SEISMIC ANALYSIS OF MULTI-SPAN CONTINUOUS GIRDER BRIDGE WITH EMPHASIS ON SOIL-STRUCTURE INTERACTION

H.Takemiya(I), T.Shimada(II)
M.Tatsumi(III), M.Katayama(III)
Presenting Author: H.Takemiya

SUMMARY

Seismic response analysis is dealt with for a high elevated multi-span continuous bridge on deep pile and wall foundations. The emphasis is placed on the investigation of the soil, foundation and superstructural interaction effect with consideration of the seismic propagation in soils. The dynamic substructure method is applied to advantage, which uses the superstructural normal modes coupled with the soil-foundation impedance. The finite element analysis is taken for evaluating this together with the effective seismic forces. Detail comparison is presented among solutions from various modeling and methods of analyses in both frequency responses and the maximum responses in time domain.

INTRODUCTION

Long multi-span bridges on deep embedded foundations(Fig.1) have been the types for modern construction in Japan. The dynamic analysis and seismic design of such structures are of interest herein, which involves the inertial interaction of individual foundations with soil and their interaction through the superstructure. For evaluating the ground motions into the respective foundation for a prescribed seismic wave, the kinematic interaction may arise.

The current method for the practical design work(Ref.1) is to separate the problem into the one for soil-foundation analysis and the superstructural analysis. However, in the former analysis a simplified stick model is ususally adopted to account for the inertial feedback from the superstructure to the foundation. Then the foundation responses are imposed as an input in turn at the base of the superstructure. This approach is referred to as the simplified interaction analysis herein, which may not be appropriate for the analysis of very extended structures like multi-span bridges.

In the present study, the more efficient and accurate method of analysis is developed from the dynamic substructure technique(Ref.2) and are coded into the computer program SUBSSIP-2D(Ref.3). This attemps first temporal partitioning of the complete soil-foundation-superstructure system into the subsystem of soil and foundation, and superstructure. At the later coupling of these substructures, however, the rigorous compatibility and equilibrium is claimed.

(I) Assoc. Prof., Department of Civil Engineering, Okayama Univ., Okayama, Japan
(II) Engineer, Construction Technique Institute Co. Ltd., Osaka, Japan
(III) Engineering Specialist, Century Research Center Corp., Osaka, Japan

FORMULATION OF THE METHOD

Site Response Analysis: The SUBSSIP-2D can simulate seismic waves as body waves (SH, SV, and P) and surface waves (Rayleigh and Love) that propagate in a horizontal direction. The finite element technique is used such that the wave amplitude varies linearly from node to node along the depth within the surface layer. In order to take into account the waves radiating into the halfspace bedrock, the hibrid approach (Ref.4) is adopted that connects the former discrete solution with the latter continuous solution at the bedrock level.

Soil-Foundation Analysis: The near field that encompases the foundation and the soil in its vicinity is modeled by the two dimensional finite elements. The types of elements implemented are the isoparametric solids and beams. In order to take into account the seismic wave radiation into the semi-infinite region of soils, the so-called transmitting boundary is introduced as a far field element at the side boundary of the FEM near field. As for the solution method, either the one-step solution or the dynamic sunbstructure approach is available. The former method evaluates the impedance functions and the seismic forces at the junction nodes with the superstructure for the base input motion through the condensation process. The latter method, on the other hand, assumes the inter-common nodes between soil and the embedded foundation, in which the substructuring is made either by placing these nodes along the foundation face or within the foundation. These are respectively referred to as the interface modeling and the interbody modeling (Ref.2). Each approach has its own advantage depending on the types of foundation. The interface model is oriented to the analysis of rigid foundations while the interbody model to flexible foundations. The former model evaluates the soil impedance and the effecrtive seismic forces at the same time for a prescribed earthqkuaqe motion at the base level through the condensation process . On the other hand, the latter concept makes use of the free field motion to evaluate the soil impedance since it is based on the material superposition, and the effective seismic input is easily obtained as the product of the free field motion and the soil impedance when it is already computed and available.

Complete Interaction System: The coupling is claimed between the soil-foundation system and the superstructure from the interface compatibility and equilibrium between them. Considering the fact that the superstructure is lightly damped so that the classical normal modes decomposition is presumed. With due consideration to the modal contribution in the frequency domain, one may effectively truncate the less significant higher modes, which reduces the degrees of freedom for the subsequent interaction analysis. The releasing the degrees of freedom at the base of the superstructure according to the soil impedance constitutes the pseudo-static displacement influence matrix besides the superstructural normal modes. Details of the formulation is referred to the Ref.2.

ANALYSIS OF THE NUMERICAL RESULTS

First, the dynamic characteristics of the respective foundation are investigated. Then the response features of the complete interaction system are discussed with emphasis on the modeling and method of analysis. In what follows the behavior in the direction perpendicular to the bridge axis is presented.

Wall Foundation: This type of the foundation, as illustrated in Fig.2, is popular in Japan for its convenience of construction. This foundation, being different from the caisson type foundation, comprises an undisturbed original soil within its structure. The interest, therefore, is placed on the understanding of the dynamic features with emphais on the internal soil behavior. Three FEM models(see Fig.2.b) are taken: namely, (i)The model which has dual planes to represent the foundation wall and the internal soil, (ii)The model with mass consideration only, and (iii)The model completely neglecting the internal soil. In Fig.3 are shown the impedance functions of the soil and foundation system evaluated at the footing top. Note that the internal soil moves almost in phase with the foundation, indicating the inertial effect rather than the stiffness effect against the wall motion. Fig.4 depicts the frequency responses at the footing top and pier top levels as well as at the free field surface in order to see the soil-foundation interaction phenomenon. Note that a predomimnant peak response appears, due to the interaction, at the higher frequency than the fundamental free field frequency. This interaction mode is dominated by the foundation rocking motion judging from the amplification from its top to the pier top ,in view of the rigidity of the pier.

Pile-Foundation: The beam elements are used to represent piles(see Fig.5). Fig.6 gives the subsystem impedance functions evaluated at the footing top. When compared with the impedance of the wall foundation, that of the pile foundation is indicative of the more flexible nature. Fig.7 shows the frequency responses at the footing top and pier top levels as well as that of the free field surface. Note that the pile foundation is much affected by the free field vibration modes in the low frequency range and the inertial interaction is negligibly small.

Superstructure: The lumped mass modeling is taken for the bridge given in Fig.1(see Fig.8). The results of the normal modes analysis are shown in Fig.9 only for those of significant participation factors. Note that the predominantly contributing modes differ as the section considered.

Complete System Analysis: Since the bridge for the present analysis is an extended structure on multiple different types of foundations, the interest is placed on the modeling as well as on the method of anlysis. Hence, the following cases are considered: (i) Rigorous interaction analysis for a uniform seismic input at the base rock level, (ii) Rigorous interaction analysis for a progressive seismic input at the base rock level as SH wave, (iii) Approximate response by using the free field surface response as an input for the superstructure with soil-foundation impedance at its base, (iv) Analysis with fixed base assumption for the superstructure, and (v) Simplified interaction analysis as stated in INTRODUCTION. For the analyses (i), (ii), the impedance functions of the respective foundation and the corresponding effective seismic input are used.

Fig.10 gives the frequency responses for the above cases. The difference of the solutions between (i) and (ii) explains the out-of-phase effect of the seismic input due to its propagation in the horizontal direction. The comparison of the solutions between (i) and (iii) makes clear the kinematic interaction between the seismic waves and the foundation. The difference of the solution of (i) from that of (iv) implies the soil-foundation interaction effect. The soil amplification effect appears in the difference of the solutions between (iii) and (iv). Finally, the comparison of the solution of (i) with that of (v) infers the accuracy of the evaluation of the inertial force feedback from the superstructure to the foundation.

Through the frequency responses one may conclude that:

(1)The use of the free field surface response as an input for the interaction system analysis may misleads the response evaluation when the kinematic interaction is significant.

(2)The soil-structure interaction is important for the structure on deeply emnbedded rigid foundations.

(3)The simplified interaction analysis tends to yield the greater response at the superstructural natrural frequencies.

(4)The progressive seismic waves turn out to give the smaller response in the frequency range of interest, which of course is strongly related to the dynamic characteristics of the interaction system and the wave types considered(Refs.5,6).

Figs.11 and 12 are the maximum response accelerations and the maximum interanl forces for the Taft 1952 earthquake, N21W component which is adjusted to have the maximum input acceleration of 100 gal as inciden wave.

In these figures note that:

(1)The soil-structure interaction works to reduce the response from when rigly supported situation.

(2)The traveling input results in a smaller responses which may be reasoned from the statement in Ref.5.

(3)The free field suface response as an input give a poor response evaluation.

(4)The simplified interaction analysis results in about 1.5 times or more lartger response at the girder responses.

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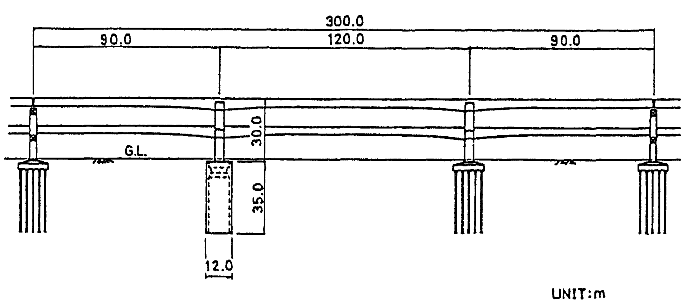


Fig.1 General View of Structure

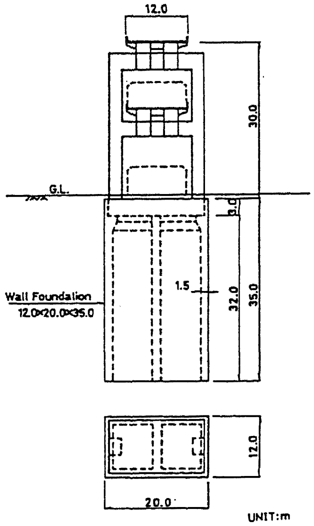
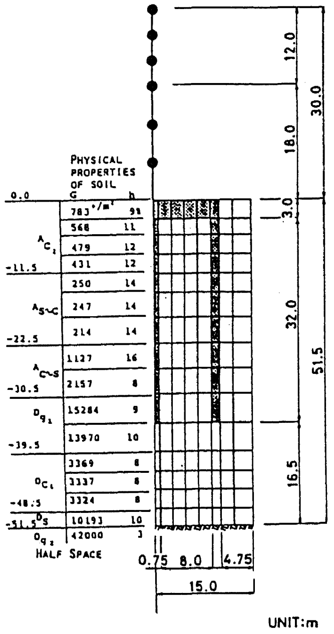
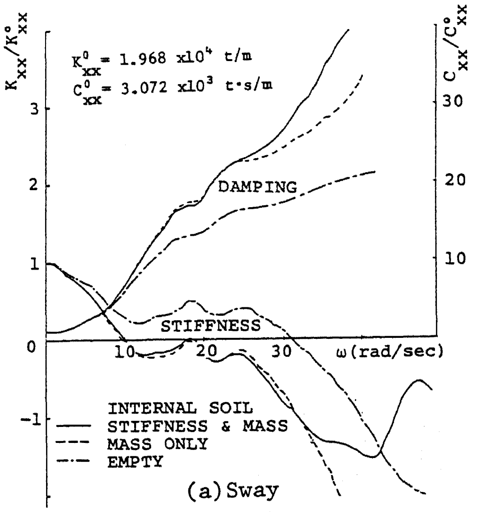


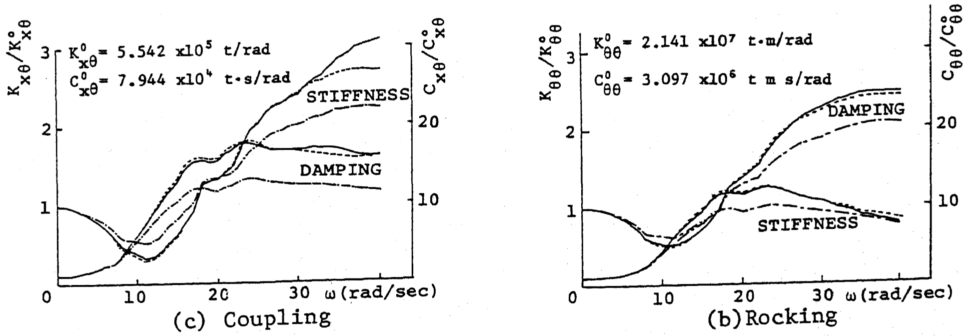
Fig.2 Wall Foundation
(a) Side View



(b) FEM Model



(a) Sway



(c) Coupling (b) Rocking

Fig.3 Impedance of Wall Foundation

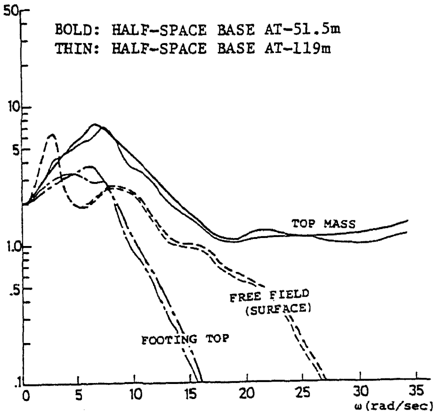


Fig.4 Frequency Response of Wall Foundation

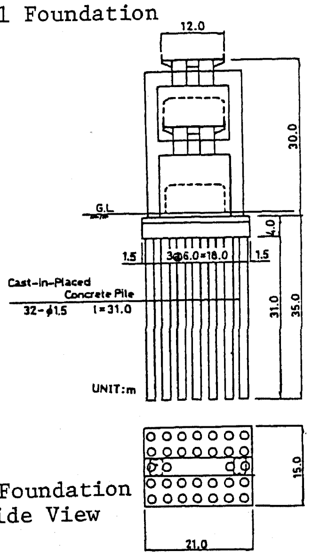


Fig.5 Pile Foundation
(a) Side View

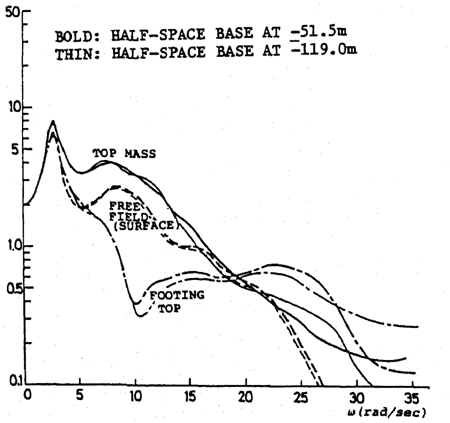
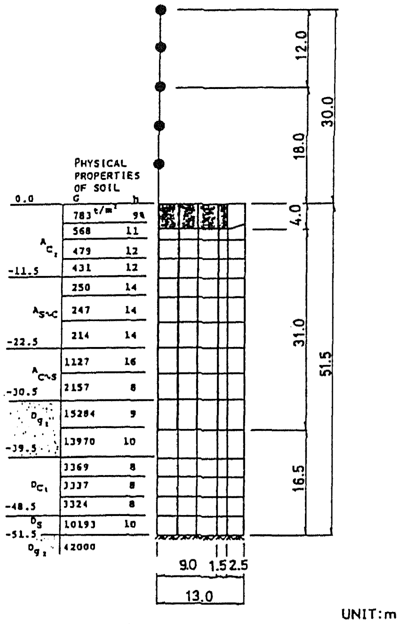
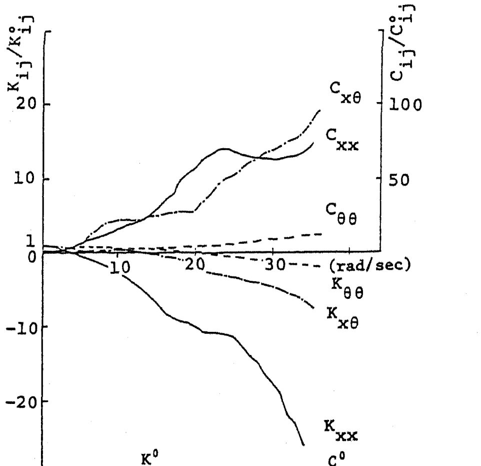


Fig.7 Frequency Response of Pile Foundation



(b) FEM Model



	K^0	C^0
xx	1.686 $\times 10^3$ t/m	0.263 t·s/m
xθ	2.099 $\times 10^4$ t/rad	1.481 $\times 10^3$ t·s/rad
θθ	2.574 $\times 10^6$ t·m/rad	3.675 $\times 10^5$ t·m·s/rad

Fig.6 Impedance of Pile Foundation

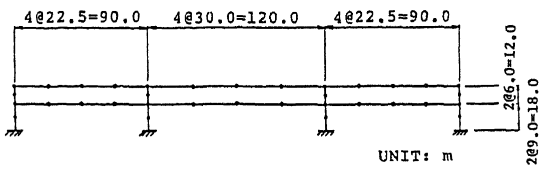
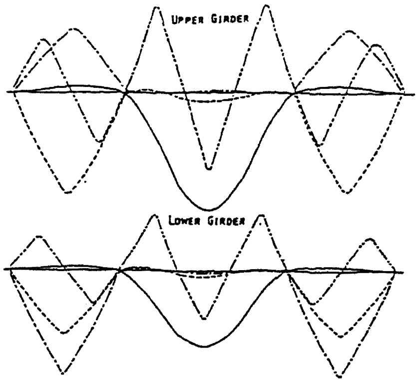


Fig.8 Lumped Mass Model for Superstructure



	MODES	PARTICIPATION
1st	6.157 rad/s	2.907
4th	12.44	3.934
6th	13.51	0.818
9th	31.73	-1.417

Fig.9 Vibration Modes

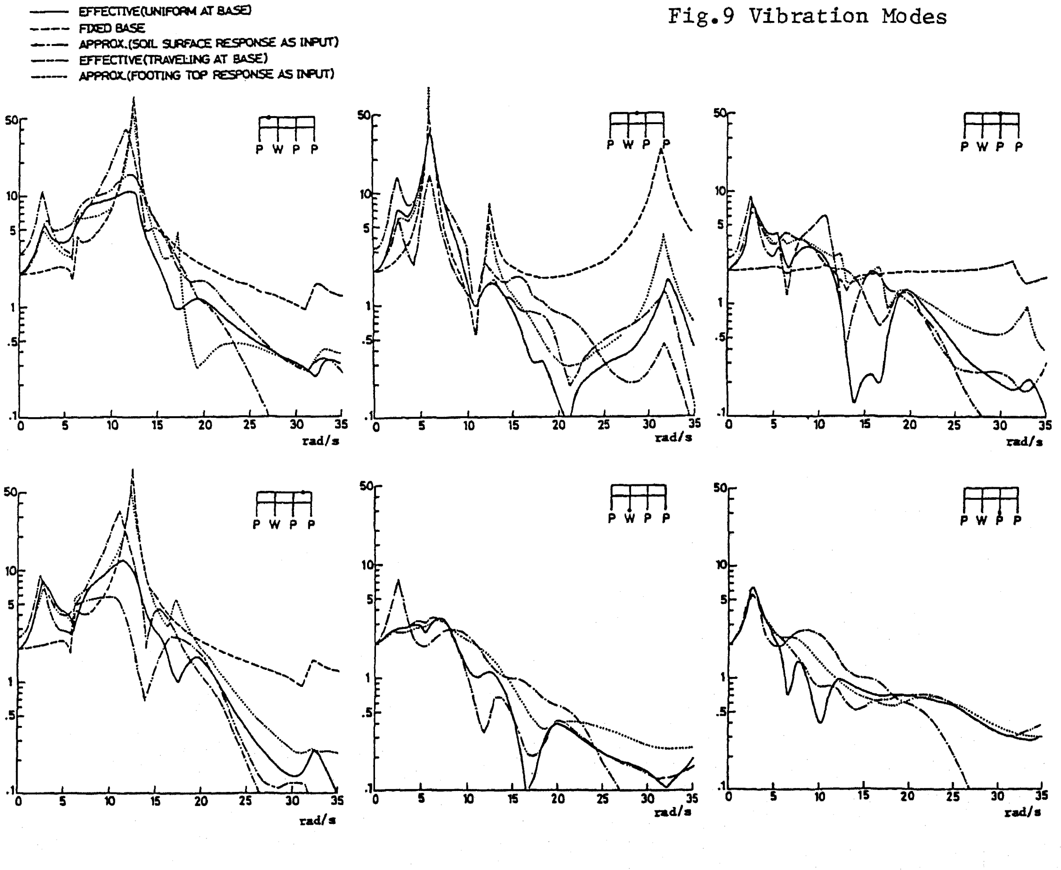


Fig.10 Frequency Response of Interaction System (Pile and Wall Foundations)

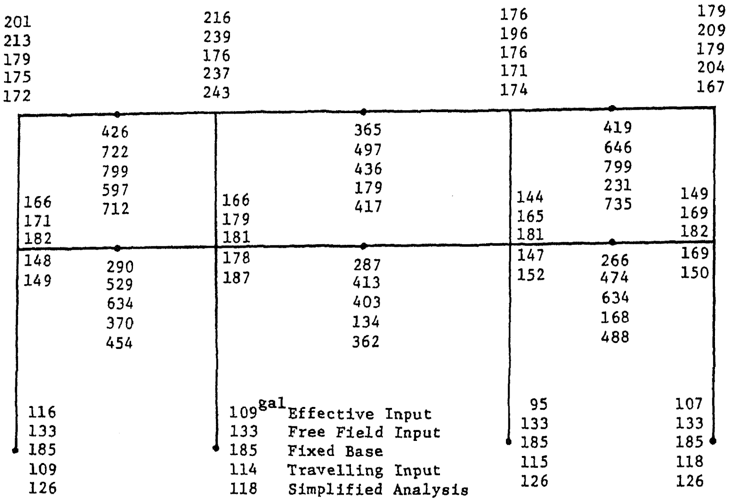


Fig.11 Maximum Response Acceleration
Input: TAFT 1952, N21W Max.Acc.100 gal

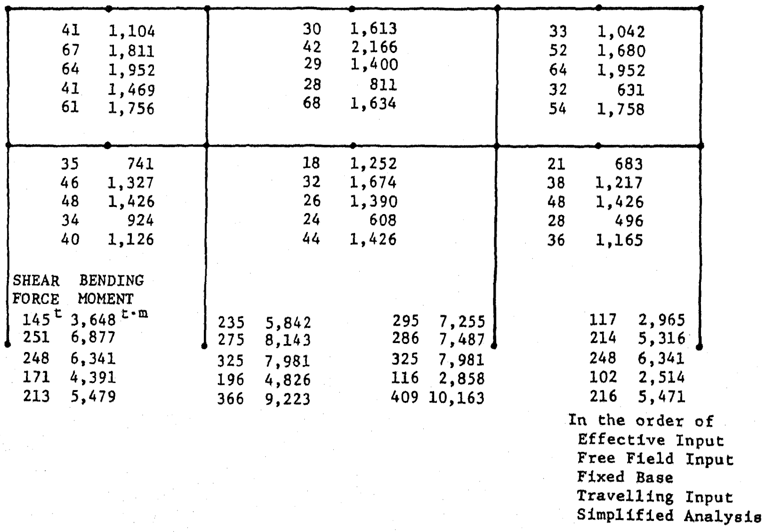


Fig.12 Maximum Internal Forces
Input: TAFT 1952, N21W Max.Acc.100 gal