Numerical Evaluation of Overall Seismic Performance of Underground RC Structures

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This paper presents a FEM code for analyzing the kinematic nonlinear interaction of coupled RC/soil system under seismic loads. The constitutive model of RC is a path-dependent one that is composed of the models of cracked concrete, tension stiffening crack shear transfer and reinforcing bars. The full entire system of RC/soil foundation is treated as being coupled, by considering the constitutive models of soil and RC/soil interface. The unstable progress of diagonal shear cracking before and after yield of main reinforcement can be simulated and the associated size effect is consistently taken into account in the seismic performance evaluation. This computational tool is systematically verified through coupled RC/soil system subjected to static reversed cyclic loads. The damaged underground RC framed during Hanshin Great Earthquake are investigated and parametic studies are carried out to get knowledge for seismic resistant design and strengthening of existing structures.

1. INTRODUCTION

The Hanshin Great earthquake on January 17, 1995 brought about catastrophic damage and collapse to some of the RC underground structures serving subway in Kobe city. At the same time, many other underground structures survived and exhibited soundness with different level. It is a duty of structural engineers to analyze the dynamic behaviors of RC underground structures in view of seismic resistant design.

This paper presents a computational tool for analyzing the seismic behavior of underground RC. The dynamic nonlinear response of coupled soil-reinforced concrete structures are simulated by using two dimensional finite elements. The full path dependent constitutive models of RC, soil and their interface zones are installed in the FEM program **WCOMD-SJ**[5]. These models are systematically verified by simulating the experiments of RC and coupled RC/soil system subjected to static reversed cyclic loads. Using this program, one underground RC structure that failed seriously in this earthquake is investigated, aiming at earning some engineering lessons for future seismic resistant design for RC underground structures.

2. CONSTITUTIVE MODELS FOR RC/SOIL SYSTEM

At present, the practical use of finite element analysis makes it possible to deal with material nonlinearity. The major issue in the nonlinear finite element method 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 discretization of RC/soil system with different elements and models. **Fig. 1** shows the proposed discretization of RC/soil system in use of different elements and models.

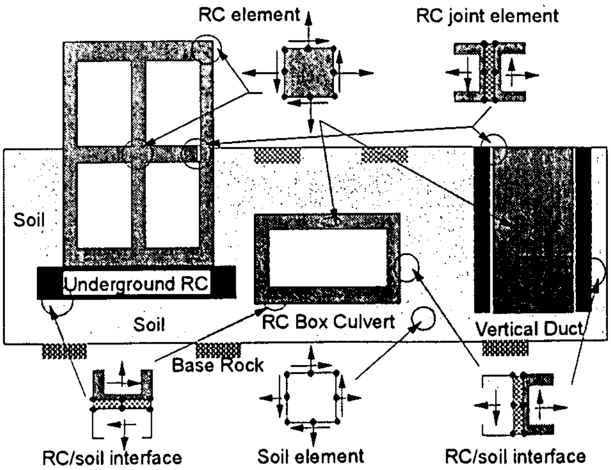

Fig. 1 Discretization of RC/soil system for different elements and models.

Key Words FEM, Nonlinear dynamic analysis, Underground structure, RC

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(1) Reinforced concrete constitutive models

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 contains cracks. To describe cracks, microscopic discrete crack modeling and macroscopic smeared crack modeling are most used for this propose.

In this study, the combination of smeared and discrete crack models subjected to reversed cyclic loads is adopted for any type of RC underground structures[1]. Smeared crack model is applied 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.

(a) In-plane constitutive model for RC

Nonlinearity of reinforced concrete depends mainly on bond between reinforcement and concrete, compressive characteristics of cracked concrete and shear transfer along cracks. The RC smeared crack constitutive model applied is derived from cyclic path-dependent tension stiffness model, stress transfer model and elasto-plastic and fracture model for concrete including cracks. 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[2]. **Fig. 2** shows the proposed model for RC element under cyclic load.

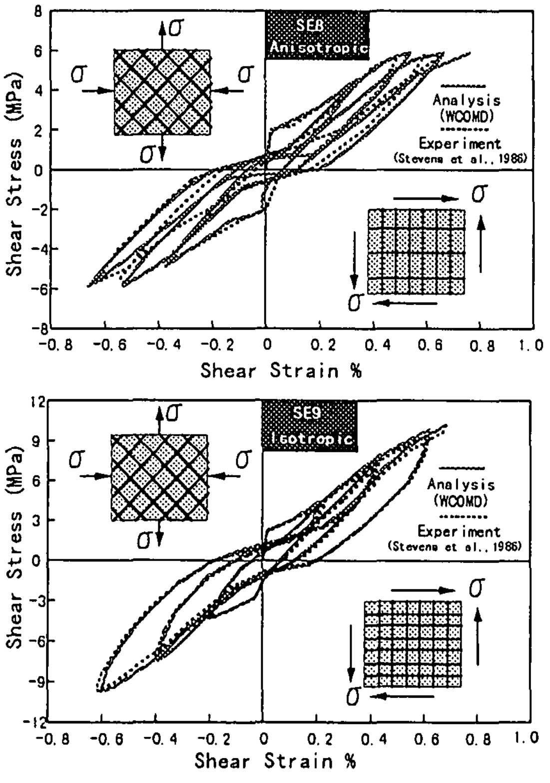


Fig. 2 Computed shear stress-strain relation of RC panel by smeared crack approach[1].

(b) RC joint interface constitutive model[3]

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 model is employed for stress transfer along a crack. **Fig. 2** shows the computed load-displacement relation by using RC joint model.

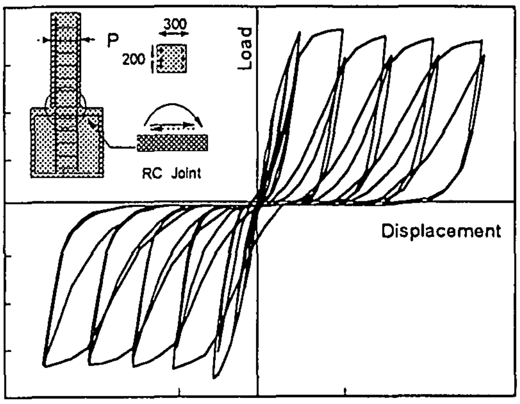


Fig. 3 Computed load-displacement relation by discrete model.

(c) Cracked concrete model for RC with low reinforcement ratio

In dealing with the concrete member with low reinforcement ratio, the spatially averaged mechanical property of concrete near or far away from reinforcement is supposed totally different as the concrete confined by steel bars will show stable stress release owing the bond effecting. The concrete outside the bond effect volume is supposed the same as plain concrete, showing sharp strain-softening feature as the tensile stress is transferred only through the bridging action at the crack surface. The size of RC control volume can be decided by the arrangement of steel bars. **Fig. 4** shows the size effect simulation of RC beams by using the proposed model and zoning method[4].

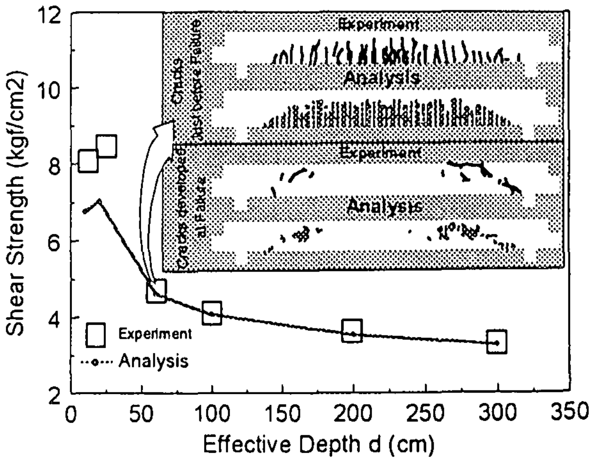


Fig. 4 Size effect simulation for shear strength of RC beams[4].

(2) Constitutive models of soil and RC/soil interface[5]

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, Ohasaki's model defines the formula for envelope to express the nonlinear relation of the shear stress-strain for soil as well as internal loop with Masing's rule, as shown in **Fig.** 5[5].

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.** 6[5].

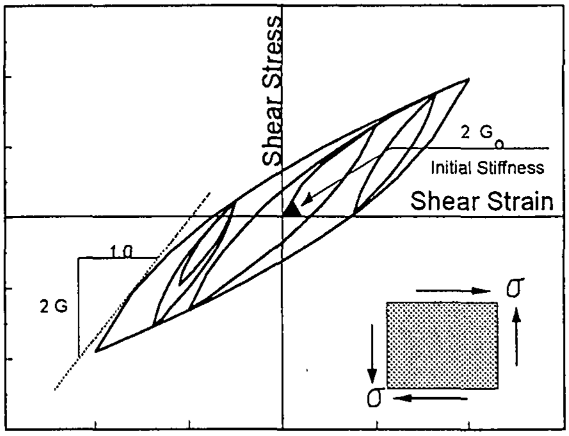


Fig. 5 Computed shear stress-strain relation for soil[5].

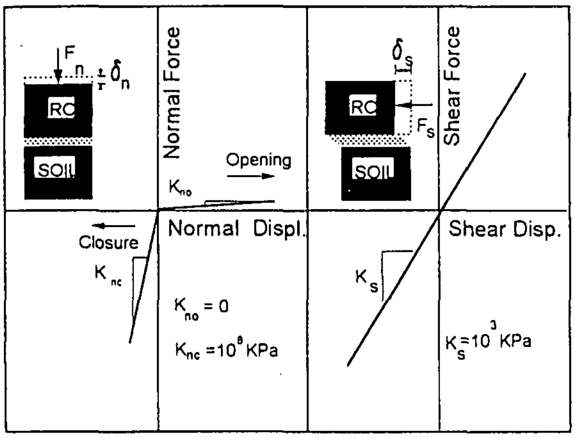


Fig. 6 Normal and shear relations for RC/soil interface crack model[5].

3. COMPUTER PROGRAM AND EXAMPLES OF COMPUTATION

(1) Outline of FEM program

Based on the RC nonlinear finite element analysis applicable to reversed cyclic loads, the path-dependent constitutive models for soil and RC/soil interface are installed in the computer code **WCOMD-SJ**[5]. 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[7] at any loading level. **Fig.** 7 shows the outline of the computer code **WCOMD-SJ** and the combination of different elements.

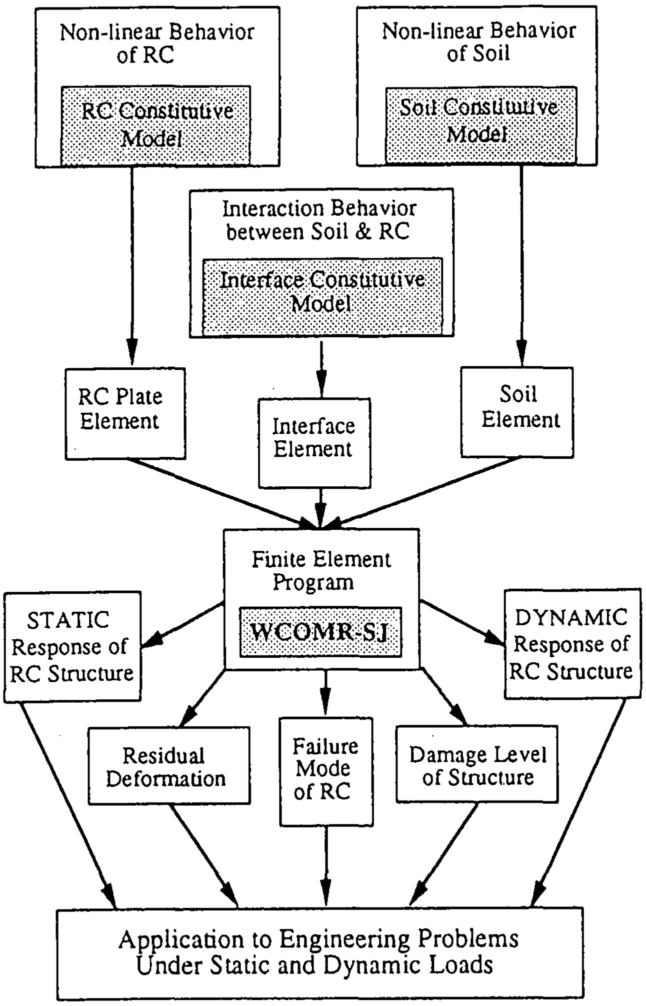
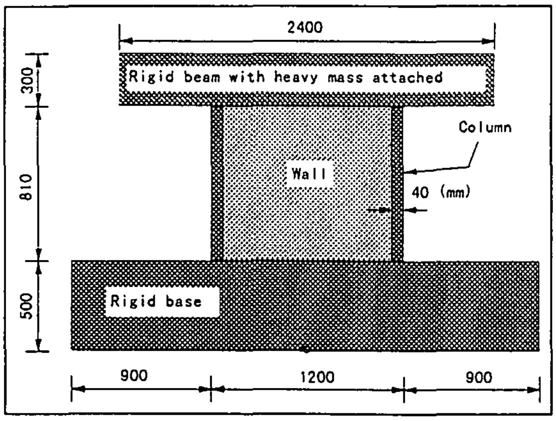


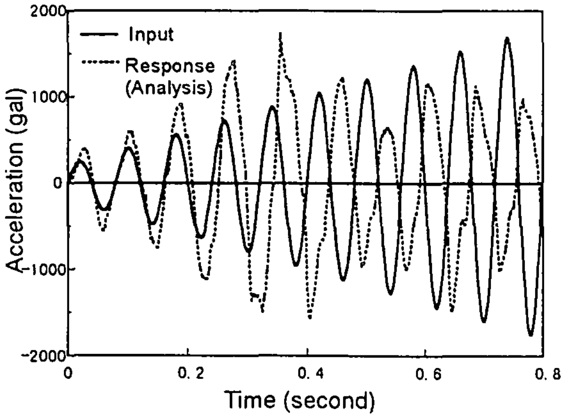
Fig. 7 Outlines of WCOMD-SJ[5].

(2) Dynamic response of framed shear wall

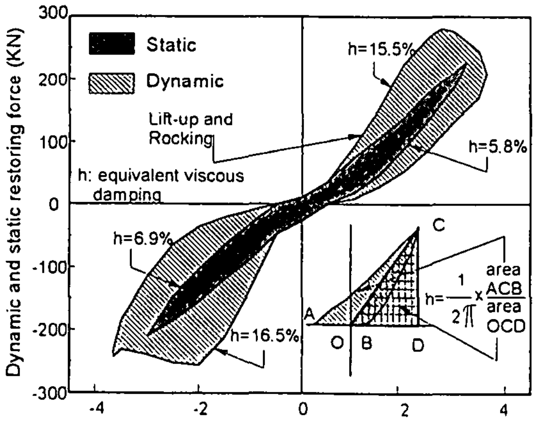
As a example of dynamic analysis, the dynamic response of a framed shear wall is computed by FEM code **WCOMD-SJ**[6]. The framed shear wall and computed hysteresis under static and dynamic actions are shown in **Fig. 8**. Compared with static alternate action, the loop area of dynamic horizontal force-displacement relation is enlarged owing to the dynamic internal moment and vertical forces.



a) Framed shear wall.



b) Induced base acceleration and response.

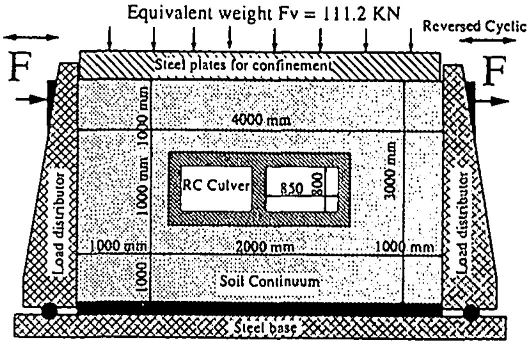


c) Dynamic and static restoring force.

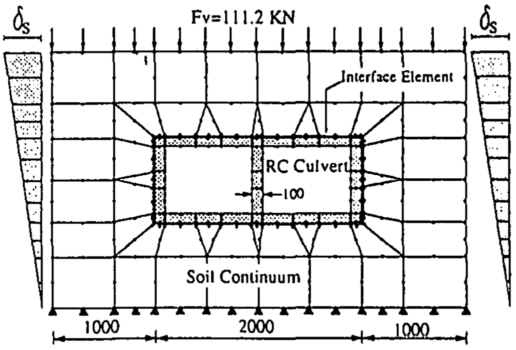
Fig. 8 Dynamic response of framed shear wall[6].

(3) RC/soil system verification

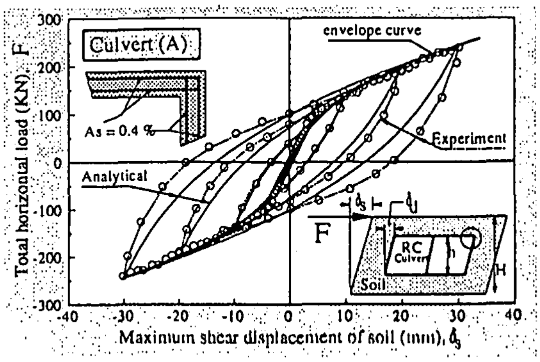
In an attempt to verify the analytical results of **WCOMD-SJ**, a experiment of RC box culvert surrounded by sand under reversed cyclic shear is examined (**Fig. 9a**)[7]. This experiment was conducted by JSCE committee on limit state design of underground RC structures for nuclear power plants[8]. Finite element discretization which is used in the analysis as composed of eight node quadrilateral analysis is shown in **Fig. 9b**. The experimental and analytical results of total horizontal load verus the maximum shear displacement of soil are shown in **Fig. 9c**. The loading-unloading paths and the residual deformation are predicated well for all the induced paths and it can be said that the constitutive models have reasonable accuracy.



a) Experiment setup for RC/soil system.



b) 2-D Finite element mesh.



c) Cyclic load-displacement relation of RC/soil system.
Fig. 9 Verification for RC/soil system[7].

4. COLLAPSE SIMULATION OF UNDERGROUND RC STRUCTURE

(1) Computation targets

Along the Kobe subway line, a lot of damages were brought about to the underground structures. As for the completely damaged sections, the columns with diagonal shear crack loose load carrying mechanism against the vertical forces associated with dead loads applied on top slab and soil overlayer[9]. As a result, the top slab was completely collapsed as shown in **Fig. 10**.

As for extreme cases, two sections will be analyzed to identify the failure mechanism in use of the numerical analysis[10]. **Fig. 11** shows two different sections which are used in this study. Section A is one of the sections of the station which has complete collapse of the intermediate column. The other section which is on the tunnel line between two stations has few diagonal shear cracks (Section B). The distance between both sections is less than 10 m. As a matter of fact, section A was completely damaged and section B underwent very few cracks. The same earthquake action is supposed to be applied to both sections. The finite element discretization of these two sections are shown in **Fig. 12**.

Fig. 10 Collapse of RC underground structure.

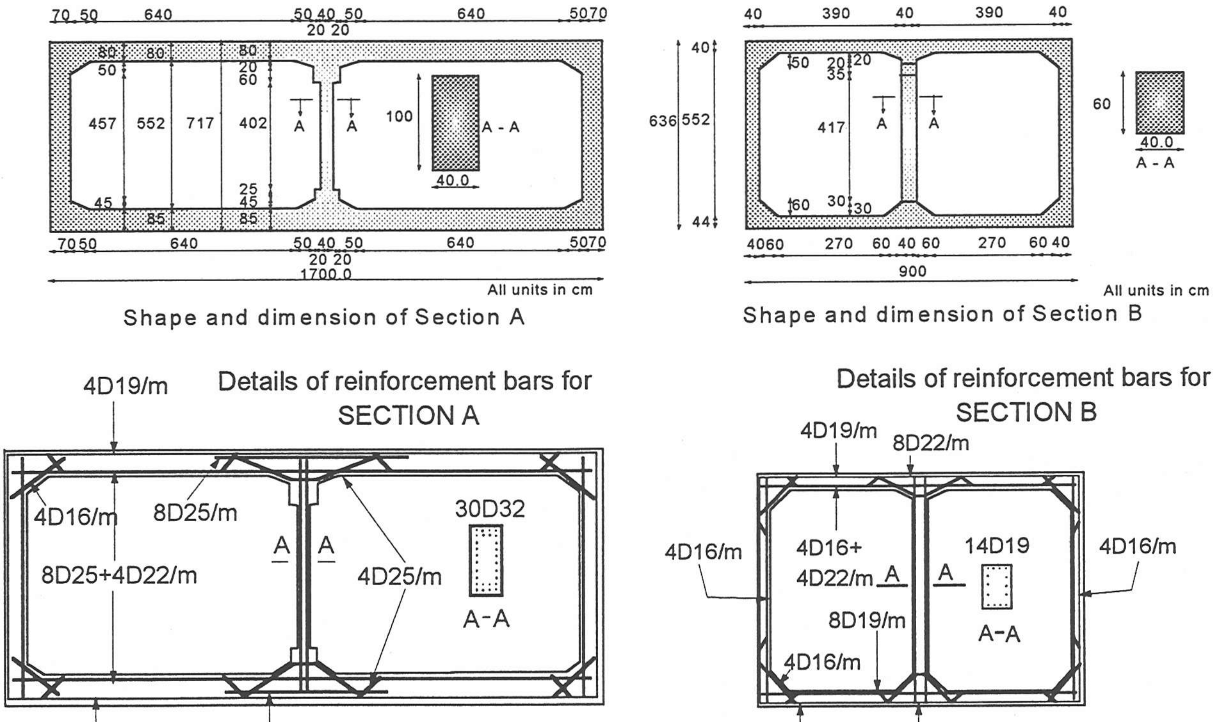
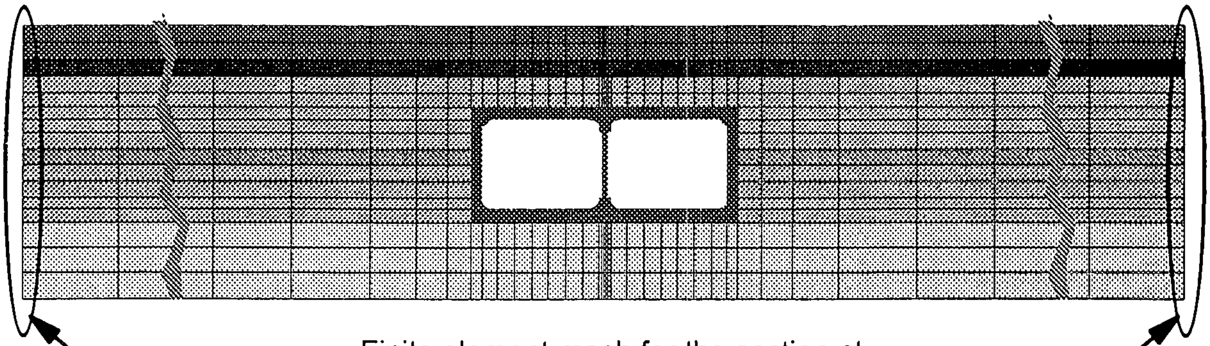
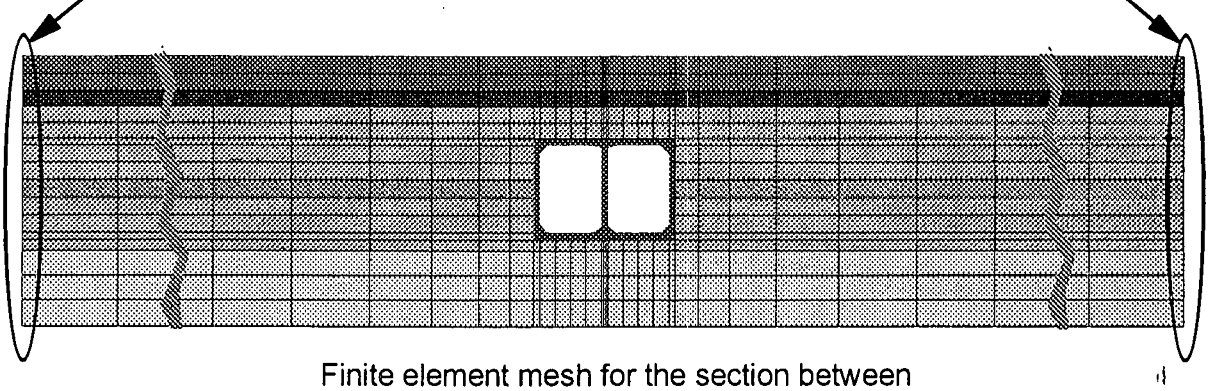


Fig. 11 Shape and dimension of the target structures.



Finite element mesh for the section at the subway station (Section A)



Finite element mesh for the section between two subway stations (Section B)

Fig. 12 Finite element discretization used in the analysis.

(2) Computation results

The ground motion obtained at Kobe meteorological observatory, were used for the dynamic analysis. One of the characteristics of the seismic load in Kobe is its higher level of up-down component of the ground motion. Both the horizontal and vertical acceleration records are used for simulating the seismic response of the soil-RC frame system.

We focus on the collapse mechanism of the RC underground structure, especially the intermediate column, in the analysis. At the same time, the induced forces to the intermediate column are discussed to identify the failure mechanism.

(a) Inelastic deformation of structure

The spatially averaged inelastic deformation which represents the "crack strain" associated with yielding of reinforcement crossing cracks, are shown in **Fig. 13** in time domain. We use this index to present qualitatively how much damage to the structure is induced and how much residual deformation after the earthquake remains. For section A, collapse occurred after 8 second, higher damage and deformation are seen compared with section B.

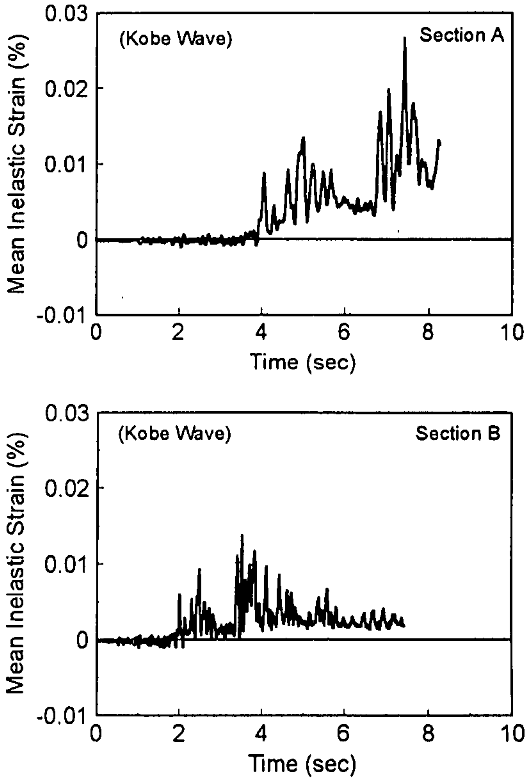


Fig. 13 Inelastic deformation representing damage in time domain.

(b) Failure mode

Fig. 14 shows the deformational profile of the structure at the failure for section A. It can be seen also that the separation between the soil and RC exists because of the difference between soil and RC shear deformation in detail.

Fig. 15 shows the crack pattern of the structure at the failure for section A and at the maximum shear deformation for section B. The cracks having shear strains greater than 0.05% are shown in **Fig. 15**. Other cracks are cut off from the figure for simple and clear illustration.

The computed failure mode for section A is "diagonal shear failure" after the yield of main reinforcement in the intermediate column as shown in **Fig. 15**. Higher shear strain along bi-directional cracks can be seen within the localized zone of the finite elements. At this moment, main reinforcement has already come to the strain hardening at individual cracks. For section B, few cracks with small shear strain are shown in **Fig. 15**. These cracks, originated from the flexural action, are distributed in both the column and side walls.

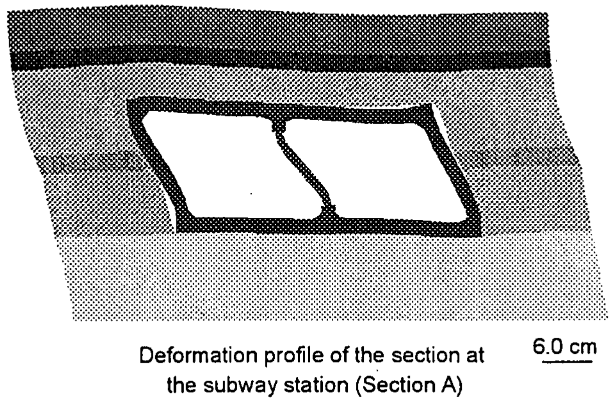


Fig. 14 Deformational profile of the underground structure at the maximum response.

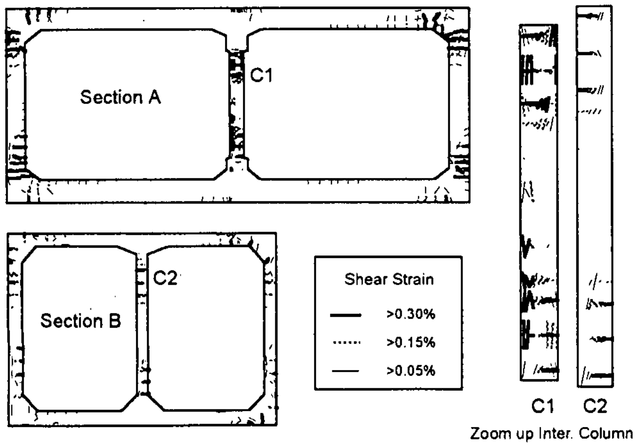


Fig. 15 Crack pattern of structures at the maximum deformation.

(c) Internal stresses in the intermediate column

Most of the damages which came to the underground structures serving subway in Kobe are concentrated at the intermediate columns. It is important to discuss the induced forces and ductility of the internal columns. **Fig. 16** shows the internal nominal shear stresses and ductility of the column for both sections A and B under different waves.

Fig. 16 shows the relation between the averaged nominal shear stress and the relative displacement between top and bottom of the column. In these figures, the relative displacement is normalized by the height of the column. For section A under Kobe wave, the column fails with maximum normalized displacement 1.5% and maximum shear stress 16 kgf/cm^2.

According to the JSCE code, the shear capacity of the middle column of Section A is about 15 kgf/cm^2[11]. But shear stress at the yielding of main reinforcement is 24 kgf/cm^2. During the earthquake the shear stress computed is more than 15kgf/cm^2. This is why the column failed in shear mode before the yielding of main reinforcement.

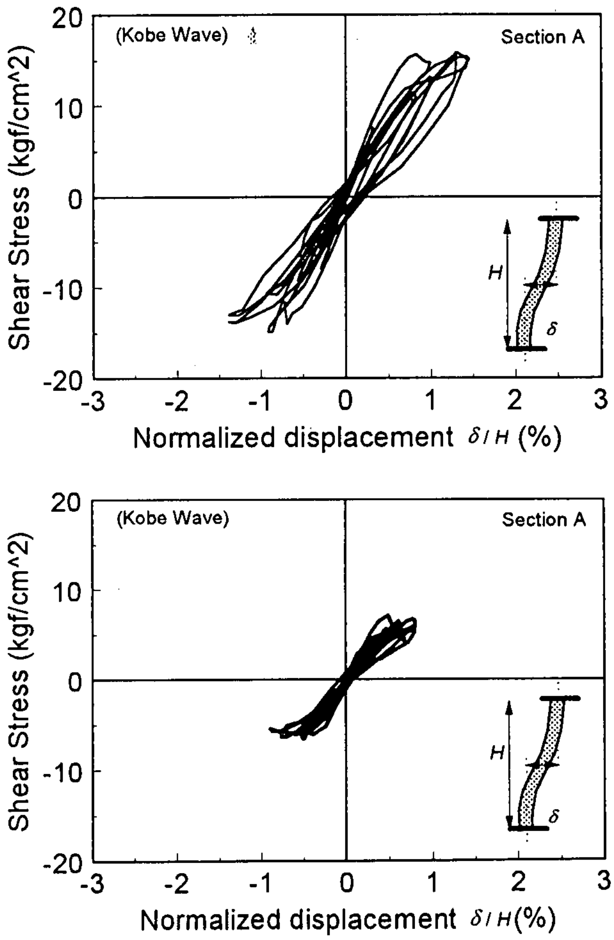


Fig. 16 Shear force-displacement relationship and restoring force characteristics.

5. EFFECT OF LATERAL TIE REINFORCEMENT AND REDUCTION OF MAIN REINFORCEMENT

In order to enhance the seismic resistance of the subway station, both the shear capacity and the ductility level should be increased. One way of enhancing the seismic resistance is to properly reduce the main reinforcement while increasing the amount of web reinforcement. This method is economical as fewer reinforcement bars are needed and it may be suitable for newly constructed RC structures.

In the computation of Section A, the main reinforcement is reduced 10% comparing with the original case, the amount of web reinforcement is increased to 1.5%. **Fig. 17a** shows the inelastic strain of the subway station during the earthquake. It can be seen structure survives without collapse the computation.

Fig. 17b shows the shear stress-displacement relationship for the intermediate column. It can be seen that the shear stress reaches 20kgf/cm^2 due to very high axial compression. The maximum shear deformation is more than 2%. As the yielding shear stress is still a little higher than the shear stress, so that no obvious yielding takes place at the column.

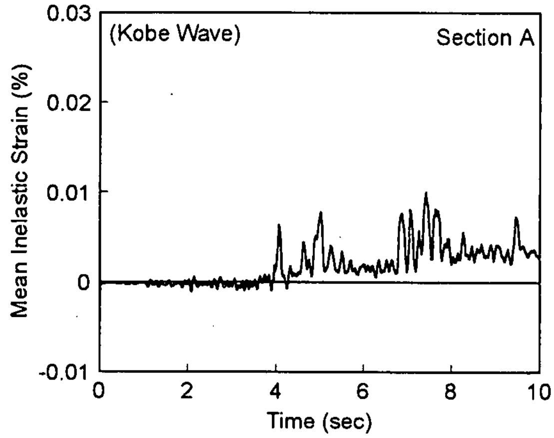


Fig. 17a Inelastic deformation representing damage in time domain.

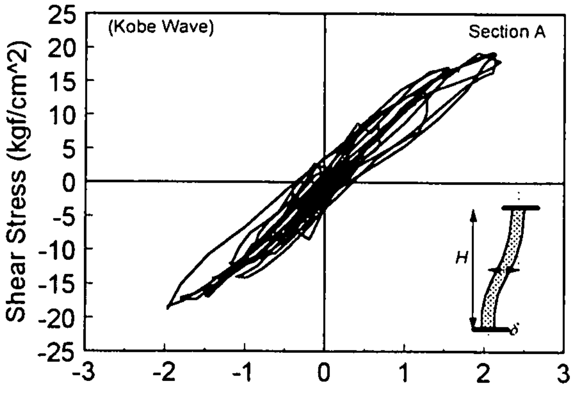


Fig. 17b Shear stress-deformation relationship.

6. CONCLUSIONS

The collapse mechanism of RC underground structure is still under investigation. Within the authors' analytical discussions based on nonlinear dynamic FEM with path-dependent constitutive laws for cracked reinforced concrete, soil and interface between RC and soil, the followings can be tentatively concluded.

(1) FEM program WCOMD-SJ can reasonably simulate the collapse of underground structure under seismic action.

(2) The collapse of subway station is rooted in the low shear capacity with relatively reduced flexural performance and poor ductility of the intermediate column.

(3) In the seismic resistant view point, increased shear capacity is verified to be much effective for enhancing ductility.

Other factors that affect the seismic resistant behaviors of underground RC can also be conducted by using FEM analysis.

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