

## [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 sites, 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"<sup>[5]</sup> 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

Combination of smeared and discrete crack models<sup>[5]</sup> 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<sup>[5]</sup>. 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<sup>[5]</sup>.

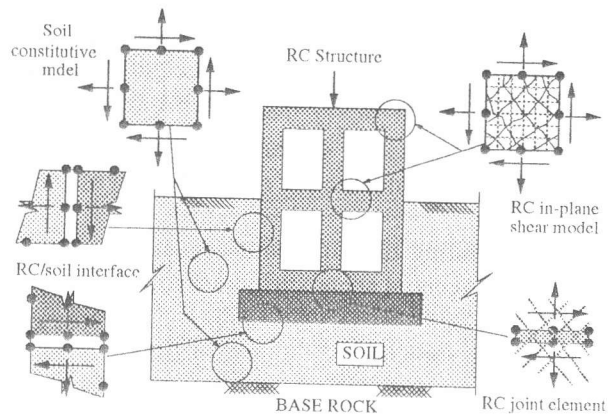


Fig.1 Discretization of RC/soil system structures.

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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<sup>[5]</sup>. 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<sup>[4]</sup> 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,

$$\begin{aligned}
 J'_2 &= \int dJ'_2 & \text{and} & & J_2 &= \int dJ_2 \\
 dJ'_2 &\equiv \frac{\bar{e}_{ij}}{2 \cdot \sqrt{\frac{1}{2} \bar{e}_{kl} \cdot \bar{e}_{kl}}} de_{ij} & \text{and} & & dJ_2 &\equiv \frac{\bar{s}_{ij}}{2 \cdot \sqrt{\frac{1}{2} \bar{s}_{kl} \cdot \bar{s}_{kl}}} ds_{ij} \\
 \bar{e}_{ij} &= e_{ij} - e_{ij}^T, & e_{ij}^T(t) &= e_{ij}(t^-) & \text{if } & dJ'_2(t), dJ'_2(t^-) < 0 \\
 \bar{s}_{ij} &= s_{ij} - s_{ij}^T, & s_{ij}^T(t) &= s_{ij}(t^-) & \text{if } & dJ_2(t), dJ_2(t^-) < 0
 \end{aligned} \tag{1}$$

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,

$$\frac{J'_2}{M} = \frac{J_2}{2G_o M} \left( 1 + A \left| \frac{J_2}{S_u M} \right|^B \right), \quad A = \frac{G_o}{100S_u} - 1 \tag{2}$$

where, B : 1.6 for sandy soil and 1.4 for clay,  $S_u$  : 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,

$$2\bar{G} = \frac{J_2 - J_2^T}{J'_2 - J_2'^T} \quad \text{and} \quad 2G^t = \frac{2G_o}{1 + A(B+1) \left| \frac{J_2}{S_u} \right|^B} \tag{3}$$

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

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

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.