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Development of distributed hybrid experimental system of coupling 1G-40G fields for soil-foundation-structure interaction

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Abstract

In this research, distributed hybrid experimental system of coupling 1G-40G fields is developed to consider soil-foundation-nonlinear structure interaction. Static loading test on nonlinear structure on 1G field and pile foundation on 40G field are connected by computer, then this computer conducts seismic response analysis by applying results of static loading tests. From comparison with this experiment, another hybrid experiment and numerical analysis, it revealed that developed hybrid experimental system works well and it can be evaluate soil-foundation-nonlinear structure interaction.

Keywords: hybrid experiment, shake table test, soil-foundation-structure interaction, centrifuge

1. Introduction

Soil-foundation-structure interaction (SFSI) has great influence on the response of structural system during earthquake. Because of this fact, many experimental or analytical researches are attempted to evaluate SFSI.
For example, Nishimura[1] conducted shake table test for soil-pile foundation-RC column system on 1G field to discuss the relationship between nonlinearity of RC column and SFSI during earthquake. As a result, the fact that influence of kinematic interaction can be stronger than that of inertia interaction when RC column shows nonlinear behavior was revealed. Boulanger[2] conducted shake table test by using centrifuge. Comparing experimental result with reproduce analysis of experiment, interaction springs between pile and soil are developed. Penzien[3] modeled soil-foundation-structure system as concentrated mass system to make formularization of equation of motion easier. Then calculation speeds become faster than previous numerical model.
Large scale shake table test can evaluate precise seismic response of structural system because real scale specimen is used. On the other hand, experimental scale is so huge that experiments can't be conducted repeatedly. Centrifuge test can make smaller the structural system. Then the scale of experiment becomes smaller and many times of experiments is able to be conducted. While nonlinear behavior of soil can be evaluated quite precisely, that of superstructure is very hard to reproduce. Numerical analysis is another method of evaluating SFSI. In numerical analysis, real scale model is considered easily. However, if constitutive laws or parameters used in numerical model are invalid, results of analysis become meaningless. Hence constitutive laws or parameters should be selected considerably carefully.
To deal with these problems, Takahashi[4] developed experimental system, called "hybrid experiment with centrifuge". The objective of this research was showing the validity of experimental system, so superstructure was assumed as linear elastic. Shake table test was also conducted in centrifuge to compare with hybrid experiment. From these results, it was clarified that developed experimental method can evaluate vibration phenomena of structural systems.
In this paper, another new hybrid experimental system named "distributed hybrid experiment with centrifuge" is developed and discussed. This experimental system is developed to evaluate the nonlinearity of superstructure. In experiment, RC column is assumed as superstructure. Experiment is conducted with connecting RC column on 1G field and pile foundation by computer and the validity of this experimental system is discussed.

2. Hybrid experiment and distributed experiment

2.1 Hybrid experiment

Hybrid experiment is the method of evaluating seismic response of the structural system with combining model test and numerical analysis. Fig.1 shows concept of hybrid experiment. Structural system is divided into a few subsystems. Model test is conducted on elements which show complex nonlinear behavior because these elements are generally very difficult to describe by numerical model. Other parts of structural system are modeled in client computer. Then, load-deformation relationship of each time step can be gain from model test. This nonlinear characteristic is used in seismic response analysis in client. Hybrid experiment can evaluate seismic response of structural system having complex nonlinear elements without constructing monolithic large scale model.

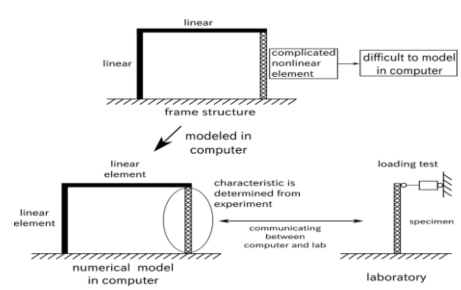

Fig. 1 – Concept of hybrid experiment

2.2 Distributed experiment

Distributed experiment is defined as experimental system of determining behavior of structural system with conducting experiments on some geographically separated places, and experimental data is communicated by using network. In distributed experiment, the structural system is divided into smaller structural system. Only data communication system is needed on each experimental site to communicate sites each other, experiments on each substructure system can be conducted depending on its capacity.

By using distributed experimental system, behavior of structural system can be evaluated with experiments on smaller subsystems. Moreover, if the model scales are different subsystems each other, distributed experiment must be used. Takahashi et. al. [5] conducted distributed experiment with connecting Japan and America to evaluate seismic response of L-shaped RC column.

2.3 Similitude rule

Similitude rule has a great effect on model test. Similitude rule of shake table test on 1G field, hybrid experiment and experiment in centrifuge is confirmed and applicability of similitude rule to "hybrid experiment with centrifuge" is discussed by Takahashi[4].

Equation of motion on 1G field is described as follows.

$$M_p \frac{d^2 x_p}{dt_p^2} + C_p \frac{dx_p}{dt_p} + R_p = -M_p \frac{d^2 u_{gp}}{dt_p^2} \tag{1}$$

In equation, subscript p means prototype, m means model. M , C , R mean mass, damping and reaction force each. x means response displacement of structural system and u_g means displacement of input motion. Prototype scale and model scale is characterized as follows by using coefficient α .

$$\begin{aligned} x_p &= \alpha_l x_m, \qquad & u_{gp} &= \alpha_l u_{gm} \\ t_p &= \alpha_t t_m, \qquad & M_p &= \alpha_m M_m \\ R_p &= \alpha_r R_m, \qquad & C_p &= \alpha_c C_m \end{aligned} \tag{2}$$

α_l, α_m, α_r, α_c mean similitude ratio of length, mass, force and damping. From () and (), () is gained.

$$\left(\frac{\alpha_m \cdot \alpha_l}{\alpha_t^2}\right) M_m \frac{d^2 x_m}{dt_m^2} + \left(\frac{\alpha_l \cdot \alpha_c}{\alpha_t}\right) C_m \frac{dx_m}{dt_m} + \alpha_r R_m = -\left(\frac{\alpha_m \cdot \alpha_l}{\alpha_t^2}\right) M_m \frac{d^2 u_{gm}}{dt_m^2} \tag{3}$$

This equation is equivalent to () if all of coefficients are the same in (). Thus,

$$\left(\frac{\alpha_m \cdot \alpha_l}{\alpha_t^2}\right) = \left(\frac{\alpha_l \cdot \alpha_c}{\alpha_t}\right) = \alpha_r \tag{4}$$

If the scale factor is defined as $1/n$, α_l becomes n. Assuming that model and prototype are consisted of the same material, α_m becomes n^3. To satisfy geometric similarity, the surface ratio is n^2 and $\alpha_r = n^2$ in condition that stress ratio is same as prototype and model scale.

() is not satisfied in shake table test because acceleration ratio α_l / α_t^2 is fixed as 1. Owing to this fact, another mass is put on structural model to make $\alpha_m = n^2$ to satisfy similitude rule. By the way, Strain rate of material is ignored at hybrid experiment or centrifuge experiment, load R is the same as static load. Thus, $\alpha_r = n^2$ can be satisfied. From (), relationship showed below is derived.

$$\alpha_t^2 = \frac{\alpha_m \cdot \alpha_l}{\alpha_r} = n^2 \qquad \therefore \alpha_t = n \tag{5}$$

Acceleration ratio is described as follows.

$$\frac{\alpha_l}{\alpha_t^2} = \frac{1}{n} \tag{6}$$

In centrifugal field, similitude rule is satisfied due to centrifugal force acting on experimental model. In hybrid experiment, only displacement x and reaction force R are communicated between computer and experimental

setup, mass M and time t are only given to computer. Satisfying similitude rule, stress of model and prototype are fit by actuators.
Table.1 shows calculated similitude ratios. From this discussion, the same similitude ratio can be used between hybrid experiment and centrifuge experiment.

Table 1 – Similitude ratio

	Similitude ratio (prototype/model)		
	centrifuge	Hybrid experiment	1G shake table test
Length	N	N	N
Mass	N^3	N^3	N^3
Stress	1	1	1
Acceleration	N	N	1
Time	N	N	$N^{0.5}$
Frequency	$1/N$	$1/N$	$N^{-0.5}$

3. Distributed Hybrid Experiment witn Coupling 1G-40G Fields

3.1 Concept of distributed hybrid experiment

Fig.2 shows developed hybrid experimental system in this paper, named “distributed hybrid experiment with centrifuge”. In this system, soil-foundation-structure system is modeled as 2 DOF system in client computer. Characteristics of these two springs at each time are determined from static loading tests on superstructure and pile foundation. Using results of static loading tests, seismic response analysis is conducted.
In seismic response analysis, the follow equation is solved.

$$\begin{bmatrix} M_s & 0 \\ 0 & M_f \end{bmatrix} \begin{Bmatrix} \ddot{x}_s \\ \ddot{x}_f \end{Bmatrix} + \begin{bmatrix} C_s & -C_s \\ -C_s & C_s + C_f \end{bmatrix} \begin{Bmatrix} \dot{x}_s \\ \dot{x}_f \end{Bmatrix} + \begin{Bmatrix} R_s \\ R_f \end{Bmatrix} = -\begin{Bmatrix} M_s \\ M_f \end{Bmatrix} \ddot{u}_g \tag{7}$$

R_s and R_f mean restoring force of superstructure and pile foundation determined from static loading tests.
Static loading test on superstructure is conducted in Katsura Campus, Kyoto University on 1G field and used specimen is prototype scale. The experimental result is passed from Katsura Campus to client computer at Uji Campus, Kyoto University by using Internet. Static loading test on pile foundation is conducted in centrifuge at Uji Campus and used specimen is small model. When experimental data is communicated between client and experiment system of pile foundation, control displacement and acquired force of pile foundation should be converted according to similitude rule because equation of motion is solved by using real scale parameters.

Fig.3 shows the flowchart of loading test on pile foundation. Displacement $x_f(t)$ is given to specimen and restoring force $R'_f(t)$ is measured. Then $R'_f(t)$ is converted as real scale value $R_f(t)$. Using this $R_f(t)$, client computer calculates the next step displacement $x_f(t+1)$. $x_f(t+1)$ is converted as model scale value and given to pile foundation, then restoring force $R'_f(t+1)$ is acquired. The nonlinearity of soil in experiment can be taken into account in term of $R'_f(t+1)$ by iterating this operation. Moreover, using centrifuge, the smaller pile foundation can be used compared to prototype scale.
In this hybrid experimental system, OpenFresco[6, 7] and OpenSees[8, 9] are used. OpenFresco is the hybrid simulation framework and OpenSees conducts numerical analysis.

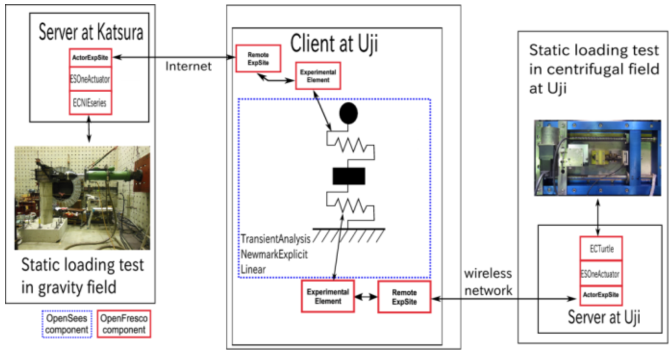

Fig. 2 – Distributed hybrid experiment with centrifuge

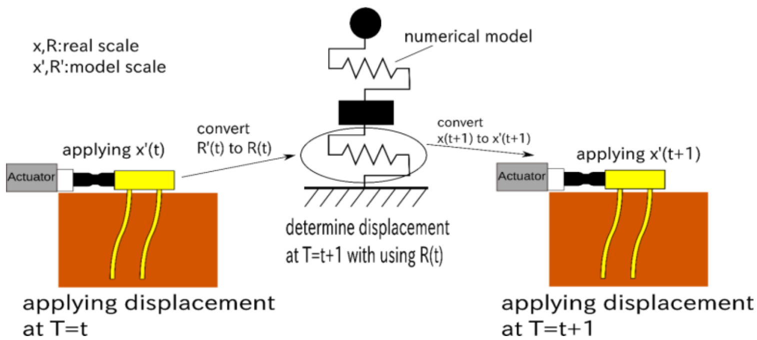

Fig. 3 – Flowchart of static loading on pile foundation during hybrid experiment

3.2 Target Model

Fig.4 shows soil-foundation-structure system considered in this paper. To evaluate the nonlinearity of superstructure, RC column is applied. This RC column is assumed that its height is 1600mm, section is 320mm square and weight of mass is 10.1 t.

Footing is assumed that its height is 2000mm, section is 2000mm square and its weight is 80.64t. Piles are assumed that its length is 7200mm, section is 200mm×400mm, ground depth is 6400mm and piles keep elastic during vibration.

Input motion is shown in Fig.5. This wave was observed at Hyogo-ken Nanbu Earthquake.

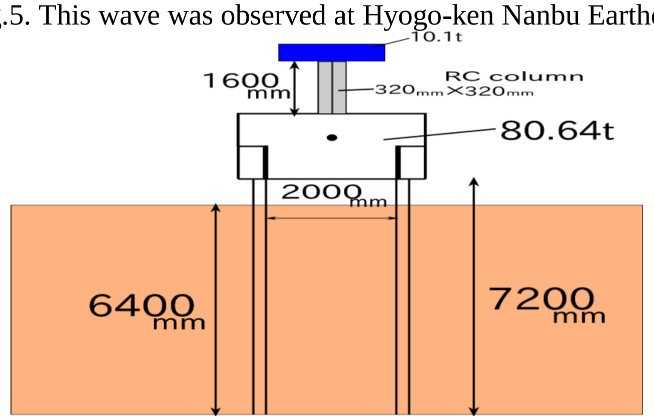

Fig. 4 – Targetted soil-foundation-structure system

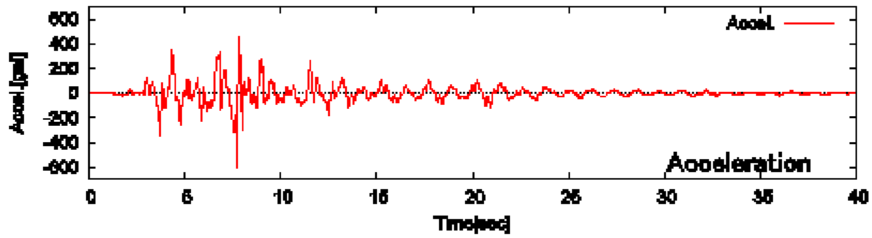

Fig. 5 – Input acceleration

3.3 Structural model of RC column and experimental setup

The detail of RC column used in this experiment is shown in Fig.6. The height of RC column is 1800mm. This column is consisted of RC part and jigs for loading.
The height of RC part is 1370mm, its section is 320mm square. 16-D10 main reinforcement is inserted and D4 tie foops are put at 40mm pitch. Intermediate foops are put at the center of section. Height of jigs are 430mm and these are fixed at the top of RC part. This RC column is fixed on the ground by using footing shown in left of Fig.6.
Nominal strength of concrete is 24N/mm^2, slump value is 12cm, the maximum size of coarse aggregates is 15mm. Result of compressive strength test is 30.49 N/mm^2.
Right of Fig.6 shows experimental setup for RC column. Load is applied by actuator at jigs, so loading point become 1600mm from the bottom of RC column. Swivel head is used for preventing that moment is generated during loading test. Weight of superstructure is applied by axial force installed by prestressing steel bars. Applied axial force on each steel bars are 50kN, thus RC column has 10.1t mass at the top of column.

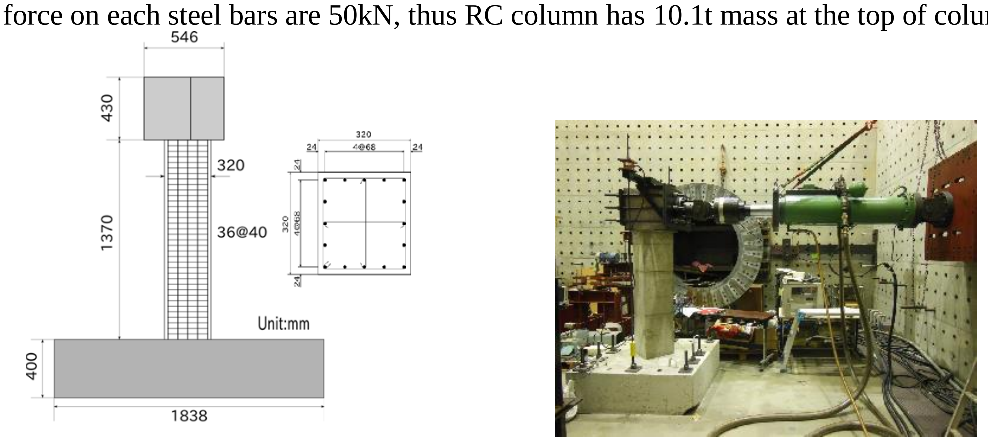

Fig. 6 – Detail of RC column and static loading system

3.4 Structural model of pile-soil system and experimental setup

Pile models used in this experiment has 5mm×10mm section, 200mm length and are made of phosphor bronze. Weight of pile is 0.00801kg in model scale. In prototype scale, each pile has 5.13t weight. To fix piles and footing, the net length of piles become 180mm in pile foundation. Pile tips are also fixed at base.
Fig.7 shows footing and piles. Height of footing is 30mm, section is 50mm×72mm and weight is 0.7655kg.
The size of soil tank used in experiment is 450mm×150mm×300mm and its boundary is fixed. Soil foundation is made of dried silica sand. The depth of soil foundation is 160mm.
Fig.7 also shows the detail of loading test on pile foundation. To apply displacement from actuator to footing, another block is put on the footing. Displacement of footing is measured by laser displacement transducer. Strain gauges are put on each pile to measure strain of pile.
Static loading test is conducted in centrifuge at Uji campus. Centrifugal acceleration is kept 40G during experiment.
In this experiment, loading direction for pile foundation is restricted only horizontal. Moreover, because mass of footing is set on numerical model in client computer, mass of footing model used in centrifuge has no influence on experimental result.

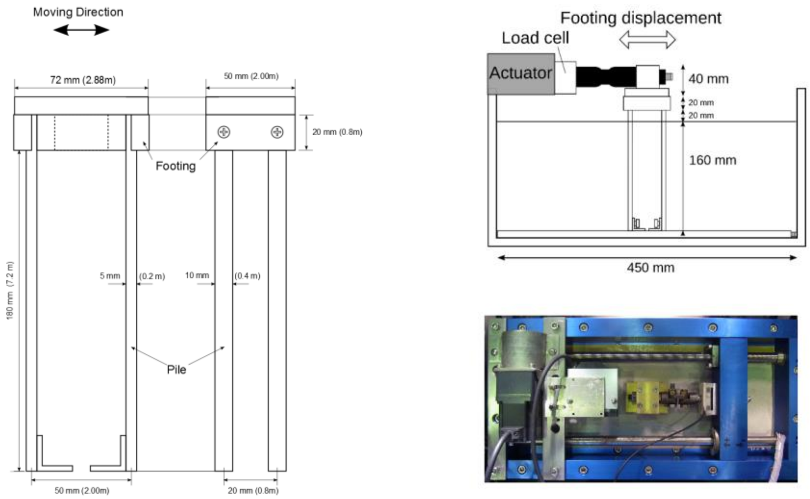

Fig. 7 – Detail of pile foundation and Static loading system

3.5 Preliminary experiment

Developed experimental system needs to conduct distributed experiment. Thus, "hybrid experiment with centrifuge" is conducted as preliminary experiment to verify the validity of distributed experimental system.
Fig.8 shows preliminary experimental system. The same soil foundation-pile system and experimental equipment are used between preliminary experiment and developed hybrid experiment. On the other hand, RC column is described as fiber element in client computer. Thus, preliminary experiment is conducted on locally.

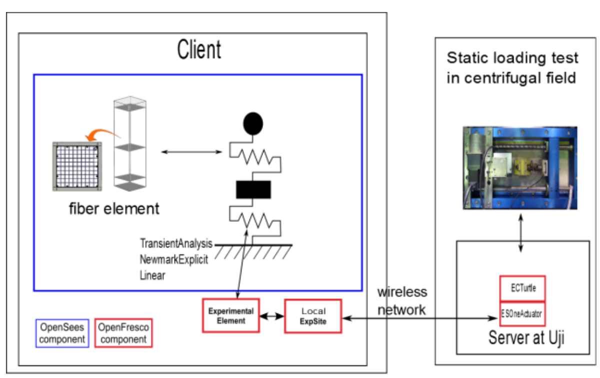

Fig. 8 – Preliminary experimental system

5.6 Preliminary analysis

Developed experimental system needs to connect 1G field and 40G field. Thus, to verify its validity, a numerical analysis is conducted as preliminary analysis.
Fig.9 shows numerical analysis model. Material parameters are used in analysis model. Pile is described by beam element, soil movement is ignored and interaction spring[2] is applied between pile and soil. In real vibration problem, soil movement should be considered. However, soil movement isn't considered in developed hybrid experimental system in this paper. Thus, soil movement isn't considered in preliminary analysis for fitting conditions between experiment and analysis. This analysis model is constructed by 1G prototype scale.

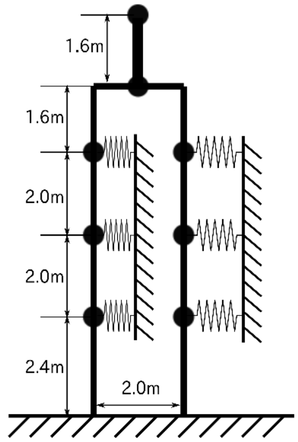

Fig. 9 – Preliminary analysis model

4. Results of distributed hybrid experiment and discussion

Fig.10 shows displacement time series of developed hybrid experiment and preliminary analysis. Displacement of RC column is defined as relative displacement between top of column and footing, and that of footing is defined as relative displacement between footing and base. Fig.11 shows load-deformation curves of RC column and footing. Load of RC column is derived from inertia force of RC column and that of footing is derived from sum of inertia force of RC column and footing. Except for negative response and stiffness of RC column, responses of RC column and footing show good agreement.

Considering that all elements of preliminary analysis model are constructed on 1G prototype scale and 1G field and 40G field are connected in developed hybrid experiment, the system of connecting 1G field and 40G field works well.

Fig.12 shows displacement time series of developed hybrid experiment and preliminary experiment, Fig.13 shows load-deformation curves of RC column and footing and Fig.14 and Fig.15 show moment distribution of pile of two experiments. Similar to consideration of preliminary experiment, except for negative response and stiffness of RC column, responses of RC column and footing show good agreement. Moreover, moment distribution of pile has also no difference between two experiments. From these results, distributed experimental system is working well. Hence, it can be said that combining distributed experimental system and the system of connecting 1G field and 40G field is possible.

Buckling of main reinforcement is considered as a main reason of difference of RC column displacement and stiffness among distributed hybrid experiment, preliminary analysis and preliminary experiment. In general, buckling causes reduction of stiffness of RC column and it has great influence on the ultimate behavior of RC column. However, it is quite difficult to describe buckling phenomenon by analytically because of its complexity. In developed hybrid experiment, the complex nonlinear behavior of RC column can be considered by conducting model test.

Analysis time step of developed hybrid experiment is 3.65×10^{-3}, this is equal to that of input motion. As a result, 20 seconds vibration phenomenon is reproduced by spending about 6 hours, which is very close to the test duration of preliminary experiment. Thus, experiment speed of developed hybrid experiment is equivalent to previous hybrid experiment with centrifuge.

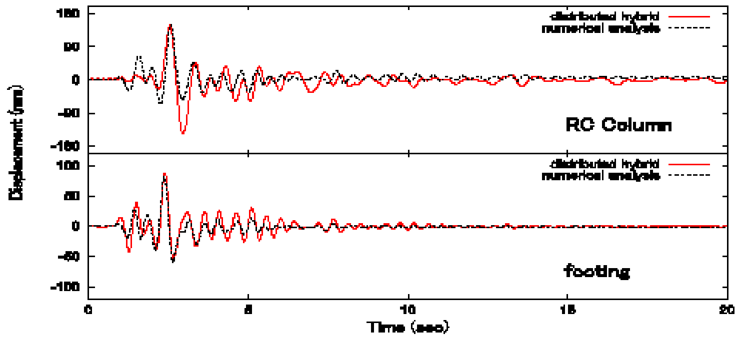

Fig. 10 – Displacement time series of distributed hybrid experiment and preliminary analysis

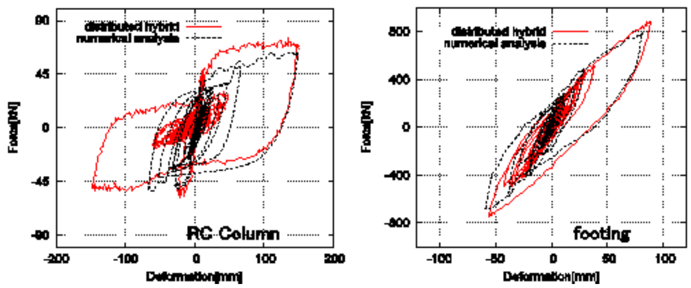

Fig. 11 – Load-deformation curve of distributed hybrid experiment and preliminary analysis

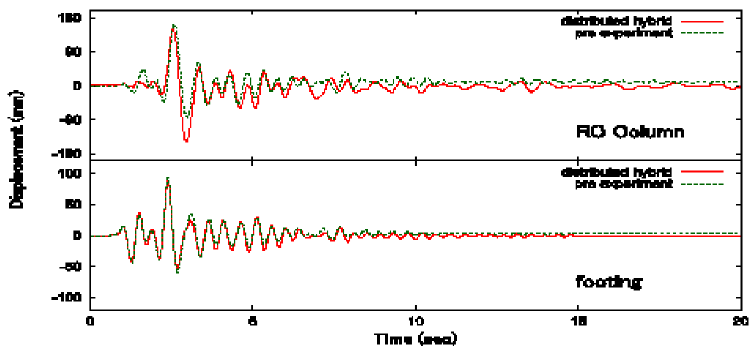

Fig. 12 – Displacement time series of distributed hybrid experiment and preliminary experiment

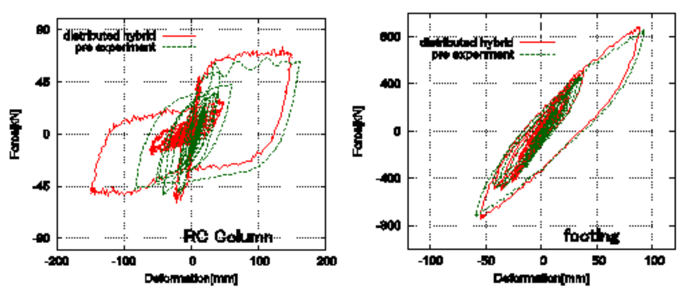

Fig. 13 – Load-deformation curve of distributed hybrid experiment and preliminary analysis

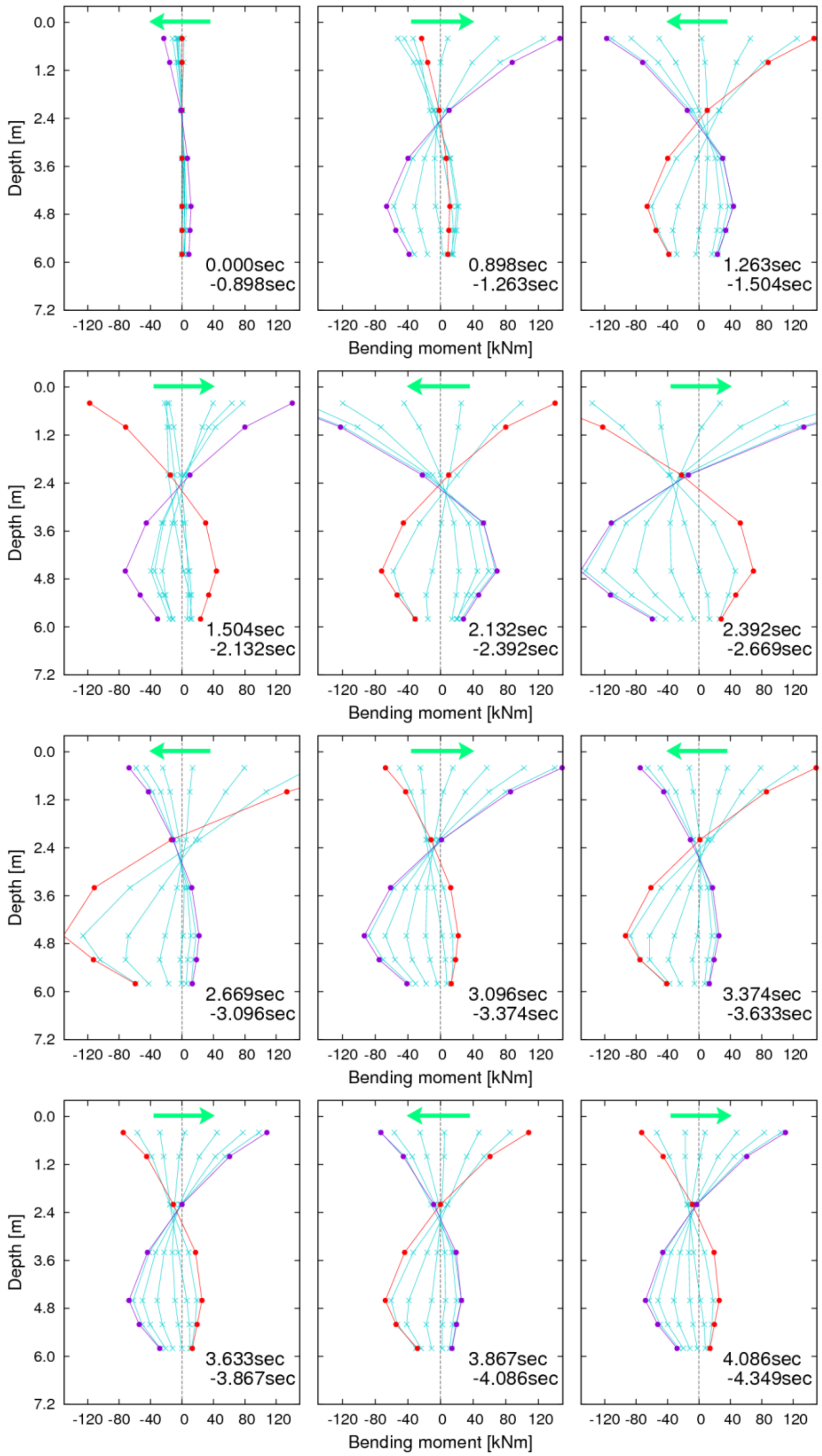

Fig. 14 – Moment distribution of pile (developed experimental system)

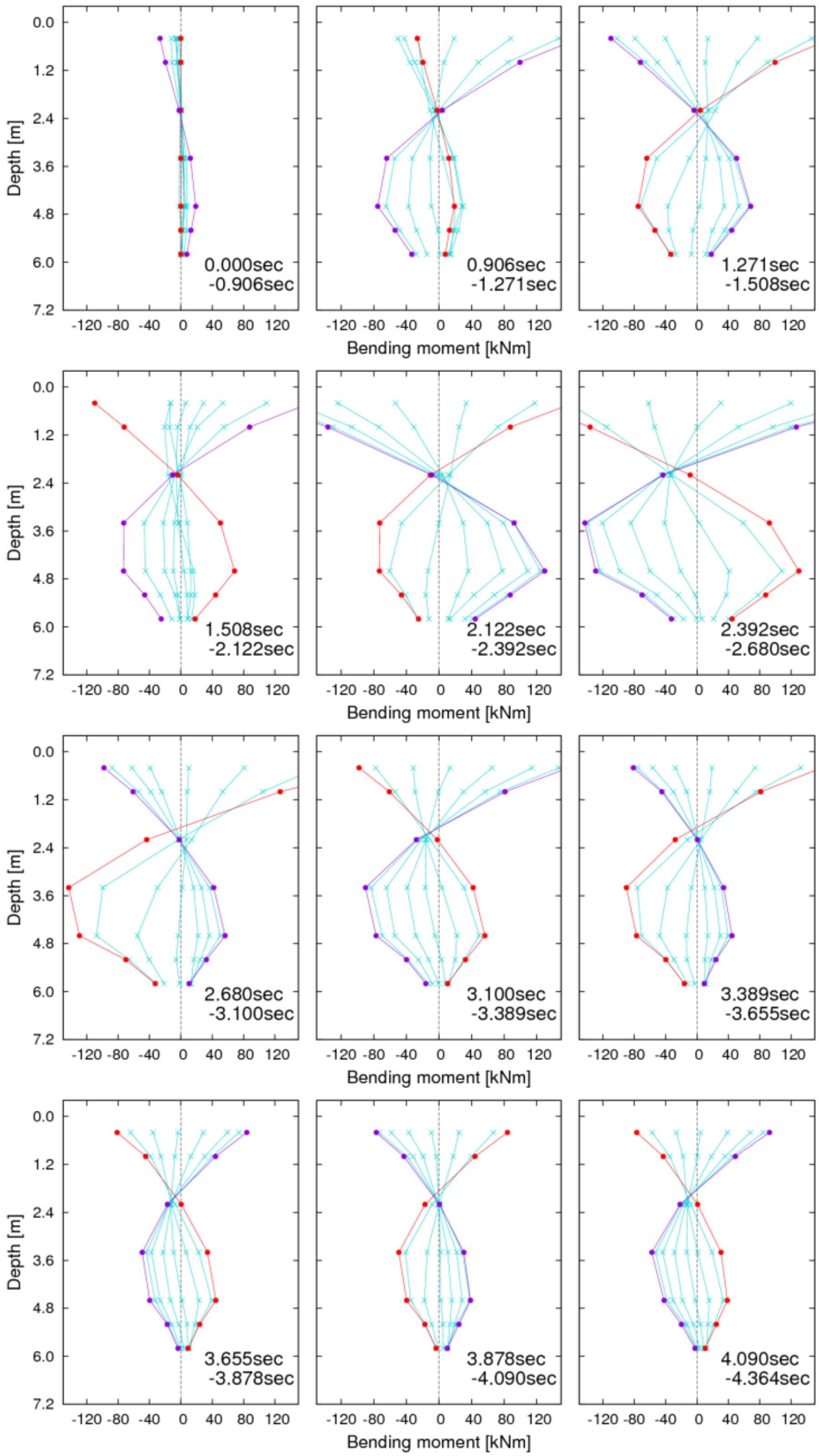

Fig. 15 – Moment distribution of pile (preliminary experiment)

5. Conclusion

In this paper, new hybrid experimental system named "distributed hybrid experiment with centrifuge" is developed. This experimental system has the system of connecting 1G field and 40G field. Experiment is conducted by setting RC column at Katsura campus and small pile foundation model at Uji campus. During experiment, the Internet is used for data communication.

Compared to preliminary experiment and analysis, it revealed that distributed experimental system and system of connecting 1G field and 40G field work well and combining these two experimental system is possible. Furthermore, this experimental system can evaluate buckling or rapture of steel reinforcement, which is very difficult to describe by numerical analysis, and continue experiment stably in spite of complex nonlinear behavior.

Only sway movement is assumed in this consideration. However, the influence of rocking can't be ignored in real structure. Hence, it is needed to clarify whether this experimental system is applicable when foundation form is changed and rocking motion is large.

Soil deformation is also an important factor on evaluating response of structural system. To consider its effect, the loading system of applying soil deformation in hybrid experiment should be developed.

6. References

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