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Experimental Study on Soil-Structure Interaction of Underground Reinforced Concrete Ducts Subjected to Earthquake Loading

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ABSTRACT

It is of importance to design earthquake resistant underground reinforced concrete structures such as ducts for accommodation of emergency cooling water pipes, taking due account of interaction between soil and structures. In the present study two 1/4 scale section models for reinforced concrete ducts were embedded in a box filled with dry sand and subjected to simulated earthquake loading through the reversed shear deformation of soil. Experimental results showed that the post-cracking and also post-yielding non-linear behaviors of the structures play a marked role in reducing the load to be considered in design. Experimental results are compared with non-linear FEM analysis, taking the material non-linearity into account.

1. INTRODUCTION

Reinforced concrete ducts for accommodating emergency cooling water pipes (abbreviated as R.C.D.E below) are generally embedded under ground. Aseismic design of these structures has hitherto been conducted considering the non-linear properties of soil. In order to rationalize the design procedures for R.C.D.E it seems to be of cardinal importance to take into account also the non-linearity of reinforced concrete structures combined with the effects of interaction between the two structural components.

In this paper the results of the tests are described, in which 1/4 models of double box R.C.D.E were subjected to staticaly simulated earthquake loading in a sand box. Also, a numerical simulation was conducted to help interpret the experimental results.

2. EXPERIMENTAL PROCEDURES

2.1 Experimental apparatus

Reinforced concrete scaled models of R.C.D.E were embedded in a sand box in which dried sand was filled(Fig-1). The structural model was subjected to reversed shear deformations indirectly through the deformation of sand fill. To simulate the surcharge steel ingots were placed on the surface of sand.

2.2 Test specimens

Two one-fourth scale models were constructed, changing the axial

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reinforcement ratios(Fig-2).

2.3 Instrumentation

Measurements were made on the deformations of models and the strains in concrete and reinforcements. Also, normal as well as shear earth pressure measuring devices were attached to the specimens. All the loading and recording procedures were controlled by a micro computer.

3.EXPERIMENTAL RESULTS

3.1 Overall behaviors

Fig-3 shows the relationships between the top displacements of the loading bulkheads of the sand box and the total load. The symmetry of load-displacement loops is seen almost completely preserved. A typical spindle configuration of loop at initial stage shifts to a shear-slip loop at the later loading stage. This indicates the effect of increasing non-linearity with the increment of shear strain in sand.

3.2 Deformation modes of the models

Displacements of No-1 duct model are depicted in Fig-4. The displacements seem to be composed of the three modes : that is, translational horizontal movement, downward sinking and shear deformation.

Fig-5 shows the relative shear deformations between upper and lower slabs of the models versus average shear strain in the sand box. It can be seen that the shear rigidity of the lower steel model (No-1) deviates from the initial value at relatively small displacement stages, while that of the higher steel model with haunches retains its initial value up to larger displacement stages. The phenomena infer that the relative shear stiffness of the structure and the soil plays an important role in determining the mechanical behaviors of embedded duct type structures.

3.3 Cracking patterns

Main cracks appeared in the vicinity of the corners of the models(Fig-6).Due to the reversals of loading almost all the cracks penetrated through the section. For both the models the first cracks were confirmed at the shear deformation levels of around 1/1000 in the top and bottom regions of the partition wall. The cracks occurred in the order of partition walls, bottom slabs, top slabs and side walls.

3.4 Earth pressures acting on the models

In Fig-7 measured values of normal earth pressure acting on the side wall of No-1 model are drawn as a function of shear deformation of the sand box. Two comparatively distinct turning points are recognized. One is the point at the sand displacement of around 5mm and the region ranging from 10 ~ 15mm, which correspond to the initial cracking and the yielding in reinforcements, respectively. The same tendency could been seen in the results of shear earth pressure measurements on the top slab. The earth pressure measurements also support the importance of appropriate assessment of relative shear rigidities between soil and structures.

4.ANALYTICAL INVESTIGATIONS

Numerical analyses were conducted to simulate the earth pressures acting on the periphery of the models.
Basic assumptions were as follows :
① Forced displacements are given to the inner face of the duct as well as to the sand box.
② Non-linear constitutional equations are employed in an increment strain analysis.
③ The interface between soil and structure is represented by thin elements, which possess the same stiffness as that of soil and fail in shear according to Coulomb's failure criteria.

An example of comparisons between analytical and experimental values for normal earth pressure is shown also in Fig-7, which may indirectly justify the validity of the experiment.

5.CONCLUSIONS

Following conclusions could be summarized within the limit of the experimental study :
① Section forces in the embedded duct type structures are reduced due to non-liniarities both in the soil and in the structure, being superimposed by their interactions.
② Basic assumptions as well as analytical procedures employed in the numerical analysis were confirmed in the light of comparisons with the experimental results.
③ The shear deformations of the R.C.D.E models, at which the first yielding in steel occurred, far exceeded the corresponding design values, which were obtained by the procedures stipulated in the drafted design guidelines(Table-1). This may suggest that the proposed design method will result in a safer side.

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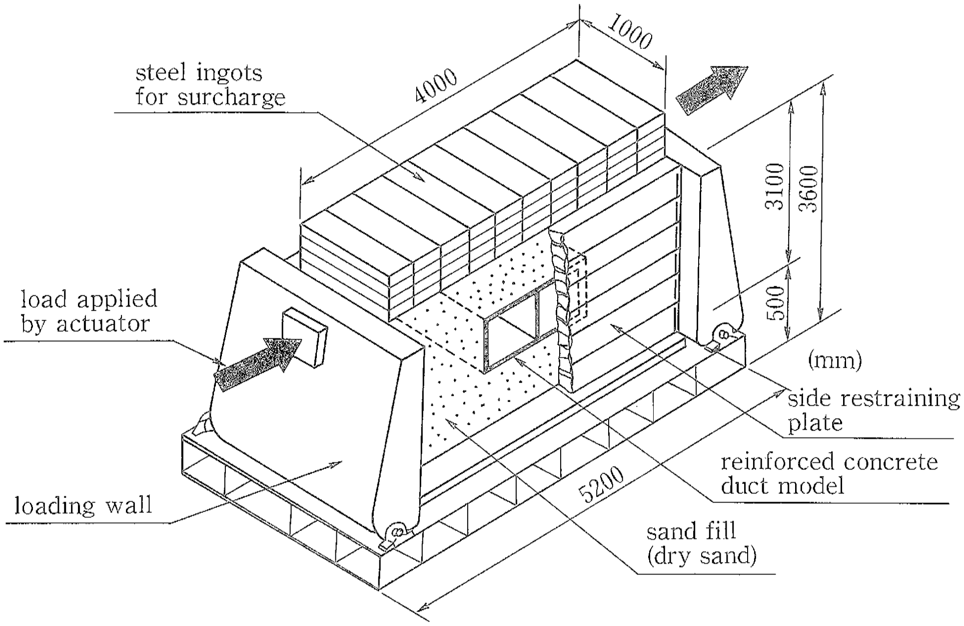
REFERENCE

Y.Aoyagi, T.Endo and K.Iida "Cross sectional design of reinforced concrete ducts for accommodation of emergency cooling water pipes" Transactions of 9th SMiRT Volume A pp171 ~ 176, Lausanne 1987

Y.Aoyagi and T.Endo "Lateral deformational behaviors of double box reinforced concrete ducts for emergency cooling water pipes" Transactions of 10th SMiRT Volume H pp101 ~ 106, Los Angeles 1989.



dimensions of sand box ; height 3m, length 4m, width 4m.
maximum top displacement ; 30mm(shear strain 1/100)
loading unit ; dynamic hydraulic actuator 2units,
maxmum capacity 50tons.

Fig-1 Sand box for testing interaction between soil and embedded reinforced concrete structures during earthquake.

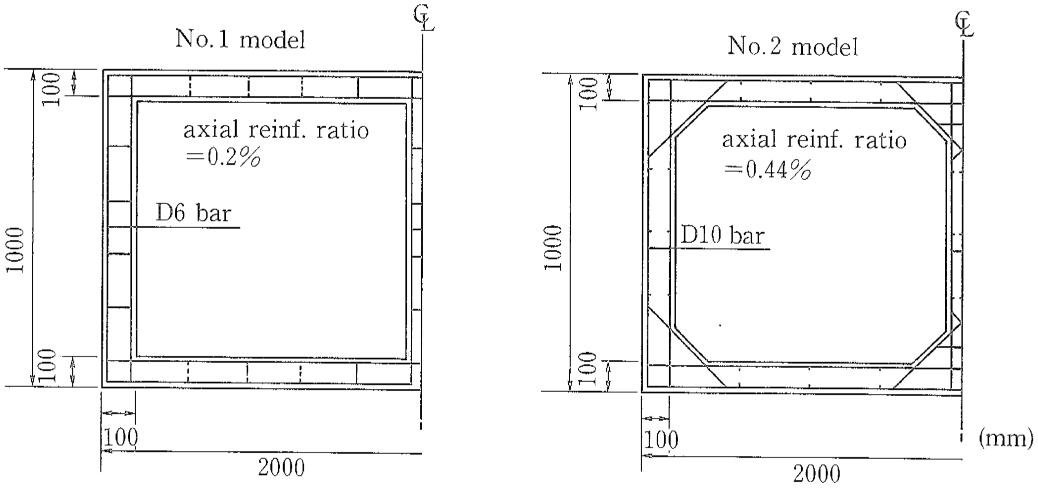


Fig-2 Section properties of the models

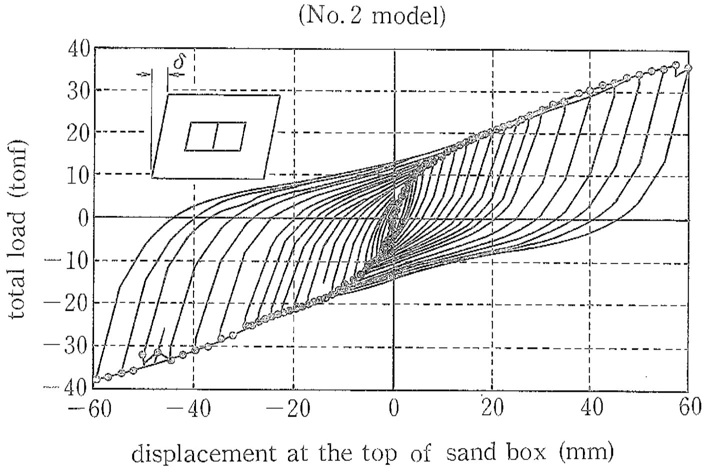


Fig-3 Relationships between total loads and displacements at the top of the sand box

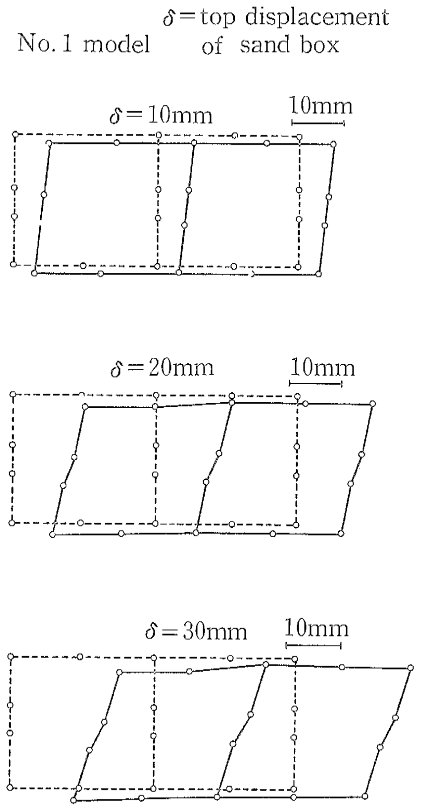


Fig-4 An example of displacement and deformation modes.

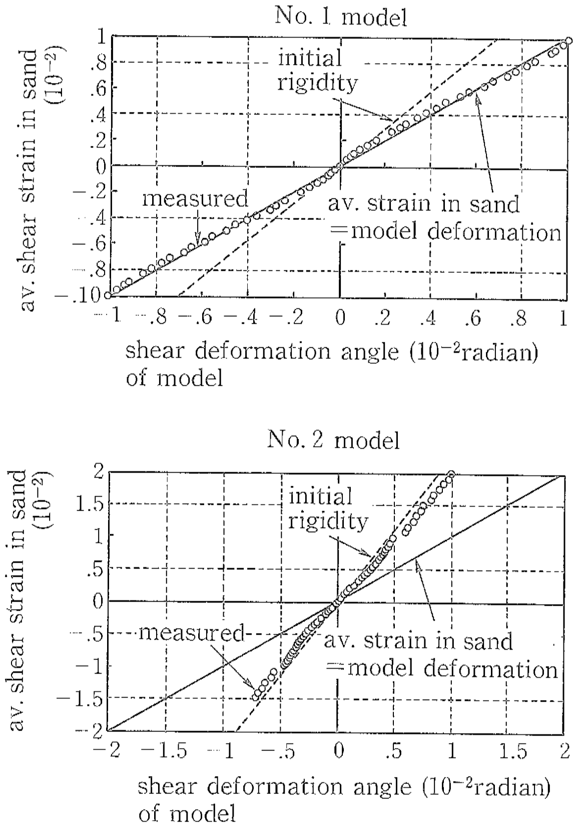


Fig-5 Measured shear deformation angle versus average shear strain in sand.

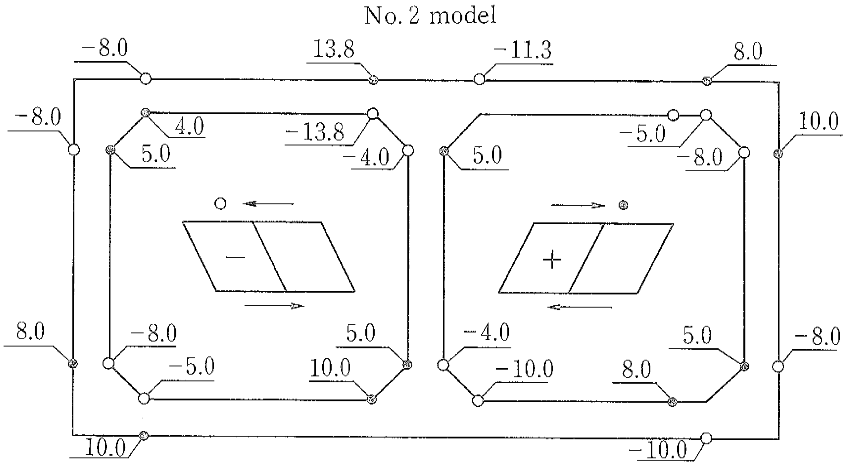


Fig-6 Sand box deformations at the initiation of cracks.

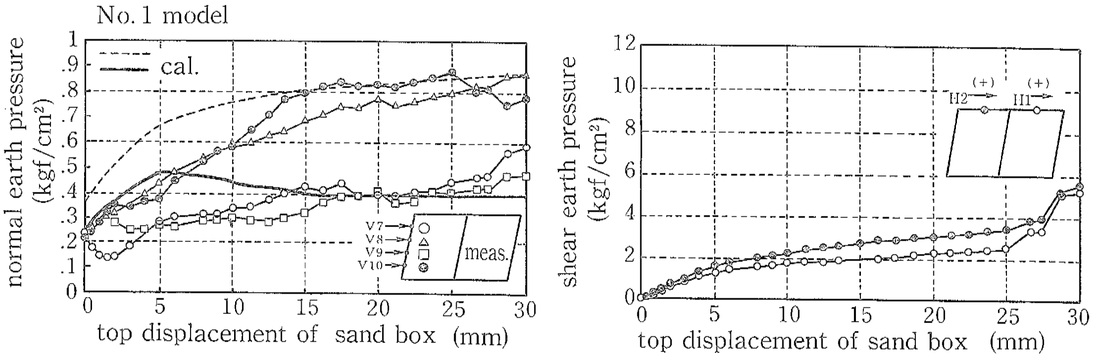


Fig-7 Measured normal and shear earth pressure versus top displacement of sand box.

Table-1 Comparisons of design and measured relative shear displacements of the models at which first yielding of steel occurs.

No of the model	design displacement (mm)	Measured displacement (mm)
No. 1 low reinf. ratio	5．5	8．0
No. 2 high reinf. ratio	13．0	30．0