■ Hazard inspection for landslides on roads using quantification theory — A case study of the Abay Gorge in the Federal Democratic Republic of Ethiopia —

Takeshi KUWANO* / Kokusai Kogyo Co., Ltd.

Takashi HARA / OYO International Co., Ltd.

Fumihiko YOKOO / OYO International Co., Ltd.

Mitsuya ENOKIDA / Japan Conservation Engineers Co., Ltd.

Key words : landslide, hazard evaluation, slope disaster inspection, multivariate statistical analysis, international cooperation project

Abstract

Main road 3, a major arterial road in Ethiopia, steeply climbs nearly 1,500 meters over 40 kilometers through the Abay Gorge. It is plagued by landslides in the rainy season. Some of these are up to two kilometers wide, jeopardizing this vital link. To fundamentally solve this problem it is necessary to implement appropriate countermeasures after clarifying the mechanisms that trigger landslides in this stretch of road.

Therefore the authors have implemented a slope disaster inspection on roads to clarify the mechanisms in the Abay Gorge. To prepare the slope disaster inspection sheet in Ethiopia where there are few engineers who have experience on slope disaster inspection, the authors have discussed the factors and their contributions that affect on landslides and decided the item in the list on the slope disaster inspection sheet using multivariate statistical analysis, namely quantification theory.

Through the multivariate statistical analysis, the following was observed: 'result of aerial photo interpretation' and 'main rock formation of landslide body' should be paid attention, which affect the hazard of landslide greatly in the area. Based on the analysis, new evaluation sheets are proposed for the slope inspection on the roads, which are suitable to the conditions of geology and topography in Ethiopia. The authors have also ranked them into five levels from A (extremely high hazard) to E (lowest hazard) on the landslides in the Abay Gorge.

1. Introduction

In the Federal Democratic Republic of Ethiopia (hereinafter Ethiopia) (Figure 1), Main Road No. 3, one of the main trunk roads, is part of the African Transit Corridor connecting the capital Addis Ababa and the Republic of the Sudan, constituting an essential route for the life and economy of Ethiopia. A section of this route passes through the Abay River Gorge, a steep gorge with an elevation difference of about 1,500 me-

ters in a road length of 40.45 kilometers (Photo 1, 2), where serious landslides repetitiously occur in the rainy season, threatening the road function itself.^{1)~3)} Therefore, it is necessary to implement appropriate countermeasures after clarifying the mechanisms that trigger landslides in this stretch of road.

The Ethiopian Road Authority (hereinafter ERA) has responsibility to maintain the road and to take care of the landslide disasters. However it is difficult for engineers who have little experience on landslide investiga-

Fig. 1 Study area

*corresponding author
Kokusai Kogyo Co., Ltd, Disaster and Water Resources Management Division,
Rokuban-cho2, Chiyoda-ku, Tokyo, Japan, +81-3-6361-2452,
e-mail: kuwanota@gmail.com

Photo 1 Overview of the Abay Gorge

Photo 2 Winding road in the Abay Gorge

tion to clarify the mechanism and to evaluate the hazard.

With this background, the Government of Ethiopia asked the Government of Japan for technical help to enhance the capability of ERA to identify road slopes that require landslide management and to implement countermeasures. In response to the request, the Japan International Cooperation Agency (hereinafter JICA) decided to transfer the necessary technology to Ethiopia and to implement a technological cooperation project¹⁾ (Hereinafter the JICA Project).

In the JICA Project, a slope disaster inspection⁴⁾, which is one of the most significant hazard evaluation methods for landslides on major roads in Japan, has been performed on roads of Ethiopia. Moreover, standard formats for identifying and recording hazards including necessary check points are utilized for the slope disaster inspection. The check points in the formats were discussed with experienced engineers and authorized by the Road Management Technical Center.⁴⁾ The biggest advantage of the slope disaster inspection is to be able to check potential factors of landslides in a relatively short time by following the simplified formats. Therefore, the methodology is effective in the case that limited engineers conduct simple evaluation of the landslide hazards for innumerable slopes in several roads. Another advantage is that less variable results with the standard formats are obtained regardless of engineers' experience. Accordingly, it is conceivable that the slope disaster inspection is suitable to easily identify the hazards on landslides.

The slope disaster inspection should be used as a method of preliminary screening of the priority of landslides. The results can be used as a first step of detailed evaluation. The high-risk landslide hazard ar-

eas determined by the inspection should be investigated and monitored in detail after the screening.

In the JICA Project, to prepare the slope disaster inspection sheet in Ethiopia, where there are few engineers who have experience on landslide inspection, the authors have discussed the factors that may be correlated with landslide occurrence and the influence of each factor on each landslide. Furthermore, the items on the list for the slope disaster inspection sheet in Ethiopia were also decided using multivariate statistical analysis, namely quantification theory. This type of discussion helps the Ethiopian Government understand which features and conditions should be paid attention to accurately identify the hazard on landslides in Ethiopia.

Incidentally, though quantitative hazard evaluation by using the quantification theory has been conducted for slope disasters, those studies are targeted only for rockfalls and rock mass failures in Japan^{5)~10)} and slope disasters in the Kingdom of Bhutan¹¹⁾. In this study, the authors have analyzed on landslide, and proposed higher hazard items and the contributions on it in Ethiopia.

A landslide in this study is defined as follows. The landslide occurs on the slopes where the soil mass on one or more slip surfaces deep in the ground. The slipped land mass gradually and slowly shifts downward, triggered by one or several factors such as heavy rain, an earthquake, river erosion, and/or earthworks. The land mass moves forming specific topography, landslide topography, in a relatively large scale. The inclination of the landslide slope is relatively gentle in comparison with that of debris slope failure.

2. Study area

Main road 3, a major arterial road in Ethiopia, through the Abay Gorge has an elevation difference of 1,060 m over 40.45 kilometers between Goha Tsiyon and Dejen villages (Figure 2). The road along numerous steep cliffs is extremely winding in the gorge. The rainy season is from June to September, with July and August accounting for about 50% of annual precipitation. Annual average rainfall is 1,394 mm/year (from 49 years of average data) in Dejen and 1,195 mm/year (from 34 years of average data) in Filiklik Village²⁾. The geology is characterized by stratified sedimentary rocks capped by a basaltic plateau¹²⁾ (Figure 3). The area is plagued by landslides in the rainy season (Photo 3–6). Some of which are up to two kilometers wide, jeopardizing this vital link.

Fig. 2 Main Road No. 3 (bold line) passing through the Abay Gorge²⁾

Fig. 3 Schematic geological section in the Abay Gorge¹²⁾

According to a previous survey on landslides in the Abay Gorge by the Japanese Government²⁾, 167 potential landslide blocks were identified in the Abay Gorge. The hazards of which had been assessed with satellite image identification and site reconnaissance by Japanese geotechnical experts,²⁾ who have more than 30 years' experiences in landslide investigation and analysis at private consulting companies. Moreover, at least 90 landslides among the 167 are located on or crossed

Photo 3 Step by a landslide on the road

Photo 4 Vehicles stacked at landslide deformation

Photo 5 A broken church by a landslide

by a main road.

3. Landslide inspection

3.1 Inspection format

In order to enable Ethiopia to evaluate the hazard on road slopes, it is of great importance to develop a

4. Multivariate statistical analysis for landslides

4.1 Explanatory variables and dependent variables

The factors of landslide occurrence do not only depend on topographic features and geological conditions, but also on hydraulic condition and landslide history. These items intricately affect the factors of landslide occurrence. A quantification theory which is one type of multivariate statistical analysis facilitates analyses for these kinds of intricate data.

Explanatory variables are the results of the inspected items by the Ethiopian engineers for the 90 landslides of the JICA Project. Each item and category on the slope disaster inspection sheets were checked during the inspection of the 90 landslides.

Dependent variables are the sum score of ranks evaluated by the four Japanese experts of the JICA Project. The four Japanese experts independently conducted the evaluation of the 90 landslides based on aerial photo identification and site reconnaissance, and ranked them on a scale of 1 to 5 from the viewpoint of necessity of countermeasures. A score of 5 is defined as 'countermeasures are immediately needed,' because a landslide already happened and it is affecting the road traffic. Scores 4-2 are defined as 'countermeasures are preferable in the future,' because landslides could happen and affect the road traffic. A score of 1 is defined as 'countermeasures are not needed for now,' because potential deformation is minor and daily maintenance by ERA is sufficient to control the disaster. Thus, the higher the score (5-1) the higher the urgency of the countermeasure. The sum of the four Japanese experts' rankings, from 4 to 20, were used for the analysis as dependent variables.

4.2 Methodology of quantification theory

The quantification theory enables quantitative dependent variables to be predicted based on various qualitative explanatory variables. Dependent variables are the desired result of analyses. Explanatory variable items affect dependent variables. In this case, the explanatory variables are not quantitative data but qualitative

data such as topographic interpretation, surface anomalies and geological structure, etc. On the other hand, the dependent variable is the result of hazard evaluation which is classified into 4 to 20 ranks, by the experienced Japanese experts mentioned before.

Items and categories of the qualitative explanatory variables are as shown in the evaluation sheet in Table 1 for the analysis. In the JICA Project, items, which could affect the hazard of landslides, were picked up on the basis of the Japanese forms.⁴⁾ The categories were repeatedly calculated with changing the partition and classification of them on trial and error basis. The items and categories which are high correlation with other explanatory variables and low correlation with the dependent variable or theoretically contradicted, have been integrated and deleted through the calculation. As a result, the items and categories which are the highest correlation with the dependent variable in Ethiopia have been decided under the condition of the lowest multicollinearity.

In the quantification theory, each category should be allocated the numerical values so that the variable would be able to be calculated the same as a multiple regression analysis. The outline of the calculation method of the quantification theory is described as follows ; ¹⁰⁾

Hypothetically, the dependent variable and the answer of the category for each item are shown in Table 2.

Here, dummy variables are assigned to indicate which data corresponds to which category on each item.

$$\delta_i(jk) = \begin{cases} 1 \dots \text{In case that data } i \text{ corresponds to Category } k \text{ on Item } j \\ 0 \dots \text{In case of others} \end{cases} \quad \dots \dots \dots (1)$$

In the Table 2, the data No. 1 is $\delta_1(11) = 0$, $\delta_1(12) = 1$, $\delta_1(1c_1) = 0$, $\delta_1(21) = 1$, $\delta_1(22) = 0$, $\delta_1(2c_2) = 0$, $\delta_1(R1) = 0$, $\delta_1(R2) = 0$, and $\delta_1(Rc_R) = 1$. Based on this data, the following formula on the dummy variables is utilized to predict the dependent variables :

Table 1 Item and category on landslide in the Abay Gorge

Item	Category-1	Category-2	Category-3	Category-4	Category-5	Category-6	Category-7
Result of photo interpretation	exist clearly	exist but partial and not clear	exist but not clear				
Surface anomalies	large and new cracks, steps and subsidence	small and old cracks, steps and subsidence	slight deformation	no anomalies			
Geological structure	fault, fracture zone, dip slope	undip slope					
Main rock formation of landslide body	colluvial deposit	pyroclastic materials	basalt	limestone	gypsum	siltstone	sandstone
Hydrological feature	much springs / seepage	little springs / little seepage	surface water / trace of water	no water observed			
Existing record (documents, patrimony)	obvious	slight	none				
Damage on road facilities and houses	obvious	slight	none				

Table 2 Data format on the quantification theory

No. <i>i</i>	Item <i>j</i> Dependent variables	Category <i>k</i>		1		2				<i>R</i>	
		1	2 ... <i>c₁</i>	1	2 ... <i>c₂</i>	1	2 ... <i>c₂</i>	1	2 ... <i>c_R</i>	1	2 ... <i>c_R</i>
1	<i>y₁</i>	0	1 ... 0	1	0 ... 0					0	0 ... 1
2	<i>y₂</i>	1	0 ... 0	0	1 ... 0					0	1 ... 0
3	<i>y₃</i>	0	0 ... 1	0	0 ... 1					1	0 ... 0
⋮	⋮	⋮	⋮	⋮	⋮					⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮					⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮					⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮					⋮	⋮
<i>n</i>	<i>y_n</i>	1	0 ... 0	1	0 ... 0					0	0 ... 1

$$Y_i = a_{11}\delta_i(11) + a_{12}\delta_i(12) + \dots + a_{RC_R}\delta_i(RC_R) \\ = \sum_{j=1}^R \sum_{k=1}^{c_j} a_{jk}\delta_i(jk) \dots \dots \dots (2)$$

a_{jk} is a weighting factor of Category k on Item j , which is generally called a category score. a_{jk} should be calculated to match the predicted value Y_i to the actual value y_i , i. e. the following value should be minimized by the least-square method which is the same as regression analysis.

$$\sum_{i=1}^n (y_i - Y_i)^2 \dots \dots \dots (3)$$

The category score is a weighting factor of the items and directly affects the dependent variable. Therefore, a category range, which is defined as the difference between the maximum and minimum category score, is the degree of contribution to the dependent variable. To put it simply, the larger the category range of the item, the higher its contribution to the predicted value of the dependent variable.

A partial correlation coefficient, which is obtained with the above mentioned analyses, can be considered to be a correlation coefficient that does not influence other items. For example, a partial correlation coefficient r of three variables X , Y and Z is calculated as follows:

$$r = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{1 - r_{xz}^2}\sqrt{1 - r_{yz}^2}} \dots \dots \dots (4)$$

r_{xy} : correlation coefficient of variable X and Y

r_{xz} : correlation coefficient of variable X and Z

r_{yz} : correlation coefficient of variable Y and Z

5. Results of multivariate statistical analysis

The category scores are indicated in Figure 5 for the 90 landslides. The score is a coefficient that correlates to the contribution of the item, and it influences the dependent variable directly. The hazard on landslides is large when the category score is high, and

Fig. 5 Category score for landslides

conversely is small when the category score is low. For examples, 'fault, dip slope' is larger than 'undip slope' in 'Geological structure', which means that 'fault and dip slope' is more influence landsliding than 'undip slope' in the Abay Gorge.

The analysis assesses the hazard of each slope with disaster causes such as topographic features and geological conditions, and disaster history. As a result, factors and their contributions that affect the hazard on landslide have been ascertained.

Category ranges and partial correlation coefficients on each item are indicated in Table 3 for the landslides. The range indicates the contribution of the dependent variable. In other words, an item with a large range has a greater effect when predicting the dependent variable. Partial correlation coefficient is the index that shows the contribution of each item on the dependent variable. The nearer the absolute figure of the partial correlation coefficient to 1.0, the higher the contribution to the dependent variable.

The analysis leads to the results that 'main rock for-

Table 3 Category range and partial correlation coefficient for landslide

Item	Category range		Partial correlation coefficient	
Result of aerial photo interpretation	4.756	2nd	0.675	1st
Surface anomalies	2.583	5th	0.307	6th
Geological structure	0.030	7th	0.006	7th
Main rock formation of landslide body	4.888	1st	0.526	2nd
Hydrological feature	2.313	6th	0.313	5th
Existing record (documents, patrimony)	4.166	3rd	0.490	3rd
Damage on road facilities and houses	2.987	4th	0.406	4th

mation of landslide body' and 'result of aerial photo interpretation' affected the hazard of a landslide greatly, and the 'geological structure' seldom affected it. For the reasons mentioned above, the authors take into consideration the following. The landslides are highly concentrated on specific 'soft' layers, such as pyroclastic materials and silt stone in the area, while rockfalls are scattered on 'hard' layers of gypsum and sandstone. The contrast of development of the landslides seems to be extremely clear in the Abay Gorge. 'Main rock formation of landslide body' has high correlation with landsliding, and therefore results in having a higher score on the evaluation sheet. These 'soft' layers are also easy to deform by the movement of landslides; therefore, landslide topography tends not to have been developed or used such as for residential purposes. As a result, the topography can be easily identified using aerial photo interpretation. 'Geological structure', such as 'fault' and 'dip slope', tends to be mainly developed on the 'hard' layers with steep scarp and not on the 'soft' layers with gentle gradient slopes, which means that the geological structures have low relationship with the landslides in the Abay Gorge. Regardless of the presence or absence of the geological structures, it can be concluded that landslides frequently occur in the area.

6. Discussions

6.1 Prediction and accuracy

Figure 6 indicates scattered plots of the actual measurement values and the prediction values that analyzed using the quantification theory. While the measurement value is the hazard score by the four Japanese experts that the score 4 is lowest and 20 is highest, the prediction value is calculated by adding all category scores on each item in Figure 5. Coefficient of

Fig. 6 Scattered plot of the score on the slope disaster inspection

determination on the hazard on landslide is 0.74. The value indicates that regression formula has explained about 74% among the total variation in this analysis. Although the analysis was done by calculating the category scores on all items in this study, the coefficient of determination could be increased by deleting the lower affected items such as 'geological structure'. However it is necessary to discuss carefully the deletion, addition and/or integration of items because the assortment and the combination of the items would highly affect the results on multivariate statistical analysis in general.

6.2 Development of Ethiopian evaluation sheet

New evaluation sheets are proposed for the inspection of landslide, which are suitable to the conditions of geology and topography in the Abay Gorge in Ethiopia, by using a category score that directly affects the dependent variables. The scoring of the new evaluation sheet is based on the relative difference of the category score and has been adjusted as 99 points at a maximum.

ERA engineers in Ethiopia could utilize the evaluation sheets and evaluate the hazard of slope disasters on roads by checking the new evaluation sheets and assigning scores. The evaluation sheets are indicated in Figure 7.

6.3 High priority areas for countermeasures

The priority for landslide countermeasures has been discussed by the statistical analysis. As mentioned be-

[Causes] (A)

Category			Score
Topographical factor	Result of photo interpretation	Exist clearly	21
		Exist but partial and not clear	4
		Exist but not clear	0
	Surface anomalies	Significant cracks, steps and subsidence	12
		Slight deformation	5
		No anomalies	4
Geological conditions	Geological structure	Fault/fracture zone/dip slope	12
		Undip slope/no characteristic feature	7
	Main rock formation of landslide body	Colluvial deposit	8
		Soft rock (pyroclastic materials/siltstone)	18
		Hard rock (basalt/limestone/gypsum/shale/sandstone)	5
	Hydrological feature	Springs water/seepage	10
		Surface water/trace of surface water	9
		No water observed	7

[History] (B)

Category			Check
Records of Landslide	Existing record	Yes	10
		No	8
	Damage on road/house	Yes	16
		No	1

Fig. 7 New evaluation sheet for landslides in the Abay Gorge

Table 4 Hazard of the landslides in the Abay Gorge
 'Landslide No.' is identification numbers of the targeted 90 landslides. A : 75–, B : 65–74, C : 55–64, D : 45–54, E : –44 by the scores of the new evaluation sheet (99 points maximum)

Landslide No.	Score Sum	Hazard rank	Landslide No.	Score Sum	Hazard rank
00-01	36	E	13-07	81	A
00-04	38	E	13-08	62	C
00-07	79	A	14-01	60	C
00-08	94	A	14-03	36	E
00-09	73	B	17-01	47	D
01-02	40	E	17-02	36	E
01-03	43	E	18-01	62	C
01-04	41	E	19-01	55	C
01-06	52	D	19-02	47	D
01-08	54	D	20-01	45	D
01-09	67	B	21-01	62	C
01-12	60	C	21-02	83	A
01-13	50	D	21-03	72	B
01-14	66	B	21-05	71	B
02-01	51	D	21-06	70	B
02-03	70	B	22-01	86	A
02-06	67	B	22-03	65	B
02-09	69	B	25-01	65	B
03-01	49	D	26-01	65	B
03-02	51	D	26-08	86	A
03-03	47	D	27-01	88	A
03-04	48	D	27-02	69	B
03-05	55	C	27-03	69	B
05-01	89	A	27-04	88	A
05-02	57	C	28-01	88	A
05-07	69	B	28-04	82	A
05-08	79	A	28-05	92	A
05-09	35	E	28-06	77	A
05-10	56	C	30-01	63	C
06-03	47	D	30-02	55	C
06-05	45	D	30-03	56	C
07-01	49	D	30-04	71	B
07-05	68	B	30-05	74	B
07-09	56	C	31-01	84	A
07-11	39	E	31-02	58	C
07-14	42	E	31-03	65	B
08-03	38	E	31-04	64	C
10-01	65	B	31-05	77	A
10-04	89	A	31-06	50	D
10-05	89	A	31-07	73	B
10-06	72	B	32-01	62	C
11-01	36	E	33-01	70	B
13-01	60	C	33-02	69	B
13-03	67	B	33-03	70	B
13-04	67	B	35-01	64	C

fore, the category score of each category is a coefficient that correlates to the contribution of the landslide. The sum of each score indicates the hazard of the landslide. The higher the score, the higher the haz-

ard; that means the landslide has a higher priority for countermeasures. The hazard rank of the landslide area in the Abay Gorge was classified A to E; A is 75–, B is 65–74, C is 55–64, D is 45–54 and E is –44, as shown in Table 4, whereby A is highest hazard area and E is lowest, based on the summed scores of the new evaluation sheet in Figure 7.

7. Summary and future plans

Through the multivariate statistical analysis in this study, the following was observed: 'result of aerial photo interpretation' and 'main rock formation of landslide body' should be paid attention, which affect the hazard of landslide greatly in the area. Coefficient of determination on the hazard of landslide is 0.74, utilizing significant items and categories. These coefficients indicate that it is good accuracy for the prediction of the hazard. Based on the analysis results, new evaluation sheets have been proposed for the slope disaster inspection on the roads, which are suitable to the conditions of geology and topography in Ethiopia, and the hazard on the landslide area were classified A to E with the summed category scores.

However, the analysis was implemented by using only 90 data in the limited roads. Therefore, continuous inspection and the hazard evaluation are necessary to consider creating a road master plan for development of the country. Data accumulation of the evaluation sheets is important for the continuous inspection to improve the accuracy of hazard evaluation on landslide.

As the next step after the evaluation, it is necessary to investigate accurate hazard and risk condition by drilling surveys and monitoring. The actual priority for the landslide countermeasures should be finalized taking into consideration the difficulty and feasibility of design and construction, the budget, and the request of the users.

The authors also suggest applying standards and methodologies of Japan in other developing countries through future projects. The biggest problems of developing countries are that there is a lack of budget and human resources. Regardless of high motivation of engineers in the developing countries, the lack of these two indispensable factors would be a trigger of the lack of technique, knowledge, tools, time, data, and co-operation with the related organizations. Therefore, sustainable technical transfer with a limited budget should be considered. The Japanese standards and methodology of slope disaster inspection that do not in-

volve a high cost or complicated equipment or technology, that are simple and easy for the counterparts to conduct and that are ubiquitous, should be transferred. Repeated trainings/seminars, handbooks/guidelines with enough figures/tables/photos and voluntary presentation by the counterparts are also inevitable for the counterparts to gain an understanding of the standards and methodology of slope disaster inspection. Needless to say, it is important when conducting such technological transfer and training of counterparts for the Japanese experts to have an understanding of the local culture and respect of religious beliefs and customs.

Acknowledgment

Our appreciation goes to Mr. Satoru Tsukamoto of Kokusai Kogyo Co., Ltd. Without his cooperative discussion, we could not have completed this study.

We would like to offer our special thanks to JICA and ERA. This study is based on one of the activities of the 'Capacity development project for countermeasure works for landslide in the Federal Republic of Ethiopia' financed by JICA in 2011 – 2016.

References

- 1) JICA (2016) : Final report, The capacity development project for countermeasure works for landslide in the Federal Republic of Ethiopia.
- 2) JICA (2012) : Final report, The project for developing countermeasures against landslides in the Abay Gorge in the Federal Republic of Ethiopia.
- 3) Enokida, M., Tsukamoto, S., Ichikawa, K. and Ichikawa, Y. (2015) : Landslide control technology transfer and challenges in Ethiopia, Journal of Japan Landslide Society, Vol. 52, No. 4, pp. 20 – 24. (in Japanese)
- 4) Road Management Technical Center (1996) : Creation and Operation Guide of Disaster Risk Management Record. (in Japanese)
- 5) Murakami, Y. and Yanai, K (1989) : The analysis of boulder-fall by the method of quantification and its application to the prediction, Japan Society of Civil Engineers, No. 406, III – 11, pp. 223 – 231. (in Japanese with English abstract)
- 6) Murakami, Y., Gomi, S. and Tsuchikura, T. (1992) : Estimation for the possibility of rockfalls through a marking method based on quantification analysis, Japan Society of Civil Engineers, No. 444, IV – 16, pp. 147 – 152. (in Japanese with English abstract)
- 7) Hashimoto, S., Kikuchi, H. and Mito, Y. (1998) : The rock evaluation method analyzed by quantification theory – Using a Sea of Japan Coast area in Hokkaido as an example –, Monthly report, Civil Engineering Research Institute for Cold Region, No. 545, pp. 8 – 16. (in Japanese with English abstract)
- 8) Hashimoto, S., Kikuchi, H. and Mito, Y. (1999) : The rock evaluation method analyzed by quantification theory, Part 2 – Analysis of the Cape Erimo Area in Hokkaido –, Monthly report, Civil Engineering Research Institute for Cold Region, No. 555, pp. 9 – 18. (in Japanese with English abstract)
- 9) Mito, Y., Aizawa, T. and Hirayama, T. (2002) : Rock slope stability classification in the welded tuff region using Quantification Theory Type 2, Landslide, Vol. 39, No. 1, pp. 95 – 103. (in Japanese with English abstract)
- 10) Kuwano, T., Sasaki, Y. and Wakizaka, Y. (2004) : Estimation of Hazard Area for Rock Mass Failure Debris using Multivariate Statistical Analysis, Journal of the Japan Society of Engineering Geology, Vol. 45, No. 1, pp. 31 – 41. (in Japanese with English abstract)
- 11) JICA (2016) : Final report, The project for master plan study on road slope management in the Kingdom of Bhutan.
- 12) Ayalew, L. and Yamagishi, H. (2003) : Slope failures in the Blue Nile basin as seen from landscape evolution perspective, Geomorphology 57, pp. 95 – 116.

(Received December 8, 2016, Accepted February 10, 2017)