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AN ADAPTIVE SELECTION SYSTEM OF BASE-ISOLATION DEVICES EVALUATED BY USING A SOFT COMPUTING METHOD THAT CONSIDERS SEISMIC PERFORMANCE

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SUMMARY

An arrangement of base-isolation devices is required in the design of base-isolated structures. Determining the arrangement of isolators during the design phase, however, is a time-consuming job. Furthermore, generally the arrangement currently depends heavily on the skill and experience of the design engineer. To overcome these drawbacks, an adaptive selection system for isolators based on their seismic performance was developed.

The main purpose of this study was to develop an adaptive selection system in which a hybrid method is used to determine the arrangement of isolators. In this system, the arrangement is determined based on the (1) maximum response displacement of the base-isolation layer, (2) maximum response acceleration of the superstructure, (3) natural period of the base-isolated structure, (4) eccentricity of the base-isolation layer, (5) vertical load for each isolator, (6) wind performance, (7) living comfort of inhabitants, and (8) cost of base-isolation devices.

First, our adaptive selection system was applied to actual structures and evaluated. The evaluation results show that our system is superior for the different arrangements and that an arrangement that adapts to a certain type of earthquake motion does not always adapt to another type. Therefore, several types of earthquake motion must be considered when determining the specific arrangement. The results also show that the adaptive arrangement for wind performance differs from that for seismic performance. Next, the living comfort for the inhabitants of a building that contained the arrangement determined by the adaptive selection system was evaluated. The results show that achieving a certain living comfort by using our system was difficult but attainable. Finally, there is a trade-off between initial cost and performance in base-isolated structures.

In conclusion, by using our adaptive selection system, multi-objective selection that satisfies safety, comfort, and cost can be achieved.

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INTRODUCTION

Japan is historically a country with frequent earthquakes, which are impossible to predict. Engineers have expended significant effort to keep people safe and buildings undamaged during earthquakes. Base-isolation systems, which are designed based on a client's needs and an engineer's skills, are now a strategy used in earthquake-resistant design. Base-isolation is one of the most successful techniques to mitigate the risk to life and property from strong earthquakes. After the 1995 Hyogoken-nanbu Earthquake, the number of base-isolated buildings has increased rapidly in Japan. The arrangement of base-isolated devices should satisfy various conditions such as safety, comfort, and cost. The Building Standards Act now advocates performance-based structural design, thus making base-isolation systems crucial. In the design of a base-isolated structure, the arrangement of base-isolation devices currently depends heavily on the skill and experience of the design engineer, thus making it difficult for the client to accurately judge the performance of the design.

The main purpose of this study was to systematize the method of design to assist engineers in their design process and to help clients in assessing the design performance. The focus was on the arrangement of base-isolation devices and on the development of an optimal selection system based on a genetic algorithm and simulated annealing.

ANALYSIS METHOD

The optimization problem to select and arrange base-isolation devices involves discrete data, thus making it nearly impossible to solve the selection problem by using conventional methods that use gradients. In this study, to solve this problem, a genetic algorithm is used in the optimization and simulated annealing is used to improve the efficiency of the algorithm with respect to computational time. This hybrid method composed of a genetic algorithm (GA) and simulated annealing (SA) is called the GA-SA hybrid method and is described here.

Genetic algorithm (GA)[2]

GA determines optimal solutions by using natural selection and genetics. In this way the best individuals survive by achieving high environmental adaptability. The GA approach can determine the optimal solution even if the objective function is not differentiable, such as a discontinuous function. In addition, because several individuals belong to the same generation, parallel search is permitted. And among these individuals GA is composed of six steps (illustrated in the flow chart in Fig. 1):

(1) Creation of the first generation

Each generation is composed of 50 individuals. The first generation is created at random. In each individual, a gene expresses the arrangement of base-isolation devices using 0 and 1. Figure 2 shows an artificial individual expressed using 0 and 1 in this study.

(2) Evaluation fitness

Each individual is evaluated based on performance and cost associated with that particular arrangement. A high fitness value is given to those individuals that have high adaptability.

(3) Reproduction

Parents for the next generation are selected according to their fitness value. An individual with high fitness value stands a good chance of selection so that adaptive individuals can survive.

(4) Crossover

Information exchange among individuals is allowed. By exchanging genes between parents, new individuals are generated. Crossover takes on during the local search in GA.

(5) Mutation

To avoid a local solution, 0 and 1 are reversed in the gene. Mutation takes into consideration the chance of obtaining a superior individual.

(6) Judgment on the termination conditions

When the maximum fitness value in a generation does not change in the consecutive generation, the calculation process is judged as a termination condition.

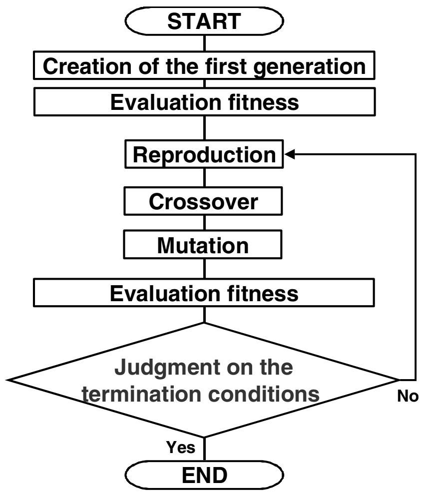

Figure 1: Flow chart of GA

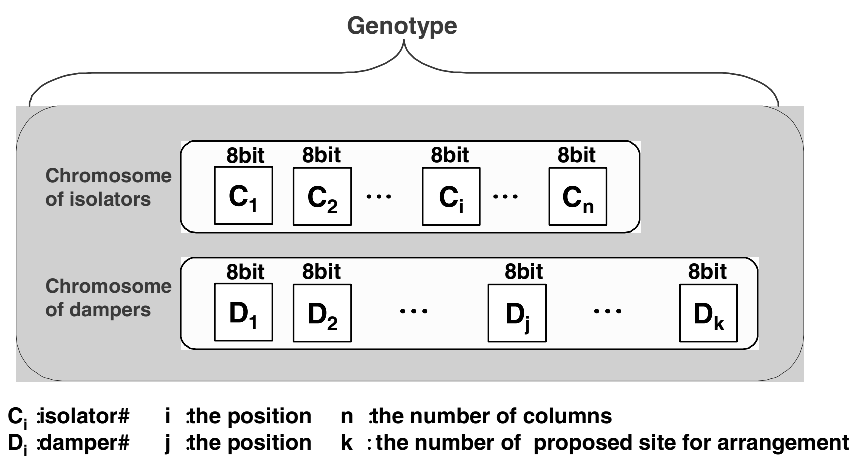

Figure 2: Artificial individual expressed using 0 and 1 by GA algorithm

Simulated annealing (SA)

The concept of SA is based on the manner in which metals recrystallize during annealing. During annealing, initially the system is at high temperature and disordered, and then is slowly cooled so that the system at any time is approximately in thermodynamic equilibrium.

As cooling proceeds, the system becomes more ordered and approaches a ground state. The process can be considered an adiabatic approach to the lowest energy state. If the initial temperature of the system is too low or cooling is done insufficiently slowly, the system might form defects (i.e., trapped in a local minimum energy state).

SA is composed of six steps (illustrated in the flow chart in Fig. 3):

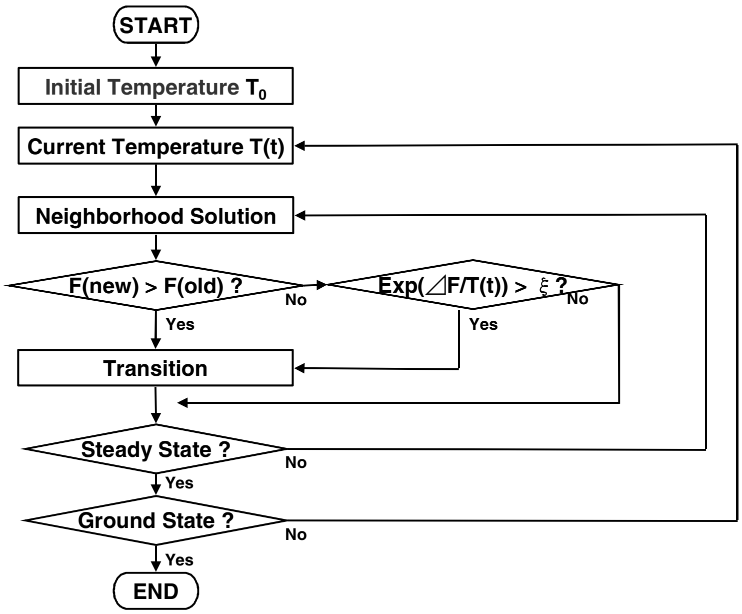

Figure 3: Flow chart of SA

(1) Initial temperature T_0

The initial temperature T_0 is set up.

(2) Current Temperature T(t)

The current temperature is defined according to the cooling schedule. In this study, we used the cooling schedule proposed by H. Szu and R. Hartley[3] expressed by the following equation (1), where "*t*" is the number of times of a repetition of annealing:

(3) $$T(t+1) = \frac{T_0}{1+t} \tag{1}$$

(3) Neighborhood solution

A new solution is generated at random near the present solution.

(4) Transition

The change (ΔF) between the evaluation function of a "new" solution (F_{new}), and the "old" solution (F_{old}) is calculated. If ΔF is negative, the individual moves to a new solution. Otherwise, a random number ξ between 0< ξ<1 will be generated, and if exp(-ΔF/T (*t*)) >ξ is, the individual will move to the new solution.

(5) Steady state

If the individual is judged as steady state, it will go to Step 5, otherwise it will return to Step 2. In this study, the time when 50 solutions were generated was judged to be steady state at that specific temperature.

(6) Ground state

If the individual is judged as ground state, operation ends, otherwise the individual will return to Step 2. In this study, if the number of the solutions generated at a certain temperature is 5 or less, then the individual is considered to be at ground state.

GA-SA hybrid method

Although GA can do parallel search and excels in large region search, the performance strongly depends on the number of individuals. On the other hand, although SA is effective in local area search, there is no guarantee that an optimal solution can be obtained. However, because SA searches for a single point and

GA searches for two or more points in parallel as an individual group, calculation time by using SA might be significantly reduced when using GA. Then, calculation time is dependent on conditions, however, such as the initial individual in each selection method. The GA-SA hybrid method utilizes the advantages of both GA and SA effectively.

In the beginning of the search for an optimal arrangement by using the GA-SA hybrid method, parallel search is done by GA. New solutions are generated for these individual groups, when individuals that fulfill certain conditions, i.e., target performance. Then, SA is applied to these individuals to optimize a target performance. This hybrid method attains a more efficient search than that by GA alone. Figure 4 shows a flow chart and Figure 5 shows a conceptual diagram of the GA-SA hybrid method.

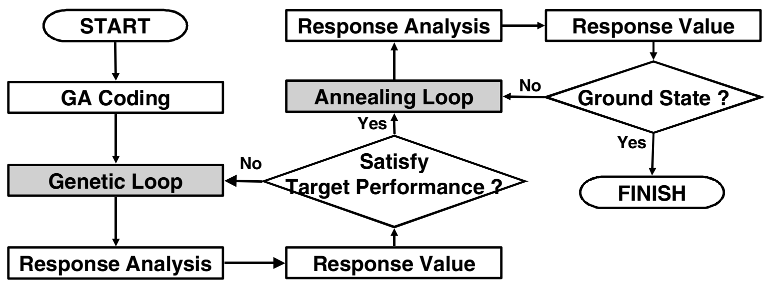

Figure 4: Flow chart of the GA-SA hybrid method

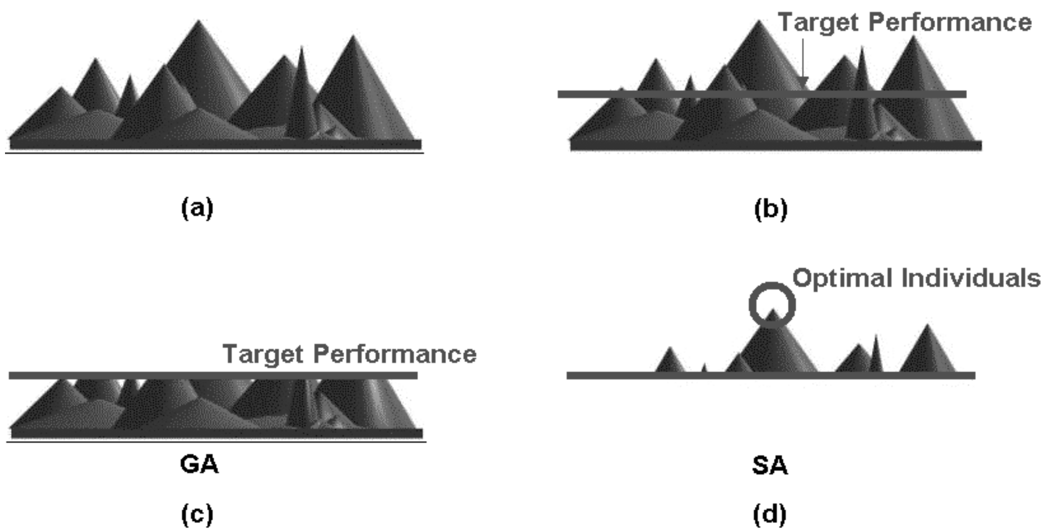

Figure 5: Conceptual diagram of the GA-SA hybrid method

EVALUATION METHOD

Criteria used in evaluating the optimal selection and arrangement of the base-isolation devices determined by the GA-SA hybrid method are as follows:

a) Maximum response displacement of the base-isolation layer.
b) Maximum response acceleration of the superstructure.
c) Natural period of the base-isolated structure.
d) Eccentricity of the base-isolation layer.

e) Vertical load for each isolator.
f) Wind performance.
g) Living comfort on inhabitants.
h) Cost of base-isolation devices.

To obtain the maximum response value, in this study, time-history analysis was used by modeling the base-isolated building as having 2 degrees of freedom. To evaluate the wind performance of the arrangement in this building, an artificial wind load with 500-yr of return period was used.

In this study, a selection result was obtained for a "safe rate" to the target performance. The safe rate shows the degree of margin to a target performance and is expressed as the ratio of the actual response value to the response value required for a target performance. For example, in response acceleration, the response shear force factor at the superstructure becomes smaller than the design base shear force of the superstructure, namely, the smaller response acceleration is the more highly valued.

ANALYSIS EXAMPLES

To validate the effectiveness of the adaptive selection system with GA-SA hybrid method, the system was applied to an actual building that was a 10-story reinforced concrete office. The primary natural period of the actual base isolated-building was 3.70 seconds. Table 1 lists the earthquake motions used in the response analysis.

Table 1: Earthquake motions used for response analysis

Earthquake	*Maximum acceleration [cm/s^2]*
El Centro 1940 NS	341.7
Taft 1952 EW	175.9
Hachinohe 1968 EW	180.2
JMA-Kobe 1995 NS	804.6

The analysis involved 56 types of NRB (Natural Rubber Bearing) and 3 types of lead dampers. The GA-SA hybrid method was used to determine the arrangement of these NRBs and dampers with the highest fitness value. The input earthquake motions were normalized to a maximum velocity of 50 cm/s.

RESULTS AND DISCUSSION

Comparison of three types of selection method

The arrangement of base-isolation devices consists of two stages.
The first stage is determination involving the search for arrangements that achieve the target performance.
The second stage is optimization involving the search for the optimal arrangement of base-isolation devices.

Selection results and search time required to find the solution were compared for three selection methods; GA target method, GA optimal method, and GA-SA optimal method. The features of these three methods are summarized as follows.

In the GA target method, only GA is used to search for the solution that satisfies the target performance. By introducing the concept of the target performance, this method chooses by replacing the optimization stage by the determination stage. Although the solution that always satisfies the target performance is obtained, it is not necessarily the optimal solution under the given conditions.

In the GA optimal method, only GA is used to search for the optimal solution, by using parallel search for all individuals from the start to the end shown in Figure 6. Once the method arrives at a local solution, it slips out from local solution only by mutation and therefore sometimes cannot arrive at the global optimal solution.

In the GA-SA optimal method, both GA and SA are used to search for the optimal solution by effectively utilizing the advantages of both GA and SA, thus reducing the number of calculations compared with those using the GA optimal method.

Figure 6 shows a conceptual diagram of each selection method.

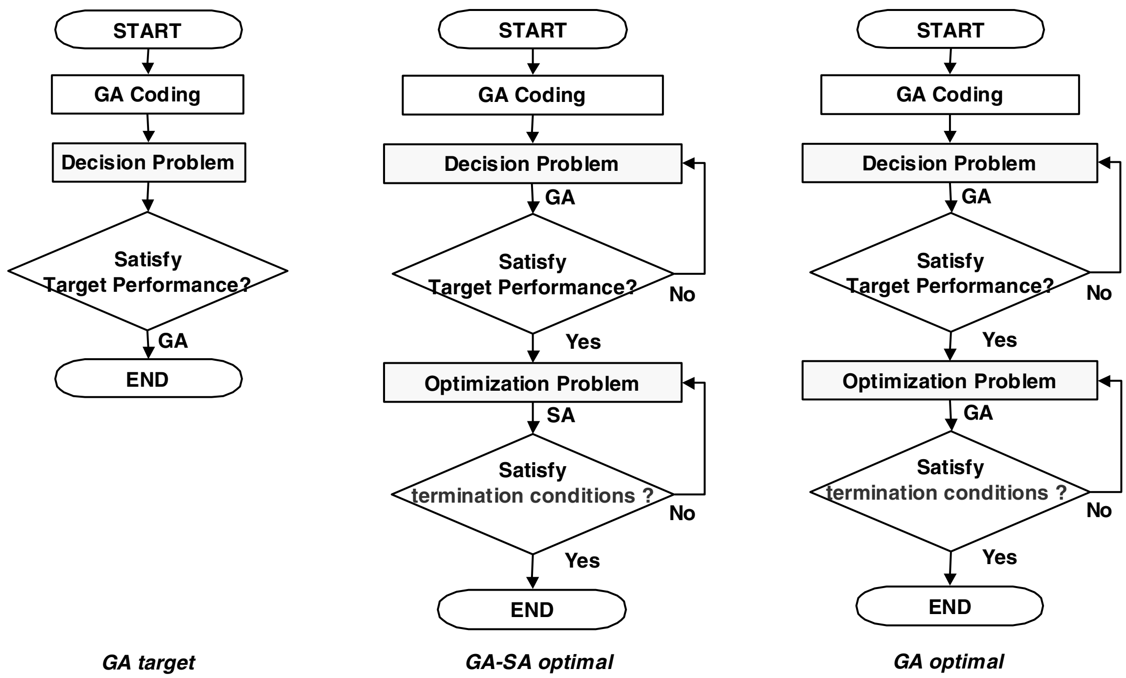

Figure 6: Conceptual diagram of three selection methods for comparison

Table 2 compares the calculation time needed to determine the optimal selection and arrangement.

Table 2: Comparison of calculation time ratio among three selection methods

Selection method	GA target	GA optimal	GA-SA optimal
Calculation time ratio	0.20	1.00	0.89

Calculation times were normalized by that for the GA optimal method, and are expressed as the ratio. By using the GA-SA optimal method, the calculation time was reduced by 11% compared with the GA optimal method.

Table 3 compares the accuracy of the solution obtained by each method.

Table 3: Comparison of accuracy among three selection methods

Selection method	GA target	GA optimal	GA-SA optimal
Accuracy of the solution	0.79	0.93	0.98

Then, “Accuracy of the solution” is defined by the equation (2), where “ $F_{selection}$ ” is the fitness value of arrangement obtained by each method and “ $F_{optimal}$ ” is the fitness value of the optimal arrangement:

$$accuracy = \frac{F_{selection}}{F_{optimal}} \tag{2}$$

Accuracy of the arrangement obtained by the GA-SA optimal method was high compared with that by the other two methods. In summary, the GA-SA hybrid method was effective in the optimal selection of base-isolated devices.

Effect of load type on the optimal selection and arrangement of base-isolated devices

The effect of the type of load, i.e., earthquake motion, that was considered during the design phase on the selection result was also evaluated.

Figures 7-9 show the response reduction achieved using the optimal arrangement that was determined by considering only one type of earthquake motion. In each figure, axes show the safe rate.

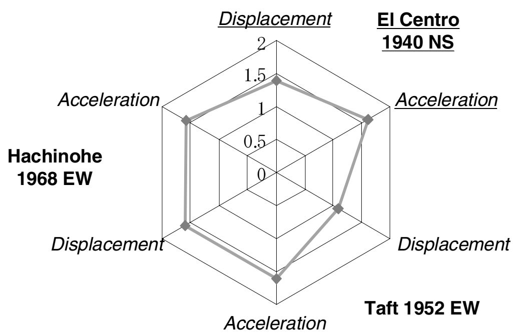

Figure 7: Optimal selection for El Centro

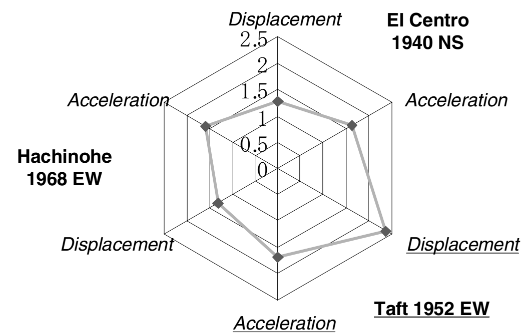

Figure 8: Optimal selection for Taft

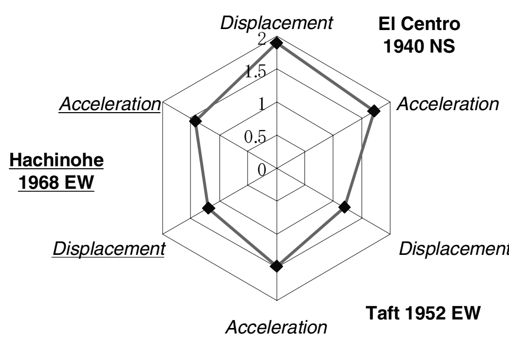

Figure 9: Optimal selection for Hachinohe1968EW

Figures 7-9 show that when only a single type of earthquake motion is considered, a high safe rate was achieved. The features of an isolation system for El Centro 1940 NS will not be optimal for Taft 1952 EW and vice versa. This means that the vibration reduction is not optimal for a wide range of input ground motion intensities. Therefore, target performance might not be achieved when the structure is subjected to an unexpected earthquake.

Figure 10 shows the response reduction achieved using the optimal arrangement that was determined by considering three different types of earthquake motion.

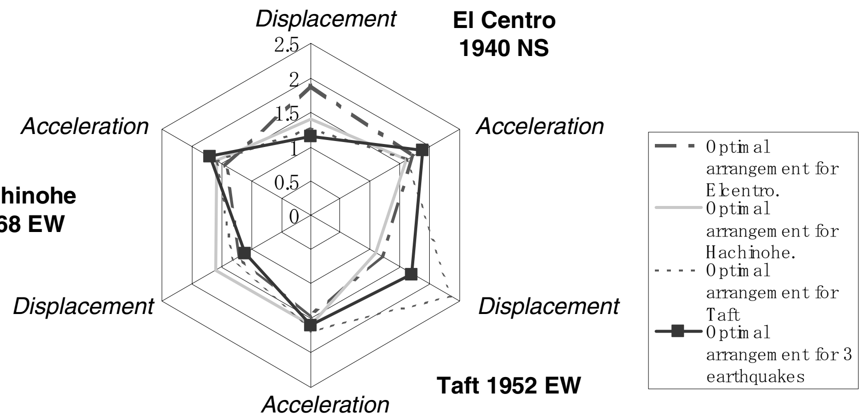

Figure 10: Optimal selection considering three different earthquakes

In each response reduction, the selection that was determined by considering three earthquakes was inferior to the optimal selection determined by considering only one earthquake. However, target performance was guaranteed to be satisfied when a building is subjected to the assumed earthquake motion. Therefore, the types of loads must be considered in the design process.

Effect of cost on the optimal selection and arrangement of base-isolated devices

The effect of cost on the optimal selection and arrangement was also evaluated. In the evaluation, we made the following four assumptions:

a) Only the initial cost of the base-isolation devices was considered. If the cost of devices is low, then the solution will be judged as excelling in economical efficiency
b) An actual base-isolated building was used for the evaluation. Therefore, the amount of cost reduction due to structural change of the superstructure was not taken into consideration.
c) Cost minimization was performed while satisfying the target performance.
d) Cost performance was evaluated based on the ratio of cost of the optimal arrangement to that of the maximum cost.

Figure 11 shows a comparison of the selection result that optimized seismic performance and wind performance and optimized cost. Figure 12 shows a comparison of the performance of these arrangements.

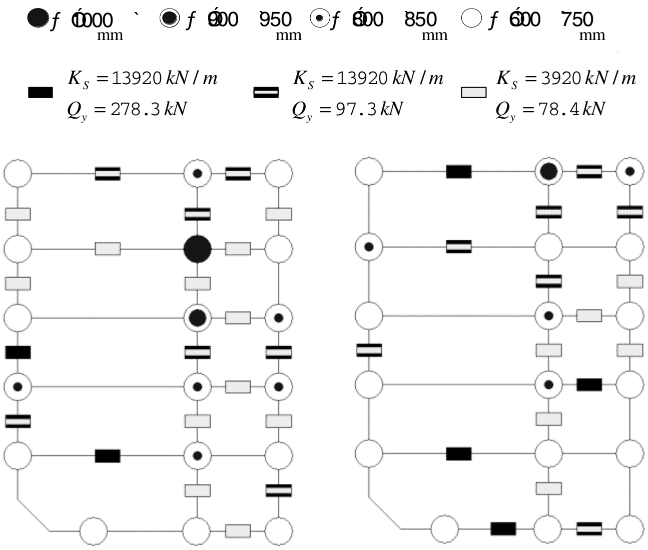

Figure 11: Comparison of the selection result that optimized performance and optimized economical efficiency

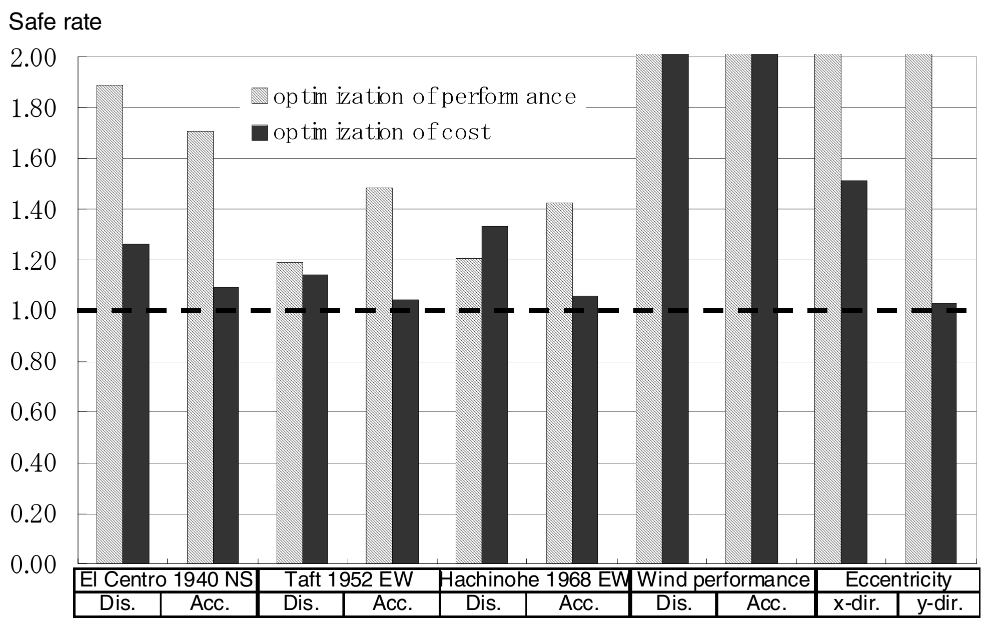

Figure 12: Comparison of performance of arrangements optimized for performance and optimized for cost shown in Fig. 11

When cost is taken into consideration in the design process, the selection of base-isolated devices are summarized as follows.

a) The adaptive selection system selects smaller isolators, and reduces the numbers of a damper.
b) Smaller isolators are used also in the central part of the building in which isolators must bear a large vertical force.
c) A damper behaves plasticity and the response value becomes large.
d) Displacement remains after the building is exposed to wind.

When cost is not taken into consideration in the design process, extremely small eccentricity can be achieved by using many dampers effectively.

Although an arrangement that minimizes cost is possible, it does not achieve a sufficient safe rate in eccentricity or wind performance.
Figure 13 shows safe rate as a function of cost. The horizontal axis shows the ratio of the cost for the selection arrangement to the maximum cost. A smaller cost ratio means superior economical efficiency. The vertical axis shows the safe rate based on target performance.

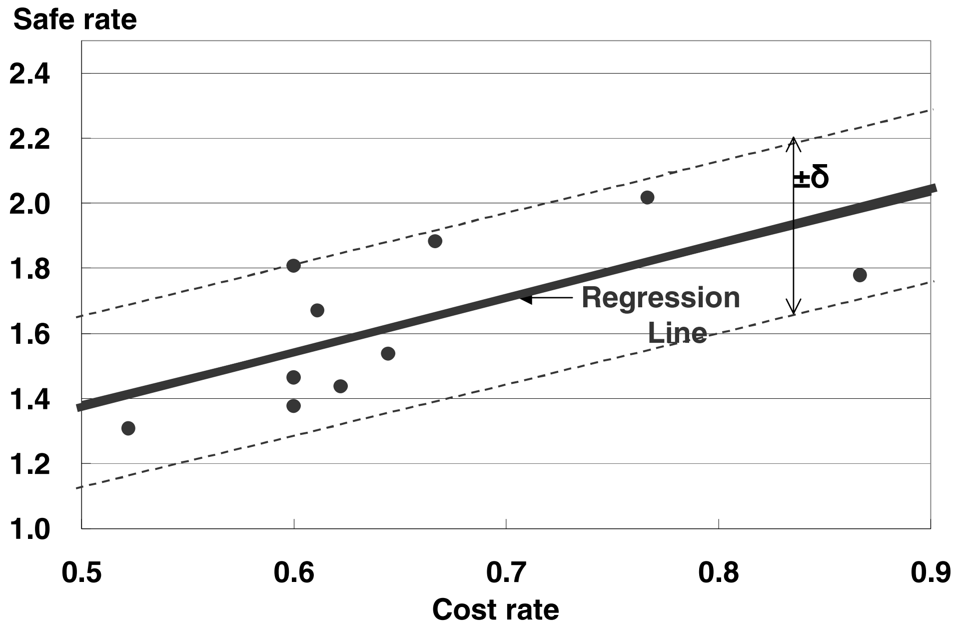

Figure 13: Safe rate vs. cost

Figure 13 yields the following conclusions:

a) There is a trade-off between cost and safe rate. When safe rate is increased, economical efficiency decreases.
b) Optimal performance based on cost is not necessarily obtained.
c) For the same cost, various levels of safe rate can be achieved.
d) An arrangement for a base-isolated building must be obtained that balances the performance with the cost.

CONCLUSIONS

The adaptive selection system was applied to actual structures. The evaluation results are summarized as follows.

a) The optimal arrangement depends on the earthquakes and winds that are considered during the design process. Therefore, the types of loads must be considered during the design process.
b) In base-isolated structures, there is a trade-off between initial cost and performance.
c) By using this adaptive selection system, multi-objective selection that satisfies safety, comfort, and cost can be achieved.

In conclusion, the adaptive selection system is useful in performance-based structural design.

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