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How Strong Should Elevated Roads Be?
— Anti-Quake Cognitive Cost/Benefit Network Design —

By

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ABSTRACT

Cost-benefit analysis (CBA) would be a scientific and rational methodology for the deciding on the level of disaster mitigation investment. However, the optimal investment level calculated by "traditional" CBA does not meet an actual and reasonable investment levels which are socially accepted. Then, how should we rationally design the level of disaster mitigation investment? In this paper we propose the framework of "cognitive" cost-benefit analysis (CCBA) in which the progressive effect of catastrophic loss is considered. After discussing theoretical phase of the progressive effect, we propose three methodologies to measure cognitive loss function and cognitive probability function. We applied CCBA on several simple road networks and find the optimal anti-quake performance of each links of each netwark. This CCBA could provide a theoretically reasonable and practical anti-quake performance more precisely in an accountable way.

1. INTRODUCTION

After the Hanshin-Awaji Earthquake, many improvements and investments for mitigating damages due to earthquakes have been made in Japan. For example, the Japanese structural design code established by JSCE (the Japan Society of Civil Engineering) for elevated roads against earthquake has been improved.

This standard defines two levels of earthquakes according to their magnitude. The first is level 1 type earthguakes that on average occur more than once during the entire service life of the structure (usually 50 to 100 years). The standards stipulate that structures should be designed so that users would not be affected by this type of earthquake. The second is level 2 type earthguakes that on average occur less than once during the entire service life of the structure but with very serious damage. The present standards stipulate two design levels against this type of earthquake, that is ensured functionality of the structure for especially important structures and not structurally broken for others. However, there still remain three questions; why the standards stipulate "two" design levels, why these design levels are stipulated at such structural strength, and how do we decide on each structure's importance? Therefore, a reasonable methodology is required so that we can decide the level of structural strength of elevated roads under level 2 type of earthquakes' exposure.

Similar problems can be easily seen when we invest in mitigating damages caused by various disasters or accidents, especially when such events occur with a very low probability but with

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catastrophic losses. How should we decide the investment level for disaster mitigation?

The methodology for evaluating investment in disaster mitigation would be normally cost-benefit analysis (CBA). However, the optimal investment level calculated by "traditional" CBA could not often explain actual investment levels, as the probability of catastrophic events is very low leading to very low expected damage (i.e. the product of probability and loss) which is usually much smaller than the investment cost, while in reality a lot of investments have already been made.

Why does this investnent gap exist? Of course, we can assume that actual investments for disaster mitigation are not rational. However, recalling that many investments have been conducted according to social requirements, it may be better to think that a calculation by "traditional" CBA is not sufficient to describe the actual decision-making process.

In this paper, we will propose a new CBA method for the design of disaster mitigation investment, termed as cognitive cost-benefit analysis (CCBA). In CCBA, we assume that investment levels are designed based on subjective judgment of the probability and amount of loss filtered through human cognitive processes, instead of the real expected value. We call these components as cognitive probability and cognitive loss.

The remainder of this paper is organized as follows. Section 2 shows the theoretical derivation that cognitive loss increases progressively as monetary loss increases (we call this characteristic as the "progressive effect of catastrophic loss"). Section 3 formulates optimal anti-quake performance design through CCBA. And then section 4 proposes three methodologies to measure cognitive loss and shows the results of each methodology. In section 5, we do trial calculations for the design of optimal anti-quake performance of several types of hypothetical transport network under earthquake exposure. The final section provides a summary and identifies directions for future research.

2. PROGRESSIVE EFFECT OF LOSS AND INSURANCE SYSTEMS

In this section, we will show the theoretical derivation that cognitive loss increases progressively as monetary loss increases, and that this progressive effect of catastrophic loss is less effective when an insurance system is introduced.

2.1 Theoretical derivation of progressive effect of catastrophic loss

Assuming one social group (population N) of which members get utility of $u(y)$ from income y, and characteristics of utility function $u(y)$ is as follows (Fig.1);

i) *Marginal utility decreases as utility increases*. That is, $u'(y) > 0$ and $u''(y) < 0$. (1)

ii) *Any member who has no income cannot be alive*. That is, $u(0) = -\infty$. (2)

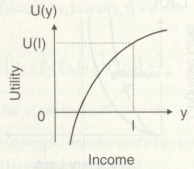

Fig.1: Utility function $U(y)$ from income y

If there is no disaster, each member of the group gains income I. When n members out of the group incur physical loss D per person due to some disaster, the income of each affected member is expressed by Equation (3).

$$y = I - D. \tag{3}$$

The decrease in utility ΔU of each affected member is expressed by Equation (4).

$$\Delta U = u\,(I) - u\,(I - D). \tag{4}$$

Total loss L_0 of the group caused by the disaster is expressed by Equation (5).

$$L_0(D) = \sum_N \Delta U = \sum_n \Delta U = n\{u(I) - u(I - D)\}. \tag{5}$$

From Equations (1) and (5), we get

$$\frac{dL_0}{dD} = n \cdot u'(y) > 0, \tag{6}$$

$$\frac{d^2 L_0}{dD^2} = -n \cdot u''(y) > 0. \tag{7}$$

By Equations (6) and (7), it is clear that $L_0\,(D)$ is convex and increases more progressively as n increases. In addition, because of $L_0\,(0) = 0$ and $L_0\,(I) = \infty$, we can gain cognitive loss function $L_0\,(D)$ as Fig.2.

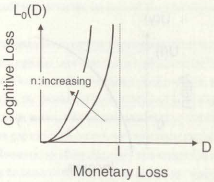

Fig.2: Cognitive loss function $L_0\,(D)$

What happens if there is some insurance system compensating loss of affected members? We assume that $\alpha \cdot D\ (0 \le \alpha \le 1)$ out of damage D can be compensated by other members who have no loss. Then income of affected members, y_A, and the income of others, y_B, is expressed by Equations (8) and (9), respectively.

$$y_A = I - (1 - \alpha)\, D, \tag{8}$$

$$y_B = I - \frac{n}{N-n}\alpha \cdot D\,. \tag{9}$$

In the extreme case that all members pay losses equally regardless of whether he or she has incurred losses from the disaster or not, through payment of the insurance premium. In this case α is maximzed and can be defined by Equation (10), from $y_A = y_B$.

$$\alpha = \frac{N-n}{N}\,. \tag{10}$$

Introducing $\beta\ (0 \le \beta \le 1)$, the possible range of α is defined by Equation (11).

$$0 \le \alpha \le \beta\,\frac{N-n}{N}\,. \tag{11}$$

Total loss $L_1(D)$ of the group is,

$$L_1(D) = \sum_N \Delta U = n\{u(I) - u(y_A)\} + (N-n)\{u(I) - u(y_B)\}. \tag{12}$$

Then,

$$\frac{dL_1}{dD} = n\{(1-\alpha)\,u'(y_A) + \alpha\, u'(y_B)\} > 0\,, \tag{13}$$

$$\frac{d^2L_1}{dD^2} = -n\,\{(1-\alpha)^2 u''(y_A) + \alpha^2 u''(y_B)\} > 0\,. \tag{14}$$

In this case progressive effect of catastrophic loss also exists.

2.2 Diluting effect of insurance systems for the reduction of progressive effect

Differentiating Equation (13) with respect to α, we get

$$\frac{\partial}{\partial \alpha}\left(\frac{dL_1}{dD}\right) = n\,\{u'(y_B) - u'(y_A)\} \le 0\,. \tag{15}$$

Because we can see Equation (16) from that the utility of those affected by disaster should be less than those not affected.

$$u'(y_B) \le u'(y_A). \tag{16}$$

Equation (15) shows that the gradient of cognitive loss function L_1 (with insurance systems) will decrease as α increases. Thus cognitive loss function $L_1\,(D)$ will shift downwards as α (i.e. as coverage of insurance) increases, shown in Fig.3.

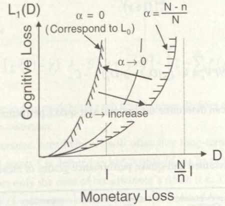

Fig.3: Cognitive loss function $L_1\,(D)$ (with insurance systems)

3. OPTIMAL ANTI-QUAKE PERFORMANCE DESIGN CONSIDERING THE PROGRESSIVE EFFECT OF CATASTROPHIC LOSS

In this section, we propose cognitive cost-benefit-analysis (CCBA) for the design of optimal investment level for disaster mitigation, considering the progressive effect of catastrophic loss. Especially, we will show the formulation of CCBA for the design of elevated road structures considering earthquake exposure.

We define an initial anti-quake performance of elevated road as *Grade 0*, and several hypothetical anti-quake performance levels as *Grade i* (see Table 1). D_i is monetary damage at *Grade i*, and C_i is cost for improvement of the elevated road from *Grade 0* to *Grade i*. $g(.)$ is the cognitive loss function considering the progressive effect of catastrophic loss. Then cognitive net present value ($CNPV_i$) of the upgrade investment from *Grade 0* to *Grade i* is formulated by Equation (17).

$$CNPV_i = \sum_{t=1}^{T_E} \frac{P_t}{(1+r)^t} \cdot \{g(D_0) - g(D_i)\} - C_i , \tag{17}$$

where,

P_t : yearly probability of earthquake at time t,

r : social discount rate,

T_E : evaluation period for the project.

Here we introduce k as

$$k \equiv \sum_{t=1}^{T_E} \frac{P_t}{(1+r)^t} . \tag{18}$$

Then,

$$CNPV_i = k \cdot \{g(D_0) - g(D_I)\} - C_I . \tag{19}$$

By Eguation (19), we can determine the optimal anti-quake performance grade i at which grade $CNPV_i$ is maximized.

Table 1 Assumed anti-quake performance grades of elevated road

Anti-Quake Performance Grade	Post Earthquake Condition	Construction Cost (Bilion ¥ / km)	Repair Cost (Billion ¥ / km)	Required Time for Repair (Days)	Death of Users (%)
Grade 0	Structually broken	7.6	9.1	196	100%
Grade 1	Lose the use of structure	8.4	0.89	78	50%
Grade 2	Maintain the use of structure	9.2	0.15	13	10%
Grade 3	No structural damage	10.1	0	0	5%
Grade 4	No damage on running vehicles	10.7	0	0	0%

4. MEASUREMENT OF COGNITIVE LOSS FUNCTION (CLF)

4.1 CLF estimation through individual insurance data

(1) Formulation of individual insurance behaviors

We consider each household's decision-making process on life-insurance and earthquake-insurance. Each household decides the rate $\gamma (0 \le \gamma \le 1)$, which is a proportion of insured assets Q out of all possibly insured assets S (i.e., $Q = \gamma \cdot S$), in order to minimize his or her cognitive expected damage. Then the insurance premium is expressed as $r \cdot \gamma \cdot S$ where r is the insurance premium rate.

If a household is affected by some disaster or accident, its loss will be $(1 - \gamma) \cdot h_x \cdot S$, where $h_x (0 \le h_x \le 1)$ is a degree of damage at a damage level x out of completed damag level X. Moreover we express a probability of earthquake occurrence to be p_x at a damage level x. Then defining $g(.)$ as a cognitive loss function and $f(.)$ as a cognitive probability function (CPF), the "cognitive" expected loss U_x ($U_x > 0$ means this household gain profit) with a damage level x and U_0 with no damage can be expressed as following equations.

i) *If some disaster happen,* $U_x = -f(p_x) \cdot [\, g\{(1-\gamma) \cdot h_x \cdot S\} + r \cdot \gamma \cdot S \,]$ (20)

ii) *If no disaster heppen,* $U_0 = -\left\{ 1 - \sum_{x=1}^{X} f(p_x) \right\} \cdot r \cdot \gamma \cdot S .$ (21)

Then total cognitive expected loss U is sum of all of U_x and U_0 .

$$\begin{aligned} U &= \sum_{x=1}^{X} U_x + U_0 \\ &= -\sum_{x=1}^{X} f(p_x) \cdot [g\{(1-\gamma) \cdot h_x \cdot S\} + r \cdot \gamma \cdot S] - \left[1 - \sum_{x=1}^{X} f(p_x) \right] \cdot r \cdot \gamma \cdot S . \end{aligned} \tag{22}$$

We assume in this model that each breadwinner decides the rate γ that maximizes U .

a) Formulation in life-insurance

In life-insurance, breadwinners will often buy long-term insurance at one time. All possibly insured assets S is defined as lost profits LI_a as he or she die at a years later from now. We consider only the case of breadwinner's death (i.e. $X = 1$ and $h_1 = 1$ in Equation (22)), then objective function of breadwinner is defined by Equation (23) where U_a is "cognitive" expected loss if the breadwinner dies between $(a\text{-}1)$ and a years later.

$$\max_{\gamma} \sum_{a=1}^{Y-a_0} U_a , \tag{23}$$

where, a_0 : breadwinner's present age,

Y: maximum age (we assume $Y = 110$ years old).

And it is also assumed that γ is constant during the validity of the insurance. That is,

$$\gamma_a \begin{cases} \gamma \textit{(during the insurance term)} \\ = 0 \textit{ (otherwise)} \end{cases}$$

Now we can define each breadwinner's monetary loss D_a (loss due to death of breadwinner between *(a-1)* and *a* years later) by Equation (24).

$$D_a = \frac{LI_a - Q_a}{(1+ii)^a} = \frac{LI_a - \gamma_a \cdot LI_{(a_1-a_0)}}{(1+ii)^a}, \tag{24}$$

where, a_1: breadwinner's age at the start of the insurance term,

ii: breadwinner's subjective discount rate (unknown parameter). It is introduced due to an assumption that more future losses have less effect on present decision-making.

Further each breadwinner will pay an insurance premium R_a (defined by Equation (25)) until he or she dies.

$$R_a = \sum_{t=1}^{a} \frac{r_{a_1,T} \cdot \gamma_a \cdot LI_{(a_1-a_0)}}{(1+ii)^t}, \tag{25}$$

where, $r_{a1,T}$: the insurance premium rate when breadwinner's age is a_1 years old and insurance contract period is *T*, as defined by Equation (26).

$$r_{a_1,T} = \frac{\left[\begin{array}{l} P_{a_1}\cdot(1+i_c)^{(T-0.5)} + (1-P_{a_1})\cdot P_{a_1+1}\cdot(1+i_c)^{(T-1.5)} + \cdots \\ +(1-P_{a_1})\cdot(1-P_{a_1+1})\cdots(1-P_{a_1+T-2})\cdot P_{a_1+T-1}\cdot(1+i_c)^{0.5} \end{array}\right]}{\left[\begin{array}{l} (1+i_c)^T + (1-P_{a_1})\cdot(1+i_c)^{(T-1)} + \cdots \\ +(1-P_{a_1})\cdot(1-P_{a_1+1})\cdots(1-P_{a_1+T-2})\cdot(1+i_c) \end{array}\right]}\cdot(1+r_c), \tag{26}$$

where, P_x: probability of death at *x* years old,

i_C: interest rate set by insurance company (We set $i_C = 2.5\%$),

r_C: charge rate of insurance company (We set $r_C = 5.0\%$).

Thus, U_a is expressed by Equation (27).

$$\begin{aligned} U_a &= -f(p_{a_0,a})\cdot\{g(D_a) + R_a\} \\ &= -f(p_{a_0,a})\cdot\left\{ g\left(\frac{LI_a - \gamma_a \cdot LI_{(a_1-a_0)}}{(1+ii)^a}\right) + \sum_{t=1}^{a}\frac{r_{a_1,T}\cdot\gamma_a\cdot LI_{(a_1-a_0)}}{(1+ii)^t}\right\}, \end{aligned} \tag{27}$$

where, $p_{a0,a}$: probability that a breadwinner at a_0 years old will die between *(a-1)* and *a* years later.

b) Formulation in earthquake-insurance

In earthquake-insurance, each breadwinner is supposed to renew his or her insurance contract every year, so his or her behavior is expressed by Equation (22). All possibly insured assets *S*, is defined as sum of the estimated value of his or her house and all furniture.

(2) Data processing

We got actual data on life insurance and earthquake insurance from the NIKKEI-RADAR survey, its data set is comprised of about 1,500 breadwinners in Tokyo including information on being insured or not, insurance premium, insured asset, and so on. From these data, we estimated some parameters such as a_0, γ, *T*, and LI_a. Then P_x and $p_{a0,a}$ were taken from life insurance statistics, and p_x was determined from historical earthquake record and durability against earthquake due to type of residence.

(3) Estimation results of CLF

a) For life-insurance

We fixed the function types and parameters of CLF and CPF, so that the sum *(235* samples) of the square of the difference between each breadwinner's actual γ and estimated γ calculated by Equation (23) would minimized. And we calculated unknown parameter *ii* as well (it is estimated *1.1%*). Fig.4 shows the results that cognitive loss is about 2-3 times as monetary loss, while cognitive probability is almost same as physical probability. According to Fig.5 which compares actual and estimated insured asset, our model doesn't appear to reproduce actual behaviors of life insurers so much. However, it could be considered sufficient and even significant, judging from the complexity of insurance decision-making and the simplicity of the model.

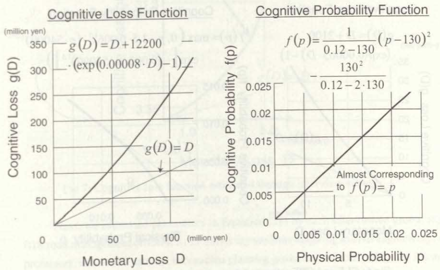

Fig.4: CLF and CPF estimated through life insurance analysis

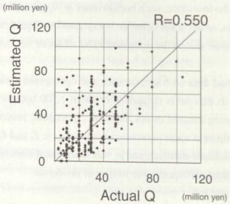

Fig.5: Comparison of actual and estimated Q

b) For earthquake-insurance

For earthquake-insurance, we calculated from *96* household's data for the function types and parameters of CLF and CPF (shown in Fig.6) by the same way as the life-insurance case. However the reproduction of result is not good, results are that cognitive loss is about 3 times as monetary loss, and cognitive probability is estimated lower than physical probability when probability is lower than 0.8% and it is estimated nearly zero when probability is lower than 0.3%.

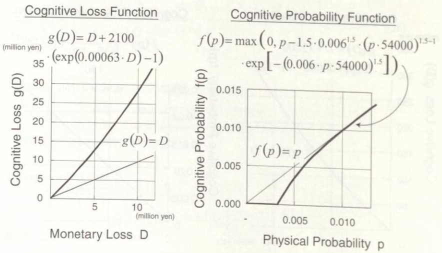

Fig.6: CLF and CPF estimated through earthquake insurance analysis

4.2 CLF estimation through interview survey

(1) Summary of interview survey and formulation for measurement

We made a questionnaire about anti-quake performance of elevated road, and interviewed 65 experts such as national bureaucrats planning governmental road policy, road management officers and professors majoring in civil engineering or disaster mitigation.

In this questionnaire, we set 16 scenarios with different probability of earthquake occurrence and projected loss. Interviewees were requested to choose an anti-quake performance level out of 5 levels considering damage and improvement cost. We set a function type for CLF as Equation (28), and from the results of their stated preference, we estimated model parameters through a multinomial logit model and maximum likelihood estimation. In this model, we didn't consider cognitive effect of probability because in the questionnaire probabilities are clearly given in advance.

$$g(D) = D + \lambda_1 D^{\lambda_2}, \tag{28}$$

where, λ_1, λ_2 : unknown parameter.

(2) Estimation results of CLF

The estimation results of parameters are shown in Fig.7. Cognitive loss is estimated 1 to 5 times more than monetary loss, and cognitive loss increases progressively as monetary loss increases.

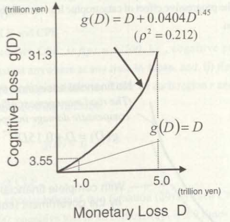

Fig.7: Cognitive loss function estimated through interview survey

Next, we estimated parameters in Equation (28) by each interviewee group, that is, i)18 road management officers, ii) 27 university students majoring in civil engineering, iii) 8 professors, and iv) 12 national bureaucrats planning governmental road policy. As illustrated in Fig.8, the progressive effect of catastrophic loss differs across interviewee category. We can deduce from this result that decision-makers who have to make decisions with much broader scope have less progressive effect.

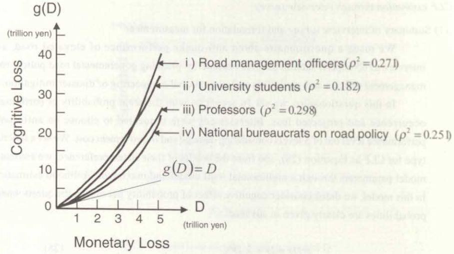

Fig.8: Cognitive loss functions by interviewee category

Then, we investigated differences due to insurance systems provided by government. In the above questionnaire, it was written that the government will completely compensate the damage of elevated roads by disaster, that is, we assumed there is a type of insurance system through the government. We prepared another questionnaire where it was written that the road management office has to compensate damage indepedently. As a result, as shown in Fig.9, the progressive effect of catastrophic loss is much bigger in case of no financial assistance system.

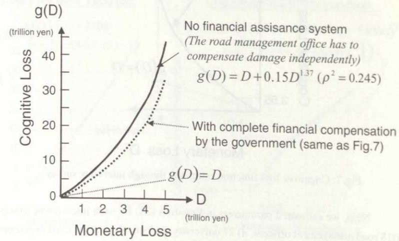

Fig.9: Effect of governmental financial compensation upon CLF

4.3 CLF estimation through actual investment data for elevated road reinforcement against earthquakes

(1) Framework of measurement and actual investment on urban expressway

Under an assumption that actual investment for disaster mitigation is decided by social decision-maker by maximizing his or her cognitive net present value (*CNPV*) defined by Equation (17), we can estimate CLF from actual anti-quake performance grade and monetary loss and cost at each *Grade i*. Here we consider actual reinforcement investment of elevated roads of urban expressway after the Hanshin-Awaji Earthquake (1995), such as Metropolitan Expressway, Hanshin Expressway, and Kita-Kyusyu & Fukuoka Expressway Public Corporations. Before the Hanshin-Awaji Earthquake, all elevated roads of these expressways were at *Grade 1* (see Table 1), then by reinforcement investment all elevated roads of Metropolitan Expressway and Hanshin Expressway and about 70% elevated roads of Kita-Kyusyu & Fukuoka Expressway have been improved to *Grade 2*, while the rest of Kita-Kyusyu & Fukuoka Expressway's elevated roads are still at *Grade 1*.

(2) Estimation of loss at each anti-earthquake performance level

We calculated the amount of monetary loss D as the sum of 8 types of damage, namely, i) users' death, ii) non-users' (roadside residents) death, iii) users' injury, iv) non-users' injury, v) damage of elevated roads, vi) damage to neighboring buildings, vii) damage to vehicles, and viii) lost time due to rerouting. By each grade and by each item, we set the proportion of persons or buildings affected by level 2 type of earthquakes, and set monetary loss per unit damage, for example, loss due to a person's death is assumed to be 40 million yen. (This is derived from average estimated income during lifetime of those who are killed by traffic accident)

(3) Preparations for CLF and CPF

We assumed two CPF; i) $f(p) = 1/100$, i.e., cognitive probability of earthquake occurrence is constant anywhere at any time in Japan, and, ii) $f(p) = P_{t,r}$, i.e., no cognitive effect on probability and probabilies are differ by each region r and with lapse of time. Then CLF was set as the following function.

$$g(D) = \eta \cdot D \,. \qquad (29)$$

(4) Estimation results of CLF

The results of calculation of η in Equation (29) by each CPF are shown in Fig.10. In case i) $f(p) = 1/100$, cognitive loss in all expressways is 2-3 times as monetary loss, while in case ii) $f(p) = P_{t,r}$ cognitive loss in all expressways is very much larger than monetary loss. Comparing these results with the results of Section 4.1 and 4.2, it may be better to assume that decision-makers actually design reinforcement investment level of elevated roads with constantly recognition of the probability of earthquake occurrence anywhere in Japan.

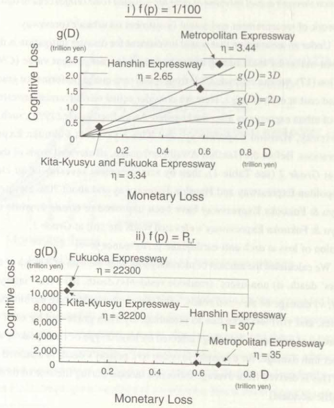

Fig.10: CLFs estimated from actual investment on urban expressways

5. APPLICATION OF CCBA FOR ANTI-QUAKE DESIGN OF ROAD NETWORKS

5.1 Road networks for the application

We tried to calculate the optimal anti-quake performance of elevated roads of a simple hypothetical network. Three types of road network are set, i.e., (A) square network, (B) rectangular network, (C) radial-circular network, as shown in Fig.11. Each node is both source and sink of traffic. Every elevated road link has one corresponding ground link which is assumed not to be affected by earthquake so that each node of elevated roads could not be totally isolated due to earthquakes (shown in Fig.12). And we set environment conditions of these networks, such as population density and traffic volume, are almost equal.

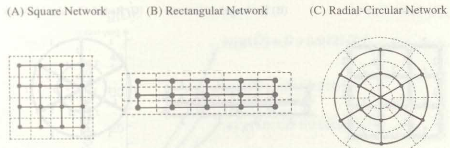

Fig. 11: Types of road network

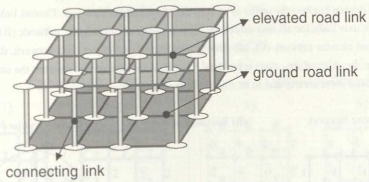

Fig. 12: Structure of road system

5.2 Optimal anti-quake performance design using GA

We will calculate the optimal anti-quake performance grade by each elevated road link according to Equation (19). However, even a calculation of the above simple network which has only 5 structural grades and 24 links will result to a possible combination of anti-quake performance of 5^{24}. To find more easily the optimal combination of each link's anti-quake performance, we used GAs (genetic algorithms) method. In this calculation, we used the results shown in Fig.7 for CLF, and set two cognitive probability of earthquake occurrence, i.e., i) $f(p) = 1/100$ (assuming seismic plate earthquake) and ii) $f(p) = 1/1000$ (assuming active fault earthquake), while monetary loss D was assumed to be the same for the two cases.

The result of case i) $f(p) = 1/100$ is shown in Fig.13. In this case, almost all links' optimal anti-quake performance grades are *Grade 2* (*maintaining the utility of structure*). Partly on (B) type network it is required to be improved till *Grade 3* (*no structural damage*). These requested grades are very reasonable, considering the probability of this type earthquake's occurrence during project life (we set 50 years) is 1/2.

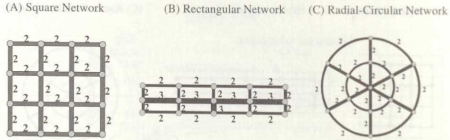

Fig.13: Optimally designed anti-quake performance (i) $f(p) = 1/100$)
(Each number denotes the optimal performance grade by link)

The result of case ii) $f(p) = 1/1000$ is shown in Fig.14. On any network type, at least *Grade 1* (*not structurally broken but lose the utility of structure*) is required for each link. Central links on square network (A), axis links for all four directions from a center on rectangular network (B), and radial links on radial-circular network (C), are strategically important links of each network, thus *Grade 2* (*maintaining the utility of structure*) is required. That is, in the case of rare disaster, the importance of a link will differ more clearly due to its role in the road network.

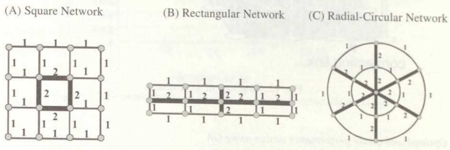

Fig.14: Optimally designed anti-quake performance (ii) $f(p) = 1/1000$)

5.3 Effect of cognition on the optimal anti-quake performances

Now we will check how the optimal anti-quake performance differs when considering different degrees of progressive effect of catastrophic loss. In the case of hypothetical square network (A) in Fig.11, four suppositions are prepared according to the degree of progressive effect, i) the case without progressive effect, ii) the case that progressive effect is lower than *iii)*, iii) the case of CLF shown in Fig.7, iv) the case that progressive effect is higher than *iii)*. Four CLFs corresponding to the above four suppositions are shown in Fig.15. The calculation results of an optimal anti-quake performance on each link of the network are shown in Fig.16 by each supposition, and by each probability of earthquake occurrence $f(p) = 1/100$ and $f(p) = 1/1000$.

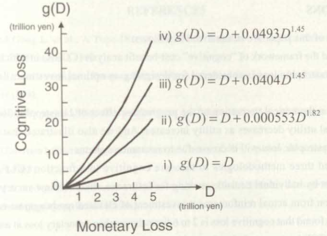

Fig.15: Four suppositions of CLF

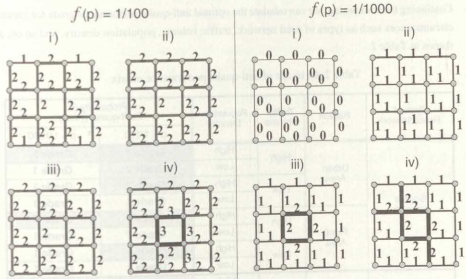

Fig.16: Effect of CLF suppositions upon optimally designed anti-quake performances

In case of $f(p) = 1/100$, no significant differences between these four suppositions. However, in case of $f(p) = 1/1000$, the consideration of progressive effect will lead to significant differences. Especially, if no progressive effect, the optimal anti-quake performance will be set to *Grade 0* (*structurally broken*).

6. CONCLUSIONS

The conclusions of this paper are summarized as follows:

1) We proposed the framework of "cognitive" cost-benefit analysis (CCBA) in which the progressive effect of catastrophic loss is considered for designing an optimal investment level for disaster mitigation.
2) We showed a theoretical derivation of the progressive effect of catastrophic loss derived from that marginal utility decreases as utility increases. And we also illustrated that the progressive effect of catastrophic loss will decrease due to insurance systems.
3) We proposed three methodologies to measure cognitive loss function (CLF) which are the measurement by individual decision-making for insurance, the interview survey of experts, and the estimation from actual reinforcement investment of elevated roads against earthquake. As a result, it was found that cognitive loss is 2 to 6 times larger than monetary loss at any methodology.
4) We applied CCBA on several simple road networks to find the optimal anti-quake performance of each links. This CCBA may provide the theoretically reasonable and practical anti-quake performance more precisely in an accountable way.
5) Continuing these inquiring, we can tabulate the optimal anti-quake performance grade for various circumstances such as types of road network, traffic volume, population density, and so on, as shown in Table 2.

Table 2 An image of anti-quake performance matrix

Type of Road Network	Region	Traffic Volume	Population Density	Probability of Earthquake (yearly)	
				p = 1/100	p = 1/1000
Square Network	Urban Area	High	High	Grade 3	Grade 2
			Low	Grade 2	Grade 1
		Low	High	Grade 2	Grade 1
			Low	Grade 1	Grade 1
	Rural Area	High	High	Grade 2	Grade 2
			Low	Grade 1	Grade 1
		Low	High	Grade 2	Grade 1
			Low	Grade 1	Grade 1
Radial-Circular Network	Radial Link	High	High	Grade 2	Grade 2
			Low	Grade 2	Grade 1
		Low	High	Grade 2	Grade 1
			Low	Grade 1	Grade 1
	Circular Link	High	High	Grade 2	Grade 1
			Low	Grade 1	Grade 1
		Low	High	Grade 2	Grade 1
			Low	Grade 1	Grade 1
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