

COMPUTATIONAL APPROACH TO PATH-DEPENDENT NONLINEAR RC/SOIL INTERACTION

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This paper presents reversed cyclic models of coupled RC/soil system. The full path-dependent constitutive models of RC, soil and their interfacial zones which are installed in the FEM program **WCOMR-SJ** are explained. Consequently, RC/soil hysteresis damping and energy absorption are coherently taken into account with corresponding states of damage and plasticity regarding concrete and reinforcement. This computational tool was systematically verified through coupled RC/soil system subjected to static reversed cyclic loads. The nonlinear interaction of RC/soil system and induced damage of underground RC are investigated.

Key Words: nonlinear analysis, RC, soil-structure interaction, FEM

1. INTRODUCTION

The last decades have seen many advanced researches on reinforced concrete structures and construction technologies. At the same time, a number of large scale reinforced concrete structures such as tanks and nuclear power plants have been built. Many of them are located in seismic active areas. Although the design of RC structures has been considerably improved, there are problems remained, especially in case of complex structures having interaction with surrounding media such as underground structures.

Dynamic forces that arise in underground RC have much to do with deformation of soil¹⁾. At the same time, dynamic soil pressure applied to RC is affected by stiffness reduction of RC members due to cracks, structural ductility and hysteresis damping characteristics. The importance and cost of underground RC structures make it necessary to analyze their response to earthquake loads as full entire system of RC/soil foundation and has to be treated as being coupled for rationalization of design.

Dynamic analyses of underground structures, whose purpose has been chiefly directed to computation of section forces of members, have extensively adopted equivalent degrading stiffness and increasing hysteresis damping of RC and soil

for simplicity of computation. No matter how effectively equivalent models of RC/soil serve, there exists limit of versatility. The residual deformation and structural damage after earthquake cannot be evaluated by this degenerated approach to RC/soil system. For examining the limit state of the earthquake directly, the constituent materials of structures and foundation have to be modeled as path-dependent media in time and space domains.

This paper aims to present reversed cyclic models of coupled RC/soil system. Full path-dependent constitutive laws of reinforced concrete, soil and interface are installed in a FEM code **WCOMR-SJ**. Consequently, RC/soil hysteresis damping and energy absorption, which are identified with seismic structural excitation, are taken into account with corresponding states of damage and plasticity regarding concrete and reinforcement.

2. ANALYSIS OF UNDERGROUND STRUCTURES

At present, finite element approach is widely used in the analysis of underground reinforced concrete structures with the surrounding soil media. The practical use of finite element analysis makes it possible to deal with material nonlinearity. The major issue in the nonlinear finite element method

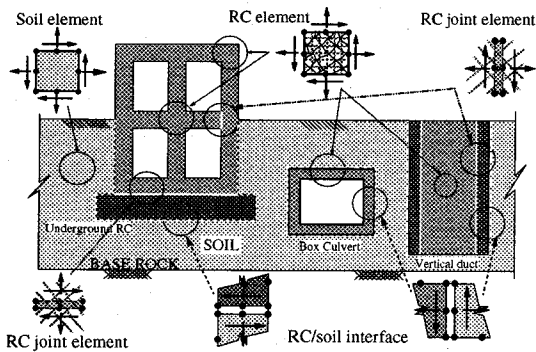


Fig.1 Discretization of RC/Soil system for different elements and models¹⁾

for analyzing the underground structures is to establish constitutive models for reinforced concrete and soil media under reversed cyclic loads. These models should be full path-dependent models in order to be capable of predicting the stress accurately for any given strain history. **Fig.1** shows the proposed discretization of RC/soil system for different elements and models.

(1) Reinforced concrete constitutive model

Last few decades have seen great improvements in the development of computer technology. At the same time, the field of structural engineering has undergone many improvements in the numerical tools of analyzing reinforced concrete under various loads. Finite element analysis is a method to solve simultaneous differential equations numerically and can be applied to a differentiable continuum. However, reinforced concrete is not a continuum since it has cracks. To describe cracks, microscopic discrete crack modeling and macroscopic smeared crack modeling are mostly used for this purpose.

In this study, the combination of smeared and discrete crack models subjected to reversed cyclic loads²⁾ is adopted for any type of RC underground structures. Smeared crack model is employed to some control volume of members and discrete ones are placed in between members with different thickness, construction joints and fewer discrete cracks intersecting reinforcement. Since both smeared and discrete cracks have distinct size sensitivity to energy dissipation, their combination is crucial for ductility and energy dissipation of scaled-up structures in seismic analysis⁵⁾.

a) In-plane constitutive model for RC

Nonlinearity of reinforced concrete depends mainly on bond between reinforcement and concrete, compressive characteristics of concrete between cracks. The used RC smeared crack constitutive model is derived from cyclic path-dependent tension stiffness model, stress transfer

model and elasto-plastic and fracture model for concrete including cracks²⁾. Crack spacing, or density, and diameter of reinforcing bars have negligible effect on spatially averaged stress-strain relation defined on RC in-plane control volume, as shown in **Fig.2**^{2),5)}. Thus in computation, the continuum damage model of concrete encompasses the reduction of compressive capacity of cracked concrete in relation to the mean strain normal to cracks.

As reversed cyclic loading causes rotation of principal axes of stresses, multi-directional crack model is adopted here²⁾. Directions of the first and second cracking are memorized as being non-rotating but fixed parameters in a path-dependent analysis. RC in-plane constitutive models are described with reference to tension-stiffness normal to cracks, shear transfer along cracks and normal stress parallel to cracks on the local coordinates of each direction of cracks. Hence, principal stress rotation after the first crack is associated with the existence of shear transfer along the first crack. The occurrence and direction of the second crack are also influenced by the shear transfer which makes the principal stress axis rotate from the geometrical direction of cracks in concrete.

b) RC joint interface constitutive model

RC joint interface model of reversed cyclic loading consists of bond pullout model of embedded reinforcing bars and stress transfer model. Steel bars are generally idealized as one-dimensional cord, and contact density model⁷⁾ is employed for stress transfer along a crack⁶⁾. Concerning heavily reinforced interfaces having flatter configuration, localized bending near a shear crack is reported to reduce the bar axial stiffness and mean yield capacity⁸⁾, which leads to the loss of confinement applied on the joint surface. This effect is incorporated in the model concerned by reducing axial mean yield strength of steel according to direction of displacement.

As far as smeared crack model and discrete crack model are concerned, a series of systematic verification in the element and member levels has been reported²⁾.

(2) Constitutive models of soil and RC/soil interface

A path-dependent constitutive model for soil is indispensable for dealing with kinematic interaction of RC/soil entire system under strong seismic loads. Furthermore, nonlinear characteristic in shear governs the magnitude of ground acceleration which in turn generates induced forces of underground RC. Here much attention is oriented to the short-term

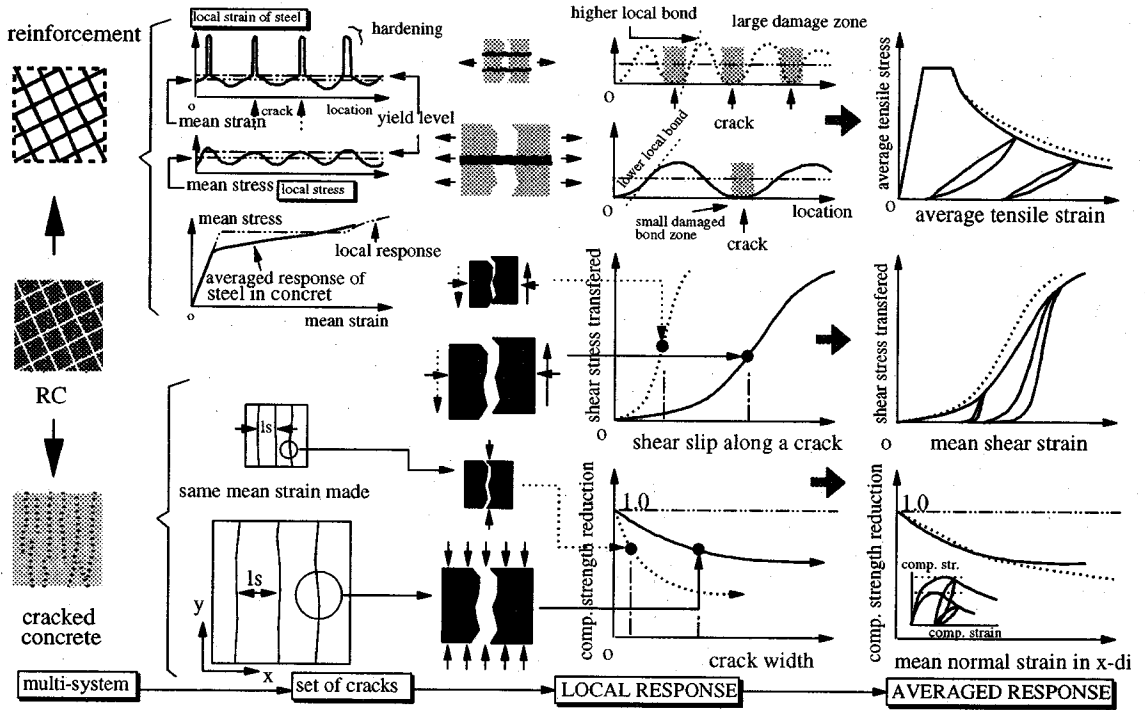


Fig.2 Composition of in-plane constitutive models of reinforced concrete ^{2),5)}

cyclic shear of geomaterials that represents soil layers located on a referential base rock.

Dynamic interaction between soil and structure is defined as a phenomenon of transmitting kinematic energy through the interface of media. The characteristics of RC/soil interaction are affected not only by mechanical properties of constituents but also by the geometrical form and condition of interface. Since stress and strain in soil close to the structure will attain high values due to heavy seismic forces applied, the separation and sliding between soil and structures most likely occur along the interfacial zone. In order to treat this effect, the RC/soil interface model is considered, as shown in Fig.1.

a) Path-dependent constitutive model of Soil

The constitutive model of soil is formulated in terms of shear and volumetric modes, which are combined together to get the behavior of soil under reversed cyclic load. Similar to the adopted concrete constitutive model, stress and strain intensity indicators⁽¹⁰⁾ are used in the model formulation where the total stress can be isotropically expressed as follows:

$$\sigma_{ij} = \int d\sigma_{ij} \quad (1)$$

$$d\sigma_{ij} = 2Gde_{ij} + 3K\delta_{ij}d\varepsilon_o \quad (2)$$

where

$$e_{ij} = \varepsilon_{ij} - \delta_{ij}\varepsilon_o \quad \text{and} \quad \varepsilon_o = \frac{1}{3}\varepsilon_{kk}$$

$$G = G(J'_2) \quad \text{and} \quad K = K(I'_1)$$

σ_{ij} and ε_{ij} represent the stress and strain tensors, respectively, along local axes, i and j . J'_2 and I'_1 are the path-dependent second strain deviator invariant and first mean strain invariant, respectively.

The generalized shear relation under reversed cyclic paths in soil (Fig.3) that governs the magnitude of ground acceleration can be expressed in terms of shear strain and stress deviator invariant as follows:

$$J'_2 = \int_{\text{path}} dJ'_2 \quad \& \quad J_2 = \int_{\text{path}} dJ_2 \quad (3)$$

$$dJ'_2 = \frac{\bar{e}_{ij}}{2\sqrt{\frac{1}{2}\bar{e}_{ij}\bar{e}_{ij}}} de_{ij} \quad \& \quad dJ_2 = \frac{\bar{s}_{ij}}{2\sqrt{\frac{1}{2}\bar{s}_{ij}\bar{s}_{ij}}} ds_{ij} \quad (4)$$

where

$$\bar{e}_{ij} = e_{ij} - e_{ij}^T \quad \& \quad \bar{s}_{ij} = s_{ij} - s_{ij}^T$$

Stress and strain with superscript "T" are defined based on the updated turning point specified in the hysteresis rule, according to the following equation:

$$e_{ij}^T(t) = e_{ij}(t^-) \quad \text{if} \quad dJ'_2(t).dJ'_2(t^-) < 0$$

$$s_{ij}^T(t) = s_{ij}(t^-) \quad \text{if} \quad dJ_2(t).dJ_2(t^-) < 0$$

For practical purposes of soil dynamic analysis of RC underground structures, soil can be assumed to

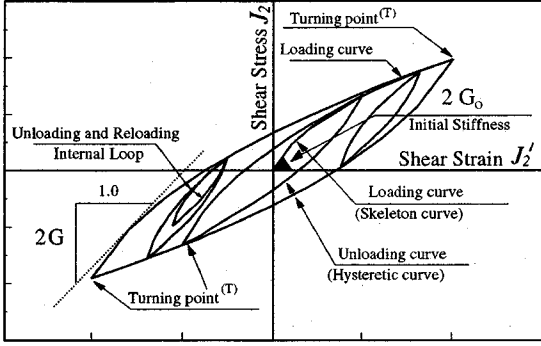


Fig.3 Cyclic shear model of soil

behave in a manner of *Masing* law, (equation (5)), in defining the hysteric curves without introducing much error as follows^{4,14)}:

$$\frac{dJ_2}{M} = f\left(\frac{dJ_2'}{M}\right) \quad (5)$$

where

$$M = \text{hysteric coefficient} \begin{cases} 1.0 \text{ for loading path} \\ 2.0 \text{ for unloading} \\ 2.0 \text{ for reloading} \end{cases}$$

Ohsaki's model⁴⁾ defines the following formula for envelope to express the nonlinear relation between the shear stress-strain for soil as well as internal loop with *Masing's* rule as,

$$\frac{J_2'}{M} = \frac{J_2}{2G_o M} \left(1 + A \left| \frac{J_2}{S_u M} \right|^B \right) \quad (6)$$

where:

$$A = \frac{G_o}{100S_u} - 1 \quad (\text{depends on failure strain})$$

S_u = max. shear strength

$$B = \text{soil type factor} \begin{cases} 1.6 \text{ for sandy soil} \\ 1.4 \text{ for clay soil} \end{cases}$$

G_o = initial elastic shear stiffness

Performing the integrals of equation (3) and equation (4) along the strain history of each element, the tangential shear stiffness (see Fig.3) can be derived from Equation (6) as:

$$2G = \frac{2G_o}{1 + A(B+1) \left| \frac{J_2}{S_u} \right|^B} \quad (7)$$

For simplicity, in formulating equation (2), the path-independent elasticity of hydrostatics is applied. It means that the volumetric relation which is expressed in terms of the 1st invariant of stress and strain, is considered as linear elastic, with volumetric elastic stiffness K_o as follows:

$$K = K_o \quad (\text{const.}) \quad (8)$$

where:

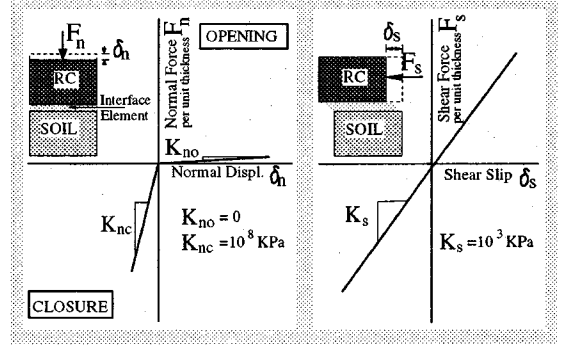


Fig.4 Normal and shear response of RC/soil interface

$$K_o = \frac{E_o}{3(1-2\nu_o)} = \text{volumetric elastic stiffness}$$

Although the dilatancy and compaction actually arise in soil and the first invariant of strains is provoked by larger shear, this coupled term with volumetric deformation is ignored here.

By substituting equations (7) and (8) in equation (2), the generic 3-D stress states can be obtained as being path dependent at any strain.

b) RC/Soil interface model

In the actual system, the separation phenomenon may occur at the interface between RC and soil where tensile stress is generated and seismic force is transmitted through decreased contact area resulting in an increase in contact stress. As the stress-strain relationship of soil depends on the intensity of confining pressure, strong nonlinear behavior will appear in the case where contact area on interface varies. Moreover, sliding phenomenon may occur during strong earthquake motion. The separation and sliding have to be of the sources of energy dissipation between structure and soil. The possibility of separation and sliding along the interfacial zone should be considered in the analysis.

In the RC/soil interface model, bilinear bond in open/close mode is assumed. By this assumption, the normal stress, which is perpendicular to the interface surface, is equal to zero in case of separation, (i.e., the normal stiffness in case of opening mode K_{no} equal to zero), and no stress will be transferred between soil and structure. In order to consider the separation at zero stress, initial condition of soil pressure and stress along the interface surface should be taken into account. For contact case, the stiffness of the interface (K_{nc}) is numerically large (no overlap is allowed), as shown in Fig.4. For shear slip relation, the shear force-displacement relation is assumed linear with shear stiffness (K_s)³⁾, as shown in Fig.4.

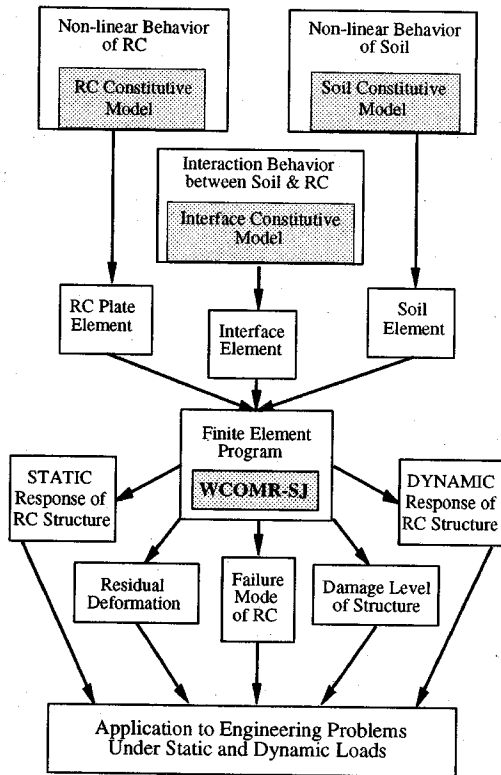


Fig.5 Outlines of WCOMR-SJ

3. COMPUTER PROGRAM

Based on the RC nonlinear finite element analysis²⁾ applicable to reversed cyclic loads, the path-dependent constitutive models for soil and RC/soil interface are installed in the computer code **WCOMR-SJ**. The advantage of path-dependent model is exhibited such that hysteresis damping and restoring force characteristics of both structure and soil are intrinsically taken into account. The residual deformation and structural damage at any loading level can be quantitatively evaluated. Adopting the proposed finite element analysis for the design of RC underground structures makes it possible to perform a safety check and to evaluate serviceability of structure based on the damage level index at any loading level¹⁵⁾. Fig.5 shows the outline of the computer code **WCOMR-SJ** and the combination of different elements.

4. RC/SOIL SYSTEM VERIFICATIONS

In an attempt to verify the analytical results of **WCOMR-SJ**, two types of experiments are

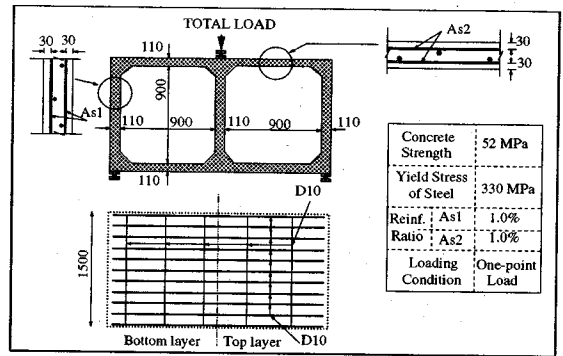


Fig.6a Details of the RC box culvert

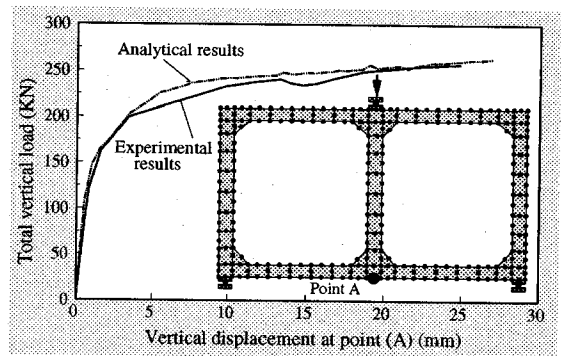


Fig.6b RC box culvert response and prediction

examined. For checking RC in-plane model and the fineness of mesh used in the analysis, an RC culvert, with the dimensions and details shown in Fig.6a, subjected to combined shear and bending was examined prior to the full RC/soil system¹²⁾ (Fig.6b). The analytical and experimental results indicate that the finite element discretization of RC by using single layer of smeared crack in-plane elements is acceptable.

Another set of experiment, RC box culvert surrounded by sand under reversed cyclic shear, is selected, as shown in Fig.7. The experiment was conducted by JSCE committee on limit state design of underground RC structures for nuclear power plants¹³⁾. The main object of this experiment was to examine the ductility of underground RC under high shear deformation and to evaluate the present design codes of underground structures. Through this experiment, the total deformation of soil and RC culvert were measured.

Two RC box culverts consisting of frames having 0.4% volumetric reinforcement ratio (culvert (A)) and 0.88% volumetric reinforcement ratio (culvert (B)) are considered, respectively. The details of the RC box culverts are shown in Fig.8.

The soil including RC box culvert was vertically loaded by weight equivalent to 5.8 m surcharge of

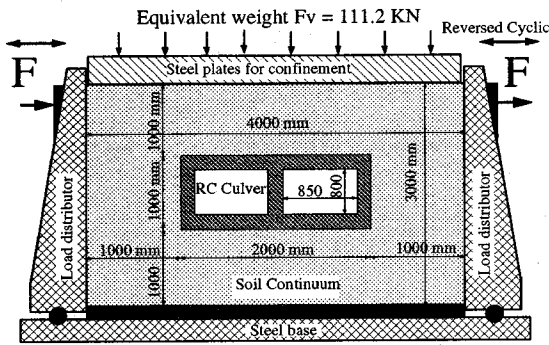


Fig.7 Experiment setup for RC/Soil system

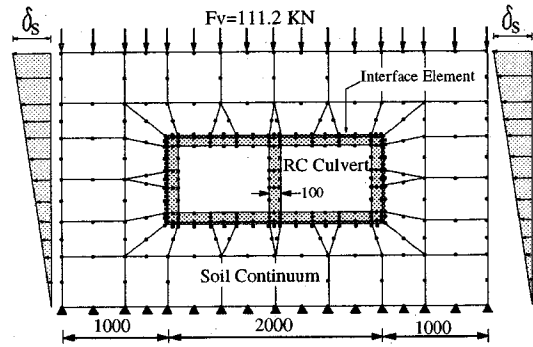


Fig.9 2-D Finite element mesh

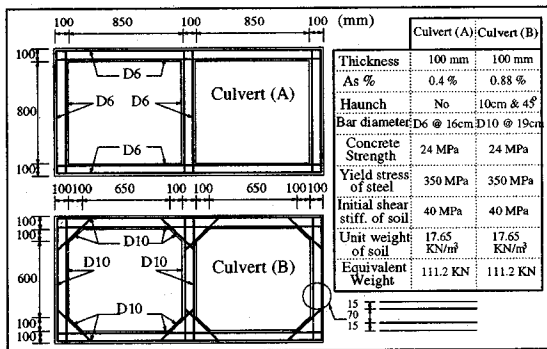


Fig.8 Details of RC box culvert (A) and (B)

soil above the structure, and forced horizontal displacement was repeatedly applied through a set of load distributors of high stiffness. The inner dimensions of soil container are 4.0 m length, 3.0 m height and 1.0 m thickness. The culvert is placed 1.0 m above the base of the container, as shown in Fig.7. The initial shear stiffness of soil used (40 MPa) was numerically identified by using a reference test for soil only which was compacted with the same manner¹³⁾.

Finite element discretization which is used in the analysis is composed of eight node quadrilateral elements, as shown in Fig.9. The RC/soil interfacial elements are placed at the interface between soil and RC. The analysis is carried out for the same reversed cyclic loading as was done in the experiments. The body force and initial earth pressure are taken into account in the analysis to represent the initial condition of the interfacial zone.

Since the sandy soil was kept in plane strain condition, a 3-D constitutive model of soil was used under the restriction of zero strain in the thickness direction. Single layer of smeared crack in-plane elements with higher order was assigned to walls and upper/lower slabs.

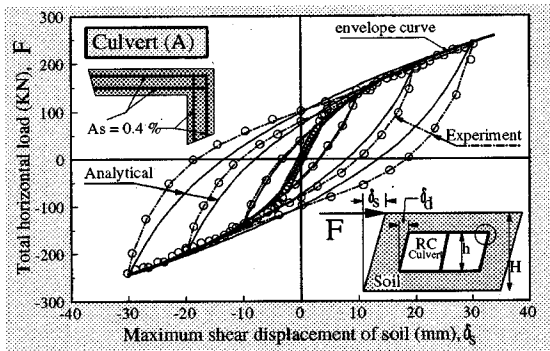


Fig.10a Cyclic load-displacement relationship of RC/Soil system for culvert (A)

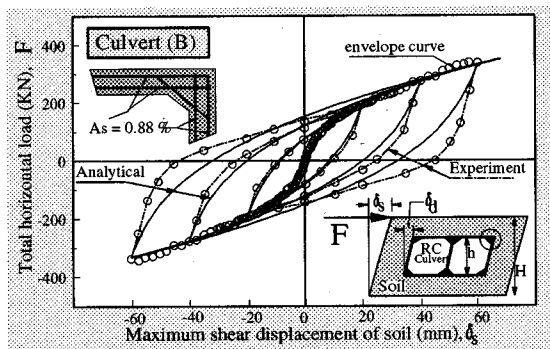


Fig.10b Cyclic load-displacement relationship of RC/Soil system for culvert (B)

The experimental and analytical results of total horizontal load versus the maximum shear displacement of soil are shown in Figs.10a and 10b. The shear displacement that is proportional to the mean shear strain of RC/soil is represented by the total horizontal displacement at the top of load distributors. Although many cycles were considered in the experiment, only three cyclic loops at different displacement levels are shown in Figs.10a and 10b for making comparisons easier.

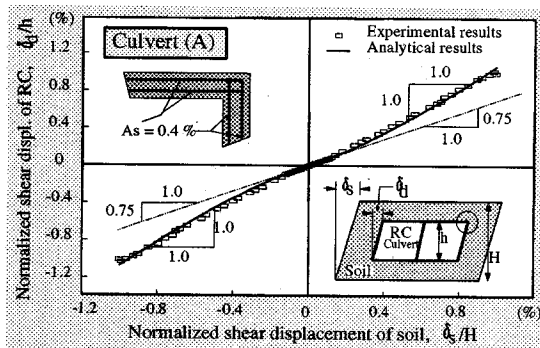


Fig.11a Mean shear deformation of underground RC and soil for culvert (A)

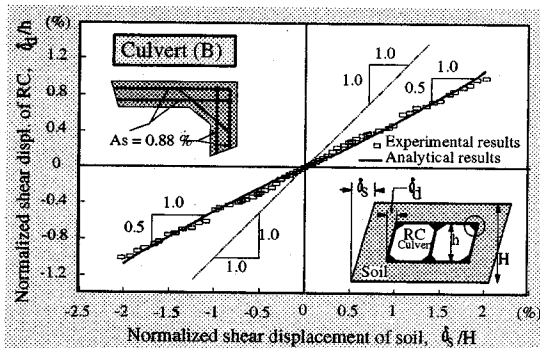


Fig.11b Mean shear deformation of underground RC and soil for culvert (B)

The analysis successfully predicts the envelope of the load-displacement relations of the RC/soil entire system for both culverts. The loading-unloading paths and the residual deformation are predicted well for all the paths. From the experimental and analytical results, for culvert (A), the maximum displacement is 30 mm and the maximum capacity of total horizontal load is 230 KN. On the other hand, the ductility and capacity of the system involving stiffer RC (culvert (B)) are higher (maximum displacement is 60 mm and horizontal load is 320 KN).

For discussing the kinematic mode of a coupled system, relations of externally enforced shear displacement versus shear displacement of embedded RC culvert are shown in Figs.11a and 11b. Both values are normalized by the height of soil and RC, respectively.

At the initial stage, the shear deformation of a lightly reinforced box culvert, culvert (A), is approximately 75% of that of the surrounding soil. For high values of externally enforced shear deformation (after cracking), the overall deformation of RC box culvert follows that of soil owing to reduction of the stiffness due to cracking and

Table 1 Parametric study for RC box culvert

Material Behavior		Interface Element				
Soil	RC	Open K _{no} KPa	Closure K _{nc} KPa	Sliding K _s KPa		
Material Effect	Non-linear	Non-linear	0	10 ⁸	10 ³	
	Non-linear	Linear				
	Linear	Non-linear				
	Linear	Linear				
Interface Effect	Non-linear	Non-linear	1	10 ⁸	10 ⁸	10 ⁸
			2	10 ⁸	10 ⁸	10 ³
			3	0	10 ⁸	0
			4	0	10 ⁸	10 ³

yielding. On the contrary, the box culvert with larger reinforcement, culvert (B), exhibits higher stiffness accompanied by nearly 50% of the displacement of soil. Furthermore, the kinematic mode of RC/soil deformation in shear is roughly constant in the whole range of loading. The analysis shown in Fig.10 is mainly influenced by the soil model due to its huge mass, but the results shown in Fig.11 are predominantly governed contrary by the models of RC and interface. Thus, it can be said that constitutive models have reasonable accuracy.

5. NONLINEAR RESPONSE OF UNDERGROUND RC BOX CULVERT

As shown in the previous section, the analytical results of the computer program WCOMR-SJ with considering the material nonlinearity and path-dependency of both RC and soil constitutive models are in good agreement with the experimental results. In this section a sensitivity analysis has been performed to investigate the influence of considering material nonlinearity and path-dependency of both RC and soil in the analysis of the RC/soil entire system. Furthermore, an evaluation of the proposed interface model has been carried out in this study.

(1) Influence of nonlinearity of materials on RC/Soil response

Either RC or soil can be considered as linear-elastic or nonlinear material. Therefore, four combinations of the behavior of RC and soil are possible and should be considered in the parametric study. Table 1 shows the details of these combinations. In all cases, other parameters (dimension, reinforcement ratio, interface element and soil stiffness) were kept constant. At the same time, to consider the effect of the stiffness of

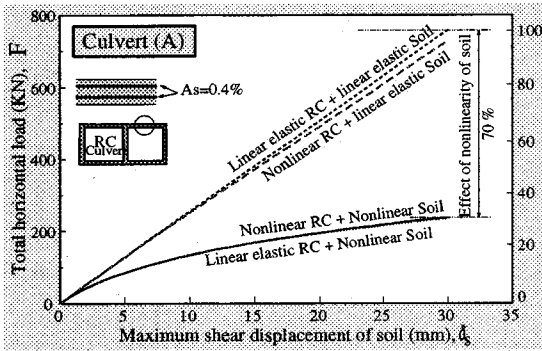


Fig. 12a Influence of nonlinearity of materials on the force displacement relationship for RC/soil system [culvert (A)]

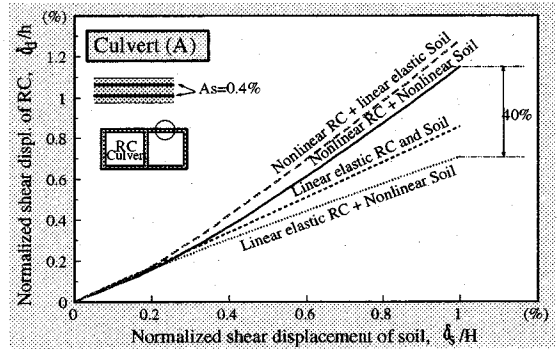


Fig. 13a Influence of nonlinearity of materials on the normalized shear displacement of RC culvert and soil [Culvert (A)]

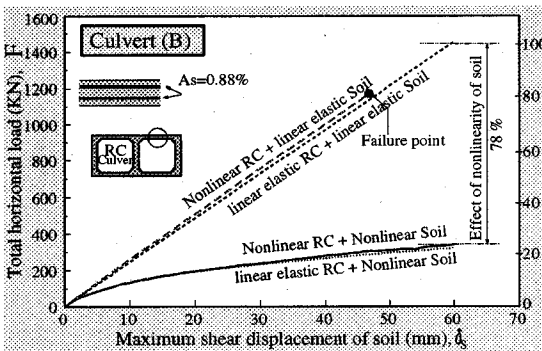


Fig. 12b Influence of nonlinearity of materials on the force displacement relationship for RC/soil system [culvert (B)]

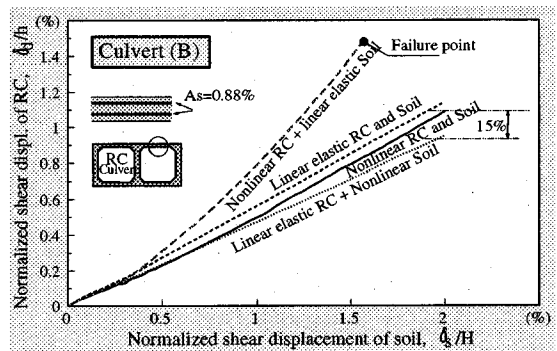


Fig. 13b Influence of nonlinearity of materials on the normalized shear displacement of RC culvert and soil [Culvert (B)]

structure, the study has been performed for the previously described two culverts (A) and (B).

a) Load-displacement relationship

The influence of considering nonlinearity of soil and RC on the load-displacement relation can be investigated for both culverts (A) and (B), as shown in **Figs. 12a** and **12b**, respectively. Considering the nonlinearity of RC, the load displacement relation is more or less the same as the linear elastic RC case. On the other hand, the total load is very high as a result for considering soil as a linear elastic material. It is about five times more than the case of considering nonlinear model for soil.

For culvert (B), **Fig. 12b**, if soil is considered as a linear elastic and the structure as nonlinear RC, the structure has compression failure after yield of steel at about 4.5 cm applied as maximum shear displacement. It can be concluded that the load-displacement relation is mainly controlled by the behavior of soil (linear elastic or nonlinear).

b) Shear deformation

In soil-structure interaction problems, the relative deformation of structures and soil should be known. In this study, the relative deformations considered as normalized mean shear displacement with height,

for soil and RC culvert are shown in **Figs. 13a** and **13b**. Through these figures, it can be seen that the effect of nonlinearity of RC is very significant for comparing the deformation.

In case of flexible structure (culvert (A)), until normalized mean shear displacement of soil equals to 0.2%, the RC is linear elastic. Then the nonlinearity takes place and the difference becomes more and more significant with increasing the mean shear displacement. At the normalized mean shear displacement equals to 1.0%, the normalized mean shear displacement of RC culvert becomes two times more than the case of assumed linear elasticity of RC.

In the case of rigid structure (culvert (B)), the structure behaves as linear elastic till normalized mean shear displacement equals to 1.0%, then the effect of nonlinearity takes place and gradually increases till the 2.0%. At that level, the effect of nonlinearity is about 15.0%.

By comparing both culverts (A) and (B) through **Figs. 12** and **13**, it can be concluded that while the effect of nonlinearity of RC is small for load displacement relation, it becomes very significant

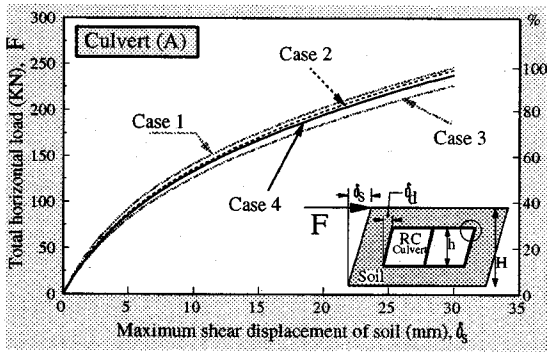


Fig.14a Influence of soil-structure interface on the force displacement relationship for RC/soil system [culvert (A)]

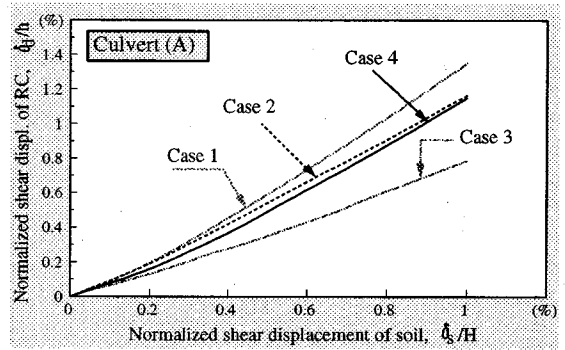


Fig.15a Influence of soil-structure interface on the normalized shear displacement of RC culvert and soil [culvert (A)]

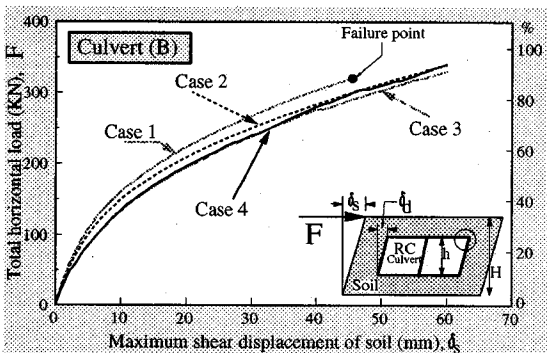


Fig.14b Influence of soil-structure interface on the force displacement relationship for RC/soil system [culvert (B)]

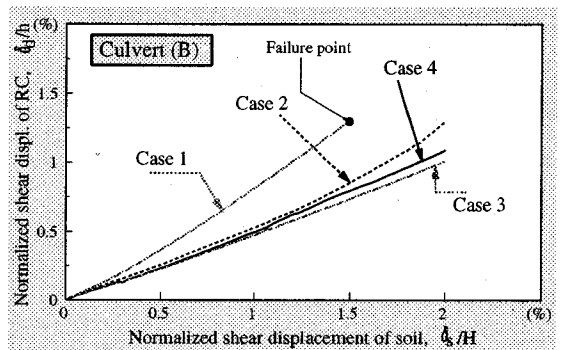


Fig.15b Influence of soil-structure interface on the normalized shear displacement of RC culvert and soil [culvert (B)]

for shear deformation which depends also on the rigidity of structure.

(2) Influence of interface behavior on RC/Soil response

To investigate the sensitivity of the proposed interface model on the coupled RC/soil interaction behavior, several combinations of the opening normal stiffness (K_{no}) and shear stiffness (K_s) have been considered. **Table 1** shows the details of the considered cases of combinations, cases 1, 2, 3 and case 4.

First, full bond between structure and soil is assumed and no shear slip is allowed (case 1). Second, perfect linear bond and allowed shear slip are assumed (case 2) to evaluate the effect of considering the separation into the analysis. Third, bilinear bond in open/close mode (separation is allowed) and no shear stress resistance (shear stiffness is zero) are considered (case 3) to identify the effect of changing shear stiffness or neglecting shear stress resistance in the analysis. All cases are compared with the proposed interface model in this study (case 4) for both box culverts (A) and (B).

a) Load-displacement relationship

Considering the interface element for different cases slightly changes load-displacement relation within $\pm 5\%$ at very high shear deformation. From **Figs.14a** and **14b**, the interface element behavior depends on rigidity of structures. For culvert (B) using full bond model, the structure failed.

b) Shear deformation

Through **Figs.15a** and **15b** the sensitivity of the interface model can be clearly evaluated. For the flexible structure (culvert (A)), the deformation of RC is almost similar to the deformation of soil. In this case, there is no separation between soil and RC. As a result, sliding behavior is very significant in the analysis. For case 3 in **Fig.15a**, the deformation of structure is reduced 50% from the experiments due to neglecting shear stress resistance. At the same time, deformation increases 20% by using the full bond (case 1).

On the other hand, for rigid structure (culvert (B)), the deformation of RC is less than the deformation of soil (50%). In this case, the separation takes place and becomes more significant in the analysis, as shown in **Fig.15b**. While in case

1, perfect bond, soil and the structure have the same deformation. As a result, the structure fails. However, in case of neglecting the shear stress resistance (case 3), the deformation of structure is slightly changed.

Through case 2, the behavior of interface in separation for both culverts is very clear corresponding to the relative displacement of structures. In this case, sliding relation is kept similar to case 4, but the relation of open/closure is assumed linear. For culvert (A), at small level of shear displacement of soil, there is difference in displacement. This difference slowly disappears by increasing soil displacement. After looking at the experimental results of this culvert, at the beginning the displacement of RC is 80% of the total displacement of soil (separation takes place), and by increasing the total displacement of soil, RC and soil have the same deformation (no separation).

From the above mentioned discussion it is concluded that, the interface element with both behaviors in open/closure and sliding, as proposed, is very important to be considered into the analysis to obtain the realistic response of RC/soil entire system and reasonable relative displacement between structures and soil.

6. CONCLUSIONS

The seismic earth pressure to underground structures predominantly influences the structural safety. However, its dependency on RC structural ductility has been neglected or simply idealized in practical design. Nonlinear characteristic of soil foundation has been of main concern and investigated in view of geotechnical problems. As a matter of fact, dynamic analysis serving practical design is conducted mostly in consideration of nonlinear soil but elasticity of underground RC structures or equivalent reduced stiffness. Based on these recent background, the following development and discussion were attempted and tentative conclusions are obtained.

1. Based on RC nonlinear finite element analysis applicable to reversed cyclic loads, a soil model which can trace path-dependency and interfacial zone was installed in computer code WCOMR-SJ. The advantage of path-dependent model is exhibited such that residual deformation and structural damage, which have much to do with remaining functions of RC, can be quantitatively evaluated.
2. To verify the analytical results of the computer program, several experiments were carried out and discussed in this study. Experimental work

for an RC box culvert, subjected to reversed cyclic loads, is carried out to verify the RC constitutive model in the level of structure subjected to shear and bending moment. Then, the analytical results of the RC/soil system are examined with the experiments of an RC box culvert surrounded by sand under reversed cyclic shear load. The experimental verification was aimed to check specific item of assumed nonlinearity described by each constitutive law used. Reasonable accuracy was confirmed.

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経路依存性を考慮したRC/地盤系の非線形相互作用に対する計算力学的アプローチ

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本研究は、交番荷重作用下での鉄筋コンクリート/地盤系の解析モデルについて論ずるものである。経路依存性を考慮可能な鉄筋コンクリート要素、地盤および両者の境界面での応力伝達構成モデルについて述べるとともに、これらを統合した有限要素解析プログラムが開発された。これによって、RC構造+地盤全体系の履歴減衰が解析において考慮され、併せて地中鉄筋コンクリート構造に導入される損傷や塑性を定量的に評価することが可能となる。本解析手法の適用性の検証は、鉄筋コンクリート単体および交番荷重を受ける地中鉄筋コンクリート/地盤系の実験等によって行われた。検証を経た解析法を基にして、地中鉄筋コンクリート構造の非線形挙動と導入される損傷について考察を行った。