Journal of JSCE, Vol. 1, 569-582, 2013

# DEVELOPMENT OF A PRACTICAL ROAD DISASTER MANAGEMENT SYSTEM BASED ON RISK MANAGEMENT TECHNIQUES

Keiichi TAMURA[1]

[1]Member of JSCE, Professor, Graduate School of Management, Kyoto University
(Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan)
E-mail: ke-tamura@gsm.kyoto-u.ac.jp

This is a study on the development of a practical road disaster management system for various natural disasters by applying risk management techniques. Risk is defined here as the product of the likelihood of disastrous event and its consequences. The road facilities targeted are bridges, embankments, tunnels, slopes, and so forth. Various natural disasters such as earthquakes, tsunamis and heavy rainfalls are included in the analysis. Both direct and indirect damages are assumed in the present study. The former includes human damage and the restoration cost of damaged facilities, while the latter includes economic loss associated with traffic detouring. Particular emphasis is put on rating the risks to various road facilities due to different natural disasters by using a common index. Based on the proposed system, a case study was performed on a 110-km section of a national highway running along the Pacific coastline of Japan. This section of the highway comprises various kinds of road facilities, and the area where the highway passes through has high seismicity and has suffered from typhoons and resultant slope disasters. The results of the case study are presented through a risk curve, risk register table, and risk treatment plan, which are readily applicable to road disaster management.

***Key Words :*** *risk management, road disaster management, road facility, disaster*

## 1. INTRODUCTION

The concept of risk or risk management has been recently introduced not only to the social and economic fields but also to the industrial field. Meanwhile, risk management techniques are less common in the management of civil infrastructures such as road and river facilities in Japan, despite the fact that they are exposed to many risks, e.g., earthquakes, heavy rainfalls, and other natural and man-made disasters. This may be attributed to the fact that management of civil infrastructures deals with disasters in different ways depending on the type of disaster and those disasters have been managed less often in an integrated manner. Besides that, judgment of the level of potential danger for a certain disaster and determination of the priority of disaster prevention measures has been mainly based on past experiences.

Under those circumstances, risk management techniques are well worth applying to the disaster management of infrastructures. A uniform quantitative evaluation of risks of various infrastructures for various disasters will be of particular interest in prioritizing disaster prevention measures. There are cases outside Japan where risk management techniques are applied to road disaster management. In New Zealand for instance, there is an established set of risk management procedures called the Risk Management Process Manual[1)], which is applied to their road management practice. This manual was published by the Transit New Zealand (currently, New Zealand Transport Agency) that is responsible for the stewardship of New Zealand's state highways, and has the following features:

1) Both threat and opportunity are considered as risks. Threat is defined as an event that has the potential to move the outcome of an activity to a more unfavorable position. Opportunity is defined as an event that has the potential to move the outcome of an activity to a more favorable position.

2) A risk is measured in terms of a combination of the likelihood of an event and its consequences, where the likelihood of an event and its conse-

quences are rated to allow quantitative evaluation of risks for various road facilities against various disasters.

The ultimate effectiveness of the Risk Management Process Manual by the Transit New Zealand lies in the fact that it provides quantitative evaluation of risks and this enables a uniform comparison of various risks. In the present study we applied the concept of this manual to proposing a practical method to systematically evaluate the risk of road facilities caused by natural disasters. Road facilities included in our study were bridges, embankments, tunnels and slopes. Earthquakes, tsunamis and heavy rainfalls were the major natural disasters considered. Regarding damage to road facilities, direct damage and indirect damage were both assumed. Particularly, emphasis was put on evaluating risks of damage to various road facilities due to various disasters by using a common index. In examining the priority of road disaster prevention measures, we incorporated into the analysis the concept of opportunity, which is a favorable outcome incidentally resulting from road disaster prevention measures.

As mentioned previously, the primary objective of this study is to present a comprehensive and practical method for evaluating risks to different road facilities caused by different disasters. In this process, it is necessary to estimate various factors such as the likelihood of hazards, damage level of each road facility and restoration cost, and then rate them in a uniform manner. Those factors were estimated in a simple and practical manner by using available information. Further study will be necessary to improve the accuracy of estimating each factor, and note that it is out of the scope of the present study. For example, new studies have been performed in relation to large earthquakes and tsunamis since the 2011 Great East Japan earthquake, and the results of risk evaluation with earthquakes and tsunamis will vary according to such studies.

Finally, we performed a case study on the proposed method for roughly 110 km section of a national highway spanning along the Pacific coastline of Japan. On this target section of the highway, there were a variety of road facilities. Seismicity of the region is high, and disasters caused by heavy rainfalls such as typhoons have also occurred. In the case study we systematically evaluated the risk of damage to the highway, and based on the evaluation results we examined the priority for road disaster prevention measures, where threats and opportunities were considered.

## 2. EVALUATION PROCEDURE FOR ROAD DISASTER RISKS

### (1) Overview

We propose a practical procedure for evaluating road disaster risks caused by natural disasters such as earthquakes and heavy rainfalls that frequently occur in Japan. The proposed evaluation procedure can be applied when examining the priority for road disaster prevention measures and is outlined as follows:

1) Identify natural disasters (hazards) that may affect the target area and roads. Then, determine if the damage actually occurs or not and the damage level by combining the vulnerability of each road facility and hazard. Evaluate the direct damage such as human damage and physical damage to each road facility, and the indirect damage such as disruption of road traffic. (Risk identification)

2) Formulate a table to rate the consequences of damage for quantification and to evaluate the impact of each damaged facility. Likewise, rate the likelihood of hazard. Then, evaluate the risk to road facility due to hazard by multiplying the likelihood of hazard and its consequences[2]. (Risk analysis and evaluation)

3) Develop a menu of disaster prevention measures for road facilities that are found to require measures, and examine the priority for road disaster prevention measures, in which opportunities, which are favorable outcomes incidentally resulting from measures against threats, are considered. (Risk treatment)

**Fig.1** shows the proposed procedure for road disaster risk management, and each process is described below.

### (2) Identification of natural disasters (hazards)

Hazards to be considered include earthquakes, tsunamis, overtopping waves and slope disasters caused by earthquake or heavy rainfall. Effects of hazards are simplified for them to be easily used in the evaluation of damage to road facilities described in the next section. For instance, the effects of earthquakes are modeled by seismic intensity, and those of tsunamis are represented by inundation depth.

### (3) Evaluation of damage to road facilities

For the road facilities, such as bridges, embankments, tunnels and slopes, on the target section of road, determine whether damage is brought by the hazards identified above to each of those facilities, and evaluate the damage level. We refer to previous research results to establish the methods for evalu-

**Table 1** Rating of consequences.

| Risk | Influence | Rating | Human damage (Fatalities) | Restoration cost | Economic loss |
|---|---|---|---|---|---|
| Threat | Major | 10 | ≥1 | ≥150M yen | ≥150M yen or no detour |
| | Medium | 5 | <1 | 50M to 150M yen | 50M to 150M yen |
| | Minor | 1 | | <50M yen | <50M yen |
| None | None | 0 | 0 | 0 | 0 |
| Opportunity | Minor | 1 | | <50M yen | |
| | Medium | 5 | <1 | 50M to 150M yen | |
| | Major | 10 | ≥1 | ≥150M yen | |

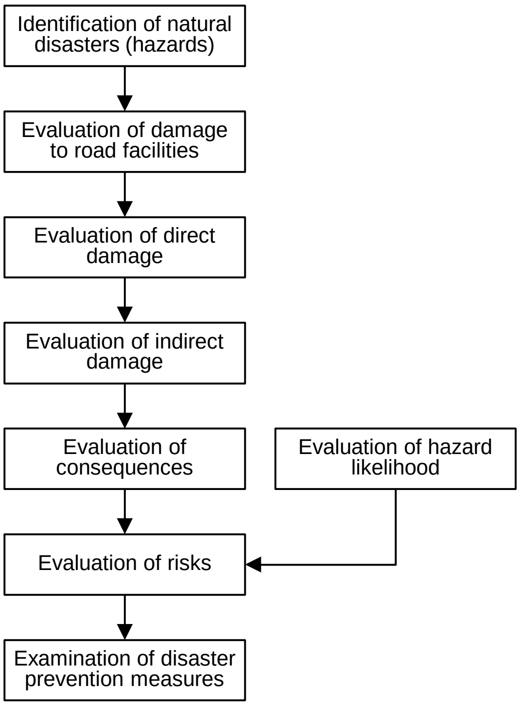


**Fig. 1** Procedure for road disaster risk management.

**Table 2** Rating of likelihood of hazard.

| Likelihood | Annual probability of occurrence | Rating |
|---|---|---|
| Likely | ≥50% | 10 |
| Medium | 10 to 50% | 5 |
| Rare | ≤10% | 1 |

ating damage to individual road facilities caused by various hazards.

### (4) Evaluation of direct damage

Direct damage refers to human damage or damage to road users and the restoration cost of road facilities, which represent physical damage to road facilities. Human damage covers damage that may cause fatalities, while restoration cost is estimated costs for both temporary repair work and permanent restoration work of the damaged facilities.

### (5) Evaluation of indirect damage

For indirect damage, we evaluated the loss due to traffic detour. The period of indirect damage refers to the period from the occurrence of the disaster to the time when the road is reopened to the general traffic after temporary restoration work.

### (6) Evaluation of consequences

In this process, we evaluated the consequences of each combination of road facility and disastrous event, assuming that the disastrous event occurs. The likelihood of disastrous event shall be evaluated in the next process, and the level of damage to road facilities varies depending on their vulnerability even if the same level of hazard occurs.

We employed a rating technique to evaluate the consequences of disastrous events, which categorizes the impact level based on an impact evaluation standard chart. In our study, the impact level for each of the three kinds of damage, i.e., human damage, restoration cost, and economic loss (the first two are direct damage and the third is indirect damage) is categorized into four classes: major, medium, minor, and none. We rated each class as 10, 5, 1, and 0, respectively, and evaluated the magnitude of the consequence by the total of those scores. **Table 1** shows the rating of consequences as the basis for evaluating the impact level in this study. The threshold levels were set for each type of damage so that equivalent impact levels were assumed among the different types of damage. We surveyed the opinions of road administrators responsible for road management when we established the scores and threshold levels in **Table 1**. There was some degree of arbitrariness in determining them, thus there should be room for reviewing and modifying them in future trials. Still, this technique enabled us to consistently evaluate the risks to diverse road facilities resulting from different hazards.

### (7) Evaluation of hazard likelihood

We employed an annual probability of occurrence for each hazard to measure its likelihood. Although large-scale and infrequent hazards such as earthquakes and tsunamis may have nonstationarity, we assumed stationary processes for simplicity. Hazard likelihood was scored on a scale of 10, 5, and 1 corresponding to the level of annual occurrence likelihood as likely, medium, and rare, as shown in **Table 2**. Similar to the above evaluation of conse-

**Table 3** Number of road facilities.

| Road facility | Number |
|---|---|
| Bridge | 51 |
| Embankment | 17 |
| Slope | 89 |
| Tunnel | 4 |
| Total | 161 |

**Table 5** Combination of hazards and road facilities.

| Hazard | Road facility |
|---|---|
| Earthquake | Bridge |
| | Embankment |
| | Slope |
| | Tunnel |
| Tsunami | Bridge |
| Heavy Rainfall | Slope |
| Overtopping wave | Road |

**Table 4** Primary references for case study.

| Item | Reference |
|---|---|
| General | Road management register |
| Traffic | Road traffic census |
| Earthquake | Expected seismic intensity map<br>Comprehensive road disaster management inspection (Earthquakes) |
| Tsunami | Expected tsunami inundation depth map |
| Heavy rainfall | Annual report of AMeDAS (Automated Meteorological Data Acquisition System)<br>Comprehensive road disaster management inspection (Heavy rainfalls and snowfalls) |
| Overtopping wave | Record of disasters, abnormal weathers and snowfalls<br>Record of traffic controls |

**Table 6** Classification of damage.

| Classification | | Remarks |
|---|---|---|
| Direct damage | Human damage | Human loss by damage to road facility |
| | Restoration cost | Cost to restore damaged road facility |
| Indirect damage | Economic loss | Loss associated with detour |

quences, we surveyed the opinions of road administrators when we introduced the rating criteria for the hazard likelihood. The scores and threshold levels in **Table 2** are somewhat arbitrary, but they are helpful in evaluating the likelihood of various hazards in a uniform manner. There is also room for reviewing and modifying **Table 2** in future trials.

### (8) Evaluation of risks

We evaluated the risk quantitatively by multiplying the likelihood of hazard and its consequences. Both the likelihood of hazard and its consequences were scored as mentioned in Sections **(6)** and **(7)**.

### (9) Examination of disaster prevention measures

We considered both structural and nonstructural measures for the risks that were revealed to need treatment. The priority of measures was then examined based on the cost of disaster prevention measures and the effectiveness of the measures. Evaluation of risks after implementation of measures was made in terms of both threat and opportunity. Applying the concept of opportunity presented in the Risk Management Process Manual of Transit New Zealand, we evaluated the favorable outcomes incidentally achieved from the implementation of road disaster prevention measures as opportunities.

## 3. CASE STUDY ON ROAD DISASTER RISK MANAGEMENT

### (1) Target area and route

We performed a case study on roughly 110 km section of a national highway running through the Pacific coast area of Japan. Along this section of the highway, natural disasters expected to occur include earthquakes, tsunamis, and heavy rainfalls. **Table 3** summarizes the numbers of road facilities on the target section. **Table 4** shows the primary references employed for the case study.

### (2) Evaluation of damage to road facilities

#### a) Direct and indirect damage and damage level

**Table 5** shows the combination of hazards and road facilities to be used for damage evaluation. **Table 6** lists direct damage and indirect damage studied. In this study, we evaluated damage with a focus on human damage at each road facility in case a hazardous event occurs. Such damage is classified into three categories: damage that may cause fatalities (Damage Level I), damage that may cause injuries (Damage Level II), and damage causing no human damage. In principle, we conducted risk evaluation for the kind of damage involving fatalities. Detailed conditions that dictate damage evaluation are as follows:

1) Both direct damage (human damage and restoration cost) and indirect damage (loss due to traffic detour) are evaluated when Damage Level I occurs, in principle. Refer to the gray areas in **Table 7**.

**Table 7** Pattern of damage occurrence.

| Hazard | Damage level | Direct damage: Human | Direct damage: Restoration | Indirect: Economic | Risk evaluation | Remarks |
|---|---|---|---|---|---|---|
| Occurred | Damage may cause fatalities (Damage Level I) | Damage | Damage | Damage | Applicable | |
| | | No damage | | | Applicable | Precautionary road closure section (Slope x Rainfall) |
| | Damage may cause injuries (Damage Level II) | Damage | Damage | Damage | Not applicable | |
| | | No damage | | | Not applicable | |
| | No human damage | No damage | Minor damage or no damage | Damage | Applicable | Traffic control (overtopping wave) |
| | | | | No damage | Not applicable | |
| Did not occur | No damage | No damage | No damage | Damage | Not applicable | Detour loss |
| | | | | No damage | | |

2) Neither direct damage nor indirect damage is evaluated in case of damage that does not cause fatalities.

3) No fatalities have been reported due to collapse of road embankments or tunnels at least in the recent earthquakes, thus we excluded the earthquake-embankment and earthquake-tunnel combinations from risk evaluation.

4) Note that no human damage is assumed to occur from a slope disaster caused by heavy rainfall on the road section with precautionary road closure; however, if damage of a scale that may cause fatalities occurs, the restoration cost and indirect damage are evaluated. This case is highlighted in blue in **Table 7**.

5) For overtopping waves, it is assumed that no human damage occurs because traffic control is applicable in advance. Since it is difficult to assume blocking materials and their amount caused by overtopping waves, no restoration cost is evaluated either. Notwithstanding the foregoing, indirect damage inflicted by stones brought over the road surface or road blockage by such stones is estimated, which is marked in blue in **Table 7**.

**b) Evaluation of damage to bridges by earthquake or tsunami**

Physical damage to a bridge by an earthquake equivalent to Damage Level I refers, in principle, to a fall of a superstructure. The procedure adopted for evaluating bridge damage level in this study is the one proposed by Kobayashi and Unjoh[3], which is shown in Appendix A. We regard Damage Level A according to their definition as Damage Level I.

The level of bridge damage by a tsunami was evaluated by a procedure proposed by the National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism[4], which is shown in Appendix B. The washing away of a superstructure by tsunami corresponds to Damage Level I. This damage level is classified as A in the appendix.

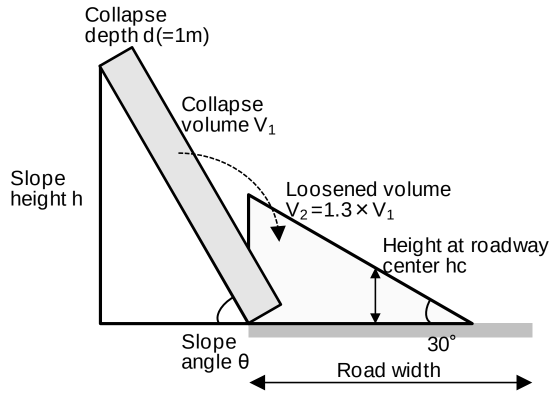


**Fig. 2** Deposit of collapsed soils on road surface.

**c) Evaluation of damage to slope by earthquake or heavy rainfall**

A slope disaster that results in Damage Level I occurs when a vehicle on the road is buried under soils. Steps in slope damage evaluation by earthquake and heavy rainfall are given in Appendix C. When the collapsed soils by earthquake or heavy rainfall are estimated to reach a height greater than the height of a vehicle window (1 m) at the center of a roadway, the damage level is judged as Damage Level I. In this process, it was assumed that surface soils on a slope collapse with a uniform depth, and the collapsed soils deposit in a triangular shape from the road edge on the slope side, as schematically illustrated in **Fig. 2**. A collapse depth on the slope was assumed to be 1 m in the case study after a geotechnical field survey of the site.

The procedure for evaluating slope damage caused by earthquake consists of evaluations of the likelihood of slope collapse studied by the Miyagi Prefectural Government[5] and the effects of slope failure on vehicles. In evaluating slope damage due to heavy rainfall, the results of the comprehensive road disaster management inspection by the Ministry of Land, Infrastructure, Transport and Tourism were applied. It was assumed that the slopes judged to require preventive measures according to the inspection but not yet measured collapse when continuous or hourly rainfall exceeds a threshold level.

**d) Road facilities evaluated to suffer damage**

As a result of the above damage evaluation, 22 cases of a combination of hazards and road facilities were identified as, in principle, they would induce damage with Damage Level I, and were qualified as subjects for risk evaluation, as shown in **Table 8**. Note that two slopes were judged to suffer damage with Damage Level I from both earthquake and heavy rainfall. Thus, 20 were identified as damaged road facilities.

**Table 8** Number of damaged road facilities.

| Hazard | Road facility | Damaged facility |
|---|---|---|
| Earthquake | Bridge | 0 |
| | Embankment | – |
| | Slope | 13 |
| | Tunnel | – |
| Tsunami | Bridge | 1 |
| Heavy Rainfall | Slope | 5 |
| Overtopping wave | Road | 3 |
| Total | | 22 |

### (3) Risk evaluation

**a) Evaluation of likelihood of hazard**

The likelihood of earthquakes and ensuing tsunami was evaluated from the mean recurrence period of plate boundary earthquakes. Note that the target section in the highway runs through the Pacific coast of Japan, and the most significant earthquake over the target section is one that occurs at a plate boundary off the Pacific coast.

A precautionary road closure section was designated within the target highway, and we assumed that slope disasters might occur at the precautionary road closure section and the rest of target highway when continuous or hourly rainfall exceeds the threshold level set for road closure. For the whole target highway section, the likelihood of heavy rainfall was evaluated from the annual average number of rainfalls exceeding the threshold level of either continuous or hourly rainfall established for road closure.

The likelihood of overtopping waves was computed from the annual average number of road closures exceeding 12 hours due to overtopping waves.

**b) Evaluation of direct damage**

The number of fatalities was evaluated from the average number of passengers for each type of vehicle and the expected number of vehicles on the road section or facility that was evaluated to suffer Level I damage. The latter was further inferred from the average traffic volume and travel velocity based on the road traffic census.

The restoration cost of a bridge damaged by tsunami includes both temporary and permanent repair costs. The former was estimated as the cost of installing a temporary bridge. The latter was estimated as the cost for replacing a bridge deck and bearings. These cost estimations are rough estimations, because restoration cost is simply classified into three categories and rated as indicated in **Table 1** in our proposed procedure, and detailed cost estimation is beyond the scope of the present study.

The restoration cost of damaged road slope by earthquake or heavy rainfall is also composed of temporary and permanent restoration costs. Temporary restoration cost was estimated as the cost of removal of collapsed soils and installation of slope protection nets. The rough estimate cost of disaster prevention measures proposed in the comprehensive road disaster management inspection was adopted as the permanent restoration cost.

**c) Evaluation of indirect damage**

For indirect damage, loss due to traffic detour was estimated according to the calculation of traveling cost before and after road work as specified in the Cost-Benefit Analysis Manual by the Ministry of Land, Infrastructure, Transport and Tourism[6]. To be specific, the traveling cost in ordinary time and in case one takes a detour instead of taking the damaged road section in the event of a disaster were calculated. The difference between the two costs was regarded as the loss resulting from traffic detour. For this calculation of traveling cost, both the "time cost," which represents the traveling time converted into the monetary value, and "driving cost," which represents all the cost related to traveling of a vehicle except the time cost, were included. It was also assumed that no change in traffic demand would occur between ordinary time and disaster time. The time cost and driving cost were calculated by using the type-specific traffic volume in the road traffic census, time-value basic unit and traveling cost basic unit in the Cost-Benefit Analysis Manual.

**d) Risk register table and risk curve**

We performed risk evaluation on the 20 road facilities identified by the damage evaluation process in Section **(2)** above. As an opportunity, we introduced a case in which slope disaster damage to houses standing along the opposite side of the road is prevented by slope measures. With this opportunity, it is possible to avert the occurrence of human damage and restoration cost, i.e., cost for sediment removal and house repair. Site No.19 is the slope where the opportunity emerges.

**Table 9** shows a risk register table. A risk is calculated here as the product of the likelihood of disaster and the magnitude of its consequences. **Fig. 3** shows a risk curve, which plots the likelihood of

**Table 9** Risk register table.

| No. | Hazard | Facility | Length (km) | Hazard rating | Threat | | | | | | Opportunity | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Human | Resto-ration | Econo-mic | Conse-quence | Risk | Order | Human | Resto-ration |
| 1 | Earthquake | Slope | 0.1 | 1 | 5 | 1 | 5 | 11 | 11 | 18 | 0 | 0 |
| 2 | Overtopping wave | Road | 8.9 | 5 | 0 | 0 | 1 | 1 | 5 | 21 | 0 | 0 |
| 3 | Earthquake | Slope | 0.2 | 1 | 5 | 5 | 10 | 20 | 20 | 8 | 0 | 0 |
| 4 | Earthquake | Slope | 0.2 | 1 | 5 | 1 | 10 | 16 | 16 | 14 | 0 | 0 |
| 5 | Earthquake | Slope | 0.4 | 1 | 5 | 5 | 10 | 20 | 20 | 8 | 0 | 0 |
| 6 | Earthquake | Slope | 0.2 | 1 | 5 | 5 | 10 | 20 | 20 | 8 | 0 | 0 |
| 7 | Earthquake | Slope | 0.5 | 1 | 5 | 5 | 10 | 20 | 20 | 8 | 0 | 0 |
| 8 | Earthquake | Slope | 0.2 | 1 | 5 | 1 | 10 | 16 | 16 | 14 | 0 | 0 |
| 9 | Earthquake | Slope | 0.2 | 1 | 5 | 5 | 10 | 20 | 20 | 8 | 0 | 0 |
| 10 | Earthquake | Slope | 0.1 | 1 | 5 | 1 | 10 | 16 | 16 | 14 | 0 | 0 |
| 10* | Heavy rainfall | Slope | 0.1 | 10 | 0 | 1 | 10 | 11 | 110 | 3 | 0 | 0 |
| 11* | Heavy rainfall | Slope | 0.3 | 10 | 0 | 5 | 10 | 15 | 150 | 1 | 0 | 0 |
| 12* | Heavy rainfall | Slope | 0.3 | 10 | 0 | 5 | 10 | 15 | 150 | 1 | 0 | 0 |
| 13 | Earthquake | Slope | 0.3 | 1 | 5 | 5 | 1 | 11 | 11 | 18 | 0 | 0 |
| 13 | Heavy rainfall | Slope | 0.3 | 5 | 5 | 5 | 1 | 11 | 55 | 4 | 0 | 0 |
| 14 | Heavy rainfall | Slope | 0.1 | 5 | 5 | 1 | 1 | 7 | 35 | 5 | 0 | 0 |
| 15 | Overtopping wave | Road | 1.4 | 10 | 0 | 0 | 1 | 1 | 10 | 20 | 0 | 0 |
| 16 | Overtopping wave | Road | 1.1 | 5 | 0 | 0 | 1 | 1 | 5 | 21 | 0 | 0 |
| 17 | Earthquake | Slope | 0.6 | 1 | 10 | 10 | 10 | 30 | 30 | 6 | 0 | 0 |
| 18 | Earthquake | Slope | 0.3 | 1 | 10 | 5 | 10 | 25 | 25 | 7 | 0 | 0 |
| 19 | Earthquake | Slope | 0.3 | 1 | 10 | 5 | 5 | 20 | 20 | 8 | 10 | 5 |
| 20 | Tsunami | Bridge | 0.03 | 1 | 5 | 1 | 10 | 16 | 16 | 14 | 0 | 0 |

* Within precautionary road closure section.

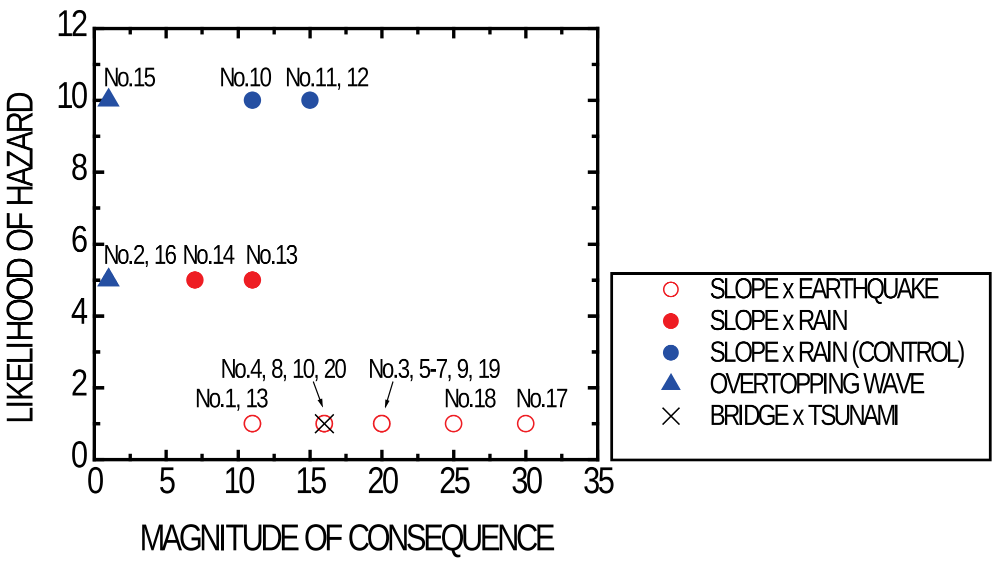


**Fig. 3** Risk curve.

disaster to its vertical axis and the magnitude of its consequences to the horizontal axis. On this diagram, a risk located in the top right region is one greater than others outside that region.

For the damage to slopes by earthquakes, although the annual likelihood of the event is small, the risk is evaluated high at sites where the human damage and/or the economic loss due to the lack of detour route is large (Site Nos.3, 5-7, 9, and 17-19).

Concerning the damage to slopes by heavy rainfall, no human damage occurs at the slopes within a precautionary road closure section (Site Nos.10-12), while the annual occurrence of heavy rainfall is judged to be "likely" because of the local rainfall characteristics at those sites. Eventually, the risks at those slopes occupy the top three in the 22 cases analyzed. Human damage may occur at slopes outside a precautionary road closure section (Site Nos.13 and 14), and the magnitudes of consequences at those sites become rather large. However, since the likelihood of heavy rainfall occurring there annually is "medium," the risks at these slopes are rated after those at the slopes within a precautionary road closure section.

Site No.20 is a bridge where tsunami is expected. The affected length of the road facility or bridge length is shorter than those of damaged slopes, and the resultant human damage and restoration cost are rated small. In addition, as the likelihood of a tsunami occurring annually is "rare," the risk at this site turns out to be small.

For damage to roads due to overtopping waves

**Table 10** Risk treatment plan.

| No. | Hazard | Facility | Length (km) | Hazard rating | Conse-quence | Reduced risk (B) | Cost (C) (1,000 yen) | B/C* | Order | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 19 | Earthquake | Slope | 0.3 | 1 | 35 | 35 | 1,000 | 3,500 | 1 | Opportunity |
| 12 | Heavy rainfall | Slope | 0.3 | 10 | 15 | 150 | 9,000 | 1,667 | 2 | |
| 11 | Heavy rainfall | Slope | 0.3 | 10 | 15 | 150 | 10,000 | 1,500 | 3 | |
| 10 | Earthquake | Slope | 0.1 | 1 | 16 | 16 | 16,000 | 788 | 4 | |
| | Heavy rainfall | | | 10 | 11 | 110 | | | | |
| 20 | Tsunami | Bridge | 0.03 | 1 | 16 | 16 | 3,600 | 444 | 5 | |
| 8 | Earthquake | Slope | 0.2 | 1 | 16 | 16 | 4,000 | 400 | 6 | |
| 1 | Earthquake | Slope | 0.1 | 1 | 11 | 11 | 3,000 | 367 | 7 | |
| 7 | Earthquake | Slope | 0.5 | 1 | 20 | 20 | 7,000 | 286 | 8 | |
| 13 | Earthquake | Slope | 0.3 | 1 | 11 | 11 | 29,000 | 228 | 9 | |
| | Heavy rainfall | | | 5 | 11 | 55 | | | | |
| 14 | Heavy rainfall | Slope | 0.1 | 5 | 7 | 35 | 19,000 | 184 | 10 | |
| 4 | Earthquake | Slope | 0.2 | 1 | 16 | 16 | 10,000 | 160 | 11 | |
| 5 | Earthquake | Slope | 0.4 | 1 | 20 | 20 | 13,000 | 154 | 12 | |
| 17 | Earthquake | Slope | 0.6 | 1 | 30 | 30 | 25,000 | 120 | 13 | |
| 3 | Earthquake | Slope | 0.2 | 1 | 20 | 20 | 23,000 | 87 | 14 | |
| 18 | Earthquake | Slope | 0.3 | 1 | 25 | 25 | 32,000 | 78 | 15 | |
| 9 | Earthquake | Slope | 0.2 | 1 | 20 | 20 | 28,000 | 71 | 16 | |
| 6 | Earthquake | Slope | 0.2 | 1 | 20 | 20 | 40,000 | 50 | 17 | |

* $B/C = B \times 10^5 / C$

(Site Nos.2, 15 and 16), although likelihood of the event is large, the risk at those sites is evaluated to be small. This is because no human damage is judged to occur as traffic control is feasible in advance. In addition, the economic loss there is small as the length of time with traffic blockage is set relatively short.

Among the road facilities with large risks, the five slopes damaged by heavy rainfall (Site Nos.10-14) are in the top positions and the eight earthquake-damaged slopes (Site Nos.3, 5-7, 9, and 17-19) follow the former. As explained above, plotting the risks for combinations of different hazards and different road facilities on the same risk curve can evaluate the magnitude of risk in a quantitative and integrated manner. One of the features of the risk evaluation conducted in the present study is that the evaluation results are generally more affected by the likelihood of event than by its consequences.

**(4) Examination of road disaster prevention measures**

Here, we introduce the idea that prevention of damage by implementing a road disaster prevention measure is the effect of that measure; define the ratio of the measure's effect to its cost as the index of cost-effectiveness; and examine the priority of road disaster prevention measures. Note that we do not consider the residual risk for simplicity reasons, and assume that disaster prevention measures remove disastrous risks from the road facilities.

The preventive measure cost of a bridge for tsunami was estimated as the cost of installing unseating prevention structures in transverse direction. We employed the rough estimate cost of disaster prevention measures proposed in the comprehensive road disaster management inspection as the measure cost of slopes for earthquake or heavy rainfall. At road facilities where opportunity exists, such as Site No.19, we included both the elimination of threat and the effects of opportunity in the the benefits of road disaster prevention measures.

Slope protection work is effective for the two types of hazards, i.e., earthquake and heavy rainfall, and the implementation of slope protection work prevents disasters by earthquake and heavy rainfall simultaneously. Thus, for the slopes where the damage levels by both hazards are rated as Damage Level I (Site Nos.10 and 13), the risks from those two hazards are put together to calculate the measure effects. Within a precautionary road closure section, the basic idea is that human damage resulting from slope damage by heavy rainfall can be prevented. However, since implementing slope protection work will mitigate restoration cost and indirect damage due to heavy rainfall, and is simultaneously capable of reducing earthquake damage, we decided to evaluate the measure effects for those slopes (Site Nos.10-12). Finally, concerning the sites affected by overtopping waves (Site Nos.2, 15 and 16), traffic control or ongoing nonstructural measures seem to be sufficient. Therefore, those sites are excluded from the list of sites that will be examined for prioritizing road disaster prevention measures.

**Table 10** shows a risk treatment plan arranged in descending order of cost-effectiveness. Note that cost-effectiveness is measured by a common index for various road facilities exposed to various natural disasters as shown in **Table 10**, and this table can be applied to prioritizing road disaster measures.

The measure costs are essentially different from the restoration costs, and it would be ideal if different ratings for the measure and restoration were developed. However, we do not have enough experience in developing different ratings for these two costs, thus we attempted to apply the rating for restoration costs, which is shown in **Table 1**, to the measure costs. In this case, measure cost at any site is classified as "minor," and this makes the ranking of cost-effectiveness the same as that of risk. Thus, we adopted the amount of money for estimating the measure cost in **Table 10**.

The effect of road disaster prevention measures at Site No.19 increased from 20 to 35 by including the opportunity, compared with the case where threat alone was considered. At this site, the implementation of slope protection work was effective in preventing damage to houses standing along the opposite side of the road, and this effect was regarded as an opportunity. However, as shown in **Table 10**, the cost-effectiveness of the road disaster prevention measures for Site No. 19 seems to be highly evaluated because of the small measure cost rather than the impact of the opportunity. Similarly, a high score is given to the cost-effectiveness at Site No.20, where the tsunami is expected to cause damage to the bridge, because of the small measure cost.

At Site Nos.10 and 13, which are slopes where damage is expected from two hazards, i.e., earthquake and heavy rainfall, the road disaster prevention measures have larger effect by considering the prevention of the two hazards rather than the prevention of either single hazard. At the three slopes damaged by heavy rainfall (Site Nos.10-12) including the above Site No.10, although the measure cost is relatively high, the risk is rated large, which eventually leads to the higher evaluation of the cost-effectiveness of the road disaster prevention measures.

## 4. CONCLUSION

We proposed a practical system to systematically evaluate damage risks to road facilities by natural disasters and conducted a case study on a section of the national highway. The proposed procedure particularly focuses on the quantitative evaluation of risks to various road facilities from various disasters by using a common index, and incorporates both threats and opportunities into the analysis. Opportunities are favorable outcomes incidentally resulting from the implementation of road disaster prevention measures. Based on the idea that prevention of damage by implementing a road disaster prevention measure is the effect of the measure, we examined the priority of measures from the viewpoint of the ratio of the measure effects to its cost.

Although further detailed study will be necessary to improve the rating of the likelihood of hazards and their consequences, which has been introduced to make the quantitative evaluation of risks in our study, the proposed procedure is helpful in prioritizing road disaster prevention measures by comparing the impacts of various disasters on various road facilities.

**ACKNOWLEDGMENT:** The author would like to express his sincere appreciation to all those who provided valuable data for the conduct of the case study.

# APPENDIX A EVALUATION OF BRIDGE DAMAGE LEVEL BY EARTHQUAKE

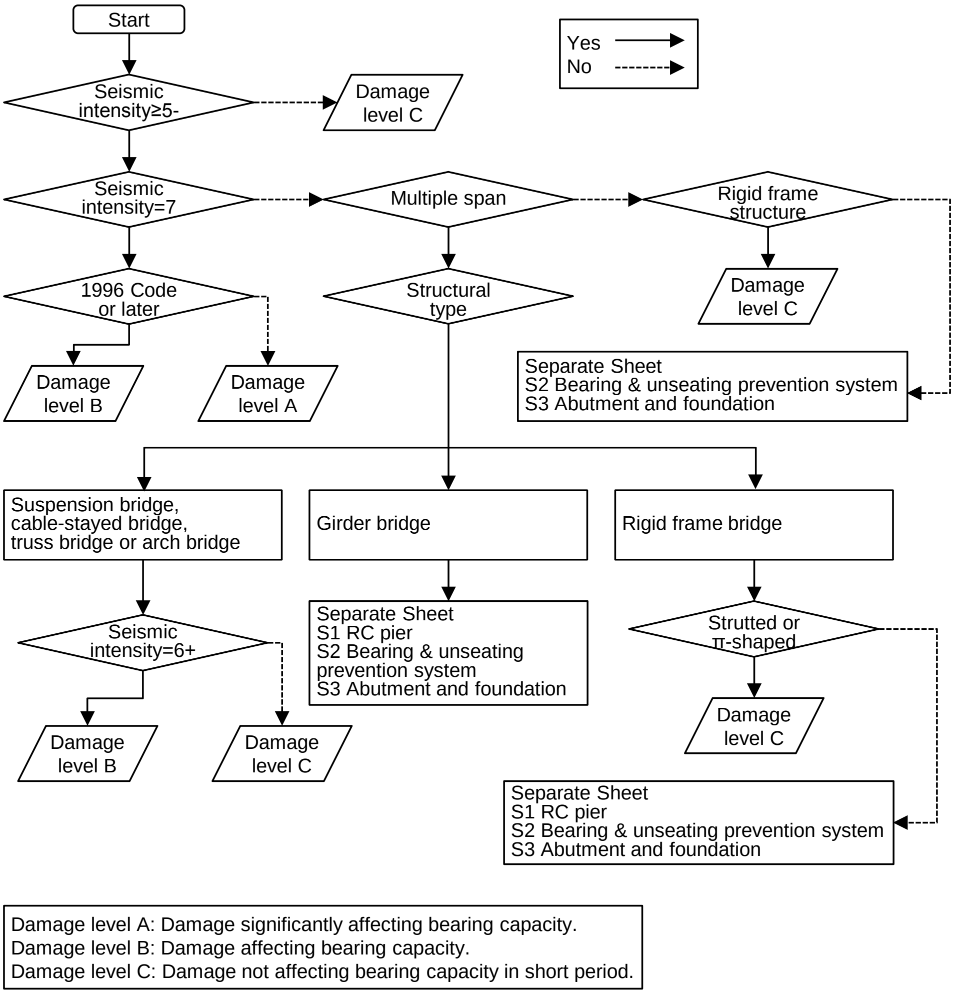


**Fig. A.1** Flow chart of evaluation of bridge damage level by earthquake.

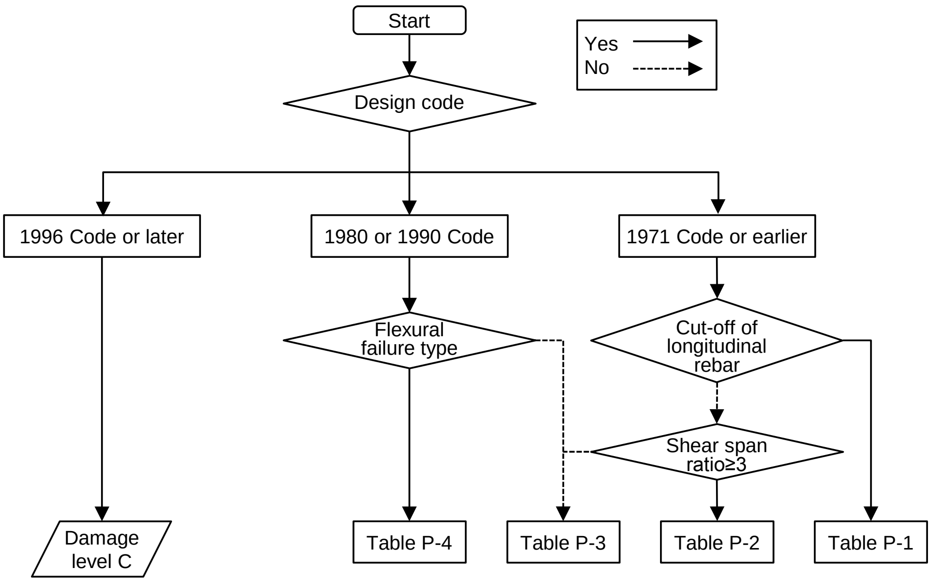


**Fig. A.2** Separate sheet for RC pier.

**Table A.1** Damage level evaluation of RC pier.

(a) Table P-1

| Support condition | Pier type (Direction) | Damage level A | Damage level B | Damage level C |
|---|---|---|---|---|
| Seated section (F-M) | Single column Rigid frame or wall pier (Long) | SI≥60 | 60>SI≥45 | 45>SI |
| | Rigid frame or wall pier (Trans) | SI≥80 | 80>SI≥45 | 45>SI |
| Intermediate support (F) Seated section (F-F) | Single column Rigid frame or wall pier (Long) | SI≥60 | 60>SI≥45 | 45>SI |
| | Rigid frame or wall pier (Trans) | SI≥80 | 80>SI≥45 | 45>SI |
| Intermediate support (M) Seated section (M-M) | Single column | SI≥60 | 60>SI≥45 | 45>SI |
| | Rigid frame or wall pier | SI≥80 | 80>SI≥45 | 45>SI |
| Rubber bearing | Single column | SI≥60 | 60>SI≥45 | 45>SI |
| | Rigid frame or wall pier | SI≥80 | 80>SI≥45 | 45>SI |

F: fixed, M: movable, Long: longitudinal, Trans: transverse
SI: spectrum intensity (cm/s)

(b) Table P-2, P-3 and P-4

| Support condition | Pier type (Direction) | Damage level A | Damage level B | Damage level C |
|---|---|---|---|---|
| Seated section (F-M) | Single column Rigid frame or wall pier (Long) | SI≥70 | 70>SI≥45 | 45>SI |
| | Rigid frame or wall pier (Trans) | SI≥80 | 80>SI≥45 | 45>SI |
| Intermediate support (F) Seated section (F-F) | Single column Rigid frame or wall pier (Long) | SI≥70 | 70>SI≥45 | 45>SI |
| | Rigid frame or wall pier (Trans) | SI≥80 | 80>SI≥45 | 45>SI |
| Intermediate support (M) Seated section (M-M) | Single column | SI≥70 | 70>SI≥45 | 45>SI |
| | Rigid frame or wall pier | SI≥80 | 80>SI≥45 | 45>SI |
| Rubber bearing | Single column | SI≥70 | 70>SI≥45 | 45>SI |
| | Rigid frame or wall pier | SI≥80 | 80>SI≥45 | 45>SI |

F: fixed, M: movable, Long: longitudinal, Trans: transverse
SI: spectrum intensity (cm/s)

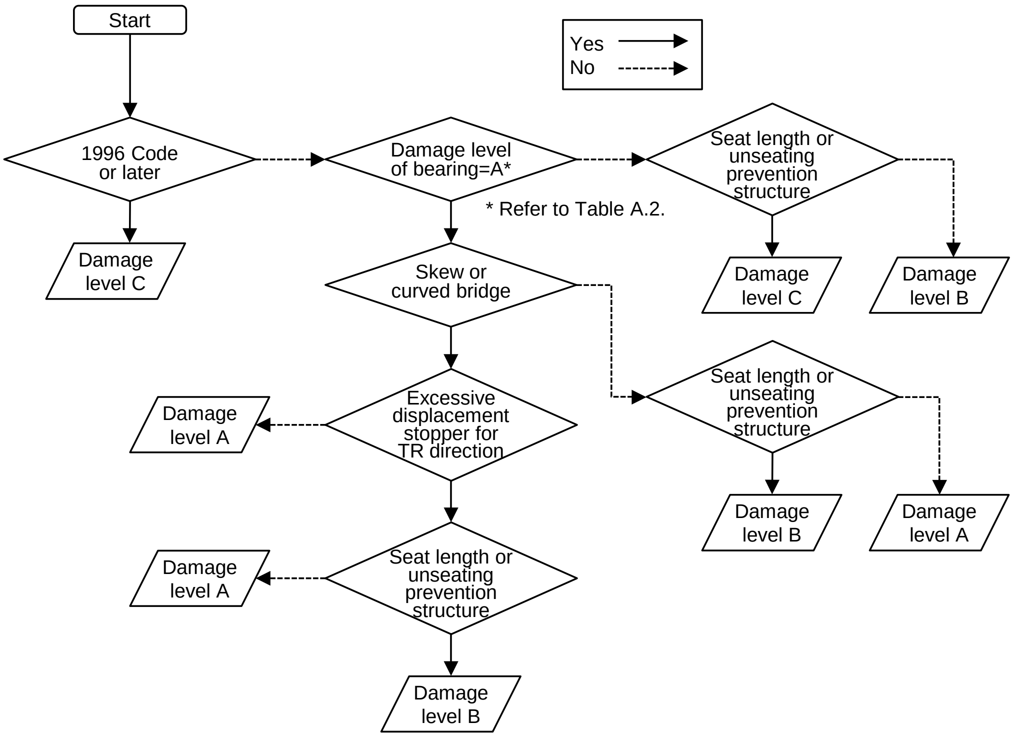


**Fig. A.3** Separate sheet for bearing and unseating prevention system.

**Table A.2** Damage level evaluation of bearing.

| Bearing type | Damage level A |
|---|---|
| Rocker bearing | SI≥40 |
| Line bearing | SI≥60 |
| Roller bearing | SI≥40 |
| Pin bearing | SI≥40 |
| Pivot bearing | SI≥40 |
| Bearing with bearing plate | SI≥60 |
| Rubber bearing | SI≥85 |

SI: spectrum intensity (cm/s)

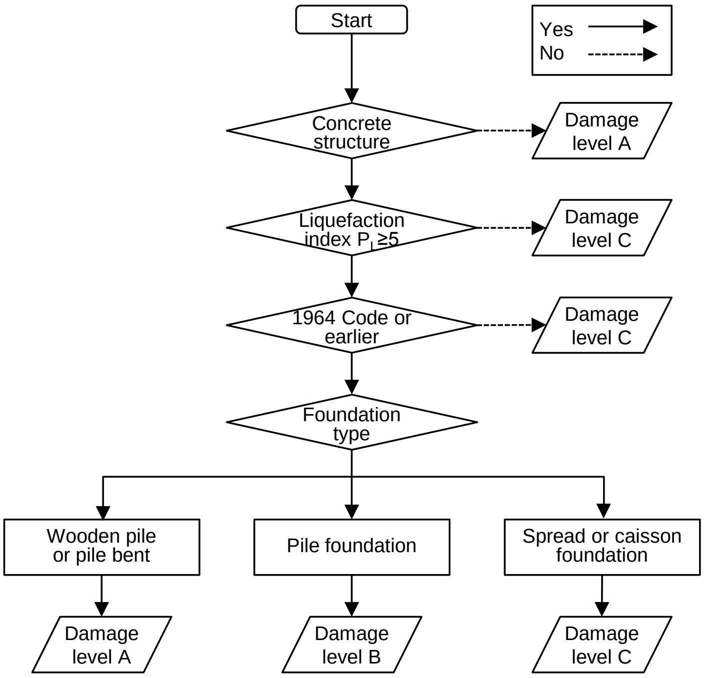


**Fig. A.4** Separate sheet for abutment and foundation.

# APPENDIX B EVALUATION OF BRIDGE DAMAGE LEVEL BY TSUNAMI

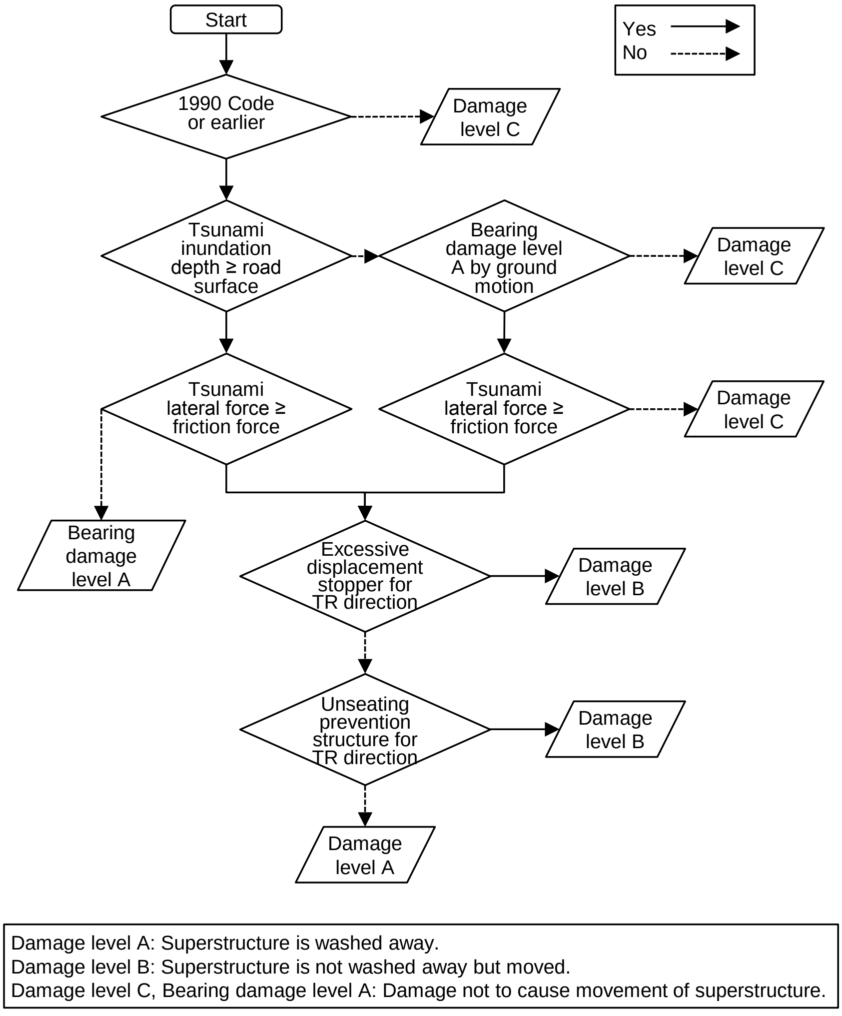


**Fig. B.1** Flow chart of evaluation of bridge damage level by tsunami.

# APPENDIX C EVALUATION OF SLOPE DAMAGE LEVEL BY EARTHQUAKE OR HEAVY RAINFALL

**Table C.1** Basic score for slope stability evaluation.

| Item | Description | Score |
|---|---|---|
| Slope height H(m) | H<10 | 3 |
| | 10≤H<30 | 7 |
| | 30≤H<50 | 8 |
| | 50≤H | 10 |
| Slope angle θ° * tan59° =5/3 (1:0.6) | θ<45 | 1 |
| | 45≤θ<59 | 4 |
| | 59≤θ | 7 |
| Overhang | Overhang without protection work | 7 |
| | Overhang with protection work | 4 |
| | No overhang | 0 |
| Slope geology * Adopt the highest value as a sore. | boulder or unsteady stones on the surface | 10 |
| | cobble stones on the cut slope | 7 |
| | weathering rock with cracks | 6 |
| | gravely soil | 5 |
| | weathering rock | 4 |
| | cracked rock | 4 |
| | sandy soil | 4 |
| | clayey soil | 1 |
| | rock without cracks | 0 |
| Thickness of surface soil D(m) | 0.5≤D | 3 |
| | D<0.5 | 0 |
| Spring water | Yes | 2 |
| | No | 0 |
| Annual occurrence of rockfall or collapse p | 1.0≤p | 5 |
| | p<1.0 | 3 |
| | None | 0 |
| Total score S | | |

**Table C.2** Likelihood of slope collapse by earthquake.

| Seismic Intensity | Total score S (Table C.1) | | |
|---|---|---|---|
| | S≤13 | 14≤S≤23 | 24≤S |
| 6+ or 7 | A | A | A |
| 6- | B | A | A |
| 5+ | C | B | A |
| 5- | C | C | B |
| 4 | C | C | C |

A: Likely to collapse.
B: Possibly collapse.
C: Unlikely to collapse.

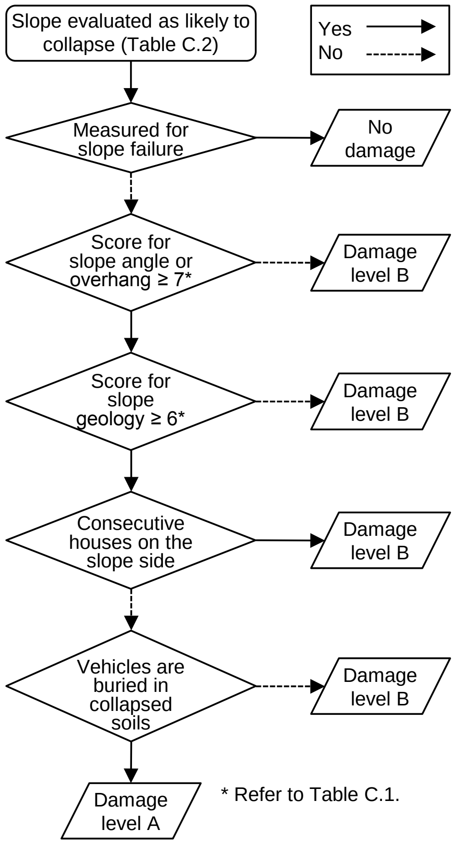


**Fig. C.1** Flow chart of evaluation of slope damage level by earthquake.

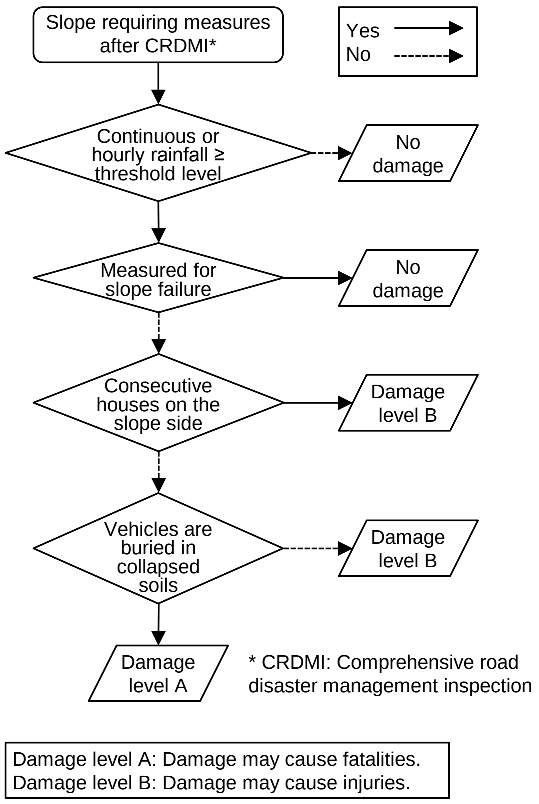


**Fig. C.2** Flow chart of evaluation of slope damage level by heavy rainfall.

## REFERENCES


1) Transit New Zealand: Risk Management Process Manual, Version 3, 2004.
2) International Organization for Standardization and International Electrotechnical Commission: Risk management - Vocabulary - Guidelines for use in standards, ISO/IEC Guide 73, 2002.
3) Kobayashi, H. and Unjoh, S.: Development of simplified seismic damage assessment method of road bridges based on past damage experiences, *Civil Engineering Journal*, Vol.47, No.12, pp.48-53, 2005 (in Japanese).
4) National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism: A draft manual for developing earthquake-tsunami disaster scenarios including damage to public works, *Technical Note of NILIM*, No.485, 2008 (in Japanese).
5) Miyagi Prefectural Government: Report on earthquake damage estimation, 1997 (in Japanese).
6) Ministry of Land, Infrastructure Transport and Tourism: Cost-Benefit Analysis Manual, 2003 (in Japanese).


**(Received September 18, 2012)**