TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Methods of Avalanche Control on Washington Mountain Highways - Summary Report		5. Report Date July 1974 6. Performing Organization Code
7. Author(s) E.R. LaChapelle, C.B.Brown and R.J. Evans		8. Performing Organization Report No.
9. Performing Organization Name and Address Geophysics Program and Department of Civil Engineering University of Washington Seattle, Washington 98195		10. Work Unit No. 11. Contract or Grant No. Y-1301
12. Sponsoring Agency Name and Address Washington State Highway Commission Department of Highways, Highway Administration Bldg. Olympia, Washington 98504		13. Type of Report and Period Covered SUMMARY REPORT 1970-74 14. Sponsoring Agency Code
15. Supplementary Notes Cooperation with U.S. Department of Transportation, Federal Highway Administration		

16. Abstract

This Summary Report synthesizes the work on avalanche control carried out at the University of Washington from 1970 through 1974. Five problem areas are addressed:

1. Identification of avalanche paths.
2. Description of historical frequency and size of avalanches.
3. Prediction of avalanching.
4. Identification of control methods.
5. Inclusion of control and prediction schemes in highway design and operation.

17. Key Words	18. Distribution Statement
Avalanche, Snow, Weather, Creep, Glide, Avalanche Forecasting	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	21	

Form DOT F 1700.7 (8 69)
HWY FORM 341-004

METHODS OF AVALANCHE CONTROL ON WASHINGTON MOUNTAIN HIGHWAYS

SUMMARY REPORT

July 1974

A Review of the Studies - the Period 1970-74

Prepared for Washington State Highway Commission, Department of Highways, and in cooperation with U. S. Department of Transportation, Federal Highway Administration, by Geophysics Program and Department of Civil Engineering, University of Washington.

TABLE OF CONTENTS

INTRODUCTION

This Summary Report synthesizes the work on avalanche control carried out at the University of Washington from 1970-1974. The Annual Reports contain a full account of all of the activities and should be referred to when further details are required.

Five problems are faced in the protection of a highway from avalanche catastrophe. These are:

1. Identification of avalanche paths.
2. Description of historical frequency and size of avalanches.
3. Prediction of avalanching.
4. Identification of control methods.
5. Inclusion of control and prediction schemes in highway design and operation.

These problems were identified in the original proposal in the objectives. Subsequent year by year proposals concentrated on various facets of the work - not necessarily in the order stated above. This summary is intended to bring together the four year study under the problem titles identified here. Most of the work has been addressed to the specific features of the North Cascades Highway (SR-20) in the North Cascade Mountains of Washington State. Application to other sites are mentioned as they arise.

1. Identification of Avalanche Paths

For the planning of a new highway or for winter operation of existing ones in terrain with avalanche activity the positive identification of avalanche paths potentially intersecting the highway is essential. Such identification has been obtained by the study of historical information and recollection, aerial reconnaissance summer field work on vegetation growth patterns and terrain features, together with direct winter observation. All of these methods have led to the compilation of a summary sheet for each path. A typical summary sheet is shown in Appendix 1. The features are:

1. Name for identification purposes.
2. Map location.
3. Avalanche dimensions (starting zone elevation, vertical fall, length).
4. Description of the special features of the avalanche.
5. Expected effects on the highway.

6. History of avalanching.

Accompanying the summary sheet are photographs and a map showing defineable avalanche boundaries, contours, road and other characteristics. Where possible a vertical profile of the avalanche path has also been furnished.

The binding of these summary sheets into a definite order for the North Cascade Highway has been in loose-leaf form. This allows for the easy inclusion of new data and also the separation of the information into particular zones for operational use. The Avalanche Atlas for the North Cascades Highway (SR-20) was issued in June 1971; a supplement furnishing additional data was issued in May 1974.

The identification of avalanches at other highway passes through the Cascades in Washington State is made in the Cascade Passes Avalanche Atlas, issued in June 1974. This has the same loose-leaf form and summary sheets.

These two complete documents constitute the response to problem 1) identification of avalanche paths.

2. Historical Frequency and Size of Avalanches

To ascertain the possible danger of avalanche to the highway some help can be obtained from historical studies. As may be anticipated, the keeping of records has not been man's main activity in remote mountain regions. The evidence for avalanche frequency and size must be mainly encoded in the record of nature. Certainly the damage to trees and growth patterns can give insight into the frequency and size problem. In the 1972-73 Annual Report, Laura Smith dealt with this problem within the botanical and dendrochronological disciplines. Eleven locations on the North Cross-State Highway were investigated. Table 1 reviews the results on the history of avalanching at these locations.

Table 1 - Avalanche History at Eleven Sites on the North Cross-State Highway

Location	Major Avalanches	Large Avalanches	Regular Avalanching
Ruby Mtn 5	1971, 1936, 1902-12, 1862		Frequent in higher elevations
Ruby Mtn 10	1952, 1932, 1862[f]		Annually (w), infrequent (d)
Granite Creek 4	1972, 1862, 1842	Every 20-35 yrs.	Annually (w)
Granite Creek 5	1972, 1897, 1887[f]		Frequent
Granite Creek 6	1938, 1902, 1842	1952, 1916	Annually (w)
Cutthroat 1	1932-37, 1902-12 1852	1952, 1922, 1882	Annually (w), (d)
Delancy Ridge 13	1932-42, 1902-22		Annually (w), (d)
Delancy Ridge 12	1971, 1942, 1902-22		Annually (w), (d)
Delancy Ridge 9	1927		Annually (w), (d)
Silver Star 2	1912, 1882-1912	Every 30 yrs.	Frequent (d)
Silver Star 1	1952, 1877-1907		Very infrequent

(w)-wet snow avalanches, (d)-dry snow avalanches, f-initiated by fire danger

The methods presented by Laura Smith not only provided a measure of avalanching frequency but also allowed the dimensions of the path to be described. The historical picture obtained has further significance since the cause of major occurrences could often be attributed to unusual events such as a forest fire. Thus, an estimate of the frequency could be obtained excluding these peculiar events. However, should an extensive fire occur in the area it is now possible to predict the subsequent avalanche hazard.

The research methods on the interpretation of vegetation patterns can provide critical information at crucial avalanche sites. The presentation allows for a systematic study of such sites and the research work initially funded has become a valuable tool in general avalanche interpretation.

The same methods for the determination of avalanche delineations have been carried out at all the sites in the Atlas. The level of sophistication is not claimed to be that of the vegetation study but an understanding of the dimensions of large avalanches over the last twenty-five years has been obtained. This has been backed-up by the recollections of local people and by direct observations over the last four years. These observations not only provide the extent of avalanching but also begin to indicate the frequency, within a season, of road crossings. Such information is recorded in the Annual Reports; the Atlas has been brought up to date on that basis by means of an Atlas Supplement.

The above deductions from observations have been augmented by a theoretical argument on the dimensions of slab avalanching by Brown, Evans and LaChapelle in the Second Annual Report. In that paper the state of stress in fallen snow was modelled and then a metamorphosed interface introduced. This interface had reduced shear characteristics and was intended to replicate the occurrences in nature of depth hoar or percolating water. The order of failure was then studied: the failure order being:

a) shear failure on the chosen interface
b) tensile top failure
c) shear side failure
d) compression failure at the slab bottom

The surfaces revealed by the failures gave the soft snow avalanche dimensions. The bottom failure (d) was considered as possible due to either fracture or buckling. The consequence of the theory are slab dimensions (breadth and slope) in terms of the thickness, slope angle, snow density and mechanical properties. These dimensions are consistent with observed slab behavior. The use of the theory in the North Cascades required the measurement of the mechanical properties as they depend on the snow density. This has been accomplished by McClung and the information is in the 1972-73 Report. The main experiments were for the tensile strength and here the results are dramatically more consistent than other measurements. This is due to the controlled and slow strain rates possible in McClung's apparatus which ensured ductile failure. Such failure is probably more typical of normal avalanche conditions. However, it must be noted that the wide scatter of tensile strengths in fast loading situations may be more like the blast-initiated conditions of a typical artificial release.

In review, vegetation studies, records and observations have identified the dimensions and frequency of avalanches affecting the North Cascade Highway. A full record of the critical avalanche paths is given in the Atlas. Additionally, the methods of the botanical work and the mechanics theory for dimensions can be applied generally.

3. Prediction of Avalanching

The study of the frequency and size of avalanching mentioned in the previous section provides crucial information for the long term planning and operation of a highway. The day-by-day operation of highways and mountain passes requires prediction schemes for the likely occurrences of avalanches over the total pass as well as at particular locations. The key to these operational questions lies in the relationship of avalanche occurrence with the history of weather conditions.

Brown, Evans and LaChapelle (1971-72 Second Annual Report) discuss the occurrence of slab avalanching and the event of the shear degeneration at an interface, either in the snow body or at the ground level. This shear degeneration was ascribed to snow metamorphism, such as depth hoar, or to ground water percolation. Whatever the reason for the degeneration, the cause was always connected with the weather history. In the 1972-73 Report, Brown, Evans and McClung describe glide measurements near Mt. Baker, Washington. These glide readings are closely related to the shear capacity at the ground-snow interface and therefore with the propensity to avalanching. It was shown that increasing of glide speeds in February, 1972, forecast a period of danger whereas the decrease in glide speeds in February and March gave cause for confidence in the snow slope stability. The increasing glide speeds appeared correlated with high precipitation and high mean temperatures: decreasing speed with dryness and low temperatures. Also, under steady mechanical and thermal conditions a terminal steady speed was attained. Again these conditions are closely tied to the weather.

Terence Fox in his article, "Avalanches and Synoptic Weather Situations in the Cascades during the Winters of 1971-72 and 1972-73," (1972-73 Report) addresses the question of identifying observable synoptic scale weather patterns which may be associated with periods of extensive avalanche release. Five periods of severe and widespread avalanche activity studied were connected with substantial precipitation as snow followed by temperature increase to near or above freezing levels. It was also evident that prolonged avalanche danger periods were maintained when temperatures remained near freezing and precipitation continued.

In the 1972-73 season another weather situation was associated with formation of wind slabs and subsequent avalanching. Increases of dry arctic air produced strong pressure gradients to the northeast of the passes and intense easterly winds. The winds forced wind slabs and avalanching was often independent of weather fronts passing through the mountains. When the temperature rose avalanching persisted for the reasons noted previously.

The work of Fox indicated the type of observational network necessary for the prediction of avalanche conditions at various passes. In particular measurements at high levels were deemed crucial in determining changing conditions in release zones.

Data transfer and analysis procedures were also dealt with in the study of Fox. The suggestions were directly applicable to avalanche prediction at Washington Pass and Stevens Pass.

The snow report on the North Cascades for 1971-72 recorded in the Second Annual Report (September, 1972) confirms the coincidence of avalanching at four different sections on the east side of the pass; however, on the west side the slides seemed to be out of phase with those on the east. This suggests an additional complexity which must be accommodated in any observational network.

Mark Moore continued the work of Fox over the 1973-74 winter. Nine storms which produced avalanching conditions were studied. Again the two different regions for northwest air flow and southwest air flow were noted. In particular, in both cases major avalanching was amplified when the upper level jet stream passed directly over the Washington Cascades. This was due to orographic precipitation being particularly heavy at these times.

The previous discussion relates to the prediction of avalanching over sections of the passes. The prediction at particular sites has to be dealt with as a special issue. This requires a knowledge of the individual terrain, snow conditions and history together with the sectional forecast or avalanche likelihood. Previous experience with the dimensions of an avalanche swath at a particular location is also of importance. The snow reports for the seasons covered under the project give information on avalanches reaching the North Cascade Highway at various locations. Of particular interest is the 1971-72 Report where the snow conditions in the mountains were very severe. The training program with Highway Department personnel was intended to provide a situation where individual avalanche path hazards could be recognized.

The above studies have been relevant to the North Cascades. Evans in the 1972-73 Report gives some responses of the organization and intentions of avalanche forecasting in Switzerland.

4. Identification of Control Methods

In the study of Decision Methods by Brown and LaChapelle in the 1972-73 Report, three classes of control methods have been identified. These are snowsheds, relocation and artillery control (including explosives). Additionally, the danger of starting zone restraint structures has been dealt with in the separate articles in the 1973-74 Report by Brown and Evans and by McClung. The work on the Franklin Falls Bridge involved the incorporation of structures which diverted the avalanche path away from critical bridge members. Thus, in the four years reported, the following control networks have been identified:

a) snowsheds
b) road re-location
c) artillery and explosives
d) restraint structures
e) diversion structures

Items (a), (b), and (e) involve extensive capital investment and careful preliminary study and design. Once accomplished they are intended to maintain a definite level of winter use without extra costs. This winter facility seldom provides a complete winter use highway. Additional to the permanent structures will be operational control by artillery (c) and the associated snow clearance methods.

a) Snowsheds: These permanent structures are a classical method of keeping avalanching snow off the roads. The problems of design involve definition of avalanche path and of snow forces. The methods described in sections (1) and (2) of this Summary give a basis for the first definition. Static forces due to glide and creep have been dealt with by Brown and Evans and by McClung in the 1973-74 Report. Dynamic forces await study. A visit to the Rogers Pass in British Columbia indicated the success of snowsheds. The main problems were the maintenance of visibility in the structure, the change of driving conditions (road surface and visibility) in passing in and out of the shed and the enveloping of the shed by avalanche paths. The first two problems still exist in the Rogers Pass and require considerable maintenance and further study. The last problem requires the proper identification of avalanche diversions, as given in sections (1) and (2), together with generosity in decisions on the length of snowsheds. In the 1973-74 Report LaChapelle describes in detail the problems at the terminal of the Naches Tunnel.

LaChapelle in the 1971-72 Report gives an impression of snowsheds and tunnelling technology in Japan. Here is displayed not only snowsheds in various materials but also the different structural forms that are incorporated into avalanche protection schemes in Hokkaido.

b) Road relocation: Existing highways do not always have the most suitable location with respect to avalanche dangers. Experience of relocation has indicated the necessity of extensive study of avalanche path dimensions and frequencies as in sections (1) and (2). In this way surprises can be avoided. The special work at the Franklin Falls Bridge on the relocation near Snoqualmie Summit may have been avoided by extensive preliminary study of the avalanche problem. In a similar way, LaChapelle's reconnaissance of the Naches Tunnel Terminal (1973-74) is of importance.

c) Artillery: The operational problem of artillery control has been a large part of the field liaison work with the Highway Department over the four contract years. The sequential operations are dealt with in the scenario in Appendix E of the 1972-73 Report and an operational algorithm is in Appendix C. The special problem of blind firing is dealt with by a device invented by LaChapelle. This is given in the Appendix D. A discerned problem is the difficulty of obtaining replacement of ammunition and barrels for the 105 mm rifles. This suggests that the future use of this method of avalanche control will require specially manufactured weapons. The operational procedures given will be largely still valid.

d) Restraint structures: Starting zone restraint structures have been extensively utilized in Europe and Japan. Evans and LaChapelle discuss these facilities in their respective reports on the work in Switzerland and Japan in the 1971-72 and 1972-73 Reports. The efforts on snow mechanics over the four years of the contract have led to methods for the prediction of snow pressures on structures. These methods are based on finite element procedures and are reported in the 1973-74 Report in articles by McClung and by Brown and Evans. A particular feature of the analyses is that they are based on glide and creep observations in the North Cascades. This ensures that they are applicable to the Washington State environment. On the other hand the approach is also applicable to other locations once certain creep and glide regimes have been described for observations. The special effect of timberland as restraint structures has been mentioned by LaChapelle on his Naches Tunnel reconnaissance (1973-74) and by Evans in the 1972-73 Report on Switzerland.

e) Diversion structures: The design of such structures has been illustrated in the Franklin Falls Bridge investigation. Short slopes employed in Japan are mentioned in the 1971-72 Report.

Snow clearing, either from the fallen state or as debris of avalanching, is a crucial part of the operational activity for mountain roads, especially when controlled by artillery and explosive release. LaChapelle gives a complete bibliography on snow clearing technology in the Appendix of the 1971-72 Report.

5. Highway Design and Operation

These problems incorporate all of the findings of the four years of study. A formal decision approach to decisions at both the design and operational level has been presented by Brown and LaChapelle in the 1972-73 Report. Appendix II gives a Decision Tree which incorporates the main features of the approach. These features are the objective, generation of alternatives, states of nature, probabilities of states of nature, utilities, criterion function and decisions. All of these features are defined and examples given in Part I of the Brown-LaChapelle section in the 1972-73 Report. Part II of the section applies the methods to three problems of the North Cascade Route. These problems are:

a) whether to keep the road open in winter,

b) how to keep the road open in winter, and

c) how to administer the operational schedule.

Of special note was the interdependence of these three problems. A certain amount of study of (b) and (c) was necessary to come to a decision on (a); the decision on (c) depends on the method adopted in (b).

For problem (a) two alternatives were considered:

A_1 - close for the winter

A_2 - keep open 350 days a year with delay conditions on 150 days

States of nature reflected the public attitude where indications of economic frustration, personal inconvenience and social paradigms of the time are contained. Hence the states of nature are:

θ_{11}, θ_{21} - favorable public attitude

θ_{12}, θ_{22} - unfavorable public attitude

The establishment of the utilities was proposed by the Delphi method. The probabilities were treated as initially nebulous and hence $p_{ij} = 0.5$. Then, based on a regrets criterion A_1 will always be the decision under $U_{21} = 100$, $U_{22} = 100$ and $U_{12} < (100 - U_{11})$. Modification for definite values of pij were also given.

In problem (b) alternatives of snowsheds, snowsheds and relocation and artillery control were considered. Extensive scenarios were developed to determine arrangements for three alternatives. The criterion for decisions was suggested as maximum expected monetary gain and the establishment of utility, for a present work basis, and probabilities were also discussed. The incorporation of definite values must rest with the design and operational practitioners.

The central feature of problem (c) concerned the possible unification of organizational operation over the whole of a mountain pass. Questions concerning field facilities, forecasting network and patrol sequences were raised in the light of the main alternatives.

In all of the decision work the essential requirement that feedback be made between an activated decision and the original goal has been emphasized. Changing input data and requirements can then be incorporated into an on-going decision scheme.

CONCLUSIONS

The four years of work summarized here is probably the most comprehensive statement of avalanche control understanding available. All of the diverse activities have a common purpose utilized in the decision-making process described. In spite of this comprehensiveness many fundamental as well as operational problems exist. Certainly, the science of snow mechanics can be expanded and lead to important results of practical significance. Novel avalanche release methods will have to be developed with the dearth of conventional artillery.

REFERENCES

Prepared for the Washington State Highway Department

LaChapelle, E. R., 1971, "Avalanches on the North Cascades Highway, (SR-20)," Avalanche Atlas and Summary Report.

LaChapelle, E. R., Brown, C. B., and Evans, R. J., 1972, "Methods of Avalanche Control on Washington Mountain Highways," Second Annual Report, Released Report Y-1301.

LaChapelle, E. R., Brown, C. B., and Evans, R. J., 1973, "Methods of Avalanche Control on Washington Mountain Highways," Third Annual Report, Research Report Y-1301.

LaChapelle, E. R., Brown, C. B., and Evans, R. J., 1974, "Methods of Avalanche Control on Washington Mountain Highways," Fourth Annual Report, Research Report Y-1301.

LaChapelle, E. R., 1974, "Cascade Passes," Avalanche Atlas, Part I: Chinook, Cayuse, White and Snoqualmie Passes.

LaChapelle, E. R., 1974 (in preparation), "Cascade Passes," Avalanche Atlas, Part II: Stevens Pass and Tumwater Canyon.

LaChapelle, E. R., 1974, Avalanche Atlas Supplement.

Prepared for General Publication

Brown, C. B., Evans, R. J., and LaChapelle, E. R., 1972, "Slab Avalanching and the State of Stress in Fallen Snow," Journal of Geophysical Research, Vol. 77, No. 24.

Brown, C. B., Evans, R. J., and McClung, D., 1973, "Incorporation of Glide and Creep Measurements in Snow Slab Mechanics," Advances in North American Avalanche Technology: 1972 Symposium.

LaChapelle, E. R. and Fox, Terence 1973, "A Real-time Data Network for Avalanche Forecasting in the Cascade Mountains of Washington State," Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources.

McClung, D., 1974, "Creep and the Snow-earth Interface Condition in a Seasonal Alpine Snow-pack," International Symposium on Snow Mechanics.

Brown, C. B. and Evans, R. J., 1974, "Effect of Glide and Creep on Rigid Obstacles," International Symposium on Snow Mechanics.

APPENDIX I

Typical Atlas Sheets

North Cascades Highway SR-20

Avalanche Summary Sheet

Name of Path: Ruby Mountain No. 4

Hazard: Very low, infrequent

Map: Ross Dam 7.5'

Location: Station 557+0 UTM 5398540 N , 645290 E

Elevation of starting zone: 3800'

Vertical fall: 1600' Length:

Description:

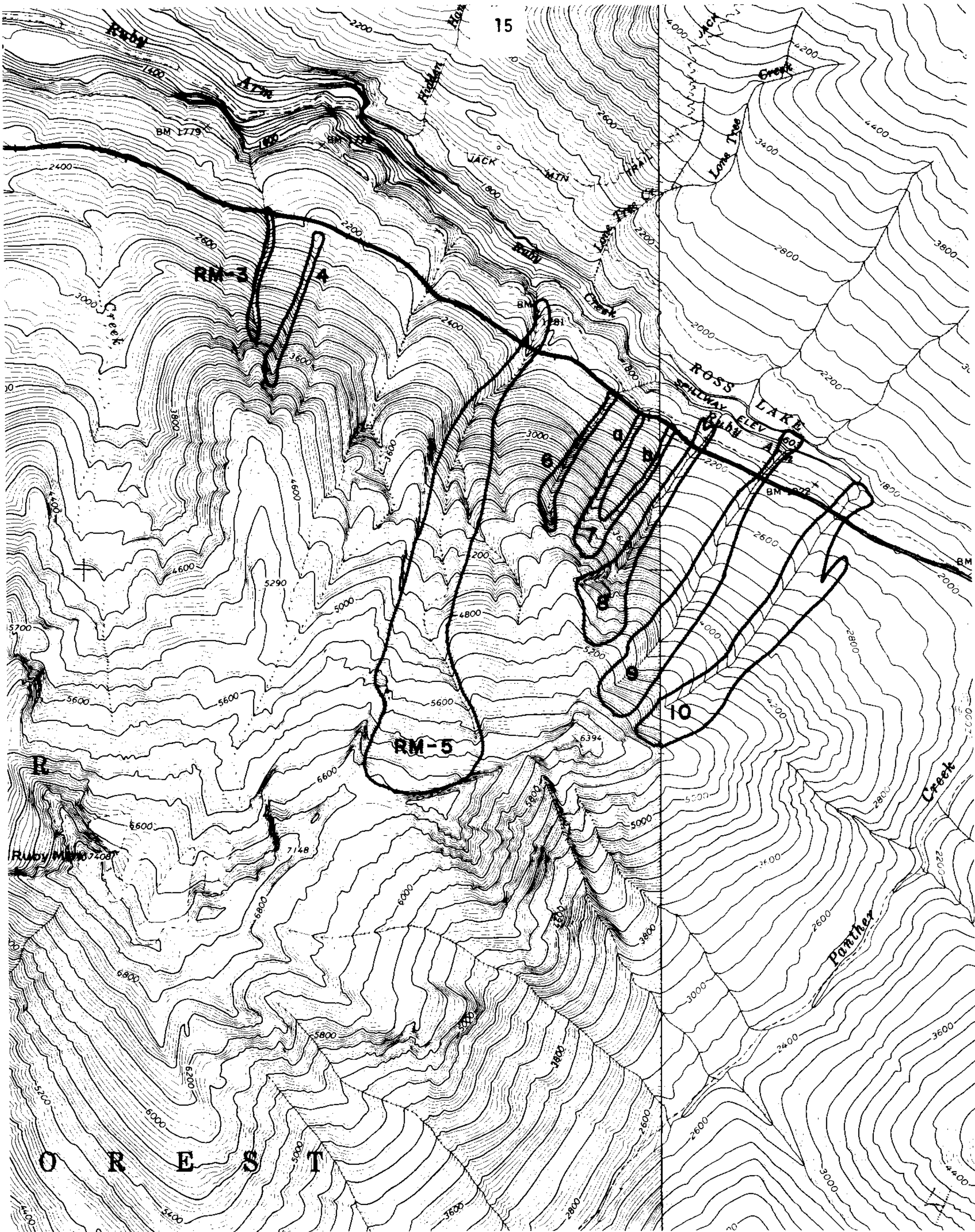
Similar to RM-3, this path descends a narrow stream bed through heavy timber on the north flank of Ruby Mountain. The release zones are adjacent, with No. 4 also originating in open scree patches. Principal slide activity appears to stop within 100 - 150' of the highway. There is a screen of heavy timber between this point and the highway, although snow may have reached the right-of-way location at Stations 557 and 558 at some time in the past. This path will predominantly be active under wet avalanche conditions.

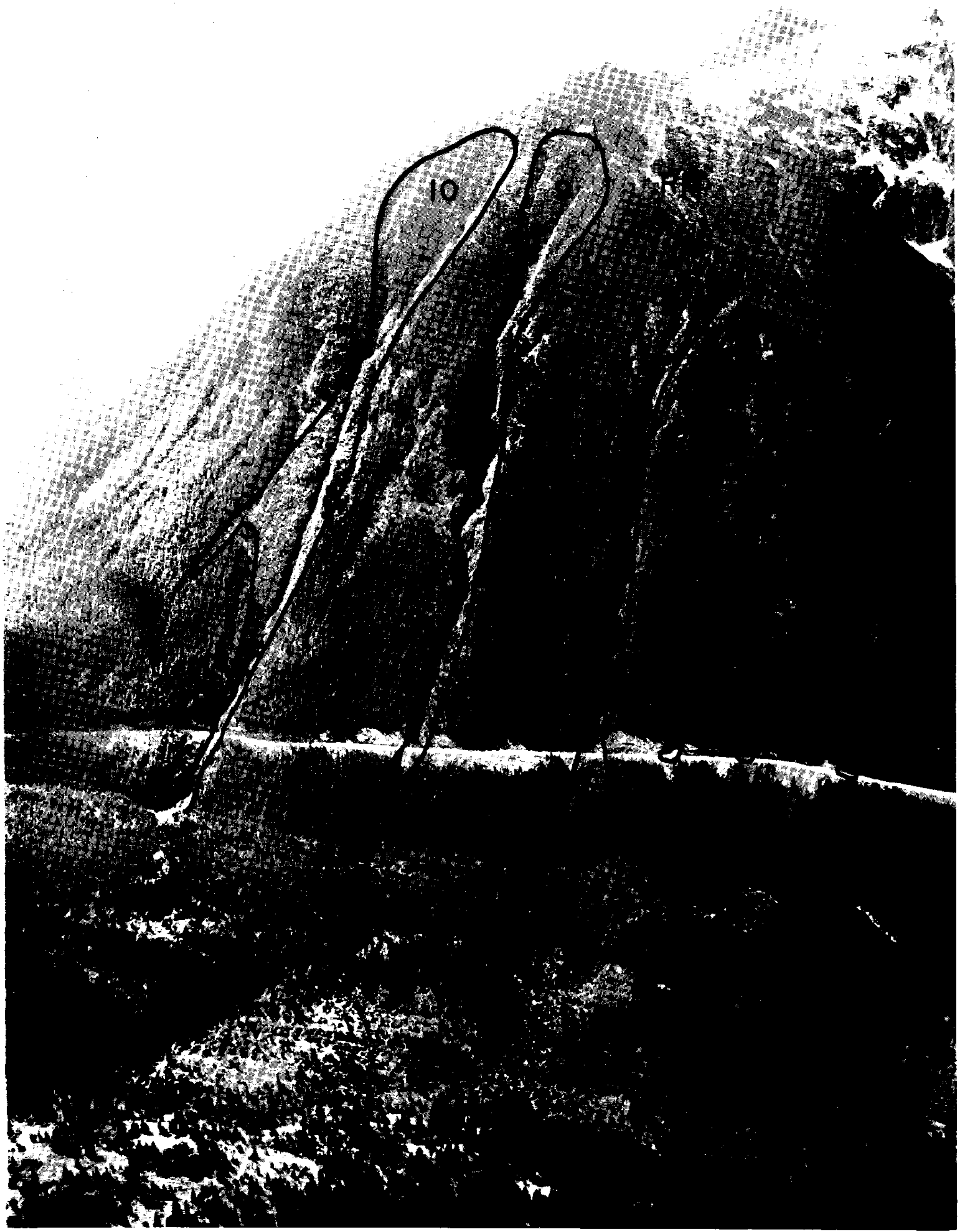
Expected Effect on Highway:

Not likely to reach the highway except under ususually bad avalanche conditions. In such circumstances the deposited snow on the highway is not apt to be large in volume, but would be heavily laden with broken trees and branches.

History:

Slides probably occur here annually or oftener, but are apt to reach the highway only at long intervals of several to many years. The spring avalanche in 1971 in this path reached within about 100' of the highway.


Ruby
Arm
Hidden
JACK
MTN
TRAIL
Lone Tree Cr
Lone Tree
Creek
Ruby
Creek
Creek
ROSS
LAKE
SPILLWAY ELEV
Ruby Arm
RM-3
4
6
a
b
7
8
9
10
RM-5
5290
6394
7148
Ruby Mtn
Panther
Creek
O R E S T


10
9

APPENDIX II

Decision Tree

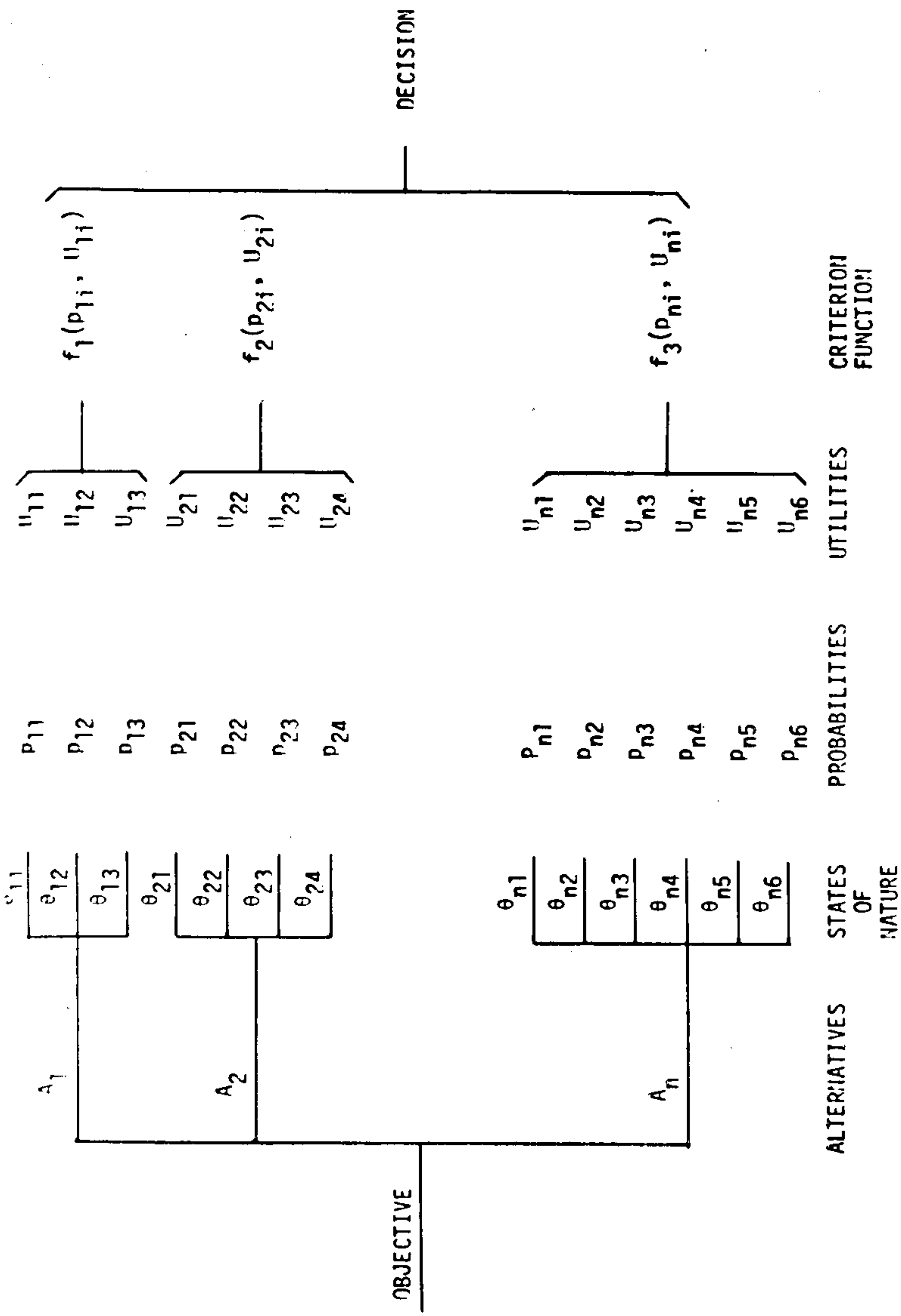

DECISION
$f_1(p_{1i}, U_{1i})$
$f_2(p_{2i}, U_{2i})$
$f_3(p_{ni}, U_{ni})$
CRITERION FUNCTION
U_{11} U_{12} U_{13} U_{21} U_{22} U_{23} U_{24}
U_{n1} U_{n2} U_{n3} U_{n4} U_{n5} U_{n6}
UTILITIES
p_{11} p_{12} p_{13} p_{21} p_{22} p_{23} p_{24}
p_{n1} p_{n2} p_{n3} p_{n4} p_{n5} p_{n6}
PROBABILITIES
θ_{11} θ_{12} θ_{13} θ_{21} θ_{22} θ_{23} θ_{24}
θ_{n1} θ_{n2} θ_{n3} θ_{n4} θ_{n5} θ_{n6}
STATES OF NATURE
A_1 A_2 A_n
ALTERNATIVES
OBJECTIVE

FIGURE 2