Tools for Risk Estimation and Cost-Benefit Analysis of Road Geohazard Risk Reduction for Nonseismic and Seismic Events

道路災害の非地震時・地震時のリスク削減に係るリスク算定と費用・便益分析ツール

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エルサルバドル国への日本国際協力機構（JICA）技術支援プロジェクトでは、道路災害リスク削減に係るリスクと便益の算定と費用-便益分析を行うツールを開発した。保全対象は、被災が懸念される斜面あるいは横断渓流を伴う道路箇所および橋梁である。このツール開発の目的は、リスク・対策の便益、費用-便益分析結果の提供による道路災害リスク削減への効率的な投資の推進である。本ツールは、道路の豪雨時等の非震災と震災を統一的に扱うことを特長としている。ある道路箇所のリスク（年潜在損失額）と年被害軽減期待値は、非震災リスク、震災リスクについて別々に算定し合算する。非震災と震災の両者に有効なリスク削減投資は高い投資効率を示し、投資の推進が期待される。

Keywords：*道路災害、リスク削減、確率論的リスク評価、地震災害、費用対効果分析*

1. INTRODUCTION

（1）FEATURES

The spreadsheet-based Road Geohazard Management Tool (GeoMT) has been developed through the technical assistance project funded by the Japan International Cooperation Agency (JICA) in El Salvador. The outline of road geohazards in El Salvador is given in Section 1.3.

The tools measure the risks and the indicators of cost-benefit analysis of projects for reducing geohazard risks on roads. The tools also analyze the effectiveness of investments related to reducing seismic and nonseismic road geohazard risks. Nonseismic damage is caused not only by heavy rain, but also by the loosening of slopes such as destabilization due to slope excavation, deterioration, and weathering.

A set of worksheets and the manual comprising the GeoMT is downloadable on the Government of El Salvador website dacger.mop.gob.sv/.

（2）PURPOSE

The purpose of developing GeoMT is to promote efficient investments in road geohazard risk reduction based on the risk estimation and indicative cost-benefit analysis results. Most of the identified measures contribute to risk reduction due for both seismic and nonseismic causes. As for the reduction measures, these comprise slope protection, structure and foundation reinforcement, surface and subsurface drainage works for ground stability and road geohazard information system. The effectiveness of the measures is evaluated as the increase in the Safety Degree of Probability (SDP) in years or the return period for a severe geohazard damage event for a road location. The details are described in Sections 4 and 5.

（3）ROAD GEOHAZARD DAMAGE EVENTS IN EL SALVADOR

El Salvador has an area of 21,040 km^2. As of December

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2016, the total length of the national highway is 6,540 km and is 57% paved. The country is in an orogenic zone of the Pacific Rim with active seismic and volcanic activities. Most parts of the territory are hilly and mountainous with lowlands along the Pacific Coast. In the plateaus and mountains including those in the metropolitan area, valley-like rivers and vulnerable volcanic grounds predominate. During the May to November rainy season, many types of geohazards occur such as slope collapse, fallen trees, rockfalls from mountainside slopes along roads, road failures due to erosion and collapse of valley-side slopes, inundation, flash flooding, and debris flows. Also, subsidence and sinkholes occur due to cavitation below the roads. Some of the landslides, road subsidence, and sinkholes occur during the annual peak for groundwater level after the rainy season from December to January. When earthquakes occur, there are possibilities of slope collapse, landslides including the deep-seated and rapid types, rockfalls, and ground liquefaction in the lowlands.

The most efficient plan to reduce road geohazard risks and prioritize the risk reduction measures can be selected using GeoMT.

2. RISK OF ROAD GEOHAZARDS

(1) DEFINITION OF GEOHAZARDS

Geohazards are "events caused by geological, geomorphological, and climatic conditions or processes, which are serious threats to human lives, properties, and the natural and built environment" (Solheim et al. 2005).

In GeoMT, the types of geohazard risks are categorized as follows:

- Geohazard material types are classified into rock mass, soil (debris or earth), and water. In most cases, it is a mixture of materials such as soil and water;
- Geohazard movement is classified into i) fall or collapse; ii) surface and subsurface erosion; iii) slide; iv) flow or flood; and v) seismic motion (including ground liquefaction). The movement types may change or be compounded;
- In GeoMT, i) the term "damage" includes all damages caused by geohazards such as structural deformation and collapse, soil or rockfall, rock collapse, and inundation and flood, which affect roads; ii) "road location" refers to a geographically distinguishable location of a road and is normally less than 1 kilometer in length. A "road section" refers to a portion of a road that is between 1 and 100 km in length; and iii) Peak Ground Acceleration (PGA) is the maximum ground surface acceleration of a location unit gal (cm/sec2). PGA can be determined by reading the peak acceleration of a seismic waveform recorded by a seismograph.

(2) ROAD LOCATIONS TO BE ASSESSED

The evaluation is performed for every hazardous road or bridge location.

The classification of roads and bridges in a location are shown in Table 1, Fig.1, and Fig.2:

Table 1 Types of Road Locations and Geohazards

Road Location	Symbol	Type of Geohazard
Road location with mountainside slope	M	Fall/collapse and slide
Road location with valley-side slope	S	Collapse, slide, and flow (road riverside erosion, flood)
Road location with stream crossing	V	Flow (debris flow, earth flow, flood, and erosion)
Road location with subsurface storm drainage	–	Subsurface erosion (Sinking due to subsurface cavitation)
Road location prone to inundation	–	
Bridge	B	Bridge failure due to collapse, slide and seismic motion including liquefaction of foundation ground

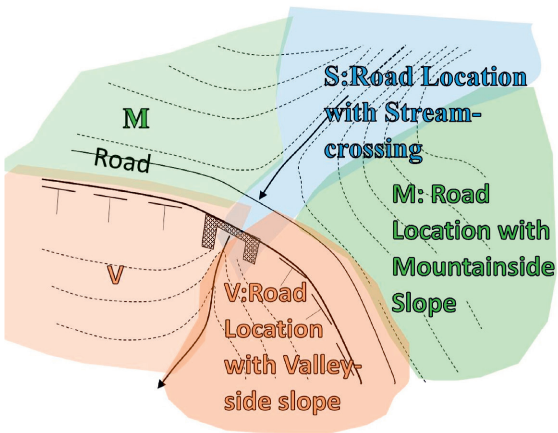


Fig.1 Classification of Road Location

The evaluation of a bridge is divided into four parts: bridge piers, bridge abutments at origin and destination sides, and superstructure (Fig.2).

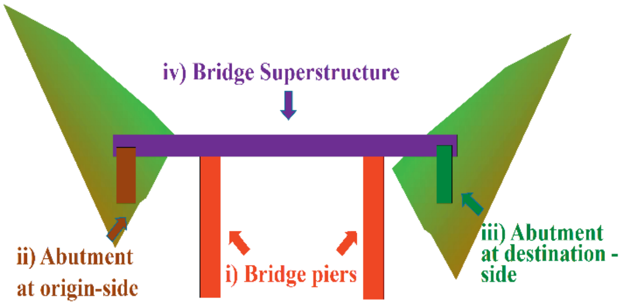


Fig.2 Classification of Bridge Parts

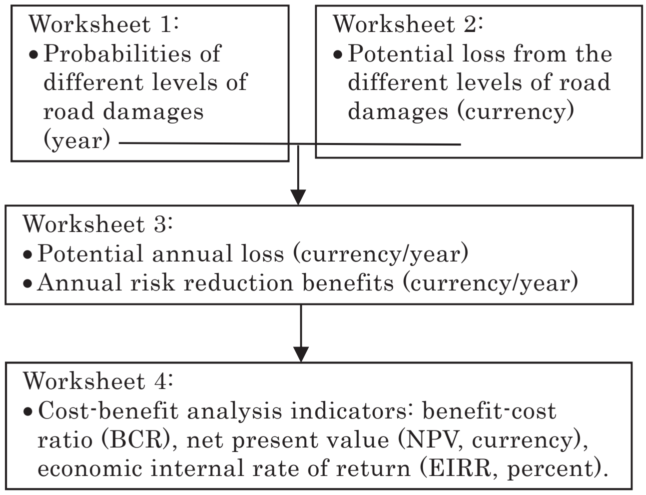
3. WORKFLOW FOR ESTIMATING RISK REDUCTION BENEFITS AND COST-BENEFIT ANALYSIS

Fig.3 shows the workflow for estimating risk, risk reduction benefits, and cost-benefit analysis for each road location.

All worksheets in GeoMT are Excel-based as given in the appendixes. Users can enter data only in the white cells. Some of the cells are provided with dropdown lists to select the appropriate situation for a road location. The worksheet automatically produces the analysis results. The list of worksheets comprising GeoMT is shown in Table 2.

Table 2 Worksheets in GeoMT

Worksheet No.	Output/Location Type
Worksheet 1	Rating checklist for the probability of geohazard damages for a road location with:
-M	mountainside slope;
-V	valley-side slope;
-S	stream crossing;
-BP	Bridge piers;
-BA	Bridge abutment;
-BS	Bridge superstructure
Worksheet 2	Potential losses due to a road geohazard event
Worksheet 3	Potential annual losses and risk reduction benefits for a:
-SS	road location with slope and stream crossing;
-BR	bridge.
Worksheet 4	Cost-benefit analysis of a geohazard risk reduction investment for a road location



Note: Analysis results are generated along the flow indicated by the arrows.

Fig.3 Workflow for Estimating Risks, Risk Reduction Benefits, and Cost-Benefit Analysis

The detailed procedures are described in the following sections of Chapters 4, 5, and 6.

4. WORKSHEET 1: RATING CHECKLIST FOR PROBABILITIES OF GEOHAZARD DAMAGES

An example of Worksheet 1 is given in Appendix 1.

(1) GENERAL

This project developed Worksheet 1 (Table 3) and workflow (Fig.4) which estimates the Safety Degree of Probability (SDP). SDP indicates the probability of a road damage event in years due to the probability of road seismic or non-seismic events. For road locations with subsurface storm drainage or in an inundation prone area, this is not prepared due to the technical issues involved.

As shown in Fig.4, one of the procedures will estimate the SDP for non-seismic events. For seismic events, the Critical Peak Ground Acceleration (CPGA) that induces damages and/or failures, is first estimated. CPGA in gal (cm/s^2) is then converted to the return period in years, which is SDP for seismic events. It is noted that SDP is for both seismic and nonseismic events.

SDP for nonseismic events and CPGA for seismic events are estimated based on the selected categories in Worksheet 1 checklist (Table 3). The categories are selected based on visual inspection and available information including geographical information and are used for the ratings. Simulation, numerical model analysis, and analysis of historical records can be used to evaluate the SDP or CPGA of road damage events and those which should be a priority to the rated SDP or CPGA using Worksheet 1.

In Fig.4, the design SDP or design Peak Ground Acceleration (PGA) refers to the SDP or PGA that was used in designing the target of the current structure before evaluating SDP using GeoMT. In the case of seismic events, the design SDP is the return period of the design PGA.

The worksheet rates the SDP in years for nonseismic events and the critical PGA in gal or cm/s^2 for seismic events simultaneously by selecting the appropriate categories in Worksheet 1.

(2) DAMAGE LEVELS FOR SDP RATING

Table 4 shows the types of road locations and the damage levels in the worksheet for rating the SDP of road geohazard damages.

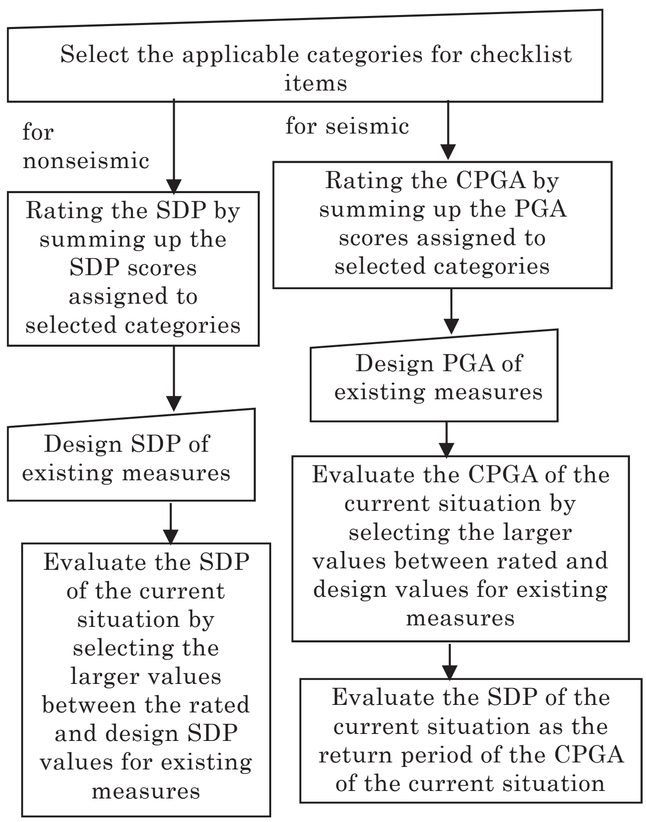


Fig.4 Worksheet 1 Workflow: Rating Checklist for SDP

Table 3 Structure of Worksheet 1: Rating Checklist for SDP

Rating checklist of probability in years		SDP in years			CPGA of seismic damage in gal
		Non-seismic damage			
Checklist items	Categories	Roadside damage	One-lane closure	Two-lane closure	
Items which may contribute to SDP or PGA	Select from the dropdown lists	Scores assigned for selected categories			
Distress items (predictable phenomena to road damages)	Select either Yes/No				
Rated SDP in years or critical PGA		Summing up of the scores assigned to selected categories			
Design SDP in years of existing measures	No existing measures, design SDP=0				
Design PGA in gal of existing measures	No existing measures, design PGA =0				
SDP or CPGA of the current situation		Select the larger values between rated and design for existing measures			
SDP in years of the current situation for seismic damage					Return period of CPGA of the cell just above

Table 4 Type of Road Location and Damage Levels to be Evaluated

Road Location	Damage Level	
	Non-seismic	Seismic
Road location with mountain side/ valley-side slope	Three levels of damages: • Roadside damage; • One lane closure; • Two lane closure	For one level of damage: First, evaluate CPGA leading to road damage. The level of damage against CPGA is determined from the site condition.
Bridge	The level of damage: Full-width closure	

As for nonseismic events such as heavy rain, SDP is determined for each location along the mountainside and valley-side slopes. SDP is estimated for the two levels of damages: One-lane and two-lane closures. In the worksheet, the function for rating SDP for more than two-lanes closure was not included as there are only a few historical events with which to calibrate the parameters of the rating function. SDP for three-lanes or more closures may be calculated by extrapolating SDPs for one-lane and two-lane closures.

SDP for road and/or bridges crossing a stream is estimated for flow-type geohazards such as flood and debris flow. In this case, SDP is estimated only for damage level defined as “full-width closure.” This is because the stream crossing and the bridge are thought to lead to severe damage requiring full-width closure when exceeding the hydrological limit of the flow rate (flow volume per second) against the discharge capacity of a watercourse. Full-width closure may occur when the hydraulic limit of the flow speed exceeds the resistance capacity of the bridge structure. Slide type or erosion type geohazards may also damage a bridge, and once the bridge is damaged, the damage would be considered severe similar to full-width closure.

The worksheets rate CPGA which lead to road damage, then evaluate the return period of CPGA for each road location. The worksheet does not include the function for rating CPGA at different levels of damages because only a few actual seismic damage cases are available to calibrate the parameters required for the rating. The damage level of a bridge is judged as full closure when PGA value exceeds CPGA. As for the location of the stream crossing, the damage level is evaluated as full road/bridge closure based on the scenario that an earthquake induces flow-type geohazards that exceeds the discharge capacity of the watercourse crossing the road.

(3) PROCEDURE FOR PROBABILITY RATING

In the worksheets, each check item has two or more choices. For example, in the item "angle of the mountainside slope up to the point of the inclination change (AS), there are four choices: "AS ≥ 60°, 60° > AS ≥ 45°, 45° > AS ≥ 30°, and 30° > AS" (Fig.5).

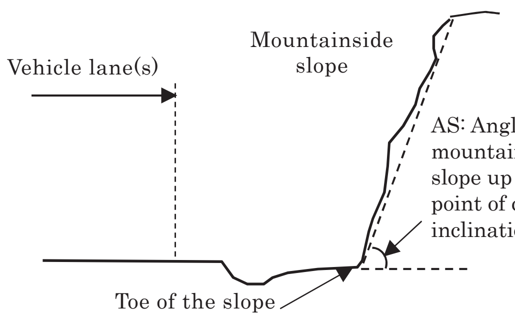


Fig.5 Angle of the Mountainside Slope

In the check item group “distress (predictable phenomena of road damage) items such as “minor collapse/ fall on the mountainside slope of the road” or “fallen/inclined trees on the mountainside slope of the road” (Fig.6), the user selects either “Yes or No.”

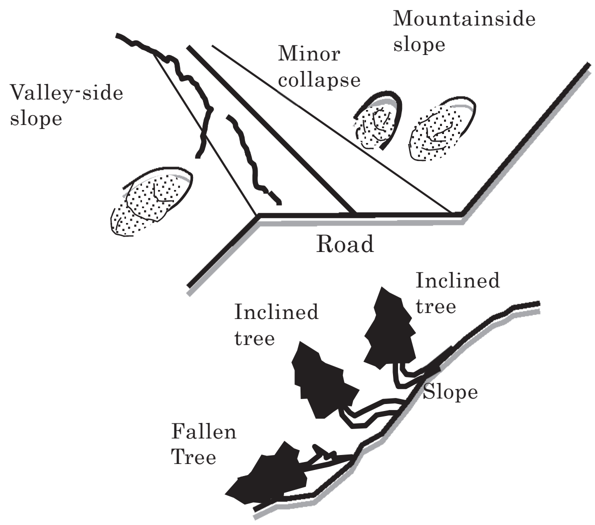


Fig.6 Examples of the Item Group: Distress

As for nonseismic events, SDP is estimated for each damage level, and CPGA is estimated for a seismic event. SDP and CPGA for each road location are finally rated as sums of the SDP and CPGA scores allocated to each selected check category. For the SDP of a seismic damage event, a return period (in years) of the CPGA is calculated for each road location.

GeoMT-PGA, an ancillary tool of GeoMT, is for formulating vulnerability curves relating to earthquakes and calculates a set of return periods for specific PGA values for a location.

(4) CALIBRATION TOOL FOR PROBABILITY RATING

In GeoMT, the calibration tool was developed to optimize the scores for SDP and CPGA for each category of the rating checklist item. This has been prepared to improve the accuracy of SDP and CPGA values for a road location.

This calibration tool has the following functions:

- Create a database of rated and actual SDP and CPGA values for road locations;
- Allocate the optimum scores of SDP and CPGA to specific categories in the checklist items so that the residual sum of squares of the rated values and the actual values are minimized based on the database above.
- Given the versatility of GeoMT, this calibration tool was developed using the “Solver” function, an Excel add-in. This tool can search for optimal predictor variable (scores for specific categories) to determine the response variable (rated result) calculated by the rating formula.

(5) ACTUAL SDP FOR NONSEISMIC ROAD DAMAGE

The actual SDP in years for nonseismic geohazards are set up as follows. The actual SDP can be applied to road locations with similar conditions as shown in Table 5.

Table 5 Procedure for Setting the Actual SDP

Geohazard Type	Actual SDP for Non-Seismic Road Damage
Mountainside fall or collapse	(1) The return period for rainfall measured by the rain gauge nearest to a road location for estimating historical road geohazard damage induced by heavy rain (2) The return period of historical road damage events repeatedly occurring such as fall/collapse of slope at a road location with mountainside slope
Valley-side collapse or erosion	(3) The number of years expected before each road damage event is estimated by the annual rate of expansion of slope failure at the road valley-side. (4) The return period of hydrological events when the peak flow rates (or speed) of flow-type geohazards (floods, debris flows, and others) exceeds the flow capacity or hydraulic resistance capacity of the stream.
Slide	(5) The probability of slide activation obtained from the following formula including Factor of Safety (FoS) for a slide type geohazard. SDP = 500 x (FoS - 1) where SDP: Safety Degree of Probability (years) FoS: Factor of Safety
Flow	Same as (4) above

Note for (5): Since there is no standard method for converting FoS to SDP, the formula was initially proposed in GeoMT. Simply set FoS = 1.2 which is equal to 100 years probability and set FoS = 1 for 0-year probability which is the situation for balanced sliding force and resistance force. FoS = 1.2 is the common target FoS for slide-type geohazard for major arterial roads in Japan and cases where slips occur again higher than measured is very rare. FoS = 1.2 was assumed to be equivalent to 100 years probability considering that no safety case had been verified for more than 100 years after measurement. The unforeseen cases on the natural conditions for design and quality in construction are considered.

(6) ACTUAL CPGA FOR SEISMIC ROAD DAMAGE

The actual CPGA values are set up as shown in Table 6.

Table 6 Procedure for Setting the Actual CPGA

Geohazard Type	Actual CPGA for Seismic Road Damage
Mountainside fall or collapse	(1) PGA of historical damage event (2) CPGA estimated from numerical slope hazard analysis
Valley-side collapse	Same as (1) and (2) above
Slide	Same as (1) and (2) above
Flow	Same as (1) above (3) CPGA estimated from numerical simulation represents slope fall/ collapse/slide into the stream resulting in flow-type geohazard at the downstream crossing for a road location.
Seismic motion including liquefaction	Same as (1) above (4) CPGA obtained from the seismic structural analysis (5) CPGA obtained from the seismic liquefaction analysis

(7) SDP OF A ROAD LOCATION WITH EXISTING MEASURES FOR NON-SEISMIC ROAD DAMAGE

SDP rating result can be replaced by the design SDP for existing measures if existing measures function properly as shown in Table 7.

Table 7 Evaluation Procedure for Design SDP

Geohazard Type	Design SDP for Nonseismic Road Damage
Mountainside fall or collapse	(1) Maximum SDP of assumed fall or collapse event(s) with measures designed for slope stability (e.g., removal of the unstable slope, slope protection) or road protection (e.g., barrier, shelter)
Valley-side collapse or erosion	(2) The expected number of years for road damage occurrence is estimated as the assumed annual rate of expansion of slope failure with measures designed at the road valley side. (3) The hydrological return period for events with measures designed where the peak flow rates/flow speed of flow-type geohazards (floods, debris flows, etc.) exceeds the flow capacity/ hydraulic resistance capacity of the stream
Slide	(4) The probability of slide activation obtained from the following formula including Factor of Safety (FoS) for a slide type geohazard. SDP = 500 x (FoS - 1) where SDP:Safety Degree of Probability (years) FoS: Factor of Safety
Flow	Same as (3) above

Note: The effects on drainage for surface runoff and vegetation works on slope stability is not considered in the current version of GeoMT. There are two reasons: (1) probability of collapse/fall or increase in FoS owing to the drainage works cannot be computed; and (2) Worksheet 1 has checklist items on slope conditions for spring water, surface water, surface erosions, and vegetation, therefore, the existing drainage and vegetation works are reflected in the rated SDP.

(8) CPGA OF A ROAD LOCATION WITH EXISTING MEASURES FOR SEISMIC ROAD DAMAGE

The CPGA rating can be replaced by the design PGA for existing measures if existing measures function properly as shown in Table 8.

Table 8 Evaluation Procedure for the Design PGA

Geohazard Type	Design PGA for seismic road damage
Mountainside fall or collapse	(1) CPGA obtained from seismic slope stability analysis for the countermeasure target slope
Valley-side collapse	Same as (1) above
Slide	Same as (1) above
Flow	(2) Design PGA with the scenario of geo-materials fall/collapse/slide into the stream resulting in flow-type geohazard at the downstream crossing with the road
Seismic motion including liquefaction	(3) Design PGA obtained from seismic structural analysis (4) Design PGA obtained from seismic liquefaction analysis

5. WORKSHEET 2: POTENTIAL LOSSES DUE TO A ROAD GEOHAZARD EVENT (CURRENCY)

An example of Worksheet 2 is given in Appendix 1.

(1) GENERAL

The estimate of potential losses due to road geohazards is conducted for the different level of damage such as roadside damage, partial-width closure, or full-closure. The potential economic loss is the sum of the following: 1) road infrastructure recovery cost; 2) road traffic losses: 3) human lives lost: 4) vehicle losses; and 5) other losses.

(2) ROAD TRAFFIC LOSSES

A simplified loss estimation is performed in the case of the full road closure. The waiting and detour losses are estimated assuming that either all vehicles decide to wait for the road reopening or, all vehicles take the shortest detour road.

The lower value between waiting and detour losses of all affected vehicles is selected as the road interruption traffic loss. The estimation uses the value of travel time (currency/hour/vehicle) per vehicle type and unit vehicle operating cost (VOC) (currency/km/vehicle) per vehicle type and road condition.

In cases of roadside damage or partial-width closure, traffic losses can be estimated by considering the increase in travel time due to reduced speeds or one-way alternating traffic operation. The increase in vehicle operating costs due to a damaged road is also considered in loss estimation.

(3) LOSS OF LIVES AND VEHICLES

The rate of lives lost (number of lives lost per total affected road user) and the rate of vehicle losses (the number of affected vehicles per total vehicle number) is determined by analyzing the actual road damage levels caused by each geohazard type.

6. WORKSHEET 3: POTENTIAL ANNUAL LOSS/ANNUAL RISK REDUCTION BENEFITS (CURRENCY/YEAR)

An example of Worksheet 3 is given in Appendix 2.

(1) POTENTIAL ANNUAL LOSSES

The potential annual losses is an index of the road geohazard risk in GeoMT, which is measured by the anticipated average losses for a road location in a year.

In Worksheet 3, the current situation refers to the current condition of a road location or section with and without countermeasures. Comparison of the risk level between the current situation and the future conditions with modified or new countermeasures will be made to evaluate the benefits.

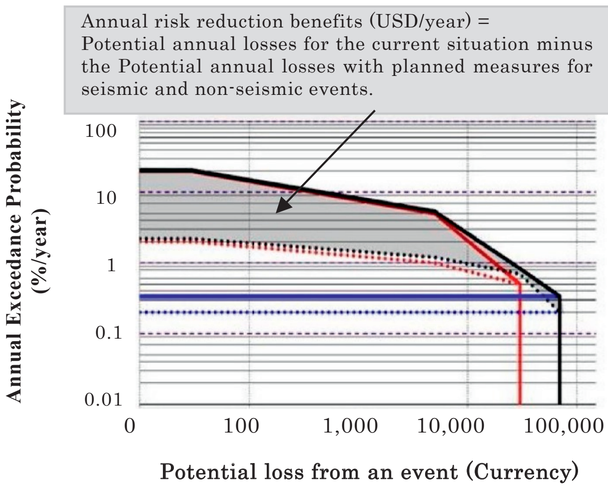
The potential annual losses reflect both the probability and losses for different levels of geohazard events for a road location. A road location has different sets of geohazard damage levels (e.g., roadside damage, partial-width closure, and full-width closure) with their corresponding probabilities and losses. Estimating risk as the potential annual loss is determined by integrating the sets of annual exceedance probabilities (%/year) and losses (currency) for different levels of road damage events due to geohazards on a road location. For simplicity, manipulation of a set of annual exceedance probability and losses from a road damage event can be used. The annual exceedance probability is the probability of an event happening annually (%/year). It is the inverse value of the Safety Degree of Probability (SDP) in years.

(2) BENEFITS OF ANNUAL RISK REDUCTION

The benefits of annual risk reduction (ARR) is the difference between the current potential annual losses (PLC) and the potential annual losses after implementation of the measures (PLA): ARR = PLC – PLA.

The risk reduction target of the design SDP in years or design Peak Ground Acceleration (PGA) should be determined by estimating the potential annual losses in the case of adopting the planned measures. The procedure for setting the design SDP and PGA is the same as shown in Tables 7 and 8.

Fig.7 shows the risk curves, which are determined by plotting the annual exceedance probabilities of road damage event occurrence (on the vertical axis) and the potential losses (on the horizontal axis). The potential annual losses are indicated as the area between the risk curve and the horizontal axis. The annual risk reduction benefits are indicated as the area between the risk curves for the current situation and the risk curves with the planned measures.



Induced cause	Measures	Symbol
Nonseismic	Current situation	———
	With planned measures	…………
Seismic	Current situation	———
	With planned measures	…………
Nonseismic and seismic	Current situation	———
	With planned measures	…………

Fig.7 Risk Curve (probability–loss plot)

7. WORKSHEET 4: COST-BENEFIT ANALYSIS FOR GEOHAZARD RISK REDUCTION INVESTMENTS

An example of Worksheet 4 is given in Appendix 2.

The input data required are as follows:

- The investment cost for the geohazard risk management measure for a road location (currency)
- Annual maintenance cost for the installed measure(s) (currency/year)
- Discount rate*) to be used for the cost-benefit analysis (%)
- Annual risk reduction benefits generated by the installed geohazard risk management measure(s) (currency/year): output of Worksheet 4.

Using the input data described, three indicators of project worth to support efficient road geohazard risk management are calculated as follows:

- Net present value (NPV) (currency)
- Benefit-cost ratio (BCR)
- Economic internal rate of return (EIRR) (%)

*) Note: The discount rate is input to the calculation of the present value of benefits and costs considering the social interest rate as recommended in the Asian Development Bank (ADB) Guidelines for the Economic Analysis of Projects (1997). The guideline describes that, for decades, the World Bank and other international development banks have used the standard real discount rate ranging from 10-12% to evaluate projects for all sectors and countries.

8. CONCLUSION

The GeoMT updates the database and calibrates it to improve accuracy in calculating risks and benefits. The GeoMT has enabled the authors to promote efficient investments in road geohazard risk reduction with the use of this tool. The authors propose to disseminate GeoMT in the Central American region to improve the safety and reliability of managing geohazards for the benefit of road logistics for goods and people within the region.

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Appendix 1: Examples of Worksheet 1: Rating Checklist for Probabilities of Geohazard Damages and Worksheet 2: Potential Loss due to a Road Geohazard Event (currency)

[Worksheet 2] Potential Loss of a Road Geohazard Event

GeoMT

white color cells are for users' input | gray colored cells include instructions or results calculated by this tool

Location ID		Road Name			
Station Origin			Station Destination		
Extension along the road (m)			Number of road lanes		
Estimated condition of road damage extent	a) Roadside-only		Occurrence probability of the road damage event : Yp (years)		
	Specify closing lanes/ total lanes	2	4	Currency	US$

Item			Unit	Symbol or calculated formula	Quantity
(1)	Probable extension of road damage of the road location	of roadside-only	m	PERD_si	30
		of partial width-closing	m	PERD_pw	10
		of whole-width closing	m	PERD_ww	5
			m	PERD	45
			km	Ders	16
			km	Ddrs	38
			vehicles/day	AADTerl_t1	10,074
			vehicles/day	AADTerl_t2	4,775
			vehicles/day	AADTerl_t3	781
			vehicles/day	AADTerl_t4	782
			vehicles/day	AADTerl_t5	1,772
			vehicles/day	AADTerl_t6	227
			vehicles/day	AADTerl_t7	0
			vehicles/day	**AADTerl**	**18,411**
			US$ /km/vehicle	VOCers_t1	0.24
			US$ /km/vehicle	VOCers_t2	0.35
			US$ /km/vehicle	VOCers_t3	0.31
			US$ /km/vehicle	VOCers_t4	0.87
			US$ /km/vehicle	VOCers_t5	0.72
			US$ /km/vehicle	VOCers_t6	0.96
			US$ /km/vehicle	VOCers_t7	1.38
			US$ /km/vehicle	**AVOCers**	**0.35**
			US$ /km/vehicle	VOCdrs_t1	0.28
			US$ /km/vehicle	VOCars_t2	0.47
			US$ /km/vehicle	VOCdrs_t3	0.64
			US$ /km/vehicle	VOCdrs_t4	1.66
			US$ /km/vehicle	VOCdrs_t5	1.26
			US$ /km/vehicle	VOCdrs_t6	1.75
			US$ /km/vehicle	VOCdrs_t7	2.55
			US$ /km/vehicle	**AVOCdrs**	**0.52**
			km/hour	VSers_t1	87.40
			km/hour	VSers_t2	86.87
			km/hour	VSers_t3	74.20
			km/hour	VSers_t4	72.18
			km/hour	VSers_t5	73.60
			km/hour	VSers_t6	65.45
			km/hour	VSers_t7	63.42
			km/hour	**AVSers**	**84.46**
			km/hour	VSehrl_t1	87.40
			km/hour	VSehrl_t2	86.87
			km/hour	VSehrl_t3	74.20
			km/hour	VSehrl_t4	72.18
			km/hour	VSehrl_t5	73.60
			km/hour	VSehrl_t6	65.45
			km/hour	VSehrl_t7	63.42
			km/hour	**AVSerl**	**84.46**
			km/hour	VSdrs_t1	39.53
			km/hour	VSdrs_t2	39.51
			km/hour	VSdrs_t3	38.90
			km/hour	VSdrs_t4	28.81
			km/hour	VSdrs_t5	36.73
			km/hour	VSdrs_t6	36.58
			km/hour	VSdrs_t7	27.14
			km/hour	**AVSdrs**	**38.74**
			US$ /vehicle/hour	VTTSerl_t1	9.48
			US$ /vehicle/hour	VTTSerl_t2	8.95
			US$ /vehicle/hour	VTTSerl_t3	20.54
			US$ /vehicle/hour	VTTSerl_t4	71.10
			US$ /vehicle/hour	VTTSerl_t5	8.91
			US$ /vehicle/hour	VTTSerl_t6	4.99
			US$ /vehicle/hour	VTTSerl_t7	5.88
			US$ /vehicle/hour	**AVTTSerl**	**12.32**
			person/vehicle	ANP_t1	2
			person/vehicle	ANP_t2	2
			person/vehicle	ANP_t3	12
			person/vehicle	ANP_t4	44
			person/vehicle	ANP_t5	2
			person/vehicle	ANP_t6	1
			person/vehicle	ANP_t7	1
			person/vehicle	**ANPVerl**	**4.20**
			person/vehicle	ANO_t1	1
			person/vehicle	ANO_t2	1
			person/vehicle	ANO_t3	1
			person/vehicle	ANO_t4	1
			person/vehicle	ANO_t5	1
			person/vehicle	ANO_t6	1
			person/vehicle	ANO_t7	1
			person/vehicle	**ANOerl**	**1.00**
			person/vehicle	**ANP&Oerl**	**5.20**
			US$ /vehicle/hour	APNV_t1	22,590
			US$ /vehicle/hour	APNV_t2	25,450
			US$ /vehicle/hour	APNV_t3	34,335
			US$ /vehicle/hour	APNV_t4	100,940
			US$ /vehicle/hour	APNV_t5	49,440
			US$ /vehicle/hour	APNV_t6	61,800
			US$ /vehicle/hour	APNV_t7	112,500
			US$ /vehicle/hour	**APNVerl**	**30,226**
			years	**AUYRVerl**	**4.5**
			percentage	**AVRPV**	**18%**
			US$ /vehicle	**AVRVerl = APNVerl x $(1-AVRPV)^{AUYRVerl}$**	**12,375**

Worksheet 1-M: Rating Checklists for Probability for Geohazard damages for a road location with mountainside slope

GeoMT

Users are allowed to enter data into white cells only.

Date of Data Entry (MM/DD/YYYY)		MM	DD	2017
I. General Data				
[I-1] Location ID				
[I-2] Road Name				
[I-3] Station Origin				
[I-4] Station Destination:				
[I-5] Extension along the road: E				m
[I-6] Number of road lanes				
[I-7] Total road width (m)				m
[I-8] Widths of road elements from the mountain-side (m)				
a) Mountain-side strip				m
b) 1st lane				m
c) Center divider between 1st and 2nd lanes				m
d) 2nd lane				m
e) Center divider between 2nd and 3rd lanes				m
f) 3rd lane				m
g) Center divider between 3rd and 4th lanes				m
h) 4th lane				m
i) Center divider between 4th and 5th lanes				m
j) 5th lane				m
k) The other lanes and center dividers				m
l) Valley-side strip				m
II. Observations				
III. Location Data				
Latitude and Longitude		Deg.	Min.	Sec.
a) Latitude	0			
b) Longitude	0			
c) Elevation				m
IV. Historical road damage events due to geohazards (Three Latest Events)				
a-1) Geohazard movement/material type				
b-1) Date of event	(MM/DD/YYYY)	MM	DD	
c-1) Historical occurrence frequency period in years of a specific extent of a road damage event (unit: years)				Years
d-1) Description				
a-2) Geohazard movement/material type				
b-2) Date of event	(MM/DD/YYYY)	MM	DD	
c-2) Historical occurrence frequency period in years of a specific extent of a road damage event (unit: years)				Years
d-2) Description				
a-3) Geohazard movement/material type				
b-3) Date of event	(MM/DD/YYYY)	MM	DD	
c-3) Historical occurrence frequency period in years of a specific extent of a road damage event (unit: years)				Years
d-3) Description				

V. Rating of safety degree of probability (SDP) in years		Safety degree of probability (SDP) in years			Critical PGA of seismic damage in gal
		Non-seismic damage level			
Checklist items	**Categories**	Roadside damage	One-lane closure	Tow-lanes closure	
[V-1] Extension (Length) of the hazardous location: E	a) $E \geq 300$ m	0.0	0.0	0.0	0.0
[V-2] Angle of the mountain-side slope up to the point of the inclination change: AS	a) $AS \geq 60°$	0.0	0.0	0.0	0.0
[V-3] Height of the whole mountain-side slope: WH	a) $WH \geq 200$ m	0.0	0.0	0.0	0.0
[V-4] Height of the mountain-side slope up to the point of the inclination change: H	a) $H \geq 90$ m	0.0	0.0	0.0	0.0
[V-5] Offset from the toe of the mountain-side slope to the nearest vehicle lane: D	b) 4 m > D ≥ 2 m	0.1	0.3	0.4	7.9
[V-6] Type of the mountain-side slope up to the point of the inclination change	a) Valley type	0.0	0.0	0.0	0.0
[V-7] Dominant material of the mountain-side slope surface	c) Gravels	0.0	0.0	0.0	0.3
[V-8] Dominant geology of the mountain-side slope	f) Quaternary: Volcanic rock (Lava)	0.0	0.0	0.1	2.0
[V-9] Geometry of the dominant discontinuity against the mountain-side slope surface	b) The discontinuity extends vertically in the slope.	0.0	0.0	0.0	0.5
[V-10] Spring (groundwater) condition of the mountain-side slope	b) Spring water is recognized seasonally.	0.0	0.0	0.0	0.5
[V-11] Surface water of the mountain-side slope	b) Surface water is recognized seasonally.	0.0	0.0	0.0	0.5
[V-12] Dominant vegetation of the mountain-side slope	b) Sparse vegetation: vegetation covers 20% or less of the slope.	0.0	0.0	0.0	0.5
[V-13] Type of the mountain-side slope up to the point of the inclination change	b) Engineered slope of cutting	0.0	0.0	0.0	0.5
[V-14] Soil covers the impervious bedrock of the mountain-side slope.	a) Yes	0.0	0.0	0.0	0.0
[V-15] A hard rock layer lies on a soft rock layer	a) Yes	0.0	0.0	0.0	0.0
[V-16] Slope protection	c) There is no slope protection.	0.0	0.0	0.0	0.0
[V-17] Frequency of rockfalls by the slope	a) Once a year	0.0	0.0	0.0	0.0
[V-18] Distresses (predictable phenomena to road damages)					
a) Minor collapses/falls on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
b) Fallen/inclined trees on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
c) Open-cracks below an overhang on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
d) Open-cracks to cause wedge-shaped slide on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
e) Continuous cracks (more than 5 m long) of the road surface	Yes	0.0	0.0	0.0	0.0
f) Upheaval on the road	No	3.1	15.4	31.0	126.0
g) Rill erosion (10-100 cm deep) on the mountain-side slope of the road	Yes	0.0	0.0	0.0	0.0
h) Erosion as trenches or gullies (deeper than 1 meter)	Yes	0.0	0.0	0.0	0.0
i) Over 5-m-long continuous cracks in the slope	Yes	0.0	0.0	0.0	0.0
j) Apparent deformation due to land-sliding	Yes	0.0	0.0	0.0	0.0
k) Open-cracks by toppling	Yes	0.0	0.0	0.0	0.0
l) Open-cracks by sliding	Yes	0.0	0.0	0.0	0.0
m) Depression of the road surface	Yes	0.0	0.0	0.0	0.0
n) Surface erosion (1-10 cm deep)	Yes	0.0	0.0	0.0	0.0
o) Subsurface erosion of the slope due to piping.	No	3.1	15.4	31.0	126.0
[V-19] Average annual rainfall: AAR	a) $AAR < 500$	1.0	0.0	0.0	0.0
[V-20] Average annual maximum daily rainfall: AAMDR	b) $50 \leqq AAMDR < 100$	2.0	0.0	0.0	0.5
[V-21] Average number of months with rainfall (more than 10mm of a month) of a year: ANMR	a) $ANMR < 2$	1.0	0.0	0.0	0.0
[V-22] Rated safety degree of probability (SDP) or critical peak ground acceleration (PGA) (when not considering existing measures)		10.6	31.1	62.5	265.6
VI. Safety degree of probability (SDP) considering existing measures					
[VI-1] Existing measures (specify in the white cells to the right)					
[VI-2] Design safety degree of probability (SDP) of existing measures (years)					
[VI-3] Design peak ground acceleration (PGA) of exiting measures (gal)					
[VI-4] Safety degree of probability (SDP) or critical peak ground acceleration (PGA) considering existing measures		**10.6**	**31.1**	**62.5**	**265.6**
[VI-5] Safety degree of probability (SDP) considering existing measures for seismic damage		**10.6**	**31.1**	**62.5**	**470.0**

Appendix 2: Examples of Worksheet 3: Potential Annual Loss/Annual Risk Reduction Benefit, and Worksheet 4: Cost-Benefit Analysis for a Geohazard Risk Reduction Investment

[Worksheet 4] Cost-Benefit Analysis for a Geohazard Risk Reduction Investment for a Road Location

GeoMH

white color cells are for users' input | gray colored cells include input names, instructions or results calculated by this tool

Project Name					
Location ID		Road Name			
Station Origin		Station Destination		Extension along road (m)	
				Currency: US$	

Investment for road geohazard measures (cost input)

No.	Work	Unit	Quantity	Unit Pri (US$)	Amount
				290	290
				3,700	3,700
					0
					0
					0
					0
					0
					3,990

ymbol of variabl	Quantity
AMC	**20**
ARRB	667
CBAETY	**100**
DR	12%
NPV	1,402
BCR	1.34
EIRR	4%

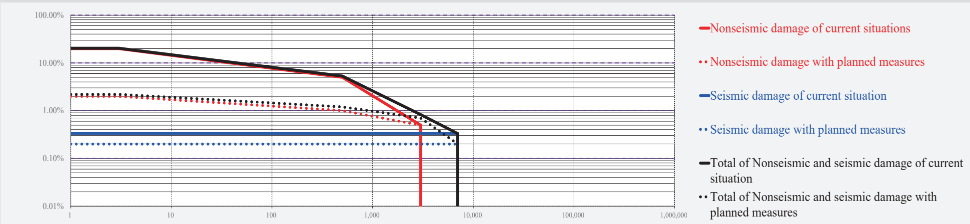
Net benefit of a year	Net present value of a year
US$	US$
NB=(ARRB-IC-AMC)	NPV= NB/(1+DR)^{age}
-3,990	-3,990
647	578
647	516
647	461
647	411
647	367
647	328
647	293
647	261
647	233
647	208
647	186
647	166
647	148
647	132
647	118
647	106
647	94
647	84
647	75
647	67
1,402	**1,402**
	1.34
	4%

[Worksheet 3-SS] Potential Annual Loss & Risk-Reduction-Benefit for a Location with Slope or Stream-Crossing

GeoMT

white color cell is for user inputs | gray colored cells include instructions or results calculated by this tool

Location ID		Road Name		Remarks	
Station Origin		Station Destination		Extension along the road (m)	
				Currency	US$



Potential losses of a road damage event (US$)

	Current situation/With planned measures	Items	Unit	Variable symbols	Calculation formula	Damage level 1	Damage level 2	Damage level 3
					Potential road damage events for different road damage level — Note: If only one level of damage will be inputted, the same values shall be inputted for all columns of damage level 1, 2, and 3. If two levels of damage will be used, the lower level goes on the first column and the other value shall be inputted for both columns of damage level 2, and 3.			
					Description of damage level	**Roadside-damage**	**Partial-width closure**	**Full-width closure**
Nonseismic Damage	Same value for current situation/with planed measures	Potential losses of a road damage event	US$/event	Lpn	Potential economic losses for each damage level obtained using a Worksheet 2.	3	500	3,000
	Current situation	Safety degree of probability of a road damage event	years	SDPn_cs	Calculated by Worksheet 1-M, 1-V, 1-S or other engineering study	5	20	200
		Annual exceedance probability of a road damage event	%/year	AEPn_cs	= 1/SDPn_cs	20.00%	5.00%	0.50%
		Potential annual losses of road damage events in a location	US$/event	ALpn_cs	= Integral computation of Lpn and their AEPn_cs			131
	With planned measures	Design safety degree of probability	years	DSDPn	-			100
		Safety degree of probability of a road damage event	years	SDPn_pm	If DSDPn > SDCn_cs, SDPn_pm = DSDPn, otherwise SDPn_pm = SDPn_cs	100	100	200
		Annual exceedance probability of a road damage event in a location	%/year	AEPn_pm	= 1/SDPn_pm	2.00%	1.00%	0.50%
		Potential annual losses of road damage events in a location	US$/event	ALpn_pm	= Integral computation of Lpn and their AEPn_pm			26
	Annual risk reduction benefits of a road location		US$/year	ARRBn	= ALpn_cs- ALpn_pm			105
Seismic Damage					Description of damage levels due to intense earthquake of higher than critical peak ground acceleration (PGA)	e.g. full of 2 lanes road closures		
	Same value for current situation/with planed measures	Potential economic losses of a road damage event	US$/event	Lps	Loss of damage calculated by using the Worksheet 2			7,000
	Current situation	Safety degree of probability of a road damage event	years	SDPs_cs	Calculated by Worksheet 1-M, 1-V, 1-S or other engineering study			300
		Annual exceedance probability of a road damage event	%/year	AEPs_cs	= 1/SDPs_cs			0.33%
		Potential annual losses of road damage events in a location	US$/event	ALps_cs	= Integral computation of Lps and their AEPs_cs			23
	With planned measures	Design safety degree of probability	years	DSDPs	-			**500**
		Safety degree of probability of a road damage event	years	SDPs_pm	If DSDPs > SDCs_cs, SDPs_pm = DSDPs, otherwise SDPs_pm = SDPs_cs			500
		Annual exceedance probability of a road damage event	%/year	AEPs_pm	= 1/SDPs_pm			0.20%
		Potential annual losses of road damage events in a location	US$/event	ALps_pm	= Integral computation of Lps and their AEPs_pm			14
	Annual risk reduction benefits of a road location		US$/year	ARRBs	= ALps_cs- ALps_pm			9
Total of Non-seismic and Seismic Damages	**Potential annual losses of a road damage event in a location of current situation**		**US$/year**	**ALp_cs**	**= ALpn_cs + ALps_cs**			**155**
	Potential annual losses of a road damage event in a location with planned measures		**US$/year**	**ALp_pm**	**= ALpn_pm_ + ALps_pm**			**40**
	Annual risk reduction benefits of a road damage in a location		**US$/year**	**ARRB**	**= ALp_cs - ALp_cs**			**115**