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APPLICATION OF A LOGIT MODEL TO STABILITY EVALUATION OF RIVER LEVEES

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ABSTRACT

The applicability of a binary logit model to stability evaluation of river levees was investigated and models for both middle/small and large-scale levees were formulated. Although only three or four of the previously determined eleven factors which could influence levee collapse were adopted in the formulated logit models, the predictability and transferability of these models are sufficiently good to make them useful tools with which to evaluate river levee stability.

1. INTRODUCTION

Evaluation of the stability of river levees is particularly necessary in Japan, where the river density is high in the narrow plains and where regional ground space is rapidly being transfered from agricultural use to building use. In this study, however, we are concerned not only with levee incidents involving flooding but also those which occur without overflow. For example, breaching of levees without overflow took place on the left-side levee of the Tama River at Sabae in Tokyo (September, 1974), on the right-side levee of the Nagara River at Anpachi in Gifu (September, 1976), and at the levee on the Kokai River, a branch of the Tone in north Tokyo (August, 1981).

Levee failures are classified into three types: the overflow type, the toe erosion type, and the seepage failure type. The studies done so far on a mechanical basis have not been sufficient to produce a definitive evaluation system for river levees because many characteristic factors have not been estimated quantitatively, owing to the compound mechanisms produced by faults and such factors as complex slope surfaces, the structure of waterproof countermeasures, and the effect of paving the top surface of levees.

We do not know on the basis of actual breachings what factors affect the damage type, even though up to now this kind of research has been done by quantitative methods or statistical analyses of data from actual breaches. These approaches have made clear the importance of selecting factors that actually affect the stability of levees, but no definitive procedure could be chosen because the results could not be expressed such that the theoretical probability of levee collapse

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accurately reflected the empirical data. We here provide a logit model [1, 2, 3] which expresses the probability of the collapse of, or damage type of, a levee, and examine it based on the data from actual levee breaches.

The uses of the probability of collapse obtained from our logit model follow.

2. STABILITY AND SAFETY

"Safety" is an important conception in that it expresses both safety and stability. The former is the protection of human life and property from disasters, and the latter strength of structure against failure. Therefore, "safety" is composed of two different conceptions: "social safety" and "mechanical stability" [4].

Assume that the probability of damage can be estimated as the "mechanical stability" and that the amount of damage produced by a certain type of collapse can also be calculated. The damage expectation expressed as cost can be calculated by multiplying the damage cost by its probability:

$$E_i=\sum_j C_{ij}P_{ij}$$

or

$$V_j=\sum_i C_{ij}P_{ij}$$

in which E_i is the damage expectation of the i-th levee, P_{ij} is probability of it being damaged by the j-th type of collapse, C_{ij} is the supposed damage at the i-th levee from the j-th type of collapse, and V_j is the damage expectation in the j-th type of collapse.

Using this information and calculating the construction costs for improvement of levees at certain positions against various types of collapse, we can decrease the probability of collapse by cost-effective countermeasures. We do not present an economic evaluation here, but do make a stability evaluation with the logit model [5].

3. BINARY LOGIT MODEL AND CHARACTERISTIC VARIABLES FOR A RIVER LEVEE

3.1. *Binary Logit Model*

We formulated a binary logit model by estimating and examining parameters in the utility function (we call it damage potential in this paper) after first determining the functional form of damage potential by the maximum likelihood estimation method and then calculating the co-variance matrix of the parameters, taking into account the t-value and likelihood. The choice probability, P_{1n}, that the model selects the choice branch 1 (damaged or collapsed) and the choice probability, P_{2n}, that corresponds to branch 2 (non-damaged or non-collapsed) are expressed as

$$P_{1n}=\frac{1}{1+\exp[-(V_{1n})]}$$

$$P_{2n}=1-P_{1n}$$

in which P_{1n} is the choice probability that the n-th levee chooses branch 1. The utility function V_{1n} is recognized as the damage potential and is given in the linear equation

$$V_{in}=\theta_0+\theta_1X_{in1}+\theta_2X_{in2}+\theta_3X_{in3}+\cdots\cdots+\theta_kX_{ink}$$

in which the suffix i is the choice branch number 1 or 2.

3.2. *Selection of Characteristic Variables of a Levee*

Of the many possible variables, we have selected eleven as characteristic: the width of the levee top, the outside and inside heights of the levee and gradient of its slopes, the outside and inside banquettes, the soil strength parameters, the structure of the bank protection, the kind of pavement on the levee top, the flow capacity of the river and the flood discharge used in planning the levee system (henceforth simply called "flood discharge"), the kind of riverbed and the circumstances (accompanying structures) of the levee, the existence of seepage water around the inside toe of the levee, and rainfall. The standards for selection are:

(1) variables which are easily obtained,
(2) variables which can be individually selected from the others with multicollinearity,
(3) variables which are clearly known in mechanics, and
(4) variables of the numerical type are preferable to dummy ones.

Based on the above, eleven variables are possible:

a. Width of the top surface (X_1) and
b. Inside height of the levee (X_2)

These are easily obtained and are important factors that express the scale of the levee, as does the next factor:

c. Area of the levee section (X_3)

This value is a function of the width, X_1, the gradient of the slope, and the height of the levee. There is a strong interrelation between them, but this still is regarded as an important resistance factor against external force.

d. Soil strength parameter (X_4; stability number)

The stability number in the slope stability analysis is an important resistance factor necessary for stability evaluation. In determining this factor we have used the data shown in Table 4, four types of soils being converted to a continuous variable in the form of the stability number.

e. Ratio of the flow capacity of the river to the flood discharge (X_5)

This is a variable that expresses the magnitude of the force acting on a levee.

f. Outside slope protection (X_6)

In this paper the dummy variable $X_6=1$ is used for a permeable structure such as bare soil, a planted grass surface, or piled-up stones or concrete blocks. $X_6=0$ is used for other, impermeable structures.

g. Kind of pavement on the levee top (X_7)

This is given the same classification standard as the outside slope protection, i.e. as to whether the pavement is permeable or impermeable.

h. Seepage water through a levee (X_8)

This dummy variable is derived from important information obtained from inspection and must be taken into account for the evaluation because a levee that shows seepage is thought to be threatened with seepage failure.

i. State of the river channel (X_9, X_{10}, X_{11})

The meanderings of the river course and the existence of accompanying structures are expressed by these variables: concave form, X_9; convex form, X_{10}; and the existence of accompanying structures upstream or downstream, X_{11}.

4. TYPES OF COLLAPSE AND THE DISCRIMINATING PATTERN FOR LOGIT MODEL ANALYSIS

Four types of damage are shown in Fig. 1: the complete breakage of the levee section, outside slope failure, inside slope failure, and slight or no failure. More than five hundred records of damage to levees of the middle and small types have been collected in Japan [6] (Table 1). These data can be placed into two classifications, overflow and no overflow. There is much less data available for large levees, but damage data for 36 cases along the Nagara River are shown in Table 1.

In order to apply not the multinomial but binary logit model for the sake of analytical simplicity, the original data classified into aforementioned four types of damage are rearranged into

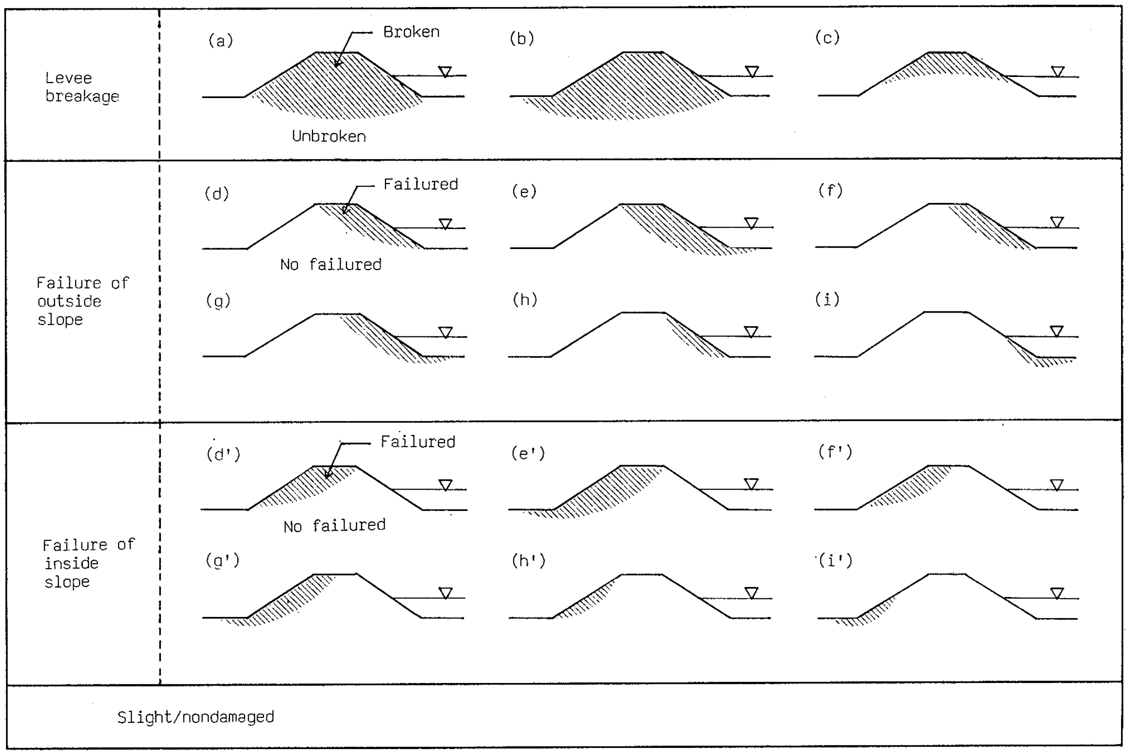

Fig. 1 Four types of levee collapse.

Table 1 Correspondence of damaged levee data to four discriminating model patterns.

(a) Middle/small-scale levees

	Collapse type	Number	Model 1	Model 2
With overflow	Breakage	120	120	120
	Outside slope failure	19	76 (Outside slope failure, Inside slope failure, Slight/nondamaged)	31 (Outside slope failure, Inside slope failure)
	Inside slope failure	12		
	Slight/nondamaged	45		

	Collapse type	Number	Model 3
Without overflow	Breakage	47	47
	Outside slope failure	118	137 (Outside slope failure, Inside slope failure)
	Inside slope failure	19	
	Slight/nondamaged	∞	

(b) Large scale levees (the Nagara river)

	Collapse type	Number	Model 4
Without overflow	Breakage	1	36 (Breakage, Outside slope failure, Inside slope failure)
	Outside slope failure	30	
	Inside slope failure	5	
	Slight/nondamaged	87	87

two categories in three different ways for middle/small and one for large scale levees as shown in Table 1. The possibility of discrimination between failure and no failure is examined in four patterns, as shown also in Table 1. Model 1 is intended to discriminate complete breakage from other types of breakage; model 2 is intended to discriminate a complete break from small-scale failure excluding the slight or no damage type. Model 1 is, therefore, regarded as evaluating the risk of complete breakage and model 2 is for judging whether or not levees come to suffer complete breakage, being confined to only damaged levees as the population. These models correspond to the overflow type. In contrast, model 3 is intended to discriminate a complete break from small-scale failure, and model 3 is an evaluation model for the same confined discrimination purpose as model 2, corresponding to the no overflow type. For a large river levee, model 4 is intended to discriminate more than small-scale of failure from slight or no failure because these are fewer in number than small-scale failures. Model 4, therefore, evaluates the risk of complete break of large levees with no overflow.

For any statistical analyses, the more data the better. For example, there is a report that about 300–500 samples are sufficient for the stable estimation of 5 variable binary logit model. Due to the limited availability of samples, however, the model variables are chosen and estimated here so that the t-value of each parameter be greater than 1.96, which indicates that the adopted variable influences the risk of damage with the confidence higher than 95% probability. It should be noted that the models 2 and 3 are confined to evaluate the conditional probability of complete breakage of damaged levees excluding slight or no failure. Therefore, if we intend to evaluate the probability of complete breakage of a given levee without overflow, for example, we have to multiply the probability calculated from model 4 by the probability calculated from model 3 (see Table 1), based on the idea of nested logit model which is one of modified multinomial logit model.

5. ESTIMATION RESULTS

5.1. *Results*

The results for these four cases of model analysis are ordered for the estimation of the parameters in the utility function (damage potential), and the t-value presented is given in parentheses under the parameters in Table 2. The likelihood ratio and % right (hit ratio) of each model are also shown in Table 2. In each model three or four variables are adopted along with an alternative specific dummy constant, θ_0.

5.2. *Consideration of the Factors (Variables) Adopted*

Table 2 shows that the 1st variable, the width of the levee top; the 2nd, the inside height of the levee; the 3rd, the area of the levee section; the 4th, the levee's soil; the 5th, the ratio of the flow capacity to the flood discharge; the 8th, the recognized seepage of water; and the 10th, the state of the river channel can be discriminated. Concerning the effects of the adopted factors:

(a) the width of the levee top (X_1)

The width of the levee top is a strongly resistant factor used in models 1 and 2, but is omitted in models 3 and 4. This variable has strong interrelation with the inside height of the levee and the area of the levee section, which is why the width of levee top is used in models 1 and 2 and why the 2nd and 3rd variables are not. This is thought to owe much to the theory that a logit model chooses one variable among several with multicollinearity.

(b) the inside height of the levee (X_2) and the area of the levee section (X_3)

The 2nd and 3rd factors are used in models 3 and 4, but the plus or minus sign is reversed because model 3 is used to discriminate a complete break from the other types of collapse while excluding cases of slight or no damage, whereas model 4 is to discriminate failure from slight or no failure.

(c) the soil strength parameter (X_4)

Table 2 Analytical results for the four logit models.

Notation	Characteristic factors (variables)	Model 1	Model 2	Model 3	Model 4
θ_0	Alternative specific dummy constant	2.156 (4.199)	4.538 (5.298)	1.962 (1.967)	−3.502 (2.637)
θ_1	Width of levee top (m)	−0.439 (3.713)	−0.628 (4.275)	/	/
θ_2	Inside height of levee from inland surface (m)	/	/	−0.839 (2.165)	0.742 (2.328)
θ_3	Area of levee section (m^2)	/	/	0.037 (2.014)	−0.014 (2.425)
θ_4	Soil strength parameter (Stability number) [0]	−1.919 (3.008)	−3.094 (3.591)	−2.195 (2.044)	/
θ_5	Ratio of flow capacity to flood discharge [0]	/	/	−1.201 (2.608)	/
θ_6	Permeable structure of outside slope protection ($X_6=1$)	/	/	/	/
θ_7	Permeable pavement of top surface of levee ($X_7=1$)	/	/	/	/
θ_8	Recognized seepage of water through the levee and its foundation ($X_8=1$)	1.590 (2.784)	/	/	1.443 (2.643)
θ_9	State of river channel: concave levee line ($X_9=1$)	/	/	/	/
θ_{10}	State of river channel: convex levee line ($X_{10}=1$)	0.981 (1.967)	2.429 (2.177)	/	/
θ_{11}	State of river channel: existence of accompanying structures ($X_{11}=1$)	/	/	/	/
% right (Hit ratio) of model		0.699	0.868	0.755	0.732
Likelihood of model		0.185	0.455	0.241	0.223

This factor is adopted in every model but 4, which indicates that it has a strong effect on failure, as expected in geotechnical engineering. The reason why it is omitted from model 4 is because soil strength data for large levees must be judged visually from the state of the levee surface.

(d) ratio of the flow capacity to the flood discharge (X_5)

This quantity expresses the scale of the river discharge, but in itself is a resistant factor of the levee because it is defined as being greater when the capacity is greater than the discharge during floods. This factor is used only in model 3, which discriminates a complete break from small-scale failures when there is no overflow. It is omitted in model 4, for large levees, this type of levee being thought to be strongly enough made to be stable for this factor.

(e) structure of the outside slope protection and the kind of pavement on the levee top

These parameters are omitted in every model, which indicates that there is little effect on the structure from the seepage of rainfall and of floods. We consider that the structure of the outside slope and the pavement on the levee top do not significantly affect the stability and that the construction work is standardized; therefore these factors have little effect.

(f) recognized seepage water through a levee (X_8)

This factor is regarded as effective because it is used in models 1 and 4. Why is it not used in models 2 and 3? Both these models exclude cases of slight or no failure; therefore, information on the recognition of seepage water effectively discriminates between failure and no failure.

(g) state of the river channel (X_{10})

The reason why the convex case alone is included, and then only in models 1 and 2, is because breaking of the levee by overflow occurs when water which has escaped from the river through a breach at another point flows back into the river.

5.3. *Factor Elasticity Analysis*

The extent of the effects of various factors on the estimated probabilities of collapse differs markedly. The relations between estimated probabilities and some factors are shown in Fig. 2, and the elasticity of the variables [7] in each model is calculated in Table 3, which gives the magnitude of the influence of a variable on the probability, the factor elasticity being defined as the proportional rate of change of the estimated collapse probability defined by the proportional rate of change of the associated factor. For example, in model 1, factor 1 (the width of levee top) is

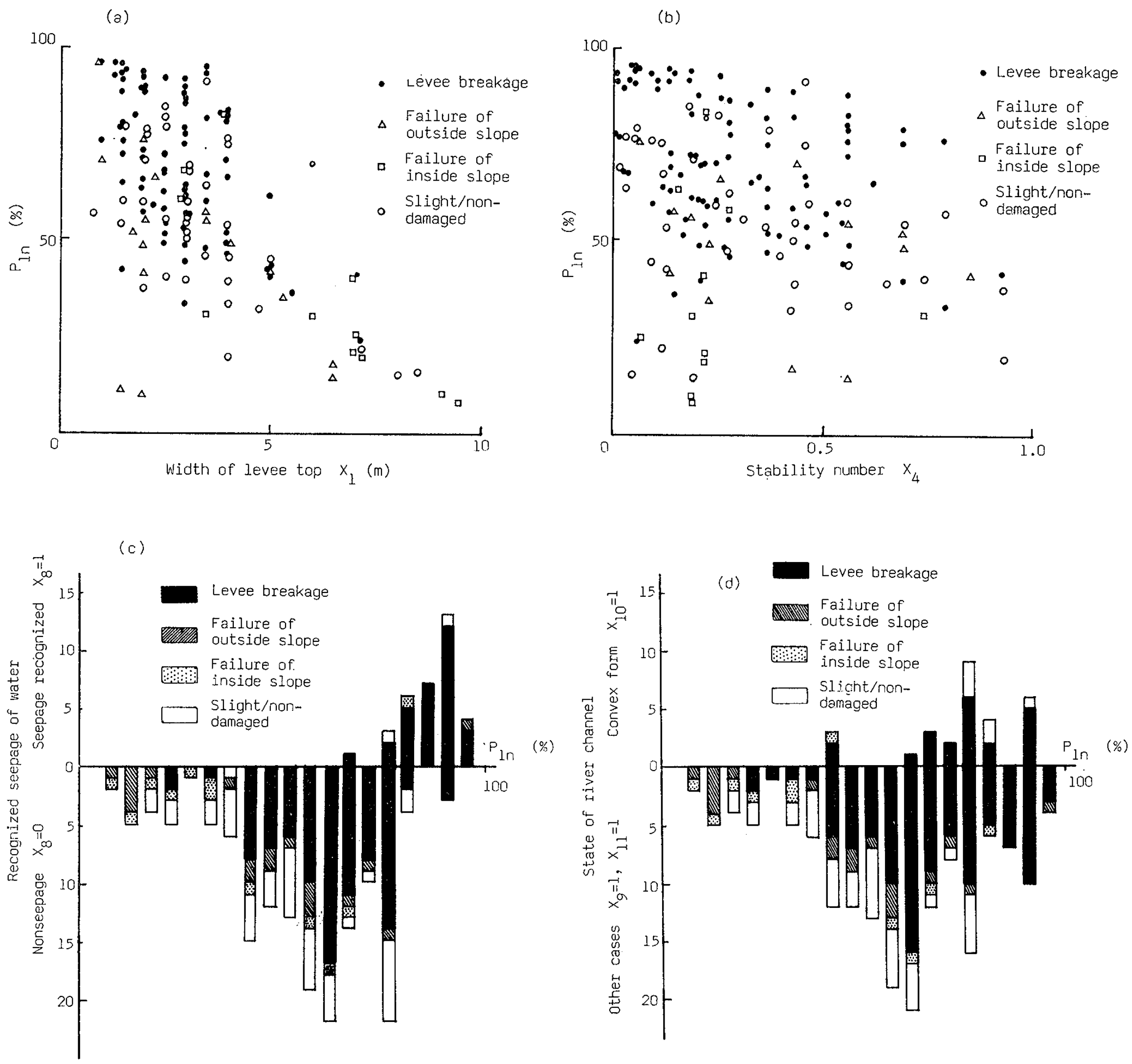

Fig. 2 Effect of factors on the probability of collapse; model 1. (a) Width of the levee top (X_1), (b) Soil strength parameter; stability number (X_4), (c) Recognized seepage water (X_8), and (d) State of the river channel; convex form (X_{10}).

Table 3 Factor elasticities for collapse probability.

i	Characteristic factors (variables)	Model 1	Model 2	Model 3	Model 4
0	Alternative specific dummy constant	/	/	/	/
1	Width of levee top (m)	−0.530	−0.424	/	/
2	Inside height of levee from inland surface (m)	/	/	−1.549	4.144
3	Area of levee section (m^2)	/	/	0.680	−2.503
4	Soil strength parameter (Stability number) [0]	−0.247	−0.210	−0.384	/
5	Ratio of flow capacity to flood discharge [0]	/	/	−1.188	/
6	Permeable structure of outside slope protection	/	/	/	/
7	Permeable pavement of top surface of levee	/	/	/	/
8	Recognized seepage of water through the levee and its foundation	0.340	/	/	0.586
9	State of river channel: concave levee line	/	/	/	/
10	State of river channel: convex levee line	0.249	0.174	/	/
11	State of river channel: existence of accompanying structures	/	/	/	/

the strongest, the next strongest being recognized seepage water, followed by the state of the river channel; the weakest one being the soil strength factor, in middle and small levees with overflow.

It is clear that when a flood flows over a levee, the width of the levee top is an important resistance factor. Strikingly, the 8th factor, recognized seepage water, plays a major role in the discrimination.

The dependence of the continuous, numerical factor (abscissa) on the calculated probability (ordinate) are shown in Figs. 2(a) and (b). The relation between the cumulative frequency of the alternative dummy variable (ordinate) and the calculated probability (abscissa) is shown in Figs. 2(c) and (d). The data for the specific dummy variable is distributed over the greater part of the calculated values of P_{1n}.

The ordinate in Fig. 3(a) shows the cumulative number of breakage (continuous line) and of nonbreakage cases (dotted line) for levees in model 1 at five percent intervals of the calculated probability of collapse (abscissa). The ratio of the cumulative number of broken levees to the total is shown in Fig. 3(b). It represents a linear relation between the cumulative frequency and calculated probability of collapse; i.e., the equality between them. Thus, the estimated probability of levee collapse is interpreted as the rate of levee collapse that has been calculated as the probability of P_{1n}.

To make clear the prediction ability of the modelling procedure, we have drawn the calcu-

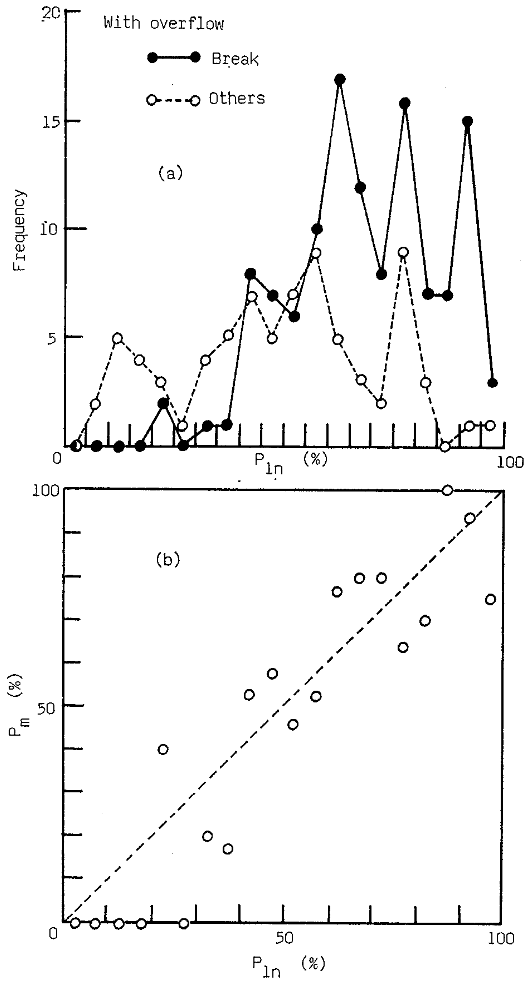

Fig. 3 Actual and estimated probabilities; model 1. (a) Relations of the cumulative frequency of damaged and nondamaged levees to the estimated probability, (b) Relations of the actual probability, P_m, defined by the rate of damaged levees, to the calculated probability.

lated probability of collapse for both damaged and nondamaged levees (Fig. 4), which shows a good fit in model 1. The calculated probability of collapse, however, remains small in models 3 and 4 as a whole because of the many undamaged cases compared to the number of damaged cases. This tendency often appears in logit model analysis, and in model 2 high probabilities are calculated because of the large number of damaged cases.

6. RELIABILITY OF THE ESTIMATED PROBABILITY AND TRANSFERABILITY

6.1. *Reliability of the Model Analysis*

The expressions shown in Fig. 3 for model 1 are adjusted in Fig. 5 (model 2), Fig. 6 (model 3), and Fig. 7 (model 4). Also, the adjustments of the factor analysis shown in Fig. 2 (model 1) are presented in Fig. 8 (model 2), Fig. 9 (model 3), and Fig. 10 (model 4). Model 3 contains no alternative dummy variable, only four variables (factors) of the numerical and continuous types; consequently, the collinearity of the relation between the actual mean probability P_m and the calculated P_{1n} is the best among the four models (see Figs. 3, 5, 6, and 7). This shows that numerical and continuous variables are preferable for logit model formation, as stated in section

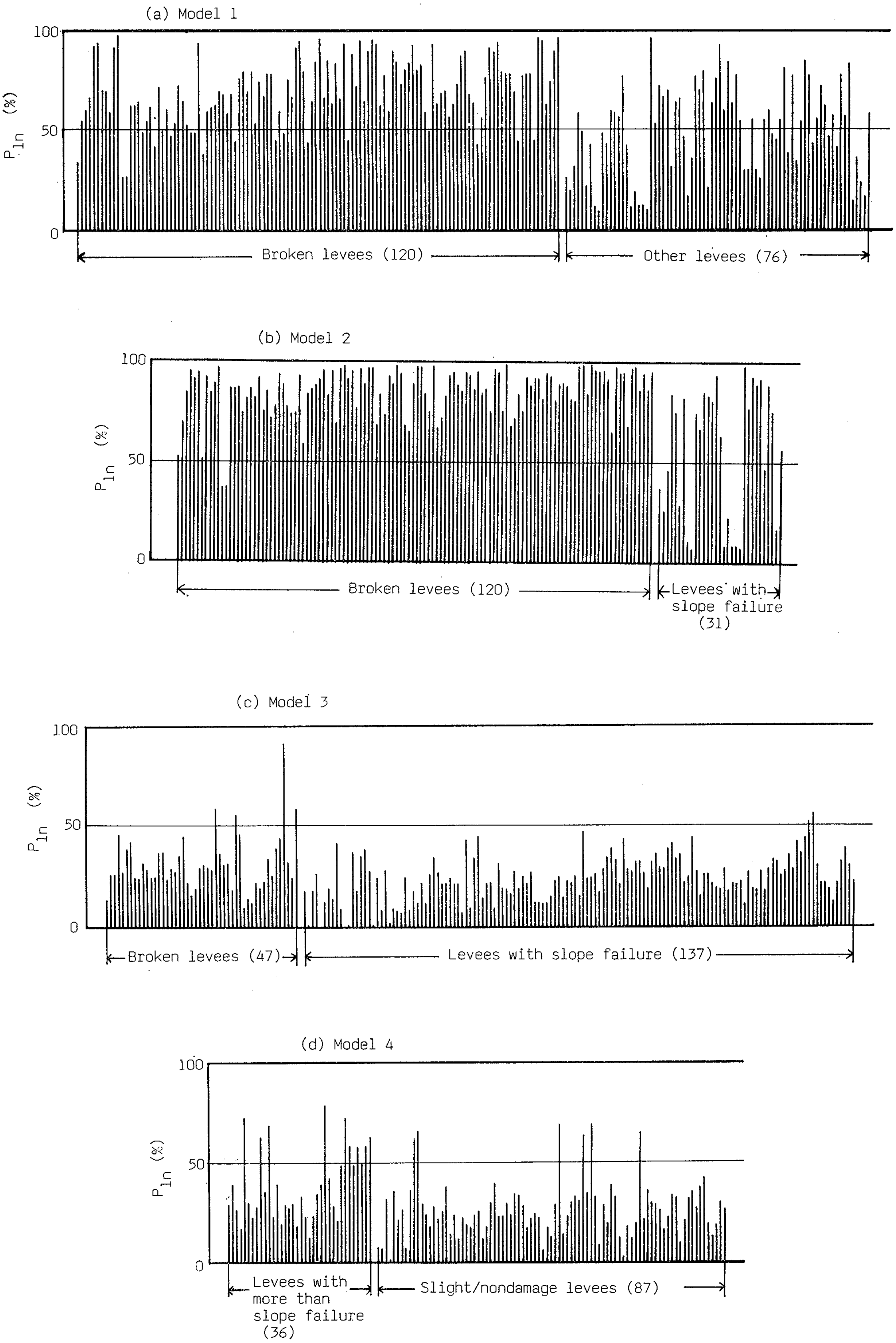

Fig. 4 Prediction ability of the logit models.
(a) Model 1, (b) Model 2, (c) Model 3, (d) Model 4.

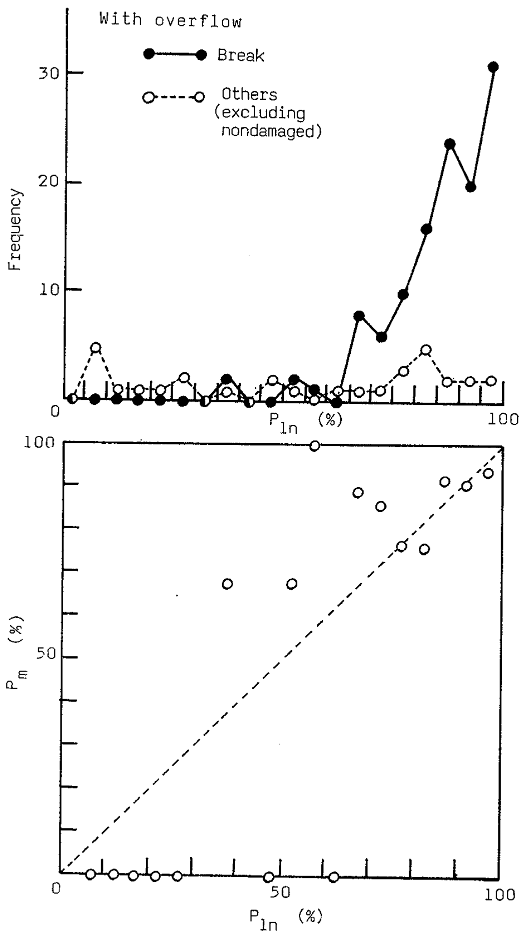

Fig. 5 Actual and estimated probability; model 2.
(a) Frequency of damaged and nondamaged levees and (b) Actual probability, P_m.

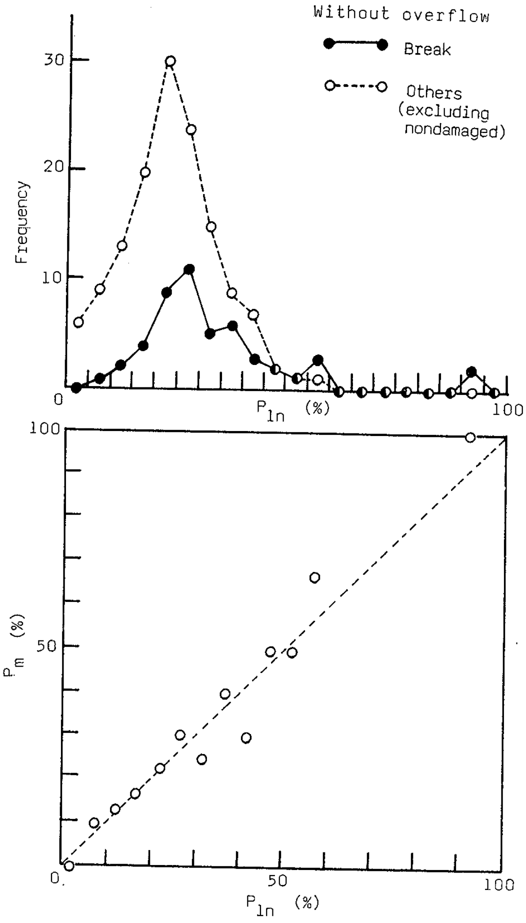

Fig. 6 Actual and estimated probability; model 3.

3.2.

In contrast, the bias of the frequency of data shown in each part (a) of Figs. 3, 5, 6, and 7 depends on the bias of the collected data. According to Table 1, model 1 contains 120 broken and 76 unbroken levees. Model 2 has more instances (120) of breaks than of slope failures (31), whereas model 3 has fewer instances of breaks (47) than of slope failures (137), and model 4 has about half as many incidents of damage (36) as of slight or no damage (87). As stated before, the bias of the data affects the prediction ability accuracy of the logit model shown in Fig. 4, which yields comparatively high probabilities in model 2 and comparatively low probabilities in models 3 and 4. The typical differences in the logit models by data are shown in the frequency distribution in Figs. 3(a), 5(a), 6(a), and 7(a).

Let us transfer, or apply, model 3 to the data of model 4. According to Table 1, model 3 excludes slight or no damage cases, so that we must consider the discrimination of one broken levee from 35 samples of outside or inside slope failure in the data of model 4. Also, the logit models shown so far are "disaggregate" models, whereas the data for model 4 is really "aggregate" data [7, 8]. Therefore, we must adjust the alternative specific dummy constant, θ_0, by β in the utility function (damage potential) as follows [8].

The sharing rate of choosing one broken levee among the total number of samples (36) is

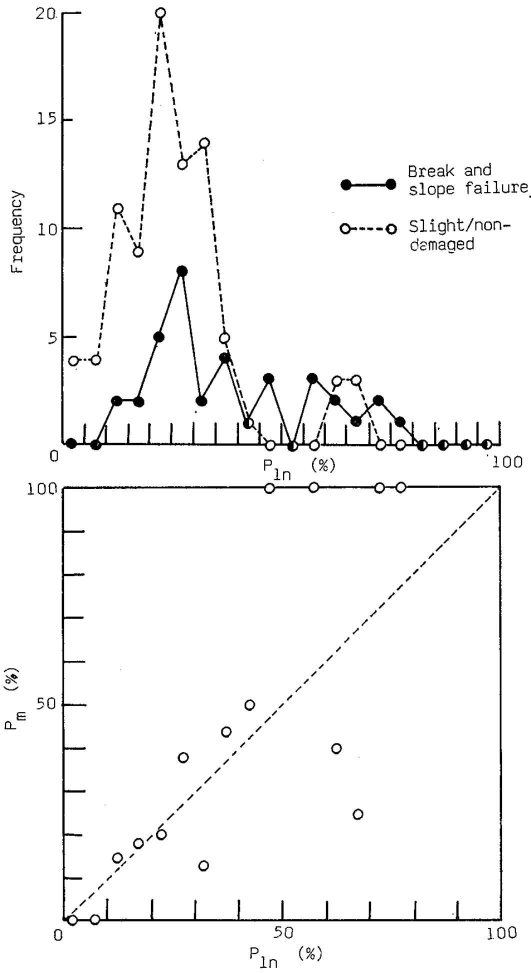

Fig. 7 Actual and estimated probability; model 4.

Table 4 Soil parameters.

Four type of soils	Cohesion (kN/m²)	Unit weight (kN/m²)
① Sandy soil	9.8	17.6
② Sand	4.9	17.6
③ Clayey soil	19.6	17.6
④ Sand and gravel	0.98	17.6

$$S_2=\frac{1}{1+\exp(-V_{1n})}=\frac{1}{36}$$

and

$$V_{1n}=\theta_0+\theta_2X_2+\theta_3X_3+\theta_4X_4+\theta_5X_5+\beta$$

in which the θ's are the parameters obtained from model 3 ($\theta_0=1.961$, $\theta_2=-0.839$, $\theta_3=-0.037$, $\theta_4=-2.195$, $\theta_5=-1.201$) and X_i is the average of each factor used in model 4. This gives $\beta=-4.718$ and a low % right of 38.9% in the case of direct transfer ($\beta=0$), whereas for adjusted transfer ($\beta=-4.718$) we get a better % right of 86.1%. Therefore, the prediction ability of the logit model can be improved by estimating the appropriate value of β.

In fact, a river levee is mainly built of soils found along the river and is very long so as not to be broken at any section; thus the probability according to a model that a levee will suffer

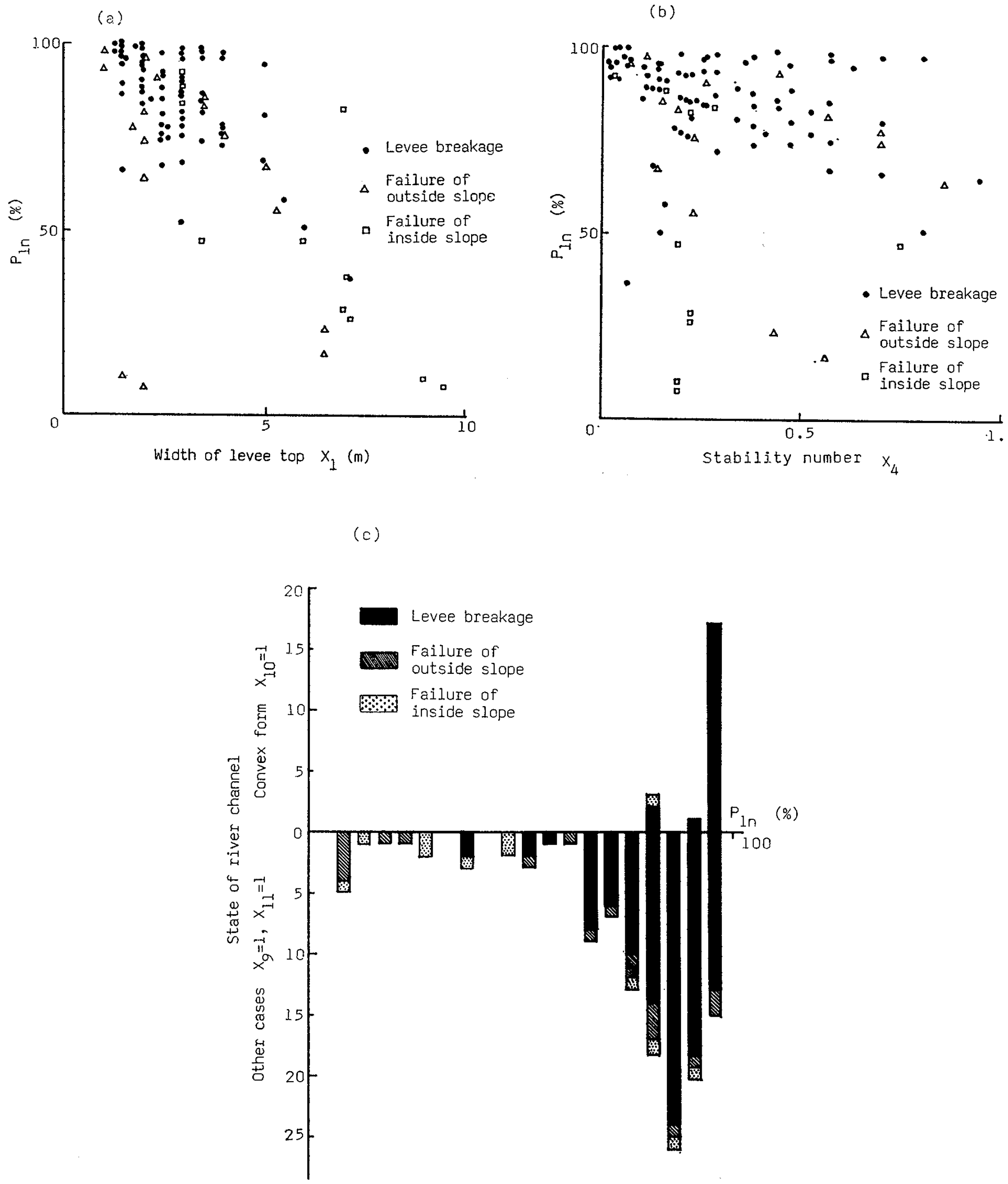

Fig. 8 Effect of factors on the probability of collapse; model 2. (a) Width of the levee top (X_1); (b) Soil strength parameter, stability number (X_4); and (c) State of the river channel, convex form (X_{10}).

damage at a given section should be very slight. Otherwise, the model is badly formulated. We have estimated here the probability by logit model using the data of actually damaged levees, and in general such adjustments as those above will be necessary when applying the obtained models to other river levees.

6.2. *Transferability of Model* 4 *to a Different Levee*

Model 4 is formulated for a large-scale levee on the Nagara River. We also collected data on the levee of the Ijira River (a branch of the Nagara River) for the same disaster period as when the data for model 4 were sampled. This is based on the consideration that the rainfall effect on these levees should be nearly equivalent because the collection positions for the two sets of

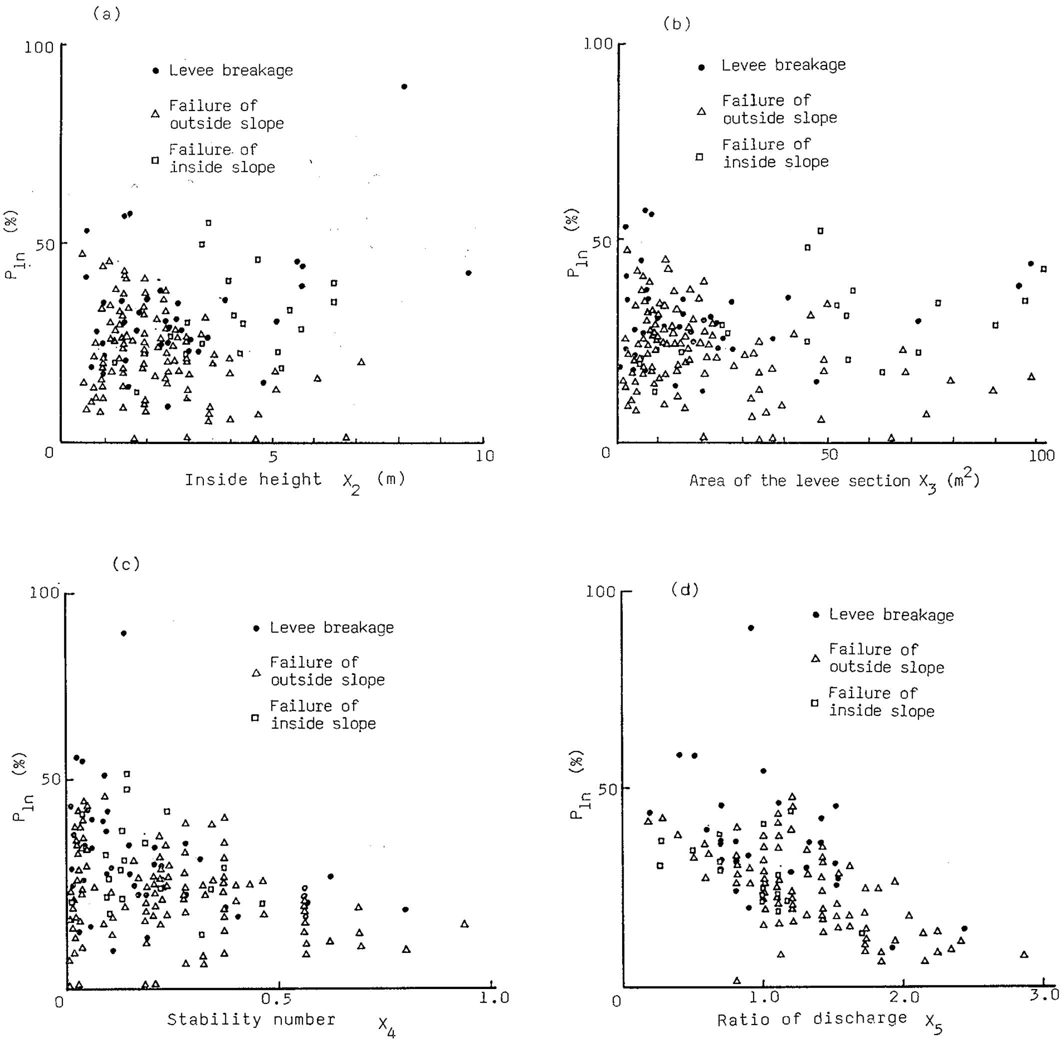

Fig. 9 Effect of factors on the probability of collapse; model 3. (a) Inside height (X_2), (b) Area of the levee section (X_3), (c) Stability number (X_4), and (d) Ratio of discharge (X_5).

data were only a few kilometers apart. In the Ijira River we investigated and collected data for 30 sections at intervals of 400 m. This data contains 9 samples of outside or inside slope failure and 21 samples of no failure, the sharing rate of collapse being 9/30=0.30. The sharing rate in the data for model 4 is 36/123=0.29 (Table 1). Although there is little difference between the sharing rates, we investigated the direct transferability of model 4 to the Ijira River levee. The estimated results shown in Fig. 11 indicate that there is very good agreement between the actual positions of slope failure and sections that had more than a 50% estimated probability of collapse. The logit model therefore provides a useful method for evaluating the possibility of levee collapse.

7. CONCLUSIONS

We made a trial application of a binary logit model to a stability evaluation of river levees and formulated models for middle/small and large-scale levees. Although there is still the problem of whether our eleven selected characteristic factors (variables) are the best, the predictability and transferability of the logit model were sufficiently good to show a high possibility of making

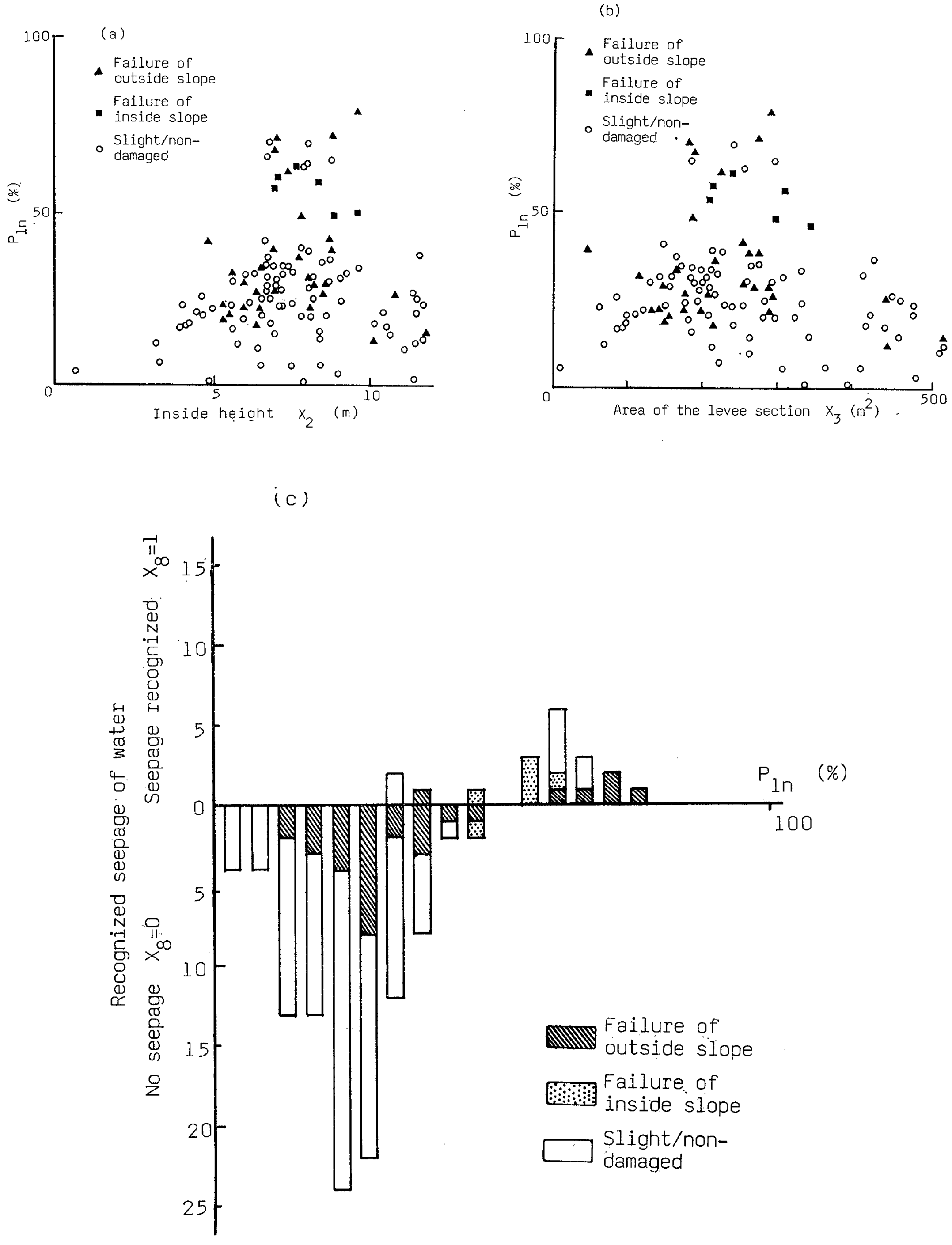

Fig. 10 Effect of factors on the probability of collapse; model 4. (a) Inside height (X_2), (b) Area of the levee section (X_3), and (c) Recognized seepage water (X_8).

stability evaluations for river levees in Japan.

For the logit model to show its characteristic utility, it is important to judge which and how many characteristic factors (variables) affect the stability evaluation. Three or four factors were adopted as a result of our binary logit model analysis, which seems to be similar to the field of transportation analysis. Alternative dummy variables (e.g., water seeping through the levee and its foundation) which are considered important factors on empirical grounds can have an important function in the stability evaluation.

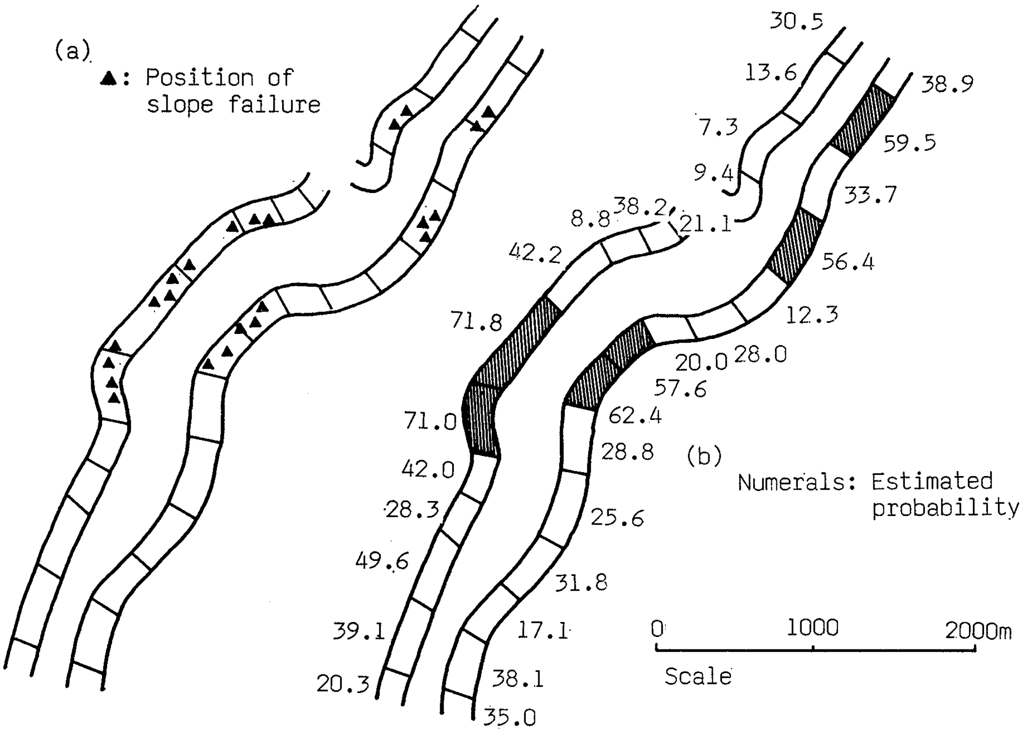

Fig. 11 Correspondence of actual positions of slope failure to sectional positions that had more than a 50% estimated probability of collapse.
(a) Actual positions; (b) Estimated probability.

The great merit of using a logit model is that stability is simply expressed by the probability of collapse, in accordance with the purpose of discriminating cases of collapse from those of no collapse.

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