論文 An Idea of Modelling Soil-RC Duct-type Structure Interface under Seismic Loads

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ABSTRACT: Dynamic finite element analysis is carried out for CRIEPI's shaking tests of RC box-culverts embedded in laminar boxes filled with sand. By introducing an idea of using soil elements with reduced shear stiffness to model the interface zone between soil and structure, very good numerical results are achieved compared to the experimental ones. The idea is proved to be effective by consistent successes in predicting dynamic response for various cases of the tests.
KEYWORDS: Soil-structure interaction, Dynamic finite element analysis, Interface, Seismic design

1. INTRODUCTION

One of the crucial civil engineering structures in a nuclear power plant is underground reinforced concrete duct-type structure for accommodating emergency services such as cooling water pipes, intake water structures, etc. Seismic resistant design, being the main concern for this type of structures has been conducted considering non-linear behaviors of soil and reinforced concrete. However, it has been realized that to better rationalize the design procedure, interaction between soil and structures must be duly considered [1].

The amazing failure of a subway station in Kobe due to the Great Hanshin Earthquake in 1995 initiated a strong impetus for more rigorous study on the soil - underground structure interaction. Some researchers have remarked again the necessity of the soil-structure interaction in analysis [4]. Recently, as an extended research to revise the seismic design of the duct-type structures, dynamic tests of large scaled models of RC box-culverts embedded in laminar sand boxes have been conducted by Abiko Research Laboratory of CRIEPI. The scope of the experiments is divided into 2 parts: Preliminary Test and Main Test. One of the targets of the tests is to clarify the interactive behavior between soil and the duct-type structure both analytically and experimentally.

This paper reports the dynamic finite element analysis of the interactive system of soil and RC box-culverts of the experiments, focusing on the effects and modeling of soil-structure interaction. Conventionally, interaction between soil and the underground structure has been modeled by interface elements with zero thickness and linear stiffness [4], which appears to be quite cumbersome for practical calculation. In this paper, an idea of directly using the soil element with reduced shear stiffness to simulate the interface zone is proposed. This way modeling of the interface appears simple, more realistic; easier to implement and also gives very good calculated results. The effectiveness of the proposed interface is confirmed via consistently successful prediction for all cases of the Tests at which the RC box-culverts reach the stage of yielding of reinforcing steels.

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2. ANALYSIS FOR THE PRELIMINARY TEST

2.1 MODELING

The FEM code COM3 Version 9.2 developed by the Concrete Laboratory of the University of Tokyo [2] is used. The 3-D FEM mesh of the Preliminary Test is established as depicted in **Fig.1**. Input acceleration is a kind of sinusoidal wave at 3Hz as in **Fig. 1(c)**. The RC specimen is a single-box culvert. The mechanical properties are listed in **Table 1**. The thickness of the side walls and the upper slab is 6cm and 10cm, respectively. Dimensions of the culvert are depicted in **Fig.1**. More detailed description of the set-up of the Test can be found in Suehiro et al. [5].

Non-linear dynamic behavior of RC and soil is incorporated. Elasto-Plastic and Fracture model and Smeared Crack model are constitutive models for reinforced concrete before and after crack occurrence, respectively [3]. These models have been proved to be effective by many successful applications elsewhere [2]. The RC element can be modeled as the standard 20-node isoparametric solid element. However, since the problem in this paper is apparently 2-dimensional, a 16-node element is used, neglecting the 4 nodes at the middle in the Z direction as depicted in **Fig. 1(a)**. Number of Gauss points is 8 per element. Soil element is also modeled as the 16-node isoparametric element. The shear constitutive model of soil is made up from Ohsaki's skeleton curve (see [4]). Soil (sand) properties varying with the depth H, including initial shear modulus G_0 and shear strength S_u, which are necessary for input, are typically listed in **Table 2**.

The laminar shear box appears to have considerable effect in this test [5]. Modeling of the laminar box is thus necessary and shown in **Fig. 1(b)**, in which the properties of the elastic column are determined equivalent to the laminar box in terms of mass and shear stiffness.

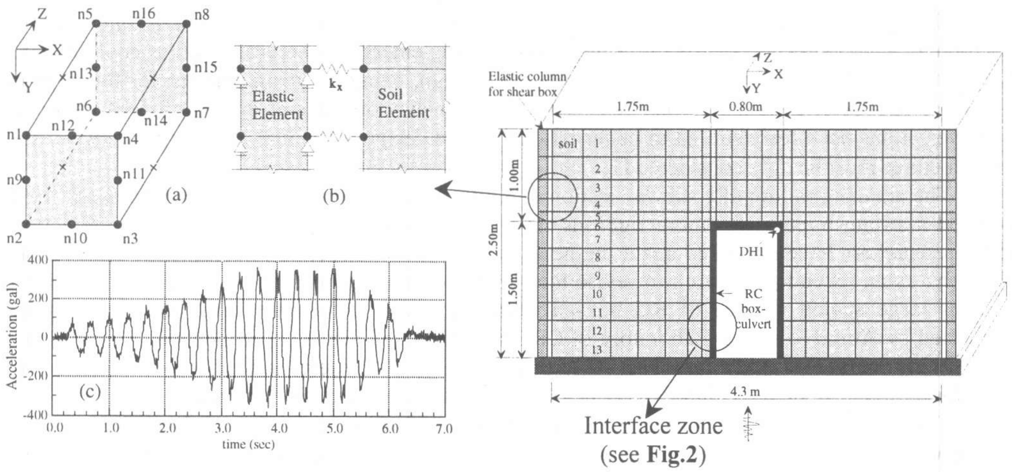

Figure 1 FEM Mesh of Preliminary Test **(a)** Isoparametric element for RC and soil; **(b)** Modeling of the laminar box; and **(c)** Time-history of excited acceleration

Dynamic interaction between soil and structure is the process of transmitting kinematic energy through the interface of the two media. It was thought [4] that due to the interaction, the separation and shear slippage between soil and structure most likely occurred along the interface. The conventional modeling [4] of the interface is therefore as in **Fig.2(a)**. The Interface Element is a zero-thickness element with linear in-plane shear stiffness and linear opening stiffness. The compressive stiffness is set at very high value as default to avoid overlapping. Such modeling was proved effective, however, renders the establishment of FEM mesh and the calculation quite cumbersome, and to a certain extent, is at odds with observation in experiments.

An idea of modeling the interface is proposed as depicted in **Fig.2(b)**. To simulate the interaction, the stiffness of soil elements near the RC culvert's wall surfaces is reduced, and hence named as 'stiffness-reduced soil element' (hereafter refers to as 'SRS element'). This idea comes up from observation in the experiments that the separation and slippage between the soil and the RC walls do not occur concentrating at the surface of the walls. Instead, the interaction appears to spread out in a certain region of the soil near the wall, and is characterized by a large shear deformation in this region due to the interactive action between the RC specimen and the massive surrounding soil.

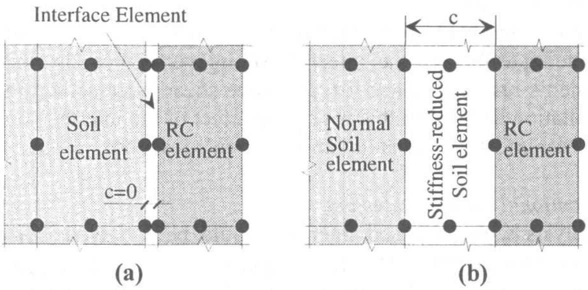

Fig.2 Modeling of interface zone: **(a)** Conventional way [4]
(b) Proposed idea: Stiffness-reduced soil element

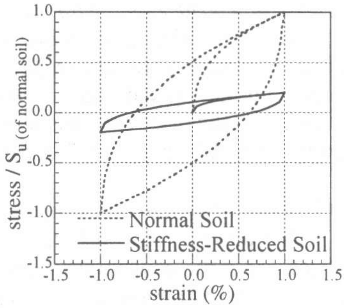

Fig. 3 Comparison of hysteretic curves of soil

As a try to model this kind of interface, the shear strength S_u of the soil elements directly contacting with the two vertical walls of the RC culvert is reduced by a factor of 5 (see **Table 2**). The thickness of the SRS element is c=10cm. This reduced factor is resulted from a parameter study for a good prediction of the response, as will be shown later. The implementation of this interface is quite simple, straightforward and very easy in the FEM mesh generating process. A comparison of hysteretic loops of the normal soil element and the SRS element with the reduced factor of 5 is plotted in **Fig.3**. Note that when reducing the shear strength, the hysteretic curve of SRS element may exceed the specified failure strain of 1%. Fortunately, the Ohsaki's skeleton curve adopted in COM3 can continue mathematically to higher strain with very small and almost linear stiffness, so that the hysteretic curve still can be employed, and seemingly well simulated the interface behavior.

2.2. RESULTS AND COMPARISON

(a) *Effect of the proposed interface along the walls*: Two cases of calculation are made as follows,

Case 1: without interface, i.e. the normal soil element links to the RC element

Case 2: with the proposed interface by SRS elements along vertical walls of the RC specimen.

Dynamic analysis of the system is carried out with time step of 0.01 sec. Input acceleration is as in **Fig.1(c)** with maximum value of 366 gal. This is the shaking step where the yielding of rebars in the RC specimen occurred. The response time histories of point DH1 in terms of its relative displacement to the base for the 2 cases are shown in **Figs. 4** and **5**, respectively. When the interface is not considered, the response is much smaller than the experimental one as presented in **Fig.4**. Introduction of the proposed interface leads the calculated response to a very good agreement with experimental result as shown in **Fig.5**. Especially, the quick growth of the response at around t=3sec is very well captured. The prediction of yielding of the rebars is therefore in excellent agreement with observation in the Test in terms of position and occurrence order, as presented in **Table.3** and **Fig.6**.

The reason of the improvement in calculated response is thought as follows. Through a usual FEM modeling scheme without interface consideration, the FEM mesh as in Case 1 is usually stiffer than the actual system, resulting in underestimating the response and smaller response frequency than the experimental. Introduction of the interface along the two walls of the RC specimen in Case 2 makes the system more flexible, and thus the response becomes better simulated. The more flexibility of the system comes up from the reduction of the shear stiffness of the SRS element in vertical direction, which allows larger strain developing in the interface zone than that in Case 1.

Fig.7 present a parameter study for the effect of the Reduced Factor on the RC specimen's response. The index value for comparison is the 'steady-state peak-to-peak' response, which is the oscillation amplitude between negative and positive peaks of the cycle in the time range from 4.3 to 4.7 sec., where the system oscillation has reached its steady state. The reduced factor of 5 then can be seen as the least value to provide good calculated results being well within 5% error from the experimental. Higher values can also be used, but they would not give much difference in the results.

(b) *Effect of interface on the top slab of the RC specimen*

The same idea of modeling interface is extended to the interface zone on the top slab of the specimen. Contrary to the response-enhancing effect of the interface along vertical walls, the interface on the top slab reduces the specimen's response, since it reduces the shear force acting on the top slab. However, up to the level of excitation handled in this paper, the effect of the interface on the top slab is still small, causing only 4.6% decrement of the maximum specimen's response.

(c) *Comparison with analysis using the conventional interface element*

Almost the same results as the analysis with proposed interface could be achieved from analysis using the conventional interface instead along the walls of the specimen as seen in **Fig.8**. The linear shear stiffness of the conventional element in this case is set equal to zero. The opening stiffness, however, must be set high enough about 10^3 kgf/cm^2 to avoid numerical divergence.

3. ANALYSIS FOR THE MAIN TEST

The proposed interface modeling along the walls of RC specimen by SRS elements with reduced factor of 5 – the same as that in the above analysis for the Preliminary Test - is applied to analyze 2 cases of the Main Test, at which the yielding of rebars occurred. The two cases are (a) Fixed Case at maximum acceleration of 225 gal, and (b) Floated Case at maximum acceleration of 223 gal. Input acceleration for both cases is a scaled version of the Great Hanshin Earthquake. Components of the system are modeled similarly to those of the Preliminary Test. The RC specimens are double-box culverts. Thickness of the walls and upper slab is 10cm. Non-linear behavior of the sand in this Test was expressed by Ramberg-Osgood model, which is incorporated in COM3 by modifying the code. The FEM meshes for the two cases are shown in **Figs.9** and **10**. More detailed description and calculated results will be reported in other occasions. Hereafter only the effect of the proposed interface is pointed out. The results of relative displacement to the specimen's base at point DH11 are presented in **Figs.11** and **12** for each case, respectively. It is interesting that the consistent manner of calculated results due the effect of the proposed interface can be achieved: the analyses without interface implementation insistently underestimate the response; and the analyses with the proposed interface always give very good calculated results compared to the experimental ones.

4. CONCLUDING REMARKS

An idea of modeling the interface between soil and underground RC duct-type structures has been introduced and proved to be effective for analysis of interactive soil-structure system through consistently successful predictions for both Preliminary and Main Tests. The idea would be very useful for practical analysis. The interface is made up by simply reducing the shear strength of soil elements directly attached to the RC structures to reduce the shear stiffness of the soil in the interface zone. Some concluding remarks are made as follows;

(a) Implementation of the interface with reduced shear stiffness is crucial to achieve good simulation of the response, not only in terms of the amplitudes, but also of the dynamic behaviors.
(b) The proposed interface modeling has the equivalent effect with the conventional interface. However, the proposed interface is much simpler, easier to implement and appears more realistic.
(c) Effectiveness of the proposed interface modeling has been proved valid up to the level of excitation at which the rebars in the RC specimen yield. More investigations on the proposed interface's performance at higher excitation level are in progress.

Table 1 Material properties of RC Box-culvert

Con-crete	Young's modulus (MPa)	2.64E+04
	Comp. strength (MPa)	36.14
	Tensile strength (MPa)	3.15
Rebar	Young's modulus (MPa)	2.0E+05
	Yield strength (MPa)	378.3
	Reinforcement ratio of walls (%)	0.84 (in Y) 0.84 (in Z)
	Reinforcement ratio of upper slab (%)	1.0 (in X) 1.0 (in Z)

Table 2 Soil (sand) properties

Layer (Fig.1)	H (m)	G_0 (MPa)	S_u (KPa)	$S_u / 5$ (KPa)
1	0.15	8.86	7.0	1.4
3	0.65	20.14	12.0	2.4
5	0.95	24.90	15.0	3.0
7	1.20	28.39	18.0	3.6
9	1.60	33.35	22.0	4.4
11	2.00	37.79	26.0	5.2
13	2.40	41.85	30.0	6.0

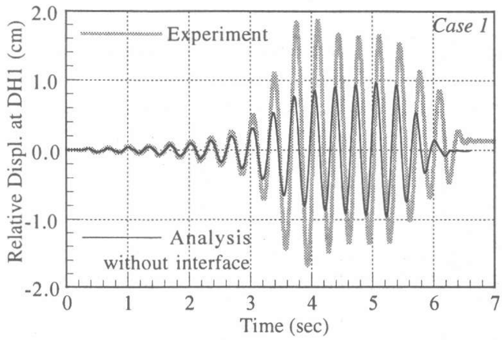

Fig. 4 Calculated response of RC specimen when interface is not considered

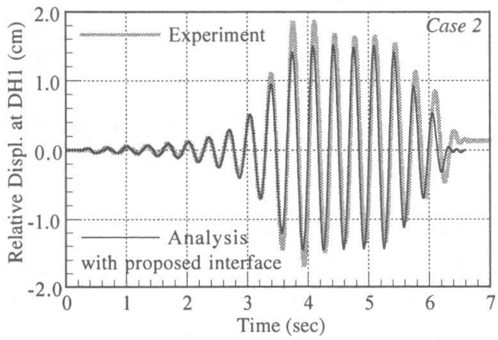

Fig. 5 Calculated response of RC specimen when the proposed interface is implemented

Table 3 Yielding of reinforcing steels (rebars)

Yielding position and time order	Time of yielding (sec)		DH1's Relative Dis--placement (cm)	
	Exp.	Ana.	Exp.	Ana.
1	3.38	3.37	1.048	0.896
2	3.54	3.53	-1.006	-0.907
3	3.55	3.54	-1.153	-1.019
4	3.72	3.70	1.488	0.988

Note: 'Exp.' is 'experiment', 'Ana.' is 'analysis'

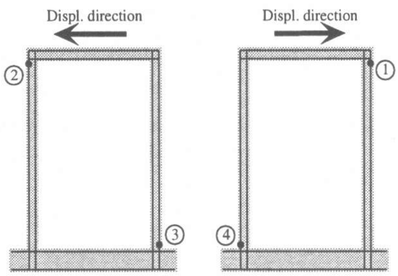

Fig. 6 Positions & time order of the yielding

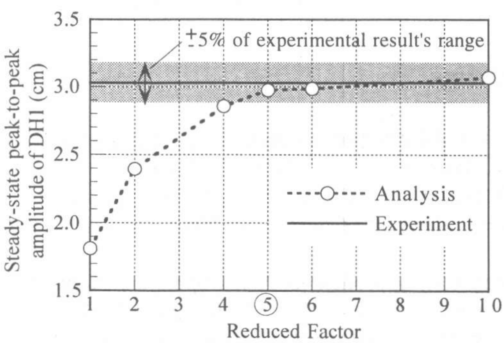

Fig. 7 Effect of the Reduced factor for the shear strength of SRS element on the result

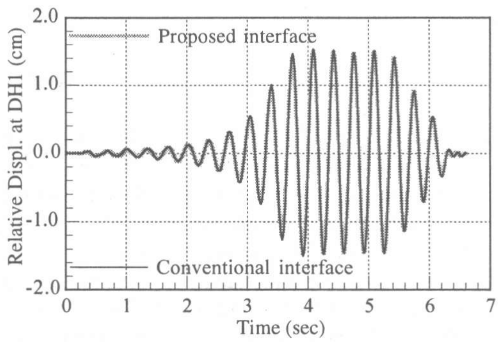

Fig. 8 Comparison of analysis results by the Proposed & Conventional Interface

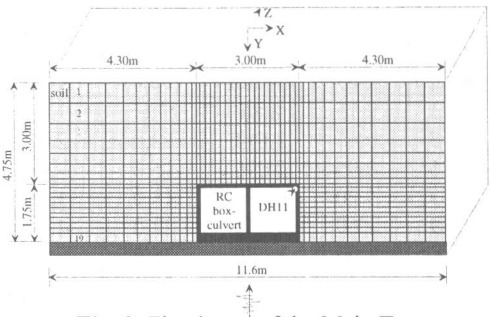

Fig. 9 Fixed case of the Main Test

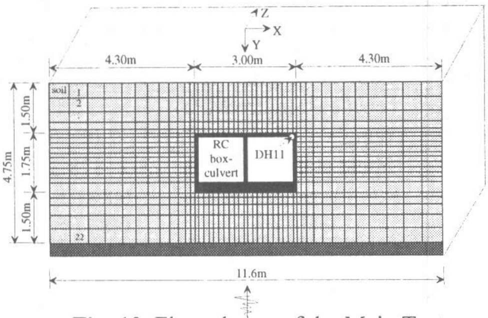

Fig. 10 Floated case of the Main Test

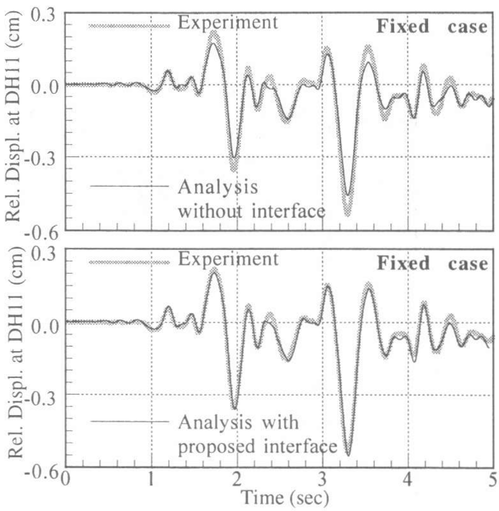

Fig. 11 Effect of interface in calculated response of the RC specimen in the Fixed case

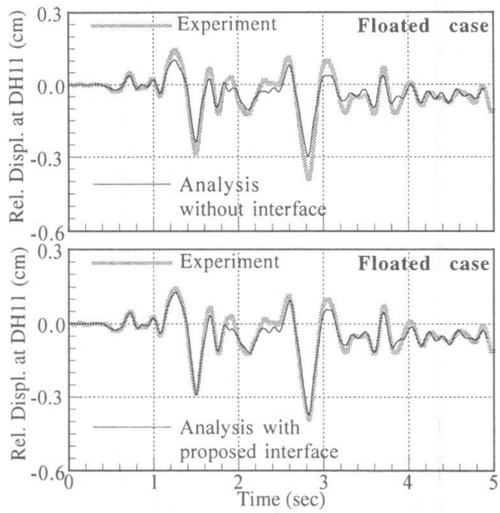

Fig. 12 Effect of interface in calculated response of the RC specimen in the Floated case

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