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PREDICTION METHOD FOR RISK RATE OF SLOPE FAILURE CAUSED BY HEAVY RAINFALL*

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ABSTRACT

An estimation of the spacial and temporal change in the risk rate of slope failure approaching the centre of a heavy rainfall area is obtained by the use of Hayashi's quantification method I. The data relevant to slope failure were obtained from topographical and geotechnical characteristics using aerial photographs and existing information. Most data is categorical except for the risk rate of slope failure and rainfall amount. Two-factor interactions among five items are checked by 5-way with one covariate (rainfall amount). The interaction between them is not found to be statistically significant.

A prediction of the risk rate of slope failure for any other given rainfall amount is obtainable with this method by the use of the scores determined from data specific to that area. The prediction results of the risk rate are automatically plotted by the computer. Prediction errors are also estimated.

1. INTRODUCTION

Several attempts have been made [2, 6] at forecasting or mapping predicted patterns of the risk rate for slope failure in an area of known topographical and geotechnical data. However, the attempts did not succeed in forecasting the variable distribution pattern of the risk rate of slope failure accompanied by a shift of heavy rainfall area. In this paper it is shown how the distribution of the occurrence of slope failure per unit area changes with a change in rainfall pattern.

Basic data were obtained on topographical and geotechnical characteristics—i. e., degree of slope failure, main direction of valley, soil condition, ground cover or planting state, and aerial density (number of valleys in a fixed unit area) by means of aerial photographs overlaid with a grid. Data were also collected on distribution of occurrence of slope failure and of grade of weathering on the specified area in which predictions of the change in distribution of the risk rate were to be made. Geographic distribution of heavy rainfall based on real data was programmed into the prediction scheme on computer.

The topographical and geotechnical data, treated in this paper are non-numerical—that is, categorical—data, which can be analyzed by Hayashi's quantification theory [4, 5, 12]. Applications of Hayashi's quantification methods I and II for categorical data to the natural disaster sciences have been made in several fields—seismology [7, 14], and civil engineering [7, 13].

2. TARGET AREA AND DATA

The research target area was the Kure City Peninsula (about 25km from Hiroshima City) which includes two small hills—Mt. Yasumi (500m above the sea-level) and Mt. Mitsumine (380.6m) (Fig. 1). This area was chosen because (1) slope failures occur frequently here, (2) information about ground cover, topographical factors, and soil condi-

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KEY WORDS: Disaster, Slope failure, Heavy rainfall, Statistical anslysis

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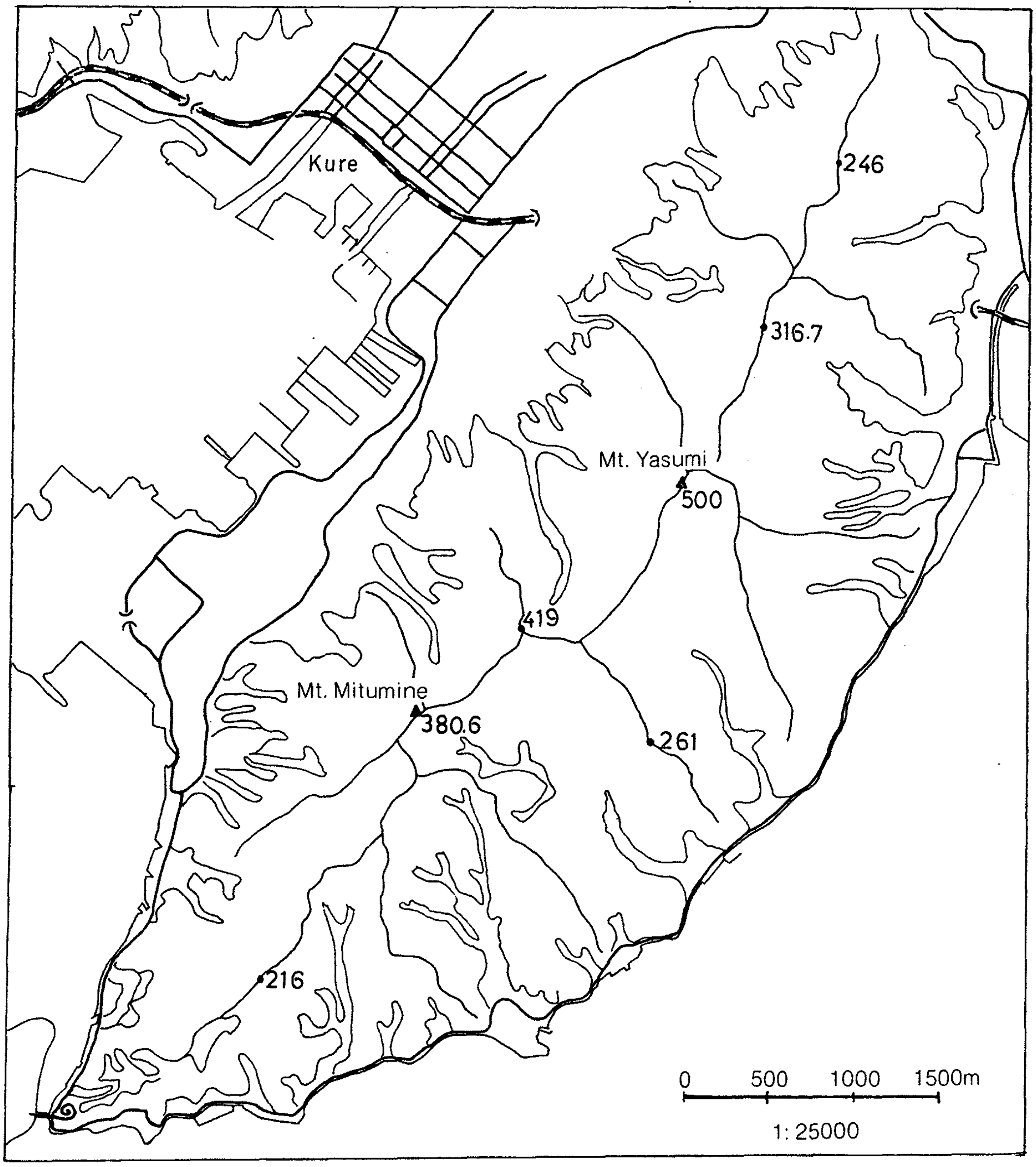

Fig. 1 Research target area, Kure City Peninsula, Hiroshima Prefecture, Japan.

tions is available, and (3) aerial colour photographs of the area are also available.

The aerial photographs published by the Geographical Survey Institute were taken at 1,620m above ground, from February 23, 1974 to March 8, 1975. One photograph covers an area 2250m×2250m (scale 1 : 8000) and photos were taken at intervals of about 800m moving eastwards. The numbers of sheets necessary to cover the target area were 23.

Data were collected on a 200m mesh grid covering the whole target area. The total of 986 grid units consisted of 339 units over sea and 647 units on land, of which 442 units contained the complete data set on six characteristics: valley slope, valley direction, valley density, grade of weathering, ground cover, and rainfall amount (Table 1).

"The risk rate of slope failure" here means the number of slope failures per hectare. The rate of slope failure was investigated in July 1967 after a severe disaster due to a heavy rainfall (Fig. 2) [1]. A risk rate was given as a total number within the area of a rectangle of 2.5km×1.4km, but this area was coarser than the mesh of the topographical and geotechnical data. The rectangle contained an uninvestigated area. This deficit must be considered in the prediction of the risk rate.

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Table 1 Characteristics (items) and categories.

Category	Valley slope	Valley direction	Valley density	Grade of weathering	Ground cover	Rainfall amount AME 1	Rainfall amount AME 2
	deg.		no. valleys/grid unit			mm/hr	
1	0-15	N	0 - 2	Paleozoic	Natural (forest)	60-62	35-36
2	16-25	NE	3 - 4	Slight	Semi-natural (planted forest)	63-65	37-38
3	26-35	E	5 - 6	Medium	Secondary grassy plain	66-68	39-40
4	36-45	SE	7 - 8	Heavy	Cultivated (paddy)	69-71	41-42
5		S	9 -10	Talus	Housing site (city, village)	72-74	43-44
6		SW					
7		W					
8		NW					

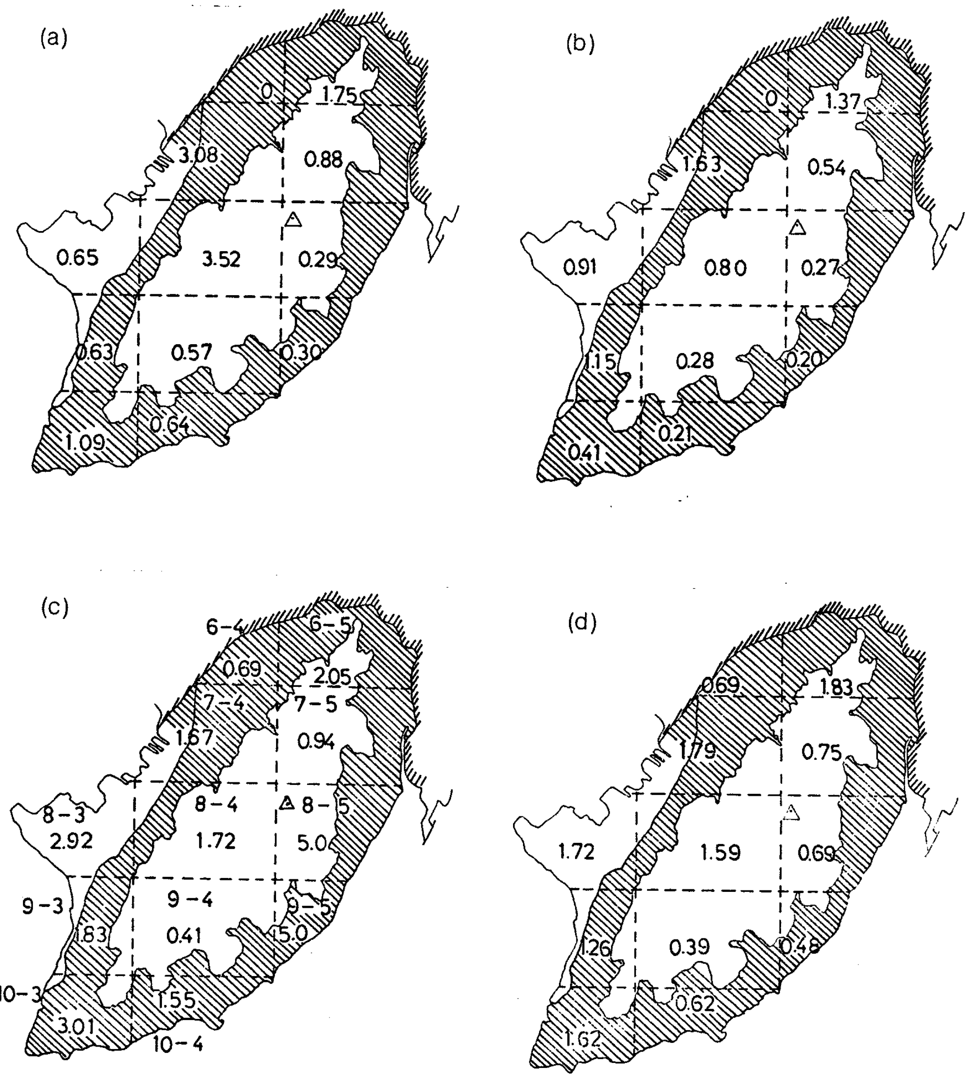

Fig. 2 The rate of slope failure by Aboshi et al. [1].
(a) Natural slope
(b) Cultivated area
(c) Artificial slope
(d) Total number of disasters per hectare (adopted here for the analysis)

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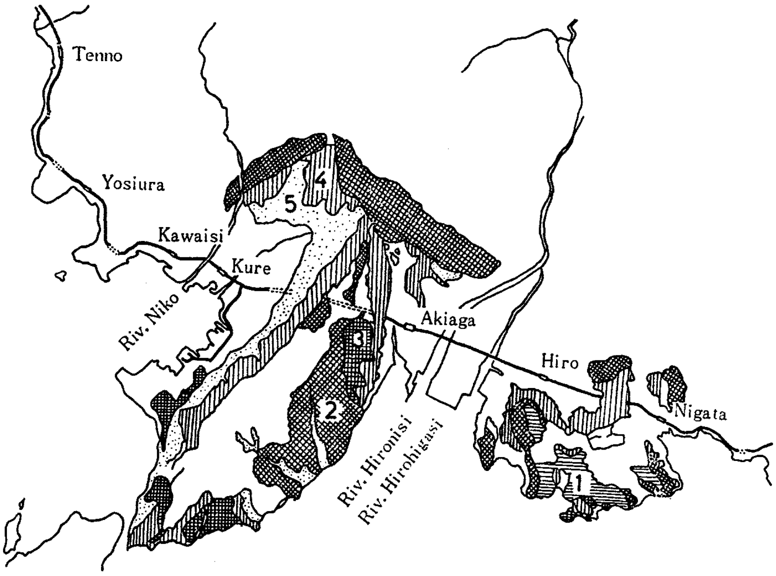

Fig. 3 The grade of weathering of granite by Umegaki et al [16].
1. paleozoic group 2. slight weathered granite 3. medium weathered granite zone
4. heavily weathered granite zone 5. talus or recent deposit.

The grade of weathering of granite was also investigated in 1967 (Fig. 3) [16]. Grade of weathering is classified into five categories: paleozoic group, slightly weathered granite zone which has many joints, traces of seepage of ground water and surface water; medium weathered granite zone, in which the texture of the original rock remains apparent, but is easily broken by a light stroke; heavily weathered granite zone, which becomes completely masa (decomposed granite soil) and includes transitive state from medium to heavil wea-

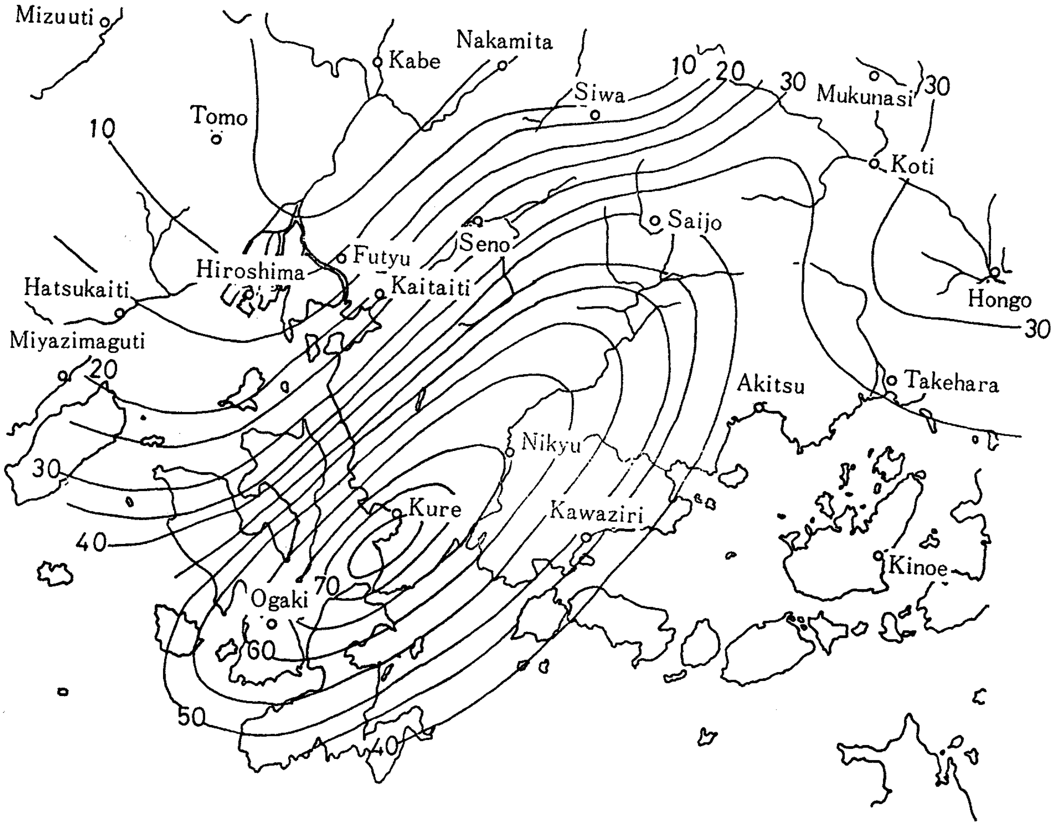

Fig. 4 Hourly distribution of heavy rainfall at maximum intensity by Maekawa et al. [8] (AME 1, 9 July, 1967, 16-17h).

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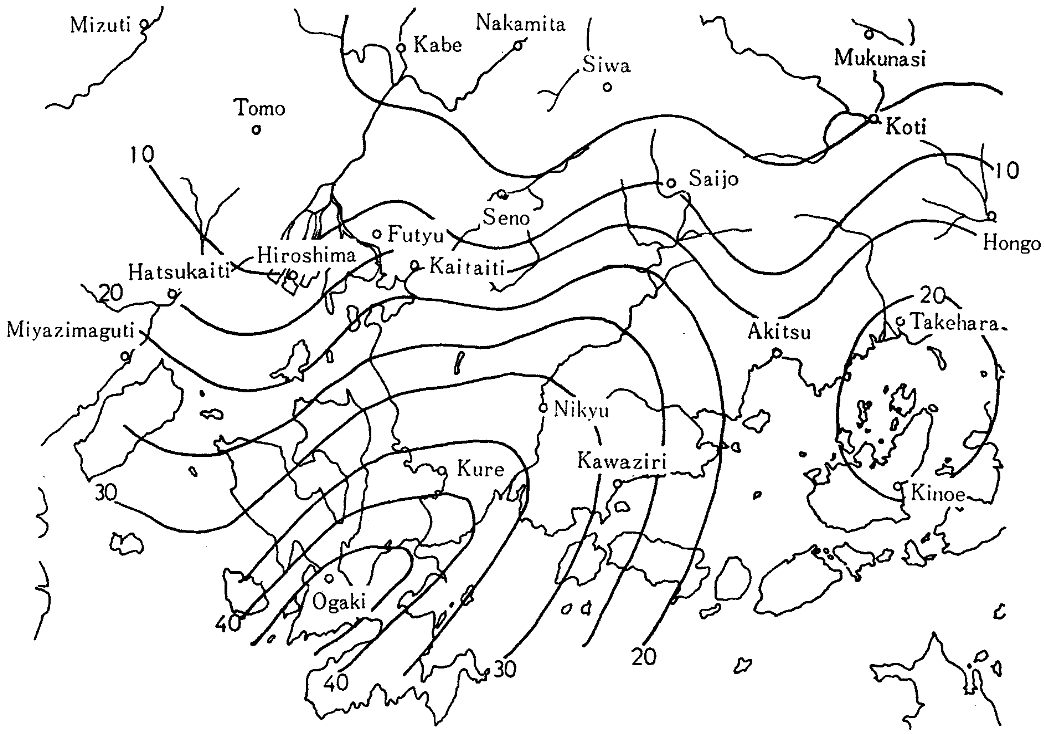

Fig. 5 Hourly distribution of rainfall before maximum intensity by Maekawa et al [8] (AME 2, 9 July, 1967, 15–16h).

thered granite zone; and talus or recent deposit.

The hourly rainfall distribution of the highest intensity for the same 1967 disaster is referred to as AME 1 (9 July, 16–17h), and the hourly rainfall distribution just one hour before is referred to as AME 2 (15–16h) [8] (Figs. 4 and 5).

3. DATA ANALYSIS

Hayashi's theory of quantification of categorical data (method I) is used for the analysis here. In Hayashi's quantification method I, the risk rate of slope failure is "external criterion variable, Y_i". For the i^{th} mesh, responses $\delta_i(jk)$ to the R categories and k_j items (characteristics) are given (Table 2). The essential point of the method is to choose weights x_{jk} such that the correlation coefficient between explained value y_i and Y_i is maximum. Response matrix $D=\{\delta_i(jk)\}$ degenerates because of the constraint condition

Table 2 Response scheme for characteristic and category.

Criterion	Sample	Characteristic												
		1			---			j			---			R
		Category												
		1	---	k_1	---	1	---	k	---	k_j	---	1	---	k_R
Y_1	1	$\delta_1(11)$	---	$\delta_1(1k_1)$	---	$\delta_1(j1)$	---	$\delta_1(jk)$	---	$\delta_1(jk_j)$	---	$\delta_1(R1)$	---	$\delta_1(Rk_R)$
Y_2	2	$\delta_2(11)$	---	$\delta_2(1k_1)$	---	$\delta_2(j1)$	---	$\delta_2(jk)$	---	$\delta_2(jk_j)$	---	$\delta_2(R1)$	---	$\delta_2(Rk_R)$
$\vdots$	$\vdots$	$\vdots$		$\vdots$		$\vdots$		$\vdots$		$\vdots$		$\vdots$		$\vdots$
Y_i	i	$\delta_i(11)$	---	$\delta_i(1k_1)$	---	$\delta_i(j1)$	---	$\delta_i(jk)$	---	$\delta_i(jk_j)$	---	$\delta_i(R1)$	---	$\delta_i(Rk_R)$
$\vdots$	$\vdots$	$\vdots$		$\vdots$		$\vdots$		$\vdots$		$\vdots$		$\vdots$		$\vdots$
Y_N	N	$\delta_N(11)$	---	$\delta_N(1k_1)$	---	$\delta_N(j1)$	---	$\delta_N(jk)$	---	$\delta_N(jk_j)$	---	$\delta_N(R1)$	---	$\delta_N(Rk_R)$

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$$\sum_{k=1}^{k_j} \delta_i(jk) = 1 \quad (i=1, 2, \cdots, N; j=1, 2, \cdots, R)$$

(all samples must respond to only one category at each item). As arbitrary choice of $R-1$ x_{jk} remains for the determination of weight, so we set $x_{jk}=0$ $(j=2, 3, \cdots, R)$ into practice. Thus determing x_{jk}, we have the prediction formula

$$y_i = \sum_{j=1}^{R} \sum_{k=1}^{k_j} x_{jk}\delta_i(jk) \quad (i=1, 2, \cdots, N) \tag{1}$$

where

$$\delta_i(jk) = \begin{cases} 1 & i^{th} \text{ grid unit responds to the } j^{th} \text{ item and } k^{th} \text{ category} \\ 0 & \text{otherwise} \end{cases}$$

Numerical data such as valley slope, valley density, and rainfall amount are stored in the computer disk file and converted to categorical data in the computer by a suitable program. The response matrix is also produced on the disk file in the computer. The calculated results of y_i are also put on the disk file in the form of an array 34×29.

4. ANALYSIS OF RESULTS

SPSS program package (e. g., Miyake et al. [9]) is used for the present analysis. Output is given in the following quantities:

(1) mean of criterion variable Y_i for each category, the whole mean and the standard deviation of Y_i.
(2) cross score between items.
(3) weight x_{jk} for each category and correlation coefficient between Y_i and y_i.
(4) Partial correlation coefficient between Y_i and y_i.
(5) prediction Y_i for each grid unit.

Table 3 shows the cross score relationship among characteristics. The relationships of all items except rainfall are expected to remain unchanged for a fairly long period, if the environment is not largely altered artificially. The examples for two cases given, AME 1 and AME 2, (Tables 4 and 5) show the frequency count, the risk rate of slope failure, and the weights x_{jk} of each category. Categories with high weight values are more likely to contribute to the risk rate of slope failure. More specifically, coefficient of determination (Table 6) is a measure of the contribution of each category to the risk rate of slope failure. One can see that the slope failure to the NW side of the peninsula shows high risk rates: At that time there was strong convergent zone of mesoscale disturbances on the SE side away from the peninsula and it rained much more on the NW slope (e. g., [10]): another possible interpretation is that a critical level of ground moisture and a maximum level of free water content relevant to slope failure (e. g., Otaki [11] and Yasui [17]) are reached easily on the NW slope compared with a SE slope as a result of less sunshine and therefore less evaporation. The greater the intensity of rainfall, the more significant the grade of weathering and ground cover to the risk rate.

Each prediction y_i of the risk rate is given as the sum of weights at each grid unit. The comparison of predicted value y_i with observed value Y_i has been made for the present data. The correlation coefficient between y_i and Y_i, and the regression equations of Y_i on y_i and y_i on Y_i given (Table 7) with mean values and standard deviations of Y_i and y_i. Because the scores for topographical and geotechnical characteristics in all categories in this area remain unchanged, a forecaster need only know rainfall amount; this is quite easy and usually necessary when the pattern of rainfall changes rapidly with time. For any other district, he must determine topographical and geotechnical scores in advance under essentially the same survey as in this study.

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Table 3 Cross scores between characteristices.

Variable		Characteristics																																				
		Valley slope				Valley direction								Valley density					Grade of weathering					Ground cover					Rainfall amount									
																													AME 1					AME 2				
		1	2	3	4	1	2	3	4	5	6	7	8	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Valley Slope	1	150	0	0	0	10	4	18	22	27	4	31	34	37	63	43	4	3	21	18	26	46	39	0	32	20	29	69	38	33	28	29	22	5	39	42	37	27
	2	0	209	0	0	14	14	47	32	28	17	27	30	22	85	73	23	6	35	72	53	14	35	2	133	27	32	15	46	78	54	29	2	3	37	77	66	26
	3	0	0	80	0	2	8	14	14	3	8	15	16	17	35	21	6	1	7	45	19	2	7	0	70	5	5	0	14	34	20	12	0	0	8	39	31	2
	4	0	0	0	3	0	0	1	1	0	0	0	1	1	2	0	0	0	1	2	0	0	0	0	2	0	0	1	1	1	1	0	0	0	0	1	2	0
Valley Direction	1	10	14	2	0	26	0	0	0	0	0	0	0	4	10	8	4	0	2	3	4	5	12	0	14	2	5	5	3	8	6	8	1	2	10	11	3	0
	2	4	14	8	0	0	26	0	0	0	0	0	0	4	10	11	1	0	2	12	5	3	4	0	18	3	3	2	10	10	4	1	1	0	6	14	6	0
	3	18	47	14	1	0	0	80	0	0	0	0	0	11	33	21	13	2	6	35	13	10	16	1	51	13	9	6	37	37	5	1	1	3	20	41	14	2
	4	22	32	14	1	0	0	0	69	0	0	0	0	15	29	17	4	4	17	26	13	6	7	0	37	11	9	12	31	29	8	0	1	0	8	27	24	10
	5	27	28	3	0	0	0	0	0	58	0	0	0	8	17	25	5	3	12	25	17	2	2	0	29	8	10	11	10	30	17	1	0	0	7	9	22	20
	6	4	17	8	0	0	0	0	0	0	29	0	0	4	10	13	2	0	9	11	8	1	0	0	16	5	5	3	7	13	5	3	1	0	1	7	17	4
	7	31	27	15	0	0	0	0	0	0	0	73	0	14	34	21	3	1	9	10	21	16	17	0	34	6	11	22	1	9	29	23	11	2	14	20	27	10
	8	34	30	16	1	0	0	0	0	0	0	0	81	17	42	21	1	0	7	15	17	19	23	1	38	4	14	24	0	10	29	33	9	1	18	30	23	9
Valley Density	1	37	22	17	1	4	4	11	15	8	4	14	17	77	0	0	0	0	18	13	12	17	17	0	24	10	8	35	25	17	10	11	14	0	11	32	20	14
	2	63	85	35	2	10	10	33	29	17	10	34	42	0	185	0	0	0	22	63	36	24	40	0	98	18	32	37	45	49	52	32	7	2	38	82	47	16
	3	43	73	21	0	8	11	21	17	25	13	21	21	0	0	137	0	0	17	51	33	16	20	2	84	20	18	13	22	62	28	22	3	5	28	39	44	21
	4	4	23	6	0	4	1	13	4	5	2	3	1	0	0	0	33	0	4	9	12	4	4	0	22	3	8	0	7	15	6	5	0	1	6	6	17	3
	5	3	6	1	0	0	0	0	2	4	3	0	1	0	0	0	0	10	3	1	5	1	0	0	9	1	0	0	0	3	7	0	0	0	1	0	8	1
Grade of Weather-ing	1	21	35	7	1	2	2	6	17	12	9	9	7	18	22	17	4	3	64	0	0	0	0	0	31	8	13	12	22	14	18	10	0	0	5	9	28	22
	2	18	72	45	2	3	12	35	26	25	11	10	15	13	63	51	9	1	0	137	0	0	0	1	111	14	7	4	25	72	33	7	0	0	11	77	45	4
	3	26	53	19	0	4	5	13	13	17	8	21	17	12	36	33	12	5	0	0	98	0	0	0	61	15	11	11	15	34	24	21	4	0	14	30	34	20
	4	46	14	2	0	5	3	10	6	2	1	16	19	17	24	16	4	1	0	0	0	62	0	0	9	3	12	38	11	9	13	17	12	4	19	18	19	2
	5	39	35	7	0	12	4	16	7	2	0	17	23	17	40	20	4	1	0	0	0	0	81	1	25	12	23	20	26	17	15	15	8	4	35	25	10	7
Ground Cover	1	0	2	0	0	0	0	1	0	0	0	0	1	0	0	2	0	0	0	1	0	0	1	2	0	0	0	0	1	1	0	0	0	1	1	0	0	0
	2	32	133	70	2	14	18	51	37	29	16	34	38	24	98	84	22	9	31	111	61	9	25	0	237	0	0	0	31	105	72	29	0	1	36	91	83	26
	3	20	27	5	0	2	3	13	11	8	5	6	4	10	18	20	3	1	8	14	15	3	12	0	0	52	0	0	25	11	6	9	1	0	11	25	15	1
	4	29	32	5	0	5	3	9	9	10	5	11	14	8	32	18	8	0	13	7	11	12	23	0	0	0	66	0	22	14	15	12	3	1	17	21	16	11
	5	69	15	0	1	5	2	6	12	11	3	22	24	35	37	13	0	0	12	4	11	38	20	0	0	0	0	85	20	15	10	20	20	5	19	22	22	17
Rainfall amount AME 1	1	38	46	14	1	3	10	37	31	10	7	1	0	25	45	22	7	0	22	25	15	11	26	1	31	25	22	20	8	0	0	0	0					
	2	33	78	34	1	8	10	37	29	30	13	9	10	17	49	62	15	3	14	72	34	9	17	1	105	11	14	15	0	84	0	0	0					
	3	28	54	20	1	6	4	5	8	17	5	29	29	10	52	28	6	7	18	33	24	13	15	0	72	6	15	10	0	0	159	0	0					
	4	29	29	12	0	8	1	1	0	1	3	23	33	11	32	22	5	0	10	7	21	17	15	0	29	9	12	20	0	0	0	136	0					
	5	22	2	0	0	1	1	0	1	0	1	11	9	14	7	3	0	0	0	0	4	12	8	0	0	1	3	20	0	0	0	0	55					
AME 2	1	5	3	0	0	2	0	3	0	0	0	2	1	0	2	5	1	0	0	0	0	4	4	1	1	0	1	5						99	0	0	0	0
	2	39	37	8	0	10	6	20	8	7	1	14	18	11	38	28	6	1	5	11	14	19	35	1	36	11	17	19						0	146	0	0	0
	3	42	77	39	1	11	14	41	27	9	7	20	30	32	82	36	6	0	9	77	30	18	25	0	91	25	21	22						0	0	103	0	0
	4	37	66	31	2	3	6	14	24	22	17	27	23	20	47	44	17	8	28	45	34	19	10	0	83	15	16	22						0	0	0	70	0
	5	27	26	2	0	0	0	2	10	20	4	10	9	14	16	21	3	1	22	4	20	2	7	0	26	1	11	17						0	0	0	0	24

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Table 4 Mean value, frequency of the risk rate, and weight for each category AME 1.

Variable	Frequency	Risk rate	Weight
Valley slope			
1	150	1.17432690	0.03153801
2	209	0.92320156	−0.03677654
3	80	0.95824599	0.03577328
4	3	0.96666622	0.03145885
Valley direction			
1	26	1.51153564	0.38342786
2	26	1.01845837	0.09745920
3	80	0.76424557	−0.11297214
4	69	0.72028625	−0.15941083
5	58	0.78810036	−0.16706008
6	29	0.71620488	−0.20022756
7	73	1.22999573	0.06233793
8	81	1.42925453	0.22814065
Valley density			
1	77	1.06648827	−0.01684897
2	185	1.06431866	0.01637020
3	137	1.00758648	0.03734189
4	33	0.82151377	−0.07376987
5	10	0.44899946	−0.44125462
Grade of weathering			
1	64	0.87233973	−0.04708306
2	137	0.82401013	−0.09172350
3	98	0.92622077	−0.05029723
4	62	1.31418896	0.08061194
5	81	1.32950020	0.19148928
Ground cover			
1	2	1.82999992	0.81654263
2	237	0.92155713	−0.06290054
3	52	0.77518898	−0.11140627
4	66	1.12681389	0.05625385
5	85	1.31658268	0.18063813
Rainfall amount			
1	99	0.74999440	−0.19806945
2	146	0.86821461	−0.02204329
3	103	1.19543266	0.18458766
4	70	1.29242420	0.05093777
5	24	1.41874599	0.01037735
For entire population			
Mean		1.01499939	
Standard deviation		0.54301351	

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Table 5 Mean value, frequency of the risk rate, and weight for each category AME 2.

Variable		Frequency	Risk rate	Weight
Valley slope				
	1	150	1.17432690	0.01278973
	2	209	0.92320156	−0.02970600
	3	80	0.95824599	0.04670811
	4	3	0.96666622	0.18473911
Valley direction				
	1	26	1.51153564	0.35242790
	2	26	1.01845837	0.01521385
	3	80	0.76424557	−0.27593648
	4	69	0.72028625	−0.23700380
	5	58	0.78810036	−0.15512592
	6	29	0.71620488	−0.13608891
	7	73	1.22999573	0.18970364
	8	81	1.42925543	0.34524620
Valley density				
	1	77	1.06648827	−0.04518217
	2	185	1.06431866	0.00389474
	3	137	1.00758648	0.02541828
	4	33	0.82151377	0.01930177
	5	10	0.44899946	−0.13607287
Grade of weathering				
	1	64	0.87233973	−0.02280160
	2	137	0.82401013	−0.06014186
	3	98	0.92622077	−0.05740998
	4	62	1.31418896	0.10406947
	5	81	1.32950020	0.10953832
Ground cover				
	1	2	1.82999992	0.45745444
	2	237	0.92155713	−0.02413887
	3	52	0.77518898	−0.13118947
	4	66	1.12681389	0.02078205
	5	85	1.31658268	0.12066084
Rainfall amount				
	1	8	1.82999992	0.48449117
	2	84	1.24166203	0.11960268
	3	159	1.06043339	0.08257794
	4	136	0.73029178	−0.25309670
	5	55	1.12344837	0.13397515
For entire population				
Mean			1.01499939	
Standard deviation			0.54301351	

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Table 6 Contribution of weight to the risk rate (Coefficient of determination).

Factors	Category	AME 1	AME 2
Valley slope	(4)	0.0918	0.0948
Valley direction	(8)	0.3445	0.5163
Valley density	(5)	0.1736	0.0811
Grade of weathering	(5)	0.2203	0.1711
Ground cover	(5)	0.2507	0.1820
Rainfall amount	(5)	0.2777	0.4041

Table 7 Risk rate of slope failure.

	AME 1		AME 2	
	Observed	Predicted (estimate)	Observed	Predicted (estimate)
Mean value	1.01500	1.01499	1.01500	1.01498
S. D.	0.54301	0.35706	0.54301	0.37940
Corr. coeff.	0.6576		0.6987	
Regression eq.	$Y_i=1.00007y_i-0.00006$ $y_i=0.43240Y_i+0.57610$		$Y_i=1.00005y_i-0.00004$ $y_i=0.48819Y_i+0.51947$	

Table 8 Two-factor interactions between categories (5-way ANOVA with one covariate).

Source of variation		Sum of squares	*DF*	Mean Square	*F*	Signif. of *F*
Main effects*		51.903	22	2.359	12.987	0.001
Valley slope		5.825	3	1.942	10.688	0.001
Weathering		15.968	4	3.992	21.975	0.001
Ground cover		5.600	4	1.400	7.706	0.001
Valley density		3.283	4	0.821	4.518	0.002
Valley direction		21.228	7	3.033	16.693	0.001
Covariate		1.612	1	1.612	8.876	0.003
Rainfall amount (AME 1)		1.612	1	1.612	8.876	0.003
2-WAY INTERACTIONS		27.171	145	0.187	1.031	0.410
V. slope	Weathering	1.514	9	0.168	0.926	0.999
V. slope	Ground cover	0.440	5	0.088	0.485	0.999
V. slope	V. density	1.371	8	0.171	0.943	0.999
V. slope	V. direction	2.903	15	0.194	1.065	0.389
Weathering	Ground cover	2.836	13	0.218	1.201	0.278
Weathering	V. density	3.212	15	0.214	1.179	0.287
Weathering	V. direction	5.388	27	0.200	1.098	0.341
Ground cover	V. density	1.776	9	0.197	1.086	0.373
Ground cover	V. direction	2.790	21	0.133	0.731	0.999
V. density	V. direction	2.173	23	0.094	0.520	0.999
Explained		80.687	168	0.480	2.644	0.001
Residual		49.594	273	0.182		
Total		130.281	441	0.295		

Covariate	Beta
Rainfall	0.026

*priority in step-down method is given as this order of category.

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However, one should check the independence of categories adopted here. To this purpose, two-factor interactions are calculated by the 5-way ANOVA with one covariate, rainfall amount. The observation number in the cells in the cross score table is not the same, so the stepdown method in the non-orthogonal factor design (Miyake et al. [9]) is used here. Two-factor interactions are not significant in the F-test with a 5% significant level for AME 1 (Table 8). The result is the same for AME 2. Very weak interaction may exist between weathering and ground cover, and also between weathering and valley

Table 9 Partial correlation ratio and deviation from the grand mean (Multiple classification analysis).

Variable		*N*	Unajusted		Adjusted for independents		Adjusted for independents +Covariates	
			DEV'N	ETA	DEV'N	BETA	DEV'N	BETA
Valley slope	1	150	0.16		0.03		0.02	
	2	209	−0.09		−0.03		−0.03	
	3	80	−0.06		0.02		0.04	
	4	3	−0.05		0.04		0.06	
				0.21		0.05		0.06
Valley direction	1	26	0.50		0.42		0.39	
	2	26	0.00		0.03		0.07	
	3	80	−0.25		−0.21		−0.15	
	4	69	−0.29		−0.24		−0.18	
	5	58	−0.23		−0.17		−0.13	
	6	29	−0.30		−0.22		−0.20	
	7	73	0.21		0.16		0.08	
	8	81	0.41		0.33		0.25	
				0.56		0.45		0.35
Valley density	1	77	0.05		−0.04		−0.04	
	2	185	0.05		0.02		0.02	
	3	137	−0.01		0.04		0.04	
	4	33	−0.19		−0.06		−0.08	
	5	10	−0.57		−0.30		−0.35	
				0.20		0.10		0.12
Grade of weathering	1	64	−0.14		−0.05		−0.04	
	2	137	−0.19		−0.08		−0.08	
	3	98	−0.09		−0.05		−0.06	
	4	62	0.30		0.10		0.08	
	5	81	0.31		0.16		0.18	
				0.40		0.17		0.18
Ground cover	1	2	0.80		0.70		0.77	
	2	237	−0.09		−0.03		−0.04	
	3	52	−0.24		−0.15		−0.14	
	4	66	0.11		0.03		0.04	
	5	85	0.30		0.14		0.13	
				0.34		0.18		0.18
Multiple R Squared						0.398		0.411
Multiple R						0.631		0.641
Grand mean=1.01								

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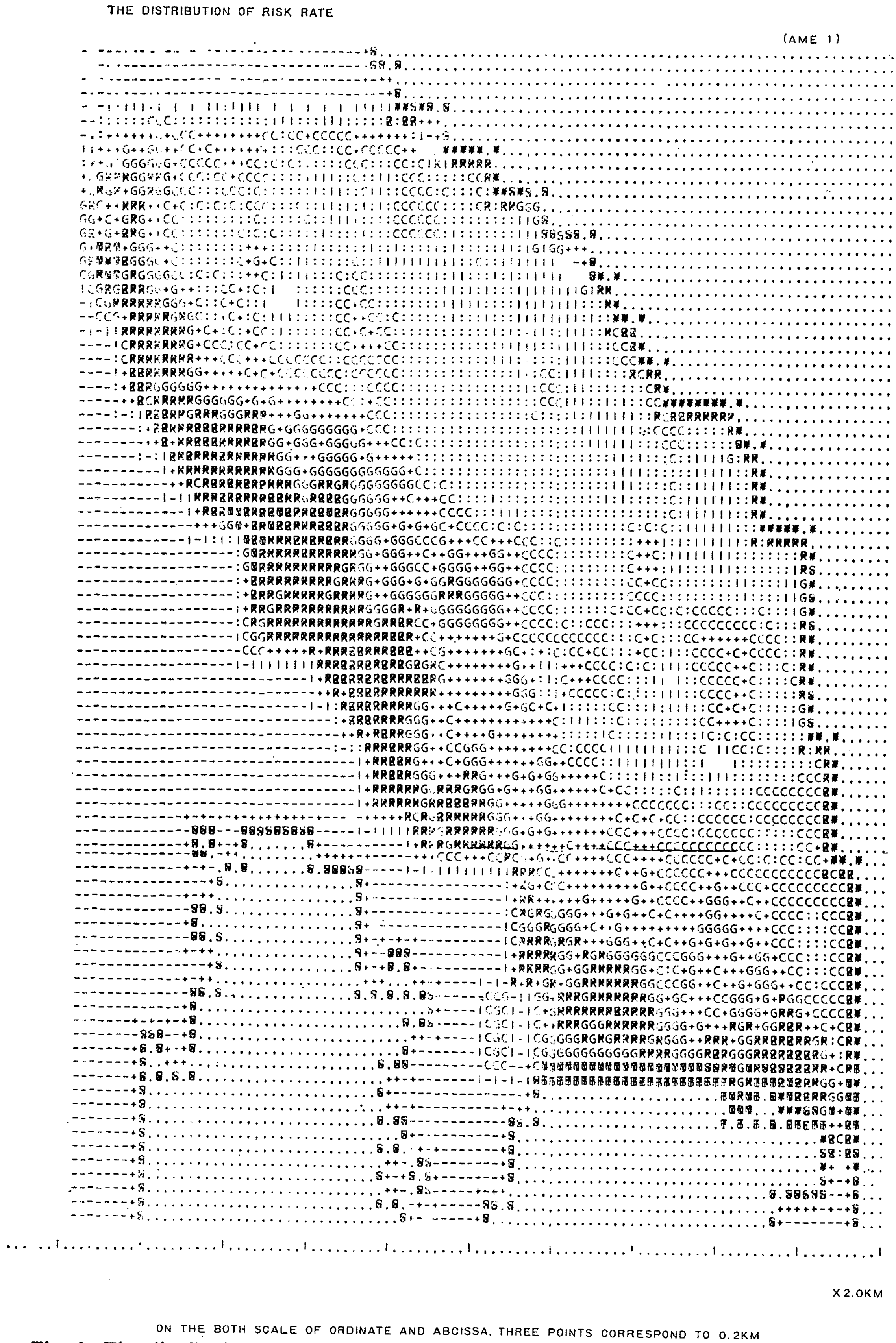

Fig. 6 The distribution of the risk rate of slope failure (AME 1). Risk value symbols are: BLANK=0.2-0.4, 1=0.4-0.6, :=0.6-0.8, C=0.8-1.0, +=1.0-1.2, G=1.2-1.4, X&P=1.4-1.6, Z&R=1.6-1.8, Y&Q=1.8-2.0, W&S=2.0-2.2, ¥&$=2.2-2.4, B&T=2.4-2.6, @&E=2.6 OVER, .=ON THE SEA, -=UNOBSERVED DATA ON LAND

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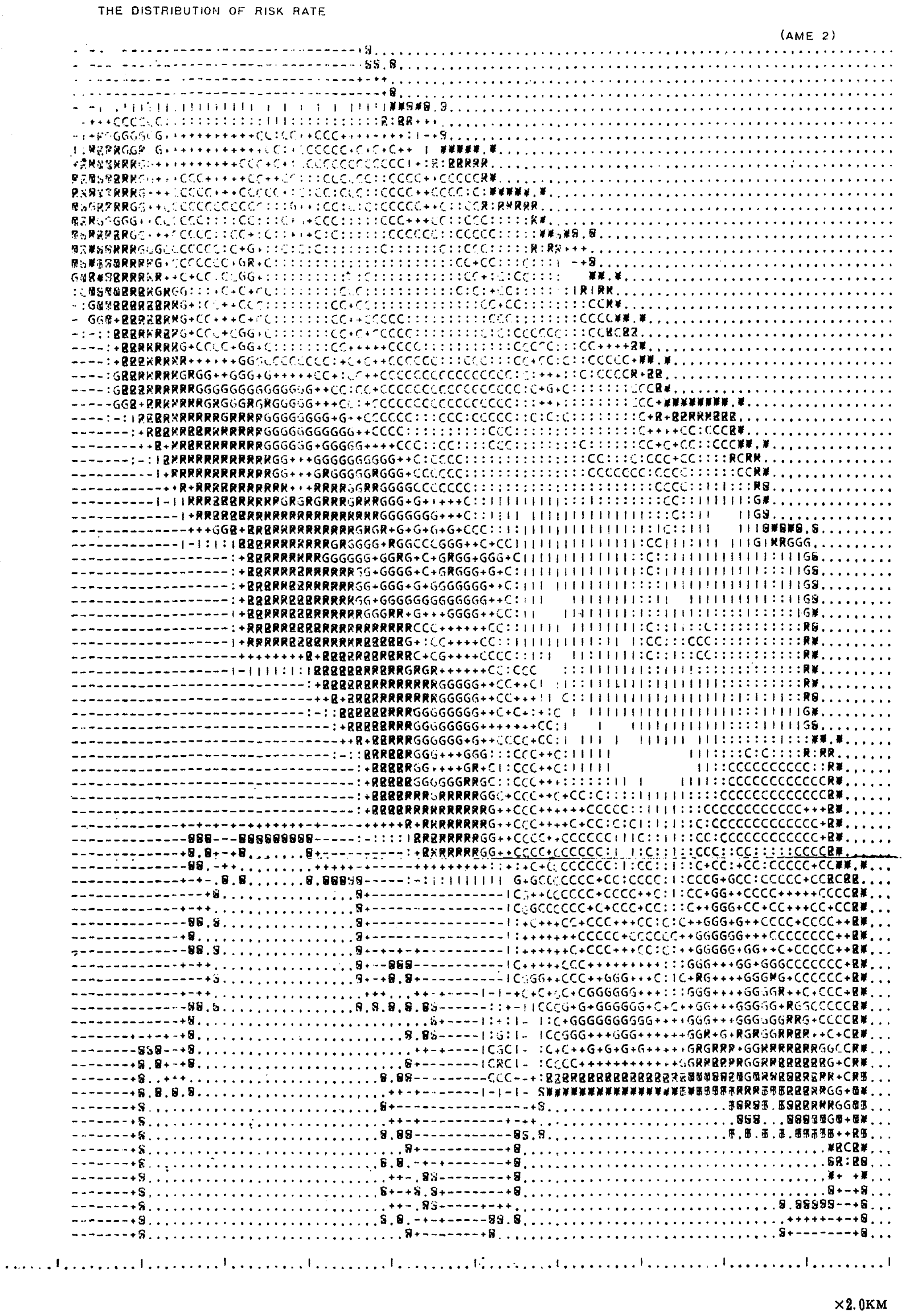

ON THE BOTH SCALE OF ORDINATE AND ABSCISSA, THREE POINTS CORRESPOND TO 0.2KM

Fig. 7 The distribution of the risk rate of slope failure (AME 2). Legend is as in Fig. 6.

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density, although these interactions are not statistically significant (Table 8). These slight interactions could be expected from the nature of weathering. The deviations of each mean of each category from the grand mean and partial correlation ratios (=BETA) of each characteristic are given (Table 9) as a measure of contribution to the risk rate and its variation. Other than rainfall, the contribution of valley direction is high, and next are weathering and ground cover. Valley direction might be related to the direction of movement of heavy rainfall already mentioned above. Contributions by weathering and ground cover are quite reasonable. Why the contribution of valley slope to the total variation is small remains unclear. There is a possibility of highly biased data on valley slope because of unobserved areas in the central mountains of the peninsula, or perhaps the degree of slope, as it is inversely related to the occurrence of houses, makes only a small contribution to a disaster.

Prediction y_i of the risk rate of slope failure is plotted automatically by a computer (Figs. 6 and 7). The ratio of ordinate to abscissa in these figures does not correspond to the real ratio, but three points of ordinate or abscissa express the real length of 200m. A comparison of the change of y_i distribution (Figs. 6 and 7) with the shift of rainfall distribution (Figs. 4 and 5) clearly shows that the area of high risk rate extends from the south to northwest on the peninsula as the centre of rainfall moves from the south to the north (from AME 2 to AME 1).

5. STATISTICAL CONSIDERATIONS

After the map of prediction of slope failure has been obtained, prediction error must be considered, particularly for the use of Hayashi's quantification method I. The weight is regarded as a regression coefficient and the response matrix as design matrix variable in

$$Y_i=(Dx)_i+e_i \quad (i=1, 2, \cdots, N) \tag{2}$$

where

$$x=(x_{11}, \cdots, x_{1k_1}, x_{21}, \cdots, x_{2k_2}, \cdots, x_{jk_j}, \cdots, x_{RK_R})$$

$$D=\{\delta_i(jk)\};\ N\times K \text{ response matrix, } K=\sum_{j=1}^{R} k_j$$

and the e_i are independent and normally distributed with zero mean and variance σ^2. The problem is to find the significant difference between a prediction y_i and the prediction y_{oi} for a given $\delta_{oi}(jk)$, $(j=1, 2,\cdots, R; k=1, 2,\cdots, k_R)$ such that

$$y_{oi}=(Dx)_{oi}+e_{oi}$$

A prediction y_i is given from the weight x^*, determined by the equation

$$y_i=(Dx^*)_i \tag{3}$$

where x^* is also the least square estimate under the constraints. Unbiased estimate $\hat{\sigma}^2$ of variance σ^2 is given as

$$\hat{\sigma}^2=\frac{1}{N-K+R}\sum_{i=1}^{N}(y_{oi}-y_i)^2$$

Then we have $(1-\alpha)$ 100% prediction region of y_{oi} given as

$$(Dx^*)_{oi}-t_{\frac{\alpha}{2}}\hat{\sigma}\sqrt{1+\sum_l\sum_m\delta^{lm}\delta_{ol}\delta_{om}}<y_{oi}<(Dx^*)_{oi}+t_{\frac{\alpha}{2}}\hat{\sigma}\sqrt{1+\sum_l\sum_m\delta^{lm}\delta_{ol}\delta_m}$$

where $\{\delta^{lm}\}$=element of $(D'D)^{-1}$ and $\delta_{ol}\delta_{om}$=element (l, m) of $D'\ D$ for δ_{oi} (see, e. g., Takeuchi [15]). In our study this method cannot be immediately applied because of degeneration of $D'D$. So only a rough estimation has been made for the present data, noting that

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$$(1+\sum_l\sum_m \delta^{lm}\delta_{ol}\delta_{om})\hat{\sigma}^2=\mathrm{Var}(y_{oi}-y_i)$$
$$\leqq \mathrm{Var}(y_{oi})+\mathrm{Var}(y_i)\simeq 2\mathrm{Var}(y_i)=0.2550$$

with $\mathrm{Var}(y_i)=0.1275$ (AME 1),

$$\sqrt{\mathrm{Var}(y_{oi}-y_i)}=0.5050.$$

$n=442$ is sufficiently large to use normal distribution instead of t-distribution. Then the 95% confidence interval of y_i is given as

$$[y_i-0.99,\ y_i+0.99]$$

For AME 2, the 95% confidence interval of y_i is

$$[y_i-1.05,\ y_i+1.05]$$

These figures mean that only difference larger than about 1.0 between adjacent predictions in Figs. 6 and 7 is statistically meaningful. The normality of prediction errors in both cases AME 1 and AME 2 are confirmed.

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