STRATEGY ON THE LANDSLIDE TYPE ANALYSIS BASED ON THE EXPERT KNOWLEDGE AND THE QUANTITATIVE PREDICTION MODEL

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ABSTRACT

This paper discusses the applicability of analysis on the "landslide types" based on the quantitative prediction model for landslide hazard mapping. The quantitative prediction model used in this study construct the relationship between the past landslide occurrences and various kinds of geographical information termed "causal factors". One of the strong demands of the experts working on the landslide is to analyze the "different types of landslides", through the prediction models. Based on a previous study, it was decided to use a fuzzy-set theory model (using algebraic sum operator) for analysis among many integration tools. The analytical procedure was divided into the following two stages:

- Comparison of the prediction maps produced by the prediction model, with respect to the various landslide types, such as scarp collapse, rotational landslide, translational landslide, flow and flowslide.
- Comparison between the prediction maps and the hazard map made by the geomorphologist.

In these analyses, two kinds of difference maps (termed DIF map-A and DIF map-B) were provided. The DIF map-A is made by the two prediction maps with respect to the different landslide types, while the DIF map-B is made by each prediction map and the hazard map produced by the geomorphologist. Based on the experiment for the Alpago region in Italy, it is indicated that the hazardous area affected by the different landslide types could be analyzed through the DIF map-A, furthermore, the DIF map-B taking account of the expert's opinion is effective to find out the hazardous area with respect to the landslide types.

1. INTRODUCTION

About one quarter of the natural disasters in the world seems to be directly or indirectly related to landslides, due to rainfall, local downpour, earthquakes and volcanic activities, etc (Hansen, 1984). "When, Where and What scale " of landslides are important aspects in prediction. The problem is especially critical in developing countries where warning and protection measures are particularly difficult to implement due to the limitation of economic conditions. Many research activities have been carried out for landslide prediction, using various kinds of spatial map data (e.g. Carrara, 1983; Chung et al., 1995, 1999; van Westen, 1993; Wan, 1992). Recently, satellite remote sensing data are also applied to the slope stability evaluation (Obayashi et al., 1991, 1999).

As accumulating the results of these studies, one of the strong demands of the experts working on the landslide is to analyze the prediction maps with respect to "different types of landslides", based on such quantitative prediction models, and to apply these results for the practical landslide prevention plans. However, under the circumstances, it is difficult to draw a conclusion on the "best prediction results" on even specific type of landslide (Carrara, 1995, 1998), much more on the various types of landslides. In tackling these issues, the following points should be considered:

- Comparison of the prediction maps produced by the quantitative prediction model, with respect to the various landslide types.
- Comparison between the prediction maps and the hazard map made by the geomorphologist.

Based on above background, the following objectives are identified in this study:

- To provide a systematic analytical procedure on the landslide types, based on the quantitative prediction model for optimizing the prediction results.
- To interpret the prediction results and to provide the "supporting information", based on the difference map (termed DIF map) for landslide prevention plans.

2. STUDY AREA, SPATIAL INPUT DATA SET AND PREDICTION MODEL

2.1 Study Area and Spatial Input Data Set

The study area is located on the east of Belluno (north-eastern Pre-Alps). van Westen(1993) constructed the data base of

Table 1 Causal factors used in this study

(a) The causal factor group made by experts

1. Surface materials

1 : ablation moraine
2 : ablation moraine and flysch mixed
3 : alluvial deposits
4 : calcareous rocks with thin or absent weathering soil
5 : cemented scree mainly from calcareous rocks
6 : colluvium
7 : fluvio glacial deposits
8 : flysch rocks with thin or absent weatherig soil
9 : landslide material(undifferentiated)
10 : landslide material from flysch
11 : landslide material from moraine
12 : landslide material from moraine & flysch
13 : landslide material from scree & flysch
14 : landslide material from subglacial till
15 : landslide material from weathered flysch
16 : moraine(undifferentiated)
17 : rockfall material mainly from calcareous rocks
18 : scree mainly from calcareous rocks
19 : subglacial till
20 : ablation moraine
21 : ablation moraine & flysch

2. Bedrock

1 : calcareous rocks
2 : flysch

3. Distance from house

1 : 0 m - 25 m
2 : <= 25 m

4. Distance from drainage line

1 : 0 m - 25 m
2 : 25 m - 50 m
3 : <= 50 m

5. Distance from paved road

1 : 0 m - 25 m
2 : 25 m - 50 m
3 : <= 50 m

6. landuse

1 : bare
2 : bare & shrubs
3 : forest
4 : forest(young)
5 : grass
6 : grass & agric
7 : grass(swampy)
8 : settlement
9 : shrubs

(b) The causal factor group made by the DEM(Digital Elevation Model)

7. Elevation

1 : 0 - 150
2 : 150 - 300
3 : 300 - 450
4 : 450 - 600
5 : 600 - 750
6 : 750 - 900
7 : 900 - 1050
8 : 1050 - 1200
9 : 1200 - 1350
10 : 1350 - 1500
11 : 1500 - 1650
(Unit : m)

8. Relief

1 : 0 - 5
2 : 5 - 10
3 : 10 - 15
4 : 15 - 20
5 : 20 - 25
6 : 25 - 30
7 : 30 - 35
8 : 35 -
(Unit : m)

9. Slope

1 : 0 - 5
2 : 5 - 10
3 : 10 - 15
4 : 15 - 20
5 : 20 - 25
6 : 25 - 30
7 : 30 - 35
8 : 35 - 40
9 : 40 - 45
10 : 45 - 50
11 : 50 - 55
12 : 55 - 60
13 : 60 - (Unit : m)

10. Aspect

1 : N
2 : NNE
3 : NE
4 : ENE
5 : E
6 : ESE
7 : SE
8 : SSE
9 : S
10 : SSW
11 : SW
12 : WSW
13 : W
14 : WNW
15 : NW
16 : NNW
17 : Flat

Note 1) "xx - xx" on the value means "more than or equal to xx - less than xx".
2) The pixels correspond to 6 m x 6 m area on the ground.

this region including the information on the landslide types. Based on these results, the following five types of landslides were selected as the training data sets: (1) Scarp collapse, (2)Rotational landslide, (3) Translational landslide, (4) Flowslide and (5) Flow.

The quantitative prediction model constructed the relationship between these training data sets and the following ten “causal factors": (1) Surface materials, (2) Bedrock, (3) Distance from house, (4) Distance from drainage line, (5) Distance from paved road, (6) land use, (7) Elevation, (8) Relief, (9) Slope and (10) Aspect. The latter four factors were produced by using DEM (Digital Elevation Model). Each map consists of 819×933 pixels (about 4.9 Km×5.5 Km, 6m/pixels). **Table 1** shows the categories of these causal factors.

2.2 Quantitative Prediction Model

Figure 1 shows the analytical concept of the quantitative prediction model. Chung and Fabbri (1993) have adopted the formulas for geologic hazard zonation as a part of "favourability function" approaches, and the method has been applied to landslide prediction. Kojima and Chung (1997) have also investigated the performance of the several quantitative prediction models and presented the strategy for application of prediction models.

Through these research results, a fuzzy-set theory model using the algebraic sum operator (gamma=1) was selected in this study. The paper presented the details of the quantitative prediction models based on the favourability function" approaches is available for reference (Chung and fabbri, 1999)

.3. ANALYTICAL PROCEDURE

The analytical procedure on the landslide types provided in this study consists of five steps, as shown in **Figure 2**, and explained below;

Step1) Preparation of causal factors and the training data sets: The causal factors and the past landslide occurrences (termed training data) were prepared. In this study, ten kinds of causal factors and four training data sets of different landslide types were prepared by the ITC team.

Step2) Making the prediction maps: The prediction maps were produced, based on the training data sets of different landslide types, respectively. As a quantitative indicator, the "success rate" is calculated with respect to the past landslide occurrences used as the training data set. The success rate is used to evaluate the performance of the prediction model itself.

Step3) Comparison of the prediction maps with respect to the different landslide types: Difference maps (termed "DIF map-A") for all possible pairs of the prediction maps were produced. The "match rate" is defined as a quantitative indicator for these DIF maps. Through DIF maps and match rates, as well as success rate, hazardous area with respect to the "different landslide types" is analyzed.

Step4) Comparison between the prediction maps and the hazard map made by experts: As for the another essential analysis, we made the difference maps (termed "DIF map-B") between the prediction maps(made by the prediction model) and the hazard map made by experts(i.e., geomorphologist), and analyze these DIF maps from the viewpoints of the expert's.

Step5) Comprehensive evaluation: Based on the interpretation of both DIF map-A and DIF map-B, the hazardous area with respect to the "different landslide types" is identified. As the final product, we specified the DIF map and its interpretation are useful for investigating the hazardous area with respect to different landslide types.

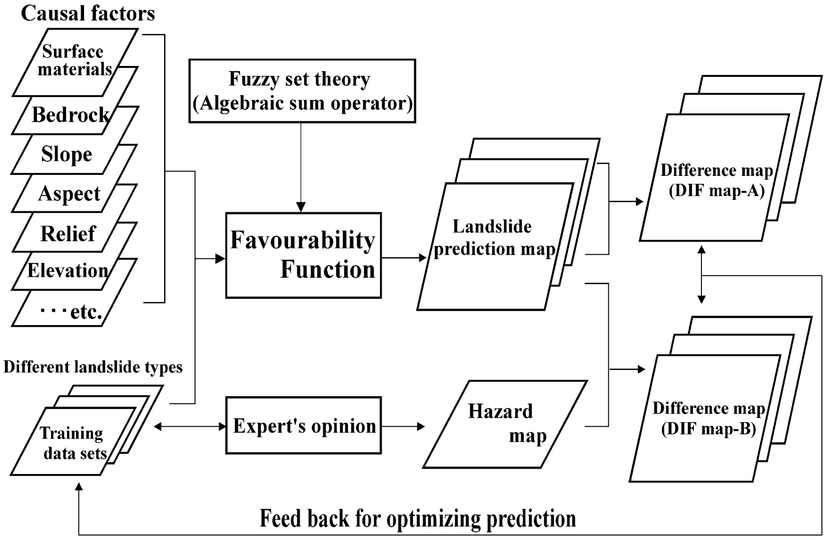


Figure 1 Concept of the prediction model

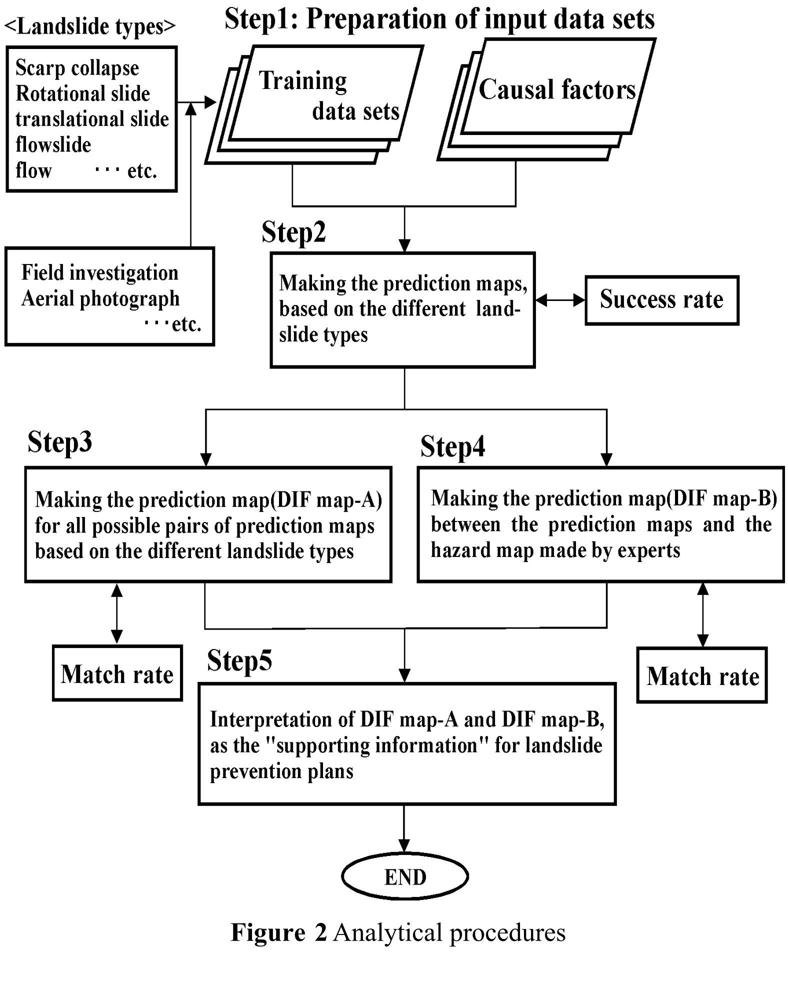


Figure 2 Analytical procedures

4. PERFORMANCE OF THE QUANTITATIVE PREDICTION MODELS

A prediction map was constructed by computing prediction values for the whole study area, which are sorted according to descending order, and the pixels are divided into nine classes depending in the sorted values. These nine classes from each model were used to evaluate the performance of the prediction results. The first class consists of the 76,412 pixels(10% of the whole area) having the highest predicted values were classified as "dangerous area". The remaining

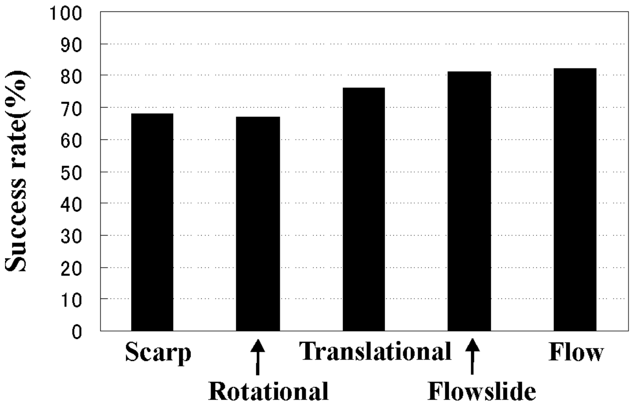


Figure 3 Success rate for the pixels with highest 10% of estimated values out of total pixels

Table 2 Combination of events in the different map

Combination of events		Map-2 Hazardous	Map-2 Non-hazardous
Map-1	Hazardous	Case-1(Red)	Case-2(Yellow)
	Non-hazardous	Case-3(Green)	Case-4(Blue)

Notes) Map-1 and Map-2 correspond to the different kinds of maps, such as the prediction maps and the hazard map made by the prediction model and the experts, respectively.

eight classes consisting of 687,715 pixels were together classified as "non-dangerous area". These two sub-areas, "dangerous" and "non-dangerous" area were used for the pair-wise comparative studies of the prediction maps based on the training data sets of the five kinds of landslide types.

For each prediction map, the nine classes were compared with the occurrences of the past landslides to evaluate the prediction results. Also, the number of pixels affected by the past landslides in each class was counted. The cumulative distribution function of past landslides, termed "success rates" with respect to the corresponding nine classes is calculated. If the prediction results is "reasonably good", then the success rate of the corresponding first class, defined as "dangerous area", should be much higher than 10%.

Figure 3 shows the success rates for the pixels with highest 10% of estimated values out of total pixels. As a whole, the high success rates(as given over 65% in **Figure 3**) derived for all landslide types. Especially, the success rates of over 80 % come from the "Flow and Flowslide". These results illustrated how the prediction model performed well with respect to each training data set on the different landslide types.

5. LANDSLIDE TYPES ANALYSIS BASED ON THE QUANTITATIVE PREDICTION MODEL

5.1 Pair-Wise Comparison of Prediction Maps

To evaluate the results of the prediction model, as an example, let us consider the prediction "map-1" and "map-2" with respect to the different landslide types. Based on the combination of results between map-1 and map-2, pixels were classified into four groups (Case-1 to Case-4) as shown in **Table 2**, and displayed on the DIF map. The descriptions on these cases are as follows:

Case-1: The pixels identified as hazardous in both map-1 and map-2 are assigned "3". On the DIF map, these pixels are colored "Red".
Case-2: The pixels identified as hazardous in map-1, but as non-hazardous in map-2, are assigned "2". On the DIF map, these pixels are colored "Yellow".
Case-3: The pixels identified as non-hazardous in map-1, but as hazardous in map-2, are assigned "1". On the DIF map, these pixels are colored "Green".
Case-4: The pixels identified as non-hazardous in both map-1 and map-2 are assigned "0". On the DIF map, these pixels are colored "Blue".

To analyze prediction results with respect to different landslide types, the "Difference (DIF) maps (termed DIF map-A)" for all possible pairs of the prediction maps were produced. To evaluate a DIF map, the following "match rate" is defined:

Match rate = # of red pixels/(Total pixels- # of blue pixels) (1)

If two maps match perfectly, then the match rate = 1. If two maps do not match at all, then the match rate = 0. Higher match rate means similar results of the two maps for whole study area. In other words, the land condition on the landslide occurrences may be similar. All match rates for all possible pairs of the

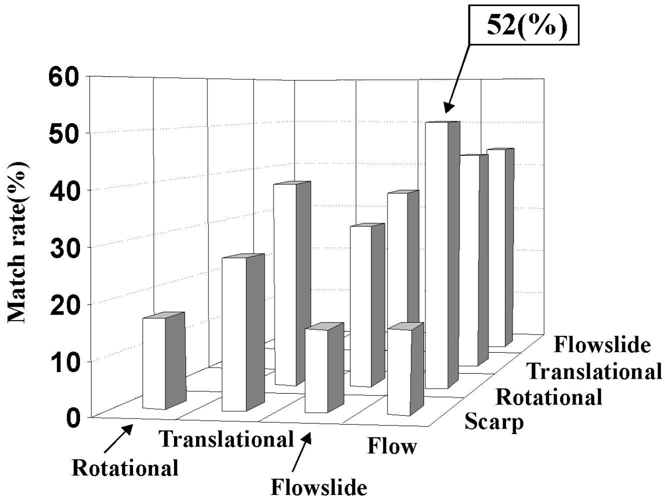
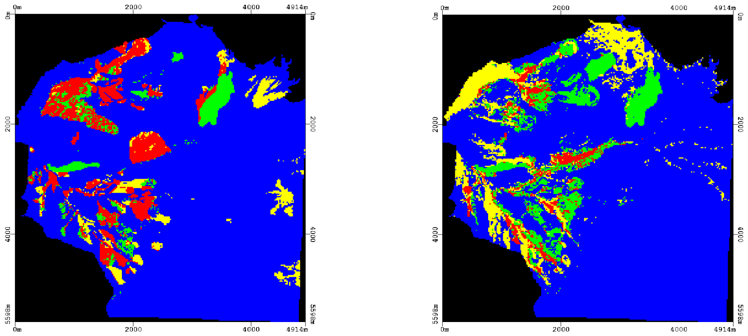


Figure 4 Match rates for all possible pairs of the prediction maps with respect to the different landslide types

prediction maps are illustrated in **Figure 4**. From these results, the following points could be indicated:

The highest match rate of 52% comes from the DIF map of "Flow vs. Rotational slide". Also, the match rates of "Flow vs. Translational" and "Flow vs. Flowslide" are higher than the other match rates. This result suggests that the land-condition on the landslide occurrence area may be similar in terms of causal factors, which is important information from the viewpoints of the periodicity of the landslide occurrences. It is obvious that match rates of "Scarp collapse vs. other landslide types" are lower than the other match rates. This corroborates that the land condition on “Scarp collapse” might be considerably different for the other types of landslide occurrences in this study area.



(a)Rotational landslide vs. Flow (Match rate=52%) **(b)Scarp collapse vs. Flowslide (Match rate=15%)**

<Interpretation of difference map of "Map-1 vs. Map-2">

Colors on DIF map	Map-1	Map-2	Interpretation	Assessment
	Hazardous	Hazardous	Hazardous area affected by both landslide types	Safe side
	Hazardous	Non-hazardous	Hazardous area affected by the landslide type-1	Risky side
	Non-hazardous	Hazardous	Hazardous area affected by the landslide type-2	Risky side
	Non-hazardous	Non-hazardous	——	——

Note) Map-1 is made, based on the training data sets of the landslide type-1.
Map-2 is made, based on the training data sets of the landslide type-2.

Plate 1 Example of the Difference map (DIF map-A) and its interpretation

5.2 Interpretation of the Difference Map (DIF map-A)

Plate 1 shows the examples of the DIF map-A of "Rotational landslide vs. Flow" and "Scarp collapse vs. Flowslide" with the highest and the lowest match rate, respectively. At a glance, the spatial patterns on the DIF maps are fairly different. As for the interpretation of the DIF map-A, let us focus on **Plate 1(a)** of " Rotational landslide vs. Flow". Assuming that the two prediction maps provide "good prediction" results (e.g., higher success rates as shown in **Figure 3**), the red pixels in the DIF map can be interpreted as having a higher possibility on the future occurrences of "both landslide types". The yellow and green pixels in the DIF map mean obscure results on future landslide occurrences with respect to the different landslide types. However, from another point of view, the yellow and green pixels may be regarded as the hazardous area on the future "Rotational landslide" and "Flow", respectively.

Another way to look at the red pixels is that the characterization of the past landslide occurrences using the causal factors, based on two kinds of landslide types, provides the same prediction results. Hence, from the viewpoint of an investigator, they can be regarded as "Safe-side assessment" sub-area. On the other hands, the yellow and green pixels in the DIF map are defined as "Risky-side assessment" sub-area, which means that these pixels may contain obscure reasons on the "type of the landslide phenomena". Such supporting information is essential for decision making in the landslide prevention plans as a pre-assessment.

6. EXPERT KNOWLEDGE-BASED LANDSLIDE TYPE ANALYSIS

6.1 Comparison between the Prediction Maps and the Expert's Opinion

As another essential evaluation procedure, we compare the prediction maps with the hazard map made by the experts of the ITC team. **Plate 2** shows this hazard map. The definition of the hazard classes is as follows:

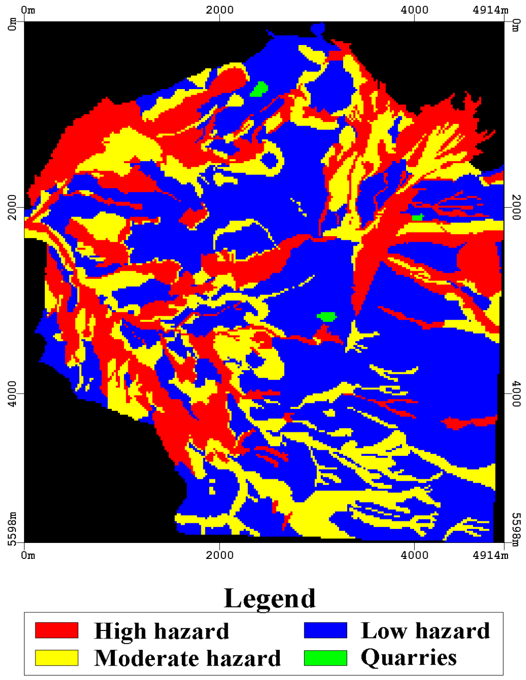
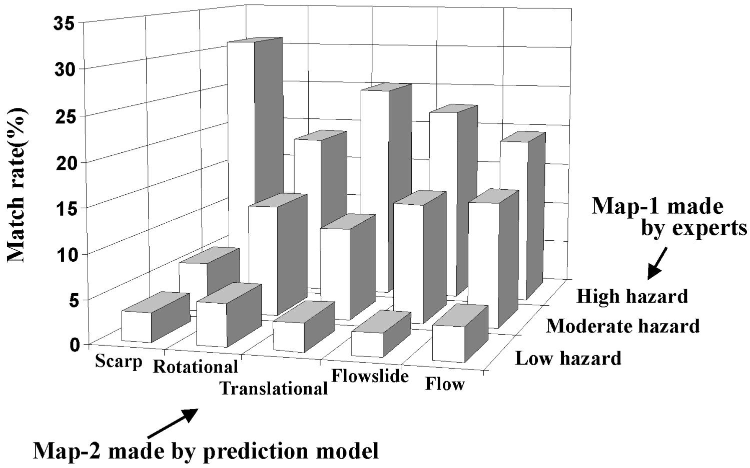


Plate 2 Geomorphologic hazard map produced by the ITC team

- **Low hazard area:** In these areas no destructive phenomena (landslides, rock fall, inundation) are expected to occur within the coming decade, given that the land use situation remains the same. However, inadequate construction of infrastructure or buildings may lead to problems.
- **Moderate hazard area:** In these areas there is a moderate probability that destructive phenomena will occur that may damage existing infrastructure or buildings. However, the damage is expected to be localized and can be prevented or evaded by relatively simple stabilization measures.
- **High hazard area:** In these area there is a high probability that destructive phenomena will occur. These are expected to damage infrastructure or buildings considerably. It is advised not to construct new infrastructure or buildings, or at least only after detailed field investigation.



Note 1) Map-1 is the geomophological hazard map made by the ITC team, based on the interpretation of the aerial photograph and the field investigation.
2) Map-2 is the prediction maps made by the quantitative prediction model, with respect to the different landslide types.

Figure 5 Match rate between the hazard map made by the ITC team and the prediction maps with respect to the different landslide types

Figure 5 shows the match rates between above each hazard area and the prediction maps with respect to the different landslide types. The corresponding different maps (termed DIF map-B) for all pair-wise comparison were illustrated in **Plate 3**. In making the DIF maps, as shown in **Table 2** before, note that "Map-1" correspond to the "hazard map" made by experts, and "Map-2" correspond to the "prediction maps" made by quantitative prediction models. These results indicated:

- All match rates are less than 35 %. However, as a whole, we can observe the higher match rates for the high hazard area based on the expert's opinion, among the other pair-wise comparison cases.
- It was found that the lower the level of hazard based on the expert's opinion, the lower the match rates is observed. From this tendency, the prediction model may be used for such pair-wise comparison and analysis with the expert's opinion.

As mentioned before, note that it may not be possible to draw the "precise" prediction results. As one of measures, let us consider on the "interpretation" of the DIF map-B for applying to enforcement plans of landslide prevention.

6.2 Interpretation of the Difference Map (DIF map-B)

As for the interpretation of the DIF map-B, let us take an example of the DIF map-B between "high hazard area" and "scarp collapse"(shown in **Plate 3(a)**). Assuming that the prediction map and the hazard map are reliable with some degree of confidence interval, the red pixels in the DIF map-B can be interpreted as having a higher possibility on the future occurrences of scarp collapse, in terms of the information of the prediction map and the expert's opinion.

The yellow and green pixels in the DIF map-B means the difference between prediction results and expert's opinion, in practice, which is obscure information for the investigator. However, from other viewpoints, it should become effective information, because yellow and green pixels can be interpret as the hazardous area based on the "expert's opinion" and the results of "prediction maps", respectively. So, in the same way as the interpretation of the DIF map-A as mentioned before, the yellow and green pixels in the DIF map-B can be regarded as "Risky-side assessment" sub-area. Also, the red pixels are defined as "Safe-side assessment" sub-area. **Table 3** shows these interpretations of the DIF map-B. To verify the effectiveness of DIF map-B shown in **Plate 3**, let us focus on the several parts of **Plate 3(a)** marked with the characters from "A" to "E"(say "area-A"-"area-E"). For these parts, the following points could be indicated:

- The area-A shows the "red pixels", which means the prediction results and the expert's opinion are matched as "High hazardous". From **Plate 3(a)** to **Plate 3(e)**, it is found that all areas corresponding to the area-A indicate the "hazardous", so it could be suggested that this area-A has a higher possibility in the future landslide occurrences.
- As for the area-B, we can also observe the "red pixels" in **Plate 3(a)** and **Plate 3(c)** as well. This area-B might be in danger of either "scarps collapse" or "translational landslide" in terms of both expert's opinion and the results of prediction model.

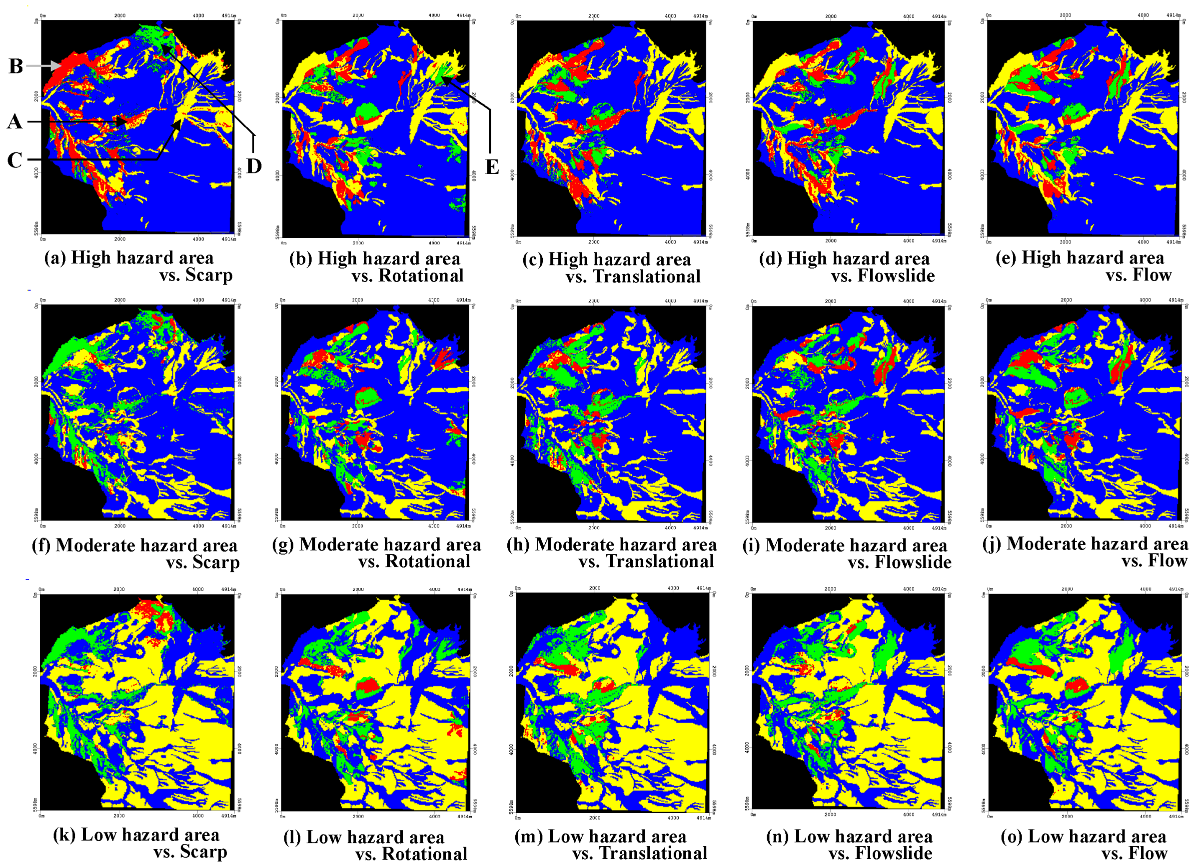


Plate 3 The difference map (termed DIF map-B) between the hazard map made by the ITC team and the prediction maps with respect to the different landslide types (cf. **Table 3** for the legend of DIF maps)

Table 3 Interpretation of the difference map (DIF map-B) of "Map-1 vs. Map-2"

Colors on DIF map	Map-1	Map-2	Interpretation	Assessment
(red)	Hazardous	Hazardous	Hazardous area indicated by both the prediction model and the expert's opinion	Safe side
(yellow)	Hazardous	Non-hazardous	Hazardous area indicated by the expert's opinion	Risky side
(green)	Non-hazardous	Hazardous	Hazardous area indicated by the prediction model	Risky side
(blue)	Non-hazardous	Non-hazardous	—	—

Note) Map-1(hazard map) is made by the expert's opinion.
Map-2(prediction map) is made by the prediction model.

- The area-C shows the "yellow pixels", which means this area is observed as "hazardous" by the expert's opinion, but not as "hazardous" by the prediction model. Further investigation on the reasons why the result between expert's opinion and prediction model is in disagreement in the area-C.
- In **Plate 1(a)** and **Plate 1(b)**, the area-D and the area-E show the "green pixels", which means that these areas are regarded as "hazardous" by the prediction model, but as "non-hazardous" by the expert's opinion. For these areas, special attention should be paid as the "Risky-side" assessment sub-area, as shown in **Table 3**.
- Through the DIF map-A and DIF map-B, we can evolve the analysis on the different types of landslides, not only based on the pair-wise comparison of the prediction results, but also by introducing the expert's opinion with various points of view. Such a practical and flexible way on the analysis of the different types of landslides is essential for optimizing the prediction results as well as for supporting decision-making in the landslide prevention plans.

7. CONCLUDING REMARKS

In this contribution, we have discussed the applicability of analysis on the "landslide types" based on the quantitative prediction model for the landslide hazard mapping, and presented a strategy for the application of prediction results for the landslide prevention plans. The results of this study are summarized as follows:

- An analytical procedure shown in **Figure 2** is effective for evaluating the prediction results derived from "different landslide types". Due to the complicated phenomena on the landslide occurrences, such systematizing approach on the landslide-type analysis would be essential component to promote the prediction model.
- Through this procedure, it could be suggested that the land condition on the "scarp collapse" in this study area may be considerably different among other types of landslide occurrences. On the other hand, it is indicated that the land conditions of the "rotational landslide" and "flow slide" might be relatively similar, which is the important information on the analysis of periodicity on the landslide phenomena.
- As a final product for land-use planners, two kinds of difference maps (termed DIF map-A and DIF map-B) were provided. The DIF map-A is made by the two prediction maps based on the training data sets of the "different landslide types". The DIF map-B is made by each prediction map and the hazard map produced by the experts. Furthermore, "Risky-side" and "Safe-side" assessment sub-area, which have been discussed in the civil engineering field, were delineated on the DIF maps. Based on the DIF maps as "supporting information", we can evolve the analysis on the different types of landslides not only based on the pair-wise comparison of the prediction results, but also by introducing the expert's opinion with various view points.

As for the subsequent subjects, in order to corroborate the practicality of the analytical procedure presented in this study, the same investigation for other study area should be carried out. In this study, only four types of the active landslides were selected. As occasion demands of investigators, we can readily add the various training data sets of other landslide types in analysis. In this point of view, the analytical procedure (**Figure 2**) is expected to contribute to the landslide hazard assessment as one of the standards.

It may be impossible make the "precise prediction maps". As one of the measures, the analytical procedure presented in this study as well as the DIF map "as a supporting information" are effective in the process of identifying the hazardous area on the different types of landslides. Such a practical way is essential to optimize prediction, as well as to promote the various kinds of quantitative prediction models.

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