

**投稿論文(英文)**  
**PAPERS**

# NONLINEAR RESPONSE OF UNDERGROUND RC STRUCTURES UNDER SHEAR

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This paper presents various aspects of the kinematic nonlinear interaction of coupled RC/soil system under static and dynamic loads. Conducted are parametric studies for two types of underground structures subjected to high shear deformation transferred through the nonlinear surrounding soil. In this analysis influences of several factors, such as material nonlinearity of RC and soil, stiffness of structure and reinforcement ratio, are investigated. Failure modes, residual deformations and induced force to the RC from soil are examined for rationalized guidelines serving future improvement of the underground structural design.

**Key Words :** soil-structure interaction, shear, FEM, underground RC

## 1. INTRODUCTION

In the frame of designing underground RC structures, the design value for earth pressure applied to underground structures predominantly influences the level of structural safety. However, its dependency on RC structural ductility has been neglected or simply idealized in practical design. It was clearly proved through experiments that induced force from surrounding soil varies with the structural nonlinearity<sup>2),13)</sup>. On the other hand, the analysis serving practical design is carried out mostly in consideration of nonlinear soil, but mere elasticity of underground RC structures, or equivalent reduced stiffness is simply assumed.

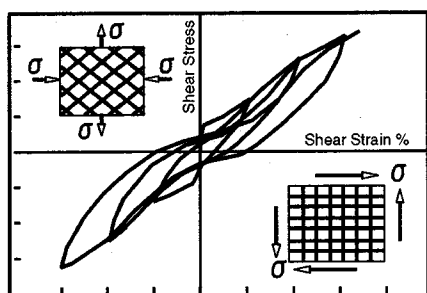
Based on these recent background, the nonlinear kinematic interactive response of RC underground structures and surrounding soil is selected as a main concern. On this line, induced force and damage of underground RC under high shear deformation of soil are to be investigated. In this study, numerical parametric analyses for two types of underground structures are conducted under static and dynamic shear transferred through nonlinear surrounding foundation.

The first parametric study is carried out on an RC underground box culvert to investigate how material nonlinearity in the analysis is influential. The effect of stiffness of structure and reinforcement ratio is

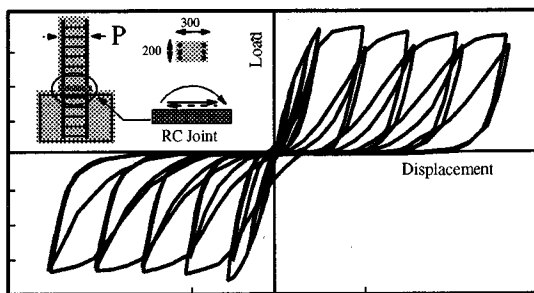
chiefly investigated. The second parametric study is for an RC underground vertical duct under static and dynamic shear loads. Several combinations of structural stiffness, reinforcement ratios and soil rigidity are analyzed for investigation of seismic response of underground RC.

## 2. ANALYSIS OF UNDERGROUND STRUCTURES

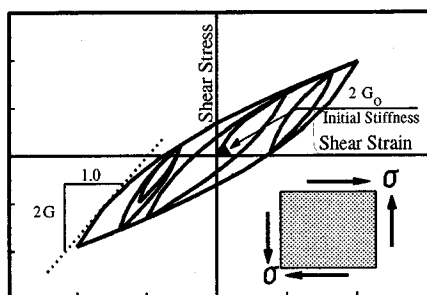
At present, finite element approach is widely used in the analysis of reinforced concrete and soil media. A major issue in the nonlinear computational approach is to establish a constitutive model of RC element under reversed cyclic actions. This model should be capable of predicting the stress accurately for any given strain history. The combination of smeared and discrete crack models subjected to reversed cyclic loads<sup>3)</sup> is adopted. 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<sup>9)</sup>, their combination is crucial for computing ductility and energy absorption of scaled-up structures in seismic analysis.



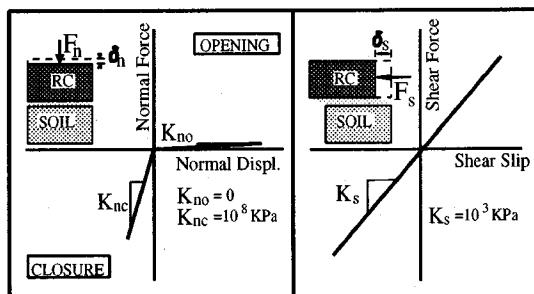
Computed shear stress-strain relation of RC panel by smeared crack model (a)



Computed load-displacement relation by discrete crack model (b)



Computed shear stress-strain relation for soil (c)



Normal and shear relations for RC/soil interface crack model (d)

Fig. 1 Outline of constitutive models for different elements <sup>3),8)</sup>

A path-dependent constitutive model for soil is indispensable for dealing with kinematic interaction of RC/soil entire system under strong seismic loads. Here, Ohasaki's model<sup>10)</sup> 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 (Fig.1c). In addition, separation and sliding between soil and structure are taken into account along the interfacial zone<sup>11)</sup> as shown in Fig.1d.

Based on the RC nonlinear finite element analysis applicable to reversed cyclic loads<sup>3)</sup>, constitutive models for soil and interface between RC and soil are installed in the computer code WCOMR-SJ<sup>8)</sup>. The advantage of full path-dependent model is exhibited, such that the residual permanent deformation and damage of materials can be quantitatively evaluated. Fig.1 shows the outline of the proposed material models used for different elements (RC element in Fig.1a, RC joint element in Fig.1b, soil element and RC/soil interface element) which is hereafter applied in analyzing underground structures. Cracks are treated as being uniformly dispersed in RC elements and RC joint element idealizes a single crack between members.

### 3. PARAMETERS DEFINING SHEAR RESPONSE OF STRUCTURES

For discussing the shear response of underground RC structures and the kinematic interaction, induced shear force to RC and RC damage level are considered by using stresses and strains obtained from the finite element analysis, as shown in the following subsections.

#### (1) Damage level of RC

The first strain invariant, denoted by  $(I_1)$ , is closely associated with the crack occurrence and expansion of the in-plane element (volumetric change of the element) associated with yield of reinforcement. RC mean strain, denoted by  $(I)$ , is the average of  $(I_1)$  for all RC elements. This value is equal to zero in the case of elastic shear behavior of RC (no volumetric change and no residual deformation exist under pure elastic shear deformation). The mean strain  $(I)$  as the indicator of expansive deformation that has much to do with leakage resistance, structural soundness and functions is adopted to represent the magnitude of damage of reinforced concrete. The values of  $(I)$  and  $(I_1)$  can be calculated as follows<sup>1)</sup>.

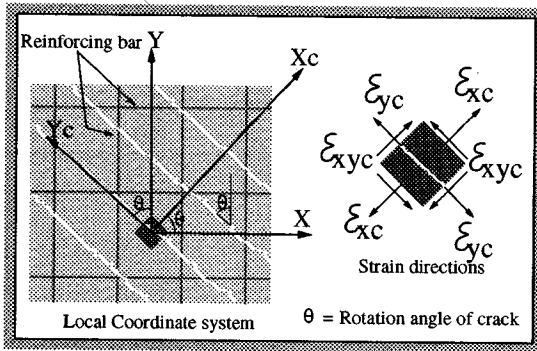


Fig. 2 Strain directions in cracked RC element

$$I = \int_{\text{all elements}} I_1(x, y) dx dy / A \quad (1)$$

where,  $I_1 = \epsilon_1 + \epsilon_2$

( $\epsilon_1$ ) and ( $\epsilon_2$ ) are the principal strains at (x,y).  
(A) is the total area of the RC in-plane elements

## (2) Average induced shear force to RC

The average induced shear force (F) along all RC elements can be obtained by multiplying the mean shear stress ( $J_s$ ) by the specified area of a reference cross section ( $A_c$ ) of the member concerned as<sup>1)</sup>,

$$F = J_s \cdot A_c$$

$$J_s = \int_{\text{all elements}} J_{2s}(x, y) dx dy / A \quad (2)$$

where,  $J_{2s} = \sqrt{\frac{1}{3}((\sigma_1 - \sigma_2)^2 + \sigma_1 \sigma_2)}$

( $J_{2s}$ ) is the second stress deviator invariant at (x,y),  
( $\sigma_1$ ) and ( $\sigma_2$ ) are the principal stresses.

The integral in Eq.(1) and Eq.(2) can be numerically conducted by summing up computed stress in each finite element.

## 4. FAILURE CRITERIA

For the RC element based on smeared crack model, the stress and strain are specified relative to the crack direction, as shown in Fig.2. Three types of failure modes can be defined based on strain components. In the case of tension failure mode, the strain ( $\epsilon_{xc}$ ) perpendicular to crack becomes an indicator. As for compression failure mode, the strain ( $\epsilon_{yc}$ ) in the direction of crack serves, while for the shear failure mode, the shear strain ( $\epsilon_{xyc}$ ) parallel to the crack surface is focused, as shown in Fig.2. The failure mode of reinforced concrete element can

be one of these failure modes or a combination of different modes at different parts of structure.

From the observation of many experiments<sup>3)</sup>, the maximum strains at failure are evaluated for RC in-plane elements. As for tension failure, the maximum tensile strain ( $\epsilon_t$ ) perpendicular to the crack is specified 3%. For compression failure, the maximum compression strain ( $\epsilon_c$ ) in the direction of the crack is -1.0% and shear failure criterion in terms of shear strain ( $\epsilon_{sh}$ ) in the direction parallel to the crack surface is  $\pm 2.0\%$ .

Considering these criteria, yield of steel and crush of concrete take place while the load carrying mechanism is maintained. In fact, the local failure at some particular element does not always mean the structural collapse. In this study, the authors adopt higher critical strain values than those stated above for judging these failure modes for a single element. The strain value for any mode of failure is specified as 20% so that structural computation would not stop due to the failure of a couple of elements, but come up to the structural collapse of load carrying mechanism. Actually, before reaching this critical strain at finite elements, the structural mechanism occurred in this study. Henceforth, the term **failure of structure** used in this study does not mean a failure of finite element but the collapse of load carrying capacity of the entire analysis domain.

## 5. NONLINEAR RESPONSE OF UNDERGROUND RC BOX CULVERT

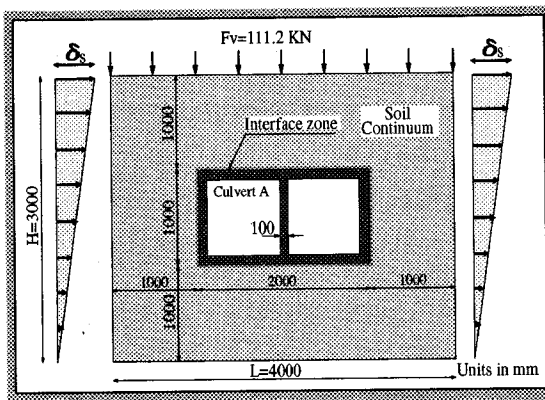
### (1) Target structures for parametric study

Two RC vents-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 outer dimension of the two culverts is 2.0 m length, 1.0 m height and 1.0 m width. The wall thickness is 10 cm for both culverts, as shown in Fig.3 for culvert (A), but in culvert (B) a haunch with 45° is attached at the corners of the box to increase the structural rigidity.

The RC box culverts with surrounding soil are analyzed under the forced shear displacement, denoted by ( $\delta_s$ ), as shown in Fig.3. For culvert (A), the maximum displacement is 30 mm but for culvert (B) it is 60 mm. The mechanical properties of surrounding soil are kept constant in all the analyses with initial shear stiffness ( $G_s$ ) equal to 40 MPa. These target structures are imported from the specimens examined by JSCE committee<sup>2)</sup> and furthermore, they serve to experimentally verify

**Table 1** Parametric study for RC box culvert

	Material Behavior		Reinforcement ratio (%)	
	Soil	RC	Culvert (A)	Culvert (B)
Material Effect	Nonlinear	Nonlinear	0.40	0.88
	Nonlinear	Linear		
	Linear	Nonlinear		
	Linear	Linear		
Reinforcement ratio	Nonlinear	Nonlinear	0.20	0.40
			0.40	0.88
			1.00	1.20
			1.50	1.60
			2.00	2.00



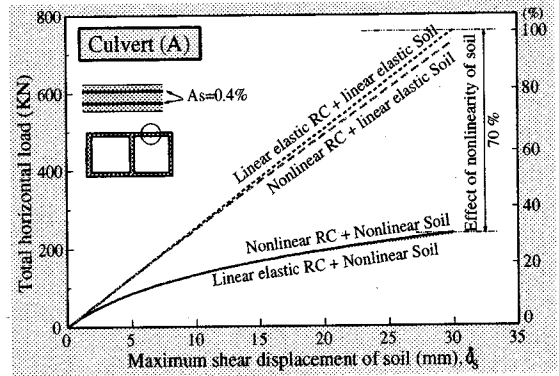
**Fig. 3** Target structure for parametric study 2) [culvert (A)]

computer code **WCOMR-SJ**<sup>8)</sup> which is used in this study.

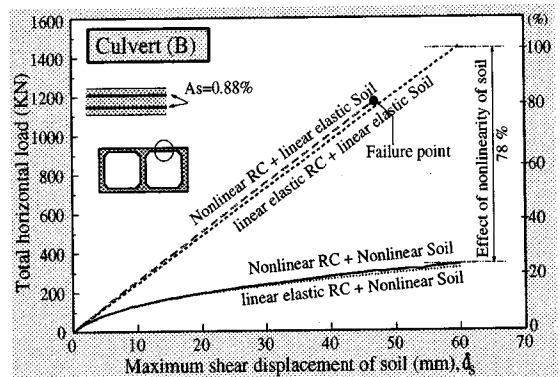
A sensitivity analysis has been performed to investigate how influential it is to consider material nonlinearity of both RC and soil in the analysis. Also, the effect of reinforcement ratio is investigated as one of the most important parameters to govern the damage of RC and the ductility of structures. All analyzed cases are listed in **Table 1**. The reliability of the computational approach adopted in this study was already checked under the above stated soil-RC interactive conditions<sup>8)</sup>.

## (2) Influence of nonlinearity of materials on RC/Soil response

To investigate the influence of material nonlinearity, four cases are focused; first, RC is assumed linear elastic while soil is nonlinear, second, RC is nonlinear and soil is assumed linear elastic and the third case, both are assumed linear elastic. These three cases are compared with the nonlinear RC and nonlinear soil case which was verified in reference (8). In all cases, other



**Fig. 4a** Influence of nonlinearity of materials on the force displacement relationship for RC/soil system [culvert (A)]



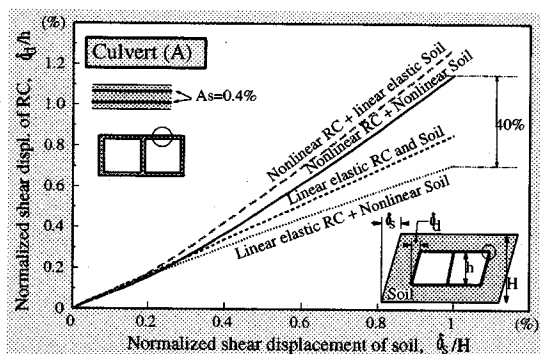
**Fig. 4b** Influence of nonlinearity of materials on the force displacement relationship for RC/soil system [culvert (B)]

parameters (dimension, reinforcement ratio, interface parameters and soil stiffness) are kept constant.

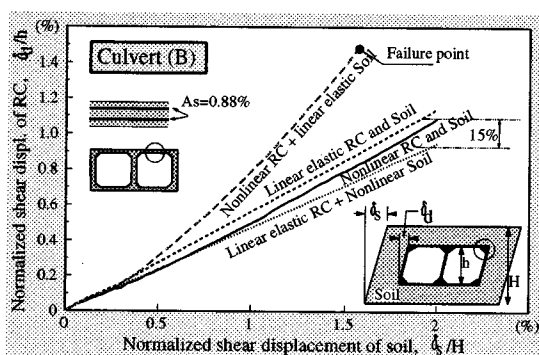
### a) Load-displacement relationship

The influence of considering nonlinearity of soil and RC on the lateral load-displacement relation of culverts (A) and (B) is shown in **Figs.4a** and **4b**, respectively. The load displacement relation in consideration of RC nonlinearity is the same as the linear elastic RC case. It can also be noticed that the total load is overestimated when considering soil as a linear elastic material. It is about five times as large as the case of nonlinear model for soil.

In culvert (B), if soil is considered as a linear elastic and the structure as nonlinear reinforced concrete, the structure exhibits compression failure after yield of steel at about 45 mm as the maximum shear displacement, as shown in **Fig.4b**. It can be concluded that the load-displacement relation is chiefly controlled by the behavior of soil and that the nonlinearity of soil cannot be ignored.



**Fig. 5a** Influence of nonlinearity of materials on the normalized shear displacement of RC culvert and soil [culvert (A)]



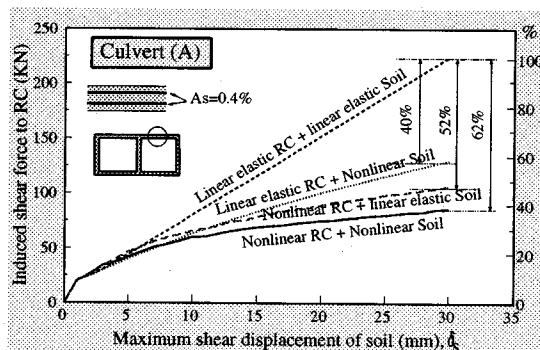
**Fig. 5b** Influence of nonlinearity of materials on the normalized shear displacement of RC culvert and soil [culvert (B)]

## b) Shear deformation

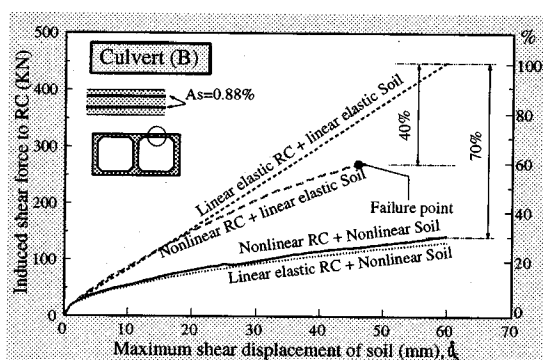
In soil-structure interaction problems, the relative deformation of structures and soil should be known. In this study, the relative deformations, considered as normalized mean shear displacement with height for soil and RC culvert, are shown in **Figs.5a** and **5b**. Through these figures, it can be seen that the effect of nonlinearity of RC is very significant.

In the case of flexible structure culvert (A), until normalized shear displacement of soil equals to 0.2%, RC behavior is close to linear elastic. Then the nonlinearity takes place and becomes more and more significant with increase in the maximum shear displacement. At the normalized shear displacement equal to 1.0%, the mean shear displacement of nonlinear RC culvert becomes greater than the case of assumed linear elasticity of RC by 40%.

In the case of rigid structure culvert (B), the influence of RC nonlinearity can be seen at the normalized shear displacement equal to 1.0%, and gradually increases till 2.0%. At that level, the effect of nonlinearity is small. By comparing both culverts (A) and (B) through **Fig.4** and **Fig.5**, it can



**Fig. 6a** Influence of nonlinearity of materials on the induced shear force to the RC culvert [culvert (A)]



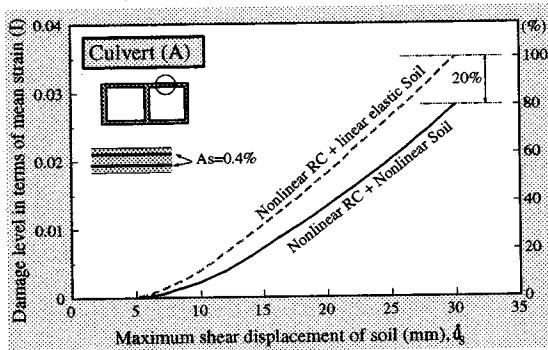
**Fig. 6b** Influence of nonlinearity of materials on the induced shear force to the RC culvert [culvert (B)]

be concluded that while the effect of nonlinearity of RC is small for load displacement relation, it becomes significant for shear deformation of reinforced concrete underground.

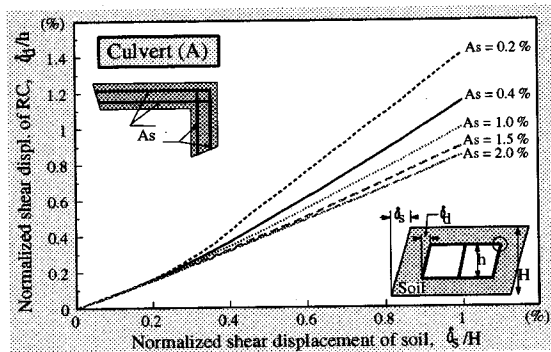
## c) Induced shear force to RC

The average induced shear force to RC and the damage level in terms of mean strain are calculated using equations (1) and (2), respectively. The relation between induced shear force to RC and the maximum shear displacement of soil is shown in **Figs.6a** and **6b**. If soil and RC are considered as linear elastic materials, the induced shear force is dramatically increased. It can be seen that the induced shear force to RC will increase by increasing rigidity of RC. In other words, the induced force to RC depends on the nonlinear feature of the structure itself.

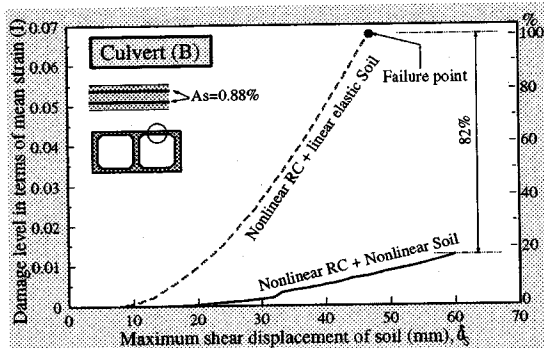
Nonlinear kinematic interaction of RC and soil is clearly comprehended, as shown in **Figs.6a** and **6b**. Average shear force induced to nonlinear RC from nonlinear soil is less than 50% of the full linear elastic solution when large displacement is considered, and it is found that nonlinear feature of soil reduces shear forces to RC predominantly



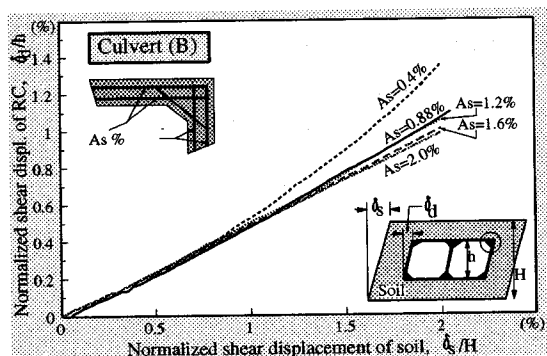
**Fig. 7a** Influence of nonlinearity of materials on the damage level in RC culvert [culvert (A)]



**Fig. 8a** Influence of reinforcement ratio on the normalized shear displacement of RC culvert and soil [culvert (A)]



**Fig. 7b** Influence of nonlinearity of materials on the damage level in RC culvert [culvert (B)]



**Fig. 8b** Influence of reinforcement ratio on the normalized shear displacement of RC culvert and soil [culvert (B)]

owing to the degraded earth pressure. It appears that the nonlinear characteristic of RC in culvert (B) is comparatively minor when soil is assumed nonlinear material. This is due to the fact that the induced force is not large enough to exhibit substantial drop of RC stiffness since larger amount of steel is placed.

#### d) The soundness of RC

The relation of damage level in terms of mean strain ( $\bar{\epsilon}$ ) and the maximum shear displacement of soil are shown in **Figs.7a** and **7b**. In the case of linear RC, in-plane mean strain is nearly zero because no crack is considered, the overall deformation is in shear and the vertical load supplied by vertical force (see **Fig.3**) is not large enough to introduce volumetric deformation. Therefore, the case of linear RC is not shown in **Figs.7a** and **7b**. If soil is idealized as linear elastic material, the induced damage related to cracking of concrete and yield of reinforcement is much overestimated.

### (3) Influence of reinforcement ratio on RC/Soil response

Concerning the effect of reinforcement ratio, several cases are analyzed for different

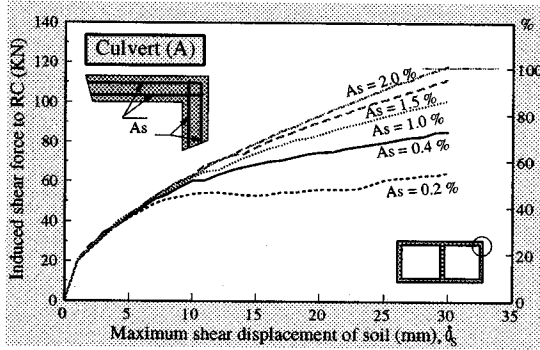
reinforcement ratios from 0.2% to 2.0%. In all cases, all other parameters (dimension, interface parameters and soil stiffness) are kept constant and the same as those in the target culverts. The same items considered in the pervious sections are discussed to evaluate the effect of reinforcement ratio on the response of under-ground structure.

#### a) Shear deformation

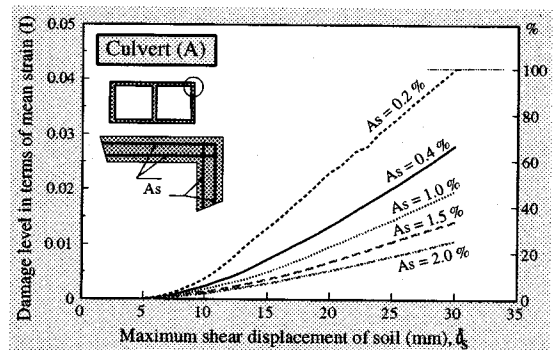
The effect of reinforcement ratio on the shear deformation is inter-linked with the rigidity of structure itself. In the flexible structure of culvert (A), the effect of reinforcement ratio is so significant for the normalized shear displacement, as shown in **Fig.8a**. By increasing in reinforcement ratio, less deformation of RC occurs. On the other hand, this effect is negligible in the case of rigid structure of culvert (B), as shown in **Fig.8b** unless very small reinforcement ratio is used.

#### b) Induced shear force to RC

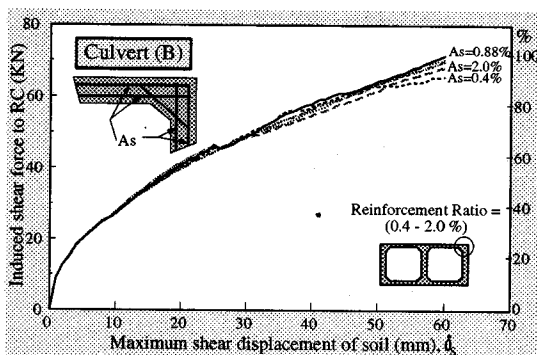
For the flexible structure culvert (A), the induced shear force transferred from soil is so much affected by reinforcement ratio, as shown in **Fig.9a**. When reinforcement ratio increases, the stiffness of RC structure and the induced force are increased. At the same time, the cross-sectional capacity is also elevated. As a result, no failure is obtained. For the



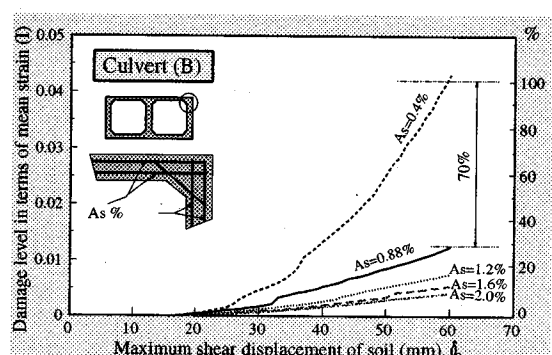
**Fig. 9a** Influence of reinforcement ratio on the induced shear force to the RC culvert [culvert (A)]



**Fig. 10a** Influence of reinforcement ratio on the damage level in the RC culvert [culvert (A)]



**Fig. 9b** Influence of reinforcement ratio on the induced shear force to the RC culvert [culvert (B)]



**Fig. 10b** Influence of reinforcement ratio on the damage level in the RC culvert [culvert (B)]

rigid structure culvert (B), reinforcement ratio slightly changes the stiffness of RC structure. It slightly affects the induced shear force to RC, as shown in **Fig. 9b**.

### c) Soundness of RC

The effect of reinforcement ratio on the damage level is shown in **Figs.10a** and **10b**. For the flexible structure culvert (A), the reinforcement ratio effectively controls the damage level and cracking condition, as shown in **Fig.10a**. When reinforcement ratio decreases, more damage and cracks are obtained even though the induced shear forces decrease. For the rigid structure culvert (B), while the effect of reinforcement ratio is very small for induced shear force, it becomes very significant for the damage level, as shown in **Fig. 10b**.

The parametric study clearly showed the importance of considering the nonlinear coupled RC/soil behavior under shear. Therefore, the nonlinearity of both soil and RC has to be taken into account for rationally estimating shear force and damage of the underground RC. It can be also seen that the damage level of underground RC are mainly controlled by reinforcement ratio which has a great effect on the soundness and leakage resistance

against liquid penetration for underground structures after removing loads.

## 6. NONLINEAR RESPONSE OF UNDERGROUND RC VERTICAL DUCT

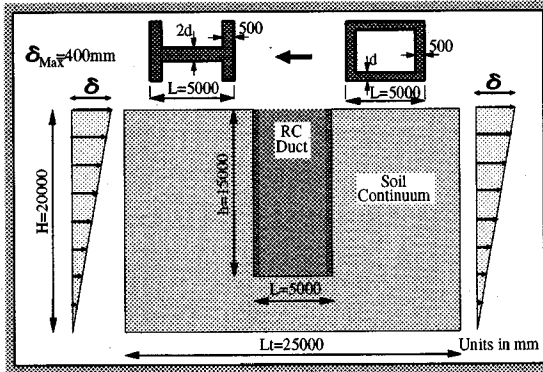
More parametric study will be advisable to understand the previously stated interaction more practically. A vertical duct with box cross-section is selected. The background of this selection is that, this type of structures (for tunnel construction) is frequently constructed in soft sedimentation, where high acceleration and large shear deformation will take place when heavy seismicity happens. Main seismic resistant elements are in-plane walls unlike framed culverts and tunnels.

### (1) Target structures for parametric study

RC underground vertical duct with height ( $H=15.0$  m) and box cross-section ( $L \times L=5.0 \times 5.0$  m) with thickness ( $d$ ) is studied. The RC duct coupled with surrounding soil is analyzed under the forced shear deformation denoted by ( $\delta$ ) acting on soil, as shown in **Fig.11**.

**Table 2** Parametric study for RC vertical duct

	Material		Reinforcement ratio %	Wall thickness d/L	Soil stiff. G MPa
	Soil	RC			
Effect of Soil Stiffness	Non-linear	Non-linear	varied from 0.3 % to 2.0%	varied from 0.025 to 0.3	10
					20
					40
					80
					120
					160
Effect of Wall Stiffness	Non-linear	Non-linear	varied from 0.3 % to 2.0%	0.025	varied from 10 to 200
				0.050	
				0.100	
				0.150	
				0.200	
				0.250	
Effect of reinforcement ratio	Non-linear	Non-linear	0.3 %	varied from 0.025 to 0.3	varied from 10 to 200
			0.5%		
			1.0%		
			2.0%		



**Fig. 11** Target structure (RC vertical duct) for parametric study

In the analysis, the normalized shear displacement ( $\delta/H$ ) is applied incrementally up to a maximum of 2.0% or failure. The mechanical properties of surrounding soil are represented by initial shear stiffness ( $G_s$ ) which varies from a very weak soil (10 MPa) to a very stiff one (200 MPa). Accordingly, the nonlinear shear stress-strain relation of soil is changed based on Ohsaki model<sup>10</sup> (Fig.1). The structural rigidity of RC, as represented by the ratio of thickness to length of wall ( $d/L$ ), is changed from 0.025 to 0.3. The reinforcement ratio of RC structure is assumed isotropic ( $A_{sx}=A_{sy}=A_s$ )

and ranges from 0.3 to 2.0%. All the considered cases are listed in **Table 2**. The interface between soil and RC is assumed perfect bond and no shear slip is allowed. This is a severe condition concerning RC failure.

## (2) Failure interaction diagram of the vertical duct under shear load

From the results of the current analysis<sup>5</sup>, the failure interaction diagrams of RC underground structures are obtained for different reinforcement ratio, as shown in **Fig.12**. These charts are drawn for the maximum normalized shear displacement of the surrounding foundation as 2.0%.

In every chart, the X-axis represents the initial stiffness of surrounding soil, and the Y-axis represents the rigidity of structure in terms of ( $d/L$ ). The hatched areas A and B represent structures which fail in tension and compression failure modes, respectively. The hatched area C represents wall thickness less than the minimum wall thickness allowed by the present code<sup>2</sup>. Above these areas (A, B and C), each hatched area from 1 to 8 represents different damage level of RC in terms of mean strain ( $I$ ). It is found that, for any point in these zones, the structure can survive under any value of normalized shear displacement less than the maximum value of normalized shear displacement of the chart (2%), but with different crack opening and damage level. The interaction diagrams are obtained from about 60 cases of parametric analysis.

It is clearly seen that the failure takes place in limited conditions, which are centered around larger stiffness of soil with smaller thickness of RC walls, as shown in **Fig.12**. Thus, 2% of the forced normalized shear deformation which corresponds to soft foundation at severe earthquake is unrealistically high and severe for the case of high stiffness ground. For more rational discussion, seismic analysis of the RC/soil entire system is required (See subsection (3)). Here, it can be said that underground RC ducts of lower capacity brought about by the small thickness of wall can be safely designed if large ductility caused by larger reinforcement ratio is maintained.

By changing the reinforcement ratio, the boundary of the structural failure zone does not change so much because the strength of RC increases with increasing reinforcement ratio, meanwhile, the induced force level in structure is also elevated proportionally.

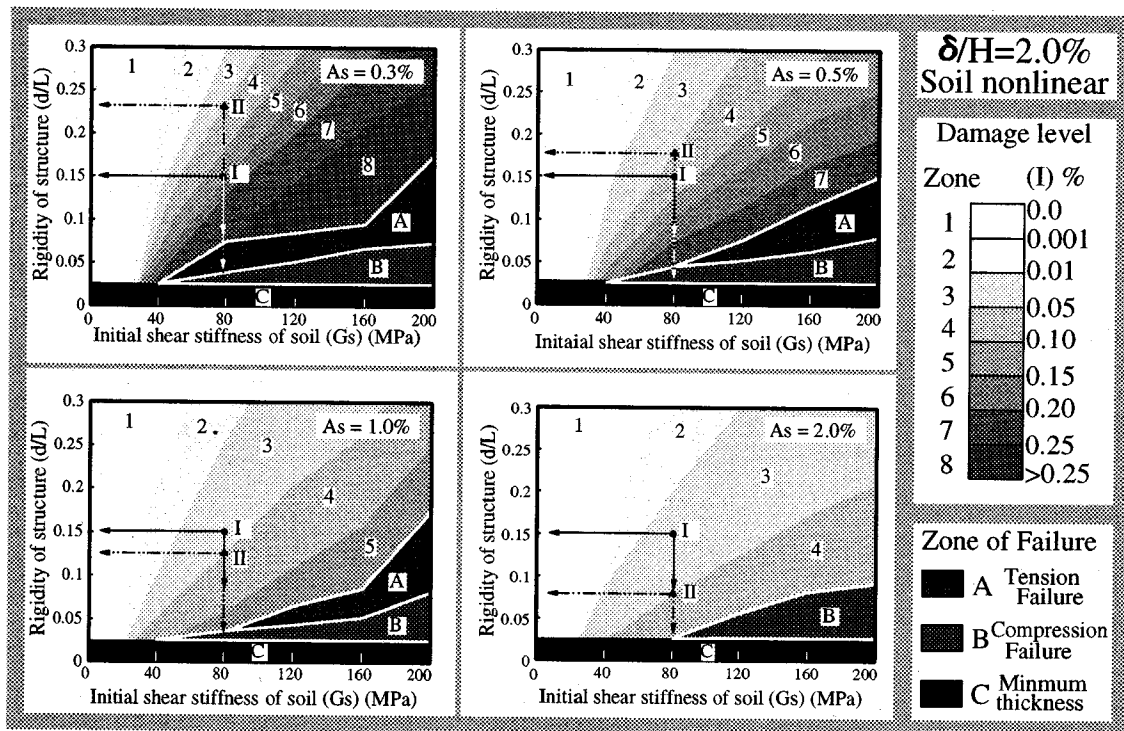


Fig. 12 Failure interaction diagram of underground RC duct surrounded by soil under forced shear deformation 2%

The effect of reinforcement ratio can be discussed also by looking at points (I) and (II) in each diagram of Fig.12. Direct your attention to points (I) in Fig.12. Different damage levels occurred for different reinforcement ratios under the same soil condition and rigidity of structure ( $G_s = 80$  MPa,  $d/L = 0.15$  at point (I)). It is clearly seen through point (I) that the damage level of structure is controlled by the reinforcement ratio. In case of point (II), the damage level is kept constant for the same soil condition. In this case, there are several choices having the same damage level all of which satisfy the safety requirement. Stiff structures with lower reinforcement ratio (low ductility in post-yield zone) or flexible structures with higher reinforcement ratio (high ductility) is to be selected.

If the dynamic soil pressure would be specified irrespective of the structural ductility, generally, the design based decision tends to lead to the stiffer structures with lower ductility and reinforcement ratio. However, consideration of the material nonlinearity results in a variety of choices for different structural stiffness with different reinforcement ratios. Choice of the proper combination of them depends on several functional

aspects which should be checked such as water tightness, leakage and serviceability.

### (3) Seismic analysis for the target structure.

Based on the RC nonlinear finite element analysis applicable to dynamic and cyclic loads<sup>(12)</sup>, the full path-dependent constitutive models for soil<sup>(8)</sup> and interface between RC and soil<sup>(8)</sup> are installed in the computer code **WCOMD-SJ**<sup>(7)</sup>. The advantage of full path-dependent model was exhibited, such that hysteresis damping and restoring force characteristics of both structure and soil are intrinsically taken into account, and the residual permanent deformation can be quantitatively evaluated.

As previously mentioned, the values of maximum normalized shear displacement of 2% could be unrealistic for high values of soil stiffness, therefore, in this section the maximum normalized shear displacement is evaluated according to the stiffness of soil by conducting dynamic analysis of RC/soil entire system. The dimension and finite element mesh of target structure, which is a simple model of RC underground vertical duct with height ( $H=15.0$  m) and a square box section ( $10.0 \times 10.0$  m), is shown in Fig.13. The purpose of choosing this type of

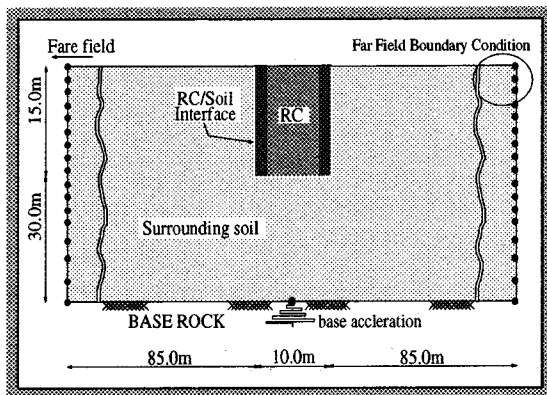


Fig. 13 Overview of underground structure surrounding by soil domain

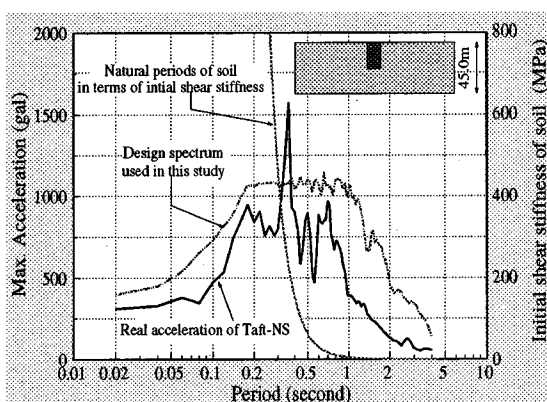


Fig. 14 Acceleration response spectrum used in the analysis and natural period for layer soil.

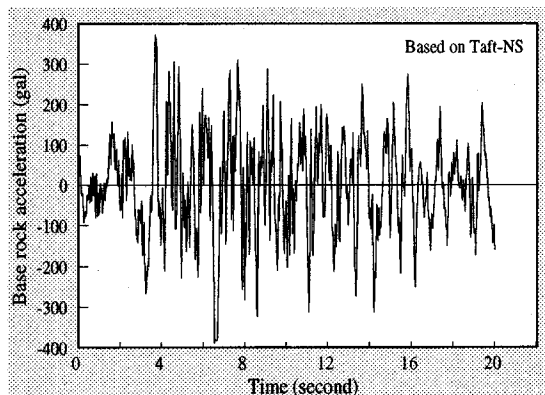


Fig. 15 Base rock acceleration based on design spectrum

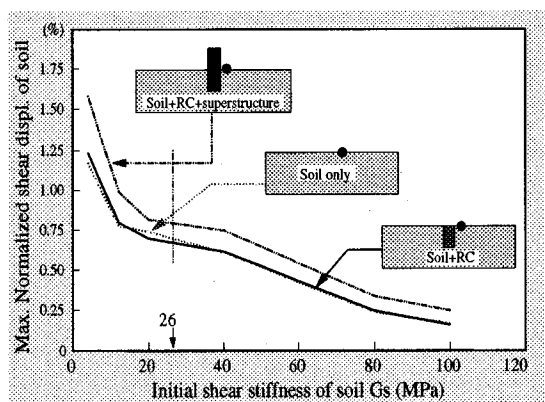


Fig. 16 Maximum response displacement of soil in terms of initial shear stiffness of soil

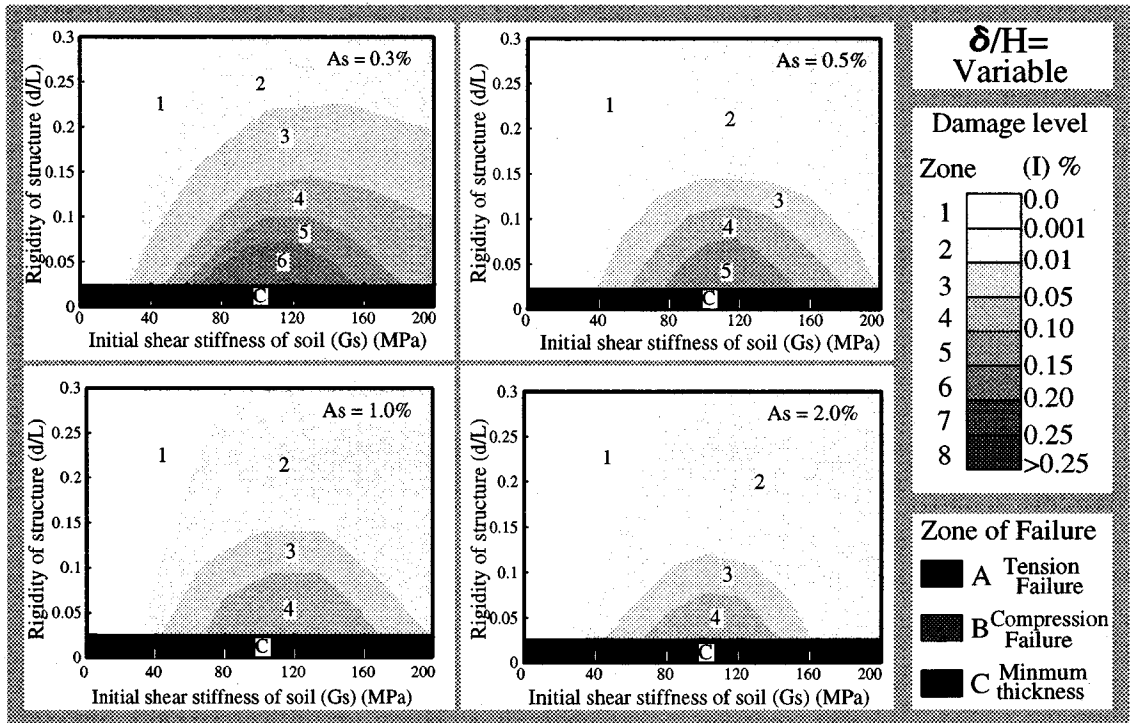
structure is to link the static interaction discussed in the previous section with the dynamic one in order to have full evaluation of the interaction between in-plane underground structure and surrounding soil under shear.

Since the discussion of static kinematic interaction reveals that in-plane underground RC structure possesses higher safety if sufficient ductility is provided, severe situations were intentionally assumed to reproduce high damage for investigating the effect of stiffness of surrounding soil. Accordingly, a thin wall (thickness/wall span = 1/36 which is approximately the minimum allowable thickness specified by JSCE code<sup>2)</sup>) with low reinforcement ratio (0.5%) was selected.

Initial stiffness of ground ( $G_s$ ) is varied from 4 MPa (soft foundation and N-value = 2) to 100 MPa (rock and N-value = 35). Accordingly, the shear stress-strain relation for soil is changed based on the soil model<sup>7)</sup>. Furthermore, the maximum shear

displacement of soil in terms of initial shear stiffness can be directly estimated under seismic loads to check the assumed value in the static analysis discussed previously (maximum normalized shear displacement = 2.0%).

In the dynamic analysis by using FEM program **WCOMD-SJ**<sup>7)</sup>, mixed artificial boundary mode of reflection was introduced for far field idealization at both extreme sides of soils<sup>4)</sup>. The total length of soil layer is checked to get the minimum appropriate length that can represent all the domain and dissipate the energy from finite analysis domain to far field. With reference to the acceleration phase record of Taft-NS earthquake and the response spectrum, **Fig.14**, the seismic base rock accelerogram was produced as shown in **Fig.15**. Referring to the present code, magnitude of seismicity used is close to level  $S_2$  regarded as the strongest level for nuclear power plant facilities<sup>2)</sup>.



**Fig. 17** Modified failure interaction diagram of underground RC duct surrounding by soil under dynamic shear deformation

#### (4) Modified failure interaction diagram of the vertical duct under shear load

In this section the response spectrum of underground structures, in terms of maximum shear displacement with respect to initial stiffness of ground is firstly discussed. Three cases have been considered in the analysis. In the first case only soil is considered without any underground structures. In the second case, soil with an underground RC structure has been analyzed. The third case is similar to the second case but with attaching a super-structure to the underground RC structure.

Concerning the maximum shear displacement of soil layer, **Fig.16** shows the relation between initial shear stiffness of soil and the maximum normalized shear displacement under ground acceleration. As a general trend, the maximum normalized shear displacement is decreasing by increasing the stiffness of soil.

Since the maximum normalized shear displacement has been considered as 2.0 % in the static analysis, regardless of the stiffness of soil, the dynamic failure interaction diagram shown in **Fig.17** is much changed as that shown in **Fig.12** after considering the maximum shear displacement based on the relation shown in **Fig.16**.

Regarding the stiffness of soil and structure it can be concluded that, in-plane underground

structures can survive under severe seismic actions with different levels of damage and cracking which are dependent on the ductility of the structure concerned (reinforcement ratio and thickness of wall). Therefore, in designing underground RC under seismic shear, reinforcement ratio and the wall thickness, which have much to do with ductility of members, are to be regarded as controlling factors of structural soundness and serviceability, which are suggested being more critical than the safety requirement.

## 7. CONCLUSIONS

Based on the parametric study and analytical investigation presented in this paper, the followings are the general conclusions reached within this scope in terms of safety and damage of the underground structure.

1. The nonlinear characteristics of both reinforced concrete and soil cannot be ignored to get realistic behavior and response of RC underground structure.
2. The rigidities of structure and surrounding soil are closely inter-linked when deciding the thickness of RC. However, in present design practice, the minimum thickness of structure is computed

based on the earth pressure, which is taken as constant and independent of the structural stiffness.

3. The reinforcement ratio hardly affects the safety of underground structures examined here because both the ultimate capacity and the induced force from surrounding soil increase accordingly. The load to be applied to underground RC depends on the feature of the structure itself.
4. The damage level and crack conditions are mainly controlled by the reinforcement ratio and the stiffness of surrounding soil. Therefore, decision of the reinforcement ratio is to be chiefly made in terms of the function and serviceability of underground structures.
5. In most cases, owing to the coupled nonlinear kinematics, structural safety for in-plane underground structures could be sustained under seismic loads with different damage level, if the minimum level of ductility would be granted.

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## 地中RC構造の非線形せん断応答

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本研究は、静的および動的荷重作用下での地中RC構造と地盤との相互作用、並びに地盤からRC構造に導入されるせん断力とせん断変位について論ずるものである。地盤からの作用により、高せん断変形を受ける地中RC構造に対して静的／動的感度解析を行った。RC構造の非線形性、構造の剛度および鉄筋比が、破壊モード、残留変形および導入せん断力に及ぼす効果について、多角的な検討を行った。これにより、地中RC構造の地震時安全性評価のためのガイドラインを得たものである。