 S. about ten miles west of Three Forks, Montana. During the summer, the highway normally is heavy with tourist traffic and many resorts, cabin camps, and campgrounds are operated for the traveling public. Many vacationers pitch their tents or park their trailers at convenient spots along the river, particularly in the reach through Madison Canyon.

5. The Madison River valley below the canyon is devoted largely to stock-raising. Several large ranches and a number of motels and lodges have extensive developments in the flood plain. The town of Ennis, with a population of about 600, and the village of Jeffers, with a population of about 40, are situated on the flood plain about 40 miles downstream from Madison Canyon. Between Madison Canyon and Three Forks there are 11 highway or road bridges, two railroad bridges, and many miles of highways, secondary roads, and railroads.

6. Hebgen Dam and Lake. The earthquake caused major faulting along the right bank of Hebgen Lake and along the mountain slope north of the lake. The right side of the lake dropped several feet and the left shore was left exposed. It is still uncertain whether the left side of the lake bed was uplifted, or whether the recession of the lake from the shore was a result of the subsidence of the right side. Several slides along the right side of the lake severely damaged the highway. Surveys made by the Coast and Geodetic Survey show that some areas along the right side of Hebgen Lake dropped as much as 19 feet.

7. The disturbance in Hebgen Lake sent a series of water waves, reported to be at least three feet high, over the dam, causing erosion of the downstream slope and toe and putting out of operation a small generator used for station service. The dam is an earth and rock fill, with a concrete core wall founded on bedrock, except the north end, where the spillway has a cutoff wall extending about 15 feet below the bottom of the structure.

8. At the right abutment of the dam the crest of the embankment on the downstream side dropped about four feet with respect to the core wall, believed to be due largely to compaction of the terrace foundation. The upstream crest of the embankment dropped as much as six feet below the top of the core wall. The core wall itself was cracked in several places, mostly near the spillway, the largest crack being about five inches wide; at two breaks lateral displacement of one to three inches occurred. The spillway and chute were seriously damaged, to the extent that replacement is planned by the owner.

9. Immediately after the quake, considerable seepage was reported issuing from the natural terrace slope just downstream from the dam. Since the seepage decreased to a small amount after the spillway discharge was stopped by placing of the stop logs, it was concluded that most of the seepage came from the spillway channel and not through the dam.

10. Madison River Slide. A massive slide, see frontispiece, covered Highway 287 and completely blocked the Madison River just upstream from the mouth of Madison Canyon. The slide originated on the south or left canyon wall and moved across and up the valley, forming a natural dam from 200 feet to 400 feet in height and about three-fourths

of a mile in width at the base. The leading edge of the slide mass came to rest high up on the north canyon wall. The lowest portion of the mass formed a saddle approximately over the old river channel.

11. The slide destroyed an undeveloped campground located on the right side of the valley. Separate families or groups of campers also were caught in or along the edges of the slide. Latest reports place the number of known lives lost in the Hebgen Lake - Madison Canyon area at seven, with an additional 19 missing persons possibly buried under the slide.

12. The presence of the slide in Madison Canyon and the unknown but apparently weakened condition of Hebgen Dam posed a serious threat of disastrous flooding in the Madison River Valley. If Hebgen Dam should fail, the release of stored water without doubt would cause a devastating flood down the entire valley and probably along the Missouri River as well. Even if Hebgen did not fail, the rising waters in the new lake formed by the slide, if permitted to overtop the slide, could cut a channel so rapidly that serious flooding would result all the way down the Madison River valley. Rough estimates indicated that failure of Hebgen Dam could cause flood damage as high as $15,000,000. Failure of the slide alone would cause damage possibly half as great. In either event, loss of life probably would be high.

13. <u>Preliminary Information</u>. First information on the disaster was received in the Garrison District Office on the morning of 18 August by telephone from Mr. Hugh Potter, Montana Civil Defense Director. Two observers were dispatched in a small plane to the disaster area. Only fragmentary information could be obtained that day, because of the absence of communications facilities and the destruction of roads, and because all efforts were devoted to rescue work. More than 200 persons, with their autos, trailers, and camping equipment, were trapped in the Madison River Canyon between Hebgen Dam and the slide. The Corps of Engineers observers were able only to view the damage from the air and to make a rough estimate of the magnitude of the slide. By the end of that day, rescue teams organized by the Forest Service had bulldozed emergency trails along the mountain side around the breaks in the highway along Hebgen Lake and had evacuated 167 persons from the canyon.

14. On Thursday, 20 August, Major General Keith R. Barney, Missouri River Division Engineer, and members of his staff flew to the disaster area from Omaha. Following an inspection of the earthquake damage, General Barney met on 21 August with Hugh Potter, Montana Civil Defense Director, and representatives of other interested agencies to discuss possible emergency measures. He advised the group that the Corps of Engineers would be willing and able to investigate the slide to estimate its stability and to take whatever steps might be indicated. Later that day, General Barney engaged Woodward, Clyde, Sherard, and Associates,

Consulting Civil Engineers, to make an appraisal of the problem and to advise on the stability of both Hebgen Dam and the slide in Madison River Canyon and on the possibility of removing a significant portion of the slide to provide a spillway that would not fail rapidly.

15. Request for Corps Assistance. The following day, Montana's Governor J. Hugo Aronson requested the Secretary of Defense to direct the Corps of Engineers to investigate and remove the serious threat to life and property, which presented a problem beyond the capabilities, both technically and financially, of the state and local government agencies. Also on that day, a joint Congressional delegation, including Utah's Senator Frank E. Moss, Montana's Representatives Lee Metcalf and LeRoy M. Anderson, Idaho's Representative Gracie M. Pfost, California's Representatives John F. Baldwin, Jr. and Harold T. Johnson, and New Mexico's Representative Thomas G. Morris, visited the area and inspected the earthquake damage.

16. In response to Governor Aronson's request, on 22 August, the Chief of Engineers, acting under the authority of Public Law 99, 84th Congress, 1st Session, directed the Division Engineer, Major General Barney, to investigate the flood problem and to take the steps necessary to remove the threat to life and property downstream from the slide in Madison River Canyon. By letter, dated 22 August, the Division Engineer directed Lt. Col. Walter W. Hogrefe, Garrison District Engineer, to proceed with the investigation and the necessary emergency measures.

Photo 2. About 21 August 1959. A Forest Service photo, looking downstream at large rocks on downstream slope of slide and at the streambed below slide. (For later view, see Photo 27).

17. <u>Preliminary Investigations</u>. The consulting engineer firm of Woodward, Clyde, Sherard and Associates, represented by Dr. James L. Sherard and Stanley F. Gizienski, made a preliminary investigation and reported verbally, with conclusions and recommendations, on the late afternoon of 22 August. They were of the opinion that Hebgen Dam was not safe at the current reservoir level and they recommended that the reservoir level be lowered to avoid the possibility of failure.

18. The consultants reported that, because of the favorable distribution of materials in the slide mass, the presence of a natural spillway channel in the lowest portion of the mass, and the extremely wide section parallel to the river, they believed the slide would act as a stable natural dam. They recommended that bulldozers be utilized to excavate a wide-crested spillway on the crest of the upstream portion of the slide, lowering the elevation as much as possible within the time available.

19. The consultants recommended the immediate initiation of a topographic survey of the slide mass and also a program of test borings, beginning with several borings in the river bottom at the downstream toe, to determine whether there was a possibility of piping beneath the slide mass. They recommended that observation wells be installed and test borings be made to measure subsurface water levels and to determine whether fine-grained materials existed beneath the downstream zone of the dam.

20. <u>Initial Activities</u>. A project office was established in West Yellowstone, Montana, on 22 August 1959, with Lt. Col. Walter W. Hogrefe, Garrison District Engineer, in charge. On 23 August a survey party started preliminary surveys for location of an access road to the top of the slide and tentative alinement of a spillway across the slide. On the following day, two bulldozers started work constructing a rough access road from the highway at the downstream toe of the slide. This preliminary work was dangerous and extremely difficult, because of the mass of large rock on the downstream portion and the jungle of trees covering a large portion of the top of the slide.

21. While the slide mass was considered stable against sliding or rapid breaching, it was recognized that additional slides might occur, considering the continuing tremors and the condition of some of the slide material on the steep-sided ridge forming the south side of the canyon.

22. At the time of the earthquake, Hebgen Lake was filled to elevation 6542.86, with approximately 330,000 acre-feet of water in storage. After the quake, the gage indicated a reservoir elevation of 6542.00. It is likely that part of the difference was due to disturbance of the gage and part was due to adjustment of reservoir capacity, as well as the loss of water when the dam was overtopped by waves.

23. Because of the damage to the dam and spillway, the full extent of which was not known, there was a constant threat that the dam would fail, releasing a flood that would overtop and probably destroy the slide dam. Thus, aside from the obvious hazard to life and property in the Madison River valley below the canyon, the early work on the slide was performed under a very real threat of danger. After a few days, a more careful inspection of Hebgen Dam could be made and it became apparent that the dam itself still was stable and was not likely to fail. Because of the damage to the spillway, however, Montana Power Company felt it was necessary to draw the reservoir down, at least below the elevation of the spillway as soon as possible. In addition, the company felt that the reservoir should be emptied entirely to permit detailed inspection of the dam; furthermore, it would be highly desirable to complete the drawdown before winter, because of the unique problem, long known on the Madison River, of flooding caused by the formation of frazil and anchor ice during high discharges in cold weather.

24. Technical Studies. A number of technical studies were made to check the preliminary findings and recommendations of Dr. Sherard and Mr. Gizienski and to obtain more detailed information than was possible in the limited time allowed for the preliminary investigation. Participating in these technical studies were two engineers and one geologist from the Omaha Engineer District and one consulting geologist and soils engineer, Mr. P. T. Bennett, formerly of the Missouri River Division office, as well as engineers of the Missouri River Division and the Garrison District. The results of the technical studies are summarized in the following paragraphs 25 through 30; complete reports on the studies are contained in the appendixes, which are published in another volume.

25. The earthquake resulted in the formation of the Hebgen fault, which runs roughly parallel to the northeast side of Hebgen Lake and extends upstream toward the reputed epicenter in Yellowstone National Park. The fault scarp is about 15 to 20 feet high at a point about 850 feet from the dam and about 250 feet higher up the mountainside. The spillway of Hebgen Dam is founded upon a terrace deposit, which is the weakest part of the dam foundation. The quake moved the terrace and the spillway structure horizontally against the concrete core wall of the dam, which is founded on bedrock.

26. Before the earthquake, the south wall of Madison Canyon was very steep, apparently supported by a buttress of outcropping quartzite and dolomite, which in turn was underlain by schist and gneiss. The supporting buttress was buckled by the earthquake and slid out on the weathered, decomposed schist formation. A secondary slide moved off the upstream end of the initial slide area, creating a terrace of disintegrated schist on the upstream face of the natural dam. Considering the predominance of quartzite and dolomite, particularly in the

downstream portion of the slide mass, the high degree of compaction, and the constriction of the downstream toe of the slide by the canyon walls, it was concluded that the natural dam would be stable and would not experience any serious movements.

27. The slide mass was U-shaped in cross section, curving smoothly from the left bank talus remaining after the slide to a thick mass of rock which surged up the face of the right wall of the canyon. The depth of material at the highest point of the saddle was about 220 feet above the original streambed. In profile, the material in the saddle, as exposed on the surface, was graded from massive quartzite blocks at the downstream toe, through schist and gneiss in the central portion, to weathered gneiss and schist, with the voids almost completely filled with fine-grained nonplastic soil, at the upstream toe. Early surface inspections indicated that the mass had roughly the characteristics of a composite earth and rock-fill dam, with the relatively impervious material upstream. Later explorations revealed considerable fines also in the central portion of the natural dam. The downstream toe was very flat, with a slope estimated at about 1 on 12. The upstream slope was estimated to be about 1 on 7. The base width was from five to eight times as great as would have been used in building a non-overflow rock-fill dam of the same height.

28. Considering the apparent gradation of the materials in the mass, it seemed that seepage water might flow over the upstream impervious mass as over a control weir, then drop sharply and saturate only the lower levels of the downstream portion. Thus, it seemed possible that low to normal flows might pass through the slide mass without overtopping it. Redistribution of fines would be expected, resulting in uneven settlement of the upstream area, but the stability of the downstream portion probably would not be affected. This concern disappeared when later explorations revealed the more uniform distribution of fines throughout the slide mass.

29. An inspection was made of the "lower slide" on the Gros Ventre River near Jackson, Wyoming, for the purpose of comparing the materials with those in the Madison Canyon slide. The Gros Ventre slide occurred in June 1925; in a short time seepage appeared on the face of the dam and soon the normal flow of the river was passing through at a point about 30 feet below the top. About two years later during high spring runoff in May, the top part of the dam suddenly failed, causing a destructive flood. In size and in volume of water stored behind them, the Gros Ventre and Madison Canyon slides were quite similar; in materials, however, the two slides were very dissimilar. The entire fill of the Gros Ventre slide was made up of a mixture of very coarse rock fragments almost floating in semipervious silts and sands. At Madison Canyon, only the upstream portion appeared to contain fines approaching the percentage observed in the Gros Ventre slide. It was concluded, therefore, that the dam in Madison Canyon should not be expected to fail as did the dam in the Gros Ventre River.

30. It was concluded that the spillway alinement should be kept as far to the right as practicable, to avoid undercutting the possibly unstable left abutment, causing uncontrolled scour of the spillway chute. In areas where the surface rock was fine, the floor and left side of the spillway should be lined with heavy rock borrowed from the quartzite ridge high on the north canyon wall. To avoid concentration of flow which might cause scouring, the spillway should be designed to spread the flow in a thin sheet of as nearly uniform depth as practicable.

31. Maps and Surveys. The only available topographic maps of the earthquake area were the AMS Series V794, with contour intervals of 40 to 80 feet, and V504, with contour intervals of 200 and 500 feet. Aerial photographs were obtained from the U. S. Forest Service. The Forest Service also furnished a contour map of the Madison Canyon slide, constructed by Kelsh Plotter from the 1:8000 aerial photographs taken by the Forest Service on 22 August 1959, and a similar preslide contour map compiled from photographs taken in 1957. These maps proved invaluable during the construction. They are reproduced as plates 2 and 3 and were used to construct the cross sections on Plates 4, 5, and 6, and as a base for plates 7 and 8 which show initial and final construction.

32. Preliminary surveys of the slide were started on 23 August, when a preliminary alinement of the spillway was laid out. A level run was completed on 24-25 August, to tie all benchmarks between the mouth of the canyon and Hebgen Dam and place them on a common datum.

33. Hydrology. The initial drawdown of Hebgen Lake to an elevation below the spillway was started on 23 August. With the reservoir about elevation 6542, the discharge was increased from about 1,000 c.f.s. to about 2,200 c.f.s., followed by a further increase to about 2,850 c.f.s. on 26 August. The discharge then was slowly reduced to approximately 2,100 c.f.s. on 4 September then reduced to about 1,300 c.f.s. On 6 September, with the reservoir about elevation 6539, the discharge was reduced to between 700 and 1,000 c.f.s. which was approximately equal to the inflow to the reservoir and maintained the reservoir approximately at that elevation. With the exception of short periods when discharges were changed for repairs or for slide spillway tests, releases were continued at that rate until 19 October. From this date to 23 October, releases were from 2,700 to 3,000 c.f.s. It was then necessary to reduce the flow for a few days for the final stage of spillway construction. On 27 October discharges were increased and regulated by Montana Power Company to draw down the reservoir.

34. A capacity curve for the pool above the slide dam was constructed from the available topographic maps. Assuming that discharge from Hebgen Lake would be held approximately equal to the flow of 26 August, it was possible to estimate the rate at which the storage space

above the slide would be filled and the depth to which it would be possible to excavate the spillway. Thus, the crest of the proposed spillway was set at elevation 6450 and it was estimated initially that the pool would reach that elevation about 4 September. Hebgen discharges were later reduced allowing additional time for preparation of the spillway channel. A continuous check was maintained on the rise of the pool by means of staff gages and inflow measurements at the existing gaging station just below Hebgen Dam. A gaging station was established below the slide to keep a record of flow at that point. Seepage through the slide was measured at that point until 10 September, when flow over the spillway became continuous and seepage was no longer distinguishable. Graphs showing inflow, outflow, elevation, and storage for both Hebgen Reservoir and Earthquake Lake are shown on Plates 9 through 14.

35. Hydraulic Design. A preliminary estimate, based on the record of flows at Hebgen Dam and on other streams in the area, indicated that the spillway should have the capacity to pass a discharge of 10,000 c.f.s. at safe velocities. Hydraulic computations indicated that the channel should be about 250 feet wide, to spread the flow and keep velocities as low as possible.

36. The initial spillway was planned to have an alinement following approximately that of the old river channel. The channel was to be level at elevation 6450 for a distance of about 900 feet upstream from the crest. From the crest downstream the design channel had a slope of five percent for 600 feet, followed by a slope of ten percent for the remaining distance, approximately 1,900 feet, to the toe of the slide. It was felt that this design would provide a spillway that would be stable with the highest discharge that could be reasonably expected. Inspection indicated that the median rock size in the channel with the steepest slope would be from two to three feet and that the maximum rock size would be from three to five feet, which would approximate the depth of flow that would occur with the highest discharges. It was believed that, even with high discharges, the fill would readjust its configuration by a flattening of the crest and an extension of the downstream toe, with some reduction of crest elevation.

37. Equipment. A representative of the Montana Chapter of Associated General Contractors was consulted on 23 August, to determine what construction equipment was available in the area. The A.G.C. was prepared for the emergency; in cooperation with the State Civil Defense Director, they had adopted a disaster plan called "Operation Bulldozer," initiated by the national organization, and the representative had the desired information at hand. On 24 August, two dozers arrived at the slide and started construction of an access road to the top of the slide. The access road was completed by 25 August and equipment rental contracts were being negotiated. By 27 August, 23 dozers were engaged

in rock movement in the spillway, at an estimated rate of 25,000 to 30,000 cubic yards per day. On the same day, two shovels arrived and were being assembled. By the following day, three shovels and eight end-dump trucks also were in operation. At the peak of activity, about mid-September, equipment working on the job included 27 dozers, 5 shovels, 29 end-dump trucks, 3 end-loaders, 1 patrol grader, 2 truck cranes, 5 light plants, 1 dragline, 1 water truck, 1 tractor-mounted drill, and one compressor, drill, and blasting outfit. A total force of 190 operators, oilers, foremen, and mechanics was required to keep the equipment in operation. Photos 3 and 4 show various pieces of the construction equipment in operation. Draglines brought in later show in photos 13, 21 and 22.

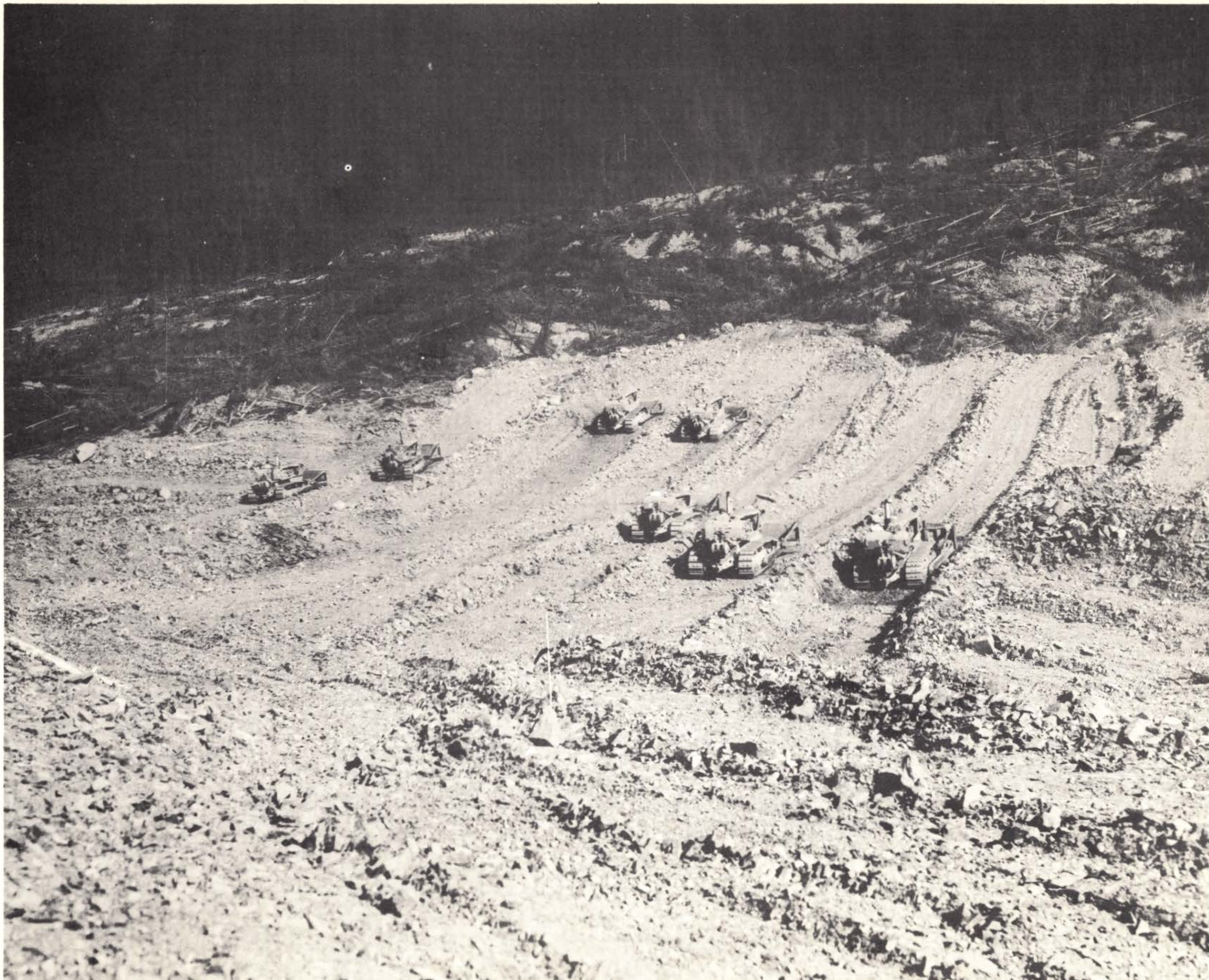


Photo 3. 27 August 1959. Bulldozers grading slide crest.

Photo 4. 28 August 1959. Equipment constructing initial spillway.

Photo 5. 3 September 1959. Aerial view of initial spillway construction.

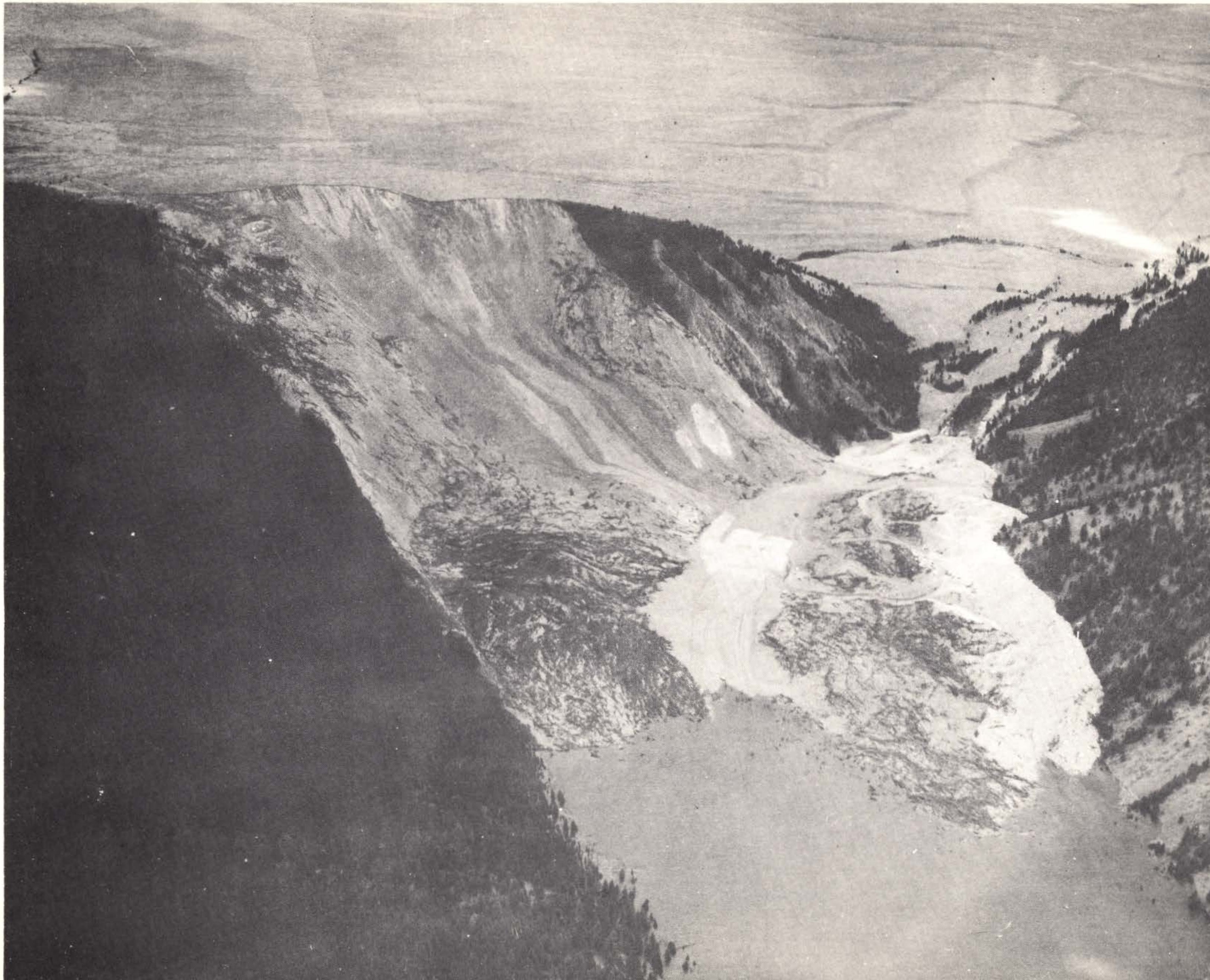


Photo 6. 3 September 1959. Over-all aerial view looking downstream showing initial spillway construction and a view of the slide scar.

Photo 7. 4 September 1959. Placing spillway armor material in channel.

Photo 8. 10 September 1959. Upstream aerial view of spillway channel on first day water passed over slide.

Photo 9. 11 September 1959. Downstream aerial view of water passing over slide in spillway channel.

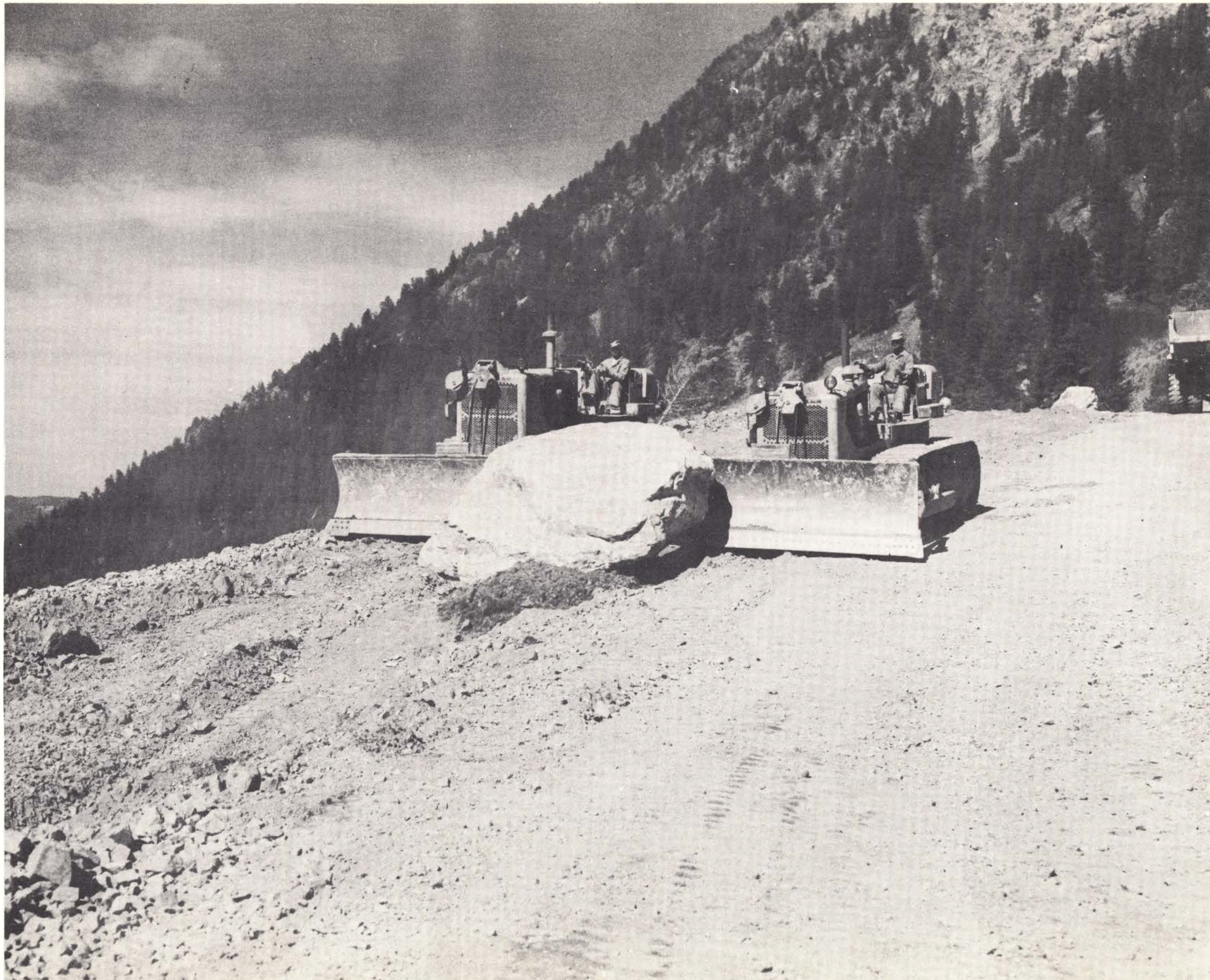


Photo 10. 11 September 1959. Two bulldozers pushing large rock.

Photo 11. 16 September 1959. Tractor pulling large rock on rock sled.

38. Contracts for equipment used on the project were negotiated on the basis of hourly rental rates, to include plant operators, supplies, and the necessary service personnel and equipment. Arrangements for hire of equipment, including rental rates were negotiated with Mr. J. W. Marlow, Secretary-Manager, and Mr. F. L. Oliver, member of the Board of Directors, Montana Chapter A.G.C. Payment for mobilization and demobilization was determined on the basis of actual costs for rail shipment, $1.50 per load mile plus actual assembly and disassembly costs for truck transport, and 75 percent of the regular hourly rate for travel of self-propelled equipment. The negotiated hourly plant rental rates were as follows:

ITEM		RATE PER HOUR
1.	Tractor, crawler w/dozer and power control attachment, Model A-D-8, Z U series	$ 19.50
2.	Tractor, crawler w/dozer and power control attachments, B-D-8 Series 13A through 15A	23.00
3.	Tractor, crawler w/dozer and power control attachments C Model D-9	25.50
4.	Shovel, crawler, w/2-yd. bucket	32.00
5.	Shovel, crawler, w/2-1/2-yd. bucket	35.00
6.	Shovel, crawler, w/3-yd. bucket	38.00
7.	Truck, Diesel End Dump 13.5-16 cu. yd. (22 ton)	20.00
8.	Truck, butane, end dump, 16-18-cu. yd. (26 ton)	23.00
9.	Motor Patrol, Caterpillar Model 14	14.00
10.	Loader (shovel) Tractor, crawler type, 2-1/2 cu. yd.	14.00
11.	Water truck, 38,000-gal. capacity w/pump	12.00
12.	Generator, light plant	
	A. 5 kw	2.50
	B. 150 kw	14.00

ITEM (Cont'd)	RATE PER HOUR
13. Draglines, crawler	
A. 4-cu. yd., 87-ft. boom	$ 38.00
B. 6-cu. yd., 120-ft. boom	48.00
14. Loaders, front end, rubber-tired, Michigan	
A. 4-yd.	33.00
B. 6-yd.	36.00
15. Cranes, lifting, truck-mounted w/2 choker setter each crane, 20-ft. boom	
A. 25-ton	33.00
B. 30-ton	37.00
16. Drill "cat," consisting of D-8 "cat" tractor, 600 c.f.m. compressor and "cat" mounted drill	36.00
17. Drilling and blasting outfit	
A. Compressor	3.50
B. Pneumatic Drill	1.50
C. Air hose, couplings & drill steel	3.00
D. Pickup truck	3.00
E. Powder Man (salary)	3.70 (with overtime)
F. Driller	3.60 (with overtime)
G. Insurance	2.70
H. Mobilization & demobilization	1.50
Total	$ 22.50

Total hours worked by the various types of equipment are shown in the following tabulation:

EQUIPMENT	HOURS
Dozers	21,737
Dump Trucks	21,195
Shovels	4,729
Draglines	1,355
Motor Patrol	1,193
Water Truck	663
End Loaders	1,352
Cranes, Truck-Mounted	239
Drillcat	45
Blasting Unit	371
Light Plants	2,780
Total	55,659

39. Construction. The construction work on the slide can be divided into three phases. The initial phase covered the period from 22 August, when the West Yellowstone project office was established, to 10 September, when flow over the spillway first took place. The second phase extended from 10 to 25 September and constituted a period of holding and maintenance, when all efforts were directed to preventing gullying and uncontrolled erosion in the spillway channel. The third and final phase began on 25 September, when the work of lowering the spillway crest was started, and lasted until 30 October, when activities came to an end.

40. Initial Spillway. In the first phase of spillway construction, the channel was excavated to a crest elevation of 6450, with a bottom width of 250 feet, and the left side and part of the downstream slope was lined with the best material that would be found in the slide. The white rock showing in Photos 5, 6 and 7 is the more competent Dolomite rock placed as channel lining. The excavation in the crest area was almost entirely a bulldozer operation. The upstream ridge, which was the highest of a series of ridges across the saddle, was cut off and the material pushed to the upstream slope. To minimize the possibility of losing control of the crest by an upstream slide, a large pocket just downstream from this ridge and about 50 feet lower in elevation was filled to an elevation about 20 feet below design crest elevation with the relatively fine material dozed from the ridges. The top 20 feet was filled with heavy quartzite borrowed from the layer on the right canyon wall.

41. To protect the spillway from scour, the bottom was armored with quartzite, to a depth of seven to ten feet, from station 26+00 downstream to station 12+00. There was not sufficient time before overflow occurred either to fill the reach downstream from station 12+00 to a ten percent slope or to armor it. The material in that reach seemed from observation to consist of very large rock and it was considered the least likely to be unstable. Due to the limited time available it was left at its original slope of approximately 14 percent. The sides of the channel also were lined with quartzite and a dike of the same material was constructed along the left side at the downstream end of the channel to deflect the current and prevent undercutting of the left abutment.

42. By the end of August, the level crest of the spillway was essentially completed to finish grade and most of the dozers were working on the downstream slope. Shovels and trucks were used to move some of the material, particularly along the right side of the channel at the crest. Typical views of these operations are shown in Photographs 3 and 4.

43. As soon as the excavation of the level crest portion was completed, shovels and trucks were put to work placing the lining, or armor. Rock was obtained from selected locations in the dolomite and quartzite ridge along the north side of the slide, where the best materials appeared on the surface. One source was located high on the south slope of the ridge about opposite the spillway crest, another at the toe of the ridge near the downstream end of the slide. The material was taken as it came, since there was no time for selection or grading. Filling above the shaped subgrade started about Station 25+50, holding the surface level to about Station 24+00, then following the spillway slope with thickness varying from 7 to 10 feet. The fill was continued to a depth of ten feet above the excavated channel grade to form a working berm and the placing of the rock armor was continued downstream by dumping from the berm and spreading with bulldozers. In sequence, first priority was given to the lip or crest of the spillway, second to the left side of the channel, and third to the downstream slope of the channel below the crest.

44. During this phase of construction, the flow of seepage water through the slide increased slowly to a maximum estimated at about 170 c.f.s. Water rose in Earthquake Lake, upstream from the slide, and began flowing over the spillway crest on the morning of 10 September. However, the overflow continued to pass into the pervious slide mass and it was not until 1 p.m. on that date that a continuous sheet of water was flowing over the crest and down the spillway channel to the riverbed below.

45. It was planned that the spillway would be watched closely for a few days, gradually increasing the flow by permitting higher discharges from Hebgen Lake, until the stability of the spillway channel could be determined. However, the flowing water soon began to remove the finer slide materials, particularly in the reach downstream from Station 12+00, where a deep gully formed and moved upstream threatening the entire spillway.

46. Maintenance of Initial Spillway. In the second phase, large quantities of quartzite and dolomite were hauled from the ridge along the north side of the slide and placed at critical locations in the channel in an attempt to stop the erosion and hold the channel in place. The largest rocks available were used for this purpose. Many single rocks made a truckload each. Many of the largest rocks were dug out of the slide and pushed down the steep slopes by dozers, two dozers frequently being required to move one rock. Some of the largest rocks were broken by drilling and blasting with dynamite. Two steel rock sleds were designed and constructed to move some of the largest rocks. Single rocks with weights estimated as high as 100 tons were moved on the sleds. Two or three tractors were required to move the sleds. Details of construction of the sleds are shown on Plate 18. Finally, a number of rock weirs or terraces were constructed all the way across the spillway channel, see Photo 14. The maximum effort of the entire operation was expended in this phase, when the amount of equipment and the number of personnel on the job reached their peak.

Photo 12. 16 September 1959. Aerial view of slide and spillway.

Photo 13. 16 September 1959. Foundation excavation for first rock filled drop structure at about Station 6+00.

Photo 14. 22 September 1959. Aerial view of slide showing water pouring over rock terraces.

47. For travel from West Yellowstone to the slide area, the only road open was by U. S. Highways No. 20 and 191 over Targhee Pass on the continental divide into Idaho, then northwest on an unimproved road over Raynolds Pass back into Montana and the Madison River Valley, to Montana Highway 287 below the slide. Since this unimproved road could become practically impassable in bad weather, the project office was moved on 20 and 21 September to Ennis, Montana, located on Highway 287, a paved road leading directly to the project.

48. It was learned that the quantities of large quartzite and dolomite rocks in the north ridge of the slide were not unlimited, as had appeared on the surface. Rather, much of the material was shattered and ground into very fine particles, including a great amount of actual dust. Many of the large, apparently solid rocks broke apart when attempts were made to move or load them. Some of the large rocks were prepared for handling by being drilled and fitted with rock pins and slings, but many fell apart when lifting was attempted.

49. Serious consideration was given at this time to obtaining durable rock from suitable quarry sites in the mountains nearby, in quantities sufficient to construct two or three permanent rock drop structures, with rock stilling basins, to stop the continued erosion of the spillway, which several times threatened to get out of control. Obviously, such a plan would be both time-consuming and costly, and it was discarded in favor of a plan to lower the spillway and reduce the storage in Earthquake Lake. Foundation excavation for part of the first drop structure is shown in Photo 13.

50. Board of Consultants. Because of the unusual character of the project and the many unique problems involved, a board of consultants, composed of engineers, and specialists eminent in their fields, was appointed, to review the work accomplished and to advise on further investigations or additional remedial work necessary. The board was composed of a soils engineer, Dr. Arthur Casagrande, Harvard University; a hydraulic engineer, Dr. L. G. Straub, University of Minnesota; a geologist, Mr. E. B. Burwell, Upperville, Virginia; and an expert on rock-fill dams, Mr. I. C. Steele, Oakland, California. The decision to appoint a board of consultants was made early in September, before the initial phase of spillway construction had been completed and before flow over the spillway took place. Prior commitments made it impossible for any of the members to visit the project at that time and a formal meeting of the board could not be arranged until late in October. The individual consultants were able to visit the project at intervals and to advise on plans and procedures.

51. Dr. Casagrande and Mr. Steele visited the project office on 18 September, inspected the slide and spillway, and made recommendations for further work. They felt that it would be necessary to lower the spillway crest in order to avoid continued maintenance expense. Dr. Casagrande suggested that the crest be breached by excavation of a pilot channel and permitted to erode. He thought the rate of erosion would not be too high, and did not think it necessary to control erosion above Station 11+00, since he felt it would proceed too slowly to be harmful. In fact, he felt that considerable work might be required to assist the water in cutting the channel deep enough. He estimated that erosion would cease when the slope of the channel reached about four percent, which would lower the crest about 50 feet.

52. Mr. Steele agreed with Dr. Casagrande in his belief that it would be safe to permit the excavation of a channel by erosion, but thought a small pilot channel should be tried as an experiment, so that complete control could be retained at all times. Dr. Casagrande suggested that attempts to lower the spillway by erosion be delayed until Dr. Straub could visit the project and furnish his advice.

53. Dr. Straub and Mr. Burwell visited the project on 24-25 September. They agreed with Dr. Casagrande and Mr. Steele that the spillway crest should be lowered. Dr. Straub recommended that a pilot channel about 50 feet wide be excavated in the center of the spillway, with enough slope to induce erosion. He recommended a cofferdam at the upstream end and along the left side of the pilot channel, to prevent flow over the sides from carrying material into the channel as rapidly as it was excavated.

54. Lowering the Spillway. Computations showed that, if the spillway crest could be lowered by about 50 feet, the volume of water remaining in storage would not be sufficient to cause a really disastrous flood downstream, even with rapid failure of the remaining slide dam. The third and final phase of construction was started on 25 September, when tractors with dozers and rippers were put to work loosening the material on the crest, to see if it would be carried downstream by the flowing water. It was found that the velocity of flow was not high enough to move any but the very fine material and that other means would have to be found to move any substantial quantities of rock.

55. Following this trial, draglines were used to excavate a channel about 50 feet wide, beginning with the terrace between Stations 20+00 and 21+00, with an average slope of about 1.5 percent upstream to the channel entrance about Station 34+00. Material was stockpiled at strategic points so that an emergency cofferdam or plug could be constructed if erosion showed signs of progressing too rapidly. This was a modification of the plan suggested by Dr. Straub.

56. Two draglines started working in the pilot channel. The material which had been placed as armor was stockpiled and the schist and gneiss was cast aside or hauled to waste areas. It was found that much of the material was too large to be handled by the 3-cubic yard and 2-1/2-cubic yard draglines already on the job and it was necessary to obtain one of greater capacity. A dragline of 6-cubic yard capacity was brought in and assembled and started working on 4 October.

57. Dr. Straub visited the project again from 30 September to 2 October. At his suggestion, discharge from Hebgen Lake was increased to 2,600 c.f.s. on 1 October, to assist in scouring the channel over the spillway crest. With the additional flow and higher velocities rapid erosion of slide material developed and the spillway structure below Station 18+00 was bypassed, the channel moving about 200 feet to the north and dropping more than 40 feet. The finer slide material in that area was eroded rapidly and on 3 October an access road high on the slide was lost, see Photo 17. A new road was constructed along the mountain side to the top of the slide on the north side of the valley. By concentrating on stopping head-cutting and diverting flow back over the former spillway, control was regained by 6 October and possible disastrous discharge from the lake was prevented.

58. Lowering of the spillway crest proceeded according to plan. Starting at the spillway entrance and working from a berm just above the water surface along the right side of the channel, the 6-cubic yard dragline moved downstream, making a cut about 50 feet in width and 10 feet or more in depth. Approximately the last 50 feet at the downstream end of each cut, which constituted a broadcrested control weir, was degraded cautiously to prevent a sudden release of the stored water behind it. After this weir or plug was cut down to the elevation of the channel above it, the dragline returned to the channel entrance and started another cycle. The excavated material was loaded into trucks and hauled to waste areas. Meanwhile, the other draglines were working along the channel downstream from the crest, removing the larger rocks and assisting the flowing water to erode the channel and carry the material downstream. Shovels and trucks, working in teams behind the draglines, cut down the working berms progressively, so that the draglines were always working just above the water.

59. As the spillway crest was lowered, the control terraces which had been constructed in the channel were breached progressively, working downstream from the terrace at Station 23+00. Bulldozers were used to breach the terraces, pushing the large rocks to either side and permitting the resulting concentrated flow to remove the finer materials. It was found that a slope of 1.5 percent was not steep enough and that at least 3.0 percent was required for appreciable hydraulic removal. When that slope was obtained, degradation of the channel proceeded as rapidly as the controlling crest could be lowered by mechanical means. Some of the largest rocks in the terraces, which had been moved to the channel by means of the sleds, could not be moved by the draglines. These rocks were broken by drilling and blasting, as they could be removed and the lowering process continued.

60. Large portions of the slide which showed now in the channel walls appeared to have moved in mass, with little breaking in the process. The rocks, mostly schistose, were still relatively in their original positions, although there was considerable cracking. Such a mass of rock was encountered on the crest of the spillway, in the vicinity of stations 28+00 to 29+00. This formation was almost completely resistant to erosion and was excavated only with considerable difficulty by the large dragline. During a large part of the time, this resistant zone effectively controlled the rate at which the spillway was lowered.

61. It was impossible to determine elevations in the spillway channel, because of the high velocity of the water and the constantly changing channel bottom under the action of the flowing water. Progress was measured by obtaining elevations of the water surface along the channel and by observing the receding stages of Earthquake Lake. Work continued until the lake had dropped to elevation 6400. Rough soundings indicated that the spillway crest had been excavated approximately to elevation 6392. Profiles of the water surface at intervals of about one week are shown on plate 8. After the desired depth had been reached, the channel was widened where necessary to about 70 feet. The berm about 100 feet wide along the north side of the channel would provide additional channel capacity for high flows.

62. Aggradation. Throughout the period when water was flowing over the spillway, the erosion of slide material varied from day to day. Although some of the very fine material remained in suspension, most of it was deposited in the river channel below the slide. The formation of this delta or fan was a necessary part of the process by which the spillway channel was eroded in the slide. When the emergency work was ended, the channel across the slide and the fan had reached an average slope of about three percent, which appeared to be a relatively stable slope for the current combination of channel bottom materials and a discharge of about 3,000 c.f.s.

63. Consultants meeting. Periodic reports were furnished the members of the Board of Consultants, to keep them advised of conditions and the progress being made in lowering the spillway crest. The Board held their only formal meeting in the Ennis project office on 29 October, with all members present except Dr. Casagrande. After a final inspection of the slide and spillway and a review of the work accomplished and the data collected, the consultants, both singly and as a board, concluded that the serious flood threat had been removed and the mission of the Corps of Engineers had been accomplished.

Photo 15. 29 September 1959. Starting to lower the spillway channel near the outlet of Earthquake Lake.

Photo 16. 5 October 1959. General view of spillway lowering operation. Draglines are working in channel and shovels are maintaining a work berm.

Photo 17. 5 October 1959. Rapid erosion of right bank between Stations 11+00 and 15+00.

Photo 18. 7 October 1959. First in a series of three photographs showing rapid development of the fan below the slide.

Photo 19. 9 October 1959. View showing rapid development of fan and damage to access road.

Photo 20. 11 October 1959. View showing rapid development of fan.

Photo 21. 11 October 1959. Large dragline lowering spillway channel near the outlet of Earthquake Lake.

Photo 23. 17 October 1959. Aerial view of slide looking downstream.

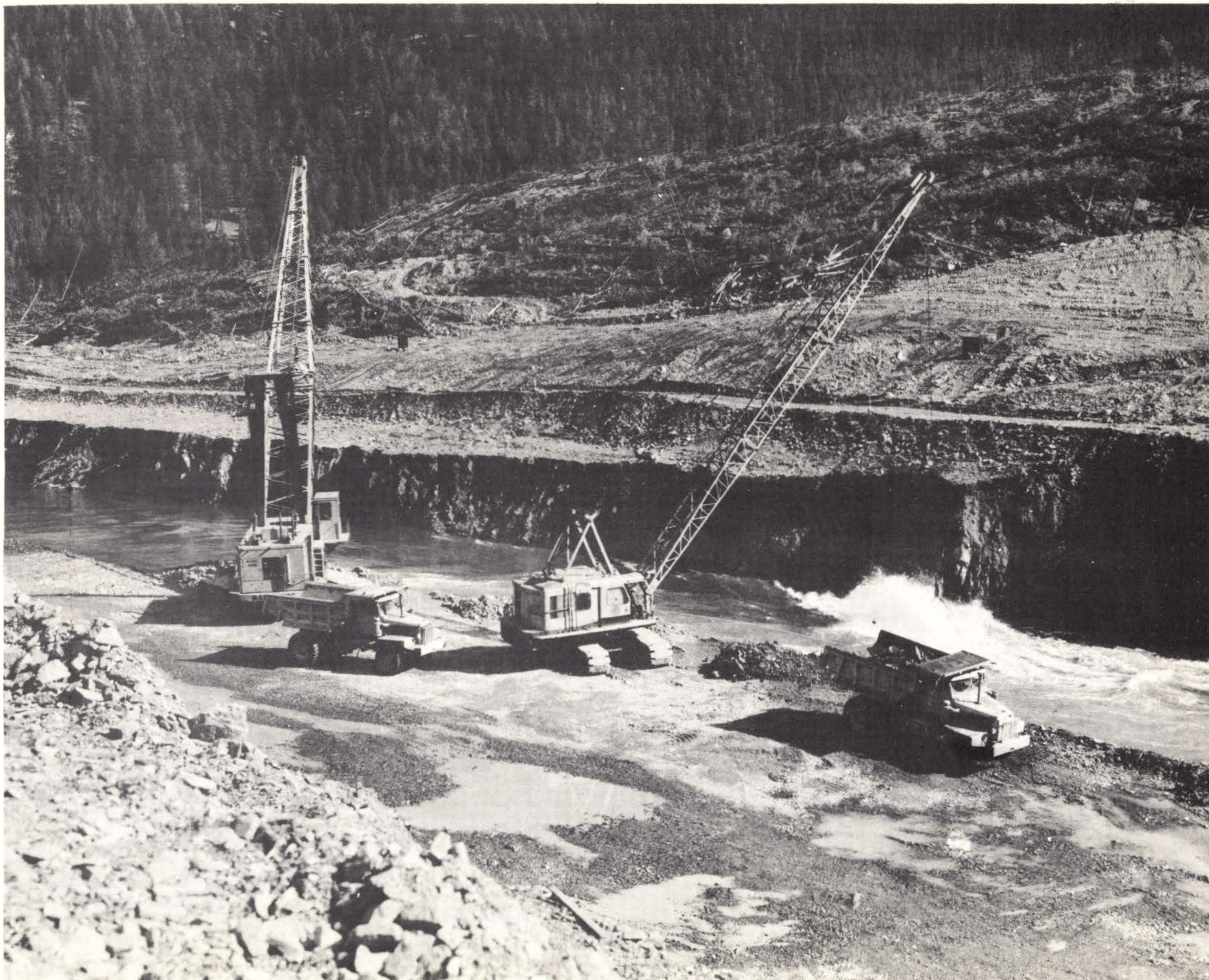


Photo 22. 14 October 1959. Draglines lowering spillway channel near Station 31+00.

Photo 24. 17 October 1959. Aerial view of slide looking downstream showing spillway channel and buildup of fan below the slide.

Photo 25. 29 October 1959. Completed spillway entrance looking upstream from about Station 30+00. Note high water line on trees about 50 feet above Earthquake Lake.

Photo 26. 29 October 1959. Completed spillway looking downstream from about Station 30+00.

Photo 27. 28 October 1959. View of fan at lower end of slide at end of construction period (for earlier view, see Photo 2).

64. The concluding comments in the final report of the Board of Consultants stated that the mission of the Corps of Engineers had been accomplished and included the following points listed here in brief form:

a. An acceptable factor of safety against failure or rapid erosion which could cause serious flooding has been provided by lowering the capacity of Earthquake Lake and by reducing the gradient of the spillway channel.

b. It is recognized that lateral erosion and shifting of the channel will occur and may induce slides of inconsequential magnitude.

c. In general, vertical erosion at the crest and in the upper approaches of the channel is expected to be slow due to the resistant character of the channel bottom.

d. There is severely cracked and disturbed material south of the slide near the upper part of the slide scar. It appears unlikely that a slide of sufficient magnitude to cause serious blockage of the spillway channel will occur unless it is subjected to further severe seismic action.

e. The high cliffs north of the slide appear stable and no danger of slides from this source is seen.

f. A yearly survey of the channel on the slide and downstream from the slide in the aggradation reach is recommended in order to observe and record further developments.

The complete final report of the Board of Consultants is included as Appendix XII.

65. Working hours. For the first few days, work on the slide spillway was carried on only during the daylight hours. Equipment operators at first were reluctant to work at night, even with flood lights. Due to the emergency, however, round-the-clock operation was essential and on 1 September contractors began working two shifts of 10 hours each. By that time, four light plants were in use. Three days later another plant was put in operation and night lighting was considered adequate. On 6 September the shifts were increased to 11 hours each, which was the maximum practicable, the remaining time being required for servicing and lunch periods.

66. Materials and stability investigations. Time would not permit more than the preliminary investigations described earlier in this report, before actual spillway construction was started. As soon as possible, however, a drilling program was started, to install piezometers and to obtain information on materials in and

under the slide. Drilling was started on 3 September, using a churn drill with a drive barrel, so that samples of materials could be recovered. Rock bits were used occasionally, but only when necessary, since their use permitted the recovery of samples only by bailing the mud sludge at the bottom of the holes. In all, six piezometers were installed along the right side of the spillway, though not all were observed concurrently. The locations and observation records of the piezometers are shown on plate 15. Full details of drilling are contained in Appendix X. In general, the observations showed that early conclusions drawn from surface inspections were in error. The earth and rock-floor fines were distributed throughout the major portion of the slide mass. Note material shown in photographs numbers 11 and 17.

67. Test holes. After the spillway lowering operation was started, three shallow test holes were drilled near the upstream part of the spillway channel. The rock formation was found to be continuous and apparently consisting of a mass of schist and gneiss which was fractured but not disturbed otherwise. The information obtained from these test holes indicated that a resistant rock formation extended at least to elevation 6380 at the location of the spillway channel. Locations of the test drill holes and data on materials encountered are shown on plate 16.

68. Materials in channel. As the lowering of the spillway progressed the exposed banks and slopes were studied in detail. Sketches and photographs were made, as well as record notes of the types of materials exposed. From this information, a generalized geologic drawing was made showing the rock formations encountered in the spillway excavation. The generalized geologic drawing is shown on plate 16; additional photographs of the chute walls are included in Appendix X.

69. Movement surveys. A system of check points was established on the slide, designed to detect any noticeable movement, either vertically or horizontally. The points were established on a reference line extending across the slide from downstream toe to upstream end, but crossing the spillway channel at an angle, so that any major movement would show up as transverse movement. Elevations of the points were established and distances between them were measured. The system was checked periodically for movement. The arrangement of the check system and results of measurements are shown on plate 17. Maximum transverse movement during the period 7 September to 23 October was approximately one-half foot, which was considered not excessive.

70. Summary of explorations. Information obtained from subsurface explorations indicated that the slide contained more fine material than was apparent on the surface. Most of the rock near the spillway was schist and gneiss, which could be penetrated by a

churn drill using a drive barrel for sampling. Much of the rock had weathered along joint planes to the point where it shattered upon impact. The upstream one-fourth of the spillway was located in massive schist and gneiss which was fractured but otherwise undisturbed and was fairly resistant to erosion by water. The lower portion contained much fine material susceptible to erosion, but also contained many large rocks which served to protect the channel after the fines were removed. The slide material was generally pervious or free-draining. No unusual settlement or transverse movement was observed.

71. Possible additional slides. Safety of the people working on the slide being of paramount importance, extensive studies were made of conditions along the crest of the slide scar and on the slide mass itself, to estimate the probability of additional slides that would endanger personnel or block the spillway channel. Visible cracks behind the crest of the slide ridge showed that two areas held a potential for movement. Sets of strain gages, consisting of pipes driven into the surface and tied together with wires, were installed across these cracked and displaced areas. Distances between the pipes were measured at frequent intervals to detect possible movement. Some of the wires were fitted with flag markers to permit airborne observers to detect any significant movement. Readings of the strain gages and aerial observations during the period from 29 and 30 August, when they were installed, to 19 September indicated that no significant movement had occurred.

72. A prominent rock pinnacle on the north wall of the canyon also was investigated for possible danger of sliding. It was found that the bedding dipped into the mountain, rather than toward the valley, which meant that the pinnacle was stable.

73. Details of the investigations, together with tabulations of results of observations and gage readings, are contained in Appendix IX.

74. Communications. Immediately after the project office was established, a radio communications network was put in operation. A mobile emergency unit, which had been procured by the Garrison District for use in flood emergencies, was installed in the project office as a control station. This unit consisted of a 100-watt AM transmitter and receiver operating on 5,400 KC, used for communication with the District Office at Riverdale, North Dakota, and a 50-watt FM transmitter-receiver operating on 38.9 mc. for local communication. A similar 50-watt FM unit was installed at Hebgen Dam. A 12-watt transmitter-receiver unit was installed in the office trailer on the slide and a similar unit in a trailer parked below the slide. Several cars and pickups were equipped with radio and several portable sets were in use. All this mobile equipment operated

on a frequency of 38.9 mc. Later, an automatic relay station was installed on Missouri Flats about five miles west of the slide, operating on frequencies of 38.9 mc. and 163.425 mc. To complete the relay, another 50-watt transmitter-receiver unit was installed in the project office, this one using the 163.425 mc. frequency. Thus, radio communication was possible between all units on the project, either direct on the high band or through the relay on the low band. Also stationed just below the slide was a vehicle with both 38.9 mc. and 163.425 mc. transmitter-receivers, for use in case the automatic relay station should become inoperative. If necessary, this vehicle could be moved down the valley and operated as a control station.

75. Emergency warning system. Soon after the establishment of the project office in West Yellowstone, an emergency warning system was evolved to warn the residents of the Madison River valley below the slide, as well as the workers on the slide, in the event failure of the slide should seem imminent. The warning system was based upon the radio communications network.

76. At least one qualified engineer was stationed on the slide at all times. His primary responsibility was the evaluation of the stability of the slide. Gages in the lake at the spillway entrance and at the toe of the slide were read each half-hour. Discharge measurements were made at the gaging station below the slide. All gage readings and discharge measurements were reported immediately to the project office and to the trailer on the slide, so that the engineer on duty could have at all times a current evaluation of conditions that might affect slide stability. When the gaging station below the slide became inoperative because of aggradation, a gage was installed at the Cliff Lake bridge about three miles downstream and a gage and cableway at the Kirby bridge about nine miles below the slide. Readings were taken at these points after 4 October and reported as before. Continual discharge measurements were made at the Kirby Bridge station, with a maximum of nine measurements per day.

77. An emergency warning stage was marked with reflectorized tape on the staff gage just below the toe of the slide, so that it could be read easily at all times. Two radio-equipped cars, supplied with electric megaphones, one with amplifiers, were stationed below the slide. Also, a telephone was installed at that station.

78. Montana Power Company kept a watchman on duty at all times at Hebgen Dam, where telephone service was maintained, as well as radio equipment for communication with a Civil Defense station on Missouri Flats.

79. An emergency warning was to be put in operation on the order of the engineer on duty at the slide, if and when in his judgement failure of the slide was imminent and evacuation of the slide and

downstream areas was desirable. A smoke flare gun was kept at the slide to signal workers to evacuate the slide area. The personnel stationed below the slide would inform the Civil Defense unit on Missouri Flats by radio. That station would notify the Sheriff's office in Virginia City, who, in turn, would notify the city police in Ennis. The Sheriff or a deputy was stationed most of the time at a roadblock about three miles below the slide or at the Civil Defense station on Missouri Flats. The Sheriff's office assumed responsibility for warning residents in the valley. Corps employees with the radio-equipped cars below the slide would assist the Sheriff's forces in that effort.

80. Hydrologic reports. Throughout the entire period of spillway construction, information on discharges and gage heights was collected continuously and reported to the slide and to the project office, so the current information was always available to all concerned. Twice a day, or more frequently when changes were made, information on elevation and discharge from Hebgen Lake was received from Montana Power Company. The gage readings that were made and reported initially as part of the emergency warning system were continued and expanded when the spillway lowering was started. Initially, stages at the toe of the slide were included in the reports. Aggradation forced the abandonment of that gage and another was installed one-half mile farther downstream. Cableways were installed at both points for making discharge measurements. When continued aggradation rendered the second gaging station inoperative, a gage was installed on the Cliff Lake bridge and a gage and cableway were installed near the Kirby Ranch bridge. After 4 October all measurements of outflow from Earthquake Lake were made at the latter station. Prior to 26 September, measurements were made as necessary to maintain a good rating curve; beginning on that date, when the work of lowering the spillway was getting underway, the frequency of discharge measurements was increased to from six to eight per day.

81. Hydraulic studies. Numerous hydraulic studies and computations were made during the progress of the emergency work. Computations were made of probable velocities and depths in the initial channel. For ready reference, charts were prepared showing the computed velocities and depths along the channel, as well as the required sizes and weights of rock, taken from chart WES 712-1, published by the Waterways Experiment Station. The chart is shown on plate 20. To check the relationships, approximate measurements were made of depth, velocity, and rock size in the channel. Because of high velocities and turbulence and the lack of proper instruments, exact measurements were not possible; however, the measurements showed reasonable agreement with the Isbash curves shown on the chart.

82. When the lowering of the crest was started, computations were made and charts were prepared showing the relationships between such factors as discharge, channel width, depth of cut, and time. These charts were used to guide the engineers on the job in analyzing conditions and achieving the highest possible rate of progress, at the same time keeping the rate of erosion under control. One of the charts, used to estimate

the desirable depth of cut across the control weir at the spillway crest, is shown on plate 21. A detailed description of these and other hydraulic studies and computations, as well as the charts prepared from them, are included as Appendix XIII.

83. Real Estate. The slide area and the activities of the Corps of Engineers in connection with the construction of the spillway over the slide were on Government-owned land in the Hebgen Lake District of the Gallatin National Forest. The Forest Supervisor issued a Special Use Permit for the activities of the Corps of Engineers in the earthquake area.

84. Right-of-entry on lands included in or occupied by the Hebgen Dam and Reservoir project was granted by Montana Power Company, to make surveys and test borings and carry out other exploratory work that might be necessary to complete investigations in connection with the earthquake project.

85. Office space in West Yellowstone and Ennis was occupied under right-of-entry occupancy and use permits granted by the respective owners.

86. When it appeared that additional rock might be required for construction of control terraces or drop structures in the spillway channel a permit or right-of-entry was granted by the owners of private land adjoining the Gallatin National Forest, for construction of an access road to haul rock across their property. Since it was decided that the spillway should be lowered, the additional rock was not needed and the right-of-entry on private lands was not exercised.

87. Log boom. The filling of Earthquake Lake created quite a debris problem. In addition to the natural debris in the canyon and that created by the earthquake, a number of cabins were floated from their foundations and were adrift in the lake. While removal of the debris from the lake was not within the emergency authority conferred by Public Law 99, it was possible for such drift to enter the spillway channel and interfere seriously with the construction operations. To prevent such an occurrence, a log boom was constructed across the approach to the channel. The boom was constructed of logs salvaged from the timber covering much of the slide, made fast to a 3/4-inch wire rope by means of eye-bolts and cable clamps near the ends of the logs. The boom, about 800 feet long, was anchored by wire rope bridles to deadmen constructed of several logs buried in the schistose slide material. The log boom was removed when the spillway lowering phase was started, since most debris was deposited above lake elevation as it dropped.

88. Personnel. Activities of the Corps of Engineers were under the direct supervision of Lt. Col. Walter W. Hogrefe, District Engineer, with Mr. H. F. Michel as Chief Engineer and Mr. H. G. Hutchins in charge of construction. At the peak of activity, the project office staff included a maximum of 72 persons, composed of 54 career employees and 18 temporary employees hired locally for the emergency. Construction forces consisted of nine men on each of the

two 11-1/2-hour shifts and a survey party of three men on the day shift. Engineering forces consisted of 21 men, including engineers, surveyors, stream gagers, and a drill crew, for the most part working in three eight-hour shifts. The rest were engaged in administrative, supply, communications, transportation, and technical liaison activities. A total of 81 Corps of Engineers career employees saw duty on the project, including 49 from Garrison District, six from Omaha District, nine from Kansas City District, 14 from Missouri River Division, and three from the Office, Chief of Engineers.

89. Reports and public information. Two daily telegraphic reports were dispatched from the project office throughout the period of the emergency. A brief report on the current status of the emergency was dispatched each morning addressed to the Chief of Engineers, Division Engineer, Headquarters Sixth Army, Northern Sector Sixth Army, Regional Director OCDM, and Disaster Service, Red Cross. A more detailed operations report was dispatched each afternoon to the Chief of Engineers and the Division Engineer. Additional special reports were made to higher authority as requested, covering specific phases of the work. Special progress reports were furnished as necessary to the members of the Board of Consultants, the Forest Service, and the State Engineer of Montana, to keep them advised of progress on the work. Copies of the daily reports also were furnished the Forest Service.

90. Constant liaison was maintained with news services, including newspaper and magazine publishers and radio and television stations. Periodic press releases were made as necessary to keep the public informed of progress in removing the flood threat. Facilities were made available to writers for both technical and news magazines, to assist them in obtaining the information they needed, including photographs for proposed articles on the project. Corps representatives granted numerous interviews for use on radio and television programs. Governor J. Hugo Aronson and other state officials participated in a ceremony on 10 September, when water from Earthquake Lake first passed over the slide spillway; the event was covered by radio and television teams, as well as news services and regional newspapers. On 29 October, immediately preceding the meeting of the Board of Consultants, General Barney, Lt. Col. Hogrefe, and the members of the board participated in a program recorded for television.

91. A photographic record was made of all phases of the work, both on the ground and from the air. This record included about 500 still photographs in black and white, about 200 color slides in 35 mm. size, and about 4,000 feet of 16 mm. movie film.

92. Cooperation of other agencies. Since the slide occurred on land included within the Gallatin National Forest, the United States Forest Service had a deep interest in the emergency work. The rescue work immediately following the earthquake was carried out by the Forest Service, and the rehabilitation of the area for purposes of public recreation also would be the responsibility of that agency. The facilities of the Service were made available to the Corps from the beginning, including the prints of aerial photographs of the area taken

on 22 August 1959, as well as earlier photographs to be used for purposes of comparison. Contour maps showing elevations before and after the slide also were furnished by the Forest Service. Constant liaison and frequent discussions and correspondence served to keep the Corps of Engineers and the Forest Service advised of each other's plans and needs. Right-of-entry was issued to the Corps for necessary activities on lands under the administration of the Forest Service.

93. The U. S. Geological Survey assisted in the emergency work by furnishing advice, personnel, and equipment for stream gaging. The Survey established gages on the major streams tributary to Hebgen Lake and Earthquake Lake and on the Madison River below the slide and made frequent measurements of streamflow at those points sufficient to establish and maintain rating curves. The cableways for making measurements were planned and installed by the Geological Survey and measurements were made by that agency's personnel until the frequency of measurements was increased, when the lowering of the spillway was started, beyond the capacity of the limited number of available employees. Geological Survey personnel continued the work of stream gaging until they could be replaced by Corps employees.

94. The initial emergency warning system involved cooperation with the Montana Highway Department, the Sheriff of Madison County, the Forest Service, the local Civil Defense organization, and the Montana Power Company. Liaison was maintained with the Highway Department regarding the use of roads and bridges. The Sheriff's forces maintained a roadblock a few miles below the slide, to prevent visitors from entering dangerous areas and interfering with the work. The roadblock was abandoned after the spillway lowering process got underway and the flood threat began to diminish.

95. Montana Power Company was intensely interested in the emergency work, because of the need to draw down the storage in Hebgen Lake so that any needed repairs to the dam could be made. Company forces were kept ready at all times to increase or decrease the outflow from Hebgen Lake as requested by the Corps. As soon as work on the slide was completed, Montana Power Company was informed that the Corps would make no further requests for regulation of outflow.

96. <u>Quantities</u>. The total volume of material in the slide was estimated by use of several cross sections, using elevations shown on the topographic maps of the area before and after the slide. The maps and cross sections are shown on plates 2 through 6. The volume of the slide mass after it came to rest was estimated to be about 43,000,000 cubic yards; the volume of the space on the mountainside previously occupied by the slide material was estimated to be about 39,000,000 cubic yards. Since some bulking would be expected, the values were considered roughly equivalent.

97. It was not practical to do the work or keep the records necessary for accurate estimates of the quantities of materials moved on the slide. However, approximations were made of some of the quantities moved in the several phases of the work. The following are values thus estimated:

a.	Excavation for initial spillway	600,000 cu. yd.
b.	Spillway lining (through 11 September)	160,000 cu. yd.
c.	Random fill in spillway (dozed in from left side)	100,000 cu. yd.
d.	Hauled and placed in spillway (12 September through 9 October)	640,000 cu. yd.
e.	Excavated in lowering crest (25 September through 27 October)	700,000 cu. yd.
f.	Deposition in delta	1,750,000 cu. yd.
g.	Removed hydraulically	1,750,000 cu. yd.
h.	Access and haul roads	20 mi.

98. Costs. Total costs of the earthquake emergency operation were approximately $1,715,000, of which $1,387,000 represented payments to contractors for equipment rental and costs of Government-furnished materials, and $238,000 represented salaries and expenses of Corps employees, consultants' fees, transportation, both air and ground, communications, office and miscellaneous expenses, and District office overhead.

99. Conditions subsequent to close of construction activities. There are no records of Earthquake Lake data subsequent to close of operations in late October. Releases from Hebgen Reservoir were increased to about 3,800 c.f.s. on 29 October and held at that rate until 13 November. At that time extremely low temperatures caused ice conditions which, combined with the high discharge, caused flooding of Missouri River near Townsend. Hebgen discharge was reduced to about 1,000 c.f.s. on 14 November, then allowed to increase gradually to 3,400 from 18 to 22 November. The discharge was again reduced on 24 November because of a recurrence of flooding near Townsend. On 6 December the discharge was increased to 3,000 c.f.s. and held near that range through December. On 5 January 1960 the reservoir was at elevation 6504 feet, storage 24,700 acre-feet, and outflow was being maintained about equal to inflow or 800 c.f.s. On 15 July 1960, the water surface elevation in Earthquake Lake was about 6,399, with a discharge from Hebgen Lake of 560 c.f.s. The spillway channel showed evidence of degradation of from two to six feet, with the greatest amount in the vicinity of station 14+00. Through the upstream part of the fan, the channel had been lowered as much as 10 to 12 feet. Aggradation of one to three feet was apparent in the lower part of the fan.

100. Aerial reconnaissance of the slide and Earthquake Lake in mid-December revealed no evidence of significant change in the lake or discharge channel over the slide. No ice trouble or flooding was reported

along Madison River although there had been some apprehension that high flows and extremely cold weather might result in flooding near Ennis. Bank erosion, probably aggravated by the high discharge, caused some damage to the levee on the right bank of the Madison River near Three Forks. The levee was repaired and the bank protected with riprap. Near Townsend the Missouri River was above bankfull from 14 to 16 November and again from 22 to 27 November. Flood damage was estimated to be $65,000.

101. Comments. In retrospect, several items seem worthy of note. Some of them undoubtedly contributed to the success of the operation, some may have increased the time required for its completion.

102. So much equipment idle and available in the area would not be expected normally. Because of a strike at the mines in Butte, the largest contractor, F & S Construction Company, had an unusual number of men and machines idle.

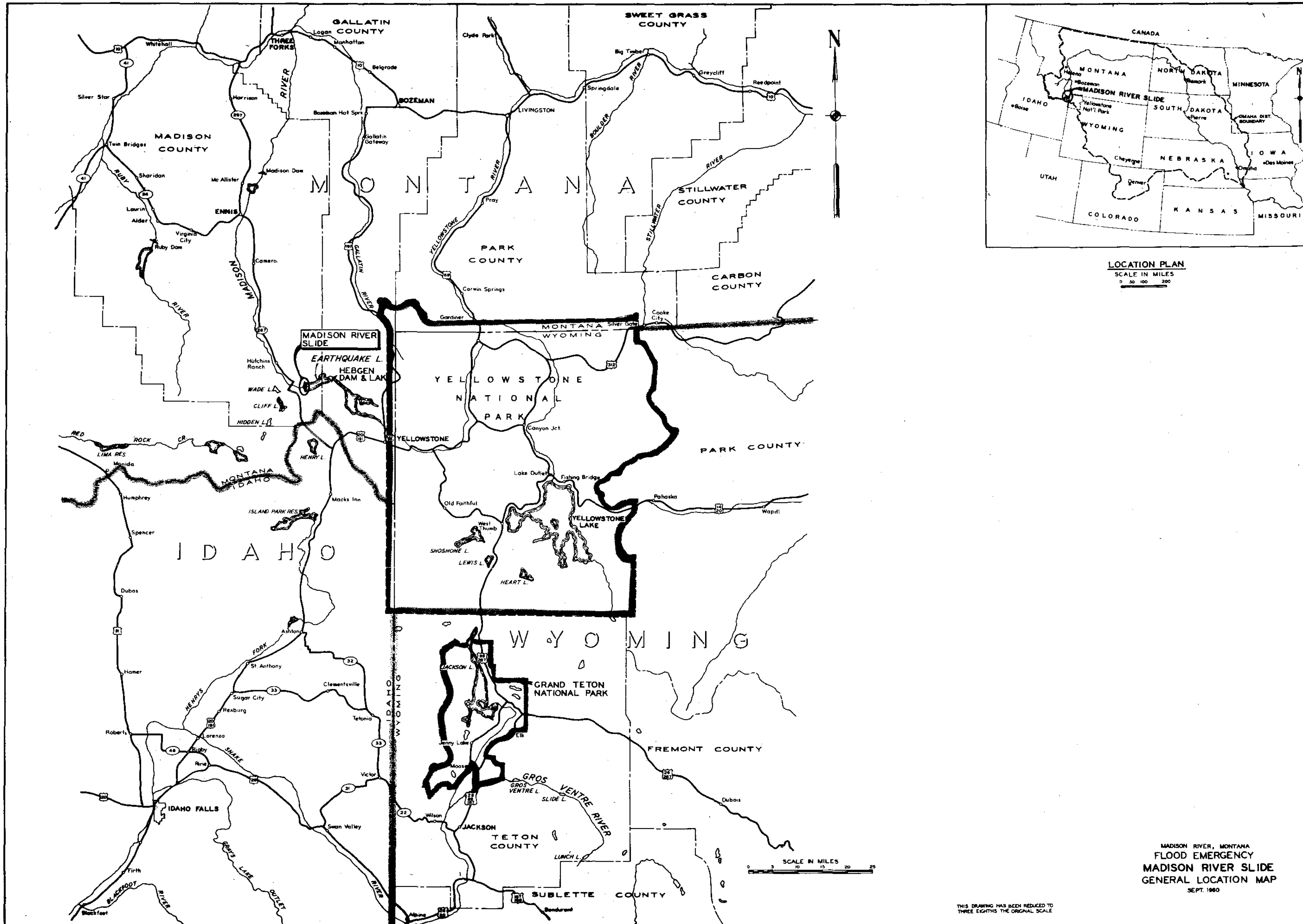
103. The safety record was remarkable, with so much manpower and equipment operating in such a confined area. No personal injury lost-time accidents were experienced, although a few accidents to the equipment occurred, the most damaging of which occurred when an end-dump truck was backed over the edge of a spoil fill into the spillway channel.

104. Had adequate information been available on the materials to be encountered, shovels and draglines with sufficient trucks could have been procured earlier, which might have reduced the over-all time required.

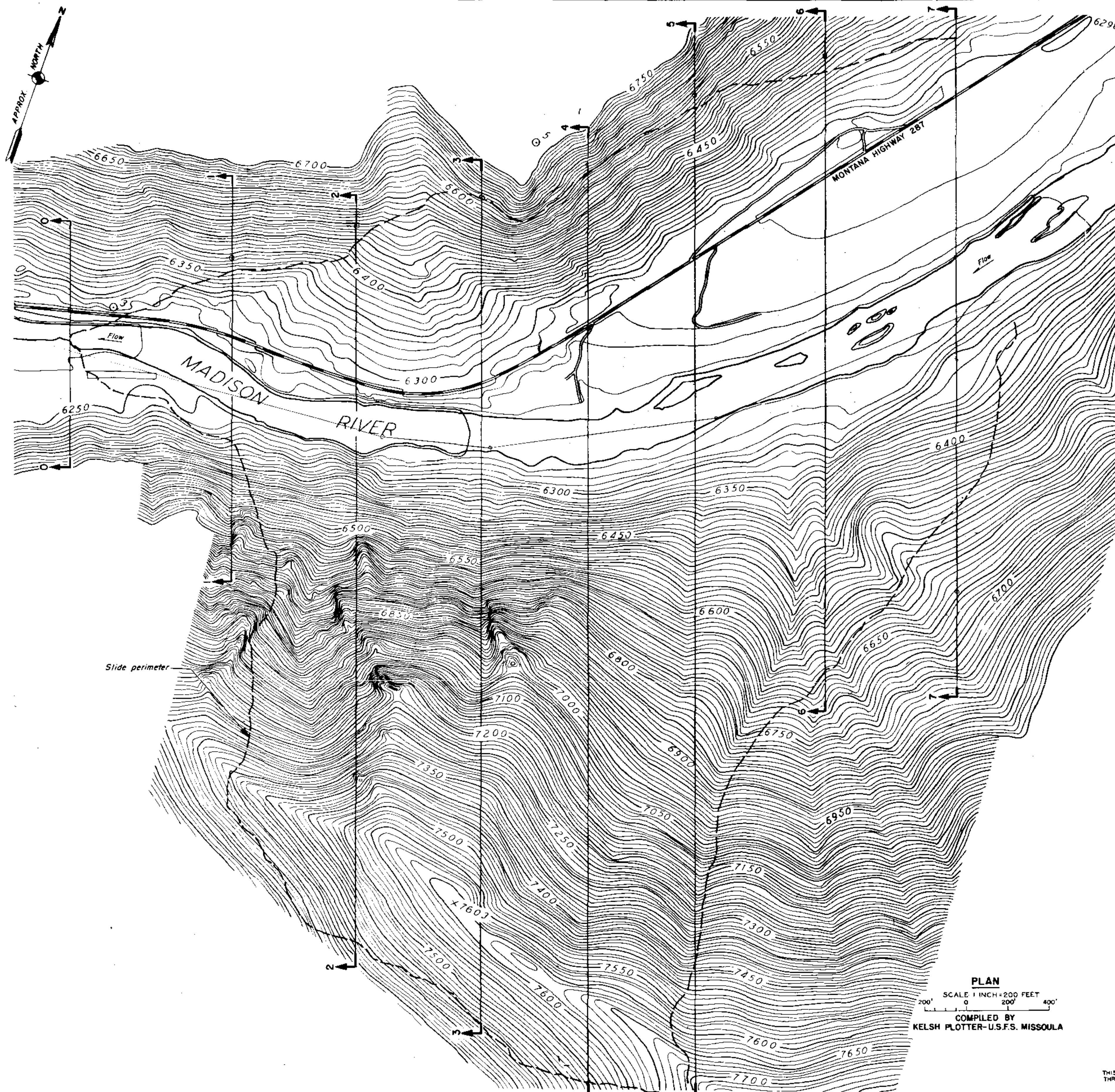
105. The amount of down time for equipment was amazingly small, considering the terrific punishment the equipment received, working in water and with very abrasive rock material.

106. Equipment contracts required operators and service but did not require supervisors. While most contractors did furnish supervisors who cooperated and took instructions from Corps representatives, a faster response to emergency situations probably would have resulted had each contractor been required to furnish a full-time supervisor.

107. Maintenance of access roads proved to be a major item, particularly near the end of the emergency. Access was provided from the downstream direction only. Due to aggradation below the slide, the river was continually changing its course and washing out the access road. Possibly a road should have been constructed along the mountainside from Hebgen Dam to the upstream end of the slide, thus avoiding the problem of access and reducing travel time appreciably.

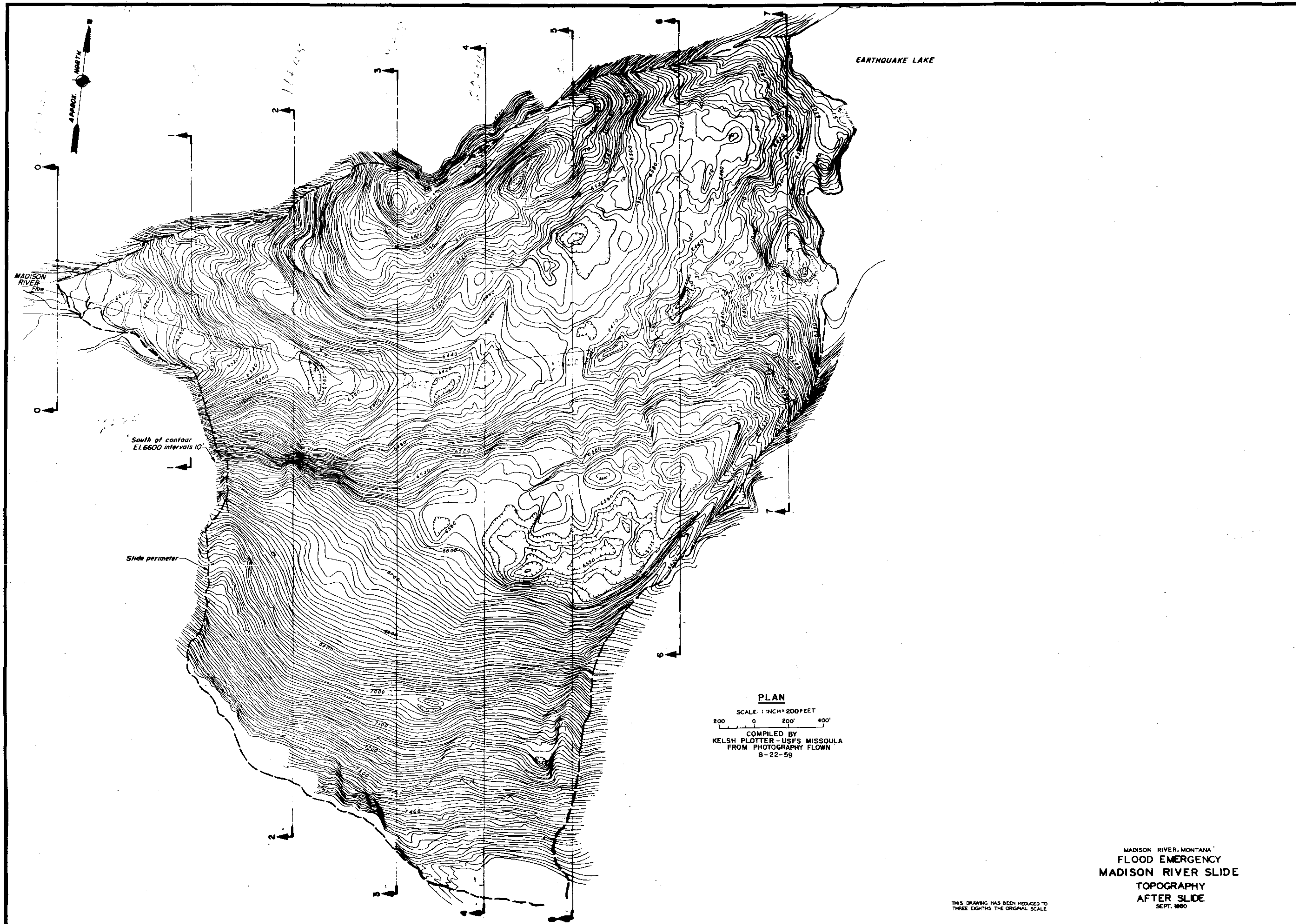


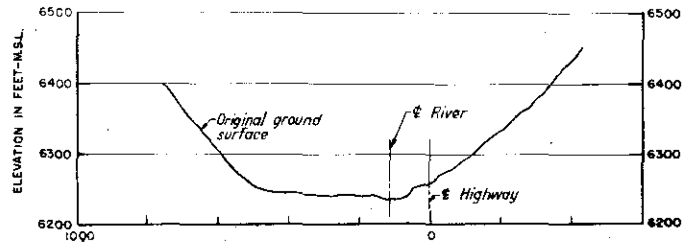
MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
GENERAL LOCATION MAP
SEPT. 1960



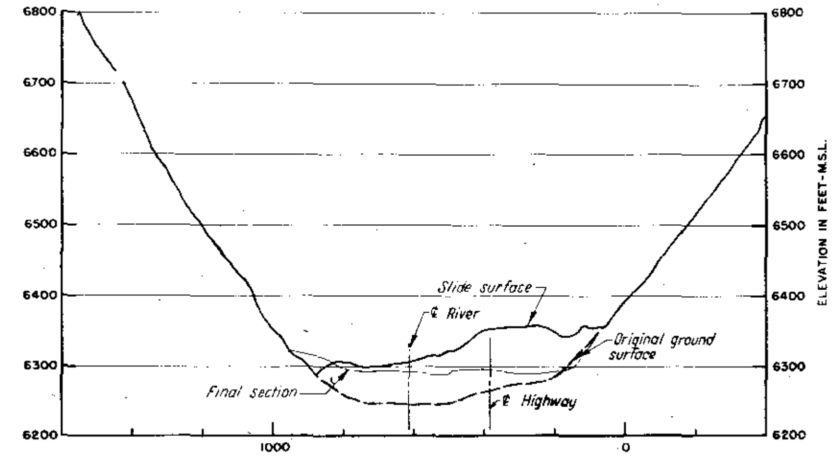
THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE

MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
TOPOGRAPHY
BEFORE SLIDE
SEPT. 1960

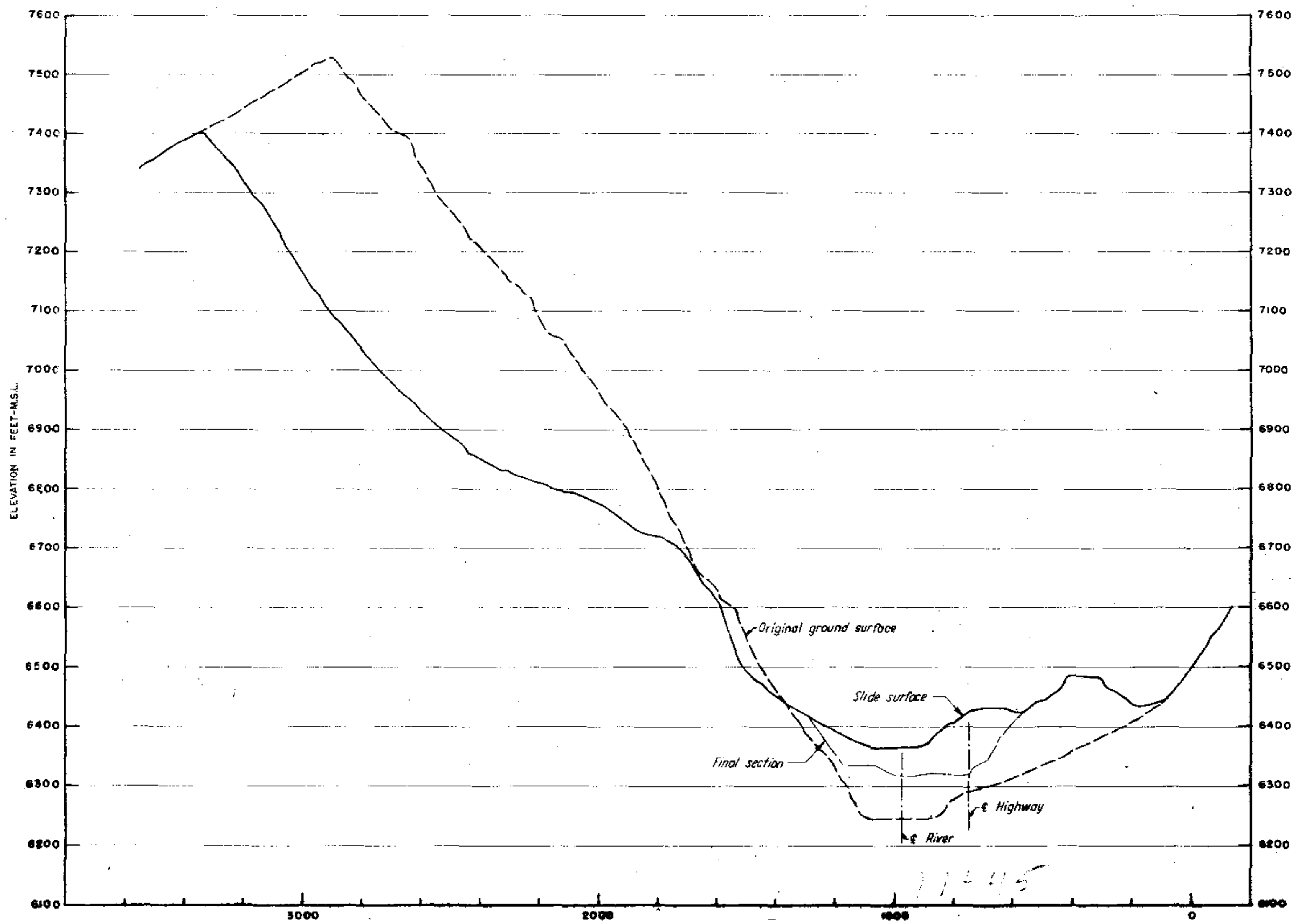

APPROX. NORTH
EARTHQUAKE LAKE
MADISON RIVER Flow
South of contour El. 6600 intervals 10'
Slide perimeter
PLAN
SCALE: 1 INCH = 200 FEET
200' 0 200' 400'
COMPILED BY
KELSH PLOTTER - USFS MISSOULA
FROM PHOTOGRAPHY FLOWN
8-22-59
THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE
MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
TOPOGRAPHY
AFTER SLIDE
SEPT. 1960



SECTION 0-0



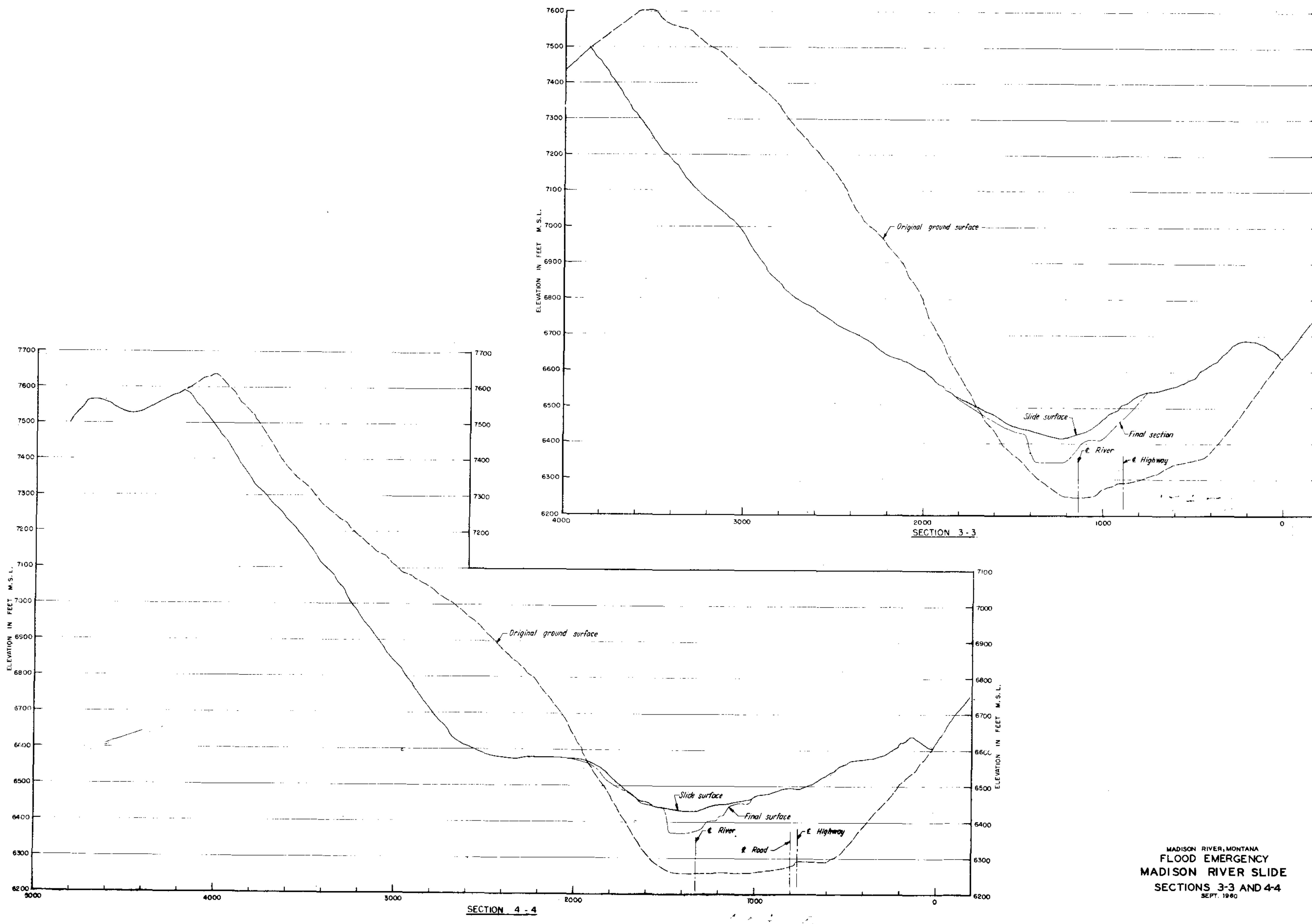
SECTION 1-1



SECTION 2-2

THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE

MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
SECTIONS 0-0, 1-1, AND 2-2
SEPT. 1960



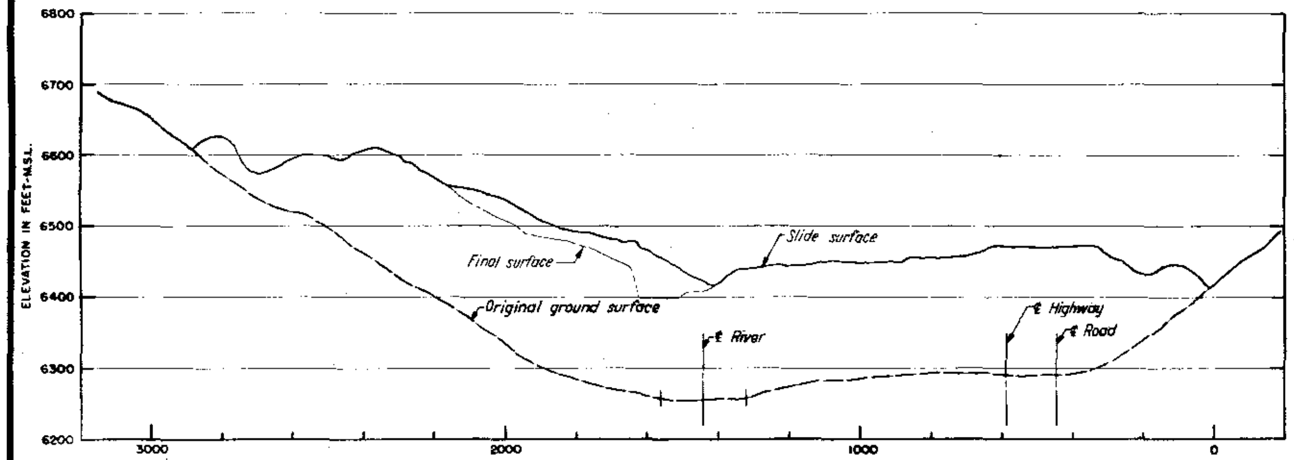
MADISON RIVER, MONTANA

FLOOD EMERGENCY

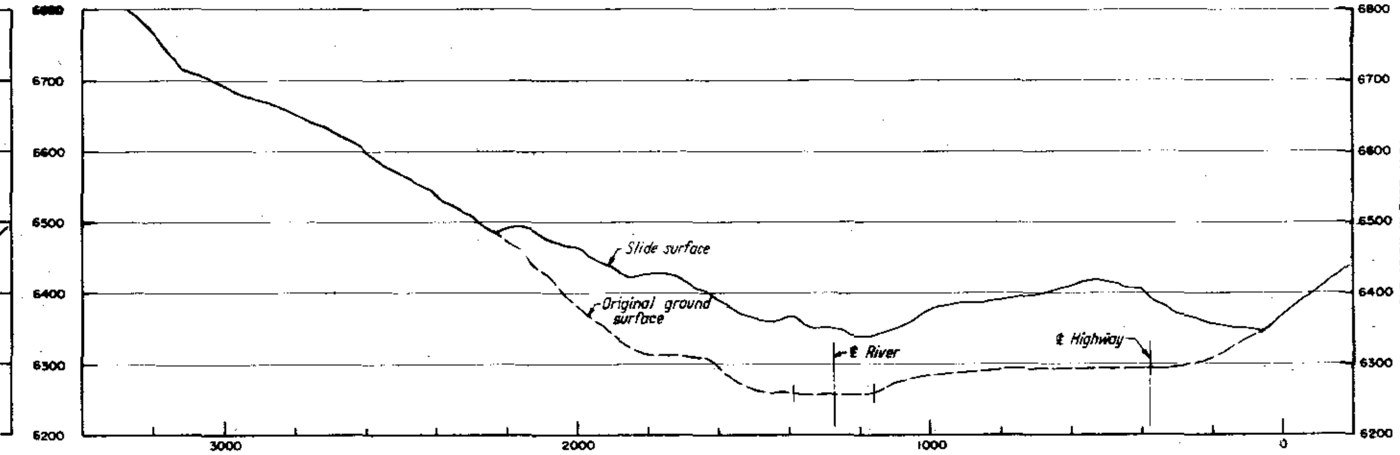
MADISON RIVER SLIDE

SECTIONS 3-3 AND 4-4

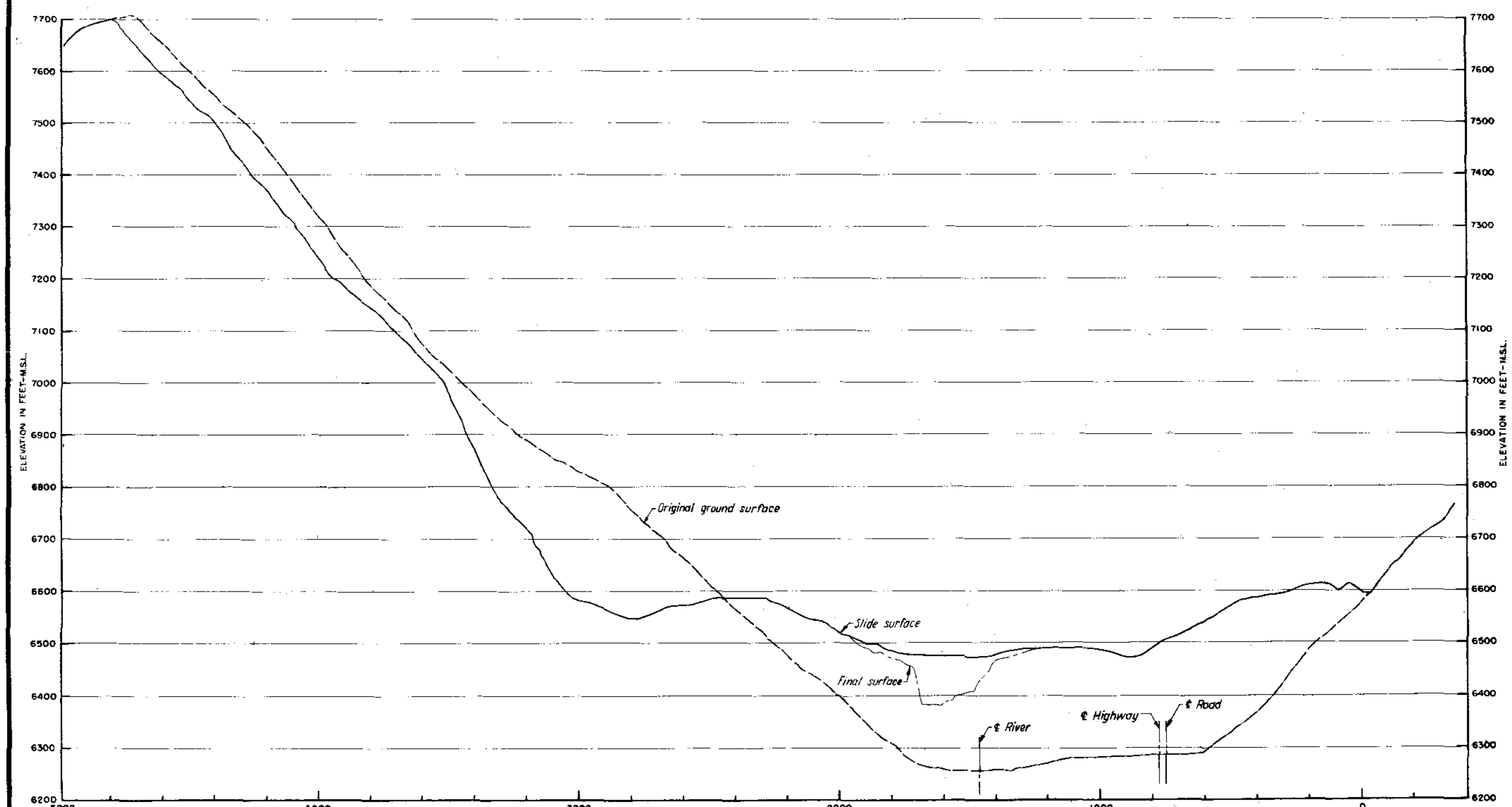
SEPT. 1960



SECTION 6-6



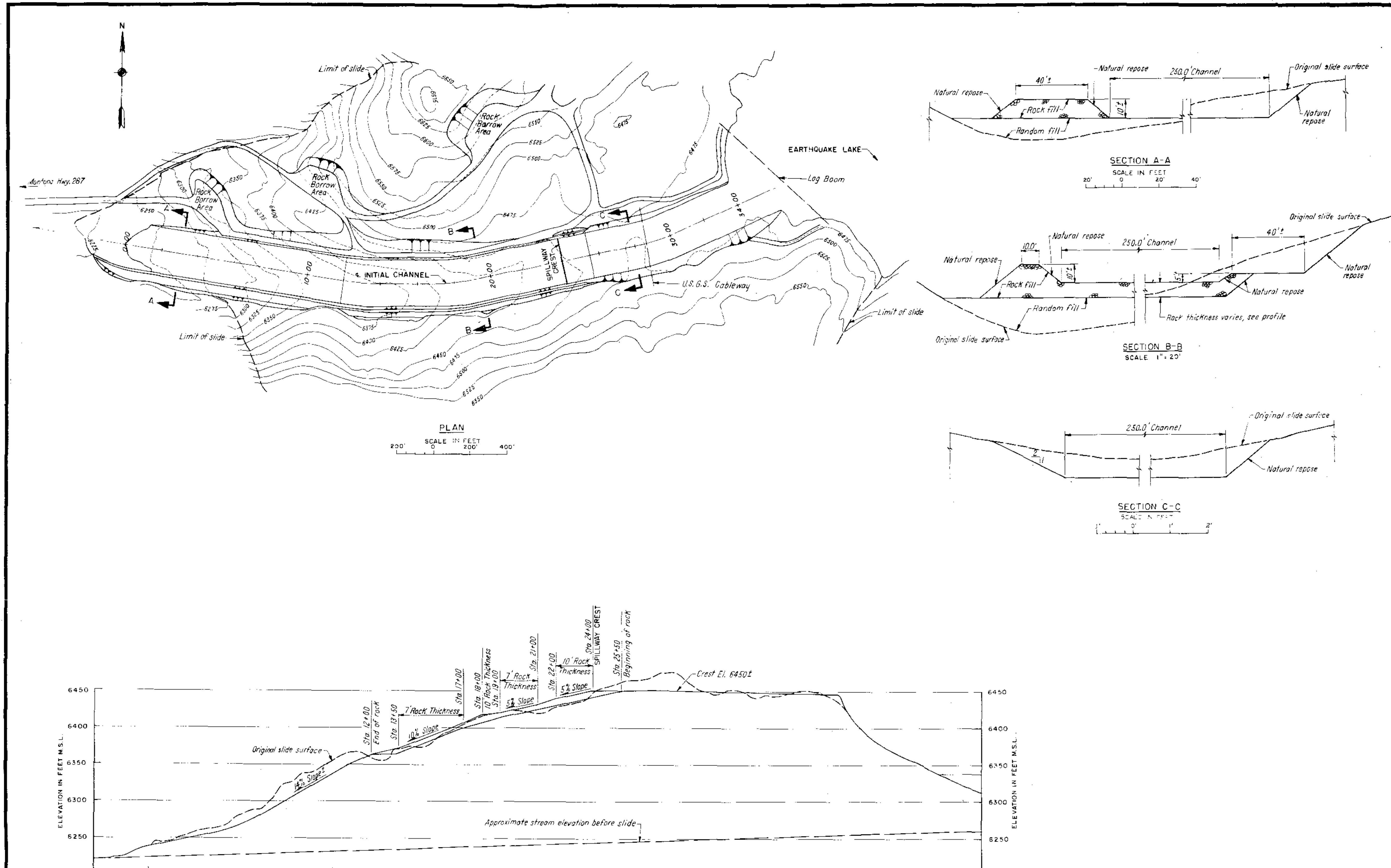
SECTION 7-7



SECTION 5-5

MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
SECTIONS 5-5, 6-6, AND 7-7
SEPT. 1960

THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE

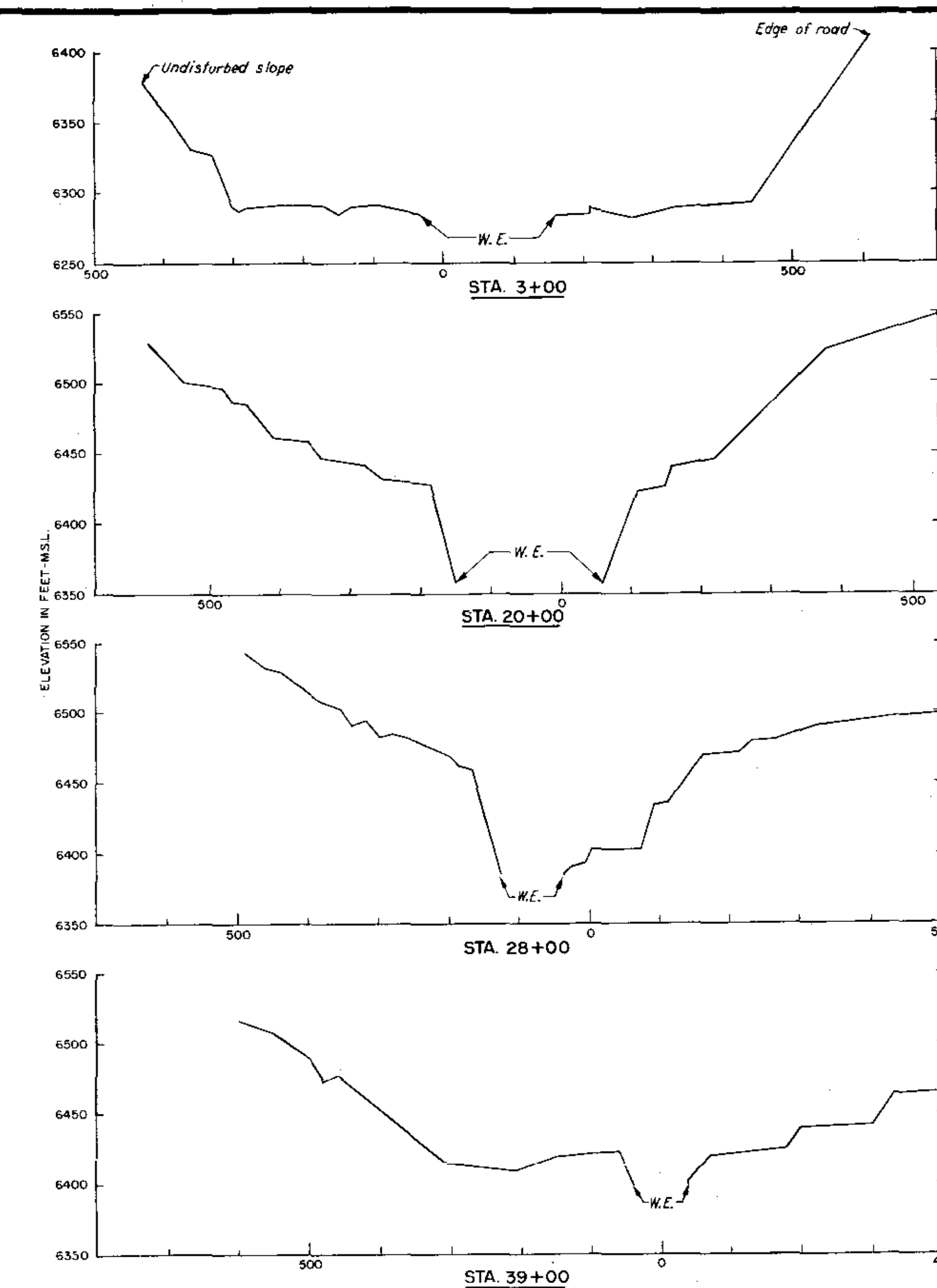


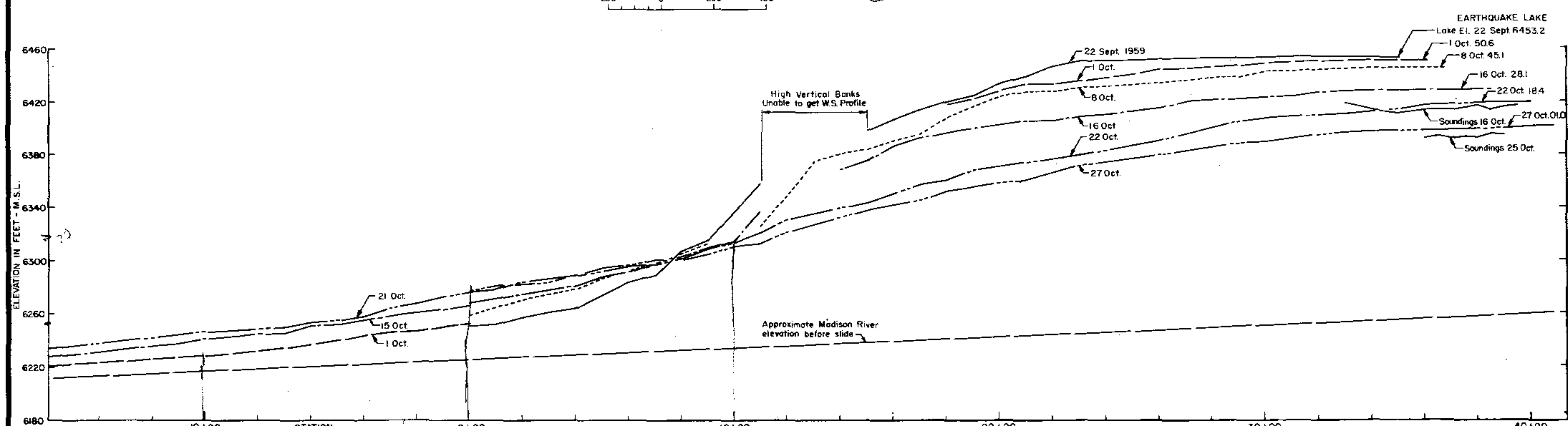
MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
SPILLWAY
PLAN PROFILE AND SECTIONS
(INITIAL CONSTRUCTION)
SEPT. 1960

THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE

PLAN

SCALE: 1 INCH = 200 FEET



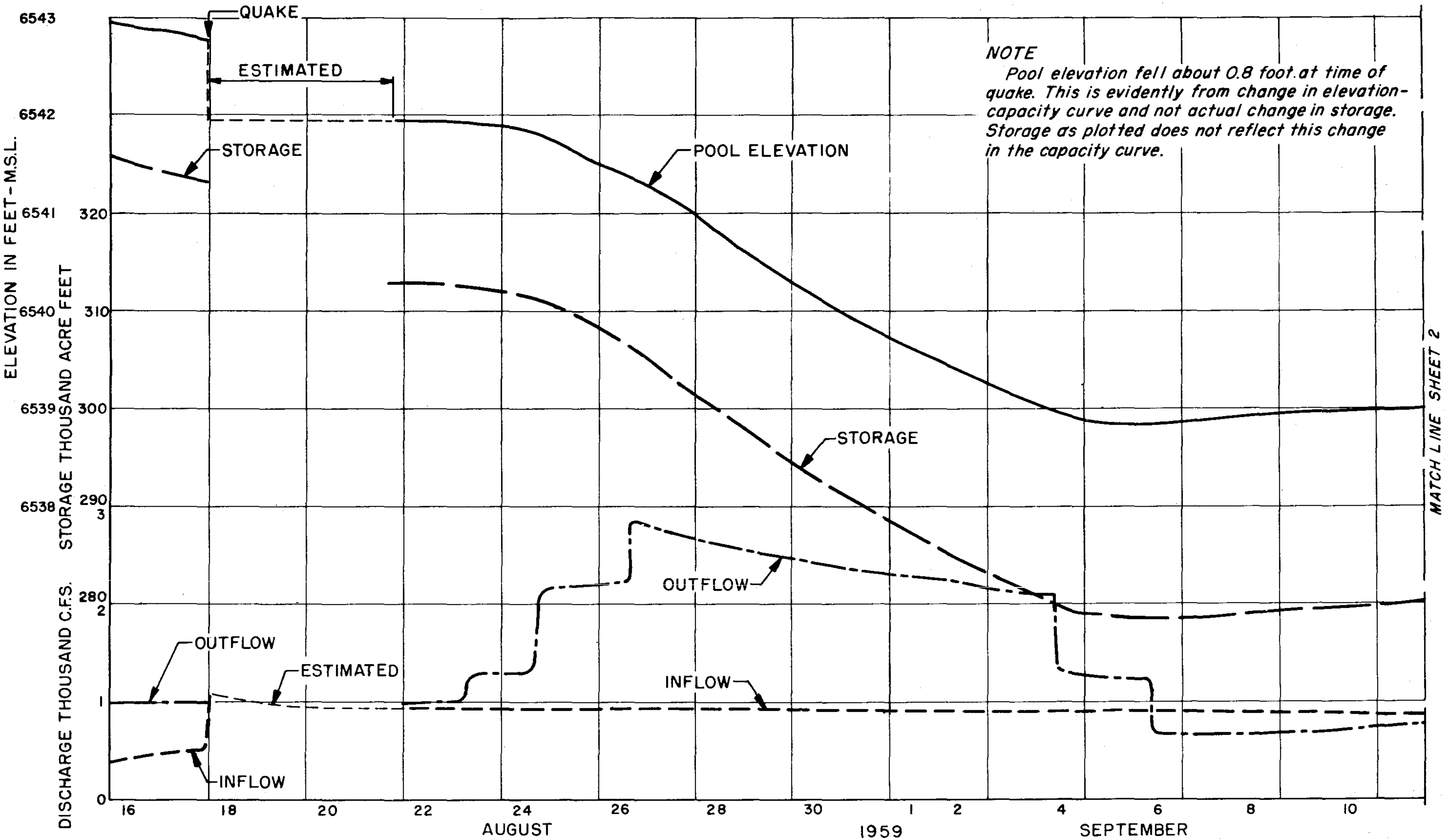


WATER SURFACE PROFILES

SCALE GRAPHIC

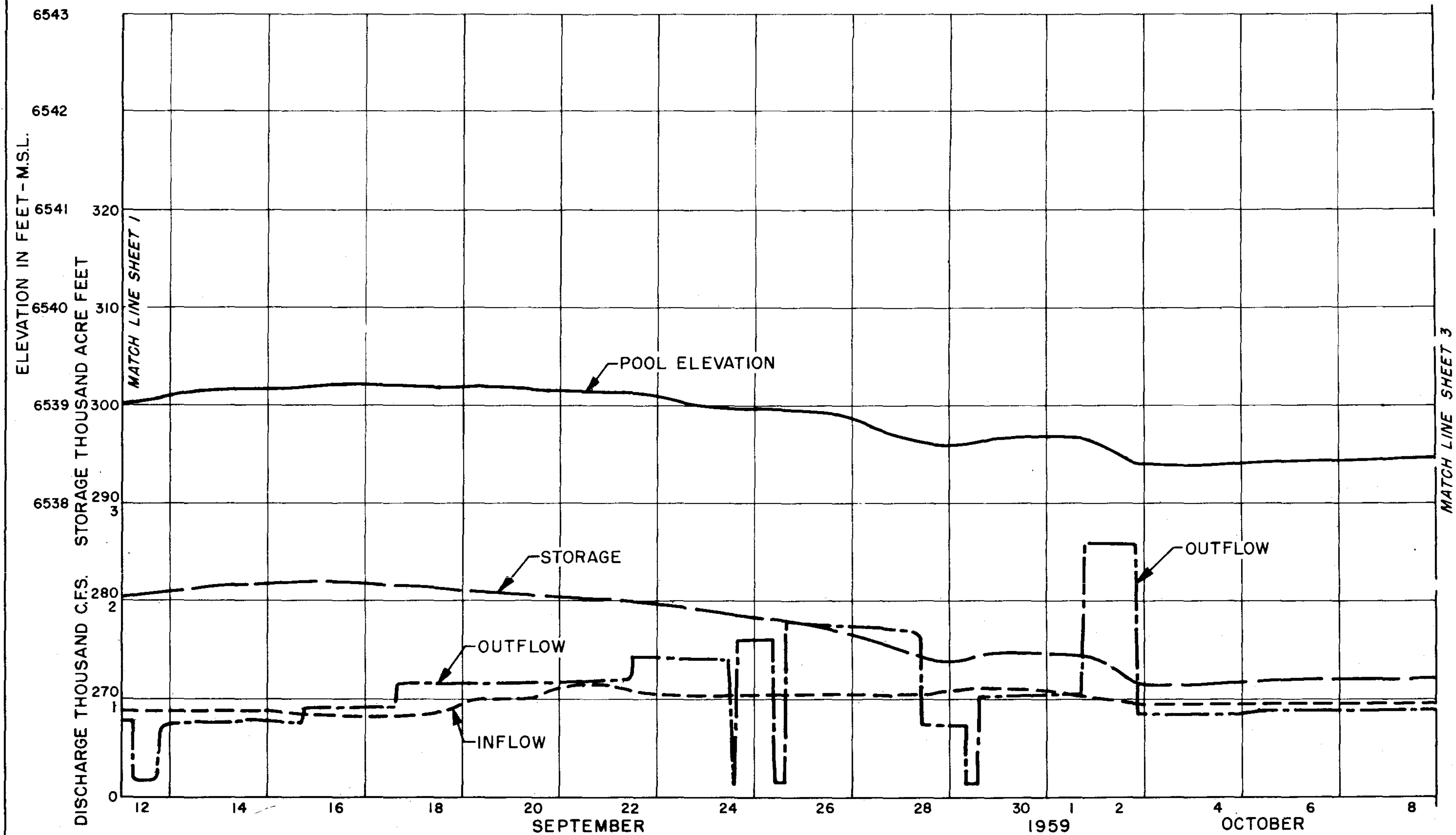
THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE

MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
SPILLWAY
PLAN, PROFILE, AND SECTIONS
(FINAL CONSTRUCTION)
SEPT. 1960

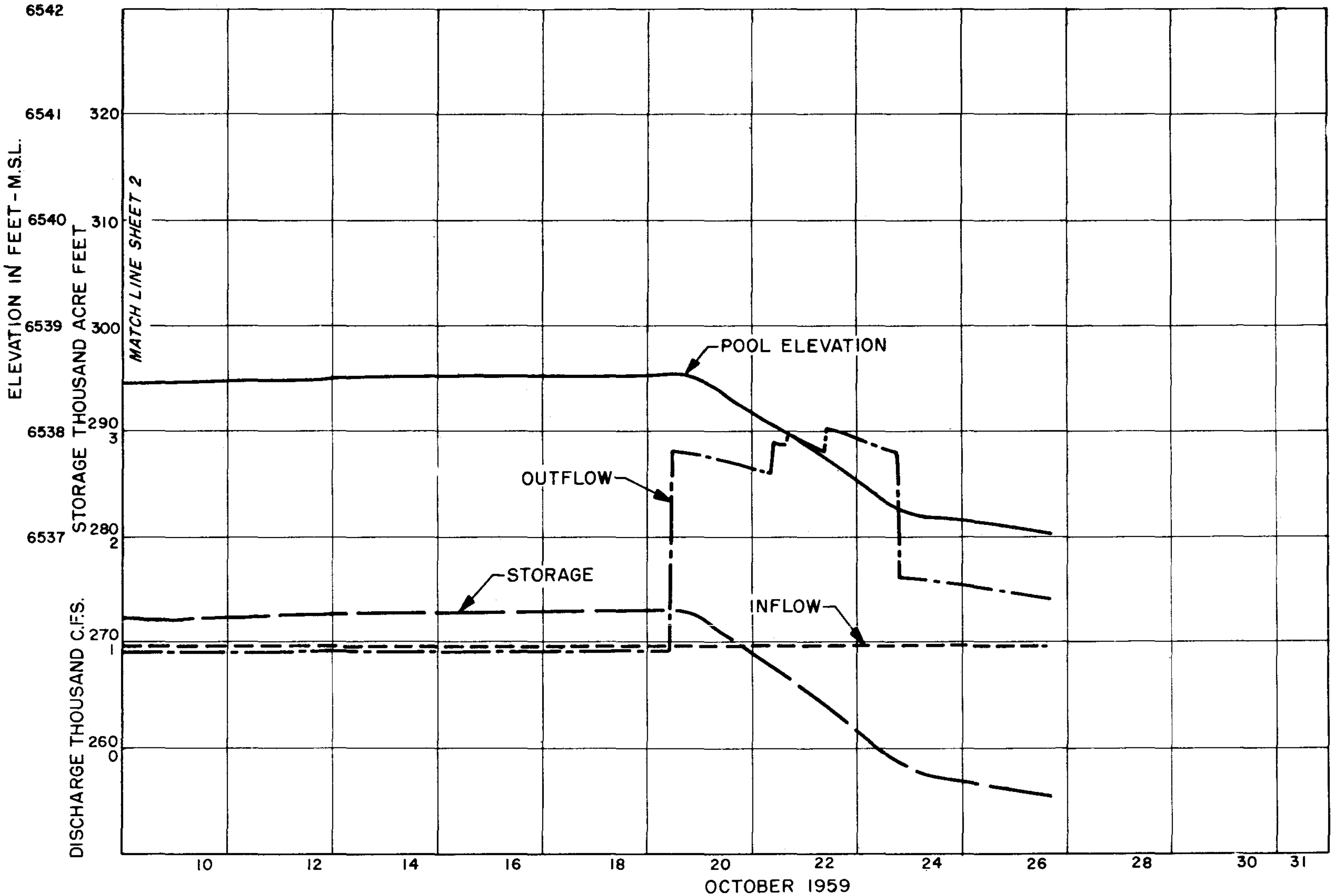


MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
HEBGEN RESERVOIR
REGULATION
CURVES
SHEET 1 OF 3 SEPT. 1960

PLATE 9



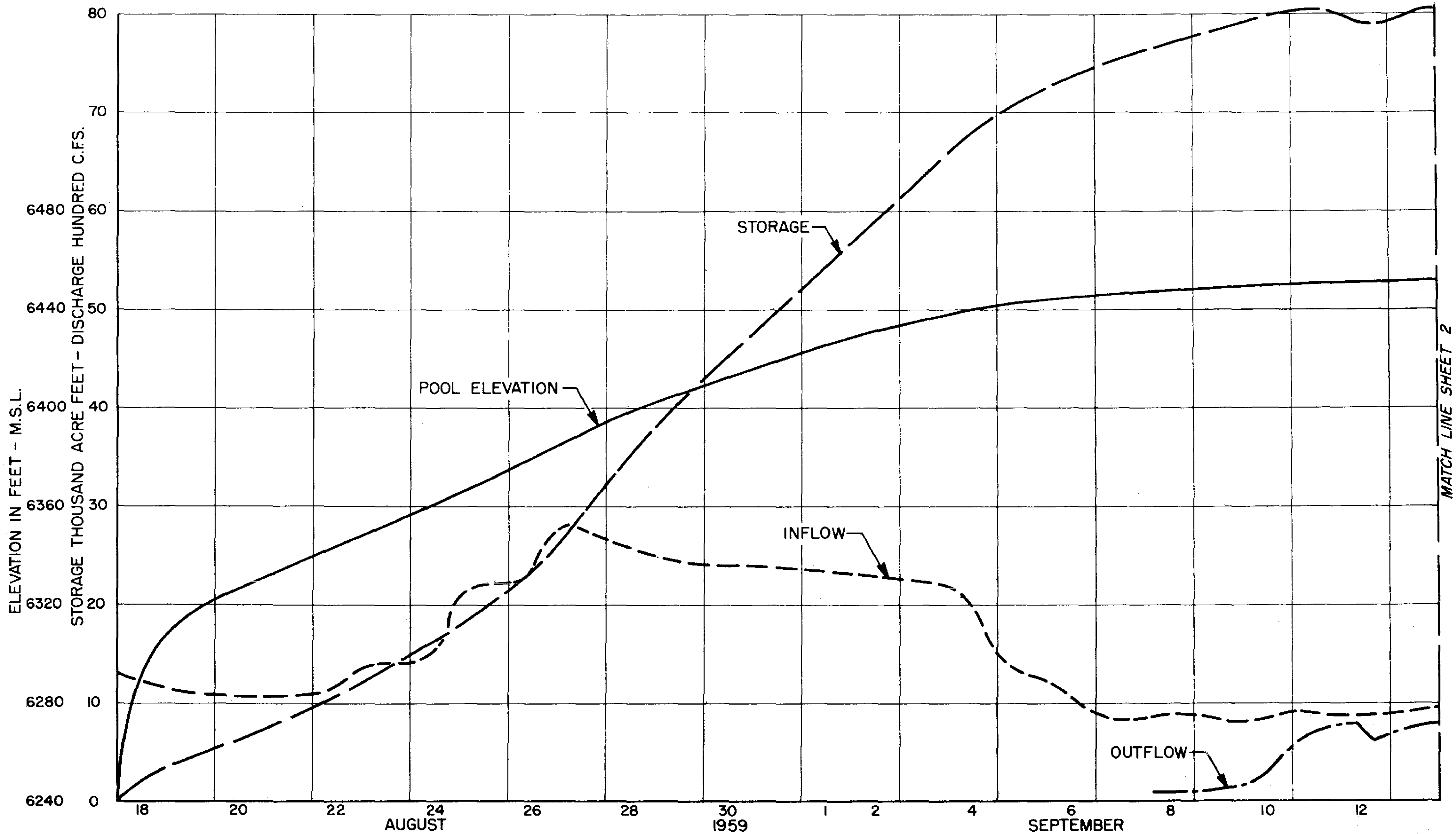
MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
HEBGEN RESERVOIR
REGULATION
CURVES
SHEET 2 OF 3 SEPT. 1960



MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE

HEBGEN RESERVOIR REGULATION CURVES

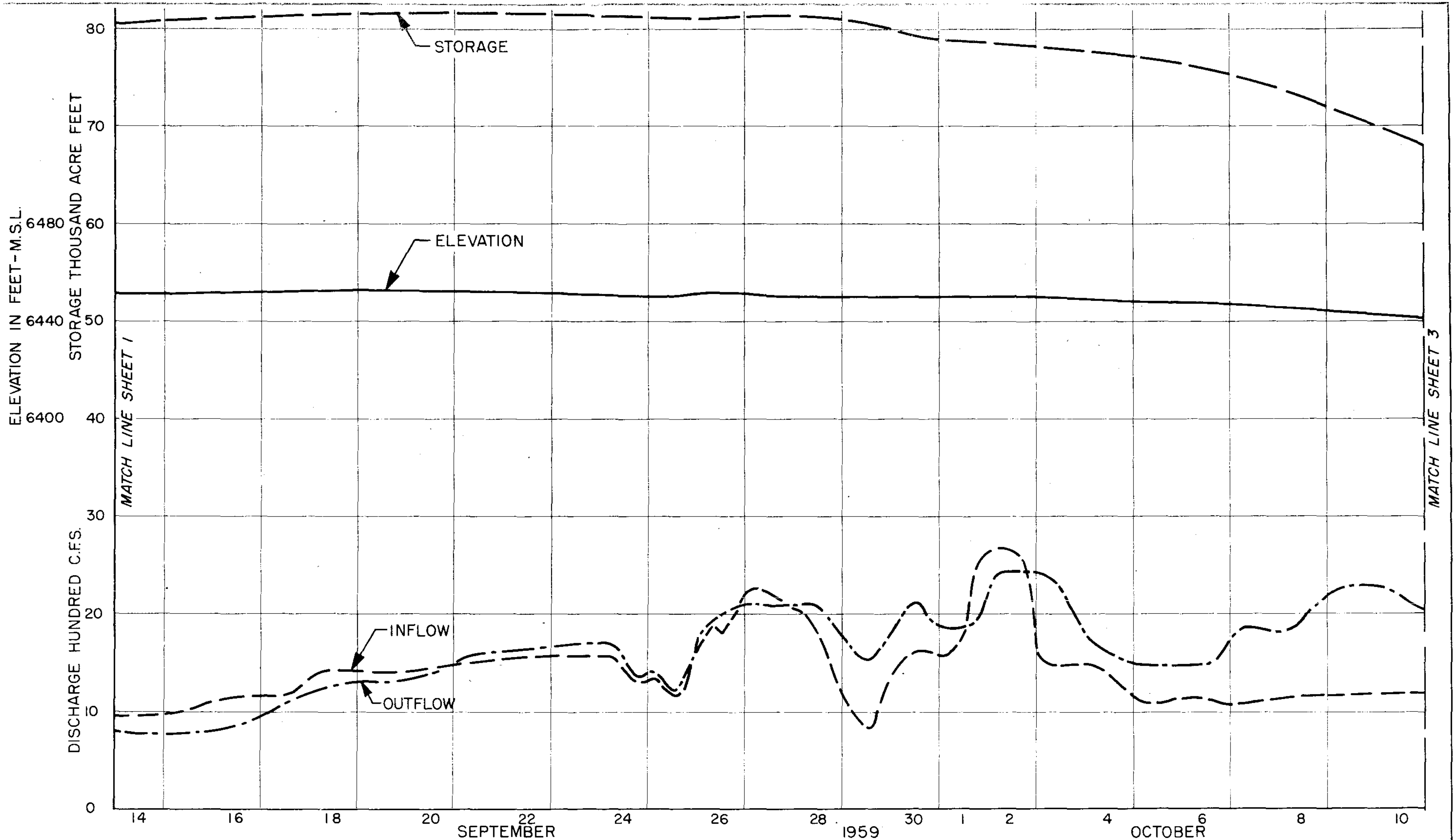
SHEET 3 OF 3 SEPT. 1960



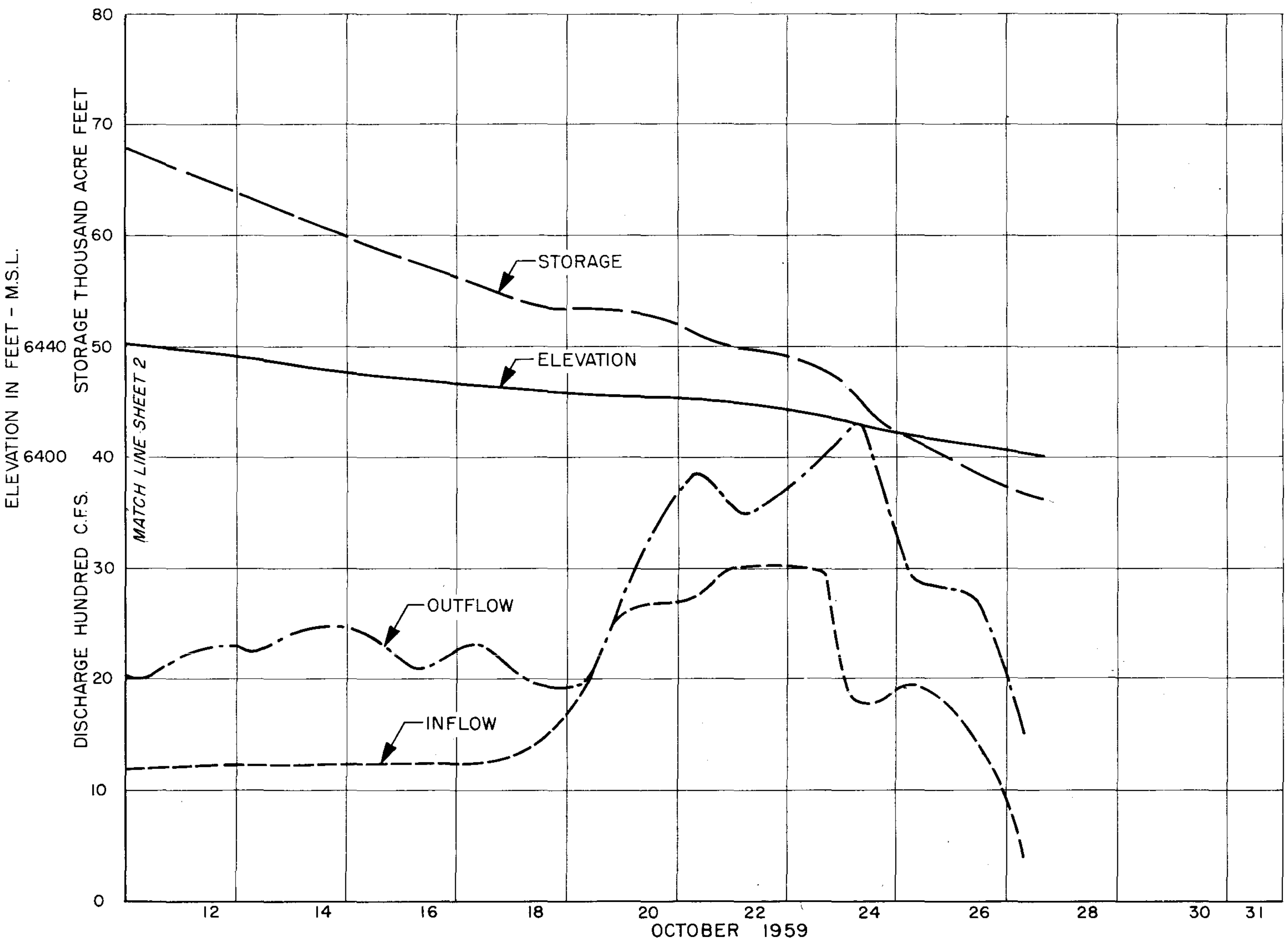
MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE

EARTHQUAKE LAKE REGULATION CURVES

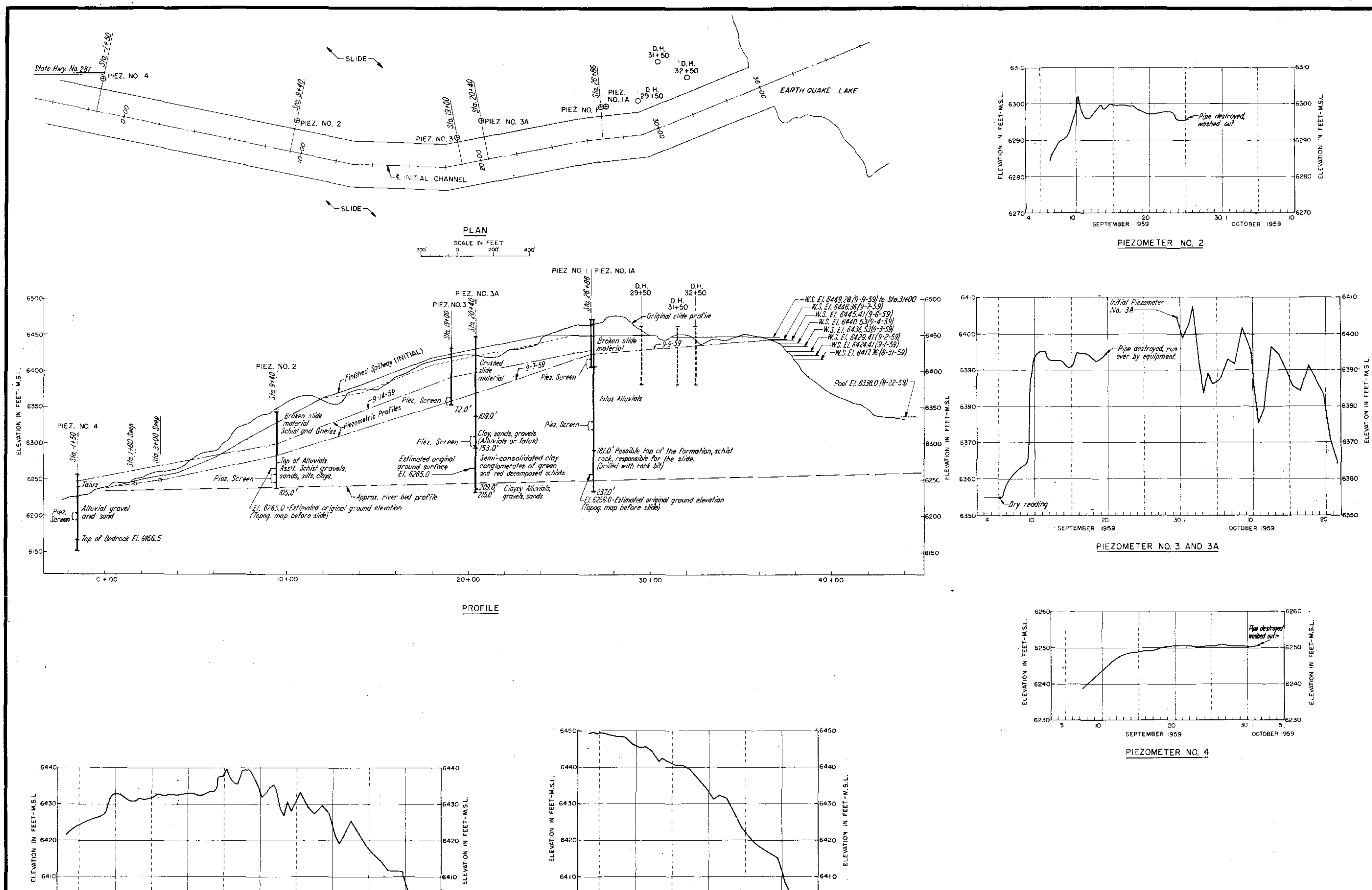
SHEET 1 OF 3 SEPT. 1960



MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
EARTHQUAKE LAKE
REGULATION
CURVES
SHEET 2 OF 3 SEPT. 1960

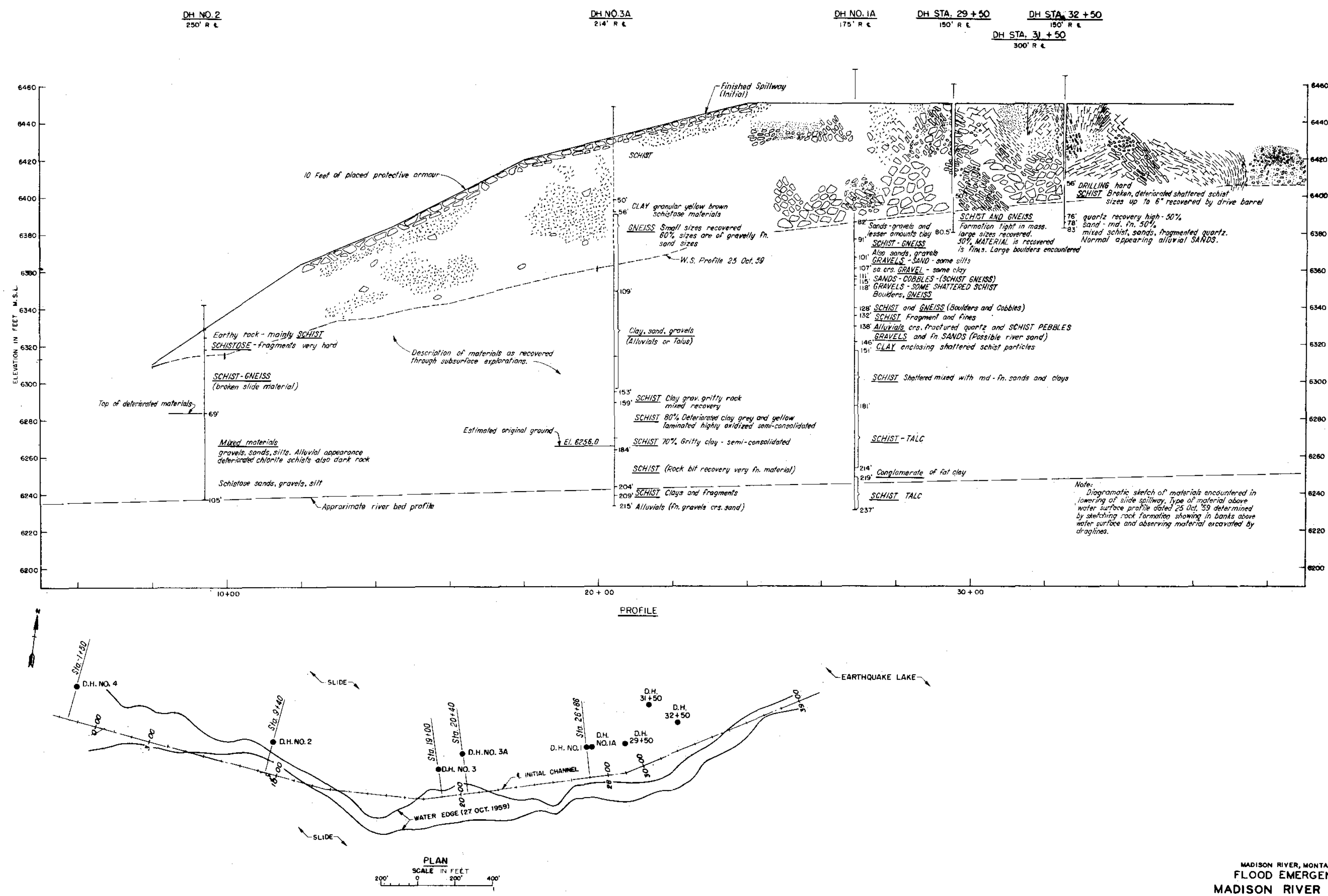


MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
EARTHQUAKE LAKE
REGULATION
CURVES
SHEET 3 OF 3 SEPT. 1960



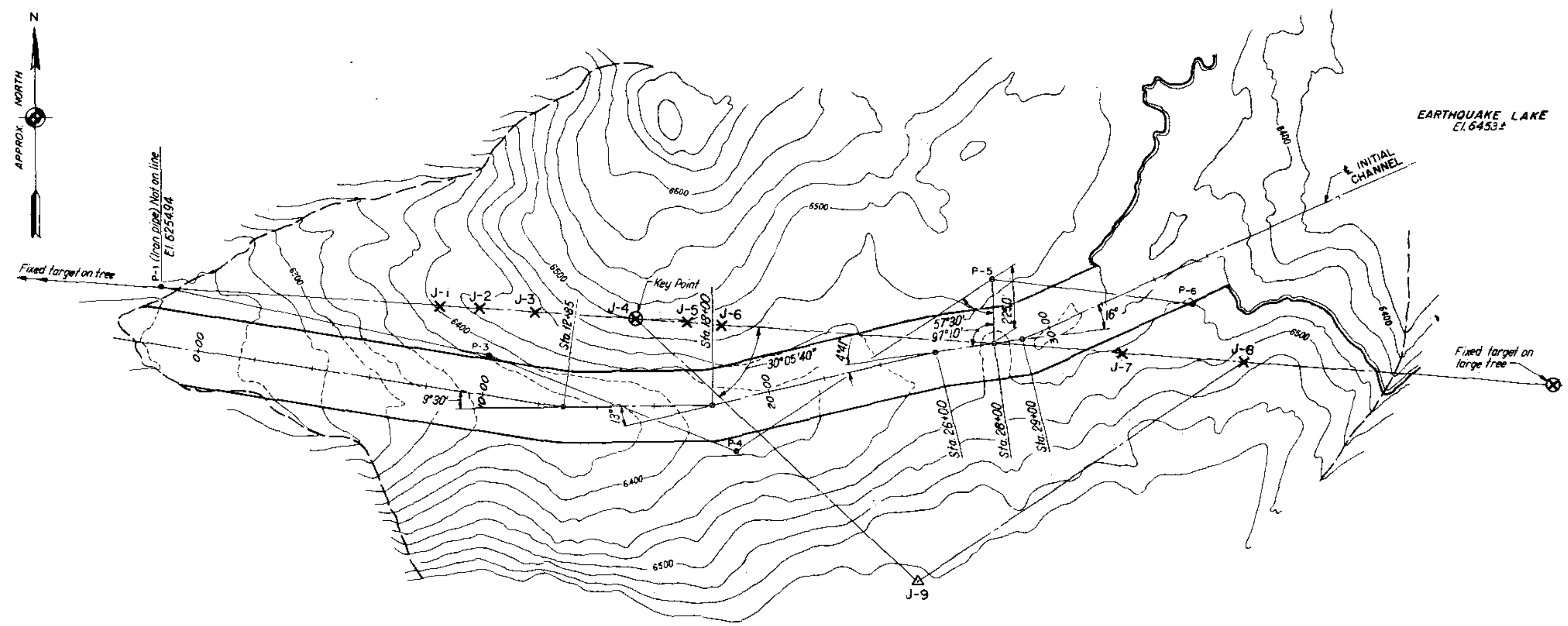
THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE

MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
PIEZOMETER
PLAN, PROFILE AND RECORD OF OBSERVATIONS
SEPT. 1960



MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
MATERIALS ENCOUNTERED IN SPILLWAY AND DRILL HOLES
SEPT. 1960

THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE



PLAN

SCALE IN FEET

200' 0 200' 400'

SLIDE MOVEMENT POINTS												
TRAVERSE MOVEMENT CHECK												
MOVEMENT POINTS	SEPT. 7 & 8, 1959	9-9-59	9-10-59	9-14-59	9-19-59	9-23-59	9-28-59	10-19-59	10-23-59			
J-1	0	.13S	.05N	.17S	Destroyed	—	—					
J-2	0	0	.12N	.06S	.08S	.09S	.08S					
J-3	0	0	0	0	.10S	.10S	.14S					
J-4	0	.11S	.15S	.33S	.42S	.42S	0.35S	0.60(S)	0.55(S)			
J-5	0	.28S	.07S	.21S	Destroyed	Destroyed	—					
J-6	0	.36S	.11S	.30S	Destroyed	Destroyed	—					
J-7	0	0	0	.04N	0.00	0.00	0.00	0.06(N)	0.06(N)			
J-8	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00			
J-8, J-4, J-9	30°05'40"							30°05'				
OBSERVER	Perry	Perry	Perry	Perry	Best	Best	Best	Best	Best			

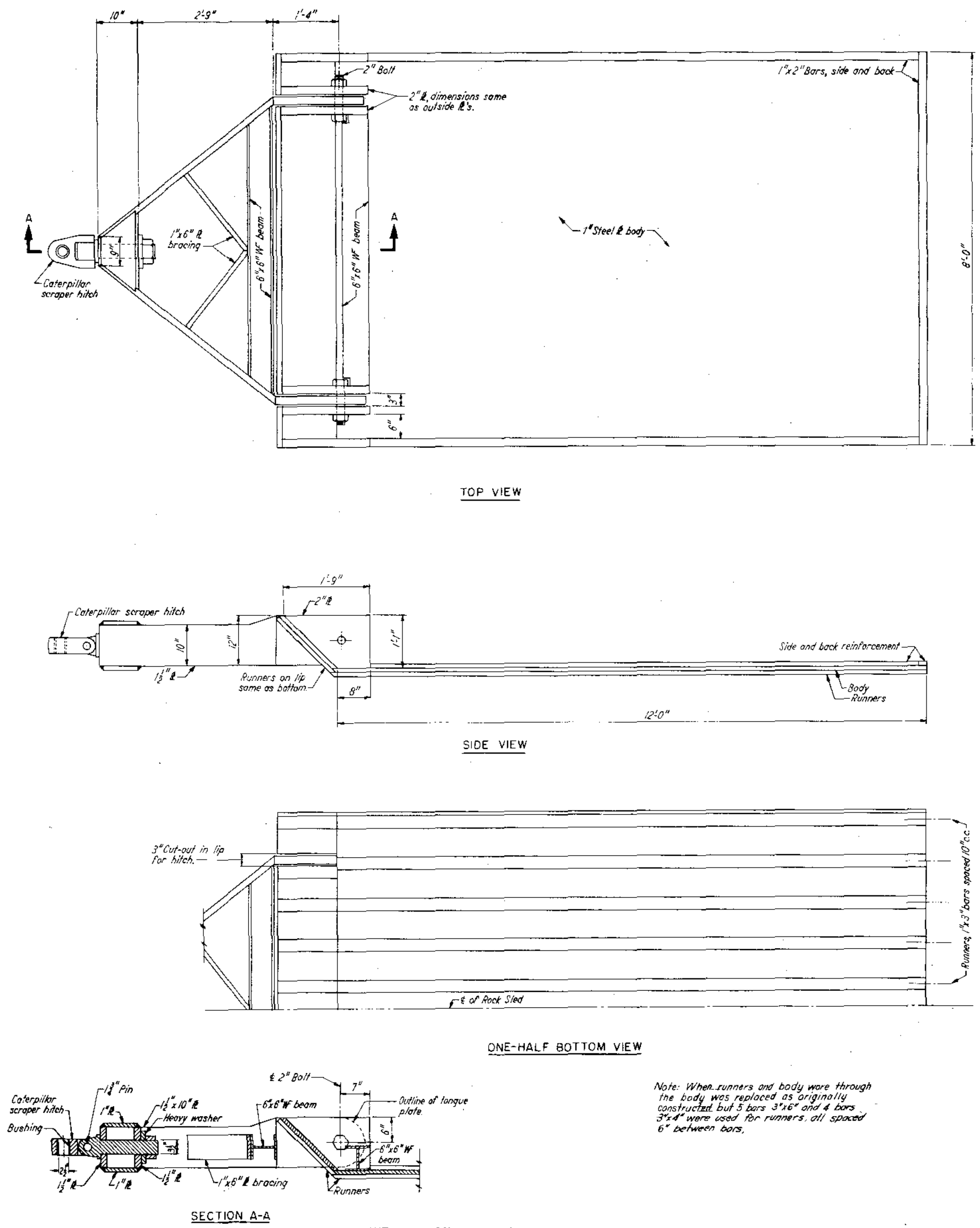
SLIDE MOVEMENT POINTS							
LONGITUDINAL MOVEMENT CHECK							
		9-10-59					
MOVEMENT POINTS	INITIAL STATION	DISTANCE	CURRENT CHANGE	ACC. CHANGE	DISTANCE	CURRENT CHANGE	ACC. CHANGE
IRON PIPE	0+00 *						
		300.0	0	0			
RED HEAD	3+00						
		300.0	0	0			
RED HEAD	6+00						
		700.0	0	0			
HUB	13+00						
		1196.5'	0	0			
J-1	24+96.5						
		136.1	0	0			
J-2	26+32.6						
		195.8	0	0			
J-3	28+28.4						
		350.0	0	0			
J-4	31+78.4						
		174.8	0	0			
J-5	33+53.2						
		124.0	0	0			
J-6	34+77.2						
		1334.0	0	0			
J-7	48+71.2						
		485.6	0	0			
J-8	52+96.8						

SLIDE MOVEMENT POINTS				
MOVEMENT POINTS	9-10-59 INITIAL ELEV.	ELEV.	CURRENT CHANGE	ACC. CHANGE
B.M. 45A-1	6195.24			
P-1	6254.94			
0+00 *	6269.00			
J-1	6398.80			
J-2	6426.50			
J-3	6440.80			
J-4	6504.47			
J-5	6497.73			
J-6	6490.66			
J-7	6472.30			
J-8	6515.58			

* 0+00 on Movement Line not shown on sheet.

THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE

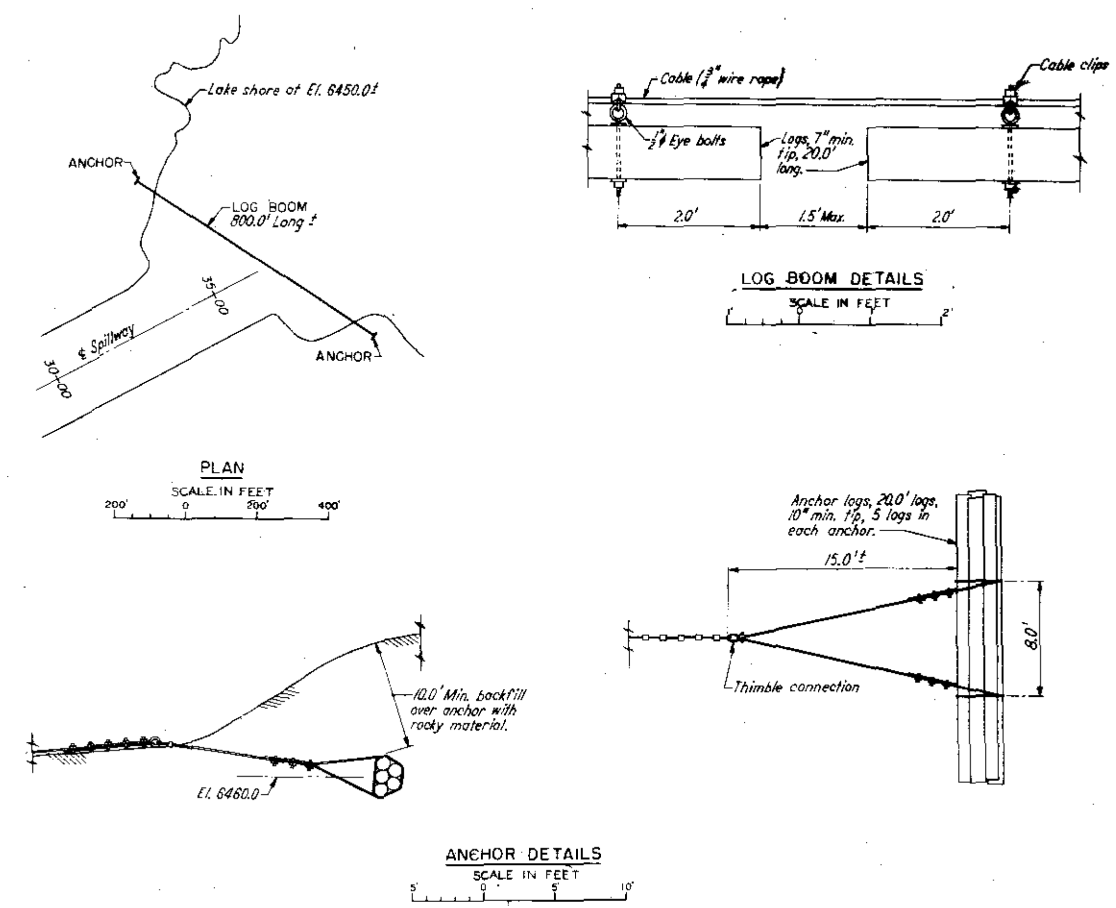
MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
MOVEMENT POINTS
SEPT. 1960



Note: When runners and body wore through the body was replaced as originally constructed but 5 bars 3"x6" and 4 bars 3"x4" were used for runners, all spaced 6" between bars.

WELDED STEEL ROCK SLED

SCALE IN FEET



LOG BOOM

MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
WELDED STEEL ROCK SLED
SEPT. 1960

THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE

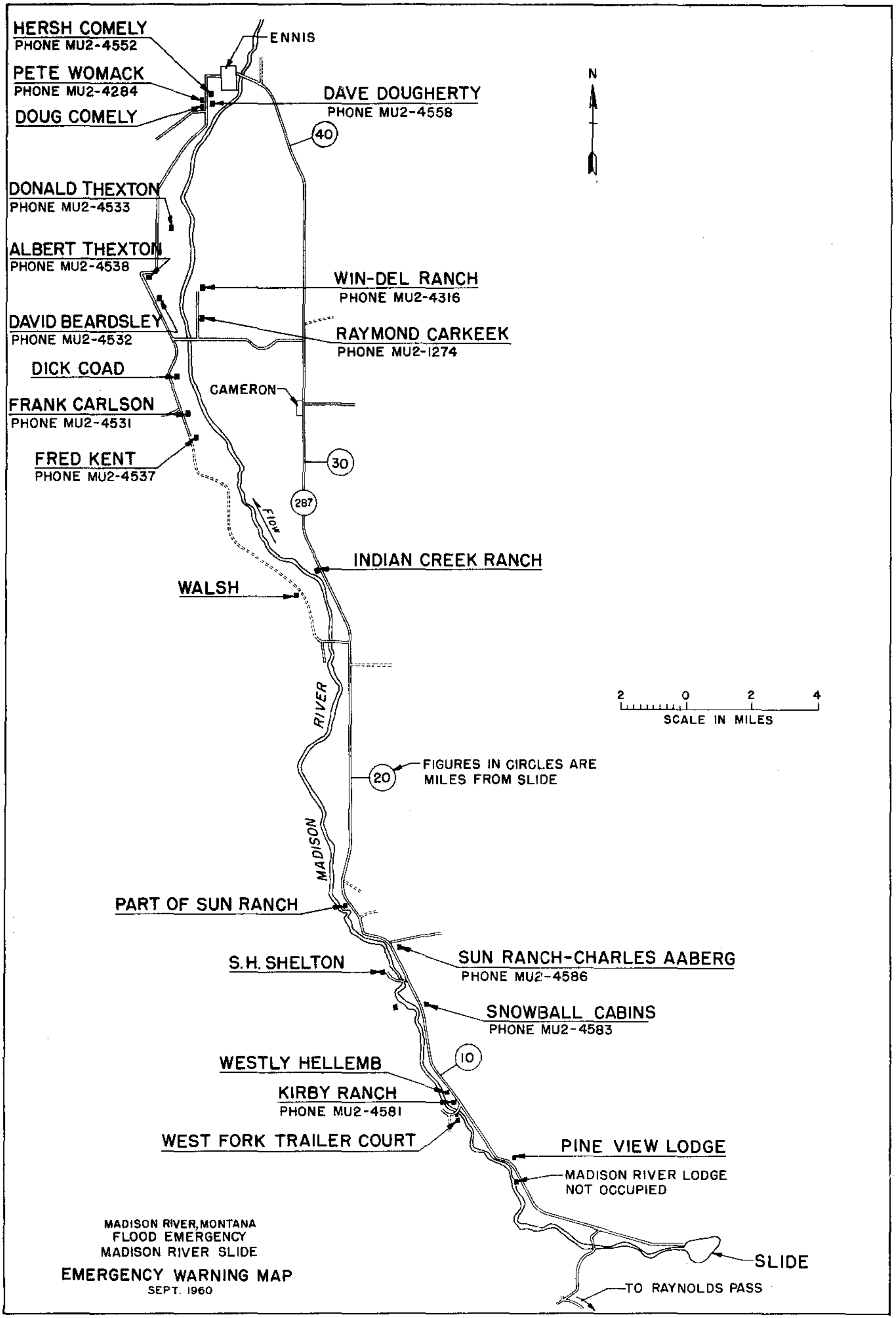
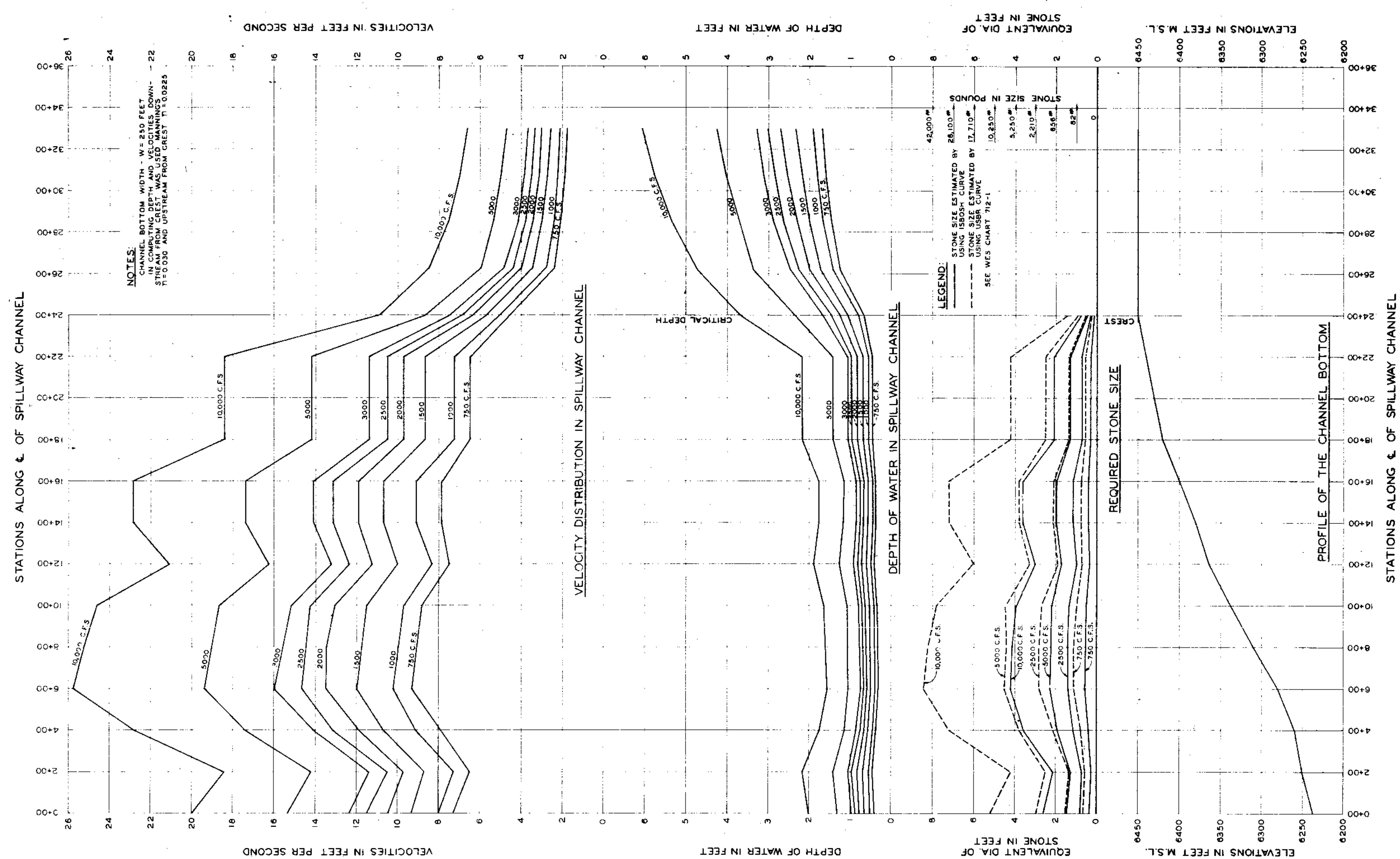

HERSH COMELY
PHONE MU2-4552
PETE WOMACK
PHONE MU2-4284
DOUG COMELY
ENNIS
DAVE DOUGHERTY
PHONE MU2-4558
40
N
DONALD THEXTON
PHONE MU2-4533
ALBERT THEXTON
PHONE MU2-4538
WIN-DEL RANCH
PHONE MU2-4316
DAVID BEARDSLEY
PHONE MU2-4532
RAYMOND CARKEEK
PHONE MU2-1274
DICK COAD
CAMERON
FRANK CARLSON
PHONE MU2-4531
FRED KENT
PHONE MU2-4537
30
287
FLOW
INDIAN CREEK RANCH
WALSH
RIVER
2 0 2 4
SCALE IN MILES
20
FIGURES IN CIRCLES ARE
MILES FROM SLIDE
MADISON
PART OF SUN RANCH
S.H. SHELTON
SUN RANCH-CHARLES AABERG
PHONE MU2-4586
SNOWBALL CABINS
PHONE MU2-4583
10
WESTLY HELLEMB
KIRBY RANCH
PHONE MU2-4581
WEST FORK TRAILER COURT
PINE VIEW LODGE
MADISON RIVER LODGE
NOT OCCUPIED
MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
EMERGENCY WARNING MAP
SEPT. 1960
SLIDE
TO RAYNOLDS PASS

PLATE 19



MADISON RIVER, MONTANA

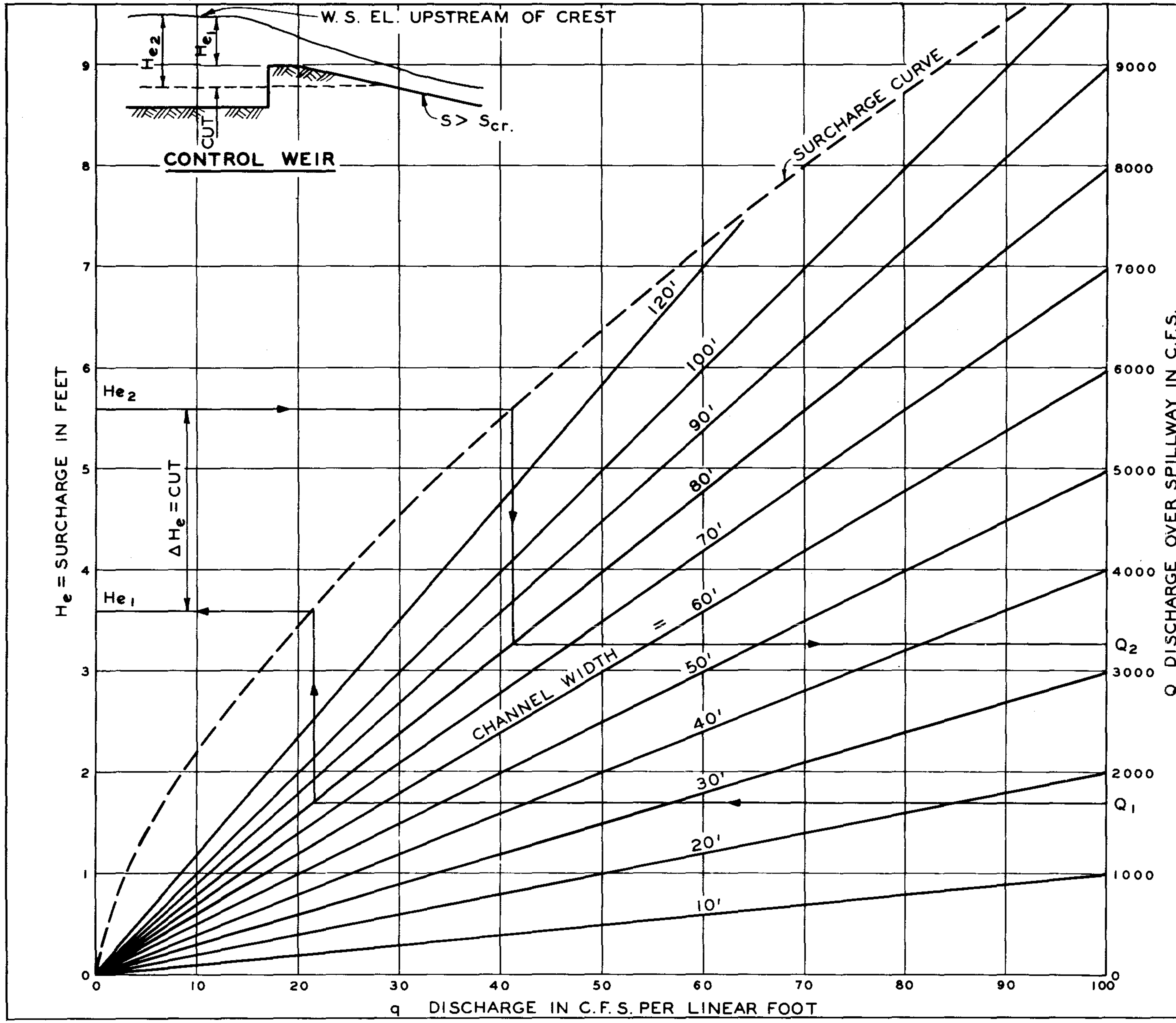
FLOOD EMERGENCY

MADISON RIVER SLIDE

VARIATION OF DEPTH, VELOCITIES AND STONE SIZE ALONG THE SPILLWAY CHANNEL AT DIFFERENT DISCHARGES

SEPT. 1960

THIS DRAWING HAS BEEN REDUCED TO THREE EIGHTHS THE ORIGINAL SCALE



NOTE:
THE PROCEDURE OF HOW TO FIND THE NEW DISCHARGE IS SHOWN ON THE CHART. THE APPROXIMATE WIDTH OF CHANNEL, THE PREVIOUS DISCHARGE AND THE DEPTH OF CUT ARE ASSUMED AS KNOWN VALUES. LOSSES ARE NEGLECTED.

MADISON RIVER, MONTANA
FLOOD EMERGENCY
MADISON RIVER SLIDE
EARTHQUAKE LAKE SPILLWAY
DISCHARGE INCREASE
BY CUTTING OF THE
CREST
SEPT. 1960