CHAPTER 3 METHODS OF SEISMIC PERFORMANCE VERIFICATION

3.3 Estimation of Response Values

3.3.1 General

(1) The response values should, in principle, be estimated by carrying out the time history response analysis.

(2) For the whole structure system, a coupled analysis considering the structure and the ground together shall be carried out. However, if dynamic interaction between the structure and the ground can be neglected or it can be appropriately modeled, the structure may be analyzed independently in accordance with 3.3.2.

(3) Structures should be modeled as 3-D or 2-D assembly of members.

(4) Structures should be analyzed using finite element or beam element models.

(5) In the case of carrying out a coupled analysis, finite element model should preferably be used to model the ground.

(6) When evaluating induced shear force and torsional moment, the actual tensile yield strength of steel and the total cross sectional area of longitudinal re-bar shall be considered.

[Commentary] (1) Recently, numerical simulation technique has been developed notably, and reliability of analytical results has also been improved sufficiently through comparisons with several kinds of experimental results. Therefore, it is in principal in this specification that time history response analysis is performed to estimate response values. When it is obvious that the response of a structure and members are in elastic region, other reliable methods may be used for verification of Seismic Performance 1.

(2) Since the response of a structure during an earthquake is strongly affected by neighboring ground and others, the whole structural system including foundation or neighboring ground should be analyzed. To do so, a coupled analysis taking the interaction between structures and soil into account directly should be used. **Table C 3.3.1** shows a general analytical method. In modeling of ground, the influence of distant ground and others should be sufficiently examined. An example of finite element model of a structure is shown in **Fig. C 3.3.1**.

According to types or characteristics of structures and ground, there are some cases which dynamic interaction between structures and ground can be neglected or modeled appropriately. In these cases, the responses of the structures and the ground may be analyzed independently according to the provision in **3.3.2,** because the response can be estimated with sufficient reliability without using coupled analysis.

(3) Since the structure is composed of members connected in three dimensions, precisely, it may be modeled in three dimensions. Two-dimensional modeling of the structure, however, may be applied in cases where the response in a two-dimensional plane is enough to be considered according to the

characteristics of the structural response.

Table C 3.3.1 Method for a coupled analysis of structure and ground

Structure Type	Ground structure, Underground Structure
Analytical Method	Time History Response Analysis
Analytical Model of Structures	Finite Element Model or Beam Element Model
Analytical Model of Ground	Finite Element Model
Input Value	Time History Acceleration Wave Form
Input Place	Base Layer

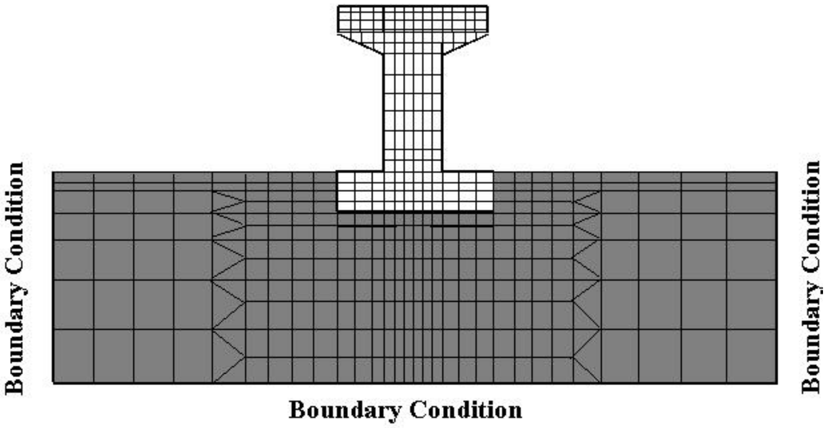

Fig. C 3.3.1 Example of modeling for structure and ground in a coupled analysis

(4) In order to estimate the structural response for an earthquake, it is necessary to represent a structure by an appropriate mechanical model and to model material properties so that the mechanical properties can be reproduced.

In modeling of a structure, generally two types of model are used: one is a finite element model representing constituent members such as column, beam, wall and so on, as an assembly of small elements. The other is a beam element model representing column and beam by one line. The beam element model directly reflecting experimental results of load and displacement relationships of members had effectively been used when processing and memory capacity of computers was not sufficient, and when numerical simulation techniques and constitutive models were not sufficiently developed. The beam element model has high accuracy and reliability in limited conditions. However, there are several kinds of limitations: (i) hysteresis modeling is very complicated when axial force is varied, (ii) special consideration is required for stiff area such as the connection of columns and beams, (iii) modeling is difficult when a structure responses in multi-directions.

On the other hand, finite element model can also simulate the load resistant behaviors of planar members accurately up to the ultimate state as the results that new constitutive models have been developed, and can be applicable to the arbitrary shape of structures and members. Moreover, it has an advantage that local damage state of members can be evaluated from stress and strain hysteresis in elements. When a finite element model is used, it is necessary to understand the relationship between displacement of members and strain of each element by a push over analysis in advance of the verification. Strain of elements depends on the element size and mesh division. When elements are divided in small, strain of elements become large.

(6) In the verification of safety against shear failure, it is necessary to estimate the actual shear force induced in a member. The maximum shear force is introduced when the member reaches bending capacity. Therefore, underestimating bending capacity as in usual verification leads to underestimating induced shear force, and it is in a dangerous side. Thus, it is necessary to consider all longitudinal re-bars and actual tensile yield strength in estimating shear force and torsional moment. When actual tensile strength of re-bar is unidentified, the upper limit value of the Japan Industrial Standard specification may be used as yield strength.

3.3.2 Method for analyzing the structure and the ground independently

(1) In calculating the dynamic response of the structure on the ground, the input wave should be taken to act at the depth, which obtain from the response analysis of only the ground, and dynamic computations should be carried out in time domain.

(2) The response of the ground should, in principle, be carried out using dynamic analysis.

(3) The analytical model for the ground may be a one-dimensional continuous model or a finite element model divided in different layers.

(4) The boundary between the ground including the foundation and the structure on the ground may be modeled using nonlinear springs that support the structure on the ground.

(5) The response of the foundation and the underground structure may be calculated using the response displacement method. The value of the response displacement may be taken as the displacement at the time when the relative displacement of the ground in the position of the structures reaches the peak.

(6) The interface between the ground and the foundation or the underground structure may be modeled using nonlinear springs, taking into consideration the characteristics of the surrounding ground.

[Commentary] **Table C3.3.2** are listed the methods for analyzing the structure and the ground independently.

Table C3.3.2 Methods to analyze the structure and the ground independently

Structural Type		Structure on the ground	Underground structure
Analysis of Structure	Analytical method	Time History Response Analysis	Response displacement method
	Analytical model of structure	Finite Element Model or Beam Element Model	
	Interaction model	Spring model	
	Input value	Time History Acceleration Wave Form calculated from analysis of ground	Displacement of ground calculated from analysis of ground
	Input place	Base part of structure	Side part of structure
Analysis of Ground	Analytical method	Time history response analysis or response analysis in frequency domain	
	Analytical model of ground	One-dimensional continuous model or finite element model divided in different layers	
	Input value	Time History Acceleration Wave Form	
	Input place	Engineering Base layer	

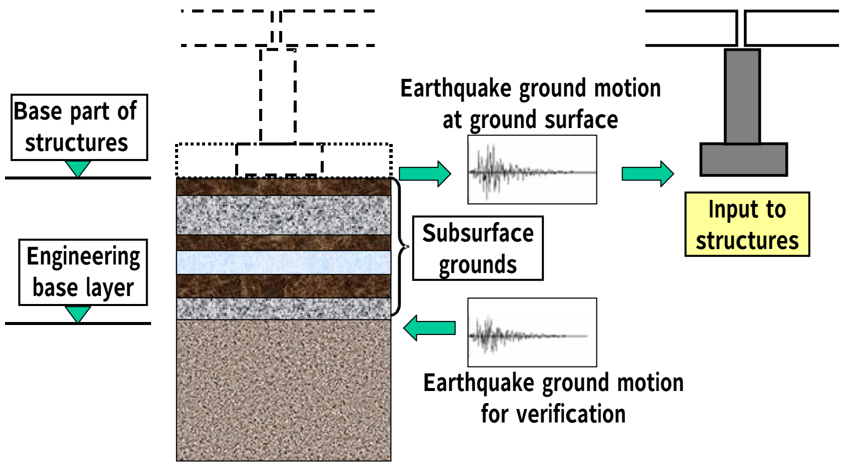

Fig. C3.3.2 Method to analyze a structure independent of the ground

(1) When analyzing a structure on the ground independent of the ground, earthquake ground motion at the base of the structure should be estimated by dynamic analysis of the subsurface ground at the site, and then dynamic response analysis of the structure should be performed using the estimated earthquake ground motion as shown in **Fig. C 3.3.2**.

(2) Analysis of seismic response of the ground, in general, is applied to the time history response analysis method and to the response analysis method in frequency domain. In the time history response analysis, the nonlinearity of the soil can be modeled as a stress-strain relationship. On the other hand, in the response analysis in the frequency domain, it is pointed out that the conformity with the actual action of the ground reduces in the large strain area where the strain level of the soil exceeds 10^{-3}, because the method approximates the nonlinearity of the soil by an equivalent linearized technique. Therefore, a proper analytical method corresponding to the strain level of the soil should be chosen.

(3) Finite element analysis may be employed for response analysis of the ground as well as the case of coupled analysis that combines the ground and a structure. In the case when the ground structure around the structure is horizontally stratified, the response analysis can be simplified by using a one-dimensional model. It is desirable to examine the dynamic properties of the soil by in-situ test and laboratory test in order to take the nonlinearity of the ground into consideration.

(4) In the nonlinear spring model that supports the structure on the ground, it is assumed that the first oscillation mode is dominant in the response of the structure. When the influence of the higher mode is dominant such as a pile and so on, the ground, foundation and superstructure should be combined and modeled by a finite element model or by an equivalent spring-mass model.

(5) Relative vibration against the ground is hard to occur on usual underground structure constructed in the subsurface ground. The structural response follows the displacement and deformation of the surrounding ground during an earthquake, and the influence of the inertia force caused by the mass of the structure is small. When the oscillation mode of the ground coincides with that of the structure, the forced displacement, which is obtained as the deformation of the ground during the earthquake (response displacement), may be acted statically on the structure.

Behaviors of an underground structure during an earthquake are affected not by the scale of the absolute displacement of the ground at the position of the structure, but by the rate of vertical change of the horizontal displacement. Therefore, the displacement used for the response displacement method is determined as the displacement of the ground at the time when the relative displacement of the ground between the top and the bottom ends of the structure is the maximum. As for long structures such as piles, the time when the relative displacement of the ground at each depth is the maximum may be different due to the stratum condition. In such a case, some ground displacements that give a great influence in each section of the pile should be chosen from the time history displacement.