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NONLINEAR RESPONSE OF UNDERGROUND RC STRUCTURES UNDER SHEAR

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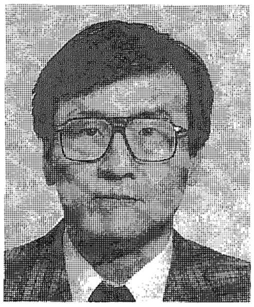

Koichi MAEKAWA

This paper describes various aspects of the kinematic nonlinear interactions in a coupled RC/soil system under static and dynamic loads. Parametric studies are conducted for two types of underground structure subjected to high shear deformation transferred through the nonlinear surrounding soil. In this analysis, the influence of several factors -- such as RC and soil material nonlinearity, structure stiffness and reinforcement ratio -- are investigated. Failure modes, residual deformations and forces induced in the RC from the soil are examined to elucidate rationale guidelines leading to future improvements of underground structural design.

***Keywords** : Soil-structure interaction, shear, FEM, underground RC*

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1. INTRODUCTION

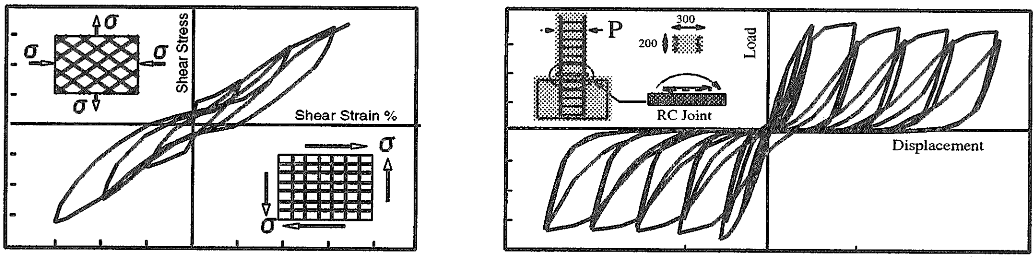
In the design of underground RC structures, the design value for earth pressure applied to the structure is the predominant determinant of structural safety. However, the dependence of earth pressure on RC structural ductility has been neglected or simply idealized in practical design. It has been clearly proven through experiments that the induced force from surrounding soil varies with the structural nonlinearity [2),13)]. On the other hand, the analysis used in practical design mostly takes account of soil nonlinearities, but mere underground RC structures are simply assumed to be elastic or to have equivalent reduced stiffness.

This background indicates that the nonlinear kinematic interactive response of RC underground structures and surrounding soil is a major concern. In this respect, the induced force and damage to underground RC structures under high soil shear deformation are investigated. In this study, two types of underground structures are subjected to numerical parametric analysis under static and dynamic shear transferred through nonlinear surrounding foundations.

The first type of structure is an RC underground box culvert and the analysis investigates how material nonlinearities influences the analysis. The effects of structural stiffness and reinforcement ratio are the chief focus of the investigation. The second parametric study is on 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 the seismic response of underground RC.

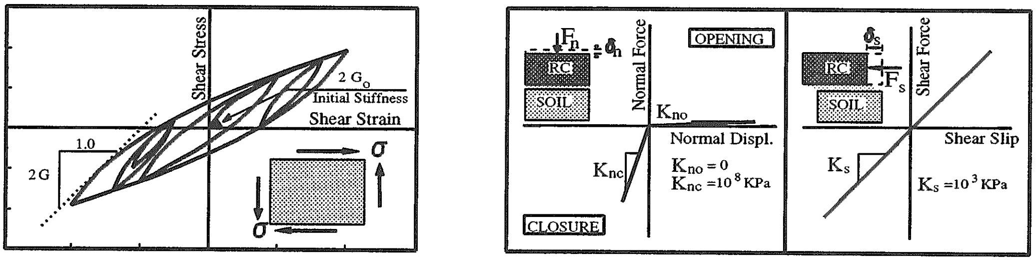
2. ANALYSIS OF UNDERGROUND STRUCTURES

The finite element approach is widely used in the analysis of reinforced concrete and soil media. A major issue in designing a computational approach to nonlinearities is to establish a constitutive model of RC elements under reversed cyclic action. The model should be capable of predicting the stress accurately for any given strain history. A combination of smeared and discrete crack models subjected to reversed cyclic loads[3)] is adopted. The smeared crack model is employed for certain control volumes of members and discrete models 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[9)], their proper 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 [3),8)]

A path-dependent constitutive model for soil is indispensable in dealing with the kinematic interactions of the overall RC/soil system under strong seismic loads. Here, Ohasaki's model[10)] gives a formula for an envelope which expresses the nonlinear shear stress-strain relation 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[11)] as shown in **Fig.1d**.

Based on a method of RC nonlinear finite element analysis applicable to reversed cyclic loads[3)], constitutive models for soil and the interface between RC and soil are installed in the computer code **WCOMD-SJ**[8)]. The advantages of a full path-dependent model are exhibited: for example, the residual permanent deformation and damage of materials can be quantitatively evaluated. **Figure 1** shows an outline of the proposed material models used for different elements (RC element in **Fig.1a**, RC joint element in **Fig.1b**, soil element in **Fig.1c** and RC/soil interface element in **Fig.1d**) in the analysis of underground structures hereafter. Cracks are treated as being uniformly dispersed in RC elements and RC joint elements are idealized as single cracks between members.

3. PARAMETERS DEFINING SHEAR RESPONSE OF STRUCTURES

In discussing the shear response of underground RC structures and their kinematic interactions, the shear force induced in the RC and the RC damage level are evaluated using stresses and strains obtained from the finite element analysis, as described in the following subsections.

(1) RC Damage level

The first strain invariant, denoted (I_1), is closely associated with crack occurrence and the expansion of the in-plane element (volumetric change of the element) associated with reinforcement yield. The RC mean strain, denoted (I), is the average of (I_1), for all RC elements. It is equal to zero in the case of elastic shear behavior (since no volumetric change and no residual deformation occur under pure elastic shear deformation). The mean strain (I), an indicator of expansive deformation that is closely related to leakage resistance, structural soundness and functionality, is adopted to represent the magnitude of damage to reinforced concrete. The values of (I) and (I_1) can be calculated as follows[1)].

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

$$I_1 = \varepsilon_1 + \varepsilon_2$$

where, (ε_1) and (ε_2) are the principal strains at (x,y), and (A) is the total area of the RC in-plane elements.

(2) Average induced shear force on 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[1)],

$$F = J_s \cdot A_c$$

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

$$J_{2s} \equiv \sqrt{\tfrac{1}{3}\left((\sigma_1 - \sigma_2)^2 + \sigma_1\sigma_2\right)}$$

where, (J_{2s}) is the second stress deviator invariant at (x,y), and (σ_1) and (σ_2) are the principal stresses.

The integrals in Eq.(1) and Eq.(2) can be numerically calculated by summing up the computed stress as in each finite element.

4. FAILURE CRITERIA

For an RC element based on the smeared crack model, the stress and strain are specified relative to the crack direction, as shown in **Fig.2**. Three types of failure mode can be defined based on the strain components. In the case of tension failure, the strain (ε_{xc}) perpendicular to crack becomes the indicator. As for compression failure, the strain (ε_{yc}) in the direction of the crack serves this purpose, while for shear failure, the shear strain (ε_{xyc}) parallel to the crack surface is used, as shown in **Fig.2**. The failure mode of a reinforced concrete element may be one of these failure modes or a combination of different modes in different parts of the structure.

From many experimental observations[3)], the maximum strains at failure have been evaluated for RC in-plane elements. In the case of tension failure, the maximum tensile strain (ε_t) perpendicular to the crack is specified as 3%. For compression failure, the maximum compression strain (ε_c) in the direction of the crack is -1.0% and the shear failure criterion in terms of shear strain (ε_{sh}) in the direction parallel to the crack surface is ±2.0%.

Considering these criteria, steel yielding and concrete crushing can take place while the load carrying mechanism is still maintained. In fact, local failure at some particular element does not always mean structural collapse. In this study, the authors adopt higher critical strain values than those stated above to judge such failure modes for a single element. The strain value for all modes of failure is specified as 20% to ensure that structural computations do not stop due to the failure of a couple of elements, but continue until structural collapse of the load carrying mechanism. Actually, before reaching this critical strain at finite elements, structural mechanism occurred in this study. Henceforth, the term ***failure of the structure*** as used in this study does not mean failure of a finite element but the collapse of load carrying ability of the entire analysis domain.

5. NONLINEAR RESPONSE OF UNDERGROUND RC BOX CULVERT

(1) Target structures for parametric studies

Two RC box culverts consisting of frames with a 0.4% volumetric reinforcement ratio (culvert (A)) and a 0.88% volumetric reinforcement ratio (culvert (B)) are considered. The outer dimensions of the two culverts are 2.0 m (L), 1.0 m (H) and 1.0 m (W). The wall thickness is 10 cm for both culverts. Culvert (A) is shown in **Fig.3;** culvert (B) has a 45° haunch attached to the box corners to increase structural rigidity. The RC box culverts plus surrounding soil are analyzed under forced shear displacement denoted (δ_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 the surrounding soil are held constant throughout the analysis with an initial shear stiffness (G_s) equal to 40 MPa. These target structures were experimentally examined by the JSCE committee[2)] and in this study, they serve to verify the computer code **WCOMD-SJ**[8)] developed by the authors.

A sensitivity analysis has been performed to investigate how influential the material nonlinearities of both RC and soil are to the analysis. Also, the effect of reinforcement ratio is investigated as one of the most important parameters governing the damage to RC and structure ductility. All analyzed cases are listed in **Table 1**. The reliability of the computational approach adopted in this study was already confirmed using the above-stated soil-RC interactive conditions[8)].

Table 1 Parametric study of RC box culverts

	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

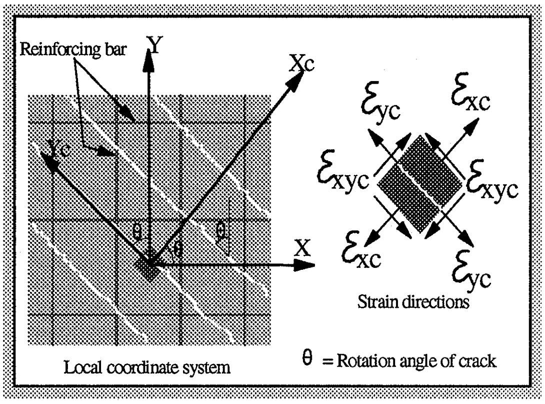


Fig. 2 Strain directions in cracked RC element

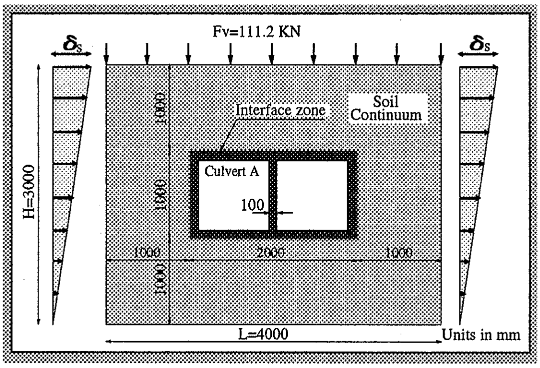


Fig. 3 Target structure for parametric study [2)]
[culvert (A)]

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

To investigate the influence of material nonlinearity, four cases are considered: first, RC is assumed to be linear elastic while soil is nonlinear; second, RC is assumed nonlinear and soil linear elastic; third, both are assumed linear elastic. These three cases are compared with the nonlinear RC, nonlinear soil case verified in reference (8). In all cases, other parameters (dimensions, reinforcement ratio, interface parameters, and soil stiffness) are kept constant.

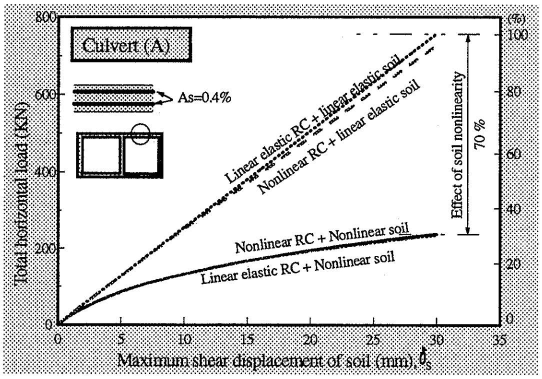


Fig. 4a Influence of material nonlinearity on the force-displacement relationship for RC/soil system [culvert (A)]

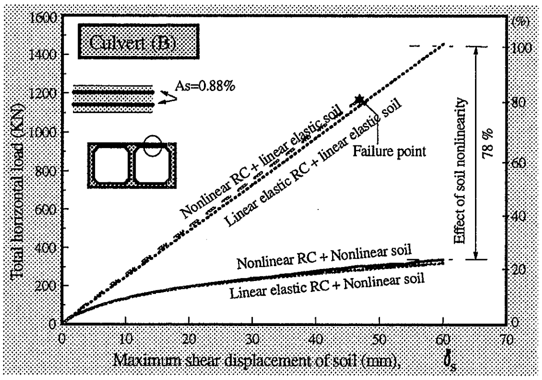


Fig. 4b Influence of material nonlinearity on the force-displacement relationship for RC/soil system [culvert (B)]

a) Load-displacement relationship

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

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

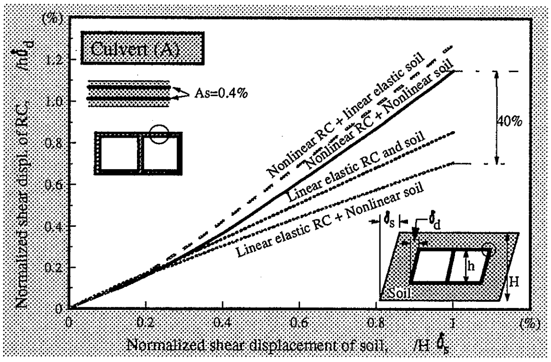


Fig. 5a Influence of material nonlinearity on the normalized shear displacement of RC culvert and soil [culvert (A)]

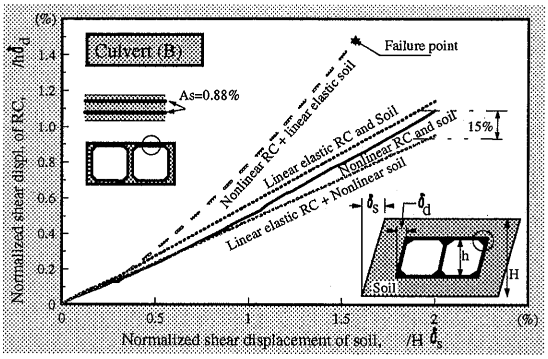


Fig. 5b Influence of material nonlinearity on the normalized shear displacement of RC culvert and soil [culvert (B)]

b) Shear deformation

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

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

In the case of the rigid structure, culvert (B), the influence of RC nonlinearity can be seen at a normalized shear displacement equal to 1.0%, and it gradually increases till 2.0%. At that level, the effect of the nonlinearity is still small. By comparing culverts (A) and (B) through **Fig.4** and **Fig.5**, it can be concluded that while the effect of RC nonlinearity is small for the load-displacement relation, it becomes significant as regards the shear deformation of underground reinforced concrete.

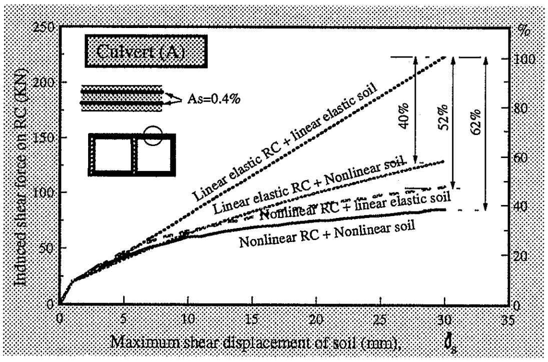


Fig. 6a Influence of material nonlinearity on the induced shear force on an RC culvert [culvert (A)]

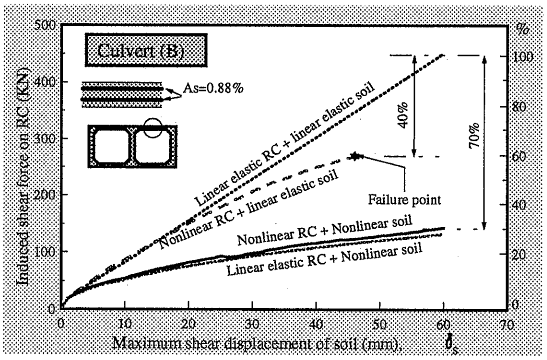


Fig. 6b Influence of material nonlinearity on the induced shear force on an RC culvert [culvert (B)]

c) Induced shear force on RC

The average shear force induced on the RC and the damage level in terms of mean strain are calculated using equations (1) and (2), respectively. The relation between this induced shear force and the maximum shear displacement of the 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 increases if the rigidity of the RC is increased. In other words, the induced force depends on the nonlinear characteristics of the structure itself.

Nonlinear kinematic interactions between RC and soil are clearly visible, as shown in **Figs.6a** and **6b**. The average shear force induced on nonlinear RC from nonlinear soil is less than 50% of the full linear elastic solution when a large displacement is considered, and it is found that nonlinear characteristics of soil reduce the shear forces significantly owing to the degraded earth pressure. It appears that the nonlinear characteristics of RC in culvert (B) are comparatively minor when the soil is assumed to be a nonlinear material. This is due to the fact that the induced force is not great enough to cause substantial fall in RC stiffness since there is a larger amount of steel.

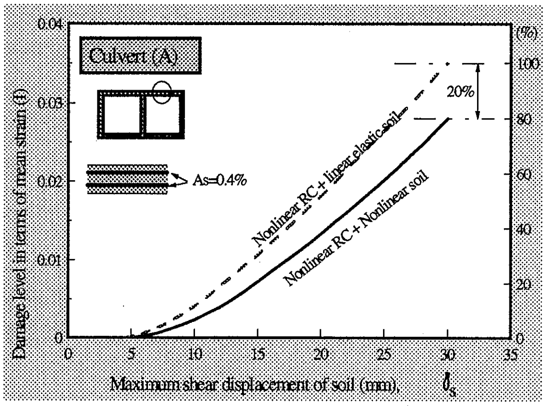


Fig. 7a Influence of nonlinearity of materials on the damage level in RC culvert [culvert (A)]

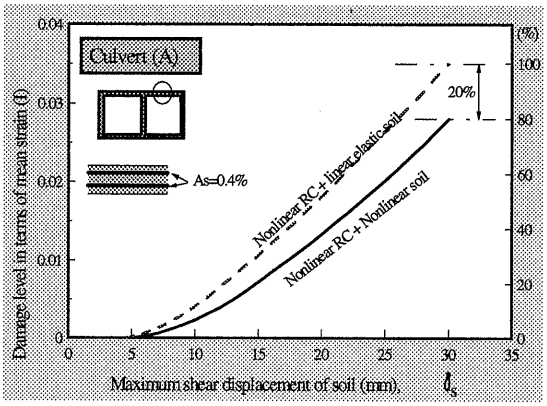


Fig. 7b Influence of nonlinearity of materials on the damage level in RC culvert [culvert (B)]

d) RC soundness

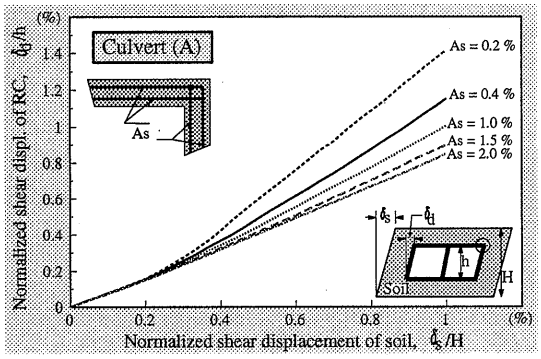
The relations between damage level in terms of mean strain (*I*) and the maximum shear displacement of the soil are shown in **Figs.7a** and **7b**. In the case of linear RC, the in-plane mean strain is nearly zero because no crack is considered, the overall deformation is shear, and the vertical load imposed by the vertical force (see **Fig.3**) is not large enough to introduce a volumetric deformation. Therefore, this linear RC case is not shown in **Figs.7a** and **7b**. If soil is idealized as a linear elastic material, the induced damage in the form of concrete cracking and reinforcement yielding 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 (dimensions, interface parameters, and soil stiffness) are kept constant and the same as in the target culverts. The same influences considered in the previous section are discussed in evaluating the effect of reinforcement ratio on the response of underground structures.

a) Shear deformation

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



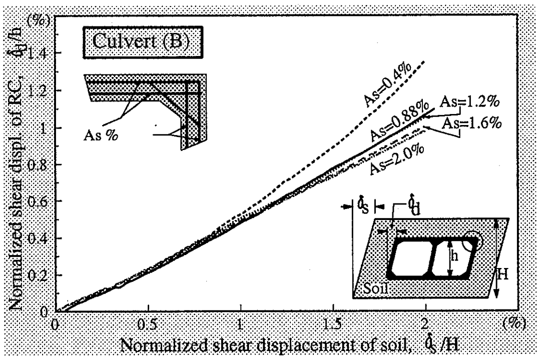


Fig. 8a Influence of reinforcement ratio on the normalized shear displacement of an RC culvert and soil [culvert (A)]

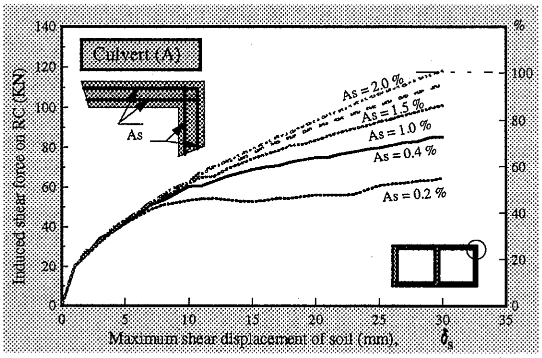
Fig. 8b Influence of reinforcement ratio on the normalized shear displacement of an RC culvert and soil [culvert (B)]

b) Induced shear force on RC

In the case of the flexible structure, culvert (A), the induced shear force transferred from the soil is considered affected by reinforcement ratio, as shown in **Fig.9a**. When the reinforcement ratio increases, the stiffness of the RC structure and the induced force rise. At the same time, the cross-sectional capacity is also improved. As a result, no failure occurs. For the rigid structure of culvert (B), a change in reinforcement ratio causes a slightly change in the stiffness of the RC structure. There is a small effect on the induced shear force, as shown in **Fig. 9b**.

c) RC soundness

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 the reinforcement ratio is reduced, more damage and cracks occur even though the induced shear force decreases. In the case of the rigid structure, culvert (B), while the effect of reinforcement ratio is very small as regards induced shear force, it is very significant for damage level, as shown in **Fig. 10b**.



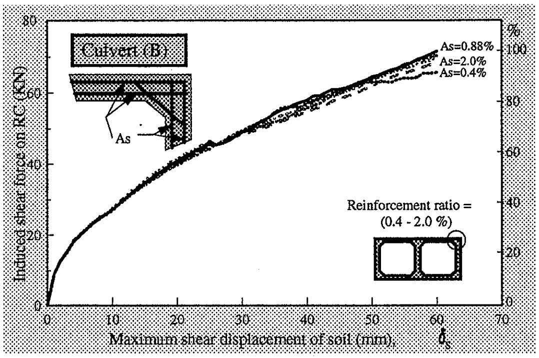


Fig. 9a Influence of reinforcement ratio on the induced shear force on an RC culvert [culvert (A)]

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

This parametric study clearly demonstrates the importance of considering the nonlinear coupled RC/soil behavior under shear. The nonlinearity of both soil and RC has to be taken into account in order to rationally estimate shear force and damage to underground RC. It can be also seen that the damage level of underground RC is mainly controlled by the reinforcement ratio, which has a great effect on the soundness and resistance to liquid penetration after the load is removed.

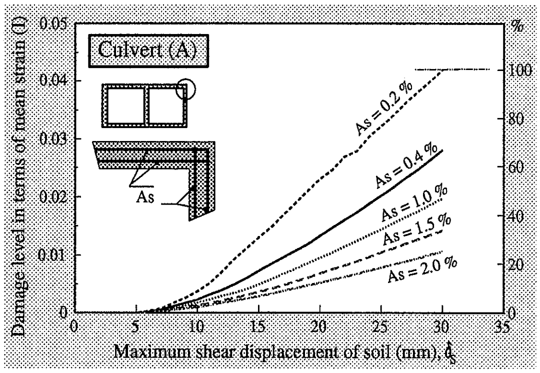


Fig. 10a Influence of reinforcement ratio on the damage level in an RC culvert [culvert (A)]

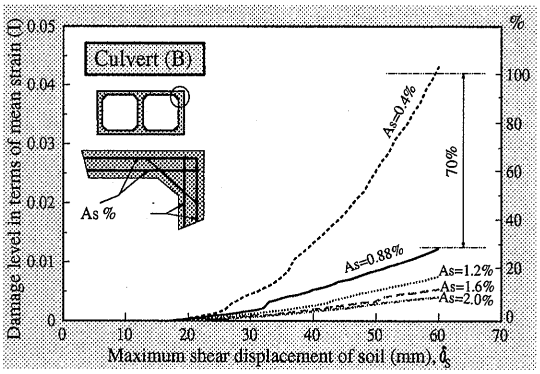


Fig. 10b Influence of reinforcement ratio on the damage level in an RC culvert [culvert (B)]

6. NONLINEAR RESPONSE OF UNDERGROUND RC VERTICAL DUCT

A further parametric study is needed to understand the previously obtained interactions in a more practical way. A vertical duct with box cross-section is selected for this study. The background to this choice is that this type of structure (for tunnel construction) is frequently built in soft sedimentary ground, where high acceleration and large shear deformation take place when heavy seismic motion happens. The main elements resisting seismic motion are in-plane walls, unlike the case of framed culverts and tunnels.

(1) Target structures for parametric study

An RC underground vertical duct (H=15.0 m) of box cross-section (LxL=5.0x5.0 m) with thickness (d) is studied. Coupling between the RC duct and the surrounding soil is analyzed under a forced shear deformation denoted by (δ) acting on soil, as shown in **Fig.11**.

Table 2 Parametric study of RC vertical duct

	Material		Reinforcement ratio %	Wall thickness d/L	Soil stiffness 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
					200
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	
				0.300	
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%		

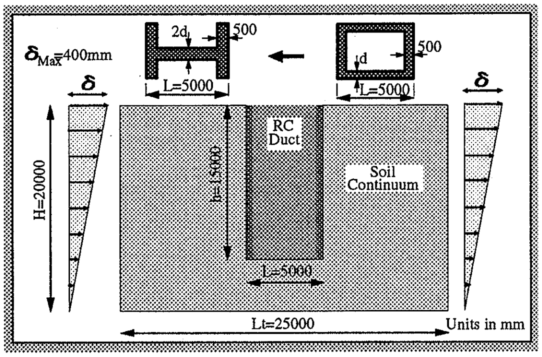


Fig. 11 Target structure (RC vertical duct) for parametric study

In this analysis, a normalized shear displacement (δ/H) is applied incrementally up to a maximum of 2.0% or failure. The mechanical properties of the surrounding soil are represented by initial shear stiffness (G_s) which varies from a very week soil (10 MPa) to a very stiff one (200 MPa). Accordingly, the nonlinear shear stress-strain relation of the soil is modified according to Ohsaki model[10] (**Fig.1**). The structural rigidity of RC, as represented by the ratio of thickness to wall length (d/L), is varied from 0.025 to 0.3. The reinforcement ratio of the RC structure is assumed to be 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 to be a perfect bond and no shear slip is allowed. This is a severe condition as regards RC failure.

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

From the results of the authors' analysis[5], the failure interaction diagrams of RC underground structures are obtained for different reinforcement ratios, as shown in **Fig.12**. These charts are drawn for the maximum (2.0%) normalized shear displacement of the surrounding foundation.

In every chart, the X-axis represents the initial stiffness of the surrounding soil and the Y-axis represents the rigidity of the structure in terms of (d/L). The hatched areas A and B represent structures which fail in tension and compression failure modes, respectively. Hatched area C represents wall thicknesses less than the minimum wall thickness allowed by the present code[2]. Above these areas, hatched areas from 1 to 8 represent different RC damage levels 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 in the chart (2%), but with a different crack opening and damage level. These interaction diagrams were obtained from about 60 cases of parametric analysis.

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

Changing the reinforcement ratio causes little change in the boundary of the structural failure zone because the strength of RC increases with increasing reinforcement ratio, while at the same time the induced force level in the structure is also elevated proportionally.

The effect of reinforcement ratio can be discussed also by looking at points (I) and (II) in each diagram in **Fig.12**. Consider first the points (I) in **Fig.12.** Different damage levels arise for different reinforcement ratios under the same soil condition and structure rigidity (Gs = 80 Mpa; d/L = 0.15) as shown by points (I). It is clearly seen that at points (I) the damage level is controlled by the reinforcement ratio. In the case of points (II), the damage level is constant for the same soil condition. In this case, there are several choices of equal damage level all of which satisfy the safety requirement. Stiff structures with lower reinforcement ratio (low ductility in the post-yield zone) or flexible structures with higher reinforcement ratio (high ductility) can be selected.

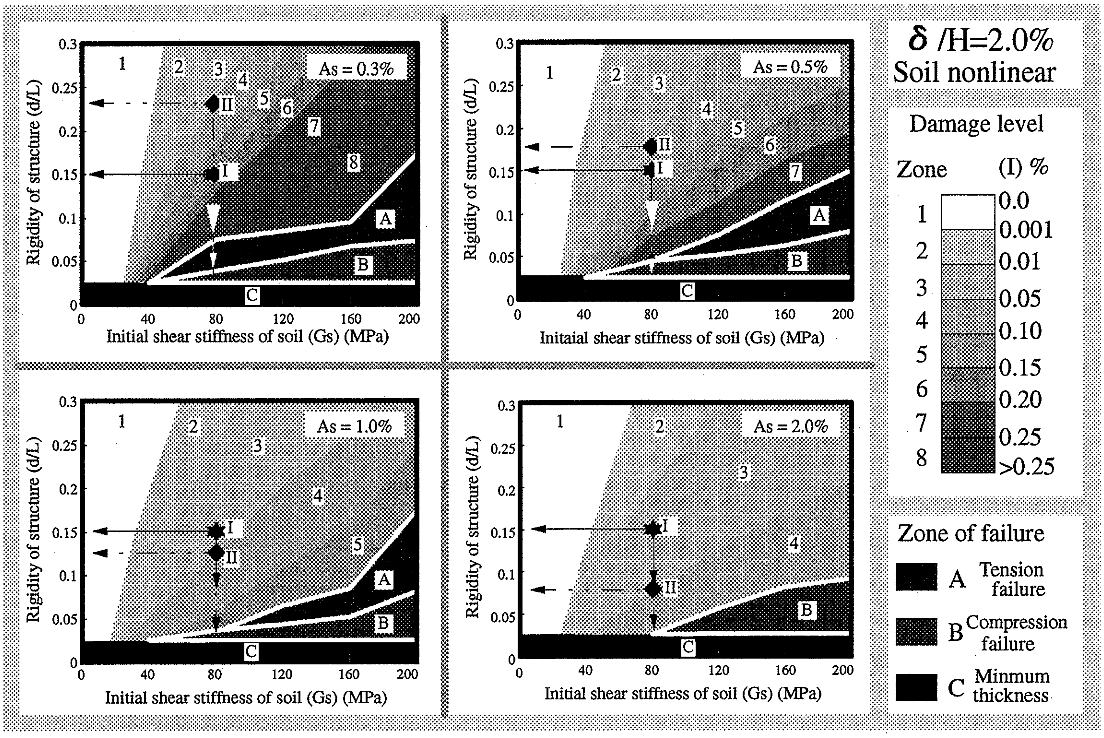


Fig. 12 Failure interaction diagram of underground RC duct surrounded by soil under 2% forced shear deformation

If the dynamic soil pressure were specified irrespective of the structural ductility, design-based decisions would tend to lead to stiffer structures with lower ductility and reinforcement ratio. However, consideration of material nonlinearity results in a variety of choices for different structural stiffness with different reinforcement ratios. Choice of the proper combination depends on several functional considerations which need to be checked, such as water tightness, leakage, and serviceability.

(3) Seismic analysis for the target structure

Based on RC nonlinear finite element analysis for dynamic and cyclic loads[12)], the full path-dependent constitutive models for soil[8)] and the interface between RC and soil[8)] are installed in the computer code **WCOMD-SJ**[7)]. This gives the advantages of a full path-dependent model, 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, a maximum normalized shear displacement of 2% could be unrealistic for high values of soil stiffness, so in this section the maximum normalized shear displacement is evaluated according to the stiffness of the soil by conducting a dynamic analysis of the entire RC/soil system. The dimensions and finite element mesh of the target structure, which is a simple model of an RC underground vertical duct (H=15.0 m) with a square box section (10.0m x 10.0m), are shown in **Fig.13**. The purpose of choosing this type of structure is to link the static interactions discussed in the previous section with dynamic ones in order to obtain a full evaluation of the interactions between the in-plane underground structure and surrounding soil under shear.

Since the discussion of static kinematic interactions revealed that in-plane underground RC structures offer greater safety if sufficient ductility is provided, harsh conditions were intentionally assumed to produce severe damage and hence investigate the effects of the stiffness of surrounding soil. Accordingly, a thin wall (thickness/wall span = 1/36, which is approximately the minimum allowable thickness specified by JSCE code[2)]) with a low reinforcement ratio (0.5%) was selected.

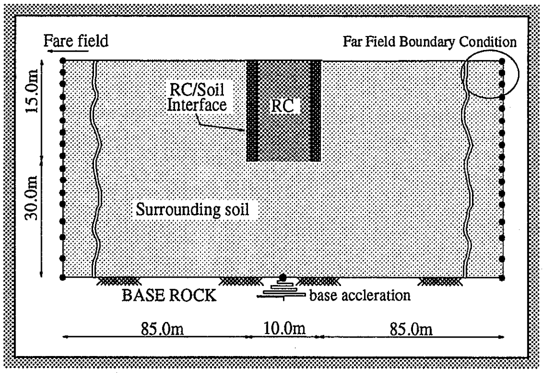


Fig. 13 Overview of underground structure surrounded by soil domain

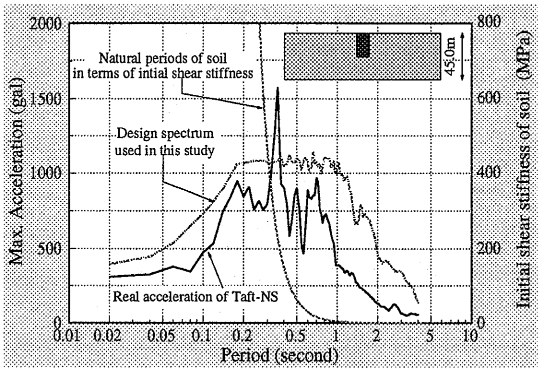


Fig. 14 Acceleration response spectrum used in the analysis and natural period for soil layer

The initial stiffness of the 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 the soil is modified based on the soil model$^{7)}$. Furthermore, the maximum shear displacement of the soil in terms of initial shear stiffness can be directly estimated under seismic loads to check the value assumed in the static analysis discussed previously (maximum normalized shear displacement =2.0%).

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

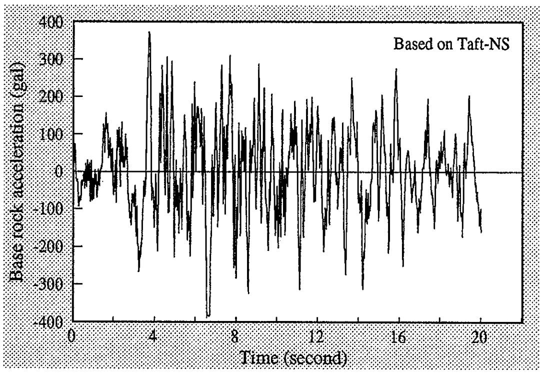


Fig. 15 Base rock acceleration based on design spectrum

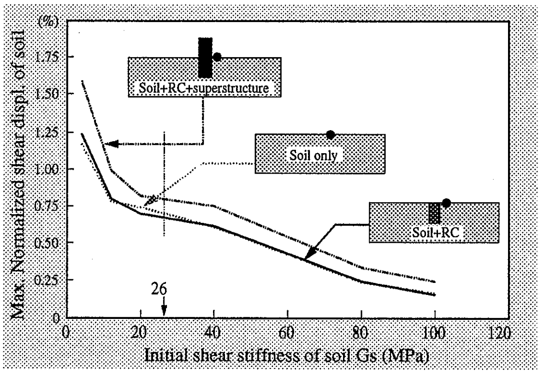


Fig. 16 Maximum response displacement of soil in terms of initial shear stiffness of soil

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

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

Concerning the maximum shear displacement of the soil layer, **Fig.16** shows the relation between initial shear stiffness of the soil and the maximum normalized shear displacement during ground acceleration. As a general trend, the maximum normalized shear displacement decreases as the stiffness of soil increases.

Since the maximum normalized shear displacement was taken to be 2.0% in the static analysis, regardless of the stiffness of the soil, the dynamic failure interaction diagram shown in **Fig.17** is much changed from that shown in **Fig.12** when the maximum shear displacement is based on the relation shown in **Fig.16**.

Regarding the stiffness of soil and structure, it can be concluded that in-plane underground structures will survive severe seismic action with different levels of damage and cracking dependent on the ductility of the structure concerned (reinforcement ratio and wall thickness). Therefore, in designing underground RC structures for seismic shear, the reinforcement ratio and wall thickness -- which correlate closely to member ductility -- should be regarded as controlling factors of structural soundness and serviceability. It is suggested that they are more critical than the safety requirement.

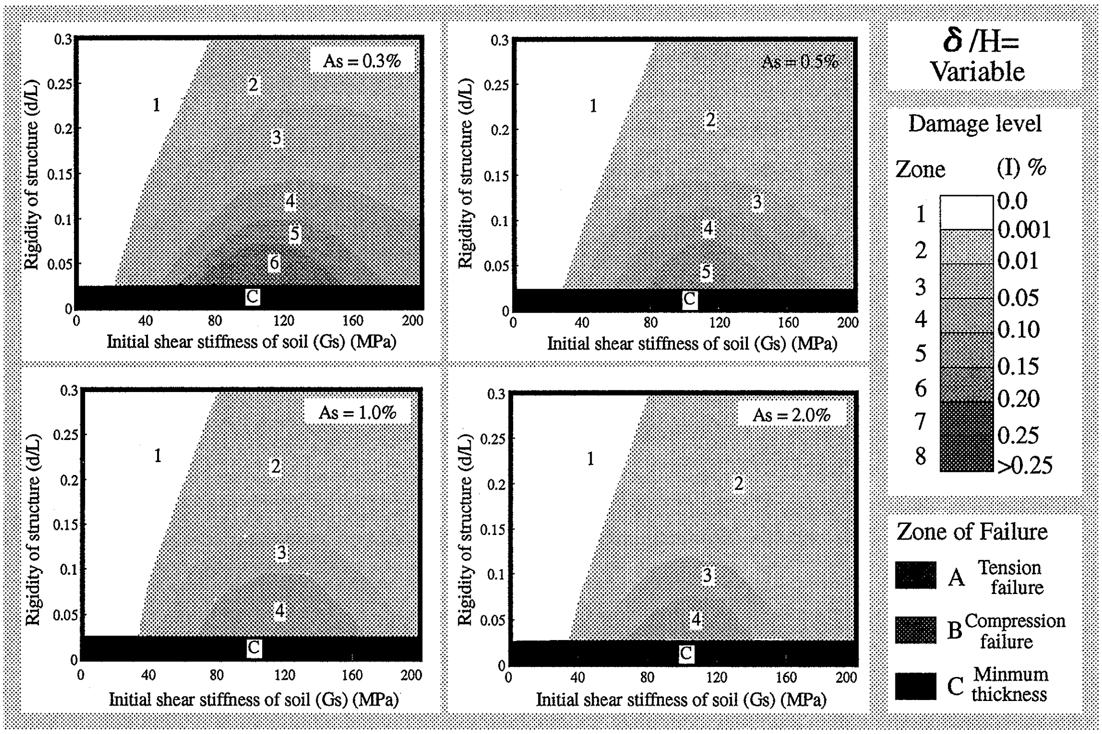


Fig. 17 Modified failure interaction diagram of underground RC duct surrounding by soil under dynamic shear deformation

7. CONCLUSIONS

Based on the parametric study and analytical investigation presented in this paper, the following general conclusions are reached as regards the safety of and damage to underground structures.

1. The nonlinear characteristics of both reinforced concrete and soil cannot be ignored if realistic behavior and response are to be determined for RC underground structures.
2. The rigidity of the structure and the surrounding soil are closely linked as regards selecting on RC thickness. However, under present design practice, the minimum thickness of a structure is computed based on the earth pressure, which is taken as constant and independent of structural stiffness.
3. The reinforcement ratio barely affects the safety of underground structures examined here because both the ultimate capacity and the induced force from surrounding soil increase with the amount of reinforcement. The load applied to underground RC structures depends on the characteristics of the structure itself.

4. Damage level and crack conditions are mainly controlled by the reinforcement ratio and the stiffness of the surrounding soil. Therefore, the reinforcement ratio must be chosen chiefly in terms of the required functionality and serviceability of the underground structure.
5. In most cases, owing to the coupled nonlinear kinematics, the structural safety of in-plane underground structures is assured under seismic loads, though with different damage levels, as long as the minimum level of ductility is ensured.

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