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COMPUTATIONAL APPROACH TO PATH-DEPENDENT NONLINEAR RC/SOIL INTERACTIONS

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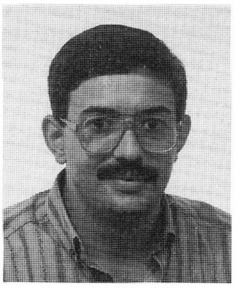
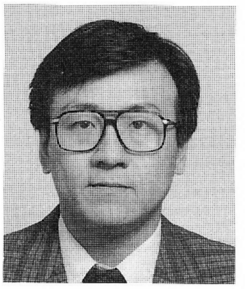


Ashraf SHAWKY



Koichi MAEKAWA

This paper describes reversed cyclic models of a coupled RC/soil system. Full path-dependent constitutive models of RC, soil, and their interface zones, which are installed in the FEM program **WCOMR-SJ,** are explained. With these models, RC/soil hysteresis damping and energy absorption are coherently taken into account with corresponding states of damage and plasticity for the concrete and reinforcement. This computational tool is systematically verified by subjecting a coupled RC/soil system to static reversed cyclic loading. The nonlinear interactions in the RC/soil system and damage induced in underground RC are investigated.

Keywords: *Nonlinear analysis, RC, soil-structure interaction, FEM*

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1. INTRODUCTION

The last decades have seen many advances in reinforced concrete structures and construction technologies. At the same time, many large-scale reinforced concrete structures such as tanks and nuclear power plants have been built. Many have been located in seismic active areas. Although the design of RC structures has been considerably improved, certain problems remain, especially in the case of complex structures which interact with the surrounding medium -- such as underground structures.

The dynamic forces that arise in underground RC have much to do with soil deformation[1]. At the same time, the dynamic soil pressure applied to the RC is affected by loss of member stiffness 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 loading as complete systems of RC and soil foundations, and these must be treated as being coupled for the purpose of design rationalization.

The dynamic analysis of underground structures, whose purpose has been chiefly the computation of section forces in members, has made extensive use of reduced equivalent stiffness and increased hysteresis damping of RC and soil for simplicity of computation. No matter how effectively these equivalent RC/soil models perform, there always exist limits of versatility. The residual deformation and structural damage after earthquakes cannot be evaluated by this degenerated approach to the RC/soil system. To examine the earthquake limit states directly, the constituent materials of the structures and their foundations have to be modeled as path-dependent media in the time and space domains.

The aim of this paper is to describe reversed cyclic models of the coupled RC/soil system. Full path-dependent constitutive laws for reinforced concrete, soil, and the interface are installed in a FEM code **WCOMR-SJ**. As a result, 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 for the concrete and reinforcement.

2. ANALYSIS OF UNDERGROUND STRUCTURES

The finite element approach is currently in wide use in the analysis of underground reinforced concrete structures with surrounding soil. This use of finite element analysis makes it possible to deal with material nonlinearities. The major issue in using the nonlinear finite element method for the analysis of underground structures is to establish constitutive models for reinforced concrete and soil media under reversed cyclic loading. Theses 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 the RC/soil system for different elements and models.

(1) Reinforced concrete constitutive model

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

In this study, a combination of smeared and discrete crack models subjected to reversed cyclic loads [2] is adopted for all types of RC underground structures. The smeared crack model is employed to some control volume of members while discrete models are placed in between members with different thickness, at construction joints, and where fewer discrete cracks intersect the reinforcement. Since both smeared and discrete cracks have distinct size sensitivity to energy dissipation, this combination is crucial for ductility and energy dissipation of scaled-up structures in seismic analysis[5].

a) In-plane constitutive model for RC

The nonlinearity of reinforced concrete depends mainly on the bonds between reinforcement and concrete and the compressive characteristics of the concrete between the cracks. The RC smeared crack constitutive model adopted here is derived from a cyclic path-dependent tension stiffness model, a stress transfer model,

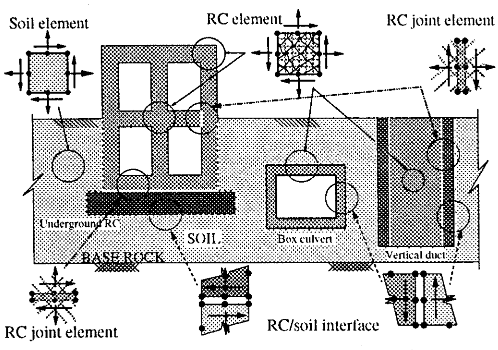


Fig.1 Discretization of RC/Soil system for different elements and models[1]

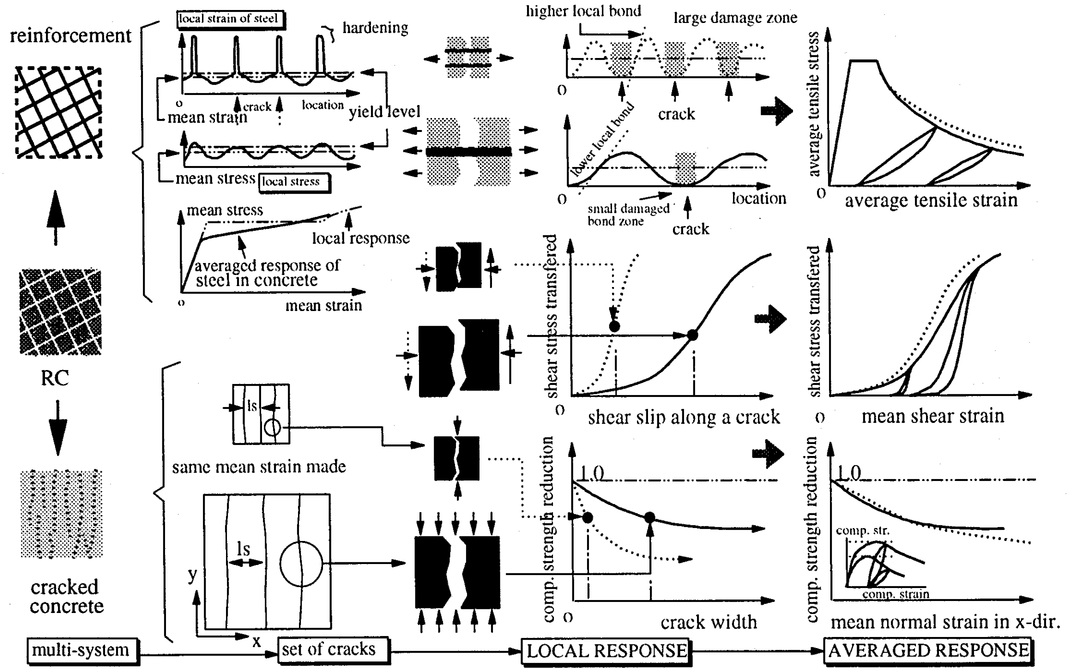


Fig.2 Composition of in-plane constitutive models of reinforced concrete [2),5)]

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

Since reversed cyclic loading causes a rotation of the principal stresses axes, a multi-directional crack model is adopted here[2)]. The orientation of the first and second cracks is stored as non-rotating but fixed parameters in 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 in the local coordinates of each crack orientation. Hence, the 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 away from the geometrical orientation of cracks in the concrete.

b) RC joint interface constitutive model

The RC joint interface model of reversed cyclic loading consists of a bond pullout model of embedded reinforcing bars and a stress transfer model. Steel bars are generally idealized as one-dimensional cords, and the contact density model[7] is employed for stress transfer along cracks[6]. In the case of heavily reinforced interfaces with a flatter configuration, localized bending near a shear crack is reported to reduce the bar axial stiffness and mean yield capacity[8], and this leads to loss of confinement at the joint surface. This effect is incorporated into the model by reducing the axial mean yield strength of the steel according to the direction of the displacement.

As far as the smeared crack model and discrete crack model are concerned, a series of systematic verifications at the element and member levels has been reported [2].

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

A path-dependent constitutive model for soil is essential in dealing with the kinematic interactions of the whole RC/soil system under strong seismic loading. Furthermore, the nonlinear characteristics of shear govern the magnitude of ground acceleration, which in turn generates induced forces in underground RC. Here, considerable attention is oriented to the short-term cyclic shear of geomaterials representing soil layers above an engineering referential rock bed.

A dynamic interaction between soil and structure is defined as the transmission of kinematic energy through the interface between the media. The characteristics of RC/soil interaction are affected not only by the mechanical properties of the constituents but also by the geometrical form and condition of the interface. Since stress and strain in soil close to the structure will reach high values when heavy seismic forces arise, separation and sliding between soil and structures are most likely occur at the interfacial zone. In order to take into account of this effect, the RC/soil interface model shown in **Fig.1** is adopted.

a) Path-dependent constitutive model of soil

The constitutive model of soil is formulated in terms of shear and volumetric modes, which are combined to obtain the overall soil behavior under reversed cyclic loading. As with 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:

$$\sigma_{ij} = \int d\sigma_{ij} \tag{1}$$

$$d\sigma_{ij} = 2G de_{ij} + 3K\delta_{ij} d\varepsilon_o \tag{2}$$

where,

$$e_{ij} = \varepsilon_{ij} - \delta_{ij}\varepsilon_o \quad and \quad \varepsilon_o = \tfrac{1}{3}\varepsilon_{kk}$$
$$G = G(J_2') \quad and \quad K = K(I_1')$$

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 the stress deviator invariant as follows:

$$J_2' = \int_{path} dJ_2' \quad \& \quad J_2 = \int_{path} dJ_2 \tag{3}$$

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

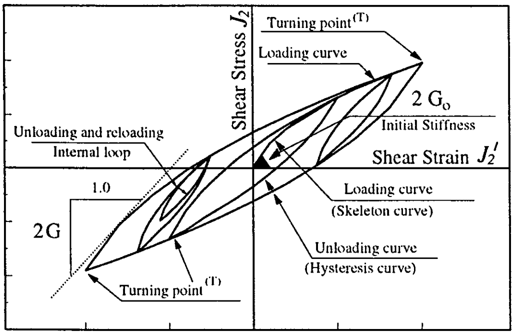


Fig.3 Cyclic shear model of soil

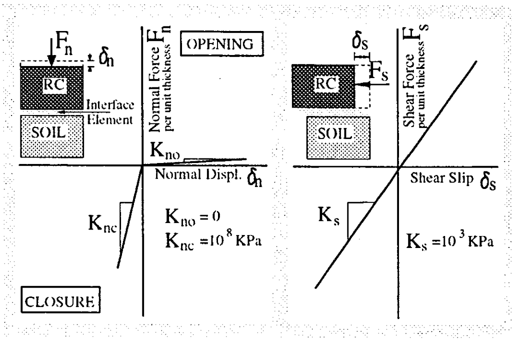


Fig.4 Normal and shear response of RC/soil interface

where,

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

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

$$e_{ij}^T(t) = e_{ij}(t^-) \qquad \text{if} \qquad dJ_2'(t)\cdot dJ_2'(t^-) < 0$$
$$s_{ij}^T(t) = s_{ij}(t^-) \qquad \text{if} \qquad dJ_2(t)\cdot dJ_2(t^-) < 0$$

For practical purposes in the analysis of soil dynamics for RC underground structures, soil can be assumed to behave in the manner expressed by the *Masing* law, (Equation (5)) by defining hysteresis curves without introducing much error as follows[4),14)]:

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

where M is hysteresis coefficient (1.0 for loading path and 2.0 for unloading and reloading paths).

Ohsaki's model[4)] defines the following formula for an envelope expressing the nonlinear relationship between the shear stress and strain for soil as well as the internal loop with *Masing's* rule as,

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

where $A = \dfrac{G_0}{100S_u} - 1$ (depends on failure strain), S_u is maximum shear strength, B is soil type factor (1.6 for sandy soil and 1.4 for clay soil), and G_o is 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:

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

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

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

where:

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

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

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

b) RC/Soil interface model

In an actual system, separation may be experienced at the interface between RC and soil where tensile stress is generated and the seismic force is then transmitted through a reduced contact area resulting in an increase in contact stress. Since the stress-strain relationship of soil depends on the intensity of the confining pressure, strong nonlinear behavior will arise in cases where the contact area of the interface varies. Moreover, sliding may occur during strong earthquake motion. Such separation and sliding have to be sources of energy dissipation between the structure and soil. The possibility of separation and sliding along the interfacial zone must therefore be considered in the analysis.

In the RC/soil interface model, bilinear bonding in open/close mode is assumed. Under this assumption, the normal stress, which is perpendicular to the interface surface, is equal to zero in the 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, the initial soil pressure and stress conditions along the interface surface should be taken into account. In the contact case, the stiffness of the interface (K_{nc}) is numerically large (no overlap is allowed), as shown in **Fig.4**. For the shear slip relation, the shear force-displacement relation is assumed to be linear with shear stiffness (K_s) [3] , as shown in **Fig.4**.

3. COMPUTER PROGRAM

Based on the above RC nonlinear finite element analysis[2] applicable to reversed cyclic loading, the path-dependent constitutive models for soil and the RC/soil interface are written into the computer code **WCOMR-SJ.** The advantage of the path-dependent model is seen in the fact 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 in the design of RC underground structures makes it possible to perform safety checks and evaluate the serviceability of structures based on the damage level index at any loading level[15]. **Fig.5** shows an 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 obtained using **WCOMR-SJ**, two types of experiments are examined. To check the 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** and subject to combined shear and bending had been examined before analysis of full RC/soil system was conducted[12] (**Fig.6b**). Comparison of the analytical and experimental results indicates that the finite element discretization of RC using a single layer of smeared crack in-plane elements is acceptable.

In another set of experiments, an RC box culvert surrounded by sand under reversed cyclic shear was selected, as shown in **Fig.7**. The experiment was conducted by a JSCE committee on the limit-state design of underground RC structures for nuclear power plants[13]. The main object was to examine the ductility of underground RC when subject to high shear deformation and to evaluate current design codes for

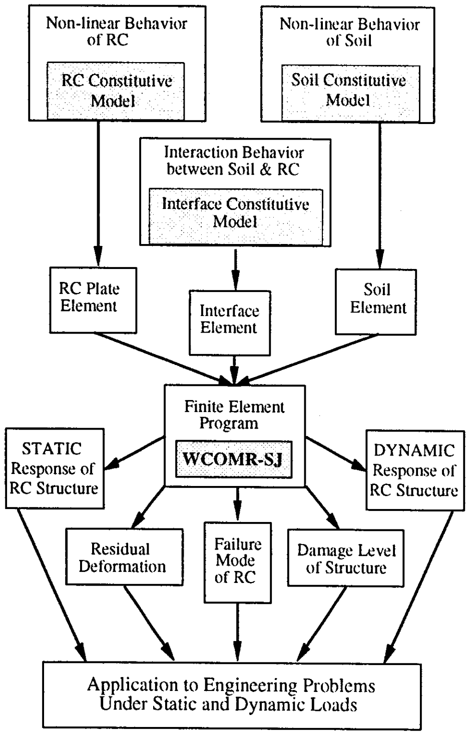


Fig.5 Outlines of WCOMR-SJ

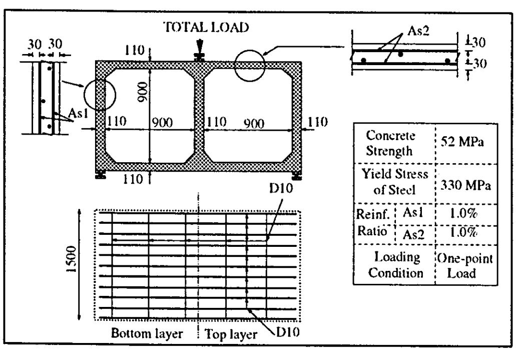


Fig.6a Details of the RC box culvert

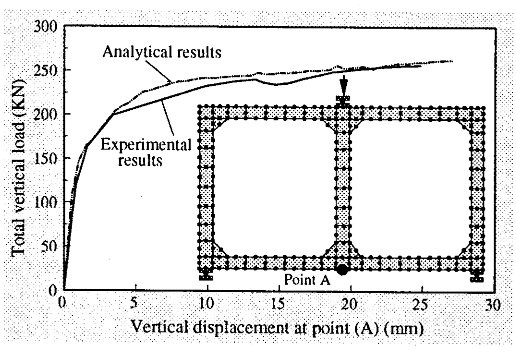


Fig.6b RC box culvert response and prediction

underground structures. Through these experiments, the total deformation of soil and the RC culvert were measured.

Two RC box culverts consisting of frames with a 0.4% volumetric reinforcement ratio (culvert (A)) and 0.88% volumetric reinforcement ratio (culvert (B)) were considered. Details of these RC box culverts are given in **Fig.8**.

Soil containing the RC box culvert was vertically loaded with a weight equivalent to a 5.8 m soil overburden, and forced horizontal displacement was repeatedly applied through a set of high-stiffness load distributors. The internal dimensions of the soil container are 4.0 m long, 3.0 m high and 1.0 m thick. The

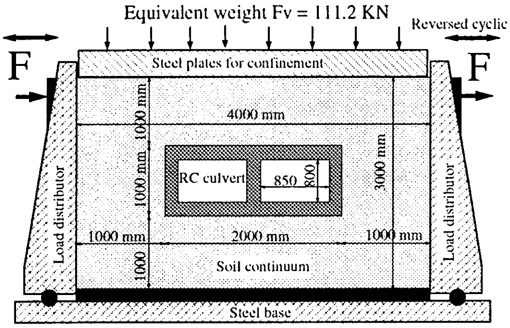
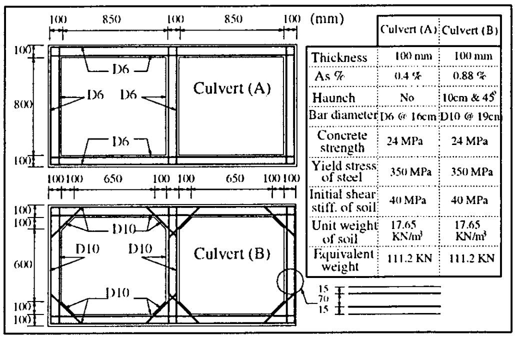


Fig.7 Experimental setup for RC/Soil system



	Culvert (A)	Culvert (B)
Thickness	100 mm	100 mm
As %	0.4 %	0.88 %
Haunch	No	10cm & 45°
Bar diameter	D6 @ 16cm	D10 @ 19cm
Concrete strength	24 MPa	24 MPa
Yield stress of steel	350 MPa	350 MPa
Initial shear stiff. of soil	40 MPa	40 MPa
Unit weight of soil	17.65 KN/m³	17.65 KN/m³
Equivalent weight	111.2 KN	111.2 KN

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

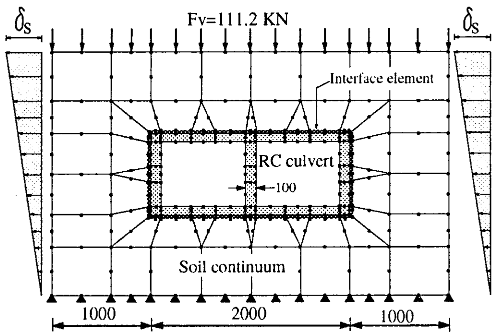


Fig.9 2-D Finite element mesh

culvert was placed 1.0 m above the base of the container, as shown in **Fig.7**. The initial shear stiffness of the soil used (40 MPa) was numerically identified by using a reference test on the soil only when compacted in the same manner[13].

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

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

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

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

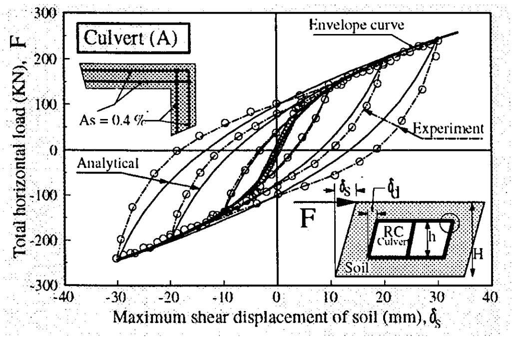


Fig.10a Cyclic load-displacement relationship of RC/Soil system for culvert (A)

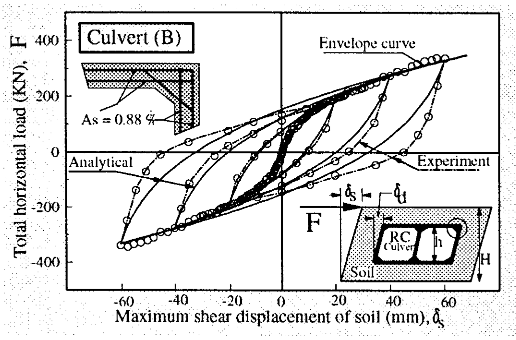


Fig.10b Cyclic load-displacement relationship of RC/Soil system for culvert (B)

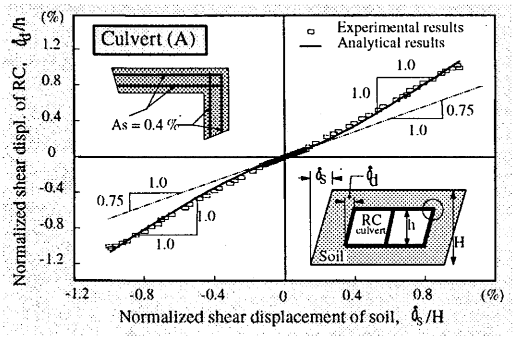


Fig.11a Mean shear deformation of underground RC and soil for culvert (A)

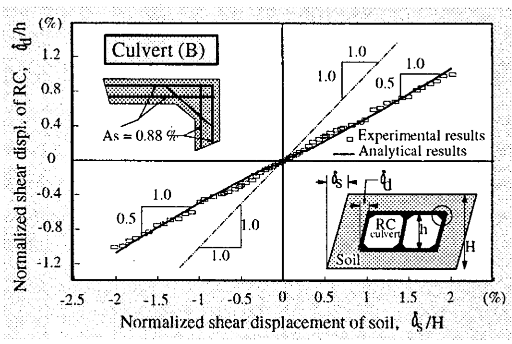


Fig.11b Mean shear deformation of underground RC and soil for culvert (B)

To discuss the kinematic mode of the coupled system, relationship between externally enforced shear displacement and shear displacement of the embedded RC culverts are shown in **Figs.11a** and **11b**. Both sets of values are normalized by the depth of soil and RC, respectively.

At the initial stage, the shear deformation of the lightly reinforced box culvert, culvert (A), is approximately 75% of that of the surrounding soil. At high values of externally enforced shear deformation (after cracking), the overall deformation of the RC box culvert matches that of the soil owing to loss of stiffness due to cracking and yielding. On the contrary, the box culvert with the heavier reinforcement, culvert (B), exhibits higher stiffness: almost 50% of the soil displacement. Furthermore, the kinematic mode of RC/soil deformation in shear is roughly constant over the whole range of loading. The analysis shown in **Fig.10** is mainly influenced by the soil model due to its huge mass, but in contrast the results shown in **Fig.11** are predominantly governed by both the RC and interface models. Thus, it can be said that the constitutive models have reasonable accuracy.

5. NONLINEAR RESPONSE OF UNDERGROUND RC BOX CULVERT

As shown in the previous section, the analytical results produced by the computer program **WCOMR-SJ**, which considers 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 is performed to investigate the influence of taking material nonlinearity and path-dependency into account in analyzing the overall RC/soil system. Furthermore, an evaluation of the proposed interface model is carried out.

Table 1 Parametric study with 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

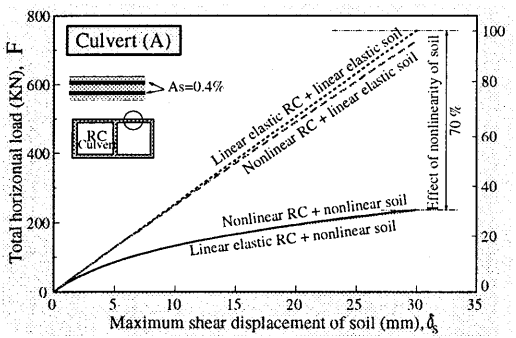


Fig.12a Influence of nonlinearity of materials on the force displacement relationship for RC/soil system [culvert (A)]

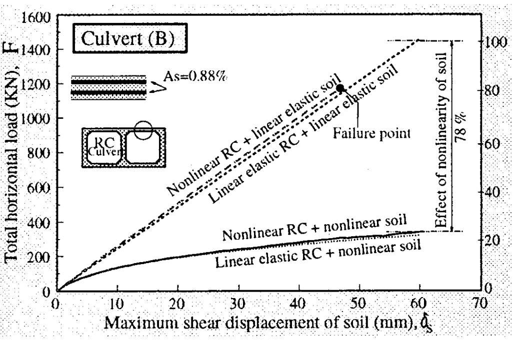


Fig.12b Influence of nonlinearity of materials on the force displacement relationship for RC/soil system [culvert (B)]

(1) Influence of material nonlinearity on RC/soil response

Both RC and soil can be considered as either a linear-elastic or nonlinear material. Thus, four combinations of RC and soil behavior are possible and should be considered in this parametric study. **Table 1** gives details of these combinations. In all cases, other parameters (dimension, reinforcement ratio, interface element and soil stiffness) are kept constant. At the same time, to consider the effect of structure stiffness, a study is performed for the two previously described culverts (A) and (B).

a) Load-displacement relationship

The influence of RC and soil nonlinearity on the load-displacement relation was investigated for both culverts (A) and (B), as shown in **Figs.12a** and **12b**. When RC is considered nonlinear, the load displacement relation is more or less the same as in the linear elastic RC case. On the other hand, the total load is very high when soil is considered a linear elastic material; it is about five times higher than using the nonlinear model for soil.

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

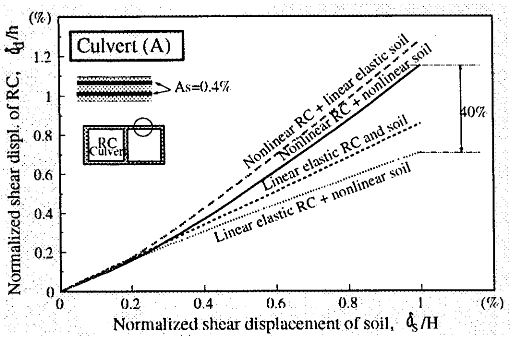


Fig.13a Influence of nonlinearity of materials on the normalized shear displacement of RC culvert and soil [Culvert (A)]

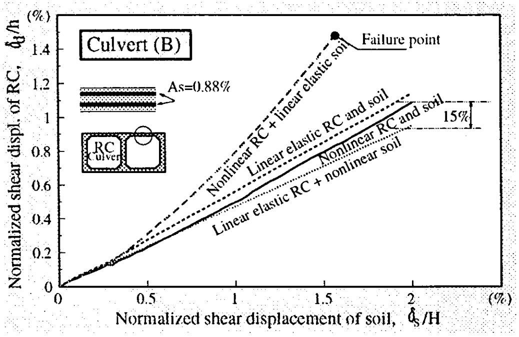


Fig.13b Influence of nonlinearity of materials on the normalized shear displacement of RC culvert and soil [Culvert (B)]

b) Shear deformation

In soil-structure interaction problems, the relative deformation of the structure and the soil needs to be known. In this study, the relative deformations -- considered as normalized mean shear displacement with height – of the soil and RC culvert are shown in **Figs.13a** and **13b**. These figures demonstrate that the effect of RC nonlinearity is very significant in comparing the deformation.

In the case of more flexible structure (culvert (A)), the RC is linear elastic until the normalized mean shear displacement of the soil equals 0.2%. Then the nonlinear behavior begins and the difference becomes more and more significant with increasing mean shear displacement. At a normalized mean shear displacement equal to 1.0%, the normalized mean shear displacement of the RC culvert reaches double the value when the RC is assumed to be linear elastic.

In the case of the rigid structure (culvert (B)), the structure behaves as linear elastic until the normalized mean shear displacement equals 1.0%, then the effect of nonlinearity grows up to 2.0%. At that level, the effect of nonlinearity is about 15.0%.

By comparing culverts (A) and (B) through **Figs.12** and **13**, it can be concluded that while the effect of RC nonlinearity is small in the load displacement relation, it becomes very significant for shear deformation -- which depends also on the rigidity of the 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 opening normal stiffness (K_{no}) and shear stiffness (K_s) are considered. **Table 1** shows the details of the considered combinations: cases 1, 2, 3, and 4.

First, full bonding between structure and soil is assumed and no shear slip is allowed (case 1). Second, perfect linear bonding and shear slip are assumed (case 2) to evaluate the effect of considering separation in the analysis. Third, bilinear bonding in open/close mode (separation allowed) and no shear stress resistance (shear stiffness 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

Taking these different cases of interface elements into account results in slight changes to the load-displacement relation (within ±5%) at very high shear deformations. From **Figs.14a** and **14b**, the interface element behavior can be seen to depend on the rigidity of the structure. For culvert (B) with the full bonding model, the structure failed.

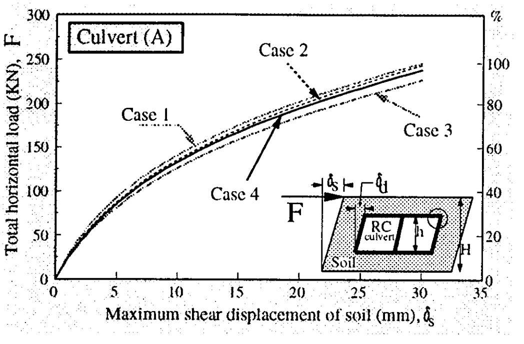


Fig.14a Influence of soil-structure interface on the force displacement relationship for RC/soil system [culvert (A)]

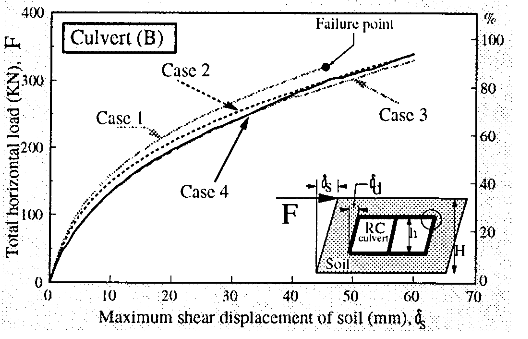


Fig.14b Influence of soil-structure interface on the force displacement relationship for RC/soil system [culvert (B)]

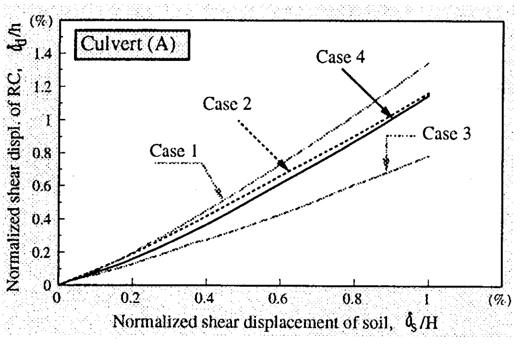


Fig.15a Influence of soil-structure interface on the normalized shear displacement of RC culvert and soil [culvert (A)]

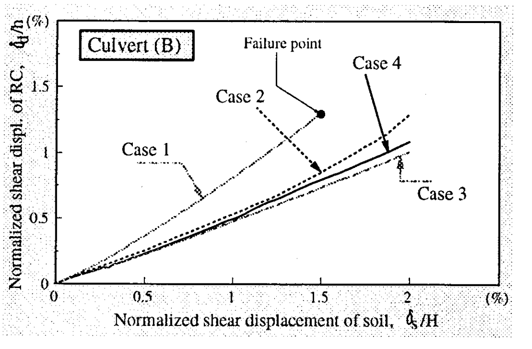


Fig.15b Influence of soil-structure interface on the normalized shear displacement of RC culvert and soil [culvert (B)]

b) Shear deformation

Through **Figs.15a** and **15b** the sensitivity of the interface model can be clearly evaluated. In the case of flexible structure (culvert (A)), the deformation of RC is almost the same as the deformation of the 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 the structure is 50% less than in the experiments due to neglecting shear stress resistance. At the same time, deformation is 20% higher when full bonding is assumed (case 1).

On the other hand, for the rigid structure (culvert (B)), the deformation of RC is less than the soil deformation (50%). In this case, separation takes place and is more significant in the analysis, as shown in **Fig.15b**. While in case 1, perfect bonding, the soil and structure undergo the same deformation and the structure consequently fails. When the shear stress resistance is neglected (case 3), the deformation of the structure is slightly different.

In case 2, the separation behavior of the interface for both culverts is very clear, corresponding to the relative displacement of the structure. In this case, the sliding relation is similar to that in case 4, but open/closure relation is assumed linear. For culvert (A), at small soil shear displacements, there is a difference in displacement. This difference slowly disappears as the soil displacement increases. The experimental results demonstrate that the initial displacement of RC is 80% of the total displacement of the soil (separation takes place), but as the total displacement of the soil increases, the RC and soil deformation converge (no separation).

From this discussion, we conclude that an interface element with both open/closure and sliding behavior, as proposed, is very important if a realistic overall RC/soil system response and a reasonable relative displacement between structures and soil are to be obtained.

6. CONCLUSIONS

Seismic earth pressure acting on underground structures has a predominant influence on structural safety and it has been specified in codes with respect to the property of foundation and geometry only. The dependence of earth pressure on RC structural ductility has been neglected or simply idealized in practical design. On the other hand, nonlinear characteristic of soil foundation has been of main concern to geotechnical engineers and investigated in view of soil foundation stability and safety. As a matter of fact, dynamic analysis serving practical design is conducted mostly in consideration of nonlinear soil and elasticity or equivalent reduced stiffness of underground RC structures. Based on this study, it was clarified that necessary and sufficient safety can not be obtained with rational manner unless the nonlinearity of entire soil-RC system is considered. The following developments were attempted and tentative conclusions have been obtained.

1. Based on RC nonlinear finite element analysis under reversed cyclic loading, a soil model which can trace path-dependency and the interfacial zone was developed as part of the computer code **WCOMR-SJ**. A path-dependent model exhibits certain advantages in that residual deformation and structural damage can be quantitatively evaluated as one of required seismic performance.
2. To verify the analytical results obtained with the computer program, several experiments were carried out and are discussed in this study. Experiments on RC box culverts, subjected to reversed cyclic loading, were carried out to verify the RC constitutive model at the level of a structure subjected to shear and bending moment. The analytical results of the RC/soil system are compared with the experiments on an RC box culvert surrounded by sand under reversed cyclic shear loading. An experimental verification aimed to check specific assumed nonlinearities in each constitutive law used. Reasonable accuracy was confirmed.

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