RECENT PROJECTS AT PWRI
FOR IMPROVEMENT OF SEISMIC PERFORMANCE OF CIVIL INFRASTRUCTURES

by

YASUDA Masahiko[1)]

1. INTRODUCTION

Since the Hyogo-ken Nanbu Earthquake four years ago, seismic performance of civil infrastructures has been improved through revising the seismic codes for newly constructed facilities and nationwide retrofit for existing facilities. However, there still exist many problems in order for farther improvement of their seismic performance. This paper describes the recent projects that are especially propelled by Public Works Research Institute (PWRI) to cope with some of the problems. Those include,

(1) Rational Methodology to Determine Seismic Potential of Civil Infrastructures
(2) Very Strong Design Ground Motions with Direct Consideration for Source Faults
(3) Development of Seismic Design Methodology for Bridges
(4) Earthquake Resistance Design for Soil Structures

2. RATIONAL METHODOLOGY TO DETERMINE SEISMIC POTENTIAL OF CIVIL INFRASTRUCTURES

The question that has been posted since the Hyogo-ken Nanbu earthquake is that if the seismic performance between different types of infrastructures or between different structures of same types is consistent. Because each facility is designed based on its own code and because the performance is required respectively, the seismic performance between different types of facilities may have imbalance in their damages and their societal effects. Also the seismic performance of facilities may deviate affecting the functions of the system such as a highway network composed of those facilities. In such cases, validity of earthquake resistant investment needs to be examined carefully by taking the seismic performance of the facilities in the earthquake. Therefore, the methodology to determine the well-balanced seismic potential for the facilities in an area by counting their seismic performance realized in the earthquakes (Fig. 2.1).

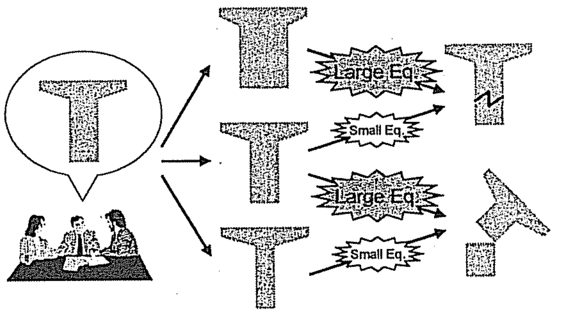


Fig. 2.1 Seismic Potential, Input Earthquake Level and Seismic Performance

Many countries are trying to revise their design codes to performance based expressions. An example of such attempt is the performance matrix proposed by the VISION 2000 committee of SEAOC, U.S.. It shows the lines indicating demanded seismic potentials corresponding to the importance of facilities in

1)Director, Earthquake Disaster Prevention Research Center, Public Works Research Institute, Ministry of Construction, Tsukuba Ibaraki 305-0804, Japan

the rectangle area provided by the input earthquake strong motion levels and the performance levels. Here, the lines mean the seismic potential that must be satisfied in the design, and their importances are supposed to be given by externally. In this sense this potential matrix can be referred as the "demanded performance matrix" (DPM), (Fig. 2.2).

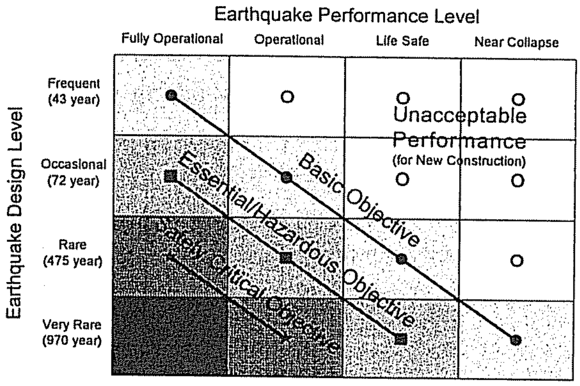


Fig. 2.2 Performance Matrix

In contrast, when a structure is designed, a seismic performance is determined from an input strong motion level dependently. Thus, the potential line that can be actually drawn corresponding to the specific design does not necessarily agree with that of conventional DPM. The performance matrix shown by this actual potential line can be referred as the "realized performance matrix" (RPM). When one consider the investment assigning plan for more than one facilities in the area, it needs to maximize the area's satisfactory by taking RPM of each structure into account.

In this research the idea of RPM is extended to the "input-output-cost curve" (IOC curve), in which the cost for structural earthquake resistant measure is displayed in addition to the input strong motion level and the seismic performance level in three dimensional space (Fig. 2.3). Given this IOC curve, decision makers can compare the earthquake resistant investment plans.

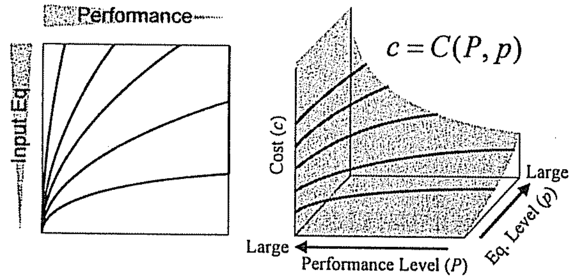


Fig. 2.3 IOC curve

Besides proposing and showing the example of the RPM and IOC curve, this research deals with a methodology to select the seismic potentials of more than one structure so that the combination of their potentials maximizes the satisfactory of the area. Assuming that there are two structures in the area, let us set the objective to maximize the quantitatively derived community's satisfactory under the several constraints such as the limit of the budget.

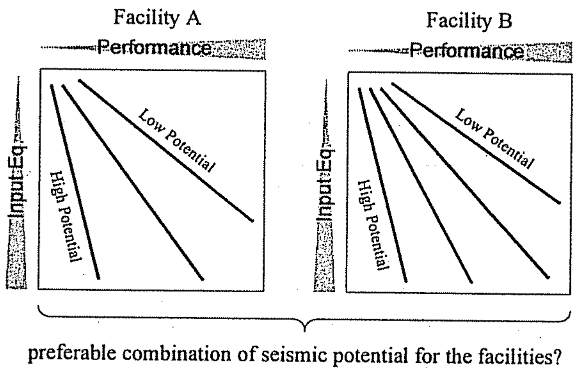


Fig. 2.4 Selecting Seismic Potentials

When the satisfactory is measured as the expected utility (EU), the problem is written as equations below.

$$\max_{P_{11},P_{12},P_{21},P_{22}} \; p_1 U(P_{11}, P_{21}) + p_2 U(P_{12}, P_{22})$$

$$\text{s.t.} \quad C_1(P_{11}, p_1) = C_1(P_{12}, p_2)$$

$$C_2(P_{21}, p_1) = C_2(P_{22}, p_2)$$

$$C_1(P_{11}, p_1) + C_2(P_{21}, p_1) = c^*$$

where, p_e : occurrence probability of level e strong motion (e = 1, 2), P_{se} : seismic performance level of structure s (s = 1, 2) revealed when it experiences the strong motion of level e, $C_s(P_{se}, p_e)$: cost for such seismic potential that performance P_{se} realizes at the input level of e with the probability p_e, ; i.e., IOC function, and c* : the limit of total cost. The equations were solved analytically by assuming the unique function forms for U and C_s. In addition, an IOC function was tentatively derived for various levels of seismic potentials of the bridge under a given condition.

The concept in this paper is expected to be utilized in the regional earthquake resistant plans in the future, and is related to the seismic codes of various facilities. To apply the methodology to the practical planning and design, several problems must be solved; i.e., expressing the facility's seismic performance in adequate manners and determining the objective function forms of the net benefit or the representative utility as the objective function.

3. VERY STRONG DESIGN GROUND MOTIONS WITH DIRECT CONSIDERATION FOR SOURCE FAULTS

Numerous valuable strong motion records were obtained by various organizations during the 1995 Hyogo-ken Nanbu earthquake and it has been found that the earthquake generated extremely strong ground motion that had rarely been recorded in Japan. Design ground motions for public works, in general, had been based on the ground motions in rather far field due to large interplate earthquakes such as the 1923 Kanto earthquake, whereas those in near field due to earthquakes by inland active faults such as the Hyogo-ken Nanbu earthquake had not been taken into account. The Hyogo-ken Nanbu earthquake triggered revision of various seismic design codes based on its strong motion records and previous researches. However, because of lack of strong motion records obtained in near field, characteristics of near field ground motion still leave much room for discussion.

To study and grasp the characteristics of near field ground motions, in addition to the conventional techniques making use of strong motion records and attenuation relations, ground motion estimation techniques based on fault models have been developed and investigated. According to the techniques, the fault plane of a target event is divided into subfaults and the ground motion of the target event is synthesized by superimposing ground motions generated by each subfault.

The techniques can be applied to estimation of near field ground motion, which may be beyond the application of the conventional attenuation relations, because the extent and rupture process of the source fault are taken into account. On the other hand, the techniques require various source parameters, such as the location, extent,

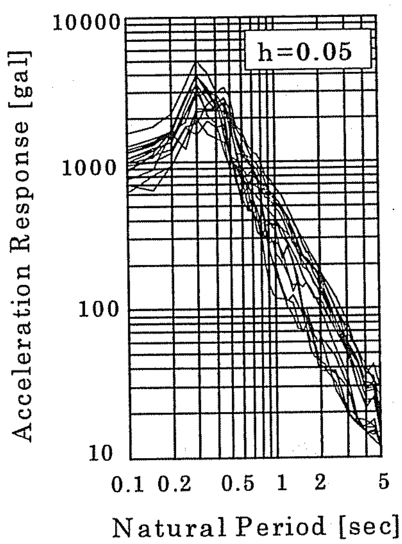


Fig. 3.1 Acceleration Response Spectra for the Estimated Ground Motions at JMA Kobe

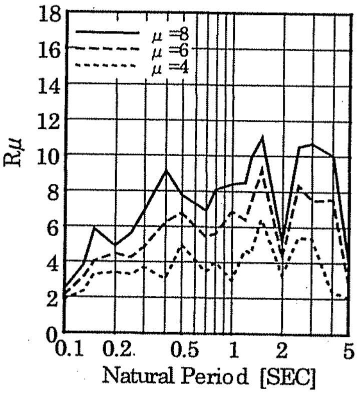
and rupture process, most of which are difficult to be determined accurately. Moreover, those parameters have noticeable effects on estimated ground motions as shown in Fig. 3.1. Fig. 3.1 compares acceleration response spectra (damping ratio h=0.05) of estimated ground motions at JMA Kobe during the Hyogo-ken Nanbu earthquake with various source parameters. We can see that the largest acceleration response may be more than 5 times as large as the smallest one at certain natural periods.

Currently, the ground motion estimation techniques based on fault models have been developed and expected to be practical for seismic design along with surveys of inland active faults. Researches on attenuation relations for near field ground motion using strong motion records due to earthquakes by inland active faults and seismic hazard analyses considering active faults and regional characteristics of seismicity have also been carried out.

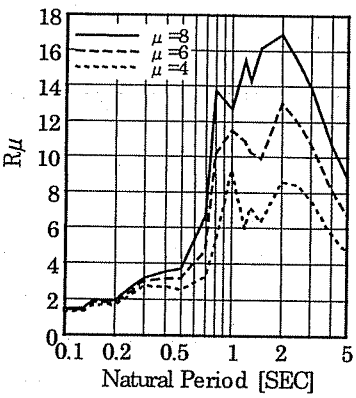
For rational seismic design against very strong ground motions, such as those generated by the Hyogo-ken Nanbu earthquake, energy absorption capacity should be improved by ensuring allowable appropriate displacement ductility. Because structures cannot withstand such ground motions only by strengthening structural members.

In order to evaluate the differences in the inelastic behavior of structures due to ground motion characteristics, strength reduction factor $R\mu$ can be used. $R\mu$ indicates the possible reduction of the strength of a structure when a certain displacement ductility is allowed. $R\mu$ can be calculated for arbitrary natural period and therefore it makes spectrum, namely strength reduction factor spectrum ($R\mu$ spectrum).

Fig. 3.2 shows $R\mu$ spectra for Kaihoku Bridge record and JMA Kobe record. Kaihoku Bridge record is ground motion from the Miyagi-ken Oki Earthquake, inter-plate earthquake, and JMA Kobe record is ground motion from the Hyogo-ken Nanbu eartquake, intra-plate earthquake. Both records were obtained on the stiff ground. The Fig. 3.2 shows that non-linear response of the structure varies depending on the ground motion characteristics.



(a) Kaihoku Bridge Record



(b) JMA Kobe Record

Fig. 3.2 Strength Reduction Factor Spectra

The effects of ground motions on inelastic behavior of structures are studied using strength reduction factor spectra and the ground motion characteristics. The ground motion characteristics affecting the inelastic response of structures should be considered when design forces and design ground motions are discussed.

4. DEVELOPMENT OF SEISMIC DESIGN METHODOLOGY FOR BRIDGES

4.1 Future Scopes for Development of Seismic Design Methodology

1) Performance-based Design

The use of the performance-based design has been recently suggested in terms of the better-cost performance of construction, the promotion of new technology and the activation of international trade. To clarify the seismic performance demand and satisfy above demands, it is needed to describe seismic performance criteria and limit states of civil engineering infrastructures and establish the performance-based approach for the seismic design. The analytical and experimental verification systems would be also required to evaluate the performance capability of the structures and to prove an applicability of new technology. Moreover, development of social system to accept the performance-based engineering would be also required

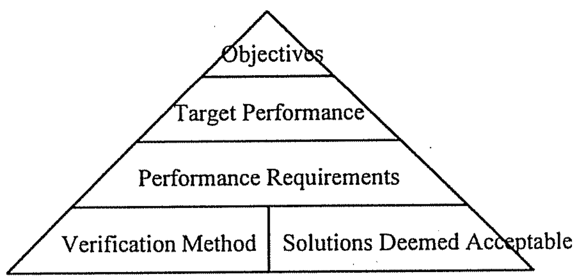
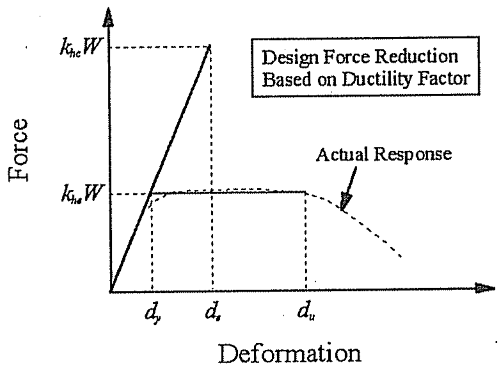


Fig. 4.1 Framework of Performance-based Design

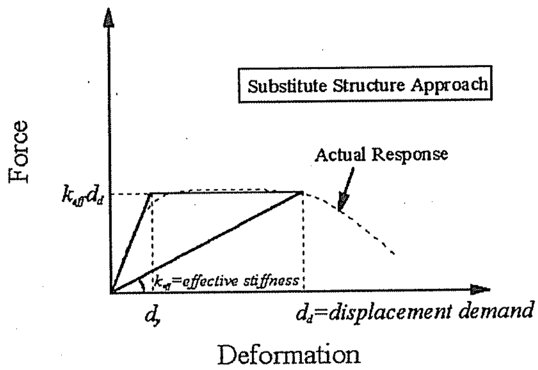
2) Displacement-based Design

Current seismic design is one of the force-based approaches in nature. Although the current force-based design approach involves allowance for inelastic damage during major earthquakes, it does not directly address the inelastic nature of a system during the earthquakes. Furthermore it requires the use of the controversial reduction factors which are based on an energy conservation assumption or displacement conservation assumptions. Seismic damage can be easily described by the deformation of the structures so that the alternative design approach using displacement as a reliable indicator of the structural damage.

The displacement-based design is a response spectra based methodology to design a structure to achieve a specified level of displacement in incorporated with the substitute structure approach. The substitute structure approach is a design approach whereby an inelastic system can be modeled using equivalent elastic properties such as the effective stiffness K_{eff} and the effective damping ξ as shown in Fig. 4.2.



(a) Force-Based Design



(b) Displacement-Based Design

Fig. 4.2 Design Concepts of Force-Based and Displacement-Based Design

3) Capacity Design and Reliability-based Design

The capacity design is a design methodology with the concept that the collapse mechanisms are clearly identified. In other words, an appropriate strength difference should be made between the plastic hinges and capacity-protected members. The concept of capacity design is illustrated in Fig. 4.3, where a ring 1 is strong enough to protect its capacity, while a ring 2 has a well-ductile property. In this system, the ring 1 cannot be subjected to its yield force or more and the ring 2 must exhibit an inelastic response when a large force is applied to the system. In order to achieve the capacity design process, the maximum feasible flexural strength for the plastic hinge regions should be adequately evaluated with considering over-strength and variation of materials using reliability based approach.

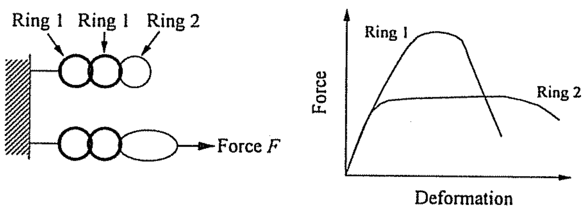


Fig. 4.3 Concept of Capacity Design

4) Strength and Ductility

It is one of options to increase a section or steel percent so as to increase the flexural strength of columns. On the other hand, the significant increase in the flexural strength causes design of a big column and thus results in high construction cost. Therefore, it may be unreasonable to design the column with high flexural strength. However, the design of well-ductile column can reduce a seismic force but causes a large displacement response and then significant residual displacement may be developed after excitation. Furthermore, P-Δ effects are not ignored if the column exhibits such large inelastic response during the earthquake. Accordingly, an appropriate balance between the flexural strength and ductility should be given to the column to satisfy the seismic performance demand.

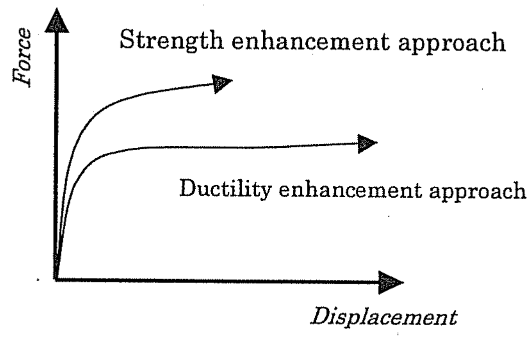


Fig. 4.3 Seismic Design Approach

5) Directional Uncertainty

Seismic forces have been applied to structures in both longitudinal and transverse directions independently, according to the current design code of highway bridges in Japan, except complicated structures such as the long-span bridges. In the United States, on the other hand, the directional uncertainty has been considered in evaluation of the seismic design forces. An

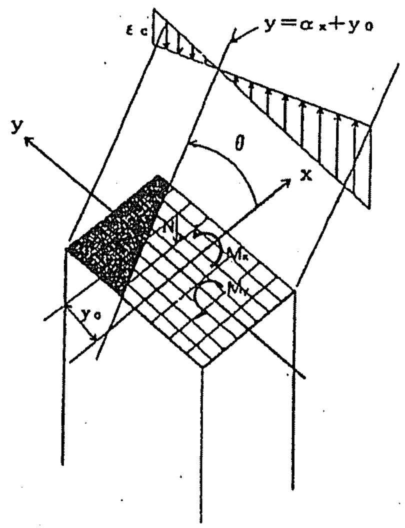


Fig. 4.4 Schematic Image of Bi-axial Bending

additional lateral force corresponding to 30% of the design force in the orthogonal direction is taken into account. Since the actual seismic force acts to the structures in two- or three-dimensional direction, the directional uncertainty effect on the structural response should be investigated.

4.2 Future Research Topics on Development of Evaluation Methodology of Structure Limit States

1) Studies on Failure Mechanisms and Inelastic Response Properties

Lack of the study on the failure mechanisms for members subjected to high axial load, variable

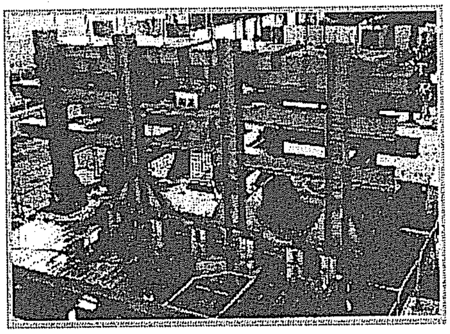


Photo 4.1 Shaking Table Test using Large Scale Unit

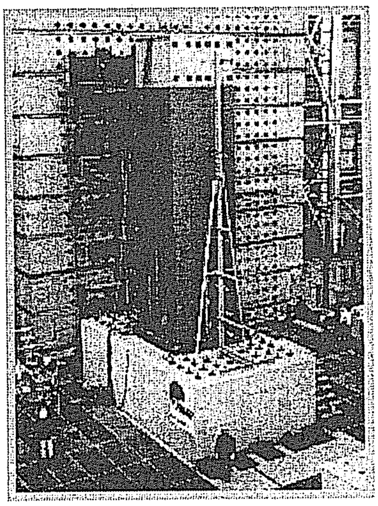


Photo 4.2 Cyclic Loading Test using a Real Scale Specimen

axial load, bi-axial bending during an earthquake is a constraint against developing the seismic design based on the structure limit states. The failure mechanism of overall structure systems and their structural members should be studied through loading tests and shaking table tests with use of large-scaled units.

2) Determination of Limit States

There are several useful limit states of structural response in the seismic design process. In terms of the reinforced concrete members, four limit states may be determined, that is, cracking limit state, yield limit state, spalling limit state and ultimate limit state. The overall structure limit states can also be determined as serviceability limit state, damage-control limit state and survival limit state. These limit states may be defined based on the strength and ductility of the structures. Therefore, it is required to clarify the relation between the strength/ductility response and damage level at the plastic hinge.

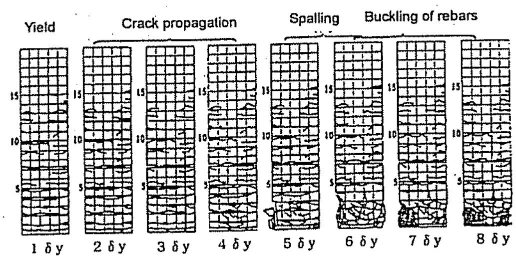


Fig. 4.6 Common Damage Progress of Reinforce Concrete Column

3) Modeling and Analysis

Nonlinear hysteresis models, in which the fundamental dynamic properties such as the stiffness and the damping of structures can be incorporated adequately, are required in the limit state design process with convenient analytical tools applicable to the dynamic response analysis.

4.3 Use of Advanced Technology

By using the interlocking steel with spiral and advanced materials such as the high strength concrete and the high performance steel, the columns would exhibit more ductile behavior than the conventional reinforced concrete structures. Development of new earthquake protective systems such as seismic isolation devices is also expected, to reduce the seismic effects.

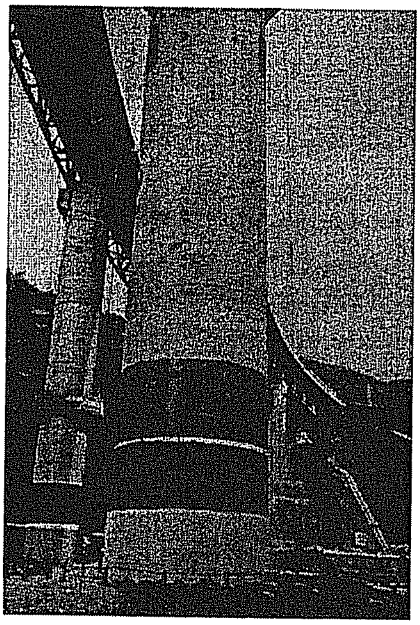


Photo 4.3 Carbon Fiber Retrofit Technology (Sakawa Bridge)

5. SEISMIC DESIGN FOR SOIL STRUCTURES

(1) Improvement of the Conventional Pseudo-static Analysis Procedure

The conventional pseudo-static analysis procedure which is based on the combined use of the limit equilibrium theory and the seismic coefficient method is considered the out-of-date technique. However, there do not exist alternative procedures to be used in the field practice with satisfactory reliability. Thus, the conventional procedure should be used until more rational and practical alternatives are developed. The use of the pseudo-static analysis procedure, which yields only a factor of safety, is justified only if there exists any correlation between the safety factor and the extent of deformation. Fig. 5.1 shows the correlation between the peak ground acceleration and the seismic coefficient to be used in the circular sliding method, which was obtained by back-analysis of damaged/non-damaged case records. The dotted line in the figure well separates both cases. This may indicate a potential of the method to predict the extent of deformation, although further study is needed to verify the procedure.

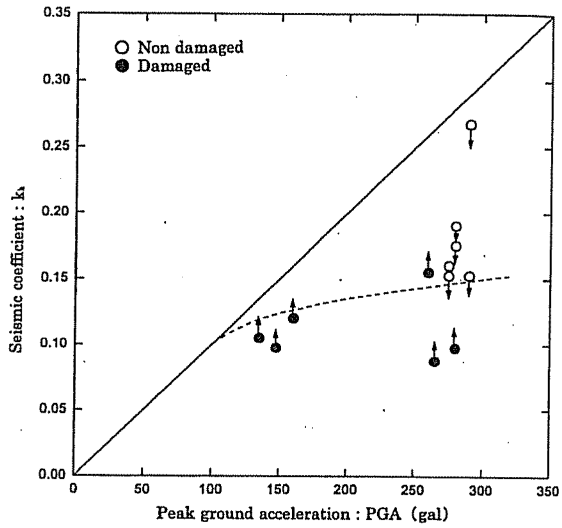


Fig.5.1 Correlation between the peak ground acceleration and the seismic coefficient to be used in the circular sliding method

(2) Development of the Deformation Analysis

Prediction of earthquake-induced deformation is usually needed when the very strong earthquake is considered in the design, as in the case of the other structures. Several methods which can predict deformation have been proposed so far, but none of the methods has reached in the level of wide practical use. Among these, the most rational and potential method would be the elasto-plastic finite element analysis method. In order to introduce the procedure into practice, more research work should be done to verify the capability through a number of case studies.

Fig.5.2 shows an example result of such case study using the elasto-plastic finite element method for a river bank which was damaged by the Hyogo-ken Nanbu earthquake. The predicted crest settlement was 2.9 m, while the measured one was 2.7 m. Although this example shows a very good agreement, if this type of analyses is established in the level of practical use, introduction of performance-based design into soil structures would be realized.

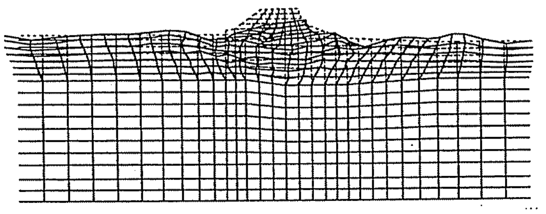


Fig.5.2 Result of the simulation, at Yodo river left bank, Torishima

(3) Development of the Rational Countermeasures Against Earthquakes

A wide variety of countermeasures such as ground improvements and soil reinforcements have been proposed to date. But the effectiveness of these countermeasures under very strong earthquake has not been evaluated quantatively, and consequently the seismic design procedures have not yet been established. Thus, further research is needed. In particular, prediction procedures of permanent deformation of soil structures with any countermeasure will play a very important role in elaborating the design methods.

Another aspect is that the cost of seismic countermeasures for the existing structures is expensive as compared with the construction cost of the soil structure itself. The cost may be sometimes as much as or more than that of the soil structure, unlike in the case of reinforcement of reinforced concrete or steel structures. Therefore to make it economical, a method or procedure which aims at making the damage to be within the allowable limit rather than preventing the damage has to be developed.

(4) Development of the Simple and Practical Soil Surveying Methods

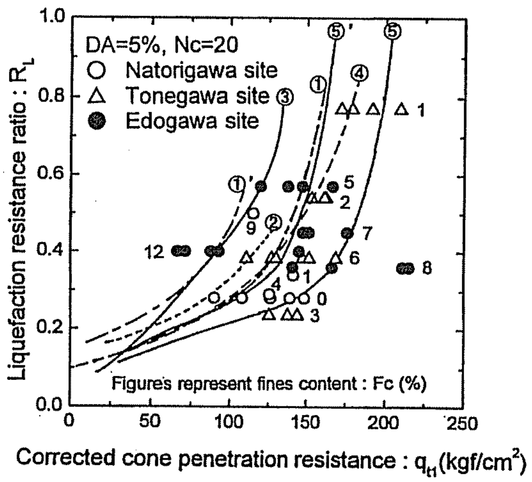
As was mentioned before, seismic performance of soil structures is strongly affected by the ground conditions. Therefore, the ground surveying and evaluation of the data play an important role in predicting seismic stability of soil structures. On the other hand, the soil structures are typical as embankments are usually large in size and in length. To grasp the soil profile along the soil structure, a number of sounding must be executed, resulting in very expensive cost. The standard penetration test has been widely used to identify the soil profile and to assess liquefaction potential of the soils. However, this is not cost-effective. One of the potential sounding techniques which can substitute the SPT and are more economical would be the piezometric cone penetration test. The advantage of this test is listed below as compared with the standard penetration test.

- cost for a unit length is about one third
- continuous data can be acquired along the vertical direction

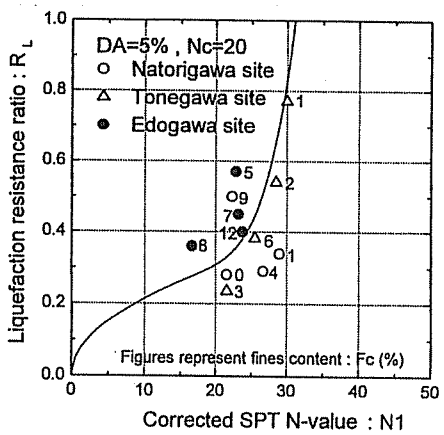
Defects are as follows:

- as the soil sample is not retrieved, the soil type must be estimated from the measured value
- it cannot be penetrated into the gravelly soil, etc.

Fig.5.3(a) shows the relationship between the cone tip resistance and the liquefaction resistance that was obtained by the field tests. Result of the standard penetration test is also presented in Fig. 5.5(b) for comparison. Judging from these two figures, the cone penetration test has almost the same accuracy as the standard penetration test. Reliability of the testing method would be enhanced by further accumulating the field data.



(a) cone penetration test



(b) standard penetration test

Fig.5.3 Relationship between the penetration resistance and the liquefaction resistance

6. CONCLUSIONS

(1) As a rational methodology to determine the seismic potential of civil infrastructure, the new concepts of the realized performance matrix (RPM) and the IOC curve was proposed. Also, the example of optimization of the earthquake resistant investment was introduced. Such approaches from the planning point of view will become important to thrust the earthquake disaster prevention measures with the consensus in the near future.

(2) The researches regarding the rational methods to determine the very strong design ground motion were introduced. The estimation of near field ground motions makes it feasible to take region specific active faults into account in the process to determine the very strong design ground motion. The strength reduction factor spectrum can be used to evaluate inelastic behavior of structures for rational seismic design against such very strong ground motion.

(3) Future scopes for development of seismic design methodology were presented and the future research needs were also discussed. Among all the research topics stated in this paper, development of the performance-based design method is one of the needed projects to be finished within a few years in Japan. The five-year project was already launched in 1998 to establish the performance-based seismic design method and to improve the related performance evaluation methods.

(4) For most of the soil structures typically as soil embankments, seismic design had not

been mandatory until the Hyogo-ken Nanbu earthquake took place. But now, very strong earthquake should be considered in the design of very important structures. Major researches that need to be focused on would be development of the new design procedure based on the allowable deformation, improvement of the conventional pseudo-static analysis procedure and development of cost-effective countermeasures.

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