Study on the Shaking Table Testing Method Based on the Substructure Method Considering Dynamic Soil-Structure Interaction(構造物と地盤の動的相互作用を考慮したサブストラクチャー法に基づく振動台実験法に関する研究)

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論文内容要旨

Chapter 1. Introduction

Many researchers have verified the feasibility of the numerical SSI model through the shaking table test with a various types of soil miniatures. The conventional testing method, however, has revealed various problems; ① Too small building model comparing to a soil one to satisfy the similarity between them ② Boundary treatment of soil model ③ Material selection for soil model ④ High expenses for carrying out the testing. For these reasons, in case of the vibration control experiment considering superstructure's non-linearities, the following items are the challenging subject in earthquake engineering: ① Investigation on the shaking table test taking into account the soil's effect on superstructure, only using the superstructure as an experimental specimen. ② Driving the shaking table with the force corresponding to the interaction force by feedback of experimental specimen's response for the soil's effect. This study presents the shaking table testing method taking into account dynamic soil-structure-interaction based on the substructure method, and verifies its applicability. The proposed methodologies are the following: ① Acceleration feedback method is that the shaking table is driven by the motion, corresponding to the acceleration at foundation of the total SSI system. It is found by observing the fed-back acceleration of superstructure and using the interaction force based on the acceleration formulation. ② Velocity feedback method is that the shaking table is driven by the motion, corresponding to the velocity at foundation of the total SSI system. It is found by observing the fed-back acceleration of superstructure and using the interaction force based on the acceleration formulation.

Chapter 2. Entire Experimental System

Chapter 2 discusses the total experimental system used in this thesis. The following Fig. 1 shows the total experimental set-up used in this study. It consists of the following devices: ① Shaking table for generating earthquake input motion ② Control computer for driving the shaking table and controlling its motion ③ Interface hardware including the Digital Signal Processing (DSP) board for both data acquisition and signal output to the shaking table ④ Three-story shear-type building specimen for experimental part of total SSI system.

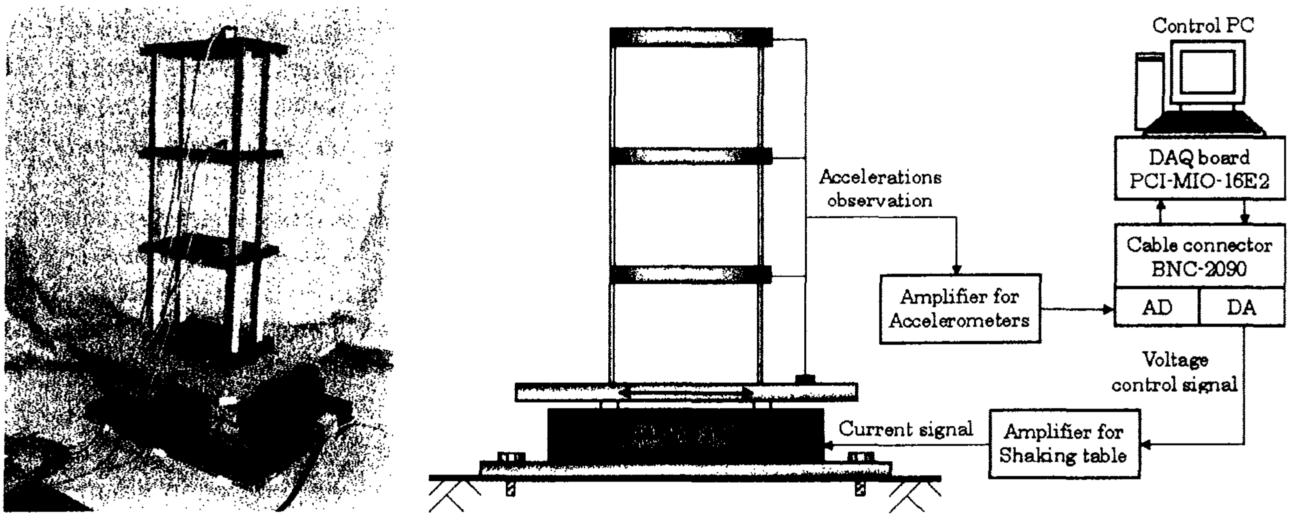


Figure 1 Experimental set-up

For the above experimental devices, a specific controller of shaking table was considered to freely control the intended motion of shaking table since the shaking table contains its own dynamic characteristic to be needed to be compensated for the generation of earthquake input motion. For the compensation, at first, the transfer function between the input signal to shaking table and the corresponding absolute acceleration at the shaking table was measured as shown in Fig. 2. The heavy dotted line represents the experimentally obtained transfer function of shaking table itself without building specimen, while the light solid line denotes that of shaking table with building specimen and the light dotted line means its fitted one in Fig. 2. Secondly, two degree-of-freedom controller as shown in Fig. 3, designed based on the observed shaking table's transfer function $G(s)$, was constructed for the compensation of the dynamic characteristic of shaking table and for the driving it according to the reference.

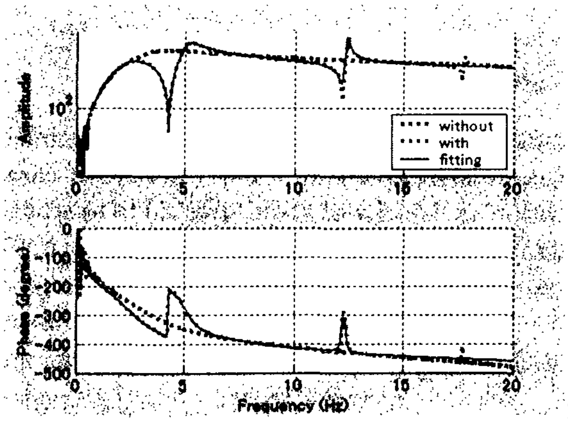


Figure 2 Transfer function of shaking table

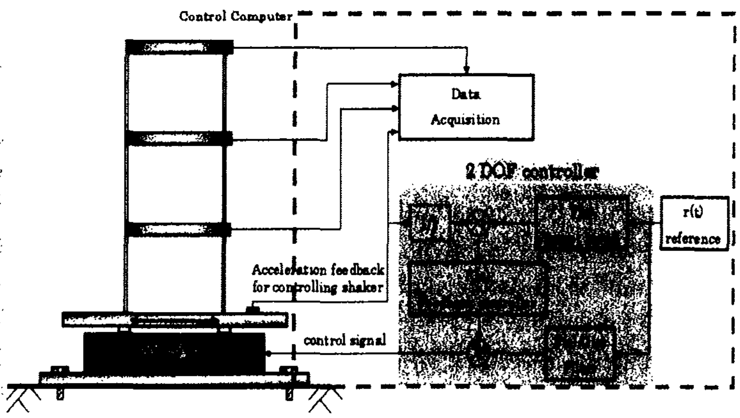


Figure 3 Schematic diagram for compensation

The damping coefficients and stiffness of the building specimen, mounted on the shaking table in Fig. 3, were also identified based on these observed absolute accelerations at the building model and the shaking table, respectively. They are used as those of an analytical superstructure model in chapter 3 for the given soil-structure-system.

Chapter 3. Dynamic Soil-Structure Interaction Analysis and Simulation Based on the Substructure Method

Chapter 3 deals with dynamic soil-structure interaction analysis and its numerical simulation based on the substructure method. A building specimen, which has been identified for its damping coefficients and stiffness in Chapter 2, was used as a superstructure of analytic soil-structure interaction system. Both half-space having a constant soil stiffness and layered soil having frequency dependent dynamic soil stiffness were also assumed as a soil model of given soil-structure interaction system considered in this study. The absolute accelerations at the superstructure and the foundation are numerically calculated from these SSI systems.

The following Fig. 4 displays the concept and the signal flows of numerical simulation on the assumed shaking table test of the dynamic soil-structure interaction system, in which the part surrounded with dotted line is simulated. At first, the required acceleration or velocity, which is to be driven by shaking table in order to simulate the motion of the total soil-structure interaction system, is calculated from the absolute accelerations at each story of superstructure and foundation. Furthermore, in case of actual shaking table test that includes the shaking table's transfer function $G(s)$, from the control signal of shaking table, $u(t)$, to its observed acceleration $\ddot{Y}_b(t)$, which has already been obtained in chapter 2, the two degree-of-controller described in chapter 2, sends a control signal into a shaking table from the reference signal which is the needed acceleration or velocity to drive the shaking table. Finally, the actual moving of the shaking table measured from the accelerometer is fed-back to the shaking table controller.

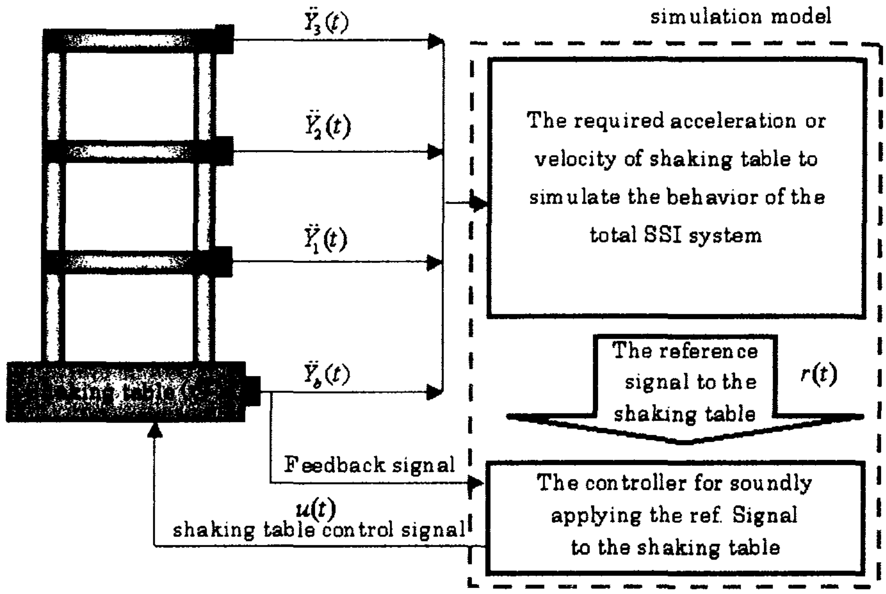
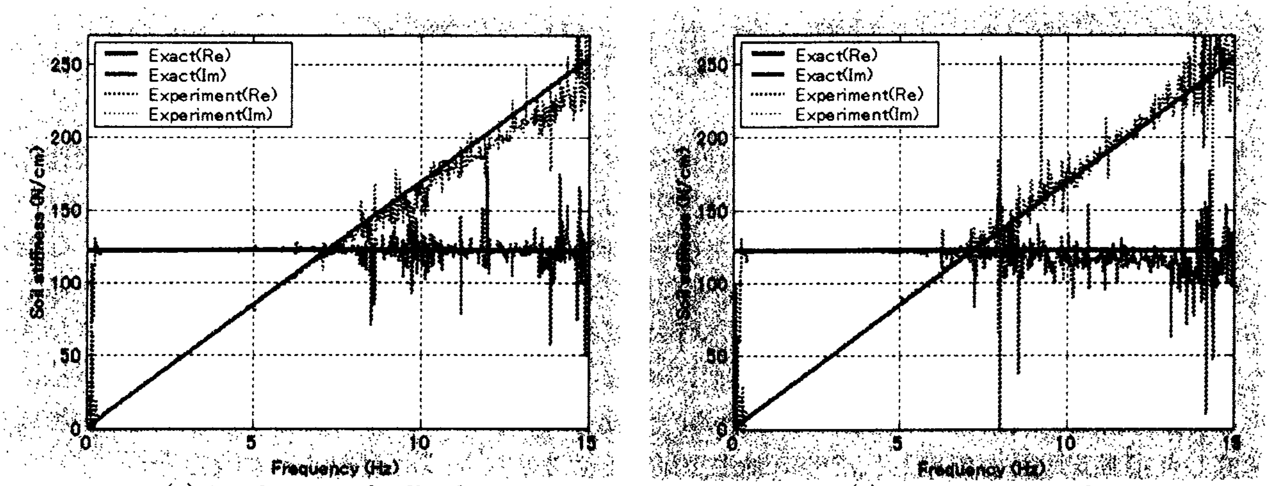


Figure 4 Concept of numerical simulation

In numerical simulation, an experimental simulation model corresponding the above assumed experimental system such as Fig. 4, is established for the acceleration and velocity feedback case, respectively. It is constructed based on the required acceleration or velocity of shaking table to simulate the behavior of a given soil-structure interaction system described in Chapter 2. Accelerations calculated from numerical analysis are inputted in, and interaction force and acceleration or velocity at the shaking table is produced from this simulation model. The validity of the proposed both acceleration and velocity feedback method is numerically shown from the comparing results through numerical analysis and its experimental simulation.

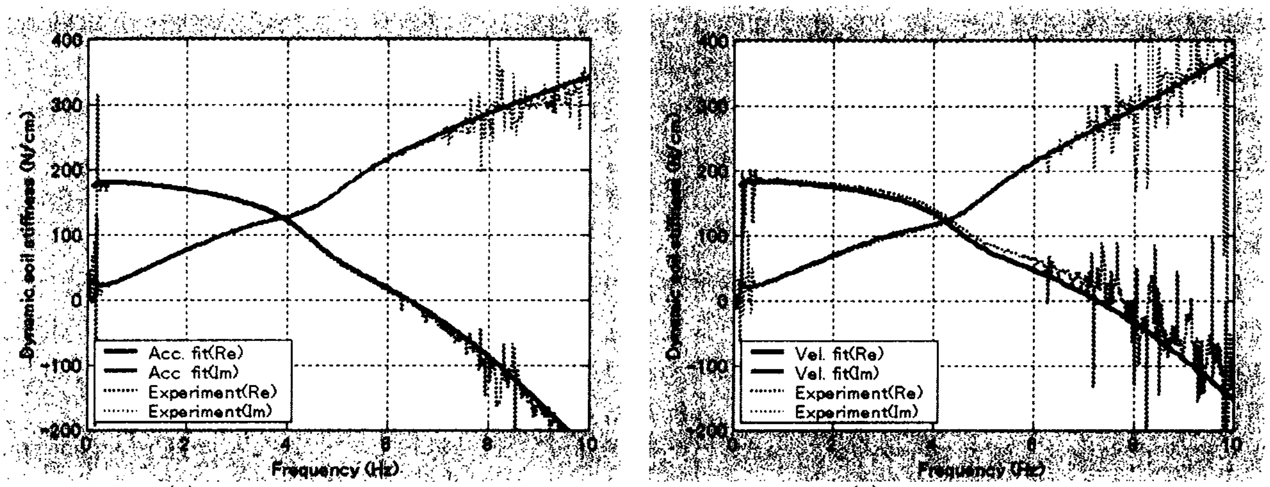
Chapter 4. Shaking Table Test of the Soil-Structure Interaction system

Chapter 4 addresses the applicability of the soil-structure interaction system numerically verified in Chapter 3 to the actual shaking table test. The soil filters corresponding to the dynamic soil stiffness is realized for both acceleration and velocity feedback. Using these filters, the actual shaking table test of the soil-structure interaction system was performed for earthquake input motion with the experimental devices explained in Chapter 2. The following Figs. 5~6 show the comparison results between the analytically and experimentally obtained dynamic soil stiffness for half-space and two-layered soil, in case of both acceleration and velocity feedback, respectively. These Figs. show the applicability of the proposed method to its actual shaking table test of dynamic soil-structure interaction system.



(a) Acceleration feedback (b) Velocity feedback

Figure 5 Comparisons between the analytical and experimental soil stiffness for half-space soil



(a) Acceleration feedback (b) Velocity feedback

Figure 6 Comparisons between the analytical and experimental soil stiffness for two-layered soil

Chapter 5. Conclusions

This study newly proposed the method of the shaking table test considering the SSI effect by observing the superstructure's response without any physical soil specimen. This study also verified the adaptability of the proposed method to the shaking table test on SSI system based on the substructure method, on condition that the arbitrary type of wave generator is used for feedback excitation of the superstructure's accelerations.

The proposed methods are summarized as:

1. The acceleration feedback method is one that the shaking table is driven by the force corresponding to the interaction force based on the acceleration formulation; in other words, the interaction force is observed from fed-back acceleration.

2. The velocity feedback is one that the shaking table is driven by the force corresponding to the interaction fore based on the velocity formulation; in other words, the interaction force is observed from fed-back velocity.

From the above point of view, it can be seen that displacement feedback method is available in the experiment on SSI system if the displacement-measuring apparatus such as laser sensor is equipped.

The above proposed methods also show that the same test can be performed with the displacement measuring instrumentation such as laser sensor.

論文審査結果の要旨

構造物の耐震設計において、構造物－地盤系の地震応答問題は地震工学における重要な問題の一つであり、敷地の地盤条件を反映した地震応答評価に基づく適切な地震荷重の設定が要求される。

本研究はこの構造物－地盤系の地震応答問題を対象とした振動台実験方法について新たな提案を行ったものである。地盤模型を用いる従来の振動台実験では、地盤の非線形性を取り入れることができる反面、地盤模型の境界処理やその材料の選択及び地盤模型に比べて構造物の寸法が小さくなりすぎるなどの問題が生ずる。これに対し、本論文はサブストラクチャー法を振動台実験法に応用し、上部構造の試験体のみを用い、試験体の信号をフィードバックすることにより地盤の影響を考慮した振動実験法を提案し、その有効性を証明したものであり、全編5章からなる。

第1章は序論であり、本論文の背景及び目的について述べている。

第2章では、本論文で使われる実験システムの構成や概略について説明し、上部構造物のパラメータ同定について述べている。実験システムの構成は地震波を発生させる動電型振動台、実験対象である上部構造物模型、振動台の動きを制御する制御コンピューター、そして、制御コンピューターの中に内蔵されている信号処理ボードからなる。振動台の動的特性を補正し、上部構造模型の加速度応答を正常にフィードバックするためのコントローラーの設計とその補正結果を示す。次に、上部構造物のパラメーター同定実験を行い、第3章の構造物－地盤系の上部構造物の数値解析モデルとなる。

第3章では、第2章で同定された上部構造物と想定の地盤モデルからなる構造物－地盤系に対して、その数値解析や実験手法のシミュレーションを示している。ここでは、①上部構造物の加速度観測によって、加速度定式化された相互作用力を振動台加振する加速度フィードバック法、②上部構造物の加速度観測によって、速度定式化された相互作用力を振動台加振する速度フィードバック法を新たに提案し、第2章で行なった振動台の伝達関数やそのコントローラーを反映した構造物－地盤系の振動台実験シミュレーションモデルに、これらの提案手法の尺度である数値解析結果を入力し相互作用力と基礎（振動台）の加速度や速度を出力し、これらが数値解析結果と良好に一致していることが確認され、提案手法の妥当性を数値的に示した。

第4章では、第3章の数値シミュレーションでその妥当性が確認された提案手法を第1章で述べた実験システムを用いて実際の振動台実験を行い、その適用性を示している。本章では、実際の実験を行なうために、第3章の数値解析で仮定した地盤モデルに対する動的地盤剛性の近似フィルタを振動台実験に適用し、実際の実験を行なった。ここでは、実験から得られた構造物－地盤系の加速度応答や動的地盤が第3章の数値解析の結果と良好に一致することにより、本論文で提案された構造物－地盤系の振動台実験法の有効性と適用性を証明した。

第5章は本論文の結論をまとめている。

以上のように、本論文はサブストラクチャー法に基づいた構造物－地盤系の振動台実験法の提案とその適用性や有効性を示したものである。新たに提案された加速度フィードバック法や速度フィードバック法は、実験で用いるセンサーに応じた実験の自由度を増大したものであり、構造工学や地震工学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。