Life cycle cost of geosynthetic-reinforced soil slopes subjected to an earthquake

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ABSTRACT: This study describes the life cycle cost of unreinforced and reinforced soil slopes subjected to seismic forces according to their seismic deformation. The life cycle cost is the sum of the initial construction cost obtained from the actual construction information and the reconstruction cost assumed based on certain reconstruction methods. From the results of the seismic life cycle calculation, the life cycle cost obtained for the reinforced soil slope is observed to be lower than that of the unreinforced soil slope. The study demonstrates the efficiency of the life cycle cost evaluation rationally and quantitatively.

Keywords: life cycle cost, reinforced soil slopes, seismic deformation

1 INTRODUCTION

Recently, the design method was revised to the performance-based design method from the allowable stress design method in civil engineering design. One of the efficient indices to evaluate the structures' performance is the life cycle cost (LCC). For the calculation of the LCC of the soil slopes, there are five required important factors, such as the investigation of statistical property of action (earthquake or rainfall), investigation of statistical property of a material or geotechnical properties, development of stability or deformation analyses, and development of reliability analysis. In this study, the LCC of the unreinforced and reinforced soil slopes subjected to a strong earthquake is rationally calculated from the viewpoint of economics.

2 LIFE CYCLE COST

LCC can be calculated as follows:

$$LCC = C + M + R \tag{1}$$

$$R = P_f \cdot R_{\mathrm{recvr}} \tag{2}$$

where C is initial cost, M is maintenance cost, R is risk-based rehabilitation cost, P_f is failure probability, and R_{recvr} is rehabilitation cost.
The calculation of the LCC is necessary to evaluate C, M, R_{recvr}, and P_f. This study describes the calculation result of the LCC of the unreinforced and reinforced soil slopes subjected to a strong earthquake.

It is important to calculate the LCC of a structure subjected to the earthquake with regard to the restoration cost according to the seismic displacement. Probably, the restoration cost of the slope collapsed by the earthquake has a positive correlation with the seismic displacement. When the seismic displacement was small, the performance of the slope could be restored via minor repairing or slight reinforcing, resulting in a low restoration cost. Conversely, when the displacement was large, reconstruction or replacement was necessary for restoring the performance, resulting in a high restoration cost. Therefore, the LCC of a structure subjected to earthquake can be calculated based on the seismic displacement.

To emphasize easy expression of the above relationship, the restoration cost R_{recvr} is assumed to be linearly proportional to the seismic displacement D. If the seismic displacement exceeded a tolerance limit with regard to the failure of the slope D_a, the slope was assumed to be reconstructed. Considering the above relationship between the restoration cost and the seismic displacement, the restoration cost can be estimated based on the degree of the damage and the LCC can be calculated with the estimated restoration cost.

3 ANALYTICAL METHOD

3.1 *Seismic residual displacement calculation*

In this research, the seismic displacement was calculated using the Newmark's sliding block analysis (Newmark 1965). Newmark's sliding block analysis will be hereafter referred to as Newmark analysis. It is a simplified procedure employed in the design code of road and railway structures in Japan (PWRC 2013 and RTRI 2007), where the seismic deformation of the unreinforced and reinforced soil slopes subjected to a strong earthquake can be calculated by integrating the equation of the rotational motion of a soil mass contained within the critical circular slip surface by assuming the failure mass as a rigid rotational block. The equation of rotational motion is solved for the rotation caused by the difference between the driving and the resisting moments. The critical slip surface is determined using the conventional modified Fellenius method (Fellenius 1936) using a specific acceleration or seismic coefficient to yield a safety factor of 1.0. A requisite for such an analysis is the unit weight, friction angle and cohesion of soil, and design strength of reinforcement. To calculate the seismic deformation, it is not necessary to consider the input parameters in addition to the abovementioned ones. The feature of this analysis is that it is practically useful and less time-consuming regarding the calculation. In this study, the seismic deformation is defined as a rotational displacement along the critical slip surface of the failure mass.

3.2 *Quasi-Monte Carlo Simulation*

The LCC can be calculated to add an economic dimension to a failure probability obtained via a reliability analysis. In the present study, the Monte Carlo simulation was adopted to calculate the restoration cost with the statistically distributed seismic displacement without the calculation of the failure probability. In this research, the quasi-Monte Carlo simulation was adopted to improve the calculation efficiency using a low-discrepancy sequence (LDS).

Shinoda (2007) demonstrated that the conventional random variable was not uniform when the average and the standard deviation could not be achieved with the prescribed values. Moreover, the abovementioned random variable significantly depends on the seed, which means that the random variable is not unique with regard to the various seeds for a small number of simulations, and thereby induces a numerical error. To reduce such numerical errors, the LDS was adopted in the proposed Monte Carlo simulation. The LDS is one of the quasi-random numbers that has a uniform distribution (i.e., Tezuka 1995). A feature of the LDS is that a set of quasi-random numbers in each simulation is unique with regard to the number of simulations. Using the LDS, the uniformity of the random variable could be significantly improved. Based on the above, it is fairly reasonable to use the LDS for random numbers in the current Monte Carlo simulation.

4 ANALYTICAL MODEL

The structures considered in this study are unreinforced and reinforced soil slopes as shown in Figure 1. The heights of the slopes are 3.0 m and 6.0 m, respectively. The slope inclination is 1:1.5. The length of the secondary reinforcement is 2.0 m. The vertical spacings of the primary and secondary reinforcements were 1.5 m and 0.3 m, respectively. The length of the primary reinforcement was sufficiently long beyond the critical slip surface to resist the rotation of the soil mass, while the length of the secondary reinforcement was set constant at 2.0 m. A surcharge of 10 kPa was applied on the crest of the slope. The horizontal seismic coefficient is 0.2.

Table 1 lists the statistical soil property of the slopes adopted in this study. According to the Railway Technical Research Institute (RTRI) design code in Japan, the properties of the foundation soil, backfill soil, and surface soil require to be determined to evaluate the safety or reliability of a structure. In the current analysis, the foundation soil was assumed to have sufficiently high strength and stiffness. Further, in practice, the surface soil along a slope is generally exceedingly difficult to compact, thus requiring a comparatively low friction angle.

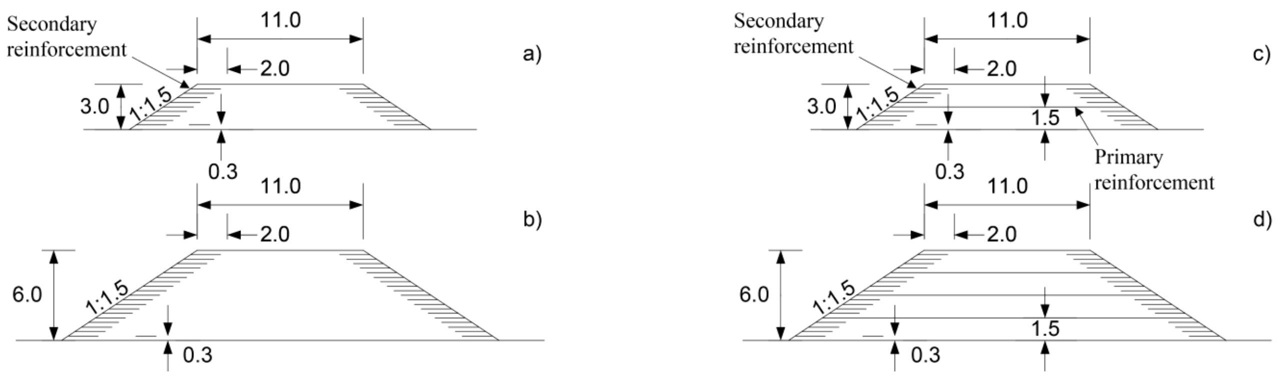

Figure 1. Analytical models of unreinforced and reinforced soil slopes: a) unreinforced soil slope with height of 3.0 m, b) unreinforced soil slope with height of 6.0 m, c) reinforced soil slope with height of 3.0 m, d) reinforced soil slope with height of 6.0 m.

Table 1. Statistical soil property

Property	Average	COV
Unit weight (kN/m^3)	18.0	0.05
Friction angle (°)	30.0 (25.0)	0.10
Cohesion (kN/m^2)	6.0 (3.0)	0.10

Note: the property of surface soil is noted in brackets.

Table 2. Statistical tensile strength of reinforcement

Property	Average	COV
Tensile strength of primary reinforcement (kN/m)	2.0	0.00
Tensile strength of secondary reinforcement (kN/m)	30.0	0.05

Moreover, the cohesion of the unsaturated surface soil generally depends on the degree of saturation. The degree of saturation of the surface soil is usually comparatively high owing to the effects of rainfall. This indicates that the cohesion of the surface soil may become lower than that of the backfill soil. Thus, the properties of the surface soil were modeled using a relatively lower friction angle and cohesion than the backfill soil. Each random variable was assumed to be statistically independent and normally distributed.

Table 2 shows the statistical tensile strength of reinforcement. In this study, based on the statistical data on the extension tests of reinforcement, the coefficient of variation (COV) of the warranted tensile strength of the reinforcements was assumed to be 10%, which is equivalent to the COVs of the internal friction angle and the cohesion of soils. Based on the result of the trial simulation, the effect of the secondary reinforcement is small to a degree that the tensile strength of the secondary reinforcement is considered to be a deterministic value. In the current analysis, the reduction factor to calculate the allowable tension load is set at a constant value of 0.9 by only considering the effects of seismic loading, installation damage, and durability. Each tensile strength of the reinforcement was assumed to be statistically independent and normally distributed.

5 INITIAL CONSTRUCTION AND REHABILITATION COSTS

Equation 1 demonstrates the calculation of the LCC that is the summation of the initial construction cost, demolition cost, and risk-based rehabilitation cost. In this study, the risk-based rehabilitation cost is calculated with regard to the summation of the demolition and reconstruction cost and the seismic residual displacement. Each cost was calculated per length of the construction. Figure 2 shows the initial construction cost regarding each height of the unreinforced and reinforced soil slopes to account for the summation of each cost calculated by each unit price and amount. As shown in Figure 2, the initial construction cost of the reinforced soil slopes became higher than that of the unreinforced soil slopes. The difference between the initial construction cost of unreinforced and reinforced soil slopes became larger with the increase in the height of the slope.

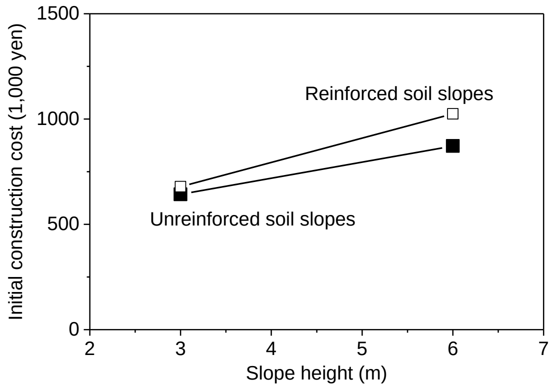

Figure 2. Initial construction cost of unreinforced and reinforced soil slopes

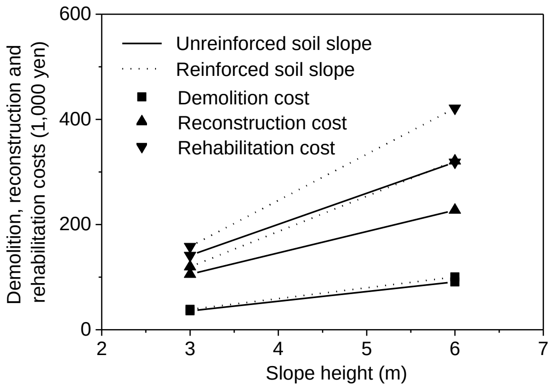

Figure 3. Initial construction cost of unreinforced and reinforced soil slopes

Figure 3 shows the demolition, reconstruction, and rehabilitation costs of the unreinforced and reinforced soil slopes in each height. As shown in Figure 3, the demolition cost of the reinforced soil slopes was slightly larger than that of the unreinforced soil. This is due to the increase in the unit price of the construction of the reinforced area. Compared with the reconstruction costs of unreinforced and reinforced soil slopes, similar to the trend of the initial construction cost, the reconstruction cost of the reinforced soil slope was higher than that of the unreinforced slope. Based on the above results, the rehabilitation cost of the reinforced soil slopes was higher than that of the unreinforced soil slopes.

Meanwhile, the rehabilitation cost as shown in Figure 3 is lower than the initial construction cost as shown in Figure 2. This is due to the consideration of the land cost while calculating the initial construction cost. The percentages of the land cost were approximately 70% and 45% of the unreinforced and reinforced soil slopes, respectively.

6 SEISMIC SAFETY FACTOR AND SEISMIC RESIDUAL DISPLACEMENT

Figure 4 shows the seismic safety factor with regard to the horizontal seismic coefficient of 0.2 of the unreinforced and reinforced soil slopes. The design values of the soil and reinforcement are average values. The safety factor was calculated with a circular slip surface using the Fellenius method. Figure 4 shows that the seismic safety factor of the reinforced soil slopes is higher than that of the unreinforced soil slopes in each height. Also, the seismic safety factor of the reinforced soil slopes decreases with increase in the height.

The seismic residual displacements of the unreinforced and reinforced soil slopes subjected to design earthquake were calculated using the Newmark method implemented in the quasi-Monte Carlo simulation with the low-discrepancy sequence. The detailed calculation method adopted in this study can be credited to Shinoda et al. (2006) and Shinoda (2007). Table 3 and 4 shows the statistical results calculated using the Newmark method implemented in the quai-Monte Carlo simulation. The seismic residual displacement of unreinforced and reinforced soil slopes became higher with increasing height. The coefficient of variation of the seismic displacement of the unreinforced soil slopes varies widely. Further, the COV of the seismic residual displacement of the reinforced soil slopes varies narrowly with an approximate value of 0.3.

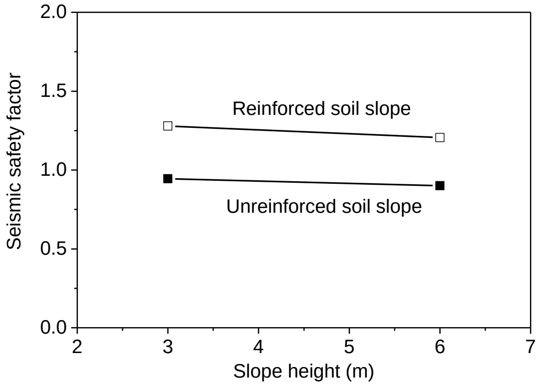

Figure 4. Seismic safety factor of unreinforced and reinforced soil slopes

Table 3. Seismic residual displacement of unreinforced soil slopes

Slope height (m)	Average (cm)	COV
3.0	79.81	0.238
6.0	129.87	0.467

Table 4. Seismic residual displacement of reinforced soil slopes

Slope height (m)	Average (cm)	COV
3.0	23.71	0.265
6.0	37.54	0.285

7 LIFE CYCLE COST CALCULATION

The confidence values can be calculated with the statistical value of the seismic residual displacement as shown in Table 3 and 4. In this study, the confidence values were used as 75% value. The probabilistic distribution of the seismic residual displacement was assumed to be a normal distribution, causing certain numerical errors. The confidence value of the seismic residual displacement of the unreinforced soil slopes was considered to be a relatively large value owing to the large COV of the seismic residual displacement. Moreover, the confidence value of the seismic residual displacement of the reinforced soil slopes was considered to be a relatively small value, which is due to the small COV. From the above, the consideration with regard to the confidence value is a rational approach to be enabled to consider the variance of the seismic residual displacement.

The LCC was calculated with the rehabilitation cost obtained from the confidence value of seismic residual displacement. To calculate the rehabilitation cost, it is considered as a sum of the demolition and reconstruction costs that can be calculated when the seismic residual displacement exceeded a threshold determined as a failure. In this study, the threshold was set as 50 cm with reference to the design standard of Japanese railway (RTRI 2007). Figure 5 shows the rehabilitation cost calculated with the confidence value of seismic residual displacement. As shown in Figure 5, the rehabilitation cost increases with the increase in the slope height in the unreinforced and reinforced soil slopes. Also, the rehabilitation cost of the unreinforced soil slopes became larger than that of the reinforced soil slopes because of the large seismic residual displacement of the unreinforced soil slope.

Using the rehabilitation cost as shown in Figure 5, the LCC was calculated with the confidence value of the seismic residual displacement as shown in Figure 6. As a result, the LCC increases with increase in the slope height in the unreinforced and reinforced soil slopes. Moreover, it is important to note that the LCC of the reinforced soil slope is lower than that of the unreinforced soil slopes in any case. In this research, the reduction rates of the LCC are approximately 17% and 33% of the slope height of 3.0 m and 6.0 m, respectively. Using the LCC, the reinforced soil slope can be rationally evaluated from the economic point of view.

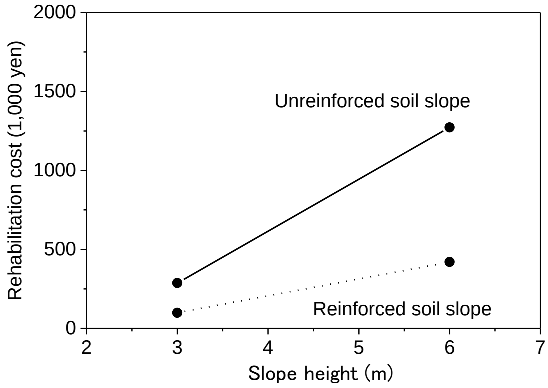

Figure 5. Rehabilitation cost of the unreinforced and reinforced soil slopes with 75% confidence value of seismic residual displacement

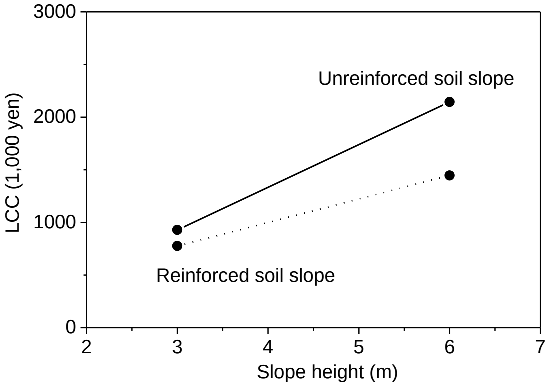

Figure 6. LCC of the unreinforced and reinforced soil slopes with 75% confidence value of seismic residual displacement

8 CONCLUSIONS

Focusing on the unreinforced and reinforced soil slopes, the seismic residual displacements of these structures were calculated using the normally distributed properties of soil and geogrid using the quasi Monte Carlo simulation. Subsequently, the life cycle costs of these structures were calculated with respect to the initial and rehabilitation cost. The rehabilitation cost was assumed to be a function of the seismic residual displacement. As a result, the life cycle cost of the reinforced soil slopes became smaller than that of the unreinforced soil slopes, indicating in the economic and aseismic structures in the life time.

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