US Army Corps of Engineers

GEOTECHNICAL LABORATORY

ADA 158 193

TECHNICAL REPORT GL-85-5

THE VAIONT SLIDE, A GEOTECHNICAL ANALYSIS BASED ON NEW GEOLOGIC OBSERVATIONS OF THE FAILURE SURFACE

Volume II

APPENDICES A THROUGH G

by

A. J. Hendron, Jr., F. D. Patton

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

June 1985

Final Report

(In Two Volumes)

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Contract No. DACW39-79-C-0063

Monitored by Geotechnical Laboratory
US Army Engineer Waterways Experiment Station
PO Box 631, Vicksburg, Mississippi 39180-0631

Contents | Page

PART X: CONCLUSIONS.. 91
General Geology.. 91
Hydrogeology.. 93
Shear Strength of Clays.. 94
Stability Analyses.. 94
Precipitation and Reservoir Levels.. 95
Slide Velocity Studies.. 96
General Conclusions and Remarks.. 96
PART XI: LITERATURE CITED.. 99
Tables 1-13
Figures 1-43
Photos 1-52
APPENDICES*
A PRECIPITATION RECORDS ERTO 1960 TO 1963.. A1
B STATIC SLOPE ANALYSIS METHOD USED FOR THE VAIONT SLIDE ANALYSES by D. L. Anderson.. B1
C SECTIONS USED IN STABILITY ANALYSES.. C1
D THREE-DIMENSIONAL SLOPE STABILITY CALCULATIONS.. D1
E CALCULATION OF SLIDE VELOCITIES by D. L. Anderson.. E1
F HEAT GENERATED PORE PRESSURE MECHANISMS by D. L. Anderson.. F1
G SUMMARY OF GEOLOGICAL STUDIES ON THE SLIDE AT VAIONT, 1959-1964 by E. Semenza.. G1

---

* Appendices A-G are contained in Volume II.

APPENDIX A: PRECIPITATION RECORDS
ERTO 1960 TO 1963

Introduction

The official daily precipitation records for the town of Erto in the Piave River basin for the years 1960, 1961, 1962 and 1963 are given in this appendix in Tables A1, A2, A3 and A4, respectively. These were supplied through the courtesy of E.N.E.L.

The daily records are given in millimeters and tenths of millimeters. The total precipitation for each month is given at the bottom of each column along with the total number of days with precipitation. Finally, at the bottom of each table the annual precipitation together with the total number of days with measurable precipitation is presented. It should be noted that snowfall is not differentiated from rainfall in these tables.

List of Tables

Table A1. Daily precipitation record, Erto - 1960

Table A2. Daily precipitation record, Erto - 1961

Table A3. Daily precipitation record, Erto - 1962

Table A4. Daily precipitation record, Erto - 1963

Table A1

ERTO - 1960

(P) Basin: Piave (elev. 726 m)

Day	J	F	M	A	M	J	J	A	S	O	N	D
1				1.4	2.4	2.6		2.4		12.4		
2				0.9				8.6		3.9	5.3	
3	1.3		2.5			0.9	1.4	3.7			2.9	
4		1.5				6.5	4.6	9.8				
5		7.8	1.2			0.8		4.9	16.9	8.6	59.7	
6								13.6	26.5		1.6	32.8
7			2.6					11.2	0.8	42.5		140.7
8						14.3	20.5	12.1	0.7	5.3	0.3	34.5
9						0.2	32.3	12.7	4.6			9.7
10	5.3		9.4			7.7		6.3		43.2		33.6
11			20.3		8.9	12.6		0.2		17.3		21.4
12		21.6	15.6				27.4			15.1	24.4	
13		30.4	16.4				11.9	19.7		8.5	27.7	
14		11.3						0.4				3.3
15	20.5			16.8	0.2	25.4		8.9		110.6		
16	20.9		20.8	2.7		12.3	27.8	0.1	6.1	57.8		5.6
17			5.9		24.3		23.3		58.9			0.5
18		8.4		4.6					37.4			27.7
19		1.5		23.4	4.7			54.9	11.5			22.1
20					8.4	1.5			36.7			0.5
21					14.5		14.2		13.1	54.7		30.2
22					0.3		18.3		7.8	0.4		15.6
23		29.7			13.7		13.5				24.9	1.2
24		12.5	0.1		0.9		1.9			5.9	4.8	
25			0.3		0.2				21.6	12.3		0.7
26	6.3		0.7			16.7				17.6		
27	7.8		0.5	0.9		14.8	0.2			4.8		
28	9.2						18.8			0.7		
29	12.9		3.4	1.5		6.7		6.9		20.3	21.3	1.9
30	3.1				0.3	19.5			15.3	52.9		
31			12.6		0.1			24.6				
Total monthly precipitation	87.3	124.7	112.3	52.2	78.9	142.5	216.1	201.0	257.9	494.8	172.9	382.0

Note: all precipitation in mm

Total annual precipitation: 2322.6 mm
Days with precipitation: 135

Table A2

ERTO - 1961

(P) Basin: Piave (elev. 726 m)

Day	J	F	M	A	M	J	J	A	S	O	N	D
1		7.8										
2	6.3	1.5				12.9				2.4		
3						0.4		0.5				
4	69.4			3.3		5.5		12.9			10.4	0.9
5	4.6					3.6	33.8				1.7	
6						0.3	5.6		1.2			18.5
7						5.6	0.5		17.6	52.6	4.9	30.6
8		4.2				2.3	10.9		0.7	76.9	3.6	
9						5.7			17.9	16.7		
10						9.8					61.9	
11	10.7					2.2					10.7	
12	19.6					7.4	3.9	4.7			12.8	
13						0.3	9.6	7.8	0.8		122.9	
14						0.4	10.4				14.7	
15				11.4				4.6			7.3	
16				22.5	21.2		29.2	10.5				
17				2.1	6.9	3.6	22.4	0.1				
18				2.6		0.5	6.8			18.9		
19				24.7			11.3			40.3		
20			12.6				10.9	1.7				
21		7.5		2.5	16.5		5.8					
22				0.8	12.7	11.7	15.2					
23				9.4		1.2	4.1					
24				14.3	6.4		4.7				4.4	0.4
25					0.6		3.2				0.7	
26					1.3	5.9						
27				3.9	8.2	7.2					13.9	2.6
28				1.3	25.8	53.3					3.7	0.4
29				5.4	34.6		13.3			9.7		
30				2.6				1.1			12.5	
31												8.5
Total monthly precipitation	110.8	21.0	12.6	106.8	134.2	139.9	201.6	43.9	38.2	217.5	286.1	61.9

Note: all precipitation in mm

Total annual precipitation: 1374.4 mm
Days with precipitation: 99

Table A3

ERTO - 1962

(P) Basin: Piave (elev. 726 m)

Day	J	F	M	A	M	J	J	A	S	O	N	D
1	10.7				0.3	4.9	6.3				51.5	
2	5.4		0.8	0.7		18.9	0.4				2.3	
3	1.6		3.6			20.7						
4	5.3		3.4	1.5			12.3					
5	0.2		41.9	13.6	1.2		11.1	0.2	7.8			
6			26.3	3.4			16.8				94.6	
7			4.7				24.5	0.3		2.4	62.4	
8								6.7	1.4	5.3	29.7	
9		10.1		1.9					0.5	1.5	47.2	
10	0.7		0.6	12.5		1.1	5.3	1.6			6.9	
11	1.6		0.3		38.5	1.4					1.2	
12	57.4		3.8		15.6	0.9					1.8	
13			0.2		11.4		8.7				3.3	31.7
14		0.9		13.8	74.3				0.2	9.8	1.4	6.1
15				165.9			0.9				16.7	
16				32.5		1.3	28.4	38.8			6.5	
17				3.3		4.8	2.9	5.2	0.3		6.3	
18				6.9		0.2		4.5	26.5		4.6	
19				1.5		0.1	3.5				4.9	
20					42.7	1.6					4.4	
21					6.9	10.7			0.6		4.9	
22						4.5		0.2			1.5	
23							1.8				0.8	
24			0.3				6.3					
25					14.6							
26		0.7			45.4	7.4						
27		13.3				22.2					60.4	
28				6.4	0.7	23.6	3.6			1.3		
29					0.4		31.9			56.7		0.2
30					4.5	2.4	18.5	2.7		3.6		3.0
31			4.8		0.6		1.3	0.6		5.4		
Total monthly precipitation	82.9	25.0	95.7	263.9	257.1	126.7	184.5	60.8	37.3	86.0	413.32	41.2

Note: all precipitation in mm

Total annual precipitation: 1674.4 mm
Days with precipitation: 108

Table A4

ERTO - 1963

(P) Basin: Piave (elev. 726 m)

Day	J	F	M	A	M	J	J	A	S	O	N	D
1	Readings Not Available				9.3				0.6		"	"
2					1.2	8.8			0.3		"	"
3		3.6			2.0	4.2	3.0			28.7	"	"
4		6.1			18.5	3.8				21.7	"	"
5					1.0	27.7	9.5		54.5	4.5	"	"
6						18.2	2.1		23.5		"	"
7				49.8		12.1		3.0	22.7		"	"
8				5.6		1.3		12.5	3.7	10.1	"	"
9							11.7	1.4	7.2		"	"
10			3.4	1.4				2.5		"	"	"
11			2.7	32.6	1.6	4.6	13.6			"	"	"
12		38.2	21.5		2.0		4.9			"	"	"
13		9.5	7.1	0.7	8.0	0.3		11.0		"	"	"
14		2.4		9.1	9.6	1.5	1.6	8.8		"	"	"
15					9.8	39.0	0.7	20.8		"	"	"
16					30.9	0.7		18.5		"	"	"
17		1.7			1.1			4.0		"	"	"
18				1.4	4.8		1.0	99.1		"	"	"
19		2.0		16.0	4.9			5.5		"	"	"
20		10.2			3.8	0.7			34.0	"	"	"
21			28.0				2.2		1.3	"	"	"
22							6.6	24.0		"	"	"
23							18.9		1.7	"	"	"
24				11.3		14.5				"	"	"
25					16.1	0.9			5.0	"	"	"
26					9.8	13.0	0.7		9.0	"	"	"
27							8.8			"	"	"
28			1.5				1.8	18.8		"	"	"
29					10.2			12.7		"	"	"
30			1.5		2.5			15.1		"	"	"
31			59.2							"	"	"
Total monthly precipitation		73.7	124.9	127.9	147.1	151.3	87.1	257.7	163.5	65.0	390.0	50.0

Note: all precipitation in mm

Total annual precipitation: 1708.4 mm
Days with precipitation: 130

APPENDIX B: STATIC SLOPE ANALYSIS METHOD USED FOR THE VAIONT SLIDE ANALYSES

By D. L. Anderson

Introduction

The program used to calculate the factor of safety (FS) considers the potential slide surface as a series of planes. The slide is subdivided into elements with vertical boundaries between elements. The effective forces between elements are inclined at the angle β to the horizontal, where the magnitude of the value of β is input to the program. The analysis satisfies the vertical and horizontal equilibrium but rotational equilibrium is not considered.

The program thus differs from the many of the more widely known methods of assessing slope stability, and is closest to the procedure of Spencer (1967).

Program Procedure

For a potential sliding surface the slide is subdivided into elements as shown in Figure B1. The forces (F) considered on each slice are shown in Figure B2.

For a known F_1 and a specified shear strength relationship between R and N, translational equilibrium determines F_2, R, and N. Once F_2 is known this becomes F_1 for the next slice downhill, and the same calculations can be performed on it and subsequent slices. Thus, by starting at the top where F_1 is zero, one can work downhill, satisfying translational equilibrium along the way, and determine what force would be required on the last slice, the toe element, in order to maintain equilibrium.

The factor of safety (FS) used here is the same as that generally used, and is the ratio of the strength of the soil to the strength required for equilibrium. The FS is incorporated in the program by altering the soil resistance R using the following equation:

$$R = (cL_s + N \tan \phi) \frac{1}{FS} \tag{B1}$$

where: L_s = the length of slice along the failure surface

c = "effective" cohesion

ϕ = "effective" angle of shearing resistance

N = "effective" normal base reaction

The computer program starts with FS equal to 1.0 calculates F_2 on the toe slice (where β_2 has been assumed zero), and on the basis of the ratio of this F_2 to the sum of the R forces over the entire slide, calculates a new FS. Using this FS the toe force F_2 is again calculated, and is then used to alter the FS again. This iterative procedure is repeated until the toe force becomes small and the change in FS from one iteration to the next is small; generally the allowable error in FS was taken as 0.001. For a well defined problem the number of iterations was generally between 2 and 8. However, in some cases the FS did not converge in 20 iterations, the maximum number ever considered. When this happened a locking wedge was generally to be found at the toe of the slide. This will be elaborated upon below.

The program has been made general enough to consider separate values of the weight, void ratio, cohesion and friction angle for each slice, different values of β between each slice and differences between the ground water level and the piezometric pressure along the base of the slide.

<u>Inclination of the Interelement Slice Forces - β Values</u>

The value assigned to β represents the shear resistance of the soil to sliding on vertical planes.

The absolute value of β is input into the problem, but the direction of β is determined by the relative slopes of the two adjacent slices. If the failure surface of three slices is as shown in Figure B3a, and if the slide moves downhill, then the lower part of slice (1) must be deformed upward, as shown in Figure B3b, and so the inter-element force must provide an upward force on slice (1) as shown in Figure B3c. Thus, β_2 for slice (1) would be positive (assuming F_2 is positive). Following the same argument β_2 would be negative for slice (2). Assigning these directions and performing the static analysis as previously described, gives the same results as accounting for the work done in deforming the slide as it moves over changes in the slope of the failure surface. The latter is similar to the upper-bound limit analysis of plasticity theory.

For slides with a relatively uniform failure surface, the magnitude of β has very little influence on the FS, as would be expected. However, for irregular failure surfaces and those slides with sharply upturning toes, the strength along vertical planes as represented by β can make a substantial change in the FS. A lower FS can be calculated by asssuming the inter-element slices to be at an angle to the vertical (while maintaining the same β frictional angle). It would be desirable to minimize the FS by altering the direction of the inter-element slices. However, this would increase the computing costs by a considerable margin. If mainly comparative values of the FS for different water conditions are desired, this increase in computing costs is not considered to be warranted.

Toe Wedges

If the toe has a sharply upturning failure surface, it may possibly form a toe wedge that theoretically makes the overall slide very stable, sometimes leading to an infinite value of the computed factor of safety, which is independent of the stability of the material above the toe wedge. In reality this would not occur as the toe would tend to fail along a different failure surface that did not provide this wedging effect, or the slope of the inter-element slide plane would be different from vertical.

Figure B4a shows a toe element and the forces acting upon it; the pore pressure forces have been omitted for clarity. Figure B4b shows the usual vector diagram of these forces where the ϕ required for equilibrium (ϕ*) is determined. If $\phi^* \leq \phi$ the toe is capable of resisting the applied F_1.

If $\phi + \beta_1 + \theta > 90°$ the toe will be stable for any value of F_1 and thus a stable wedge is formed (the pore pressure forces generally modify this result only slightly).

The computer program may converge even though an "infinitely stable" wedge is a possibility. This occurs because the definition of the FS and the way it is incorporated in the program leads to a reduction in the effective ϕ value if FS becomes large. Thus, if at any stage in the interative procedure

$$\phi/_{FS} + \beta_1 + \theta < 90° \qquad \text{(B2)}$$

the wedge is effectively removed and the program converges to something near this FS, which is not necessarily a reasonable value for the overall slide. Thus, for those cases with sharply upturning toes where $\phi + \beta_1 + \theta$ is approaching 90° the results from this or other methods of analyses should be viewed with caution.

Rotational Equilibrium - Comparison with the Program of Morgenstern and Price

The static analysis program developed here does not consider rotational but only translational equilibrium of the slide mass. Accounting for rotational equilibrium was not considered important for a translational type of slide such as Vaiont.

To check this assumption, and also to check the program, a few selected slides were analyzed using the Morgenstern and Price (1965) program, a program which accounts for rotational equilibrium. Morgenstern and Price's program (M & P program) defines the FS in the same manner, but rather than specifying absolute values of β, only relative values at the slides can be input into the analysis. The M & P program output then gives a value of FS and the values of β (consistent with the relative values input) required for both translational and rotational equilibrium, and requiring that the thrust line of the interslice forces passes through the slide mass. If the program cannot find a solution satisfying the above criteria, it does not converge.

For comparison purposes the output values of β from an M & P analysis were input into the program developed for this study. The calculated FS was the same in both cases. Thus, it was concluded that rotational equilibrium is not an important consideration in translational types of slides considered here.

The main reasons for producing a new program rather than using the M & P program were the following:

a. The value of β cannot be input into the M & P program. Consequently it is not possible to compare the FS of the same slide where, for example, only the piezometric pressures were changed. In the M & P program the value of β would also change.

b. In the M & P program, the water level can only be specified at the top and bottom of the slide. The pore pressures on the sides of the slide sections are based on the piezometric level only, which is not valid if the piezometric level is above the ground level.

c. The input and output data could be made more suitable for a large number of slide analyses, and the program was made more efficient since rotational equilibrium was not analyzed.

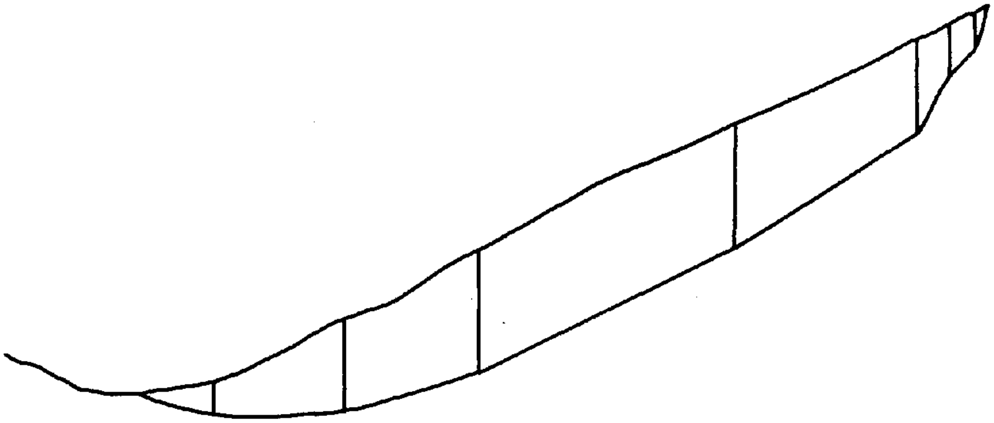
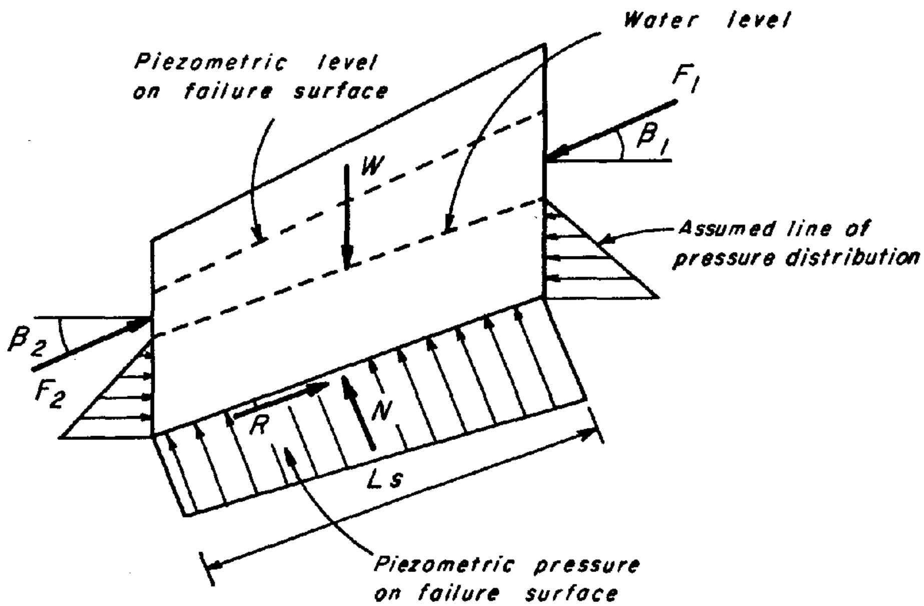


Figure B1. Subdivision of slide into slices



W = *total weight of soil and water above the failure surface*

N = *effective reaction normal to the failure surface*

R = *shearing resistance of the soil*

F_1, F_2 = *interelement forces between adjacent slices*

β_1, β_2 = *inclination of the interelement forces from the normals to the slice faces.*

Figure B2. Forces on a typical slice of a slide

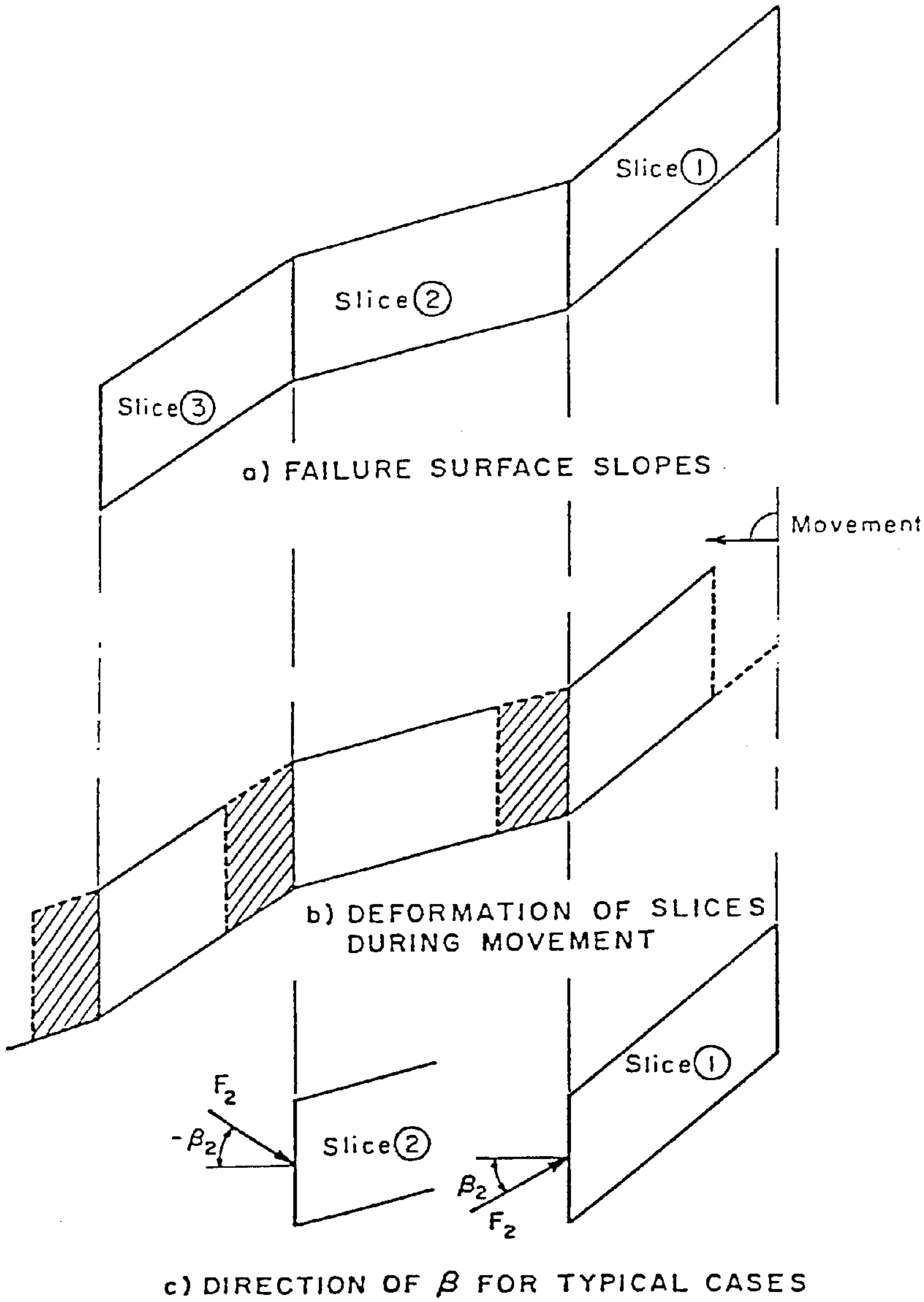
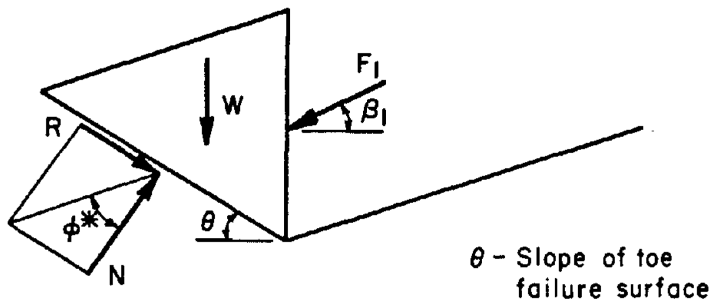
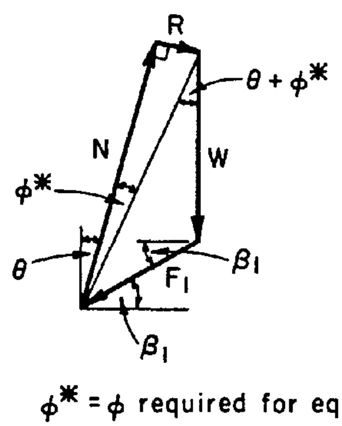


Figure B3. Illustration of method for assigning direction of frictional forces between slices



a) Forces on toe wedge



b) Vector Diagram of toe forces

Figure B4. Treatment of forces acting on the toe of a slide

APPENDIX C: SECTIONS USED IN STABILITY ANALYSES

Introduction

Computer assisted drawings of the sections used in the final stability analyses of the Vaiont Slide for this study are given in this appendix. The sections show:

a. the ground surface prior to the slide (solid line)

b. the interpreted surface of sliding (solid line)

c. the interpreted groundwater table (long dashes)

d. the interpreted piezometeric levels acting on the surface of sliding (short dashes)

e. the sides of the slices used in the analyses (solid vertical lines)

The three sections are referred to as "Semenza Section 2," "Semenza Section 5" and "Semenza Section 10 Extended." These refer to sections shown on the geologic map of the slide before October 9, 1963 by Rossi and Semenza (1965a) which is reproduced as Figure 11 in this study. These sections correspond to the geologic sections drawn by Rossi and Semenza, shown as Figures 15, 17 and 19 in this study. For geologic details we would refer the reader to the Rossi and Semenza sections. Note that elsewhere in this study "Section 10 Extended" is called Section 10A.

The analyzed sections included here are for the no reservoir condition, the 650 m reservoir and the 710 m reservoir.

Each section is analyzed for two rainfall conditions: 1) a low rainfall condition described in these figures as "no rainfall" or "no rain", and 2) a high rainfall condition described in these figures as "rainfall", "with rain" or "with rainfall."

The figures are plotted to true scale, i.e., the horizontal scale equals the vertical scale. The actual scale used was 400 ft (122 m) for each major division shown.

List of Figures

Figure C1. Vaiont Slide - Semenza Section 2,
No reservoir, no rainfall

Figure C2. Vaiont Slide - Semenza Section 2,
No reservoir, rainfall

Figure C3. Vaiont Slide - Semenza Section 2,
650 m reservoir, November 1960, no rainfall

Figure C4. Vaiont Slide - Semenza Section 2,
650 m reservoir, November 1960, with rain

Figure C5. Vaiont Slide - Semenza Section 2,
710 m reservoir, October 1963, no rainfall

Figure C6. Vaiont Slide - Semenza Section 2,
710 m reservoir, October 1963, with rainfall

Figure C7. Vaiont Slide - Semenza Section 5,
no reservoir, no rainfall

Figure C8. Vaiont Slide - Semenza Section 5,
no reservoir, with rainfall

Figure C9. Vaiont Slide - Semenza Section 5,
650 m reservoir, November 1960, no rain

Figure C10. Vaiont Slide - Semenza Section 5,
650 m reservoir, November 1960, with rain

Figure C11. Vaiont Slide - Semenza Section 5,
710 m reservoir, October 1963, no rain

Figure C12. Vaiont Slide - Semenza Section 5,
710 m reservoir, October 1963, with rainfall

Figure C13. Vaiont Slide - Semenza Section 10 Extended, Shallow
no reservoir, no rainfall

Figure C14. Vaiont Slide - Semenza Section 10 Extended, Shallow
no reservoir, with rainfall

Figure C15. Vaiont Slide - Semenza Section 10 Extended, Shallow
650 m reservoir, November 1960, no rain

Figure C16. Vaiont Slide - Semenza Section 10 Extended, Shallow
650 m reservoir, November 1960, with rain

Figure C17. Vaiont Slide - Semenza Section 10 Extended, Shallow
710 m reservoir, October 1963, no rain

Figure C18. Vaiont Slide - Semenza Section 10 Extended, Shallow
710 m reservoir, October 1963, with rain

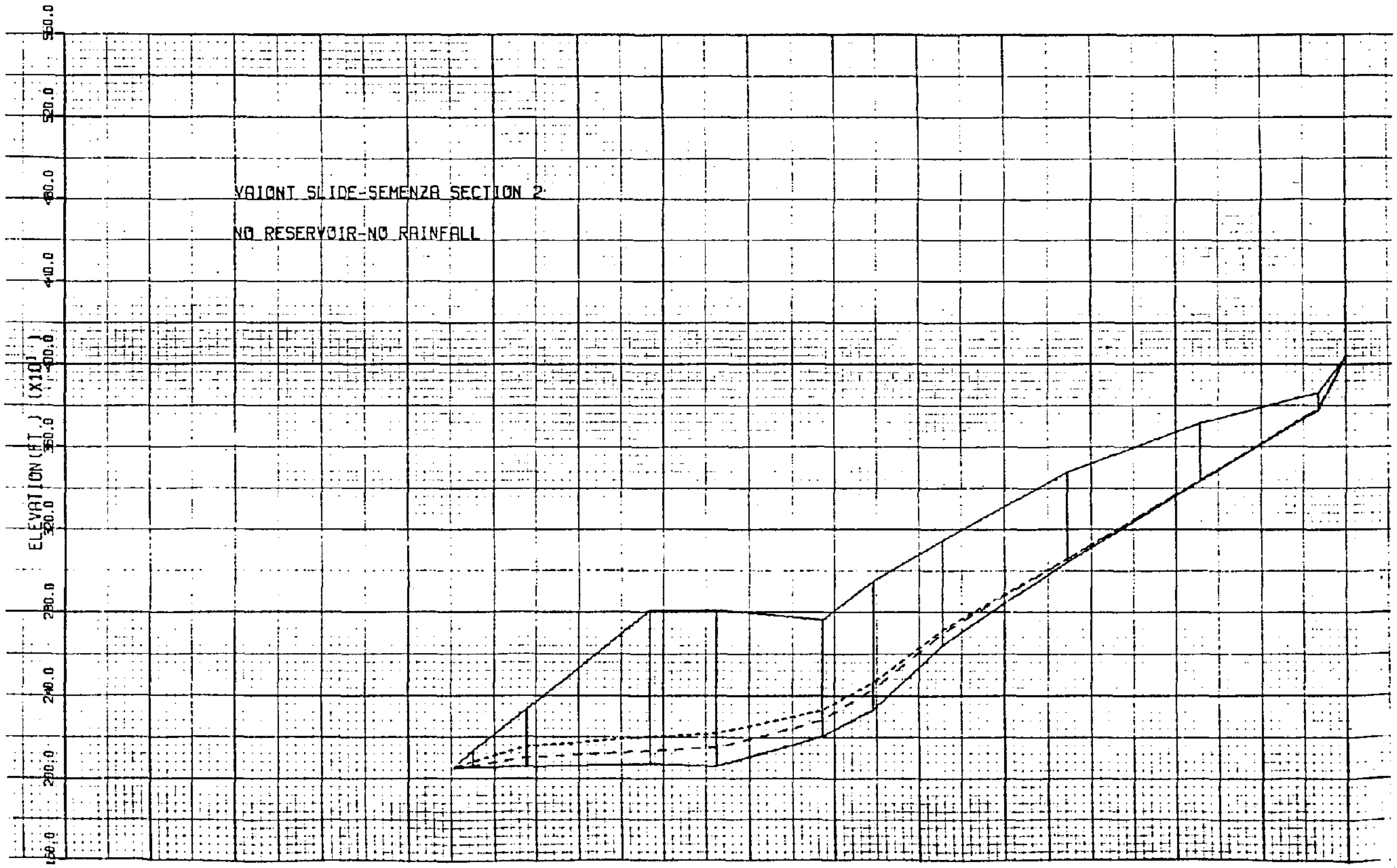


Figure C1. Vaiont Slide - Semenza Section 2, No reservoir, no rainfall

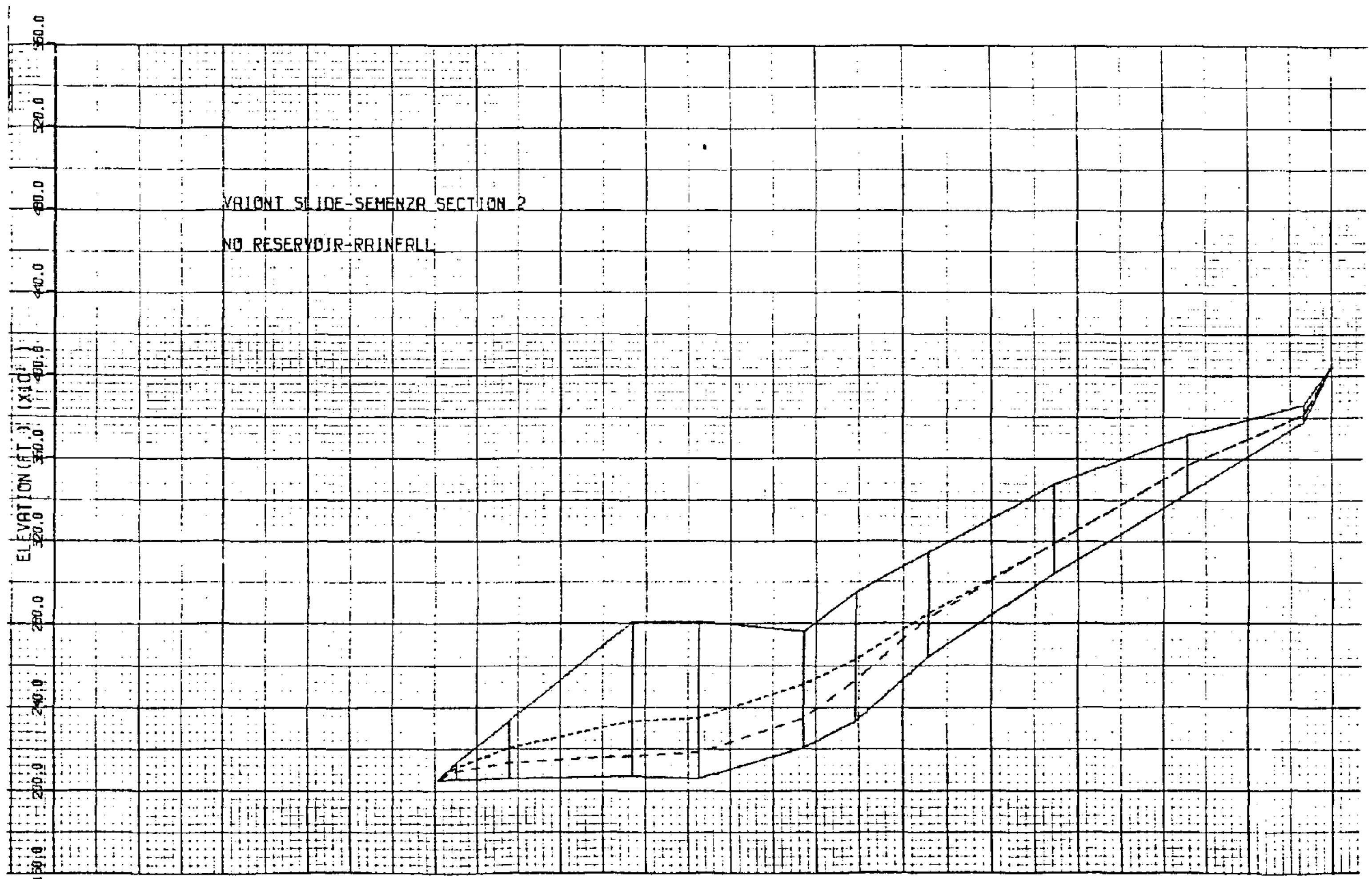


Figure C2. Vaiont Slide - Semenza Section 2, No reservoir, rainfall

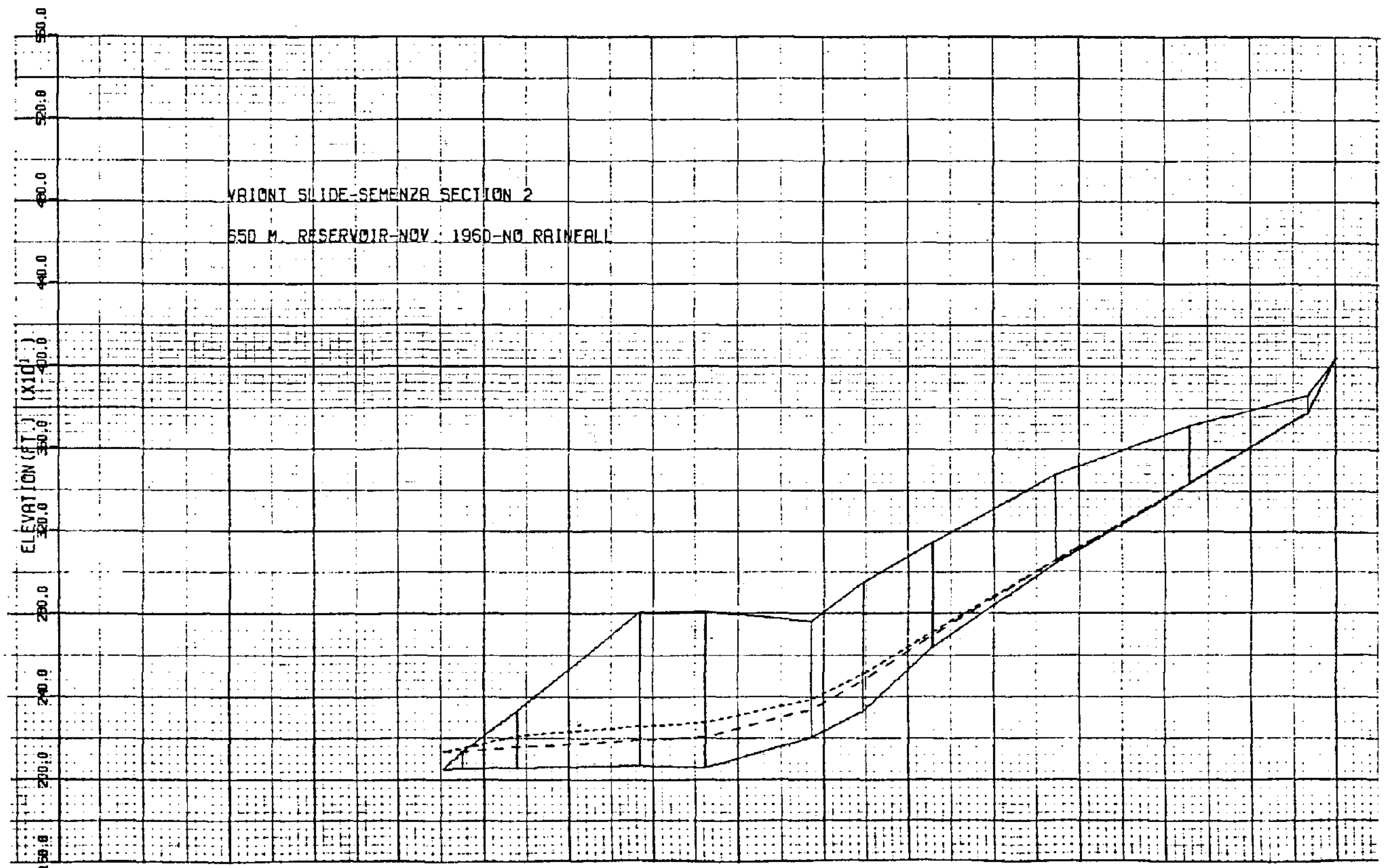


Figure C3. Vaiont Slide - Semenza Section 2, 650 m reservoir, November 1960, no rainfall

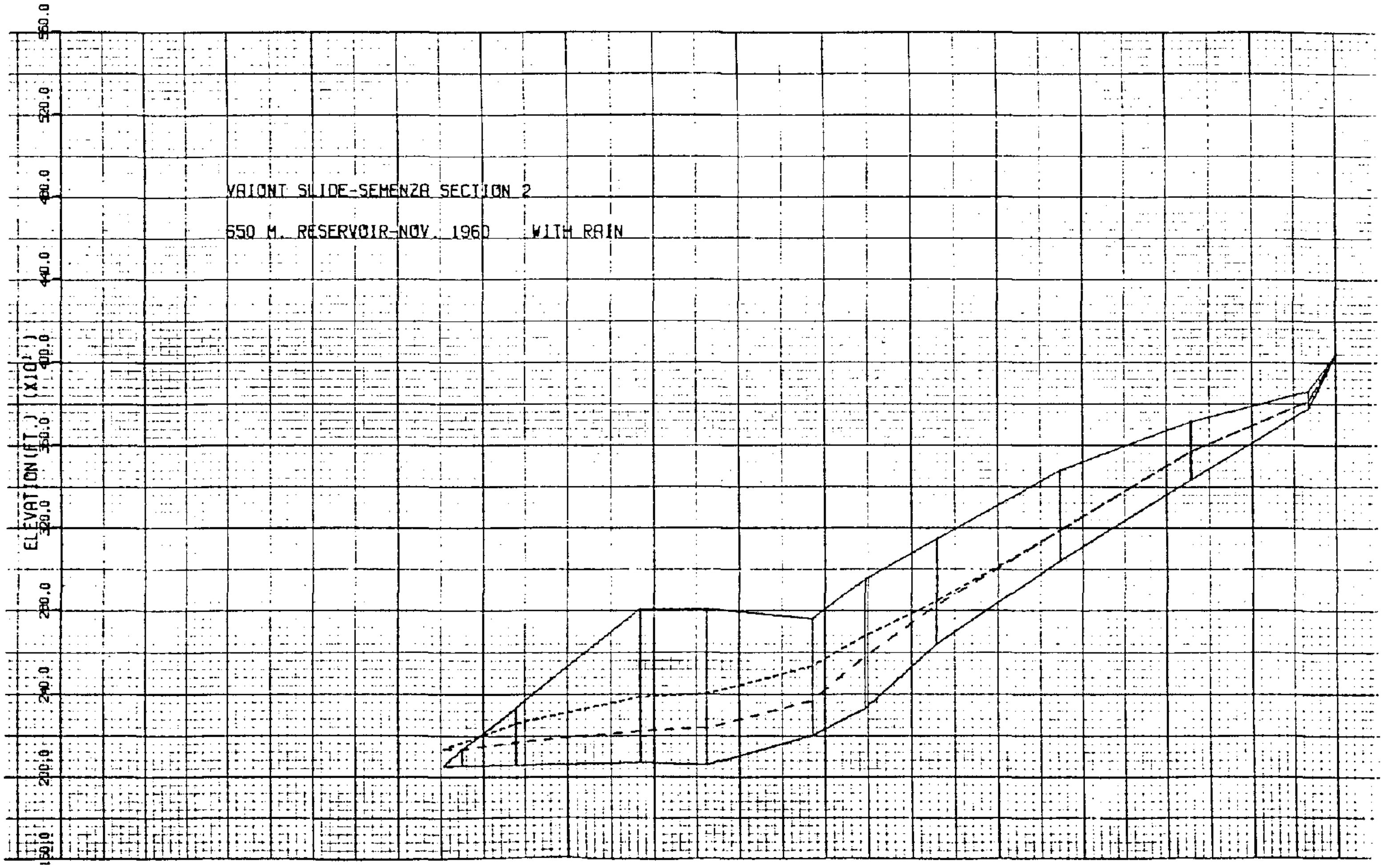


Figure C4. Vaiont Slide - Semenza Section 2, 650 m reservoir, November 1960, with rain

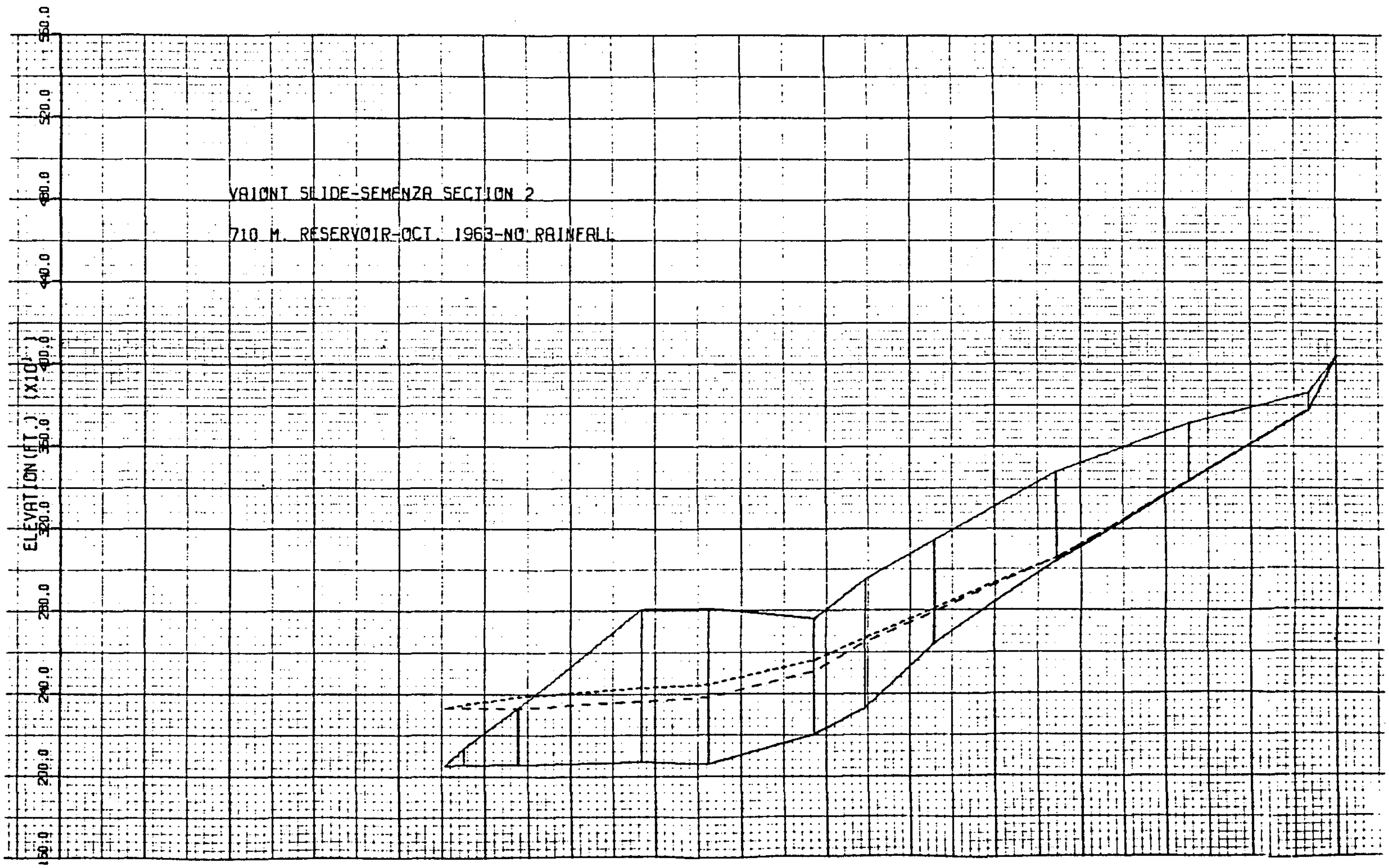


Figure C5. Vaiont Slide - Semenza Section 2, 710 m reservoir, October 1963, no rainfall

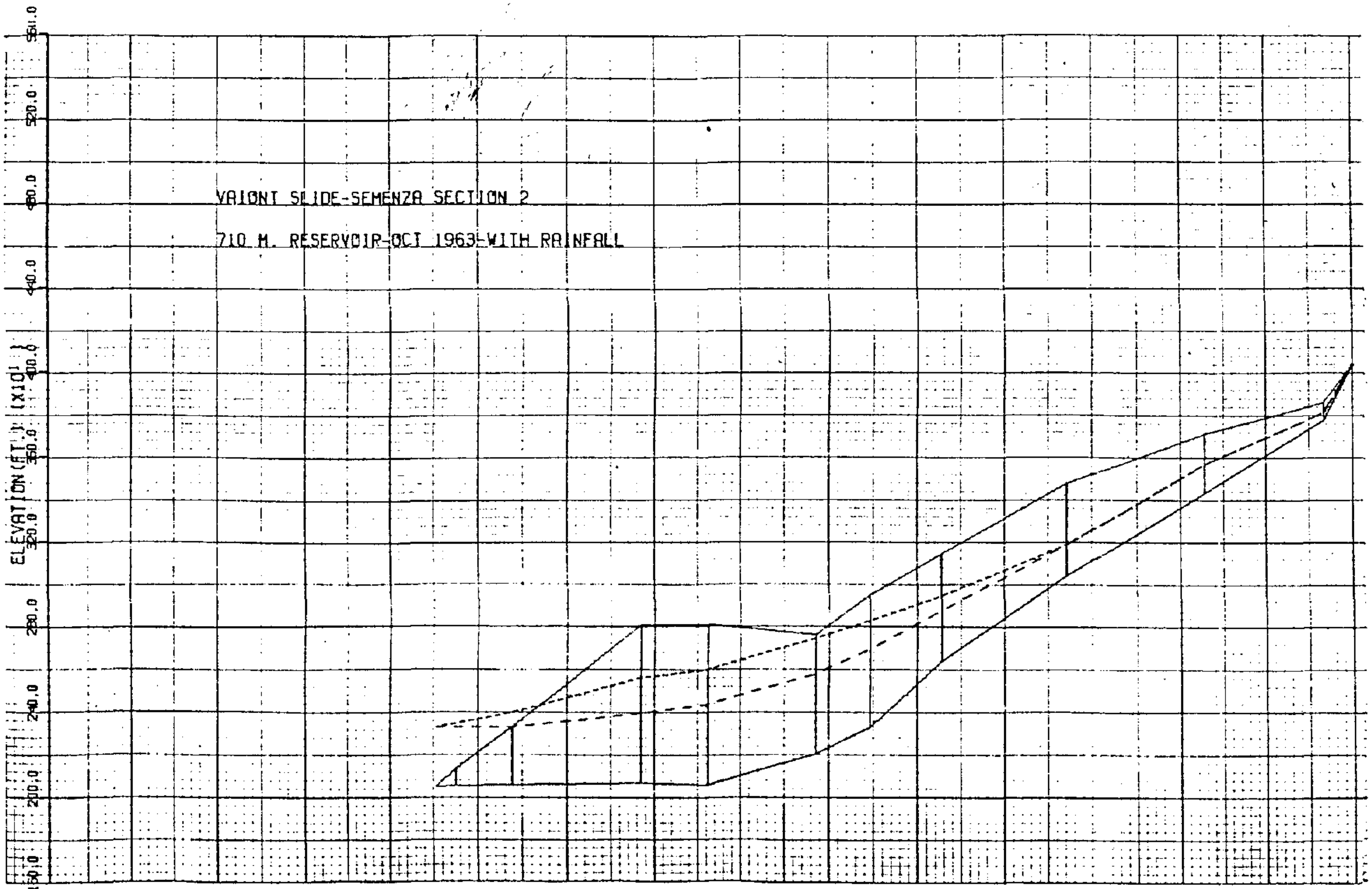


Figure C6. Vaiont Slide - Semenza Section 2, 710 m reservoir, October 1963, with rainfall

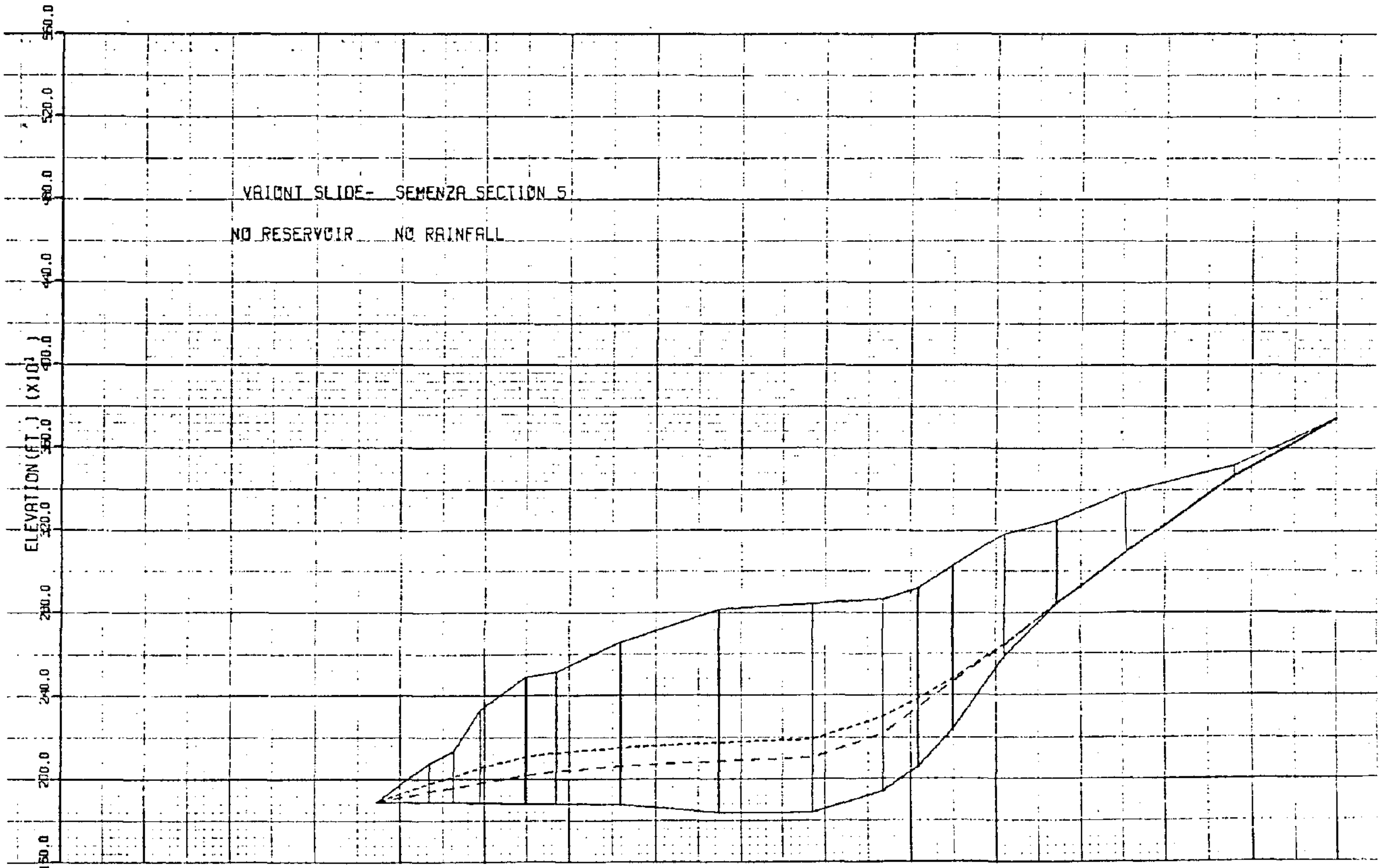


Figure C7. Vaiont Slide - Semenza Section 5, No reservoir, no rainfall

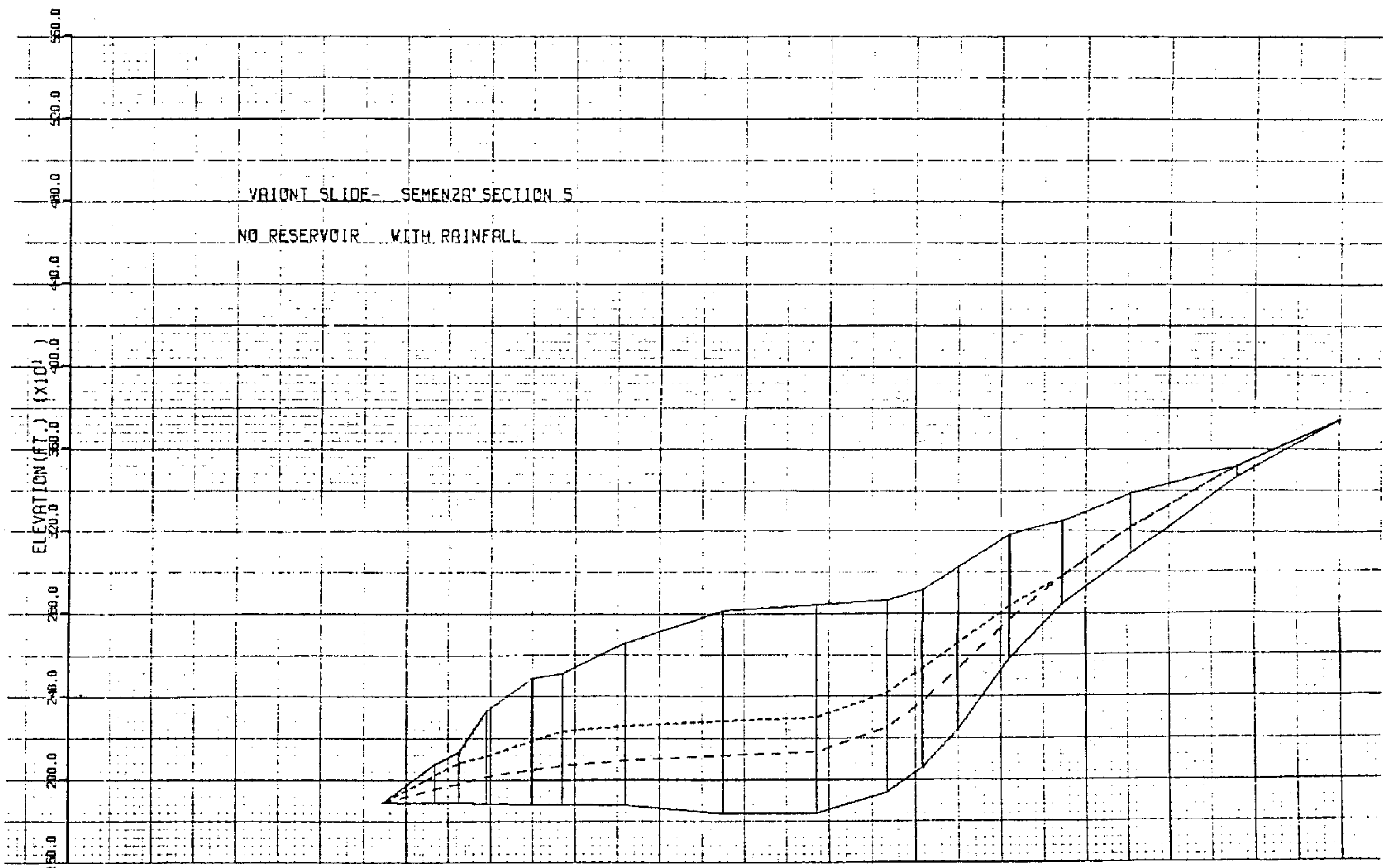


Figure C8. Vaiont Slide - Semenza Section 5, No reservoir, with rainfall

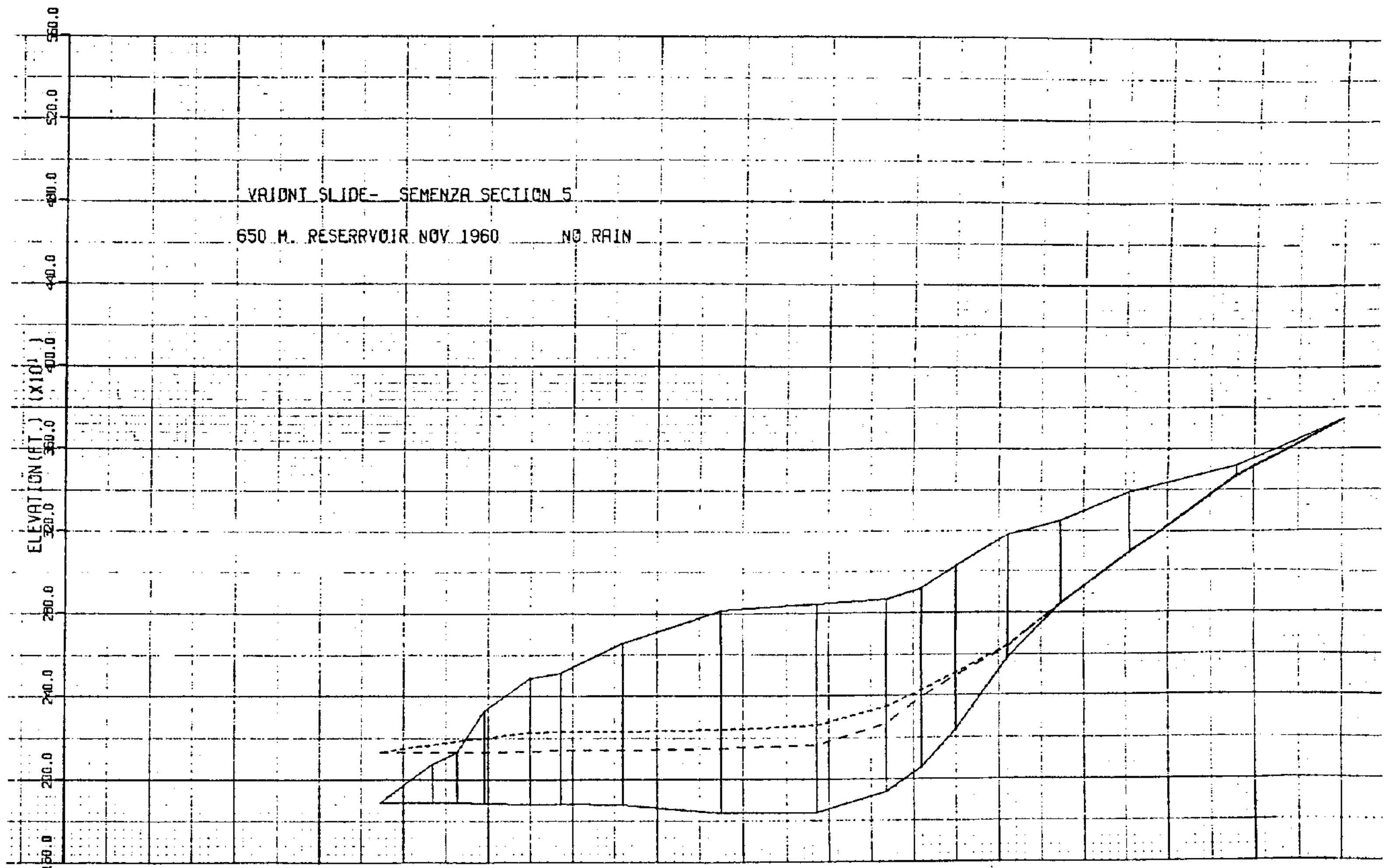


Figure C9. Vaiont Slide - Semenza Section 5, 650 m reservoir, November 1960, no rain

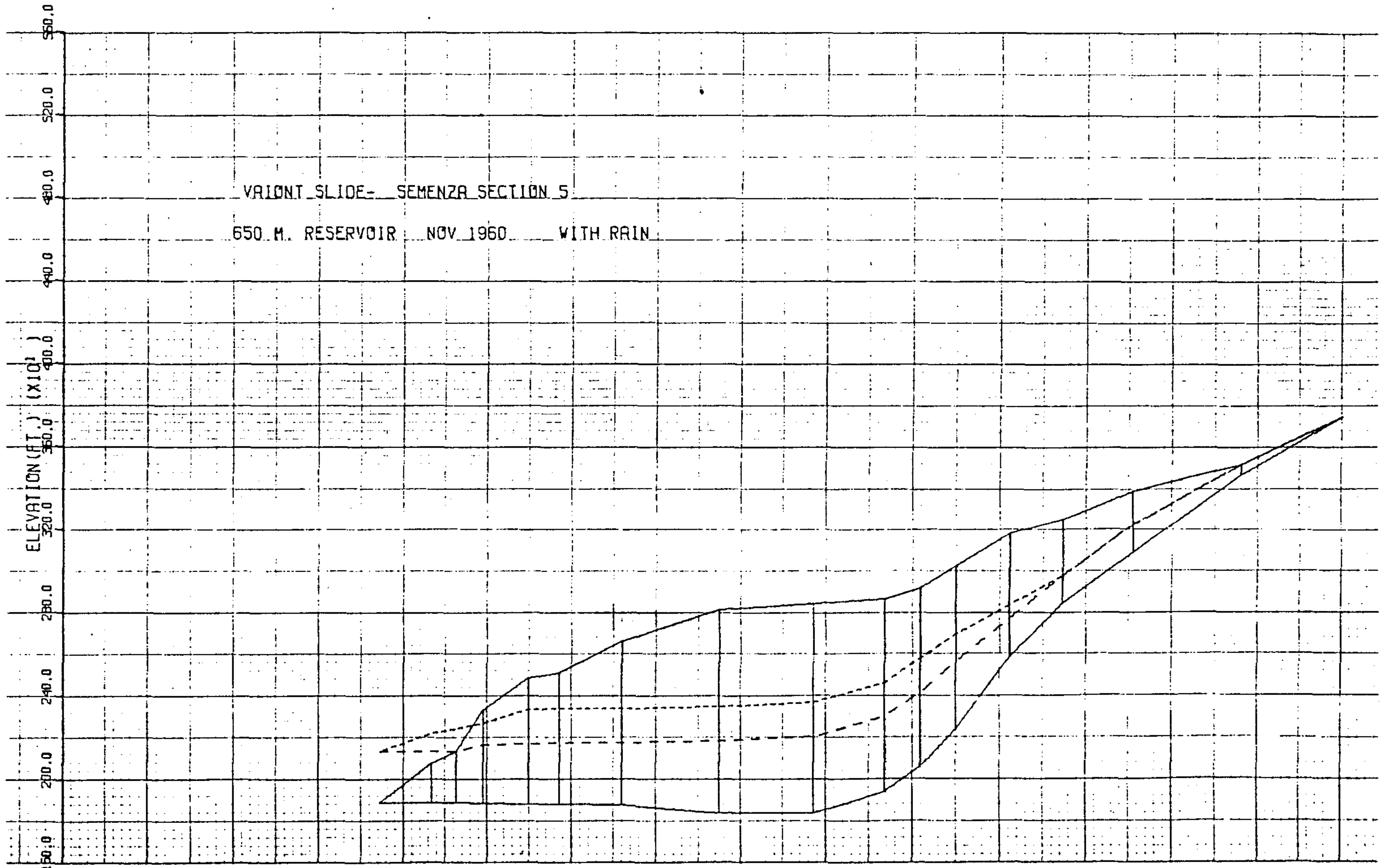


Figure C10. Vaiont Slide - Semenza Section 5, 650 m reservoir, November 1960, with rain

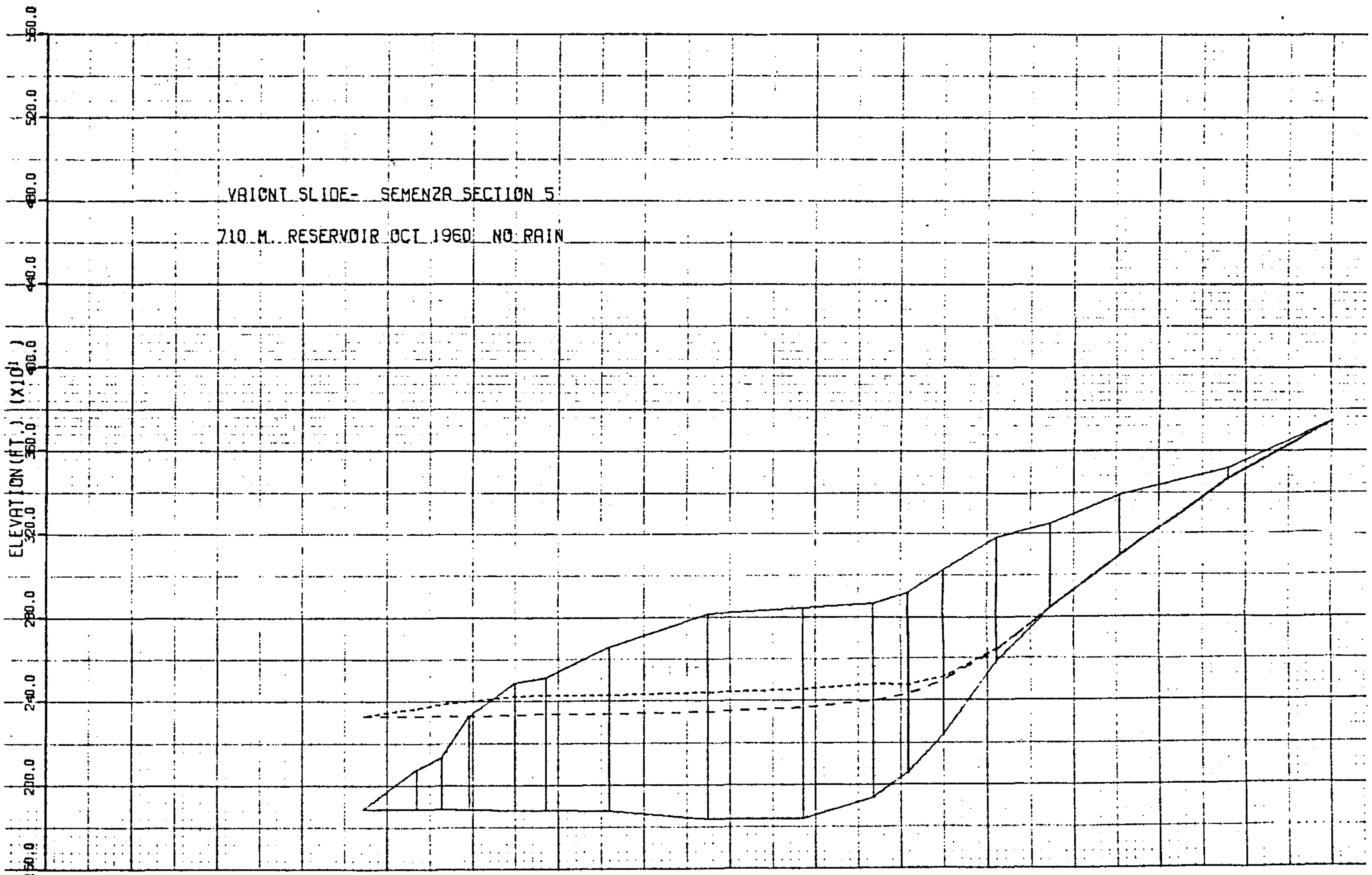


Figure C11. Vaiont Slide - Semenza Section 5, 710 m reservoir, October 1963, no rain

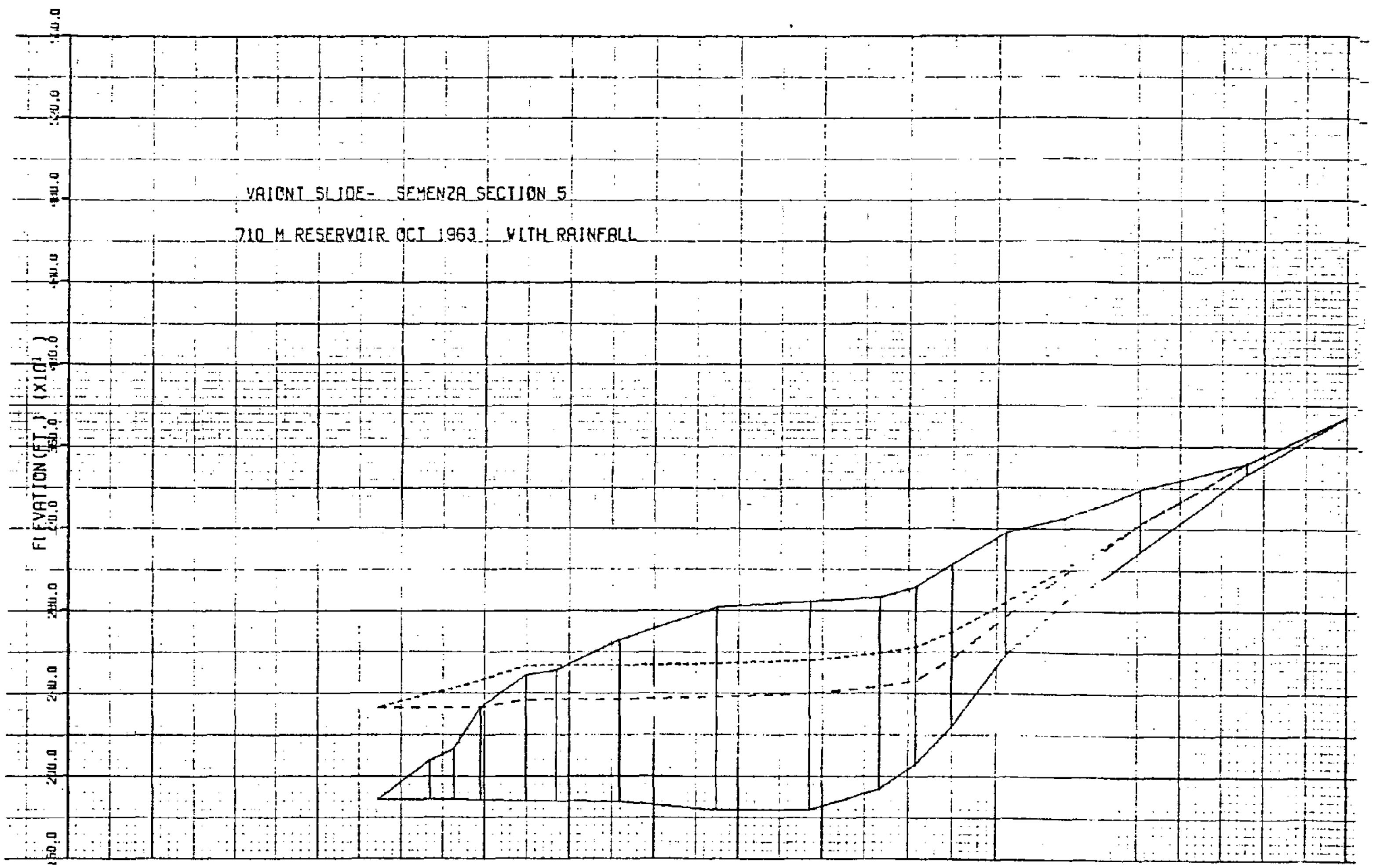


Figure C12. Vaiont Slide - Semenza Section 5, 710 m reservoir, October 1963, with rainfall

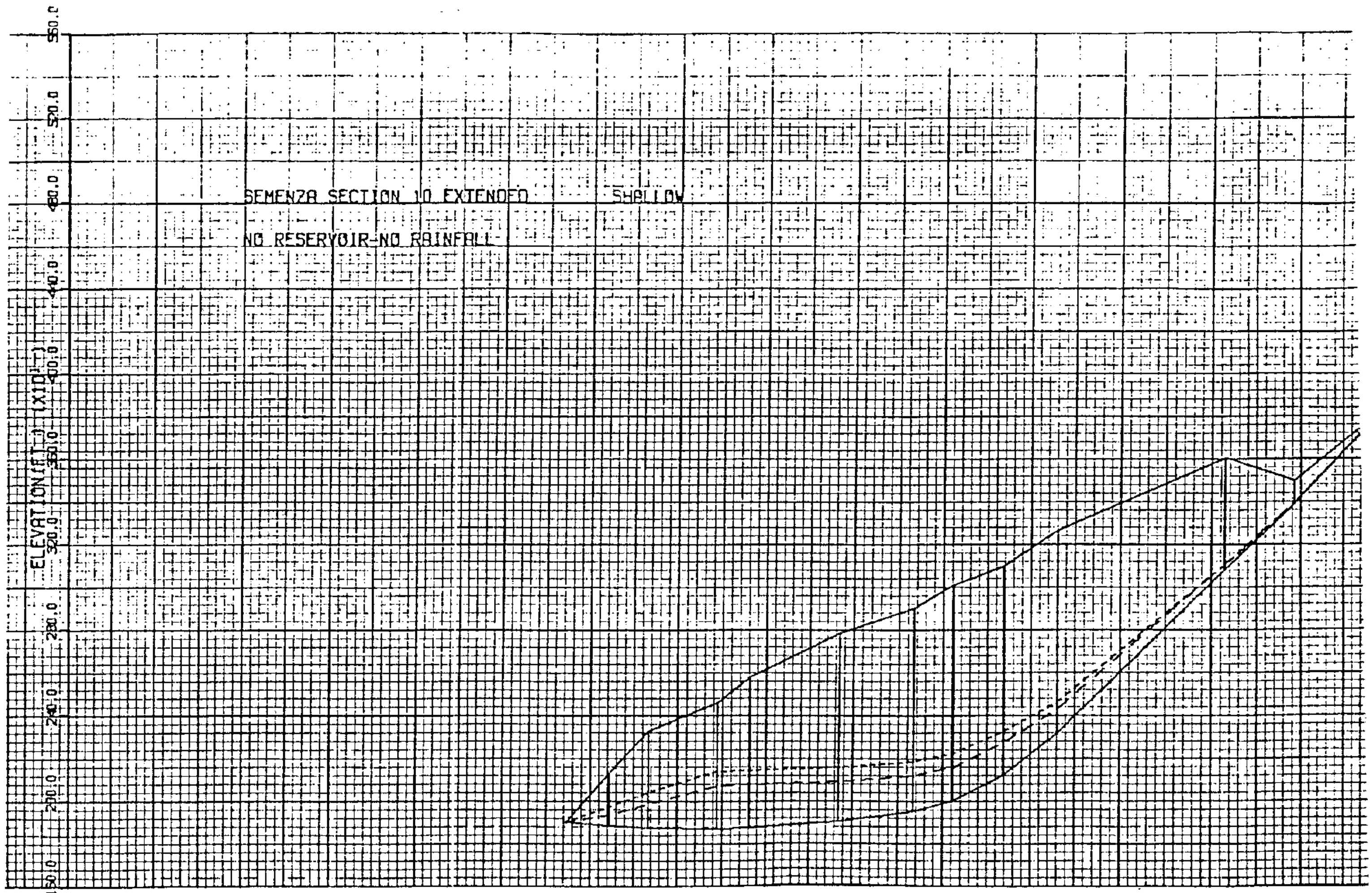


Figure C13. Vaiont Slide - Semenza Section 10 Extended, Shallow, No reservoir, no rainfall

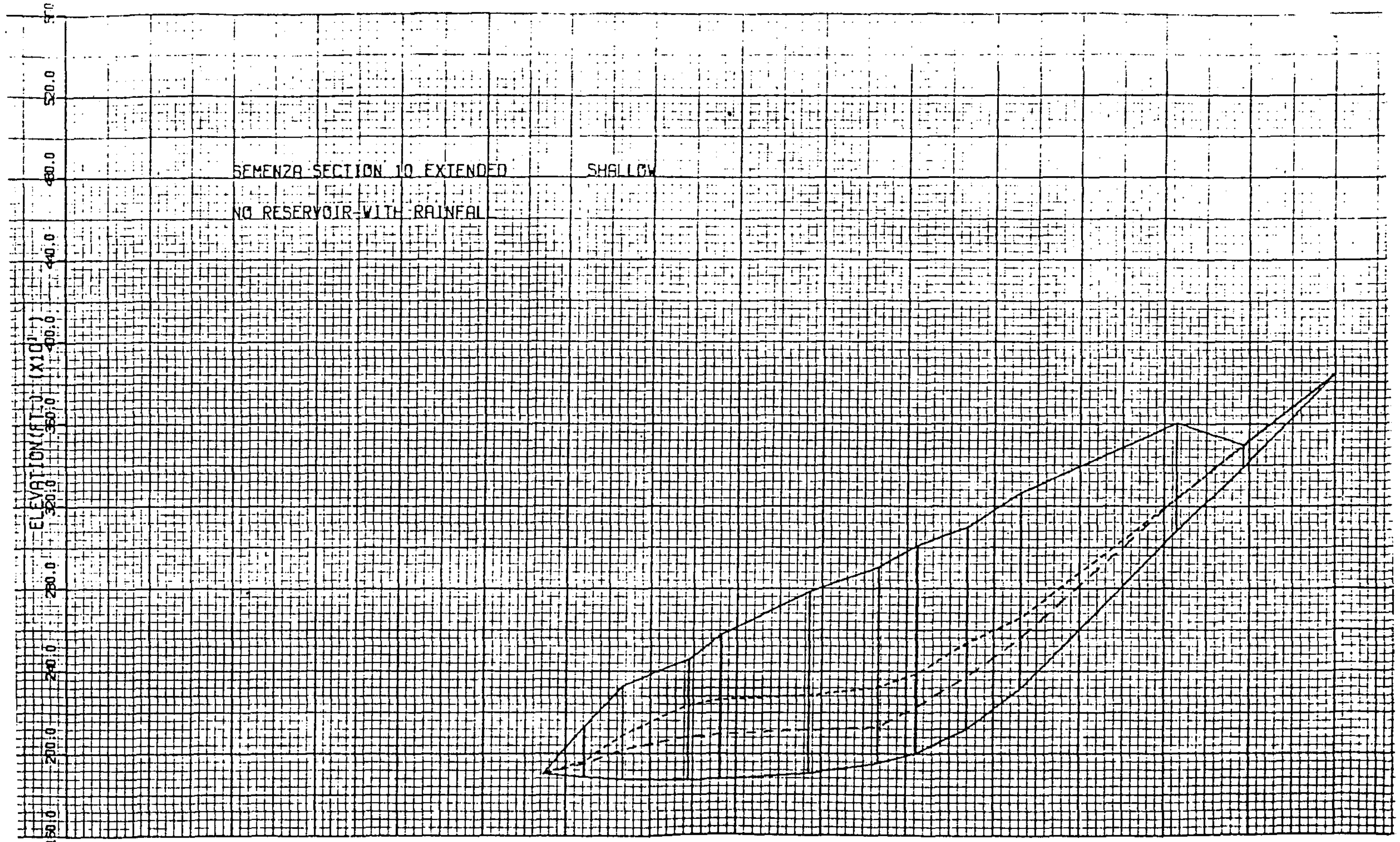


Figure C14. Vaiont Slide - Semenza Section 10 Extended, Shallow, No reservoir, with rainfall

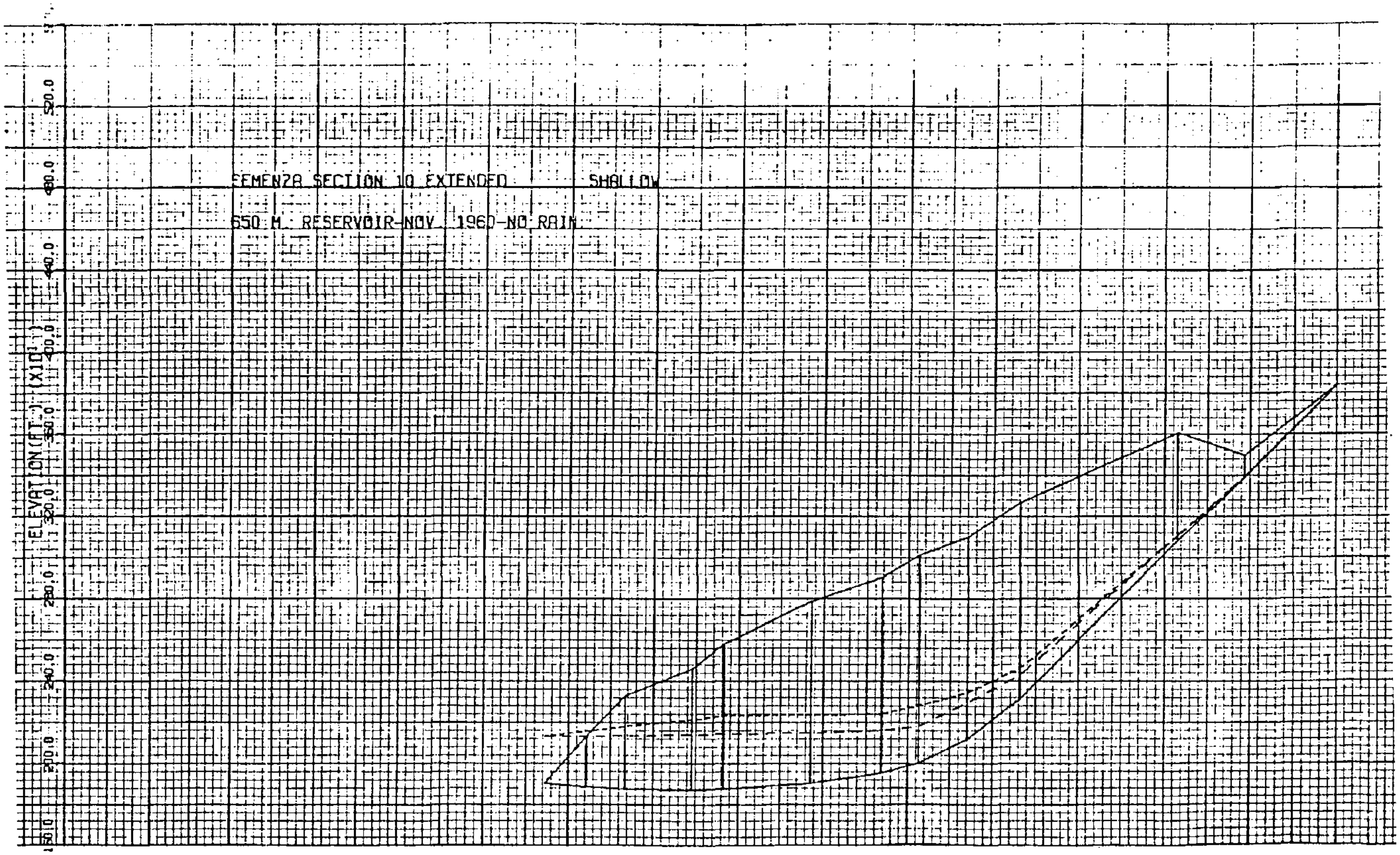


Figure C15. Vaiont Slide - Semenza Section 10 Extended, Shallow, 650 m reservoir, November 1960, no rain

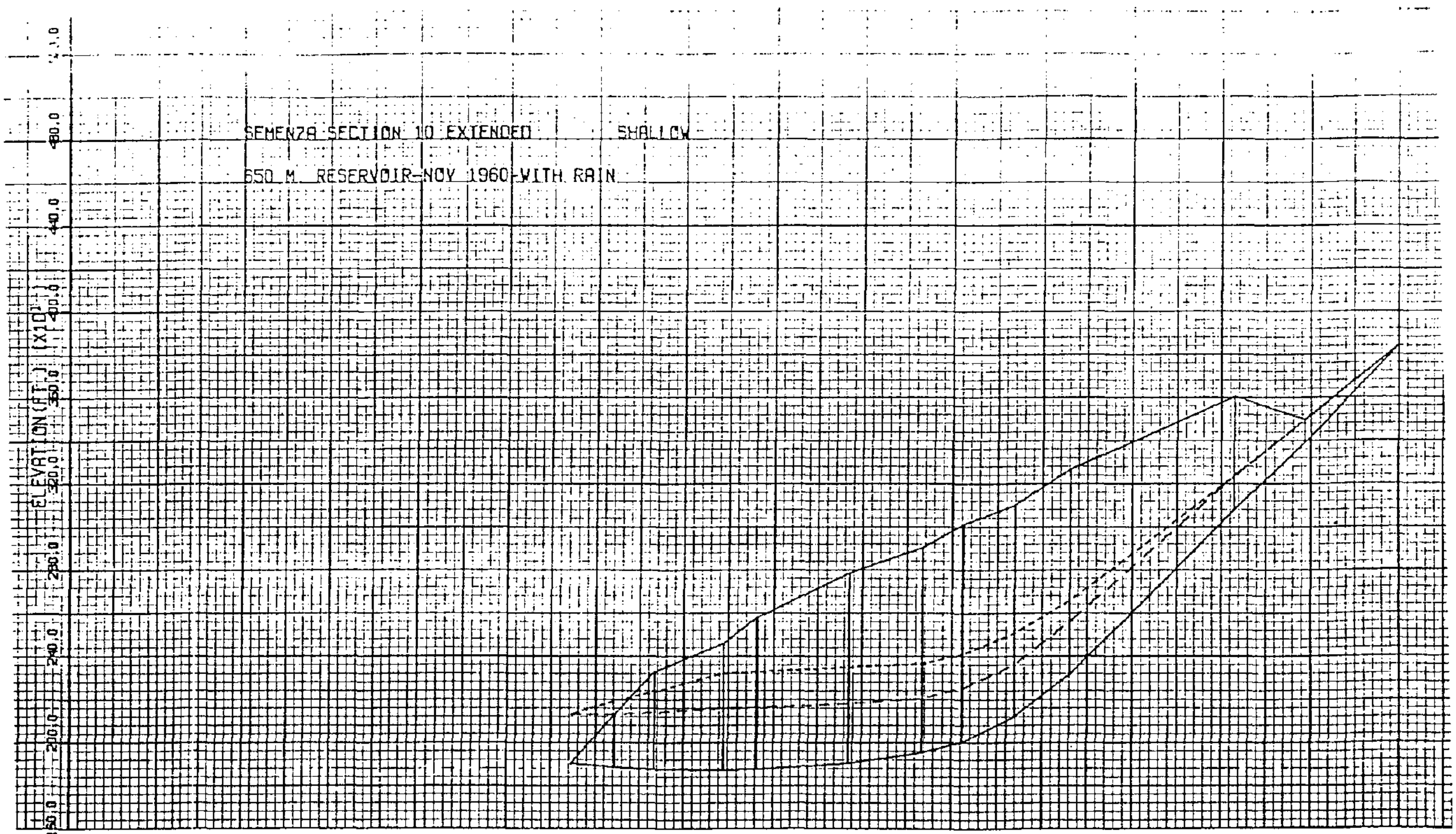


Figure C16. Vaiont Slide - Semenza Section 10 Extended, Shallow, 650 m reservoir, November 1960, with rain

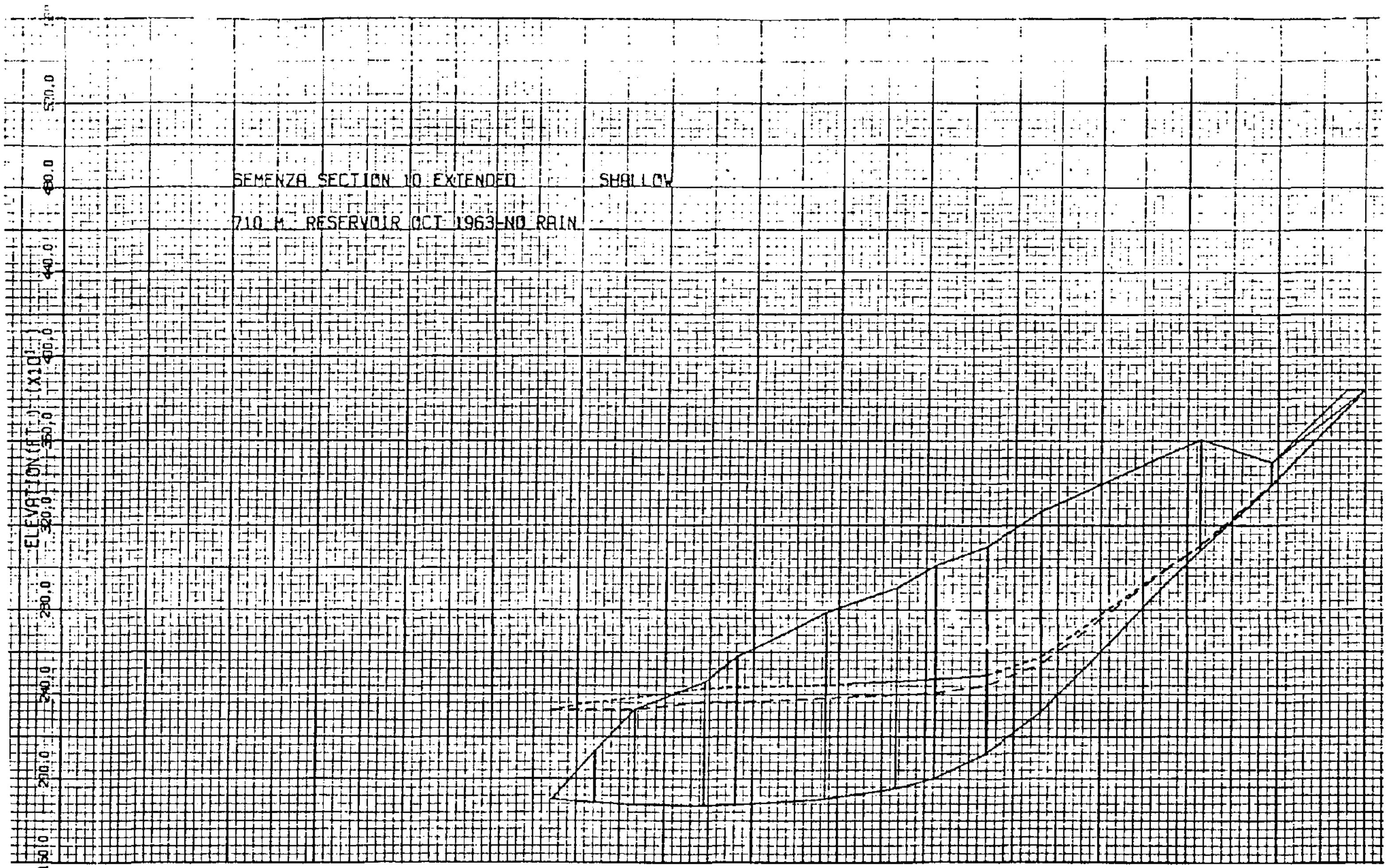


Figure C17. Vaiont Slide - Semenza Section 10 Extended, Shallow, 710 m reservoir, October 1963, no rain

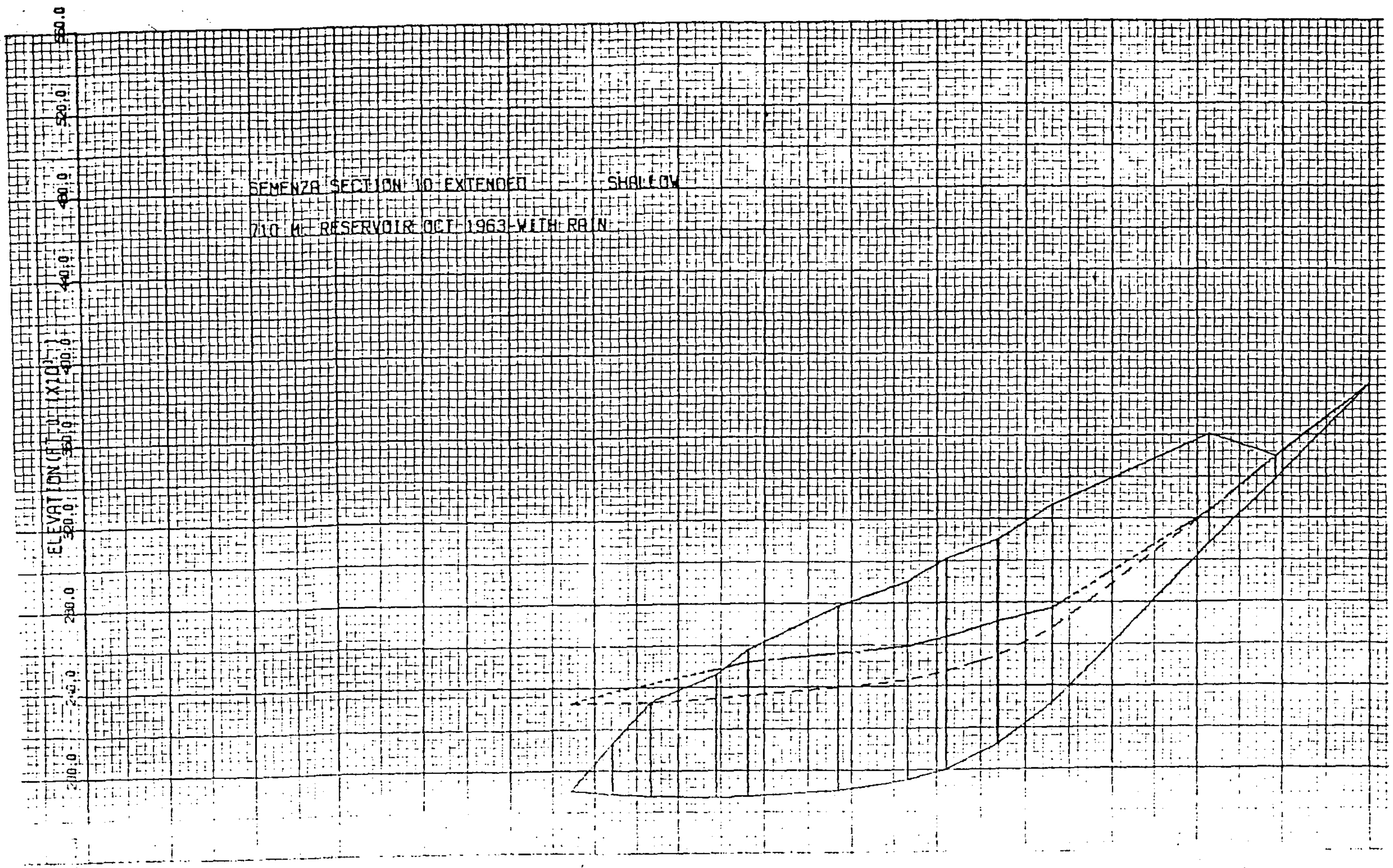


Figure C18. Vaiont Slide - Semenza Section 10 Extended, Shallow, 710 m reservoir, October 1963, with rain

APPENDIX D: THREE-DIMENSIONAL SLOPE STABILITY CALCULATIONS

An example of the calculations carried out to determine the overall factor of safety of the sliding mass which take into account the three-dimensional wedge which results from the bowl-shaped nature of the sliding surface is shown in this appendix.

The example shown in this appendix corresponds to the slide conditions at failure. These conditions were as follows:

a. Water elevation in the reservoir at 710 m
b. A high rainfall period,
c. A friction angle, ϕ, along the base sliding surface equal to 12°, and
d. A friction angle of 36° on the eastern wall boundary or on any vertical cross-section parallel to the direction of sliding.

Stability analyses of two-dimensional cross-sections 2, 5 and 10, representative of the western, center and eastern portion of the sliding mass respectively, resulted in the static factors of safety, F.S., and equilibrium forces, F_δ, shown in Table D1.

Table D1

Static Factors of Safety and Equilibrium Forces, F_δ, for Two Dimensional Cross-Sections Analyzed

Section	F.S.	F_δ, lbs/ft	Width of Sliding Mass Represented by Two-Dimensional Cross-Section, ft	Total Equilibrium Force F_δ Total Required on Slide Portion Represented By the 2-D Cross-Section, lbs.
2	.52	22.73×10^6	1036	23.55×10^9
5	.899	3.58×10^6	1353	4.84×10^9
10A	.445	41.32×10^6	1517	62.68×10^9

Table D1 also shows the length of the sliding mass section in feet, considered to be represented by each of the two-dimensional cross-sections analyzed, as well as the total equilibrium force, $F_{\delta total}$, required at each section.

As discussed in Part VIII, the driving and resisting forces acting on each one of these slide sections can be calculated as:

Section 2

$$\Sigma\ w_i \sin \alpha_i = \frac{F_{\delta}total}{1 - F.S.} \tag{D1}$$

$$\Sigma\ w \sin \alpha = \frac{23.55 \times 10^9}{1 - 0.52} = 49.06 \times 10^9 \text{ lbs} \tag{D2}$$

$$\frac{\Sigma(w_i \cos \alpha_i - u_i) \tan \phi}{\Sigma\ w_i \sin \alpha_i} = F.S. \tag{D3}$$

$$\Sigma\ (w_i \cos \alpha - u_i) \tan \phi = 49.06 \times 10^9 \times 0.52 = 25.51 \times 10^9 \text{ lbs} \tag{D4}$$

Section 5

$$\Sigma\ w_i \sin \alpha_i = \frac{F_{\delta}total}{1 - F.S.} \tag{D5}$$

$$\Sigma\ w_i \sin \alpha_i = \frac{4.84 \times 10^9}{1 - 0.899} = 47.92 \times 10^9 \text{ lbs} \tag{D6}$$

$$\Sigma\ (w_i \cos \alpha_i - u_i) \tan \phi = 47.92 \times 10^9 \times 0.899 = 43.08 \times 10^9 \text{ lbs} \tag{D7}$$

Section 10A

$$\Sigma\ w_i \sin \alpha_i = \frac{F_{\delta}total}{1 - F.S.} \tag{D8}$$

$$\Sigma\, w_i \sin \alpha_i = \frac{62.68 \times 10^9}{1 - 0.445} = 112.94 \times 10^9 \text{ lbs} \qquad \text{(D9)}$$

$$\Sigma\, (w_i \cos \alpha_i - u_i) \tan \quad = 112.94 \times 10^9 \times 0.445 = 50.26 \times 10^9 \text{ lbs} \qquad \text{(D10)}$$

The weights of the sliding mass resting on the upstream dipping portion of the sliding surface corresponding to each one of the slide portions represented by the three 2-dimensional cross-sections analyzed were calculated as:

Cross-section 2

$$w_1 = 800' \times 1200' \times 544.5' \times 140 \text{ lbs/ft}^3 = 0.73 \times 10^{11} \text{ lbs} \qquad \text{(D11)}$$

$$w_2 = 800' \times 1600' \times 492' \times 140 \text{ lbs/ft}^3 = 0.88 \times 10^{11} \text{ lbs} \qquad \text{(D12)}$$

Cross-section 5

$$w_3 = 800' \times 2000' \times 1353' \times 140 \text{ lbs/ft}^3 = 3.03 \times 10^{11} \text{ lbs} \qquad \text{(D13)}$$

Cross-section 10A

$$w_4 = 920' \times 1500' \times 1517' \times 140 \text{ lbs/ft}^3 = 2.93 \times 10^{11} \text{ lbs} \qquad \text{(D14)}$$

The horizontal components of these loads in the direction normal to the two-dimensional cross-sections analyzed were calculated at locations half-way between these cross-sections. As indicated in Part VIII these horizontal components between each cross-section were estimated as:

$$w_h = w \tan \theta \qquad \text{(D15)}$$

where: w = the weight of the sliding mass calculated above, and
θ = the average upstream dip of the sliding plane.

The effective horizontal load at these locations was then calculated as:

$$\bar{w}_h = w_h - u_h \tag{D16}$$

where: u_h = horizontal hydraulic force. Then:

<u>Between Cross-sections 2 and 5</u>

$$w_{h1} = w_1 \tan 22° = 29.49 \times 10^9 \text{ lbs} \tag{D17}$$

$$w_{h2} = w_2 \tan 12° = 18.70 \times 10^9 \text{ lbs} \tag{D18}$$

$$w_{htotal} = (29.49 + 18.70) \times 10^9 = 48.19 \times 10^9 \text{ lbs} \tag{D19}$$

$$u_h = \frac{1}{2}\, 62.5 \times 1600 \times 470^2 = 11.04 \times 10^9 \text{ lbs} \tag{D20}$$

$$\bar{w}_h = (29.49 + 18.70) \times 10^9 - 11.04 \times 10^9 = 37.15 \times 10^9 \text{ lbs} \tag{D21}$$

<u>Between Cross-sections 5 and 10A</u>

$$w_{h3} = w_3 \tan 9° = 47.99 \times 10^9 \text{ lbs} \tag{D22}$$

$$w_{htotal} = (29.49 + 18.70 + 47.99) \times 10^9 \text{ lbs} = 96.18 \times 10^9 \text{ lbs} \tag{D23}$$

$$u_h = \frac{1}{2}\, 62.5 \times 1750 \times 530^2 = 15.36 \times 10^9 \text{ lbs} \tag{D24}$$

$$\bar{w}_h = 96.18 \times 10^9 - 15.36 \times 10^9 = 80.82 \times 10^9 \text{ lbs} \tag{D25}$$

Between Cross-section 10A and Eastern Boundary

$$w_{h4} = w_4 \tan 8° = 41.18 \times 10^9 \text{ lbs} \qquad (D26)$$

$$w_{htotal} = (29.49 + 18.70 + 47.99 + 41.18) \times 10^9 = 137.36 \times 10^9 \text{ lbs} \qquad (D27)$$

$$u_h = \frac{1}{2} 62.5 \times 1500 \times 520^2 = 12.67 \times 10^9 \text{ lbs} \qquad (D28)$$

$$\bar{w}_h = 137.36 \times 10^9 - 12.67 \times 10^9 = 124.69 \times 10^9 \text{ lbs} \qquad (D29)$$

The factor of safety against sliding along any slide cross-section was then calculated as:

$$F.S. = \frac{\sum_j \sum_i (w_i \cos \alpha_i - u_i) \tan \phi - \sum_j w_h \tan \phi_r}{\sum_j \sum_i w \sin \alpha_i} \qquad (D30)$$

where: $\sum_j \sum_i (w_i \cos \alpha_i - u_i) \tan \phi$ = the <u>cumulative</u> base resistance acting on the portion of the slide to the west of cross section j,

where: $\sum_j \bar{w}_h \tan \phi_r$ = the friction along the face of the cross-section j where sliding may take place,

$\sum_j \bar{w}_h$ = the effective force normal to the face of the cross section

$\sum_j \sum_i w_i \sin \alpha_i$ = the driving force acting on the portion of the slide to the west of cross-section j

Therefore, factors of safety were calculated as follows:

For Sliding Between Cross-sections 2 and 5

$$F.S. = \frac{25.5 \times 10^9 + 37.2 \times 10^9 \tan 36°}{49.05 \times 10^9}$$

$$= \frac{(25.5 + 27.0) \times 10^9}{49.05 \times 10^9} = 1.07 \qquad (D31)$$

For Sliding Between Cross-sections 5 and 10A

$$F.S. = \frac{(25.5 + 43.1) \times 10^9 + 80.8 \times 10^9 \tan 36°}{(49.05 + 47.92) \times 10^9}$$

$$= \frac{(68.6 + 58.7) \times 10^9}{97 \times 10^9} = 1.31 \qquad (D32)$$

For Sliding Along the Eastern Wall Boundary

$$F.S. = \frac{(25.5 + 43.1 + 50.3) \times 10^9 + 124.7 \times 10^9 \times \tan 36°}{(49.05 + 47.92 + 112.94) \times 10^9}$$

$$= \frac{118.9 + 90.6}{209.9} = 1.00 \qquad (D33)$$

These calculations show the gravity load component along the upstream dip of the sliding surface to be large enough to have prevented separate sliding of portions of the unstable mass maintaining it as a rigid body. They also show that the lowest factor of safety occurs at the eastern wall boundary where sliding took place.

APPENDIX E: CALCULATION OF SLIDE VELOCITIES

By D. L. Anderson

The calculation of exact slide velocities is a difficult problem that would require an extensive computing effort plus the knowledge of and modelling of many complex physical phenomena. A somewhat less exact analysis is described here, but one that is believed to account for the major factors affecting slide velocity.

Description of Method

The method described and used here employs the static analysis program to estimate the overall forces acting on the entire slide mass at any given position as it progresses downhill, then uses these forces to calculate the accelerations, and ultimately the velocities. The dynamic shear strength of the material and the piezometric and water levels must be chosen for each position of the slide, at best an educated forecast.

The advantage of the method is that the failure and run-up surface can be described as accurately as they are known, varying shear strengths and piezometric levels can be considered, internal energy disipation is accounted for (by the β friction angles), and new failure surfaces that form over the tops of the parts of the slide mass that drop into and fill up valleys can be considered. The process of updating the geometry of the slide as it moves downhill was not programmed but generated by hand. Despite this, the input data was not excessive.

Figure E1 shows the sliding mass at three different positions as it moves down the slope. At each position the static analysis program is used to give the FS (based on an assigned value of ϕ) and the sum of the resisting R forces (see Fig. E2b) that would be required to hold the slide in equilibrium [recall that $R = (cL_S + N \tan \phi) \times 1/F.S.$]. The accelerating force is taken as the difference between the sum of the resisting R forces required for static equilibrium, and the sum of the R forces that could be mobilized with the soil strength existing during the motion. Assuming the N forces do not change appreciably during the motion, these latter resisting forces are given by

$$R = c_d \, L_s + N \tan \phi_d \qquad \text{(E1)}$$

where: c_d and ϕ_d = the soil strength parameters during the motion

Let R_s = sum of the resisting forces required for static equilibrium, given by the static analysis program

R_d = sum of the dynamic resisting forces

If the ratio of the static soil strength parameters used in the analysis and the dynamic soil strength parameters is the same for each element, then

$$R_d = R_s \, (FS) \, \frac{\tan \phi_d}{\tan \phi} \qquad \text{(E2)}$$

The net force (the force causing the acceleration) is then given by

$$F_a = R_s - R_d = R_s \, (1 - (FS) \, \frac{\tan \phi_d}{\tan \phi}) \qquad \text{(E3)}$$

and the acceleration is taken as

$$a = \frac{F_a}{M} \qquad \text{(E4)}$$

where: M = the total mass of the slide.

The force F_a is not dependent upon the value of c and ϕ used in the static analysis as the ratio FS/tan ϕ is a constant for any value of ϕ (assuming c and tan ϕ are linearly related). Thus only one set of static analyses need be performed and the results can then be used in conjunction with any dynamic strength.

Let Δ be the increment of movement and let a_1 and v_1 be the acceleration and velocity at the beginning of an increment where $x = x_1$, and a_2 and v_2 the acceleration and velocity at the end of the increment where $x = x_2$ ($\Delta = x_2 - x_1$). Assuming the slide has the acceleration a_1 for one half the time it takes to go from x_1 to x_2, and a_2 for the other half of the time, velocity v_2 is given by:

$$v_2^2 = v_1^2 + \Delta\ (a_1 + a_2) \tag{E5}$$

Starting at x = 0, where $v_0 = 0$, the velocities at each stage can then be calculated.

In the analysis here, the R forces were summed algebraically, which ignores the fact that they are not colinear, and the acceleration and velocities were calculated as if the movement of the entire slide mass was in the same direction. These simplifications were accepted in this case since the slide was reasonably planar, and in view of the many unknowns and assumptions further refinement did not appear warranted. If the failure surface is a circular arc, the sum of the R forces would represent a tangential force and the resulting acceleration would be a tangential acceleration.

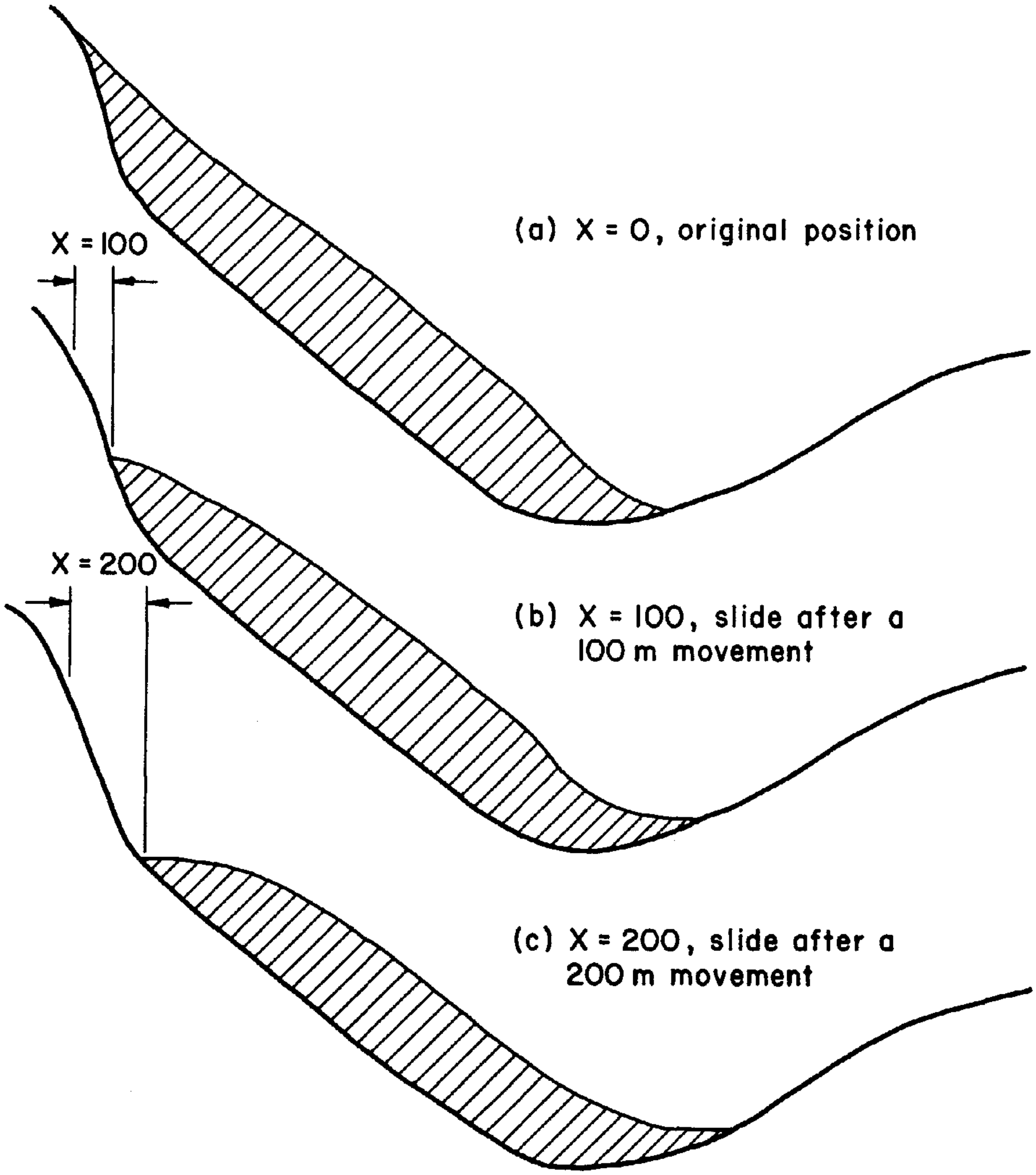
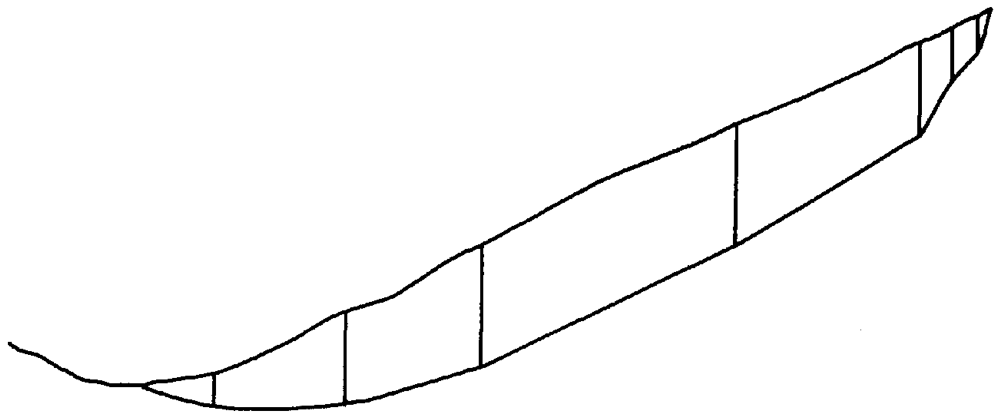
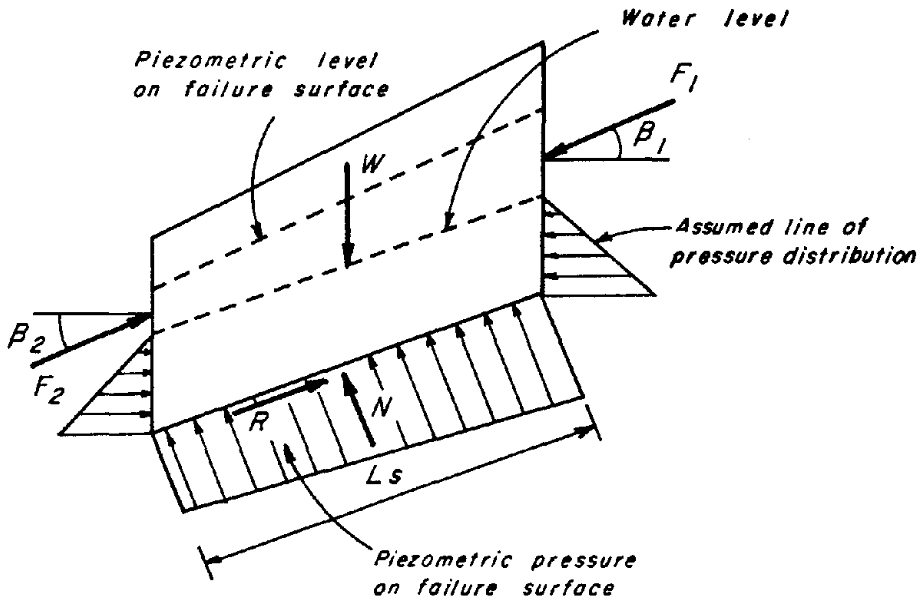


Figure E1. Slide at Various Stages of Movement



a) SUBDIVISION OF SLIDE INTO SLICES



W = total weight of soil and water above the failure surface

N = effective reaction normal to the failure surface

R = shearing resistance of the soil

F_1, F_2 = interelement forces between adjacent slices

β_1, β_2 = inclination of the interelement forces from the normals to the slice faces.

b) FORCES ON A TYPICAL SLICE OF THE SLIDE

Figure E2. Selection of typical slices and forces acting on a typical slice

APPENDIX F: HEAT GENERATED PORE PRESSURE MECHANISMS

By D. L. Anderson

Introduction

Given below are the equations on which the results of the heat generated pore pressure rise are based. They should be read in conjunction with the text and figures in the main body of the report.

Implicit Flow Equations

Consider the flow of pore water into layer n if the pressure p_n' is assumed constant in time during the interval Δt.

$$\Delta Q_n = 2\left(\frac{k_{n-1}\,L_{n-1} + k_n L_n}{L_{n-1} + L_n}\right)\left(\frac{p_{n-1}' - p_n'}{L_{n-1} + L_n}\right)\Delta t$$

$$- 2\left(\frac{k_n L_n + k_{n+1}\,L_{n+1}}{L_n + L_{n+1}}\right)\left(\frac{p_n' - p_{n+1}'}{L_n + L_{n+1}}\right)\Delta t$$

$$= \left[\bar{k}_{n-}\,(p_{n-1}' - p_n') - \bar{k}_{n+}\,(p_n' - p_{n+1})\right]\Delta t = \Delta Q_{n-} - \Delta Q_{n+} \quad \text{(F1)}$$

where: ΔQ_n = increase of water in layer n

k_n = permeability of layer n

In the numerical work, p_n' is taken to be the pressure at the end of the time step before the increase in pressure due to temperature change is added, i.e.,

$$p_n' = p_n + \Delta p_{pn} \tag{F2}$$

The increased volume Q_n is related to the increased pore pressure through a constitutive relation given by

$$\Delta p_{pn} = p_n' - p_n = \frac{\Delta Q_n}{L_n} K_{en} \tag{F3}$$

where: K_{en} = effective bulk modulus which accounts for the bulk modulus of the water and soil, under the assumption that the total vertical load (or total stress) does not change. Its derivation is given below.

Substituting for ΔQ_n we have

$$\frac{\Delta t\, K_{en}}{L_n} \left[\bar{k}_{n-}\, p_{n-1}' - p_n' \left(\bar{k}_{n-} + \bar{k}_{n+} + \frac{L_n}{\Delta t\, K_{en}} \right) + \bar{k}_{n+}\, p_{n+1}' \right] = - p_n \tag{F4}$$

This forms a system of algebraic equations which, when coupled with boundary conditions at the top and bottom of the layered region that assumes that the pressure does not change, can be solved for p_n'.

Once the p_n' values are determined, the flow of fluid ΔQ_n can be determined.

Heat Convection

The heat flowing into a layer by the flow of the pore water during the time increment Δt is given by

$$\Delta q_{vn} = C_w \gamma_w \left[\left(\frac{T_{n-1} L_n + T_n L_{n-1}}{L_{n-1} + L_n} \right) \Delta Q_{n-} - \left(\frac{T_n L_{n+1} + T_{n+1} L_n}{L_n + L_{n+1}} \right) \Delta Q_{n+} \right] \quad \text{(F5)}$$

where: C_w = specific heat per unit mass of the pore water

γ_w = mass of water

The temperature terms in the brackets represent the temperatures at the boundaries between the layers rather than the weighted average temperature of the layers.

Heat Conduction

The heat conducted into a layer during time t is given by

$$\Delta q_{dn} = \left[\left(\frac{K_{n-1} L_{n-1} + K_n L_n}{L_{n-1} + L_n} \right) \left(\frac{T_{n-1} - T_n}{L_{n-1} + L_n} \right) - \left(\frac{K_n L_n + K_{n+1} L_{n+1}}{L_n + L_{n+1}} \right) \left(\frac{T_n - T_{n+1}}{L_n + L_{n+1}} \right) \right] (2)\ \Delta t \quad \text{(F6)}$$

where: K_n = thermal conductivity per unit area of the saturated soil.

Heat Generated Within the Shear Zone Elements

The total heat generated within the shear zone is the minimum shear resistance τ_{min}, times the distance that the slide moves relative to the foundation, i.e. $(\tau_{min}) |\Delta v| C$, where C is a suitable constant to keep the units consistent. The heat generated in any layer depends upon the amount of shearing in that layer and can be written as

$$\Delta q_{gn} = \tau_{min} \left| \Delta v_n - \Delta v_{n-1} \right| C \quad \text{(F7)}$$

The distribution of the displacements through the shear layer are based on the assumption that the shear strain is proportional to a shear modulus that varies with the temperature and the square of the shear strength of the layer.

It it is assumed that the shear modulus in a layer is given by

$$G_n = \left(\frac{273}{273 + T_n}\right) \left(\frac{\tau_n}{\tau_{min}}\right) 2 \tag{F8}$$

where: τ_n = the shear strength of the layer, then

$$\Delta v_n - \Delta v_{n-1} = \frac{(\Delta v - \Delta u)\ L_n}{G_n} \left(\sum_{i=1}^{N} \frac{L_i}{G_i}\right)^{-i} \tag{F9}$$

which satisfies the requirement that

$$\sum_{n=1}^{N} (\Delta v_n - \Delta v_{n-1}) = \Delta v_n - \Delta v_0 = \Delta v - \Delta u \tag{F10}$$

With the above assumption the middle layer(s) of the shear zone, which even for a uniform shear modulus would develop the highest pore pressure and temperature, gradually become weaker, attract more deformation, generate more heat and so become weaker yet. Thus the deformation is gradually concentrated at the center of the shear zone. This is somewhere between a slip-plane model with an infinitesimally thin shear zone and a model with the deformation uniformly distributed through the depth.

Temperature and Pressure Change

During each time interval the change in heat within a layer is given by the sum of the heat convection, conduction and generation terms. Thus

$$\Delta T_n = \frac{1}{\bar{C}_n \, L_n} \left(\Delta q_{vn} + \Delta q_{dn} + \Delta q_{gn} \right) \tag{F11}$$

where: $\bar{C}_n$ $= C_n \gamma_n + n_n C_w \gamma_w$ is the specific heat per unit volume of the soil and water mixture

C_n, C_w = specific heat/unit mass of the soil particles, water

γ_n, γ_w = unit mass of soil particles, water

n_n = porosity

Following the derivation below the change in pressure caused by the change in temperature is given by

$$\Delta p_{Tn} = \Delta T_n \left[n\alpha_w + \frac{2}{3} (1-n_n) \, \alpha_n \right] K_{en} \tag{F12}$$

where: α_n, α_w = coefficient of thermal volume expansion of the soil, water.

The pressure at the end of the time interval is then taken as

$$p_n = p_n' + \Delta p_{Tn} \tag{F13}$$

for use at the beginning of the next time interval. If the pressure p_n is less than the boiling pressure of the water at the temperature T_n, p_n is set equal to the boiling pressure on the assumption that a small amount of water would boil, creating steam that would increase the pressure to the boiling pressure. The latent heat required to change the water to steam has not been accounted for since it is considered that only a very small amount of water would have to boil.

Pore Pressure-Temperature Relation

The change in pore pressure in a layer is caused by a change in volume of the pore water and a change in temperature. Let ΔQ be the inflow in pore water volume per unit area, and let ΔT be the increase in temperature, for a layer of thickness L. The material in the layer can deform vertically but is restrained from lateral deformation. Figure F1 shows an idealization of the situation.

If we let Δp be the change in pore pressure, then $\Delta\sigma' = -\Delta p$, where $\Delta\sigma'$ is the change in effective stress in the vertical direction (compression positive), since the change in total stress must be zero. Then:

$$\text{change in water volume} = \eta L(\alpha_w \Delta T - \frac{\Delta p}{K_w}) + \Delta Q \qquad \text{(F14)}$$

where: K_w = bulk modulus of water and the other symbols are defined in the main text.

change in soil particle volume

$$= (1-\eta) L (\alpha_n \Delta T - \frac{\Delta p}{K_{pn}}) - \frac{\Delta\sigma' L}{K_n'} \qquad \text{(F15)}$$

where: K_{pn} = bulk modulus of the soil particles

K_n' = effective bulk modulus for the particles when subjected to a vertical stress

The change in volume of the water and soil particles causes the layer to expand vertically. If ε represents the strain in the vertical direction, then εL = total change in volume

$$\therefore \quad \varepsilon = \Delta T \left(\eta\alpha_w + (1-\eta)\,\alpha_n\right) + \Delta p \left(\frac{-\eta}{K_w} - \frac{(1-\eta)}{K_{pn}} + \frac{1}{K_s'}\right) + \frac{\Delta Q}{L} \qquad \text{(F16)}$$

Now the strain in the soil in the vertical direction is related mainly to the change in effective stress and can be written as

$$\varepsilon = -\frac{\Delta\sigma'}{K_n} + (1-\eta)\,\alpha_s\,\frac{\Delta T}{3} - (1-\eta)\,\frac{\Delta p}{3K_{pn}} \qquad \text{(F17)}$$

where: K_n = modulus of deformation for a uniaxial strain condition.

The temperature and pressure terms corresponding to linear expansion are also included. Equating the two expressions gives

$$\Delta p = K_{ne}\left[\Delta T\left(\eta\alpha_w + \frac{2}{3}(1-\eta)\,\alpha_s\right) + \frac{\Delta Q}{L}\right] \qquad \text{(F18)}$$

$$\text{where} \quad \frac{1}{K_{en}} = \frac{\eta}{K_w} + \frac{1}{K_n} - \frac{1}{K_n'} + \frac{2}{3}(1-\eta)\,\frac{1}{K_{pn}} \qquad \text{(F19)}$$

The modulus K_n should be greater than the deformation modulus associated with a triaxial test. Also, in this application the effective stress is decreasing and so K_n should be taken from an unloading test.

The modulus K_n' represents a measure of the volume change of the soil particles, not the volume change of the sample, when subjected to a uniaxial strain condition. Since most of the deformation in a sample is associated with shearing and rearranging of the soil particles, and not with volume changes of the particles, K_n' should be much greater than K_n and of the same order as K_{pn}.

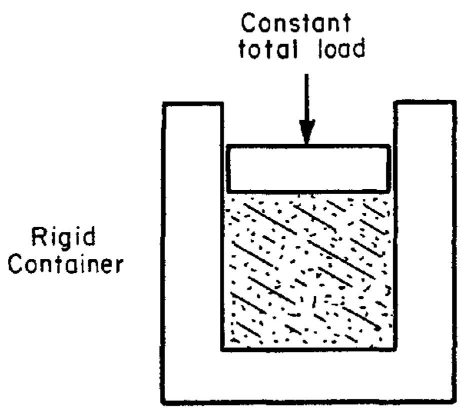


Figure F1. Idealization of vertical deformation with lateral restraint (uniaxial compression test)

Material Properties

Some of the material properties are reasonably independent of the type of soil or rock in the slide mass and shear zone, or they have little influence on the results and are listed here.

a) Thermal Properties

thermal conductivity - cal/m sec °C

water $k_w = 0.16$

soil or rock $k_n = 0.20$

shear zone material $k_n = 0.10$

specific heat - cal/gm °C

water $C_w = 1.0$

soil, rock, shear zone material $C_n = 0.20$

coefficient of thermal volume expansion - $°C^{-1}$

water $\alpha_w = 10^{-4} [-1.20906 + 0.491195 \sqrt{T} + .057443T - .000184232T^2]$

$4 < T \leq 100$ °C

$T > 100$ °C

soil, rock, shear zone material $\alpha_n = 0.00003$

b) Mechanical Properties

porosity

rock $n = 0.1$

shear zone material $n = 0.2$

unit mass - gm/cm^3

water $\gamma_w = 1.0$

soil and rock $\gamma_n = 2.7$

shear zone material $\gamma_n = 2.5$

bulk or elastic modulus - kg/cm^2

water $K_w = 21000$

soil, rock $K_n = K_n' = 400{,}000$

soil, rock or shear zone material $K_{pn} = 400{,}000$

APPENDIX G

SYNTHESIS OF GEOLOGICAL STUDIES OF THE VAIONT LANDSLIDE FROM 1959 TO 1964

EDOARDO SEMENZA

Translated from "Memorie del Museo Tridentino di Scienze Naturali"
A.XXIX-XXX, 1966-67, Vol. XVI, Fasc. I
under the direction of E. Semenza

Original in Italian
Published by
Museo Tridentino di Scienze Naturali
Via Rosmini n. 39
Trento, 1965

INDEX

A. Introduction.. G4

B. First Geological Survey 1959.. G6

B.1 General evaluation program... G6

B.2 Geological survey of the reservoir................................... G7

B.3 First doubts about the Pian del Toc.................................. G7

C. Attempts to Assess The Instability and Estimate The Volume of The Potential Sliding Mass; Winter 1959, Fall 1960.. G9

C.1 First geophysical investigation, Winter, 1959-1960... G9

C.2 Diagnosis of the situation during the Spring of 1960. G9

C.3 Start of benchmark monitoring, Spring, 1960.......... G11

C.4 Exploratory drilling program S and trench investigations of the Pozza, Spring-Summer, 1960..... G11

C.5 Updating of the diagnosis, Summer, 1960.............. G12

C.6 Detailed geological surveys, Summer, 1960............ G12

D. The Landslide of November 4, 1960, and Subsequent Field Surveys in 1961.. G14

D.1 Opening of the perimetral fissure, October 1960...... G14

D.2 Landslide of November 4, 1960........................ G14

D.3 Site investigations, surveys and appraisals, Winter, 1960-1961.................................. G15

D.4 Expansion of the benchmark system.................... G16

D.5 Second geophysical investigation, Winter 1960-1961... G16

D.6 Adits in the Massalezza Valley....................... G18

D.7 Exploratory drilling program P, Spring and Summer, 1961.. G19

D.8 Final diagnosis of the situation, Summer, 1961...... G20

E. Studies on The Hydraulic Model, 1961-1962.................. G22

F. Reservoir Operation, 1961-1963.............................. G23

G. Second Geological Survey, Winter 1963...................... G25

G.1 Stratigraphy of the landslide mass and the surrounding zone.................................... G25

G.2 Structural conditions of the slide mass.............. G29

G.3 Hydraulic effects on the slide mass and on surrounding zones.................................. G31

G.4 The scarps, and the visible portions of the surface of sliding.................................. G32

G.5 Unexposed portion of surface of sliding............. G34

H. Hypothesis Regarding The Dynamics of The Movement and Failure.. G35

H.1 General mechanical characteristics of the formations involved.............................. G35

H.2 Period of slow movement........................... G36

H.3 Failure threshold................................. G38

H.4 Kinematics of the collapse........................ G40

Summary... G43

Résumé.. G43

Riassunto... G44

Bibliography.. G46

Figures 1 through 16

A. Introduction

In October, 1963, the management of the ENEL Hydraulic Construction Service, formerly SADE, verbally requested the author to conduct a detailed geological survey of the landmass which had slid from Mount Toc.

This survey was carried out with the cooperation of Prof. Daniele Rossi of Ferrara University. The major field campaign was concluded in December, 1963; the survey was rendered more accurate in certain details and more complete during a series of successive field trips. In addition, the study was extended toward the east to include the "Costa delle Ortiche."

The geological studies conducted after the slide of October 9, 1963, in collaboration with Prof. D. Rossi, will be published in the future by Prof. Rossi and this author. The pertinent material in this proposed monograph is summarized here. Therefore, this publication reflects, as far as the studies after the slide movement are concerned, results and opinions acquired jointly.

The author became involved in the problems of the possible instability of the Vaiont reservoir slopes in July, 1959, when he participated in the field trips and discussions which led to the formulation of a rationally organized program of research in successive phases. This exploratory program was officially presented to SADE by Dr. Leopold Müller in October, 1959, but it had already been outlined in a previous letter dated July 24, 1959.

Following the acceptance of the proposal by SADE, this author participated, from then until now, in many of the more interesting aspects of the problem of Mount Toc. This participation included personal surveys of the site, supervision of field studies and borings, and judgments regarding the results of these activities.

All the geological and geotechnical studies assumed great importance, both due to the in-depth research in an absolute sense, and because of the influence that the conclusions regarding the site had upon the decisions taken at the time. Keeping this in mind, the author feels that it is useful to present a comprehensive picture of all studies--to his knowledge--regarding the region surrounding the Vaiont basin. This seems even more appropriate considering the fact that, in everyday practice, prompt decisions are routinely made without any formalities by some of the parties in charge. Therefore, since all the activities carried out and all the studies conducted have not yet been formally reported, it could appear that this research might have been inconsistent, incomplete or inadequate to the observer who referred only to the documents available at present. In addition, great scientific interest is naturally aroused by such an exceptional event in the field of study dealing with landslide phenomena. The Vaiont event was characterized by such exceptional volume, compactness of the sliding mass, and slide velocity that it was unique with respect to any other landslide phenomena in recent times (at least in populated areas). Therefore, the only alternatives for comparison are the enormous landslides of the post-glacial period. However, the fundamental characteristics of these slides can only be the object of indirect evaluations or approximate interpretations.

This report presents, therefore, the studies and research conducted in the vicinity of Mount Toc from 1959 to 1963, as well as the present geological conditions. This study also investigates the probable causes of the slow movement during a three-year period, and then seeks to analyze the reasons for the sudden transformation of this movement into the unexpected, very rapid sliding of an enormous, rigid rock mass. The disastrous effects of this sudden slide greatly exceeded the most pessimistic forecasts that had been previously formulated as based upon the experience acquired in studies of the mechanisms of similar phenomena.

B. First Geological Survey 1959

B.1 General evaluation program

In the summer of 1959, Engineer Carlo Semenza deemed it necessary to verify the stability of the slopes of the entire Vaiont reservoir. The collaboration of Dr. Leopold Müller[1]--well known expert of geomechanics and already called by the SADE to consult for the Vaiont dam abutments--was sought in order to determine the best way to organize and execute such a study. The collaboration of the writer was also enlisted for this project.

Following an inspection of the site by the researchers on July 21, 1959, a series of detailed surveys was determined to be opportune according to directions outlined verbally by Dr. Müller, confirmed in his letter of July 27, 1959, and included in his report No. 6 of October 10, 1959.

Precisely, it was decided to conduct:

a) a general geological survey of the entire basin up to the height of the road surrounding the reservoir (maximum elevation approx. 850 m) without going into great detail.

b) a successive detailed structural geology survey--for which Dr. Müller gave precise suggestions--of those zones which, after the general survey, had revealed potential danger of instability.

c) any additional in-depth surveys of particularly suspicious zones--in case such studies were considered necessary for a more complete understanding of the situation--using borings and exploratory excavations.

[1]Dr. Müller published an excellent, well-illustrated paper (1964) to which the reader is referred for many details regarding research before and after the landslide of October 9, 1963.

B.2 Geological survey of the reservoir

The survey was carried out in two principal phases in the period from July 22, 1959, to early December, 1959. The first phase consisted of the general survey conducted by the writer between July 22 and September 8, 1959. Phase two, consisting of the detailed survey, was performed by Dr. Franco Giudici, under the supervision of this author, in the period from the first of October to the first of December, 1959. The necessity of several revisions, which could not be effectuated during the winter season, delayed the publication of the study by Franco Giudici-Edorado Semenza entitled "Geological Study of the Vaiont Reservoir, 1960," until June, 1960 (Figs. 2 and 3).

B.3 First doubts about the Pian del Toc

It should be noted that the first results concerning the "Pian del Toc" (plain of the Toc) were completed and had been transmitted verbally to SADE technicians during the last week of August, 1959. Additional details were discussed during a successive survey of the site in which Prof. Giorgio Dal Piaz participated.

During the survey of the Pian del Toc and Colomber areas, numerous signs of stress were observed along the left flank indicated by small elongated depressions, by abrupt stepping and by numerous fractures (Fig. 4). More precisely, starting from the "Punta del Toc" (Toc Point) toward the south, a first fracture was noted after a few meters, which was several meters deep and 3-4 meters wide. Loose fill material and blocks were observed inside this fracture which cut through the entire Point. Thirty meters further south, another deep fracture was noticed, with an approximately constant and parallel direction to the former. Between these two fractures, other minor ones appeared, ranging from a few centimeters to half a meter across, but rather well-developed vertically. Moreover, a milonitic zone was found outcropping at the foot of the cliffs below Punta del Toc (or Toc wall) near their eastern extremity. It was assumed that this milonitic zone continued along the entire cliff under the ledge covered by detritus which separated the upper and lower cliffs (Figs. 5 and 6).

On the right side of the valley, loose and fractured rock masses were observed. A tectonic discordance could be noted between these masses and the cliff in place behind them. These masses had gravels and sands at their base and were located where the Vaiont gorge narrowed considerably (Figs. 7 and 8).

The sum of all these considerations led to the formulation of the probable hypothesis that the Pian del Toc as well as the above-mentioned masses at the right were the remains of a slide which came from the left side of the valley, probably when the glacier receded. The slide mass had obstructed the old valley, and then stream erosion had excavated a new, epigenetic channel.

According to another hypothesis which was also proposed in the 1960 publication, the mass that constituted the Pian del Toc had indeed slid to the valley, but without closing it. Valley obstruction had occurred only when a relatively small mass, originally situated to the west of Punta del Toc, broke away from the recessed slopes of the left flank and blocked the valley. The masses on the right side of the valley were therefore interpreted as the remains of this small slide.

In any case, however, the Pian del Toc was included among those areas which, based on the above-mentioned criteria, required a more detailed study. This research, which will be described, was begun in the Fall of 1959.

C. Attempts To Assess The Instability and Estimate The Volume of The Potential Sliding Mass; Winter 1959, Fall 1960

C.1 First geophysical investigation, Winter, 1959-1960

While awaiting the possibility of in-depth geologic research following the winter season, SADE arranged for seismic surveys to be conducted by Prof. Caloi in the hope of shedding more light on the origin of the rock mass on the left side of the basin. Was the mass in question actually "in place" or was it the remains of a mass that had slid from the mountain? Fifty blasting points were distributed along two different profiles (established during a visit to the site on October 13, 1959, by the author and Mr. Maddalena, assistant to Prof. Caloi), reaching elevations of 776 meters and 850 meters respectively. The measurements registered and interpreted by Prof. Caloi gave very high seismic velocity values thus confirming, in the Professor's opinion, the existence of a rock of very high elastic modulus. Based on these figures, Prof. Caloi concluded that the rock mass on the left side of the basin was "formed in place" and was extremely stable.

C.2 Diagnosis of the situation, during the Spring of 1960

The conclusions reached by Prof. Caloi contrasted sharply with those of the writer. The latter summarized his ideas in a letter to his father in April, 1960: the zone under examination could not be considered as in-situ rock, on the contrary it was composed of a huge rock mass which had broken away from the mountain in a remote epoch and slid, due to gravity, in a general northeasterly direction; the volume of the sliding mass in question was estimated as several tens of million cubic meters; a possible old slide plane could have run from the milonitic zone outcropping at the top of the Vaiont gorge to the depression of

"Pian della Pozza" (Pozza Plain) or "Pozza". The writer indicated one of the possibilities in a sketch of a geological cross-section attached to the letter. In fact, it then appeared probable to this author that the rocky strata outcropping at the top of the lower walls of the gorge continued--following a constant or almost constant curvature plane--in the rocks outcropping on the southern side of the depression of the Pian della Pozza. As a result, the zone between this depression and the Vaiont River had to be considered potentially unstable. For these reasons, the following operations were decided:

a) first exploratory survey by Caloi, 1959, and placement of the related seismic profiles (see C.1);
b) first geologic borings (S1, S2, S3) (see C.4);
c) first monitoring of the movements (see C.3).

Regarding the dynamics of any future movements, the author maintained that there could be successive slides or falls of relatively small proportions along the fractures observed. From a theoretical point of view, he also considered the hypothesis that the entire mass could begin moving again, particularly in the case that the presumed contact surface might have presented an unfavorable inclination and low shear strength. Considering the impossibility of establishing the fundamental characteristics of this surface externally, it was determined that in-depth research be conducted by the borings listed above. This procedure also conformed to the general criteria established at the beginning of the study.

These opinions were expressed by the writer and by Dr. Giudici in the report of June, 1960, in general and precautious terms, given the impossibility of actually determining the existence and nature of the surface prior to undertaking the in-depth research, which was still underway.

C.3 Start of benchmark monitoring, Spring, 1960

In order to verify any possible movements in the zone considered unstable, about ten bench marks were installed. Periodical trigonometric surveys were conducted to check their location.

C.4 Exploratory drilling program S and trench investigations of the Pozza, Spring-Summer, 1960

As soon as the weather permitted, SADE officials arranged for the borings in order to determine the depth of the potential surface of sliding of the rock mass. From May to July, 1960, three geologic borings (S1, S2, S3) were drilled in the Pozza along an axis running approximately normal to the Vaiont River. The first boring was made at the bottom of the Pozza depression, the second on the Pozza plateau and the third on the slope between the Pian della Pozza and the lake.

The actual drilling was done by two specialized firms, Consonda and ICOS, under the supervision of the author and Dr. F. Giudici, who remained permanently at the site during the operation.

The three borings reached depths of 172 m, 71 m and 105 m respectively, thus drilling down to elevations of 658.50, 779.50 and 602.50 meters above sea level. It was impossible to proceed to greater depths due to extreme difficulties in drilling operations (continual collapse of the borehole). The borings encountered rock that was, for the most part, minutely fractured and where the water circulated was frequently lost.

All the materials encountered belong to various levels of the lower Cretaceous. These levels were studied later in greater detail and included various types of limestones, red or greenish marly limestone, etc. These rocks formed an intensely fractured and therefore highly permeable rock mass. The Dogger formation was not reached nor, in all probability, was the Malm formation which overlies it. No trace of the surface of sliding was found.

During the same period, three trenches were also excavated in the depression of the Pian della Pozza. In these trenches, and particularly in the westernmost one, the limestone was crossed by numerous wide fractures, however the stratification was well preserved, only slightly inclined, dipping to the NNE.

C.5 Updating of the diagnosis, Summer, 1960

As a result of the geologic research described above, the author felt he could modify his hypotheses in a more optimistic sense than those previously formulated. It was hoped to find milonites extending into the mountain as a continuation of the milonitic zone visible at the base of the wall bordering the Toc plateau. The fact that in the boreholes, no trace of the rupture surface was found, led the author to seek another explanation. It was assumed that the surface of sliding, which started at the milonitic zone of the gorge, did not rise immediately toward the depression of the Pian della Pozza. It was thought that it extended for an ample stretch towards the interior, running almost horizontally. Thus the surface of sliding would have passed under the depths reached by the borings, only to rise beyond the zone of the Pian della Pozza. The hypothesis was then formulated that the configuration of the contact surface was still roughly concave, as previously supposed. However, it must have had a wide lower portion which, although it had not been precisely determined, was certainly sufficient to provide adequate stability for the overlying mass.

C.6 Detailed geological surveys, Summer, 1960

Given the result of the borings, the search for surface evidence of the outcropping of the slide plane was extended to the region above the Pian della Pozza.

At the end of July, 1960, it was observed that the two branches (western and eastern) of the Massalezza stream ran along the outcrop of a contact surface between lower Cretaceous bedrock (then identified as Malm) and layers, dipping north at about 40°, of varied materials which were generally loose or highly fractured rock. The morphology also changed along the line of this outcrop; in addition to the channels of the two Massalezza branches, there were small plateaus or slightly inclined areas near the head of each branch, lying at an elevation of about 1,200 m to the west and between 1,250-1,300 m to the east of the Massalezza. In the western part of the zone, a depression of considerable proportions was at approximately 1,150 meters. Just to the southeast of this depression, the bedrock was oolitic limestone of the Dogger, rather than the usual lower Cretaceous, due to the presence of an east-west fault whose sub-vertical walls were easily observed (Figs. 9 and 10).

All of these elements were considered by the author as indications of the probable upper limit of the landmass which had slid across the valley in an ancient post-glacial epoch. They constituted, in his opinion, the confirmation of his hypothesis regarding the phenomena which had involved the rock masses under investigation.

The exact expanse of the mass involved in this ancient slide had not, however, been determined--particularly with respect to its eastern part. This fact was soon established and will be described subsequently.

D. The Landslide of November 4, 1960, and Subsequent Field Surveys in 1961

D.1 Opening of the perimetral fissure, October 1960

Near the end of October, 1960, a fissure was discovered around the upper part of the zone in question. It followed a line rising from just above the dam and heading straight up the slope to an elevation of about 1,100-1,200 meters. Here the fissure turned eastward, proceeded horizontally for a short stretch, then descended along the western branch of the Massalezza Valley and entered the main Massalezza Valley at about 900 meters. The fissure rose gradually again along the eastern branch of the Valley reaching 1,300 meters. There the line dropped towards the lake and disappeared at an elevation of about 1,100 meters (Figs. 9 and 11).

Thus, the existence of the unstable mass was clearly manifested, and the fissure outlined its surficial expanse. This cleft or crack was, therefore, referred to as the "perimetral" fissure.

On the other hand, the thickness of the mass remained hypothetical since no evidence regarding the exact location of the surface of sliding had been found. Many hypotheses were formulated; the most likely was, in the writer's opinion, that the surface of sliding followed, more or less irregularly, the bedding of the rock strata. These strata lay almost horizontally just below the milonitic zone visible at the upper part of the gorge. Somewhat southward the strata rose in a steep incline, and it was assumed that they were correlated with the strata outcropping in various places along the upper part of the perimetral fissure.

D.2 Landslide of November 4, 1960

On November 4, 1960, a landslide involving approximately 700,000 m^3 took place below the Pian della Pozza along a 300 meter front. The movement of the mass into the lake was relatively slow, producing modest wave action.

D.3 Site investigations, surveys and appraisals, Winter, 1960-1961

The writer visited the site on November 8 and 9 and, in the company of Eng. Ruol, examined the entire extension of the recently formed perimetral crack. In the afternoon, he met Dr. Müller who had been called to Vaiont following the landslide, and together they inspected the Pian della Pozza where numerous fractures had also appeared.

On November 15 and 16, Dr. Müller and the writer again met at Vaiont and Dr. Müller, after due consideration of the situation as modified by the recent landslide, expressed his opinions regarding the phenomenon in course. They are summarized as follows:

> "The geological structure and the mechanics of movement differed on the east side and the west side of the Massalezza stream. The western part should also be divided in two sections: first, the section above the Pian della Pozza rested on a steep slide plane and moved downward with a translatory movement; the other section, located beneath the Pozza, rested on an almost horizontal base and was divided into different parts by vertical fractures parallel to the valley; each small part, Dr. Müller explained, would rotate toward the valley with a movement comparable to that of glaciers. The eastern part on the contrary, for almost its entire expanse, presented characteristics similar to the upper part of the western section; that is, it was supposed that the frontal part of the eastern section lay on a very small base, whereas the majority of its expanse rested on an inclined plane. Dr. Müller concluded with the estimate that the movements would probably involve a mass of about 200 million cubic meters. The continuation of this phenomenon could result in future slides involving partial falls along the front of the large mass in movement."

During November, 1960, Dr. Broili and Eng. Fally, assistants to Dr. Müller conducted an exhaustive study of the zone which included geotechnical measurements. Dr. Müller's opinions, as quoted above, were presented in report No. 15 of February 3, 1961.

After the November 4 slide and the appearance of the perimetral fissure, SADE officials decided to lower the level of the lake in order to construct a bypass tunnel along the right side. The work was carried out between December, 1960, and September, 1961.

During this period, the writer and Dr. F. Giudici were able to visit the tunnel which was entirely excavated in bedrock in excellent condition; the rock strata dipped regularly to the ENE; the inclination of the strata was slight. This confirmed what had been observed by surveys on the surface. Along the cuts of a new access road to an intermediate entrance of the by-pass tunnel, the writer was able to observe a small mass of intensely fractured light gray limestone located about 200 meters downstream from "Ponte di Casso" at an elevation of about 650 meters. The clear stratification was discordant with that generally observed on the right slope of Vaiont. More precisely, the strata of the small mass dipped to the north with increasing inclination, whereas the general dip of the strata in the surrounding rock mass was ENE. This small mass presented, therefore, characteristics analogous to those of other masses which had been observed about one km to the west on the right slope (Figs. 7 and 8) and were described in paragraph B.3.

This was a new element to consider and, although it may not have seemed very important, it was sufficient to render the hypothesis a little more probable that the pre-historic movement of the left slope was the same for the whole expanse of the mass on the left. Therefore, the entire mass would have slid to a point of completely obstructing the old valley (see the end of section B.3).

D.4 Expansion of the benchmark system

Following the landslide of November 4 and the appearance of the perimetral fissure, the system of trigonometric control and benchmarks was expanded to cover the entire surface outlined by the perimetral crack. Ten new measuring points were constructed, some replaced those rendered useless or lost as a consequence of the November 4 landslide.

D.5 Second geophysical investigation, Winter, 1960-1961

In order to determine the depth of the mass which had now clearly revealed itself as unstable, SADE officials requested in November, 1960, that Prof. Caloi conduct a new geophysical investigation of the site. Exploration was conducted along two seismic profiles running across the western and eastern zones of the moving mass. The profiles started at 750 meters and rose to the limits of the perimetral crack at an elevation of about 1,150 meters.

At the conclusion of the study, Prof. Caloi was able to clearly identify a compact rock formation at a given depth. However, the contact between this solid surface and the one overlying it, composed of loose material or intensely fractured rock, was not a well-defined single and regular surface. It seemed to appear at extremely variable depths ranging from 100 to 150 meters from the surface.

Based on his results, Prof. Caloi estimated that the contact surface between the two formations could be established at about 640 meters near the gorge wall. This elevation did not differ significantly from that noted on the geological map provided in the Giudici-Semenza study of 1960 (see Fig. 2) whereas the 560 meter contour corresponds to the geophysical profile. The 640 meter elevation was also close to the 600 meter average elevation assumed in the hydraulic model (see section E, below).

Some of the seismic measurements taken during this investigation were made near the profiles which had already been explored in 1959.

The difference between the elastic features encountered in these measurements and those registered previously led Prof. Caloi to formulate the following hypothesis: the rock described as intensely fractured during the most recent investigation (the same rock that, in December 1959, showed a "very high elastic modulus") had assumed these new features due to a "fragmentation of the rock sector" which supported the overlying landslide mass, as a result of the increase in internal stresses caused by the "yielding of sound rock diaphrams" found at higher elevations. This yielding was considered as a consequence of earthquakes occurring in the first months of 1960 and up to the middle of November of the same year.

D.6 Adits in the Massalezza Valley

In the Spring of 1961, both due to the general exploratory criteria established by Dr. Müller and at the specific request of Prof. Penta--geologist member of the Commissione Ministeriale di Collando (Ministerial Commission of Testing)--an adit (exploratory tunnel) was excavated on the left slope of the Massalezza Valley. It was located just below the perimetral fissure, and its axis ran straight into the mountain. During numerous visits to the excavation site, it was noted that, after the first 30-40 meters of loose material observed at the entrance, one encountered fractured rock in distorted strata. Slightly deeper into the adit, after encountering ultra-milonitic zones, a sound almost uniformly dipping formation was found. Some evidence of small north-verging folds were visible inside, similar to those outcropping not far from the adit. However, on the whole, the strata in sound rock dipped at approximately 30° to 40° northward.

A few months later, in April, 1961, the geologists Dr. Broili and Dr. Weber inspected this adit on the left side of the Massalezza Valley. Their survey included exploration both inside the adit and on the surface of the mass in question. They concluded that the upper and middle parts of the moving mass rested on a plane with an average inclination of 30°. The lower part of that plane, although not visible, probably coincided with the almost horizontal contact surface of the Dogger-Malm.

Later in 1961, another adit was dug at a higher elevation. The mouth was located just above the fork of the two principal branches of the Massalezza stream. The tunnel, excavated eastward, was dug almost entirely through bedrock; three branches of the adit again reached the surface after passing through a few meters of loose material which was probably landslide detritus, but which could also have been interpreted as normal talus material.

D.7 Exploratory drilling program P, Spring and Summer, 1961

In agreement with the technicians of the Testing Commission, it was decided in April 1961, to drill four more borings, (P1, P2, P3, P4) located in two sections to the east of the previous ones (S1, S2, S3). One section was located 200 meters west of the Massalezza; the other, 400 meters to the east. The purpose of these new borings was to install piezometers to measure the water table, considered an essential element in maintaining the equilibrium of the mass. The new borings were also drilled by Consonda and Icos under the supervision of the author and Dr. Giudici. They reached a depth of 170 m and 220 m, arriving at elevations between 620 and 670 meters.

Although the borings were drilled quickly in order to provide rapid installation of the piezometers, all the data obtainable from cuttings were analyzed to acquire as complete a picture of the situation as possible.

The borings crossed zones of compact limestones as well as zones of more or less intensely fractured rocks. The borings were stopped after having deeply penetrated the water table.

This drilling operation once again confirmed the hypothesis that the contact (or slide) plane--which was not encountered by the borings--would be found at a greater depth. In fact, the intense fracturing and the extreme permeability found within the mass seemed to verify the writer's hypothesis that, down to the depth reached by the borings, the materials composing the mass were all part of the ancient landslide.

On the other hand, the considerable depth of the contact plane at the base of the mass seemed to give assurance that it rested on a plane of adequate strength, at least on the western side of the Massalezza. To the east of the stream, the data recovered were not sufficient to define the limits of the "foot" of the contact plane.

D.8 Final diagnosis of the situation, Summer, 1961

The extensive research conducted during the two preceding years made it possible to gather ample information sufficient to draw a conclusion--in the summer of 1961--regarding the dynamics of the phenomenon. This diagnosis is described as follows:

The mass moved along a slide plane that ran from the milonite to the perimetral crack. Although only a small part of the milonite was visible, it was assumed that it existed along the entire front. It was further supposed that the contact plane approximately followed the stratification incline of the bedrock. Consequently, it was possible to estimate the volume of the moving mass, a figure set at about 200 million cubic meters.

This mass was primarily composed of compact limestones and marly limestones with soft calcareous or marly interbeddings. The entire mass was more or less intensely fractured; it often presented cascade folding; it was highly permeable and, on the whole, it was characterized by poor mechanical properties. The one exception was the wall, to the east of "Punta del Toc," which appeared more solid, perhaps because of secondary cementation, a phenomena that is frequently found on the external surfaces of poorly consolidated masses.

With regard to how future movement might evolve, the author shared the opinion that slow block sliding of the entire mass would be likely; cracks would open within the mass itself, and displacements, with rates up to a maximum of a few centimeters per day, would ensue. Based upon this assumption, the frontal part of the landslide would fall first, then other portions would fall or slide from time to time. The material--probably composed of numerous blocks, more or less independent from one another--which had fallen into the gorge and filled it, would act as brakes and stabilizers thus continuing to support the material remaining higher up. Nonetheless, even if the worst hypothesis were verified, the mass would definitely halt its movement when one of the block slides reached the opposite slope and formed a solid base.

The opinions presented above, as well as those formed previously, were expressed verbally by this author to his father, to the geologists and to the technicians in charge of study and control. In many essential points, the author's opinions conformed, in particular, with those of Dr. Müller, and there was general agreement that this was the most prudent and pessimistic analysis of the dynamics of any future movement, in the unfortunate case that such a phenomenon should be verified.

E. Studies of the Hydraulic Model, 1961-1962

After the 1960 landslide and the discovery of the moving mass at the site, Eng. Carlo Semenza thought of reproducing the possible future sliding phenomenon in a hydraulic model. It was intended that the model should taken into consideration all of the concerns regarding the existence of a moving mass at the Vaiont site. In particular, it should reproduce the magnitude of the potential slide and all the dynamics of the movement under the most pessimistic previsions. With this in mind, all the opinions of the consultants, no matter how negative, were considered while working with the model.

Therefore, a model was built at the Centro di Nove (Nove center) in which, initially, a plane slide surface was simulated, and the experiments dealt with two different slope inclinations: 30° and 42°.

In the model, the landslide material used was gravel, chosen to facilitate movement. All the material immediately slid into the reservoir when the supports were removed. During one of these tests, in August, 1961, the writer and his father visited the Nove center. At that time, this author suggested that it might be useful to modify the contact (or slide) plane in order to create a surface that more closely reflected the actual attitude of the strata.

In order to accomplish this plan, the author was requested to prepare a series of profiles which--in his opinion--could represent the conformation of the assumed slide surface. These profiles were drawn up with the writer's supervision by the Ufficio Lavori del Vajont (Vaiont Works Department) and were then used as the basis for constructing a new contact surface. Consequently, a new series of tests was performed.

During the same visit, the writer's suggestion to substitute the gravel with bricks was discarded because it was felt that the gravel corresponded more accurately to the supposed dynamics of the phenomenon.

In the future, the author was no longer directly involved with the model; however, he was informed on various occasions of the regular progress of the studies.

F. Reservoir Operation, 1961-1963

Early in 1961, as a result of lowering the reservoir water level to an elevation of about 600 meters, it was observed that the movements of the unstable mass were slowing down and had almost come to a complete stop.

This fact tended to support the experts' opinion, expressed earlier, that the unstable mass could be kept under control by the appropriate operations of filling and draining the reservoir. The goal of the operations was to achieve a new position of the mass resulting in a definitive new equilibrium.

Since the problem of the volume of the moving mass had not been directly and securely solved (on the contrary, it was still the source of contrasting hypotheses and debates among the specialists), all of the experts studying the problem, including those of the Testing Commission, agreed upon a program of prudent experimental impoundings of the reservoir in the hope of achieving a more complete understanding of the nature and size of the sliding mass.

The writer participated in surveys of the site on April 19, 1961, (together with Penta, Sensidoni, Esu, Dal Piaz, C. Semenza, Biadene, Tonini, and Pancini) and on October 17, 1961, (with Penta, Frosini, Sensidoni, Dal Piaz, D. Tonini, Biadene, and Pancini) conducted by the Testing Commission. During these meetings, opinions were exchanged about the problem and the writer had the opportunity to express his point of view to the other participants.

Although the writer did not directly and systematically participate in the program of the raising and lowering of the reservoir water level, he was kept informed of the behavior of the moving mass through occasional contact with SADE managers and technicians. Thus, he came to understand that the velocities of displacement (measured by an expanded bench mark system) were influenced primarily by the first saturation of zones that had until then always remained above the water level. Furthermore, the movement stopped when the water level was lowered, and the phenomenon did not repeat itself during successive impoundings--or if some displacement did occur, it was very slight. In any case, the displacement velocities maintained levels far lower than those registered in the Fall of 1960.

At the seismic station installed at the dam, which had registered a series of important shocks in the landslide zone during the Fall of 1960, the seismographs now registered periods of relative calm, alternated with periods of activity. The latter coincided prevalently with impounding operations as could be expected due to the enormous pressure of the water against the sides of the basin. The intensity and frequency of these readings remained, nevertheless, inferior to those of the Fall of 1960. Several strong and isolated tremors, which were also felt by the population in the valley, were found to have an epicenter lying outside of the reservoir.

The entire body of facts, objectively considered, that seemed to confirm the previous diagnosis of a slow and gradual movement of the mass, led to the conclusion, easily accepted by all concerned, that the movement of the mass could be kept under control, and that even more hopefully, the mass would tend to establish its own new equilibrium through a process of slow displacements of modest proportions.

G. Second Geological Survey, Winter 1963

As stated in the introduction, this chapter and the following one reflect the results of research carried out in collaboration with Prof. D. Rossi (D. Rossi and E. Semenza, 1964 and 1965). Micropaleontological research carried out jointly by C. Broglio Loriga and M. G. Mantovani (1965) established the age of the materials included in this paper.

G.1 Stratigraphy of the landslide mass and the surrounding zone

The numerous cracks, small faults and, above all, the almost complete removal of the vegetation and topsoil over most of the slide mass due to wave action, allowed a much better surveying of the zone than was previously possible. This resulted in a more precise knowledge of the different formations involved in the landslide mass as well as their stratigraphic succession (Figs. 13, 14A, and 14B show the area just after the slide).

The following sequence can be observed proceeding from the oldest to the most recent formations.

do Dogger: oolitic and crystalline limestones

The Dogger is a very compact and extremely rigid formation, poorly stratified in thick layers, intensely fractured and very permeable. The formation is about 300 m thick. The dam lies upon this formation. In addition, the Dogger formation is the basal structure of the slide zone. The Dogger outcrops on the Mount Toc slopes above the area from which the landslide moved as well as to the west of that area and in the Vaiont gorge, below the dam. This formation was not involved in the movement.

ma <u>Malm</u>: Gray cherty limestones with black cherts, which can be nodular

The Malm formation is composed of very thin strata (not more than 15 cm) with abundant interlacing of cherty material or scattered cherty nodules. The Malm has some interbedding of thin calcareous sheets or soft marly-calcareous materials. It is easily fractured or folded, but the Malm is much more compact than the formation just above it. The overall thickness of the Malm cannot be precisely evaluated, but ranges from 30 to 50 meters. The Malm formation outcrops at the top of the Costa delle Ortiche and in other points along the slope of Mount Toc beyond the surfaces where the landslide broke away. It can also be observed at the right side of the Vaiont Valley above the dam.

a <u>Lower and middle Cretaceous</u> (lower part ≈ Aptian)

This formation is formed of a complex of limestones or marly limestones, containing cherts, with thin soft calcareous, marly or clayey-marley interbeds. The color is prevalently red in the upper part, greenish in the middle, and light gray at the base. The formation is made up of intensely fractured thin strata and, on the whole, it is rather easily deformable. Its thickness is 120 m and can only be estimated along the fault wall coinciding with the eastern boundary where the mass broke away. In addition to this area, the formation appears on slabs remaining along the rupture surface. In fact, the surface of sliding corresponds to many wide tracts of different strata of the lower part of complex "a", which are joined by almost vertical cuts perpendicular to the strata. Complex "a" may be found in various places in the slide mass, usually at the peripheral zones but also, in particular, in the zone of the craters near the dam, and in the eastern lobe.[1]

---

[1]These and other names have been used to indicate various points of the new landscape (see Fig. G14B).

b Middle Cretaceous (middle-upper part): conglomerate with pinkish or gray cement

This unit forms a bed about 10 meters thick, which is topped by a calcareous layer about 1 meter thick. It can be distinguished from the conglomerate of level "d" because the cement uniting the fragments is pinkish or gray rather than white. This extremely compact conglomerate stands out from other formations, frequently forming a step. It is visible in numerous points; in particular along the western flank of the "Colle Isolato," at the base of the "Pinnacolo" and on the southwestern side of the "Conca delle Pozza" (see Fig. 14B).

c Middle-upper Cretaceous (Albian ≈ Cenomanian)

This complex was originally formed of rather compact beds of gray limestones that alternated with sequences of less resistant thin layers of greenish limestones and calcareous marls. On the whole, the original permeability probably was quite low: today the permeability is high due to intensive fracturing. This sequence may be easily observed on the "Pinnacolo" and at the SW edge of the NW wall of "Punta del Toc."

d Upper Cretaceous (≈ Turonian)

This complex consists of red marly, silty limestones interbedded with conglomerates and limestones. Three distinct and characteristic units appear in this complex: the upper and lower units are red, and the intermediate unit is often conglomeritic, sometimes revealing syngenetic folds. All three units together are about 14 m thick. On the whole, they have low strength characteristics. This complex is found in many parts of the slide mass, in particular along the northwest and north walls of "Punta del Toc," and along both sides of the Massalezza Valley.

e Upper Cretaceous (≈ Coniacian)

This complex consists of fine-grained limestones with various colored cherts. This complex is about 27 meters thick, formed of limestones of various types, rich in cherts and showing a prevalently nodular structure at the base. Originally this complex must have been extremely strong and compact, even now its strength is greater than other horizons, as may be seen on the north wall of "Punta del Toc" and on the plateaus of the "Pozza" and east of the Massalezza where this cherty limestone outcrops extensively.

f Upper Cretaceous (≃ Santonian)

This is a complex of light red and green limestones and marls with red cherts. The general pinkish coloration of this complex is lighter than that of the levels described above. It is, however, more compact. This complex outcrops primarily in the northeastern zone of the slide mass.

cs "Scaglia rossa" of the Upper Cretaceous

The "scaglia rossa" consists of marly-limestones at its base and of marls in the remainder. These marls are generally red except for a gray intercalation. This formation was not involved in the movement.

q Quaternary

This unit consists of deposits older than the landslide--specifically, morainic, detrital and alluvial. For the main part, they consist of coarse detrital material containing somewhat rounded elements. This material is abundant in the northeastern zone. A limited area of lacustrine clays is visible on the Pozza plateau. The presence of morainic deposits remains problematic.

q'o Detritus: deposited by the wave produced by the landslide

This unit consists of detritus of various origins stripped away from detrital or alluvial slopes or torn from outcrops of intensely fractured rock by the force of the wave. These materials are easily recognized because they show no cementation, compaction or settlement.

The form assumed by these deposits permits a reconstruction of the movement of the wave. They are widely distributed over the area, especially in the lowest zones.

q'd <u>Detrital masses and alluvial fans</u>: formed after the landslide

This material consists of detritus of rock slides that slid from the slabs exposed along the slide surface and of alluvial cones which formed primarily during the rains of November, 1963. In various places, these materials have considerably modified the topography to the point that it no longer corresponds to the topographical conditions noted immediately after the slide. This applies, in particular, to the internal lake (B) which was almost half-filled by such detrital materials (see Fig. 14).

G.2 Structural conditions of the slide mass

Some approximately east-west folds can now be observed in the area. The most important ones, listed from north to south are:

1. Toc Syncline, clearly visible on the NW wall of "Punta del Toc"; the syncline is subdivided by a minor faulted anticline.
2. "Main" Anticline, faulted along the entire southern side, easily observed in the northern part of the Massalezza Valley.
3. Syncline of the Pozza Plain, which is rather broad, and also subdivided by a small anticline; it can also be very well observed in the Massalezza Valley.

To the northeast, there is a mass formed by materials from unit "a" overlying material of level "f" which remains in its normal position above the older units of the series. As had already been stated in the 1959-60 report, this is a smaller mass which had slid from Mount Toc onto a larger mass whose movement dated to a prehistoric epoch. Another similar mass of the "a" formation, also overlying several more recent levels, may have been connected originally to the first. This mass is found in the area of "Colle Isolato."

Many faults, which can now be easily observed in the area, existed before the 1963 slide. Along some of these faults, displacements, on the order of one meter, also occurred during the slide.

Some faults were not displaced at all during the slide. For example, two small faults dipping to the north may be observed on the NW wall of Punta del Toc; the northernmost fault crossing the Massalezza; and two faults cutting the crest of the secondary anticline which divides the Pozza syncline.

Other surfaces of sliding observed on the "Costa Rossa" probably correspond to small, slightly inclined break-thrusts.

Among the displacement phenomena which occurred during the slide, the following should be noted:

1. The second from the north of the faults which cross the Massalezza. This fault crosses the entire mass from the "Valle di NW" to the "Vallaccia." It is an old reactivated fault which now shows a displacement of one or two meters in its western part, about ten meters in its eastern part, with uplift of the northern part. It resulted from compression during the slide.
2. The northern border of the eastern lobe, which corresponds to the surface where this part of the slide overrode the rest of the mass. In fact, the eastern lobe may have slid just after the rest of the mass, or, more probably, while sliding with the rest of the mass, it may have overthrust the frontal part due to the compression process which occurred when the latter collided with the opposite flank of the Vaiont Valley. This is verified by the grassy surface of the main sliding mass which dips under the toe that forms the northern limit of the eastern lobe. This interpretation

is also supported by the discordance existing between the northernmost limit and the strata of the main body of the slide (Fig. 15).

3. Folds present in both the eastern and western lobes; these are folds only in the broadest sense of the word since the extremely intense fracturing of the rock caused the transformation of the folds, appearing at the surface, into compressed synclinal nuclei and extended anticlinal ridges; these too run approximately in an east-west direction.
4. The direct fault that separates the "Pinnacolo," Fig. 14, from the rest of the slided mass. This fault probably moved during a relaxation phase when the sliding mass moved back down and to the south after the principal northward movement.
5. The disorderly layering and faulting of the "Dosso dello Spartiacque," Fig. 14. Given the low elevation at which these masses are found, it seems most likely that they correspond to a slide, in recent epochs that came from the north walls of "Punta del Toc," which preceded the principal event. Apparently, the masses did not reach the bottom of the gorge which was already filled with other previously fallen material. Thus, they were pushed forward with the principal mass.
6. Numerous fractures, many with an opening of several meters, with two prevalent directions--generally east-west and north-south. It is probable that many of these fractures pre-dated the slide, but they were certainly widened during the mass movement. Sometimes a block compressed between two fractures is lowered considerably (even several meters).

G.3 Hydraulic effects on the slide mass and on surrounding zones

Many details reveal the action of the water during the landslide. One is the bending of objects such as the two metal posts visible in

Fig. 16. The grass in the surrounding zones was completely flattened. In many cases, much of the detritus was removed from the zone. Finally, alluvial deposits of various types were formed. It was, therefore, reasonably simple to reconstruct the movements of the water as produced by the mass sliding into the reservoir.

First of all, the water hit the right side of the Vaiont Valley at different levels depending on the zone. Generally speaking, the water was deepest in the valleys and where it was easily channeled. Water pushed both east and west along the Vaiont Valley. The eastern wave decreased gradually, increasing only when various obstacles were encountered; the hill of "Le Spesse" village (Fig. 14B), the promontory of "La Pineda" and the area of "San Martino." On the other hand, due to the obstacle of the dam and the steep walls of the gorge, the western wave shot upwards almost reaching the village of Casso. Farther to the west, the water rose above the dam and crashed into the Vaiont gorge. Naturally, to the west, the water level then decreased rapidly.

A wave of tremendous momentum rose up the left slope of the valley above the dam where it reached very high elevations and even hit the western side of the slide mass.

It is remarkable that the water which was pushed up the right side of the Vaiont Valley fell back to the south, overran the slide mass, and broke violently into the Massalezza depression. Here, an internal lake (B) was formed (Fig. 14); it drained quite rapidly leaving an abundant accumulation of detritus and tree trunks which had been uprooted from the mass that had slid from Mt. Toc. This wave did not, however, hit the eastern and western lobes due to their elevated and distant position.

G.4 The Scarps and the visible portions of the surface of sliding

Two distinct sections of the slide surface are visible: the "slabs" or "lastroni" (Figs. 14A and 14B) which form the visible part of the slide surface, both in the eastern and western zones; the fault wall forming the eastern lateral scarp.

The "slabs" are the surfaces of those strata (base of level "a" of the Lower Cretaceous) remaining in place; these surfaces are parallel to the principal plane of movement which was located just above them. In fact, it becomes clear that, during the movement, some strata--up to several meters thick--were pulled away from the bedrock underlying the old contact surface, and they were dragged down with the rest of the mass. In addition, after the landslide, considerable rocky material which had remained in place, but was precarious under the new conditions, broke away creating small localized translational block slides or rock slides which are more frequent during rains and thaws. These phenomena will continue over the years and will occur especially where stepping, that cuts through the strata, is now visible.

On the whole, the rock "slabs" or "lastroni" tend to follow the general dip of the strata forming a gentle recess because the strata in the western part dip to the north, whereas toward the east, they rotate gradually until they dip to the NNW in the eastern part.

The condition of the rock is, on the whole, reasonably good except for some "packs" of intensely fractured strata which are in an unstable position.

The lateral fault wall on the eastern side was originally quite regular (see the 1:5000 map). This continuity was partially altered in various points due to the sliding of sections to the NW. In general, the surface dips N 67° W, with an incline of 55°. Along the fault wall, the units "a," "b," "c," and "d" may be observed dipping to the NNE with a slightly greater, or locally equal, inclination to that of the wooded slope above. In areas where the friction breccia was removed (two or three meters?), the rock was found in good condition. This confirms the fact that this portion of the mass never participated in sliding movements, either ancient or recent.

G.5 Unexposed portion of surface of sliding

It is the author's opinion that the contact plane, along which the movement of October 9, 1963, occurred (as yet not directly established in the lower section), is located near the separation zone between bedrock and rock displaced previously. This zone was located primarily in level "a" (which, as has now been established, is rather brittle). These conditions did not exist in the lower part of the eastern section where the separation zone probably rose obliquely through the series, cutting at least up to level "e". It is interesting to note that all of these strata ("b" to "e") were originally quite compact.

The writer also believes that displacement of a small part of the bedrock, mainly in the central and eastern areas of the mass, probably occurred during the collapse. The resistance of this rock had been gradually reduced due to the stress to which it was subjected during the most recent years; thus the resistance was finally overcome at the initial moment of the sliding.

In conclusion the surface of sliding does not correspond, in the writer's opinion, to one single bedding plane. Instead it is formed by more or less extensive stretches, located along different bedding planes. These portions of the surface of sliding are connected to each other by steps corresponding to perpendicular fracture planes which, during successive periods, gradually interrupted the continuity of the strata.

Based upon these considerations, an estimate of the slide mass was approximately 270 million cubic meters.

H. Hypothesis Regarding the Dynamics of the Movement and Collapse

H.1 General mechanical characteristics of the formations involved

The behavior of the various geological formations during the final collapse, as deduced from the conditions observed during the survey, now permits a more precise analysis of certain rather unique mechanical characteristics in the formations involved. Furthermore, a better interpretation and understanding of events preceding the slide can be achieved.

In fact, it became quite clear, after the waves caused by the slide removed the superficial cover over most of the topographic surface, that the upper formations (indicated on the map and profiles as "c," "d," "e" and "f") consist primarily of intensely fractured rock. However, the individual elements appear quite solid.

The lower formation "a," also highly fractured, now appears less sound and more easily deformed than the overlying formations. This weakness is due both to the thin bedding and to the presence of numerous, small intercalations of soft materials.

In addition, exposure following the slide confirmed that all of these formations as well as the underlying Malm (ma) and Dogger (do) lie in slope position (i.e., with the strata dipping northward) in their southern portion near the upper part of Mt. Toc. In the northern portion, these formations display a wide fold, thus forming a somewhat chair-like structure with a horizontal lower section. This structure can be easily observed, with respect to the Dogger formation, by looking from Longarone toward the opposite left wall of the Piave Valley, downstream from the confluence with the Vaiont Valley.

H.2 Period of slow movement

The writer now believes that, generally speaking, his previous opinion is confirmed. Thus, the instability of the mass which moved on October 9, 1963, originated in sliding movements that took place during previous geological stages and affected the upper part of the complex forming the left side of the basin. These ancient movements, which are neither clearly identified or defined, eventually caused the obstruction of the then-existent valley, coming to rest against its right flank.

Gradually, the river eroded the newly slid rock mass, thus creating the gorge that existed in recent times, prior to the 1963 landslide. The eastern portion of the new gorge closely followed the course of the old valley, making it deeper. On the contrary in the western part, the slide rock mass was eroded somewhat south of the old riverbed, which remained buried under the mass identified today as "Colle Isolato" (Fig. 14). More precisely, this mass, remaining on the right flank of the valley, was originally much larger; it was naturally reduced and subdivided by erosion into various smaller portions--the largest remaining one was "Colle Isolato." The complexity of the phenomena occurring from 1960 to 1963, nevertheless seem to indicate that the nature of the old movements and particularly, the characteristics of the contact surface between the bedrock and the mass already involved in the ancient landslide, are more complicated than hypothesized in the 1960-1961 model.

Given the numerous signs of structural strain observed in the past, it may be assumed that, after the ancient sliding phenomenon, the mass had undergone minor and irregular movements, during the shaping of its recent morphology. It is also probable, as the name "Toc"[1] and local tradition suggest, that these movements continued in a slow but perceivable fashion sufficient to slightly modify the surface features,

[1] In regional dialect, "toc" means "crazy."

even up to the present. A fundamental contribution to these movements was the action of rainwater that easily permeated the entire zone as well as the action, in depth, of the water table. Groundwater action caused both hydrostatic pressure on the mass and reduction in strength of the weakest materials as a result of water absorption.

The water of the reservoir, seeping deeply into the rock mass, fostered the renewal of these movements, causing slow displacements primarily during the impounding of the reservoir or heavy rainfall. However, a systematic relationship between the displacements and the raising of the reservoir level was not established. It was noticed, however, that after the first filling, movements of the entire mass tended to decrease during the successive increasingly higher impoundings of the reservoir. The movements in the area below the Pozza plain were deformations and rotations of vertical elements, which were separated by more or less vertical fractures or discontinuities that sometimes coincided with break-thrusts. In the zone above the Pozza plain, on the contrary, probably as a result of the different structure existing there, translatory movements occurred which were probably distributed over the surface of various strata joints.

The complexity of the movement during this period in which the different parts of the sliding mass were characterized by diverse slide phenomena is clearly shown by the planimetric features of the perimetral crack. On the western side, this fissure stopped at an elevation of 850 meters, about 150 meters above the maximum water level and about 200 meters away from the reservoir. On the contrary, on the eastern side, the distance increased to over 300 meters above the water level, and the crack lay 600 meters away from the reservoir. The irregular distribution of displacement sectors confirms the complexity of the movement: maximum displacements were registered under the Pozza plain, west of the Massalezza stream, where the wide "chair-like" structure was expected to provide greater stability and therefore smaller displacements; nevertheless, the movement decreased progressively moving eastward (where the eastern extremity remained almost stable) into a zone in which the support at the base was supposed to be the weakest.

On the whole, these phenomena displayed aspects which would have been considered characteristic of relatively plastic mass. This assumption is further supported by the fact that after the slide in the Fall of 1960, no other cracks appeared in the terrain until October, 1963.

It is therefore reasonable to assume that the slow movements, registered between 1960 and October, 1963, with alternating static and dynamic periods (the movements were extremely slow right up to the last), were caused by a combination of sliding along planes of minor resistance (possibly formed during the ancient landslide) and of the deformations of discontinuous rock structures under the stress imposed by the overlying masses. It may now be assumed that this combination of actions, which were also influenced by the hydrostatic pressure on the rock mass induced by the reservoir water and by the reduction in frictional strength of the weaker materials, may have accelerated the process leading to the subsequent collapse. This process consisted of a gradual, imperceptible weakening of the materials and the resulting gradual failure of the bedrock under the toe of the sliding mass, especially in the eastern part, where the resistance of this rock--potentially very strong due to the irregularity of its surface--was progressively reduced. With this process, it would now be possible to explain the sudden--and, in its details, entirely unpredictable--final failure and the subsequent collapse of the entire mass.

H.3 Failure threshold

During the days just before the collapse, the velocity of the moving mass gradually increased, surpassing the values registered in 1960, but still remaining within the limits of relatively slow movements. This fact, as well as the appearance of cracks in the moving mass near the dam (similar to those preceding the slide of November 4, 1960), were interpreted as a warning of a possible partial slide of a frontal part of the mass. This partial slide, similar to those seen in the past, even though its dimensions might be greater, was considered a typical aspect of the phenomenon in progress.

On the contrary, it is not believed that during the last days, a rapid and progressive weakening of the rock at the base of the sliding mass had been in course. Thus, the binding forces, that had acted as brakes and regulated the displacements of the moving mass, were being weakened or destroyed during this period. This process, the duration of which cannot, in any way be determined, led to the abrupt failure (which, due to its very nature, was not accompanied by the slightest warning). This failure instantly transformed the series of slow displacements into a sudden collapse of the entire mass. The mass movement, therefore, assumed aspects entirely different from those that had been previously anticipated.

The hypothesis expressed above also seems to be confirmed by the practical impossibility that other forces or actions involving the sliding mass may have been responsible for the loss of equilibrium. In fact, the stabilizing effect of the weight of the mass had been increasing for over two weeks due to the lowering of the reservoir level by about 10 m. This reduced the bouyancy force acting upon the unstable mass. The extremely slow lowering of the reservoir level maintained the hydrostatic pressure of the groundwater within acceptable limits. This fact is confirmed by piezometric readings, especially in the lower part of the mass, where the readings for the level of the lake and those of the water table were always practically identical. In the upper part of the sliding mass, some effect may have been caused by the accumulation, within the fissures, of the rather intense rainfall during August and September. Nonetheless, it is very difficult to imagine that the type of forces described above could have changed so abruptly as to cause the collapse.

The seismic activity registered within the landslide mass during the third impounding maintained even lower values than those of the two previous impoundings.

Therefore, upon due consideration, it was definitely concluded that the immediate cause of the collapse must be attributed to the failure of the last elements of the rock support system which had, up to that time, maintained the movements of the mass within the limits of slow deformations.

H.4 Kinematics of the collapse

An entirely unpredictable characteristic of this extraordinary phenomenon was the extreme velocity developed during the movement. Moreover, this velocity was accompanied by the surprising compactness maintained by the mass. In fact, in spite of its great discontinuity and fracturing, the rock mass remained practically intact and recognizable, even in many small details, during a movement of several hundred meters including the crossing of the deep Vaiont gorge. Just as astonishing is the fact that the mass climbed to a remarkable elevation along the right side of the basin although the geometrical configuration of the valley seemed to be favorable to an impact that would have stopped the sliding mass against the opposite wall.

In order to explain a movement that was so fundamentally different from anything that the experts had previously imagined, only hypotheses can be advanced. This is particularly true because there is no direct knowledge of the actual conditions of the mass in the deepest part of the gorge. Furthermore, no comparable example of the sliding of a rigid mass with similar size, compactness and displacement exists in technical literature.

Based on observations made during the geological survey and considering the mechanical characteristics of the various formations, the writer has formed the following hypothesis: the lower levels of the northernmost part of the sliding mass and the uppermost levels of the bedrock formations were reduced to flakes and then practically crushed into tiny particles. This mass was swept ahead and immediately filled the Vaiont gorge, thus forming a thick bed of loose material, which due to the presence of water was extremely plastic. Its surface was then shaped during the passage of the mass, assuming a concave form which aligned itself with the old movement plane and with the right side of the Vaiont Valley, above the gorge.

Thus, the sliding mass was able to develop an extremely high velocity (on the order of several tens of kilometers per hour, an incredible speed when compared to previous rates of displacement measured in centimeters per day); it created practically no friction resulting therefore, in its ascent along the right side of the valley. At the end of this movement, the mass must have moved backwards (several tens of meters) to the south until the actual position of equilibrium was attained. During this latter movement, which partially covered the southernmost and lowest portions of the slide mass, a rapidly increasing resistance to friction was developed which caused a certain amount of compression of the mass and the separation of the northernmost portions of the slide mass. These portions are "Colle Isolato" which formerly, during the forward movement should have been partly covered, and "Pinnacolo" (see Fig. 14).

In the eastern part of the mass, the resistance along the surface of sliding was much greater. This is shown by the absence of separated portions along the northern border of the mass and by the evidence of strong compression developed in this area. The greater resistance probably resulted from the shorter curvature radius that the concave sliding surface had here and, above all, from the presence of the elevated eastern lobe, which continued its northward thrust. It must also be remembered, as stated above, that this lobe probably slid immediately after the main mass or, more precisely, it continued to slide after the principal mass had completed its descent and its reverse movement was about to begin. Therefore, the two forces negated each other, and the reverse movement did not take place in this area.

This hypothesis, dealing with the mechanics of movement, may explain how such an enormous and intensely fractured mass of strata, such as those visible in the landslide, could have--contrary to every prediction--crossed the entire valley essentially as a whole. This explanation would also reasonably justify the extremely low resistance to friction generated during the slide which in turn allowed the enormous kinematic energy released during the slide to push the rock mass onto the opposite side of the valley, up to 100-150 meters above its original position.

The simultaneous presence and combination of these two factors--very high displacement velocity and rigid compactness of the mass--constituted an exceptional event, unpredictable in the history of man, which created the enormous wave movement and the catastrophic overflowing of the reservoir.

Geology Institute of Ferrara University, August 1965

Summary

A brief treatment of the studies in the zone of the disastrous landslide in the Vaiont Valley on October 9, 1963, is presented. The studies were conducted by the author, mainly working with F. Giudici (1959-1960) and then with D. Rossi (1963-1965). A future geological report (by D. Rossi and E. Semenza) will treat the subject in full detail. The author felt, however, that in the meantime, a panoramic view of the series of studies conducted in the zone should be available. The paper has been prepared both because of the great scientific interest in the problem as well as an attempt to clarify various aspects of such a complex phenomenon.

This paper deals with: the first geological survey, the first studies considering the stability of the "Pian del Toc," the research following these studies and the resulting hypotheses, the first movements of the mass followed by the appearance of the perimetral fissure, the second research cycle, the tests carried out with the hydraulic model, the deductions based on the relationship between the reservoir level and the movements, and a second geological survey conducted after the slide.

In conclusion, the author tries to formulate a logical explanation of how a relatively slow movement lasting for nearly three years could have suddenly changed into this entirely unexpected, extremely rapid landslide of the entire rock mass.

Résumé

Cet article contient un exposé synthétique des résultats des études effectuées par l'auteur, pour la plus grande partie en collaboration avec F. Giudici (en 1959 et 1960) et ensuite avec D. Rossi (de 1963 à 1965) dans la zone du bassin du Vaiont qui fut affectée per la terrible glissement du 9 Octobre 1963.

Une étude géologique complète sera l'objet d'une future publication signée par D. Rossi et E. Semenza.

Ici l'auteur présente--pour l'intérêt scientifique qui peut en dériver et pour essayer de éclaircir les divers aspects d'un problème très complexe--une vision panoramique des differentes études qui ont été executées à propos de cette zone.

Cet exposé synthétise donc: un premier relevé géologique ainsi que les premières études sur la stabilité de la zone de la Plaine du Toc, sur les recherches qui s'ensuivirent et les hypothèses qui en résultèrent; une relation sur les premiers mouvements de la masse, suivis par l'apparition de la fissure périmétrale, ainsi que sur la seconde phase des recherches et essais effectués à l'aide d'un modèle hydraulique; les déductions derivées du rapport entre le niveau du réservoir et les mouvements, et enfin, un deuxieme relevé géologique effectué après le glissement.

On cherche enfin d'étudier les conditions du mouvement lent, duré presque trois ans, et les causes de sa transformation soudaine en glissement inattendu et très rapide de l'énorme masse rocheuse.

Riassunto

Vengono espositi in forma sintetica i risultati degli studi compiuti dall'Autore, prevalentemente in collaborazione, dapprima con F. Giudici (nel 1959 e 1960) e successivamente con D. Rossi (dal 1963 al 1965), in quella zona del bacino del Vaiont che il 9 ottobre 1963 fu interessata dal disastroso fenomeno di scivolamento.

Mentre per una esauriente trattazione geologica si rimanda ad una future pubblicazione (a firma D. Rossi--E. Semenza), l'Autore ha ritenuto opportuno ricostruire qui in una visione panoramica il succedersi degli studi sulla zona, sia per l'interesse scientifico che ciò può avere, sia per tentare di chiarire i vari aspetti di una vicenda così complessa.

Si dà relazione perciò del primo rilievo geologico e dei primi studi sulla stabilità della zona del Piano del Toc, sulle ricerche che ne seguirono e sulle ipotesi formulate in conseguenza; sui primi movimenti della massa, seguiti dalla comparsa della fessura perimentrale, e sul secondo ciclo di ricerche, nonchè sulle prove con il modello idraulico; sulle deduzioni ricavate dal rapporto fra il livello del serbatoio e i movimenti; e infine sul secondo rilievo geologico effettuato dopo lo scivolamento.

Si cerca da ultimo di indagare sulle modalità secondo le quali si è prodotto il fenomeno di movimento lento durato circa tre anni, e sulle ragioni della sua improvvisa trasformazione nell'inaspettato velocissimo slittamento della enorme massa rocciosa.

Bibliography

Boyer R. A. (1913) - Étude géologique des environs de Longarone (Alpes Vénitiennes). "Bull. Soc. Géol. France," s. 4[a], 13, pp. 451-485, carta geol. 1:50.000. Paris.

Broglio Loriga C. e Mantovani M. G. - Le biofacies del Cretaceo della Valle del Vajont. "Riv. It. Paleont. e Str.," Milano (in corso di stampa).

Caloi P. e Spadea M. C. (1960) - Serie di esperienze geosismiche eseguite in sponda sinistra a monte della diga del Vajont (Dicembre 1959). (inedito).

Caloi P. e Spadea M. C. (1960) - Indagini geosismiche eseguite presso la stretta del Vajont durante la campagna estiva 1959. (inedito).

Caloi P. e Spadea M. C. (1961) - Indagine geosismica condotta nel mese di Dicembre 1960 a monte della diga del Vajont in sponda sinistra. (inedito).

Commissione di Inchiesta sulla sciagura del Vajont: Relazione al Ministro dei Lavori Pubblici, 1964.

Commissione parlamentare d'Inchiesta sul disastro del Vajont (1965) - Relazione finale.

Dal Piaz G. (1912) - Studi geotettonici sulle Alpi Orientali. Regione fra il Brenta e i dintorni del Lago di Santa Croce. "Mem. Ist Geol. Univ. Padova," 1, pp. 1-195, 5 tavv. di spaccati, Padova.

Dal Piaz G. (1928) - Relazione di massima su due sezioni della valle del Vajont prese in considerazione per progetti di sbarramento idraulico. 4 pp., (Relazione inedita SADE).

Dal Piaz G. (1948) - Sulla struttura geologica della valle del Vajont agli effetti degli smottamenti dei fianchi che possono derivare dal progettato invaso e dalle oscillazioni del livello del lago. 9 pp., 9 tavv. (Relazione inedita SADE).

Dal Piaz G. (1956) - Descrizione geologica del Bacino del Piave in relazione agli impianti idroelettrici della Società Adriatica di elettricità. In SADE 1956, pp. 15-37, 17 figg., 1 tav., Venezia.

Dal Piaz G. (1958) - Relazione geologica sul tracciato della strada perimetrale sulla sinistra del serbatoio del Vajont. 4 pp., 1 tav., (Relazione inedita SADE).

Dal Piaz G. (1960) - Esame delle condizioni geologiche del bacino del Vajont e della zona d'imposta della diga di sbarramento quali risultano allo stato attuale dei lavori (9 luglio 1960). 21 pp., 12 tt., (Relazione inedita SADE).

De Nardi A. (1965) - Il bacino del Vajont e la frana del M. Toc. "L'Universo," n. 1.

Feresin F. (1956) - Geologia dei dintorni di Cimolais (Udine). "Mem. Ist. Geol. Min. Padova," 20, 32 pp., 11 figg., 3 tavv., carta geologica 1:25.000, Padova.

Giudici F. e Semenza E. (1960) - Studio geologico del serbatoio del Vajont. 21 pp., 3 tavv., (Relazione inedita SADE).

Kiersch G. A., ASCE F. (1964) - Vajont Reservoir Disaster, Geologic causes of tremendous landslide accompanied by destructive flood wave. "Civil Engineering".

Kiersch G. A. (1965) - Vajont Reservoir disaster. "Geotimes".

Leonardi P. e Coll. - Le Dolomiti. Ed. Manfrini (in corso di stampa).

Müller L. (1961) - La frana della zona Toc. Diga del Vaiont, 15° rapporto geologico preparato per conto della Società Adriatica di Elettricità, Venezia (Relazione inedita SADE).

Müller L. (1964) - The Rock Slide in the Vajont Valley. "Rock mechanics and Engineering Geology," vol. II, 3-4.

Rossi D. e Semenza E. (1963) - Note illustrative della carta geologica, a scala 1:5000 del versante settentrionale del Monte Toc, comprese le zone limitrofe, quale si presenta ai primi di Dicembre del 1963. (inedito).

Rossi D. e Semenza E. (1964) - Studio geologico della massa scivolata dal M. Toc il 9 Ottobre 1963 e delle zone limitrofe. (inedito).

Rossi D. e Semenza E. (1965) - Carte geologiche del versante settentrionale del Monte Toc e zone limitrofe, prima e dopo il fenomeno di scivolamento del 9 ottobre 1963, scala 1:5.000, "Ist. Geol. Univ. Ferrara".

SADE (1959) - Società Adriatica di Elettricità. Diga del Vaiont, depliant di 27 pp., con numerose figg. e dati tecnici, Venezia.

Schnitter G. und Weber E. (1964) - Die Kathastrophe von Vajont in Oberitalien. Wasser- und Energiewirtsch., Jg. 56, H. 2/3.

Selli R. e Trevisan L. (1964) - Studio geologico della frana del Vaiont. Allegato alla relazione della Commissione di inchiesta sulla sciagura del Vaiont. 46 pp., 3 figg., 11 tavv., 4 fotogr. (Relazione ciclostilata a cura del Ministero LL.PP., Roma).

Selli R., Trevisan L., Carloni C. G., Mazzanti R., Ciabatti M. (1964) - La Frana del Vaiont. "Giornale di Geologia, Ann. Mus. Geol. Bologna," S. 2, Vol. XXXII, fasc. 1, Bologna.

Semenza E. (1960) - Nuovi studi tettonici nella valle del Vaiont e zone limitrofe. Rend. Acc. Naz. Lincei, s. VIII. XXVIII n. 2, pp. 223-229, 2 tavv., Roma.

Semenza E. (1961) - Aggiornamento e revisione delle note geologiche di Silva Zenari sulle Dolomiti d'Oltre Piave. In "Le Dolomiti orientali" Guida turistico-alpinistica. C.A.I.-T.C.I., Milano.

Ultime bozze consegnate il 23 dicembre 1965.

Finito di stampare il 28 dicembre 1965.

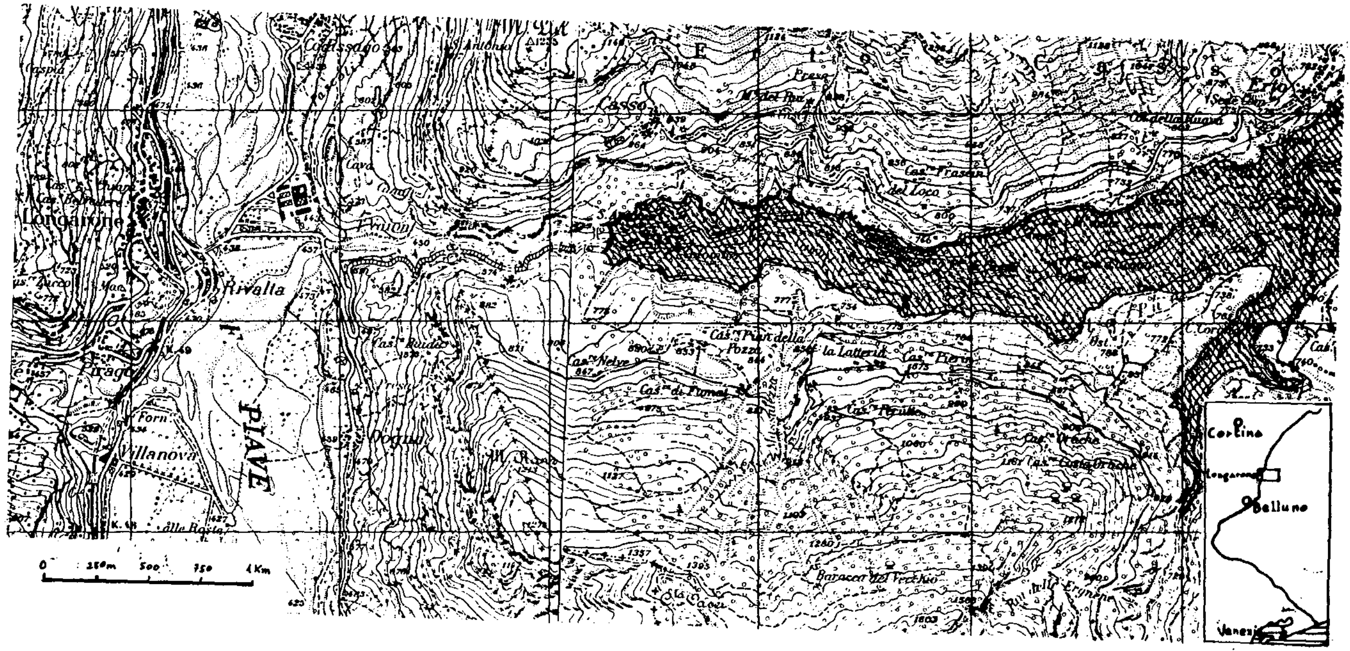
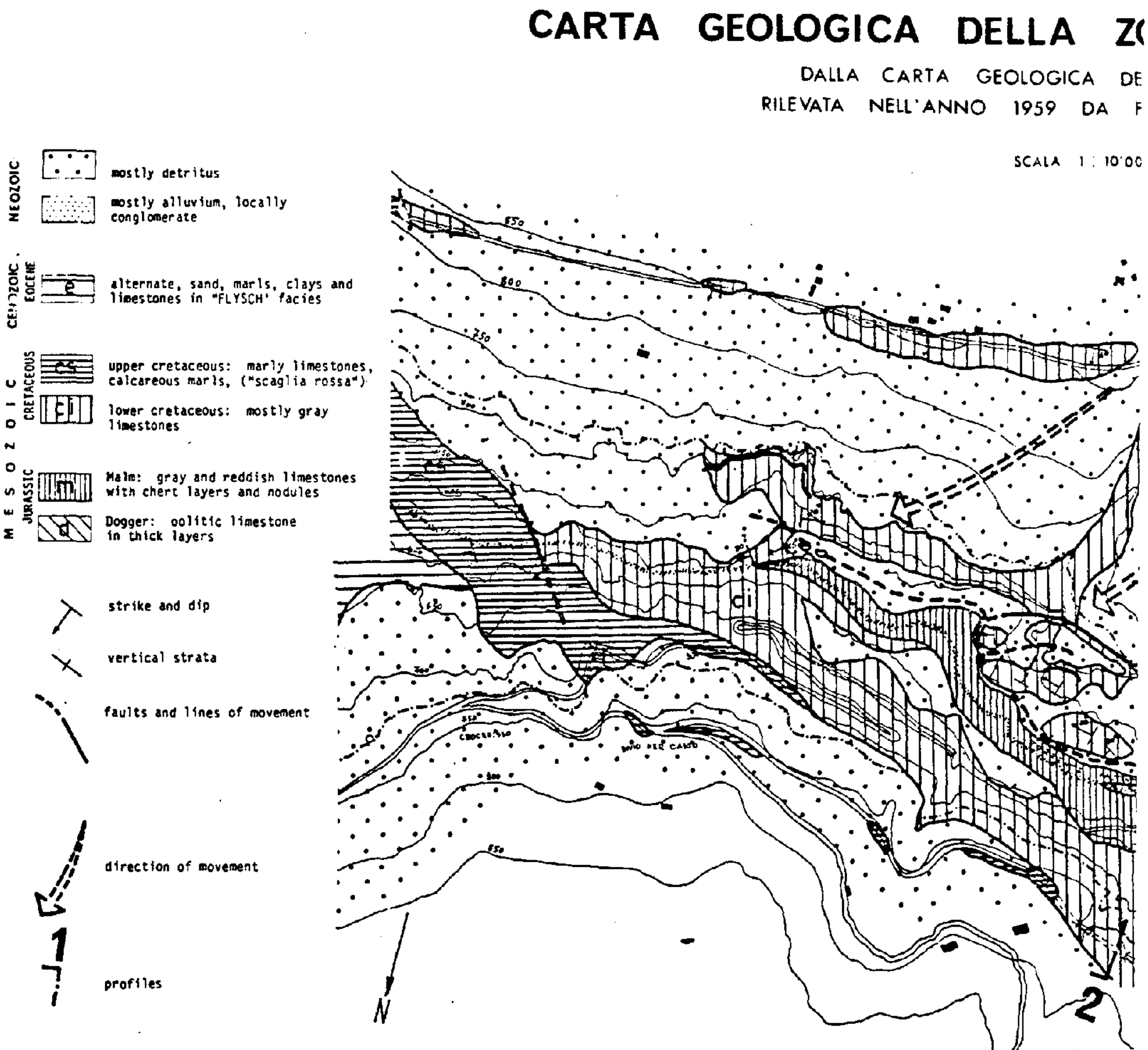


Figure G1. Topographic map of the lower Vaiont Valley



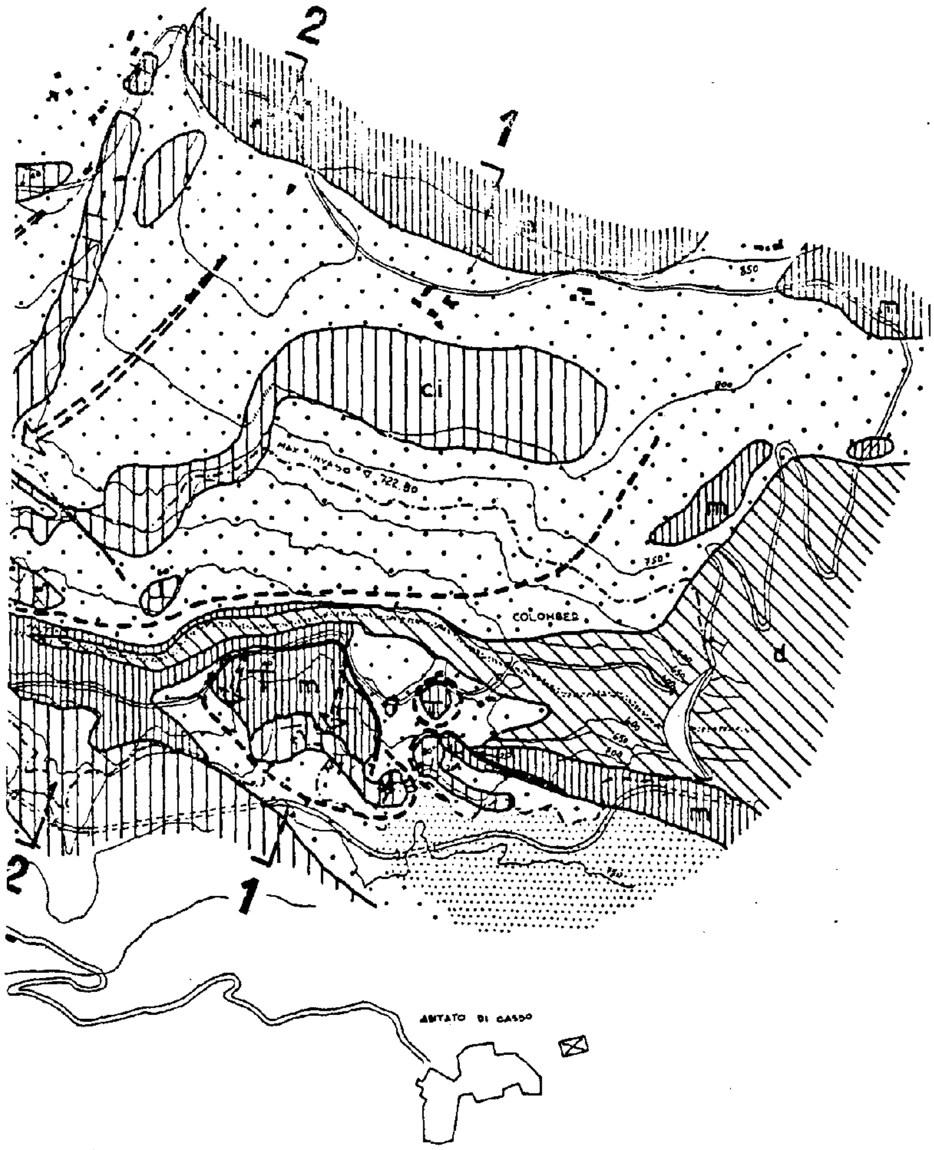
Note: The post-slide studies conducted by D. Rossi and E. Semenza (1963 to 1965), as well as micropaleontological studies by C. Broglio Loriga and M. G. Mantovani (1961 to 1965) proved that some outcrops shown on this map are erroneously dated (see D. Rossi & E. Semenza, 1965).

Figure G2. G(
tl
F.

ZONA DEL PIANO DEL TOC

A DEL SERBATOIO DEL VAJONT
DA F. GIUDICI ED E. SEMENZA

: 10'000



Geological map of the "Pian del Toc" zone taken from the "Geological Study of the Vaiont Reservoir" by F. Giudici and E. Semenza, 1960.

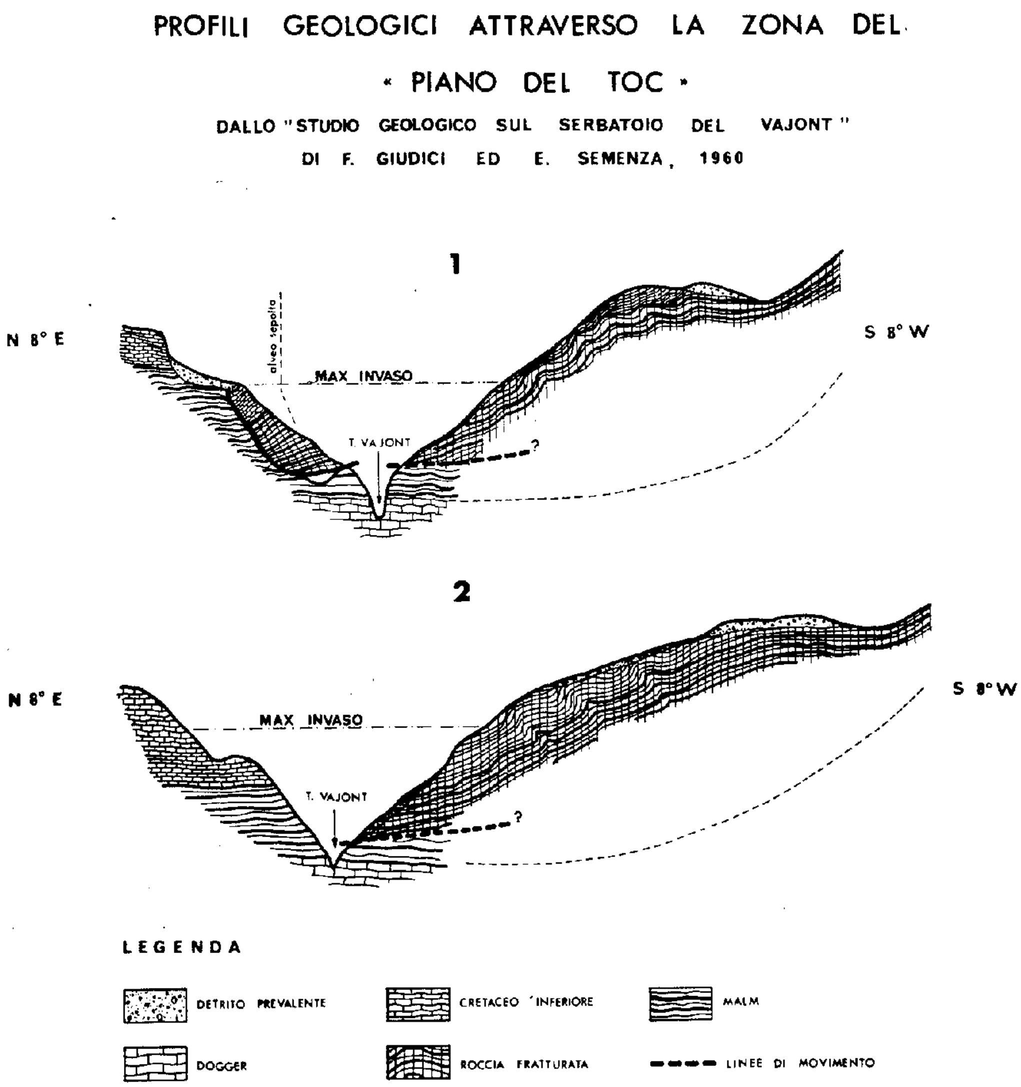


Figure G3. Geological profiles of the "Pian del Toc" zone, taken from the Geological Study of the Vaiont Reservoir" by F. Giudici and E. Semenza, 1960. (See note, Fig. G2)

Figure G4. September, 1959. Punta del Toc, seen from the right side. Note, towards the left of the wall, several fractures are opened at the top and are discussed in the text. In the foreground, note the slope where the landslide occurred on November 4, 1960.

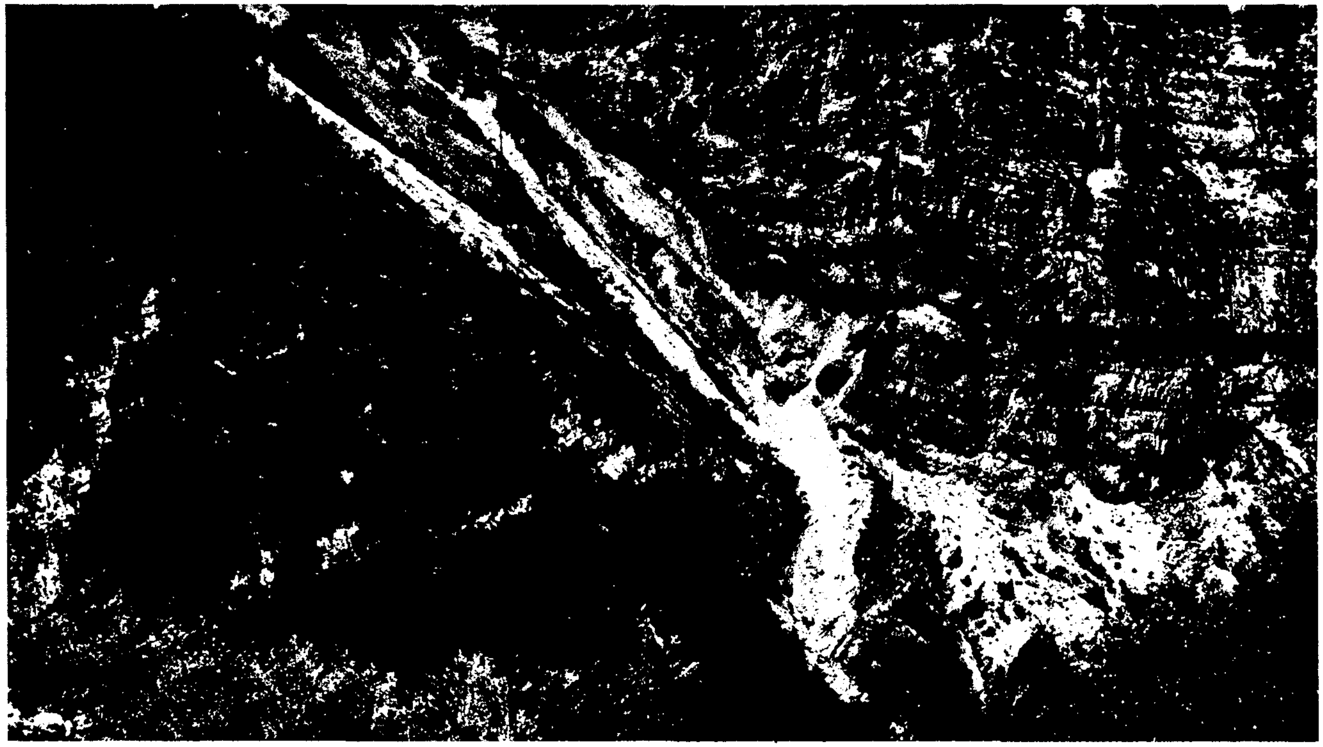


Figure G5. August, 1959. The eastern extremity of the northern wall of Punta del Toc. The strata of levels "c," "d," and "e," located in the center, dip to the right (west), especially at the base. In the wooded area to the left, the outcropping strata belonging to formation "c" dip towards the left. The inclination of these strata increases moving from left to right in this photo. The sharp tectonic discordance and the existence of a zone of milonite (see Fig. G6), brought to light while excavating along the path observed at the base of the walls, seem to indicate a movement from right to left of the mass making up the wall.

Figure G6. November, 1959. The excavation mentioned in Fig.G5 with the milonites that separate the differently dipping strata: the conglomerate of level "b" visible at the right and the basement material (fractured rock at the left).

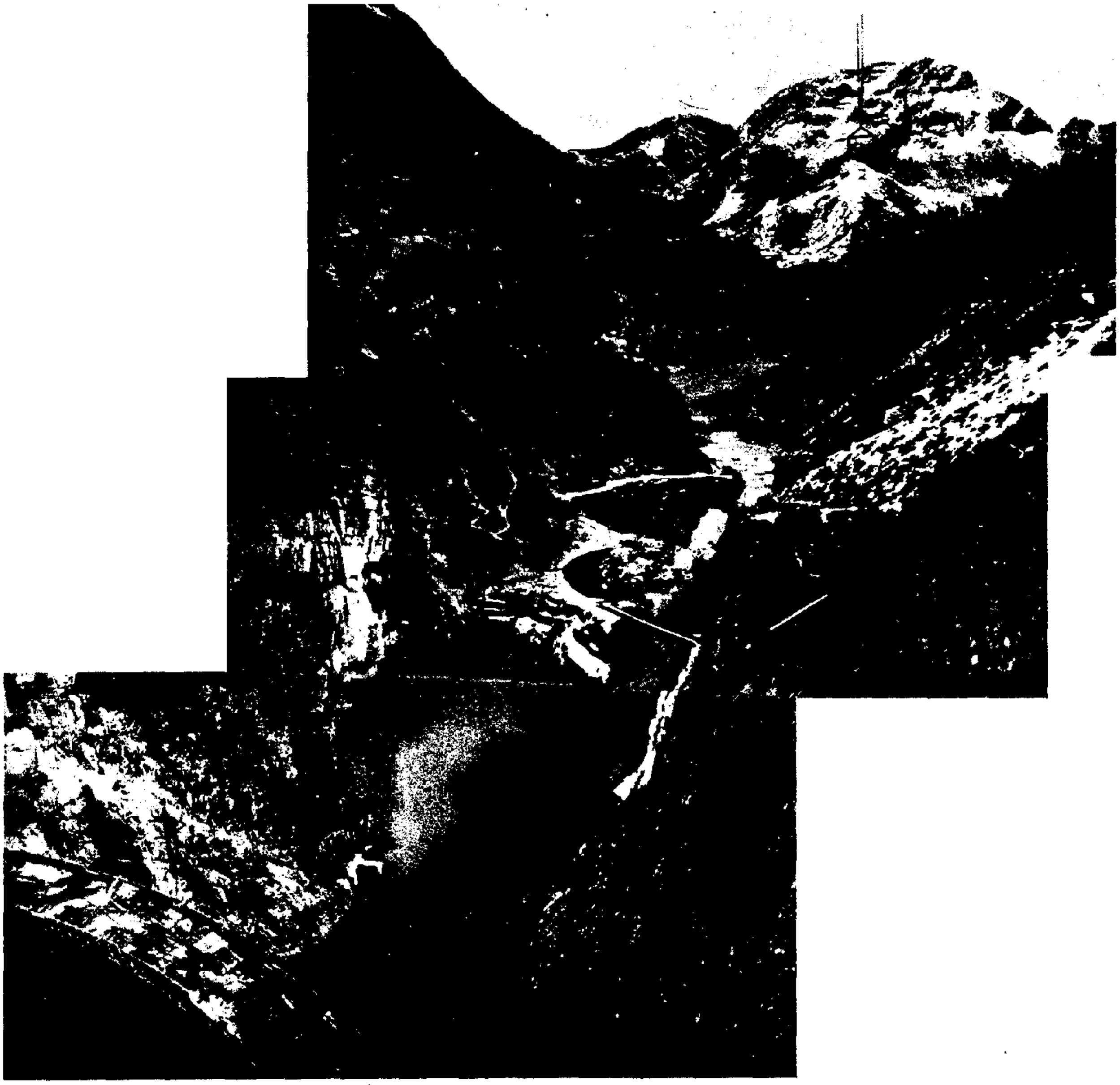


Figure G7. March, 1960. The Vaiont Valley upstream from the dam, during construction, with the reservoir level at an approximate elevation of 600 meters. The Colomber bridge and the old road are visible at the bottom; the new road can be seen at the top. Between the two roads, at the easternmost narrowing of the valley, note the loose and fractured mass with beds having an anomalous dip. At the present, following the landslide, this mass forms the "Colle Isolato." A similar mass, although much smaller, can also be seen above the old road at the second narrowing of the valley east of the dam. The presence of the three narrowings and of the stratified gravel deposits below each loose and fractured mass are fundamental elements permitting the author to formulate the hypothesis that these masses had slid, in his opinion, from the south (reader's right side) into an old Vaiont channel.

Figure G8. August 26, 1959. Frontal picture of the loose masses in Fig. G7, seen from the left side of the valley. In the section between the lower road and the base of the walls of fractured rock, alluvial sediments outcropped. The mass corresponding to "Colle Isolato" is formed primarily by strata from level "a" topped by the thick conglomerate layer of level "b". Note the dip difference between these strata and those of the *in situ* cliff in the background.

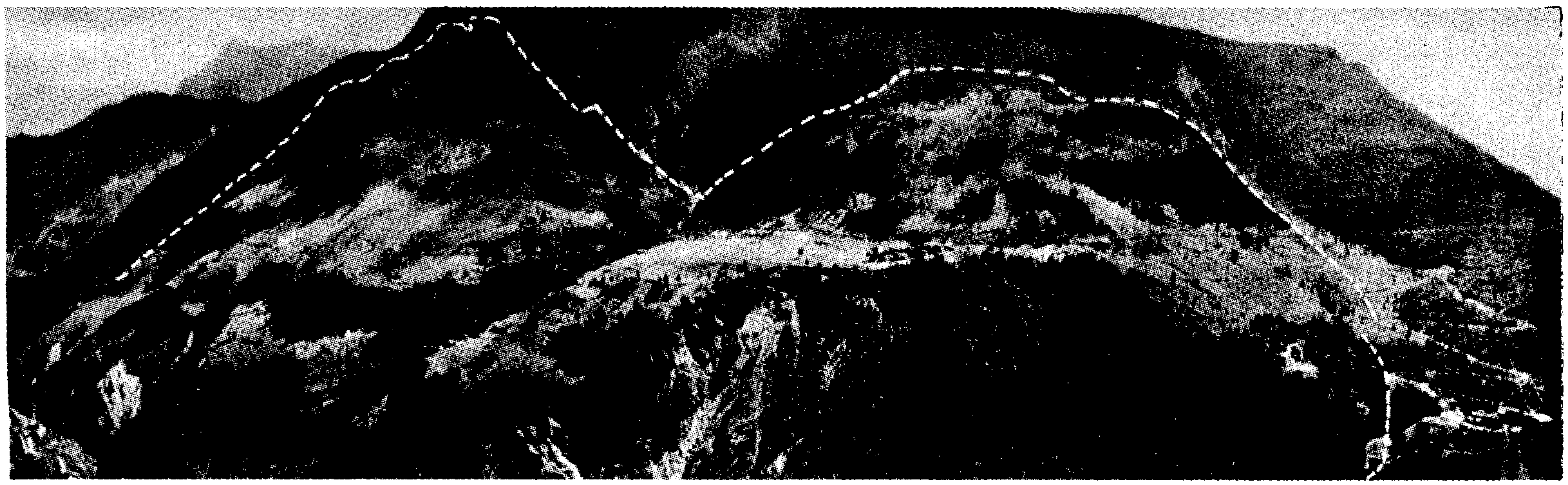


Figure G9. September 1, 1959. The northern slope of Mt. Toc as seen from the vicinity of Casso. At the lower left center, the "Pian del Toc," at the center the Piano del Toc (Pozza Plain) bounded on the left (East) by the Massalezza Valley. Note the two main branches of the stream at the head of the valley, where a year later in 1960, the perimetral fissure appeared, shown by the white dotted line.

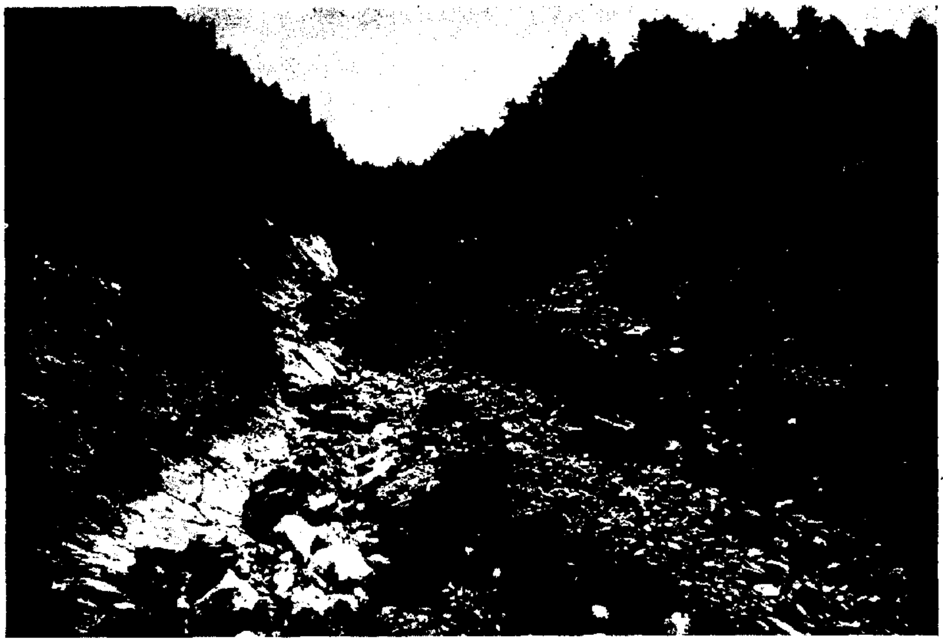


Figure G10. July 1960. The western branch of the Massalezza; the southern slope, on the reader's left, is formed by strata of the Lower Cretaceous (lower portion of level "a"), dipping north. The strata along the northern slope were intensely fractured and almost completely covered by detritus.

Figure G11. November 9, 1960. The perimetral crack at the southern boundary of the small depression (near elevation 1127) west of the Massalezza stream.

Figure G12. November 1963. Marker 54, one of the points kept under constant observation during most recent years to monitor displacements. The marker was found on the eastern lobe where it had fallen with the tree to which it had been attached.

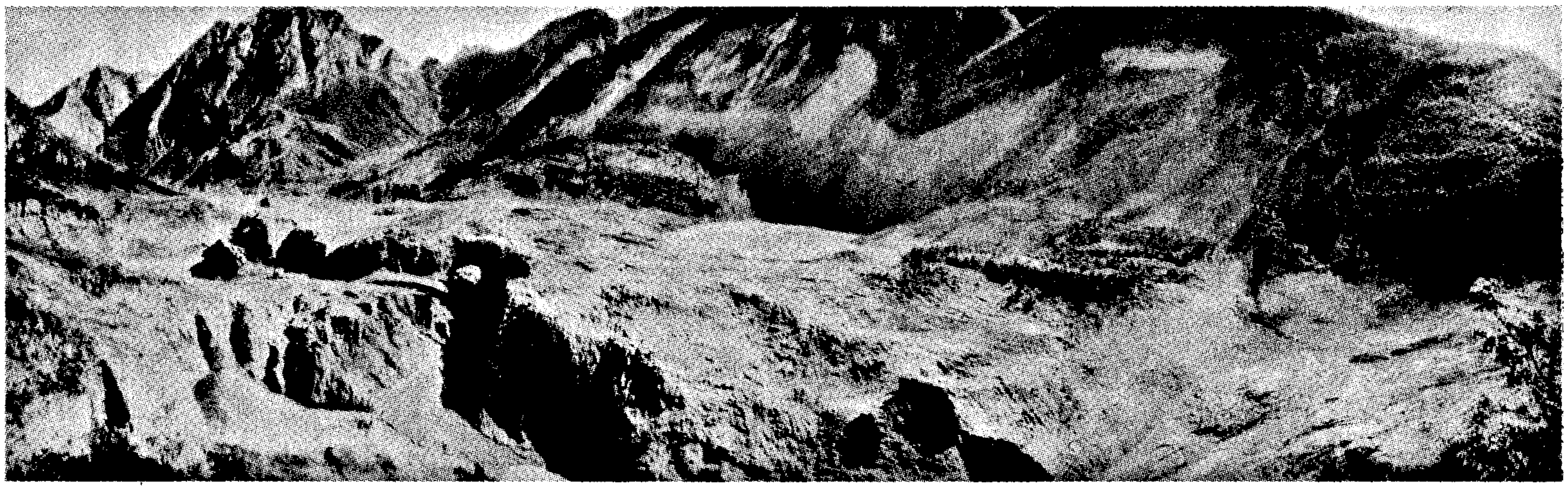


Figure G13. Panoramic view from the meadows west of Casso taken on the morning of October 10, 1963.

Figure GI4A - March, 1964. Fig. GI4A is an aerial view of the slide mass. The sketch shown in Fiq. GI4B shows all the location names used in the text.

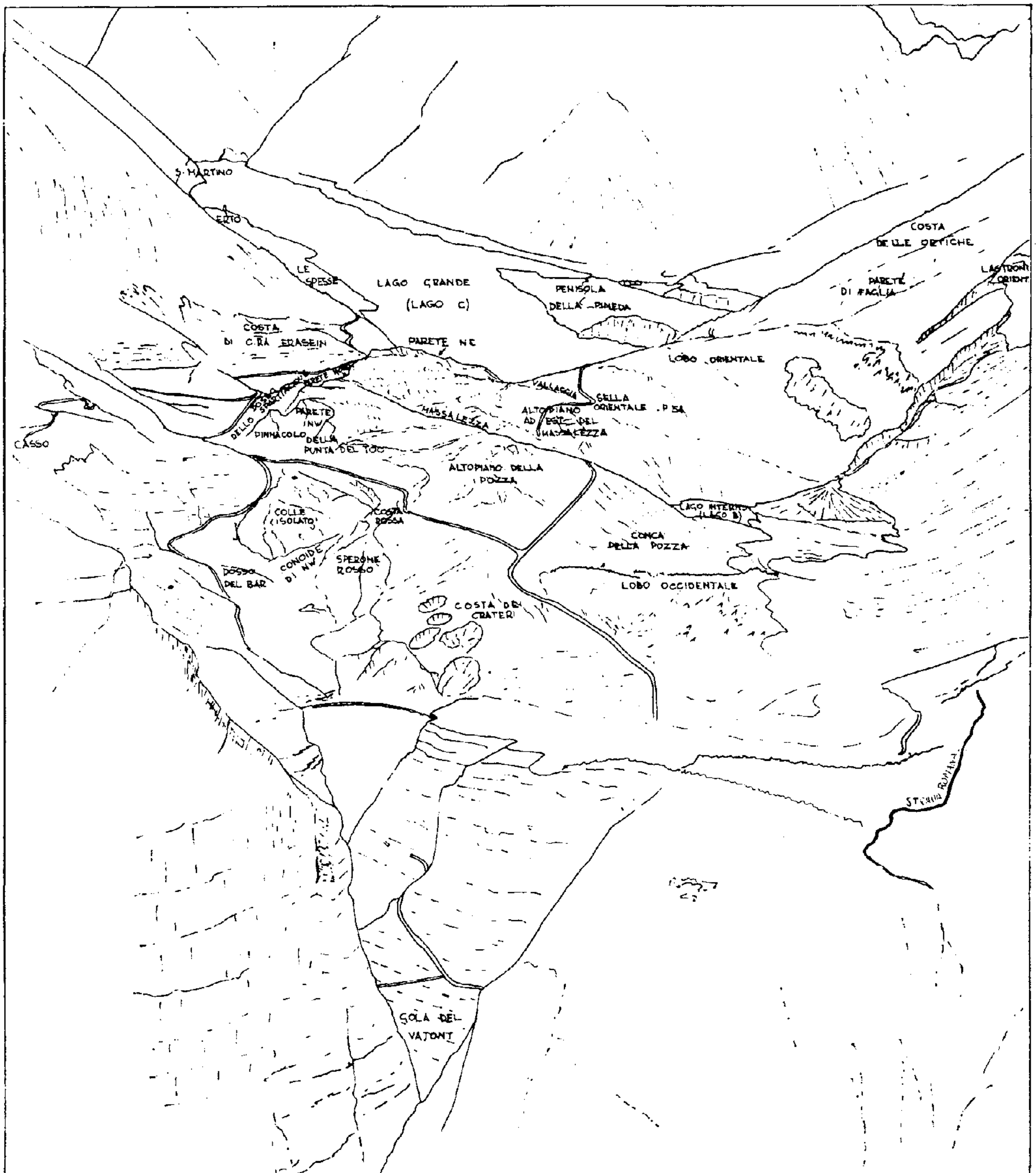

S. MARTINO
ERTO
LE SPESSE
LAGO GRANDE
(LAGO C)
PENISOLA DELLA PINEDA
COSTA DELLE ORTICHE
PARETE DI FAGLIA
LASTRONI ORIENT
COSTA DI C.RA ERASEIN
PARETE NE
LOBO ORIENTALE
VALLACCIA
SELLA ORIENTALE . P 54
ALTOPIANO AD EST DEL MASSALEZZA
MASSALEZZA
CASSO
PARETE NW
PINNACOLO DELLA PUNTA DEL TOC
ALTOPIANO DELLA POZZA
LAGO INTERNO (LAGO B)
COLLE ISOLATO
COSTA ROSSA
CONCA DELLA POZZA
CONOIDE DI NW
SPERONE ROSSO
DOSSO DEL BAR
LOBO OCCIDENTALE
COSTA DEI CRATERI
SOLA DEL VAJONT

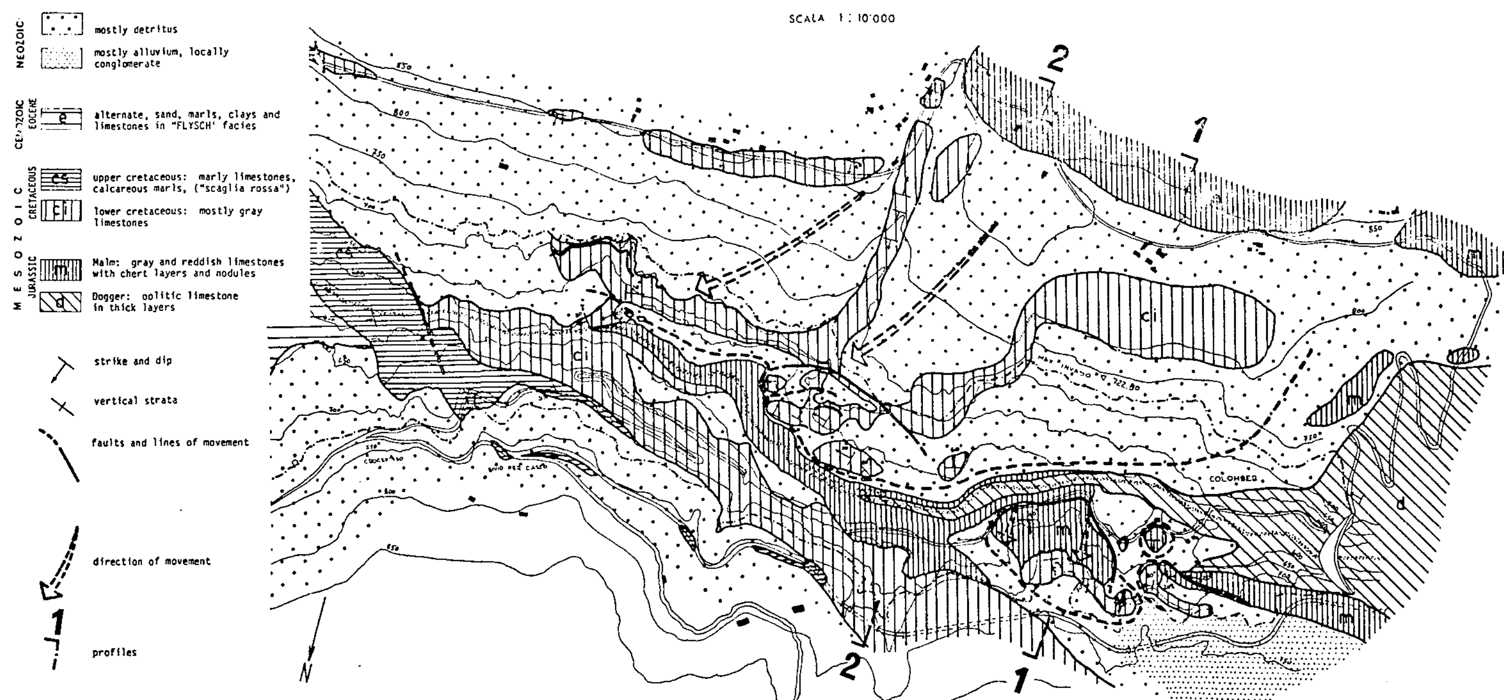
Figure GI4B

Figure G15. November, 1963. The upper portion of the "Vallaccia" with the grassy surface of the main slide mass dipping under the frontal part of the eastern lobe (lefthand side).

Figure G16. November, 1963. Two piezometric tubes observed on the Altopiano della Pozza bent by the return wave, which overran the area towards the south.

CARTA GEOLOGICA DELLA ZONA DEL PIANO DEL TOC

DALLA CARTA GEOLOGICA DEL SERBATOIO DEL VAJONT
RILEVATA NELL'ANNO 1959 DA F. GIUDICI ED E. SEMENZA



Note: The post-slide studies conducted by D. Rossi and E. Semenza (1963 to 1965), as well as micropaleontological studies by C. Broglio Loriga and M. G. Mantovani (1961 to 1965) proved that some outcrops shown on this map are erroneously dated (see D. Rossi & E. Semenza, 1965).

Figure G2. Geological map of the "Pian del Toc" zone taken from the "Geological Study of the Vaiont Reservoir" by F. Giudici and E. Semenza, 1960.

1

2