論 文 コンクリート工学年次論文報告集, Vol.16, No.2, 1994

[2017] Path-Dependent Computational Model for RC/Soil System

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1. INTRODUCTION

In the frame of seismic design, dynamic inertial forces as equivalent static loads are determined with references to seismicity of construction cites, ground characteristics, structural ductility and an associated limit state of reinforced concrete. This simplified way of design works well for particular types of structures but is no longer versatile for structures of complexity having interaction with surrounding media. Dynamic forces which arise in underground RC have much to do with the deformation of soil. At the same time, dynamic soil pressure applied to RC is also affected by the stiffness reduction of RC members and the ductility of structures. Thus, the entire system of RC/soil has to be treated as being coupled for rationalization of design. This paper aims to present reversed cyclic models of coupled reinforced concrete - soil foundation system. The nonlinear interaction of RC and soil is an authors' main concern and induced damage of underground RC having no attached superstructures is investigated. Full path-dependent constitutive laws of reinforced concrete, soil and their interfacial zones are of interest in a FEM program named "WCOMRSJ"[5] developed in The University of Tokyo. This computational tool was systematically verified through coupled RC-soil interacting systems subjected to static reversed cyclic loads.

2. REINFORCED CONCRETE MODEL

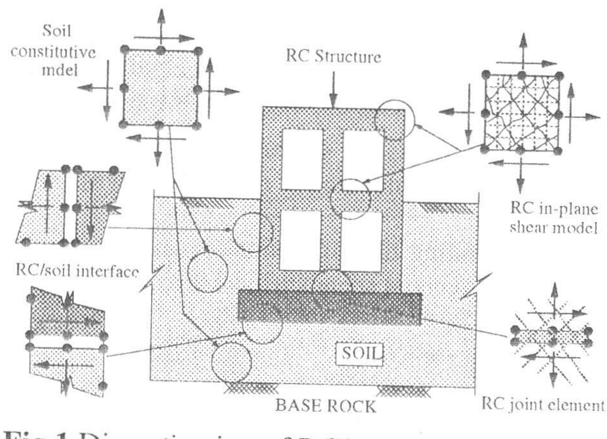

Fig.1 Discretization of RC/soil system structures.

Combination of smeared and discrete crack models[5] subjected to reversed cyclic loads is adopted for RC structures as shown in Fig.1. 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 with intersecting reinforcing bars. RC smeared crack constitutive law used derives from cyclic path-dependent tension stiffness, stress transfer and elasto-plastic and fracture model for concrete including cracks[5]. Crack spacing or density and diameter of reinforcing bars has negligible effects on the spatially averaged stress strain relation defined on RC in-plane control volume. 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 the cracks[5].

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As reversed cyclic loading causes the rotation of principal axis of stresses, and also multi-directional crack model is adopted here[5]. Directions of the first and second cracking are memorized as being non-rotating but as fixed parameters in path-dependent analysis, and RC in-plane constitutive laws are described on the local coordinate of each way of cracks. Hence, principal stress rotation after the first crack is associated with the shear transfer along the first crack and the occurrence of following secondary ones.

3. FOUNDATION MODEL

A path-dependent constitutive law for soil is indispensable for dealing with kinematic interaction of RC/soil system under strong seismic loads. Furthermore, nonlinear characteristics in shear governs the magnitude of ground acceleration which in turn generates the inertial forces of underground RC.

3.1 Soil constitutive model

In this study, Ohsaki's soil model[4] is extended to 3D generic conditions. Fig.2 shows pure shear cyclic response of modeling which was systematically examined ranging from sand to clay in view of layer soil vibration under base rock excitation. In relation to concrete constitutive model used, shear strain and stress deviator invariants are defined under reversed cyclic paths as,

$$J_2' = \int dJ_2' \qquad \text{and} \qquad J_2 = \int dJ_2$$

$$dJ_2' \equiv \frac{\bar{e}_{ij}}{2\cdot\sqrt{\frac{1}{2}\bar{e}_{kl}\cdot\bar{e}_{kl}}}de_{ij} \qquad \text{and} \qquad dJ_2 \equiv \frac{\bar{s}_{ij}}{2\cdot\sqrt{\frac{1}{2}\bar{s}_{kl}\cdot\bar{s}_{kl}}}ds_{ij} \tag{1}$$

$$\bar{e}_{ij} = e_{ij} - e_{ij}^T, \quad e_{ij}^T(t) = e_{ij}(t^-) \quad \text{if } dJ_2'(t).dJ_2'(t^-)\langle 0$$

$$\bar{s}_{ij} = s_{ij} - s_{ij}^T, \quad s_{ij}^T(t) = s_{ij}(t^-) \quad \text{if } dJ_2(t).dJ_2(t^-)\langle 0$$

where, stress and strain with superscript "T" are defined based on the updated turning point specified in the hysteresis rule, as shown in Fig.2.

For extension from pure shear to generic 3D stresses, above stated deviator invariants are designated as two axes of Fig.2. Ohsaki's model defines the following formulas for the envelope as well as the internal loop with Massing's rule as,

$$\frac{J_2'}{M} = \frac{J_2}{2G_oM}\left(1 + A\left|\frac{J_2}{S_uM}\right|^B\right), \quad A = \frac{G_o}{100S_u} - 1 \tag{2}$$

where, B : 1.6 for sandy soil and 1.4 for clay, Su : maximum shear strength , M : 1.0 for a skeleton curve and 2.0 for unloading & reloading curves and G_o : initial shear stiffness of soil.

By integrating the differential equation (1) along the strain history of each element, we have a secant and tangential shear stiffnesses as,

$$2\overline{G} = \frac{J_2 - J_2^T}{J_2' - J_2'^T} \qquad \text{and} \qquad 2G' = \frac{2G_o}{1 + A(B+1)\left|J_2/S_u\right|^B} \tag{3}$$

Concerning the stress tensor measured from the updated turning point, we have,

$$\bar{\sigma}_{ij} = 2\overline{G}\left(\bar{\varepsilon}_{ij} - \left(\tfrac{1}{3}\sum\bar{\varepsilon}_{kk}\right).\,\delta_{ij}\right) + 3K_o\left(\tfrac{1}{3}\sum\bar{\varepsilon}_{ij}\right).\,\delta_{ij} \tag{4}$$

In deriving Eq.(4), the authors apply the path-independent elasticity of hydrostatics for simplicity. Although the dilatancy and compaction actually arise in the soil and the first invariant of strains is provoked by larger shear, this coupled term with volumetric deformation is here ignored. In computation, the stress and strain tensors at turning points are stored in memory. when the subsequent path of loading exceeds the updated turning point, it is renewed step-by-step.

3.2 RC - Soil interfacial zone

The separation and closure of RC/soil interface may occur when heavy seismic forces will be induced and/or the stiffness of both underground RC and the surrounding soil differs much. Here, joint interface element with varying stiffness for open and closure modes is used[3] as shown in Fig.3. Numerically large value is designated for the fictitious stiffness in closure mode. In this paper, two types of idealization, that is, a) perfect linear bond and no shear slip is allowed, and b) bilinear bond in open/close mode and linear shear slip.

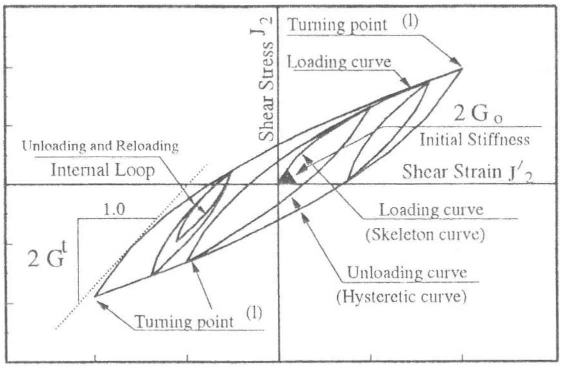

Fig.2 Cyclic shear model of soil

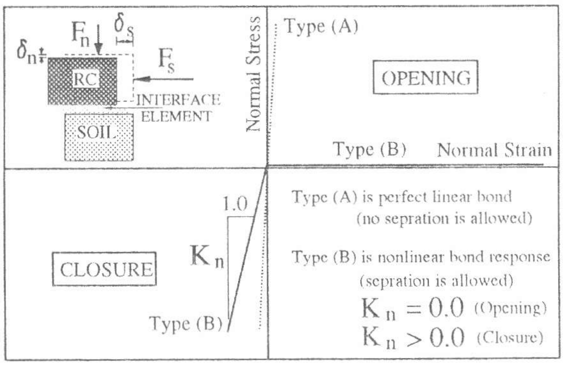

Fig.3 Normal response of RC/soil interface

4. FINITE ELEMENT ANALYSIS OF RC/SOIL SYSTEM

Experimental verification

For verifying RC/soil system with soil-structure interface, RC box culvert surrounded by sand under reversed cyclic shear is selected as shown in Fig.4. The experiment was conducted by JSCE committee on limit state design of underground RC for nuclear power plants[2]. Two cases of RC consisting of frames having 0.4%(case A) and 0.88%(case B) by reinforcement ratio are discussed, respectively. The soil including the RC culvert was vertically loaded by weight equivalent to 5.8m overlay of the soil above the structure, and forced horizontal displacement was repeatedly applied. Finite element discretization used is also shown in Fig.4. The RC/soil interfacial elements (type (B) in Fig.3.) are placed at the boundary. Since the sandy soil was kept in plane strain condition, a 3D 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. The experiment of RC/soil system as shown in Fig.4 can serve to check the soil and RC/soil interfacial models.

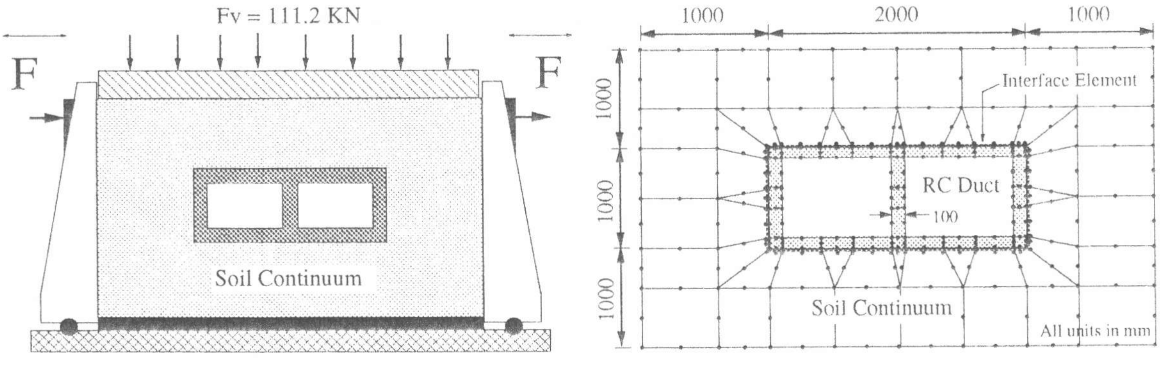

Fig.4 Experimental set-up[2] and corresponding finite element mesh

Fig.5 shows the experimental and computational results of force-displacement relations. The shear displacement which is proportional to the mean shear strain of RC/soil indicates the horizontal displacement at the top of load distributors. The initial shear stiffness of the soil used (40MPa) was numerically identified by using a reference test with just soil which was compacted with the same manner. Three cyclics loop are drawn for making comparisons easier though plenty of repetition was adopted in the experiments[2]. The ductility and capacity of the system involving stiffer RC (case B) is higher. The analyses successfully predict the load-displacement relations of soil.

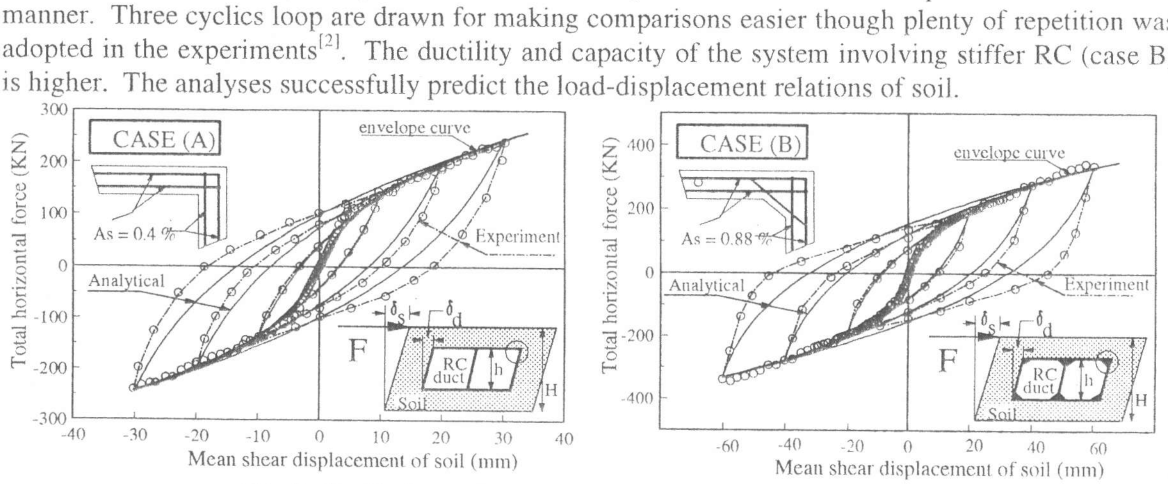

Fig.5 Cyclic force displacement relation of RC/soil system.

For discussing the kinematic mode of coupled system, relations of externally enforced mean shear angle versus mean shear rate of embedded RC duct are shown in Fig.6. At the initial stage, a lightly reinforced duct in case A deforms in shear approximately 75% of that of the surrounding soil. Under greater deformation, however, its overall deformation of RC follows that of the entire soil owing to the reduction of the stiffness due to cracking and yielding. On the contrary, the duct with larger reinforcement in case B exhibits higher stiffness accompanied by nearly 50% of the displacement of entire soil. Furthermore, the ratio of kinematic mode of RC/soil deformation in shear is roughly constant in the whole range of load. The above mentioned kinematic is reasonably predicted by the analysis proposed in this study.

For elucidating how RC/soil interfacial model acts, sensitivity analysis was performed as shown in Fig.7. The lightly reinforced concrete duct reveals that no interfacial element, which means perfect bondage, gives rise to smaller difference from the realistic idealization. In other words, stress release which takes place when the interface separates is not vital, but flexible RC deforms together with the surrounding soil owing to its smaller stiffness. However, interfacial elements play an important and substantial role in case B with larger reinforcement ratio and "haunch" as shown in Fig.7. Due to its rigidity, RC is not flexible enough to follow the soil deformation. Then, interfacial separation at corner portions of slab-wall connections develops. It is obvious that RC/soil interfacial model is not avoidable but its significance differs in relation to the stiffness of both structures and soil. Furthermore, sensitivity analysis as shown in Fig.7 exhibits a great deal of interacting nonlinearity of soil and underground RC. Thus, soil and interfacial modeling are thought to be reasonably accurate.

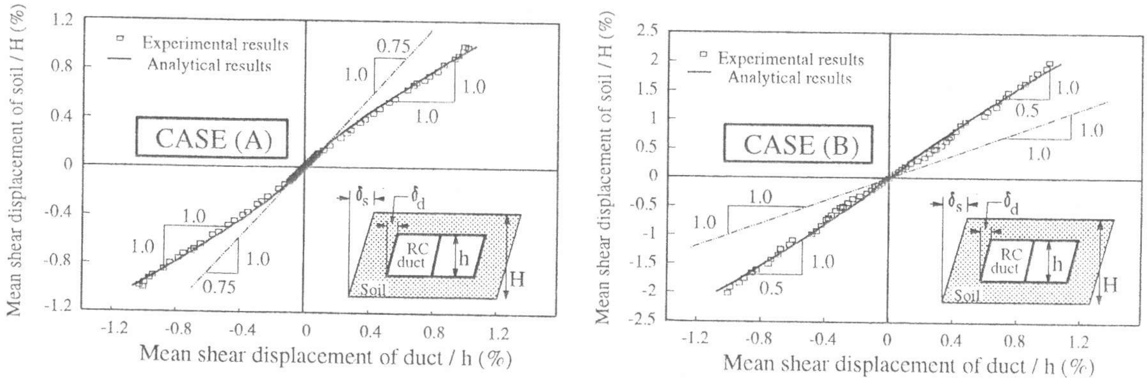

Fig.6 Mean shear deformation of underground RC duct and soil

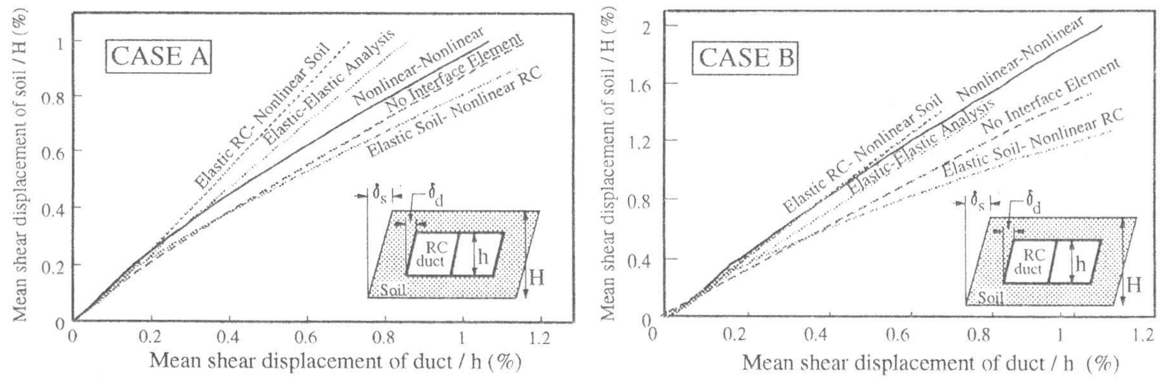

Fig.7 Influence of soil-structure interface and nonlinearity of materials

Nonlinear kinematic interaction of RC and soil is clearly comprehended as shown in Fig.8. Averaged shear force induced to RC, which is obtained by multiplying the mean shear stress along all members with specified area of a referance section[6], is less than 50% of the full elastic solution when large displacement is considered. It is found that nonlinear feature of soil reduces shear forces to RC predominantly owing to the degraded earth pressure. Furthermore, decline of RC stiffness in accordance with nonlinearity accelerates this kinematic interaction in case A where the duct is lightly reinforced. It appears that the nonlinear characteristics in case B are comparatively minor. It is because the induced force is not large enough to exhibit substantial drop of RC stiffness since larger amount of steel is placed.

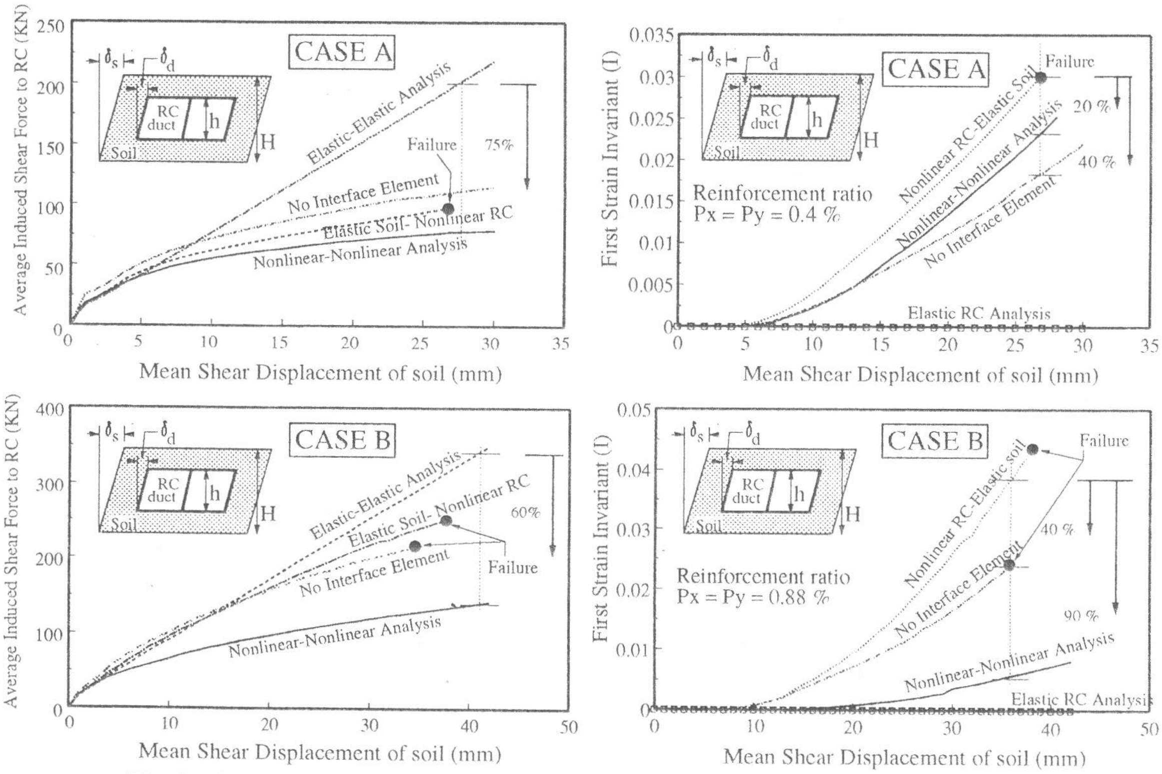

Fig.8 Kinematic interaction RC-soil in terms of shear forces and damage in RC

However, nonlinear aspect of RC is very clearly recognized in the damage index denoted by the in-plane mean strain[6]. If nonlinearity of RC would be ignored, in-plane mean strain is nearly zero because the overall deformation is shear and the dead load supplied by vertical force is not large enough to introduce volumetric deformation of elasticity. Otherwise, damage having close linkage with crack deformation is greatly controlled by the nonlinear feature of soil. The elastic foundation finally bears compression failure after yield. But, nonlinear kinematics of RC/soil system tells us that RC underground ducts cannot be destroyed by soil when both nonlinear responses be considered.

7. CONCLUSIONS

The seismic earth pressure to underground structures predominantly influences on the practical design. However, its dependency on RC structural ductility has been neglected or simply idealized in practical design. Nonlinear characteristics of soil foundation have 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 the following tentative conclusions are obtained.

(1) Path-dependent RC/soil model for dynamic finite element analysis

Based on RC nonlinear finite element analysis applicable to reversed cyclic loads, a simple soil model which can fully trace path-dependency and interfacial one was installed in computer code WCOMRSJ. The advantage of full path-dependent model was exhibited such that hysteresis damping and restoring force characteristics of both structures and foundation are intrinsically taken into account, and that residual deformation, which have much to do with remaining functions of RC to be designed, can be quantitatively evaluated.

(2) Verification

For examining reliability of a computational tool of multi-functions, systematic experimental verification is indispensable. The item discussed in this paper is RC-soil system under static reversed cyclic forces. The experimental verification was aimed to check the specific item of assumed nonlinearity described by each constitutive law used. Reasonable accuracy was confirmed.

(3) Kinematic interaction of coupled RC/soil system

It was clarified that nonlinear characteristics of both RC and soil cannot be ignored for simplicity. The degrading stiffness of RC will tend to lessen the shear force under large strain. In most cases, owing to coupled nonlinear kinematics, structural safety will be sustained. From parametric studies, reinforcement ratio was understood as crack control agent[7] but it does not sensitively influence on the shear force of section induced through the soil deformation.

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