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Unified analysis of kinematic and inertial earthquake pile responses via the single-input response spectrum method

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A R T I C L E I N F O

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A B S T R A C T

In the seismic response of a structure–pile–soil system, a kinematic response due to the forced displacement of the surface ground is important, especially in a soft ground, together with the inertial response due to the inertial forces from superstructures. In this paper it is shown that a response spectrum method in terms of complex modal quantities can be used in the evaluation of the maximum kinematic and inertial seismic responses of the structure–pile–soil system to the ground motion defined at the engineering bedrock surface as an acceleration response spectrum. The notable point is that the kinematic response, the inertial response and the total response can be evaluated by the same analysis model and method by changing the model parameters. Then it is discussed which of the simple sum or the SRSS of the kinematic and inertial responses is appropriate even in resonant cases for the evaluation of the maximum pile-head bending moment. It is concluded through many examples that the validity of the simple sum or the SRSS depends on the relation between the fundamental natural period of the surface ground and that of the superstructure while an averaged evaluation is valid in resonant cases.

1. Introduction

1.1. Conventional method for estimating seismic pile response

For the pile design under earthquake loading, the method for predicting the pile response is important. In the evaluation of the bending moment in a pile, both the effect of the forced displacement of a free-field ground (action 1) and the effect of the inertial force from a superstructure (action 2) as shown in Fig. 1 have to be taken into account in an appropriate manner (for example [1–11]). However these two effects have different characteristics and it seems difficult to include these in a simple way keeping a reasonable accuracy. Conventionally the following two methods have been used in practice.

1.1.1. Direct method

The most well-known method is the direct method. This method uses a complete structure–pile–soil system in which the soil resistance around a pile is modeled by a spring or a finite element system. The spring model is known to be practical once its accuracy is confirmed by the comparison with other methods (a finite element system, a continuum model or physical experiment). The earthquake ground motion is input into the engineering bedrock. Although the finite element method has much flexibility, it has the following issues to be resolved when used in the practical design.

(1) Three-dimensional analysis of soil and pile elements requires huge computational load and resources.
(2) Deformation compatibility between soil and pile elements is difficult to satisfy and requires a constraint on the selection of finite elements [12]. For example the program 'FLUSH' [13] uses a linear displacement in soil elements and a cubic displacement in pile elements which result in the deformation incompatibility.

1.1.2. Substructure method

Another well-known and practical method is the substructure method (see Fig. 2). The free-field ground motion is computed first to the engineering bedrock input and that is re-input to the structure–pile system. This method is aimed at superposing simply the response (kinematic response) due to the forced displacement of the free-field ground and the response (inertial response) due to the inertial force from a superstructure. There are two methods in the substructure method, i.e. the static method

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and the dynamic method. In the static method, the forced displacement of the free-field ground and the inertial force from the superstructure are given *statically*. Although the static method is a simple practical method, it has the following drawbacks.

(1) Difficulty in estimating the displacement mode of the free-field ground: the displacement mode is based on the lowest mode in general and higher-mode effects are missing. In addition, the amplitude of the displacement mode has to be evaluated independently.
(2) Difficulty in estimating the inertial force to be applied to piles: the estimation of exact inertial forces is possible through a versatile model. Although a sway-rocking model is often used, the input motion has to be evaluated as one including the surface soil amplification. This modeling of surface soil amplification and the specification of the response spectrum at the ground surface are cumbersome tasks.
(3) Uncertainty in superposing the above-mentioned kinematic and inertial responses: the simple sum is usually employed. However there is no guarantee depending on the relation of the fundamental natural period of the surface ground and that of the building.

1.2. Significance of response spectrum method in hybrid problems of structural and geotechnical engineering

After the past major earthquakes, it has been pointed out and demonstrated repeatedly that the damage to civil engineering structures is influenced greatly by the natures and conditions of surface soils and deep understanding of the soil–foundation interaction is extremely important for the mitigation of such damage. On the other hand, the soil conditions are different site by site and the definition of appropriate design ground motions at a specific site is very difficult. In the actual structural design using the structure–foundation–soil interaction models, a computationally efficient method with a reasonable accuracy is preferred from the economical and practical viewpoints. It is therefore strongly desired to develop an efficient evaluation method of the peak seismic responses of structure–foundation–soil systems at a specific site with a reasonable accuracy.

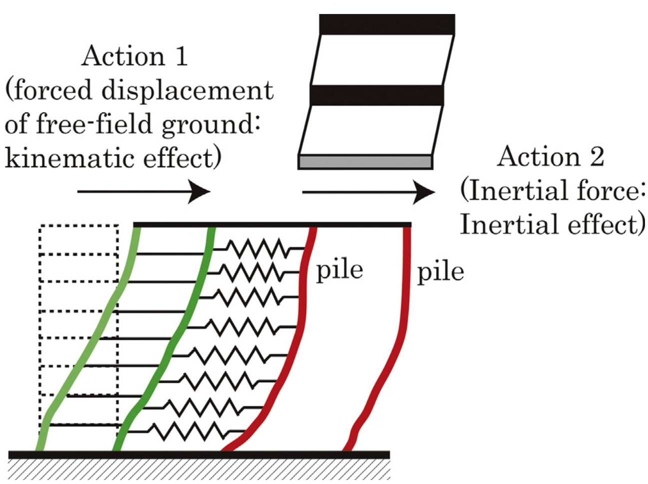

Fig. 1. Effect of the forced displacement of free-field ground (action 1) and the effect of the inertial force from superstructure (action 2).

Compared to building structures, the application of the response spectrum methods to geotechnical problems seems to be inactive. This is because the phenomena in the geotechnical engineering are mostly described by the wave propagation theories and the treatment of those phenomena as vibration problems has seldom been conducted so far except models with viscous or transmitting boundaries [10]. While the wave propagation theories can deal with an infinite medium and hysteretic damping, a complex treatment is necessary in the vibration theories. This difficulty seems to have been the principal barrier to the introduction of the response spectrum method in geotechnical problems or structural and geotechnical engineering hybrid problems.

In this paper, a pile–soil system is considered as a representative model of the foundation–soil systems. In the evaluation of the seismic response of the pile–soil system, a kinematic effect due to the forced displacement of a free-field surface ground is important, especially in a soft ground, together with the inertial effect due to the inertial forces from superstructures (see Fig. 3). A response spectrum method using complex modal combination is utilized for the simple evaluation of the maximum seismic response of the pile-soil system to the ground motion defined at the engineering bedrock surface as an acceleration response spectrum. The superposing rule of the pile bending moments due to the kinematic and inertial effects will be discussed in detail even in resonant cases.

1.3. Recent development of response spectrum methods

In Japan, the method based on time-history response analysis is the method well accepted in the evaluation of the seismic safety of high-rise buildings and base-isolated buildings. This is because the modal combination rules, e.g. the SRSS [14], the CQC [15], the absolute sum, are based on some assumptions; (1) the design response spectrum is prepared as the representative of the design ground motions, (2) only the elastic response can be dealt with, (3) the proportional damping can be assumed in the structures. However, in Japan, several recorded or simulated ground motions

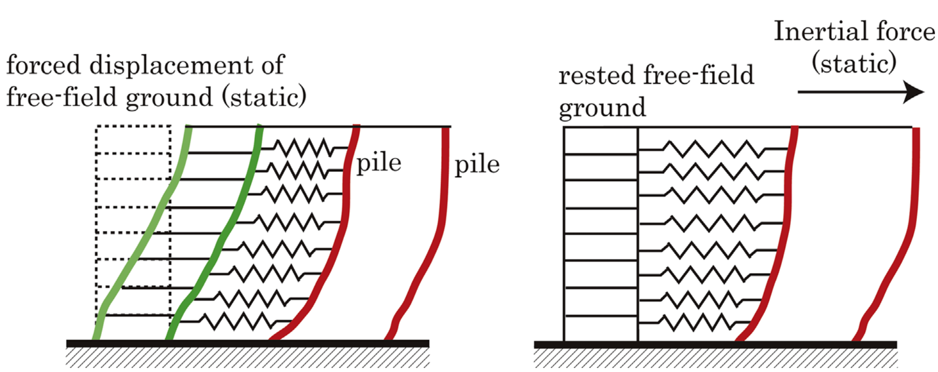

Fig. 2. Kinematic effect and inertial effect in the evaluation of pile-head moment in the conventional static method.