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An improved pseudo-static method for seismic resistant design of underground structures

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Abstract: This paper describes a commonly used pseudo-static method in seismic resistant design of the cross section of underground structures. Based on dynamic theory and the vibration characteristics of underground structures, the sources of errors when using this method are analyzed. The traditional seismic motion loading approach is replaced by a method in which a one-dimensional soil layer response stress is differentiated and then converted into seismic live loads. To validate the improved method, a comparison of analytical results is conducted for internal forces under earthquake shaking of a typical shallow embedded box-shaped subway station structure using four methods: the response displacement method, finite element response acceleration method, the finite element dynamic analysis method and the improved pseudo-static calculation method. It is shown that the improved finite element pseudo-static method proposed in this paper provides an effective tool for the seismic design of underground structures. The evaluation yields results close to those obtained by the finite element dynamic analysis method, and shows that the improved finite element pseudo-static method provides a higher degree of precision.

Keywords: underground structures; seismic design; finite element method; pseudo-static method; dynamic analysis method

1 Introduction

Methods for seismic response analysis of underground structures can be categorized as static, pseudo-static, dynamic, etc. The static method is simple but not very precise, and is rarely used. On the other hand, the dynamic response analysis method provides results with high precision, however, it requires special engineering knowledge and is time consuming. Thus, except for special projects and/or extremely complex structures and soil conditions, the pseudo-static method is more commonly used than the dynamic analysis method (Zhou *et al*., 2003; Unjyo *et al*., 2002; Kawajima, 1994; GB50157-2003; Tateishi, 1992).

The most commonly used pseudo-static methods in the seismic design of cross sections of underground structures are the response displacement method (RDM) and the finite element response acceleration method (FERAM) (JSCE, 1989). Note that for underground structures with large cross sections, these pseudo-static methods provide comparatively large errors (Sato and Liu, 1999). The present paper is aimed at improving the pseudo-static method so that it is able to provide results with satisfactory precision that are applicable to any complex soil conditions.

2 Improved pseudo-static method

2.1 Development of the improved pseudo-static method

As is well known, it is difficult to use RDM to evaluate the characteristics of soil springs that represent the effect of soil around the structure under consideration. As for the FERAM, the inertial effect of the soil is simulated when modeling a full soil-structure system, where as the effect of soil damping is neglected. It will be shown later in Section 3.2 that neglecting soil damping leads to the deviation of the pseudostatic analysis results from the dynamic analysis.

In the proposed improved finite element pseudostatic method, the main procedure is similar to that of the FERAM. In the first step, a seismic free field analysis is conducted by using a one-dimensional seismic response analysis program (such as SHAKE) under a given input of ground motion. During this step some iterations

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of analysis are performed to achieve a satisfactory approximation of the soil modulus and damping ratio consistent with the soil strain level. The second step is to conduct a pseudostatic analysis for the full soil-structure system using a plan strain FF model, in which the earthquake forces are applied at each node and derived based on information from the previous step as shown below.

2.2 Seismic action in the soil-structure system

From the seismic free field analysis performed in the first step, a time varying shear stress distribution $\tau(y, t)$, (here y denotes the depth measured from the ground surface), can be obtained. Only the distribution at a time instant t_1, i.e. $\tau(y) = \tau(y, t_1)$, is of interest, where t_1 is a definite time instant when the maximum horizontal displacement at a depth y_t relative to the displacement at a depth y_b occurs. Here, y_t and y_b represent the depths of the top and the bottom of the buried structure to be considered, respectively. Differentiating $\tau(y)$ with respect to y yields the distribution of the equivalent horizontal load, i.e.

$$q(y) = \mathrm{d}\tau(y)/\mathrm{d}y \tag{1}$$

Equation (1) can be rewritten in the discrete form:

$$q_{k,k+1} = 2(\tau_{k+1} - \tau_k)/(h_{k+1} + h_k) \qquad (k=1, 2, \cdots n\text{-}1) \tag{2}$$

where $q_{k,k+1}$ is the average horizontal load between k-th and (k+1)-th soil layers; h_k is the thickness of the k-th soil layer divided in the SHAKE calculation model; and τ_k is the shear stress at the half height of the k^{th} soil layer (in Fig.1).

After all $q_{k,k+1}$ at various soil layers have been calculated, the distribution of body forces at various depths of soil layers, which act on the unit volume of soil in the horizontal direction, can be calculated by the interpolation technique. Then, the seismic loads imposed on all nodes in the finite element model for the soil-structure system are established.

In the present method, the equivalent seismic action is based on the seismic stress response of a one-dimensional response analysis. Therefore, it is named the finite element response stress method (FERSM). In fact, the equivalent seismic action (force) obtained is identical to a joint action of the inertial and damping forces of the soil.

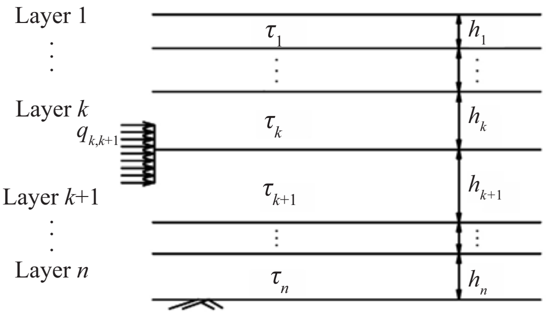


Fig. 1 Schematic drawing of soil layers and loads

3 Verification of the proposed method

3.1 Calculation object and parameters

In the numerical comparison between different methods, the SHAKE, Super FLUSH and TDAP-3 programs were adopted for the one-dimensional soil free field response analysis, the two-dimensional finite element dynamic response analysis and the pseudo-static analysis, respectively.

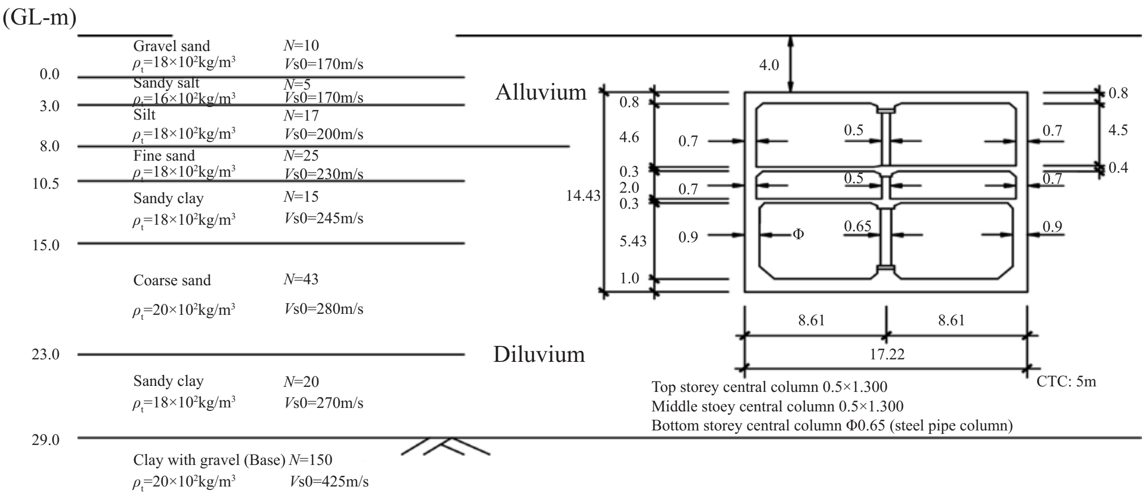
A shallow embedded box-shaped two-span, three-floor subway station structure buried at a depth of 4.0 m was used as the structure for the study. The structure had a total width of 17.22 m, and total height of 14.43m . The structure configuration and main geometry are shown on the right of Fig. 2, and the soil profile is shown on the left, where the basic parameters of the soil layers are given.

The concrete and reinforcement parameters of the structure are given in Table 1.

The models used in the analysis of FERSM, FERAM and FEDAM are shown in Fig. 3. The soil and all structural members are, respectively, assumed to be a plane strain element and linear beam element 1m thick along the tunnel in the longitudinal direction. The area and the inertial moment of the cross section can be calculated on the basis of the structural dimensions given in Fig.2. A reduced stiffness of beam elements for columns was used to consider the column dissemination in the longitudinal direction according to the pillar span.

In implementing the FEDAM, a viscous boundary is used at both lateral sides of the finite element model and the rigid boundary at the model base is assumed. The earthquake wave is input to the model base. In implementing the FERSM and FERAM, the boundary nodes at both sides of the finite element model are assumed to be fixed along the vertical direction and free in the horizontal direction, and the boundary at the base is the same as in FEDAM. To avoid the possible influences of lateral boundaries of the soil region on the structural response, the total width of the finite element model of the soil is taken to be near 10 times the total width of the structure. The depth of the soil layer beneath the structure base, 10.6m, seems to be to small, and some errors in the structure base slab response could result. The discretization of soil layers in the direction of depth is sufficient enough to enable all the frequency contents within 10 Hz of the input earthquake waves to pass through.

The standard stress-strain curves and damping characteristic curves derived from information No. 1504 and 1778 from the Japanese Civil Construction Technology Research Institute were used in this analysis.



Top storey central column 0.5×1.300
Middle stoey central column 0.5×1.300
Bottom storey central column Φ0.65 (steel pipe column)

Fig. 2 Cross sectional dimensions of the structure and soil basic parameters

Table 1 Material parameters of the structure

Material	Strength (MPa)	Mass in unit volume ($t \cdot m^{-3}$)	Modulus of elasticity (10^5MPa)	Poisson's ratio
Concrete	240 (Design reference strength)	2.5	2.5	0.17
Reinforcement bars	3500 (Tensile strength)	7.8	21.0	0.30

The horizontal NS component acceleration wave (Fig. 4) recorded at a depth of 83m at Port Island in the 1995 Kobe earthquake was adopted for the input earthquake motion with a time duration of 20.48s and a sampling time interval, Δt=0.01s.

Prior to the soil-structure response analysis, a one-dimensional analysis of the free field response using different methods was performed and compared.

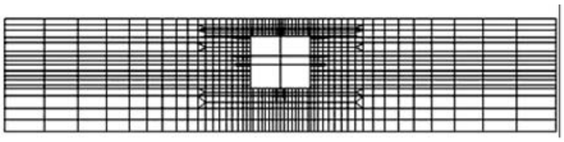


Fig. 3 Model for FEM analysis

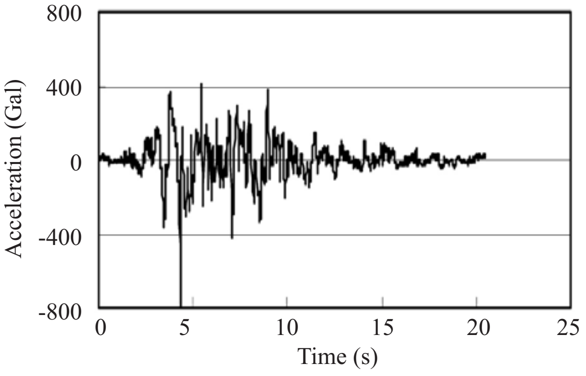


Fig. 4 Input of seismic acceleration wave

3.2 Results of one-dimensional free field response analysis of soil layers

A preliminary verification of the reliability of the FERSM and FERAM was performed by applying the free field response analysis of the soil profile with a unit thickness in the longitudinal direction as shown on the left of Fig. 2. Using the SHAKE program, the convergent values of shear modulus of various soil layers were calculated through iteration. With these convergent values, the characteristics of the soil layers in the finite element pseudo-static analysis are calculated and then the parameters of the soil springs (JRA, 1996) in the response displacement method can be determined. Figure 5 shows the seismic response, including the acceleration, velocity, relative displacement, shear stress and damping ratio, in the free field of the soil layers at a time instant of t_1=4.59s. The maximum displacement of the soil layer occurs at a depth corresponding to the top of the structure relative to that at a depth corresponding to the structure base.

The results calculated by using FERSM and FERAM are shown in Fig. 6, where the results by SHAKE are also provided for comparison. The figure shows that though both the FERSM and FERAM used the value calculated by the SHAKE program as the seismic input, the reappearance of the stress and strain status in the soil layers is achieved only by using the FERSM. The FERAM yields an error in the relative displacement on the ground surface of more than 30%. This is due

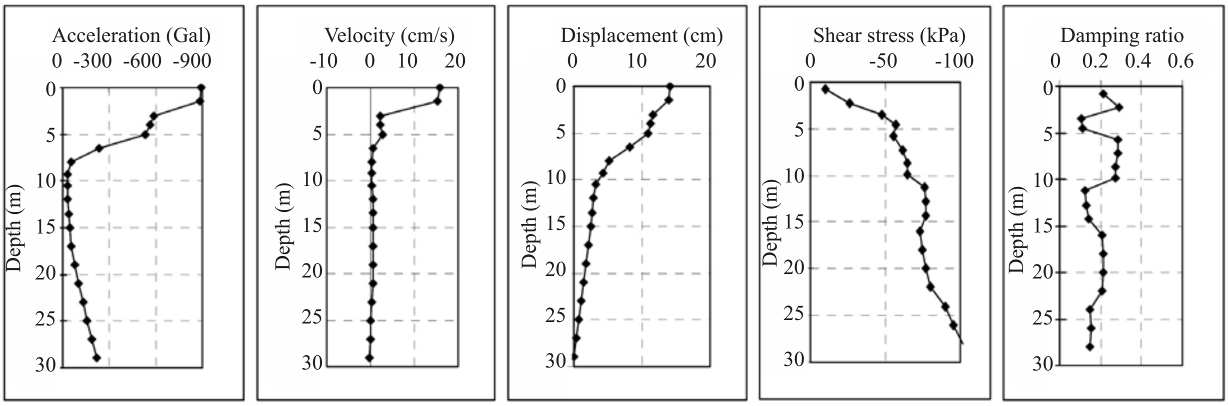


Fig. 5 Seismic response distribution with depth in free filed by using SHAKE model (t=4.59s)

to the fact that in the soil layers above the structure, as shown in Fig.5, there is a comparatively high velocity at t_1=4.59s and a high damping ratio of greater than 0.1. Consequently, a high damping force is generated, which is ignored in the analysis of the FERAM. Assuming that the damping ratio in the soil layers is very small, let h=0.005, a calculation was conducted again by using the SHAKE software and FERAM, and the results now become nearly identical (see Fig. 7).

3.3 Comparison of internal forces of underground structure

The validity of the proposed FERSM is verified by applying it to the response analysis of underground structures. The bending moment, axial force and shear force distribution obtained by using FEDAM, RDM, FERAM and FERSM are shown in Fig. 8, where only the results associated with the right half are given due to

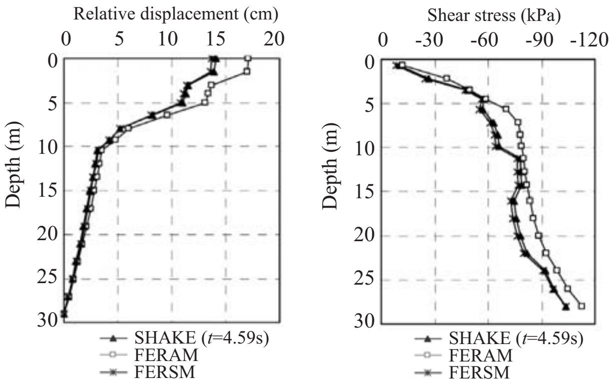


Fig. 6 Response displacement and stress of soil

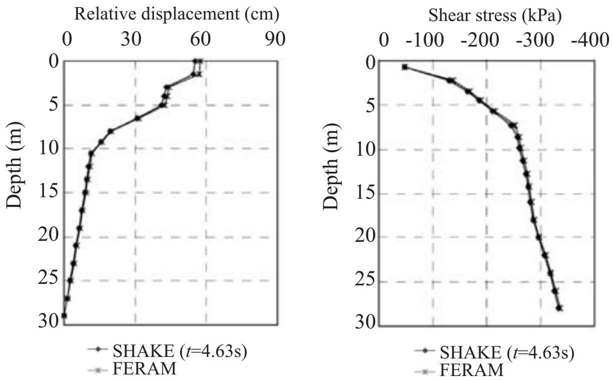
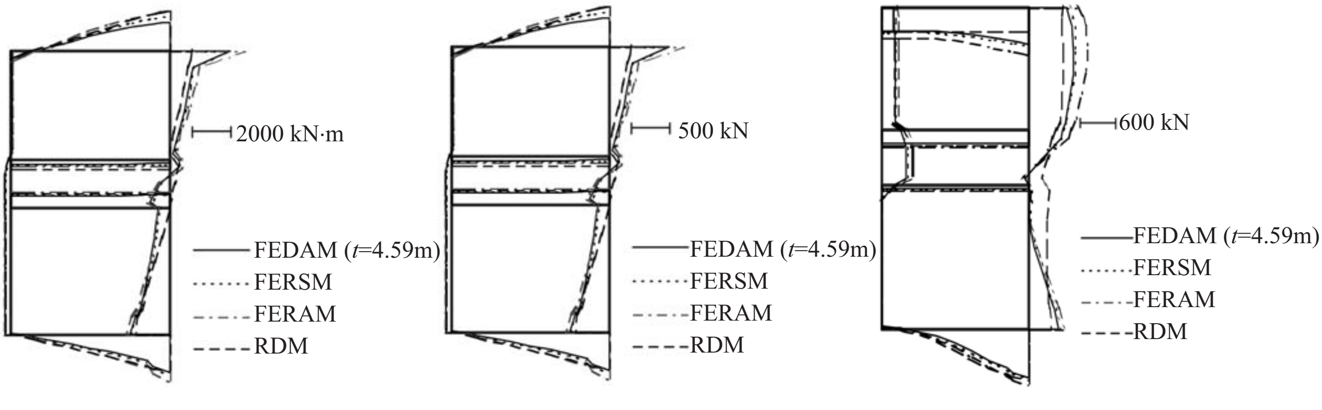


Fig. 7 Response displacement and stress of soil (damping ratio h=0.005)



(a) Bending moment (b) Axis force (c) Shear force

Fig. 8 Internal force distribution in structure (t=4.59s)

space limitiations, and the similarity of the results of the neglected left half from the geometrically symmetrical right half. The results show that compared to the FEDAM, the traditional RDM yields an error of about 30% for the internal forces of the structure at common locations and even larger errors at some local locations (such as the four corners and middle of the structure). The internal forces as a whole have no sense of direction either on the high side or on the low side, which cannot properly represent the internal force distribution of the structure. As far as the FERAM is concerned, though the calculated internal forces display some dynamic performance characteristics, they overestimate the response. The proposed FERSM is capable of providing satisfactory results, with errors in internal forces of the structure within 5% to 10%.

4 Conclusion

The following conclusions can be drawn from the numerical results:

(1) If the results obtained from the FEDAM are taken as a standard, the proposed FERSM has the highest precision, the FERAM has a comparatively high precision and the traditional RDM has the worst performance.

(2) Yielding a high precision, the proposed FERSM is not as complicated as the dynamic analysis method and is basically as simple as any other pseudo-static method. It could easily be used by engineers who are familiar with other pseudo-static methods. In the present example, the underground structure takes a box shape. However, FERSM can also be used for structures with different shapes.

(3) The proposed FERSM, or the improved pseudo-static approach, uses the static method to calculate the seismic response of underground structures. From the viewpoint of dynamic theory, as long as the equivalent mass density and stiffness of a structure are different from those of soil, neglecting the dynamic coupling between the structure and the surrounding soil layers would lead to some errors in the structure response estimated by the pseudo-static approach. This is a fundamental imperfection of this method. However, the equivalent mass density of an underground structure with a large cross section is usually much smaller than that of the surrounding soil. Furthermore, the equivalent stiffness of the structure is comparable to its surrounding soil. Therefore, either in theory or from the calculation results of actual engineering projects, the seismic response of underground structures is mainly subjected to the deformation or strain of the soil layers. Therefore, the dynamic coupling has little influence on the results.

Note that in this example, the structure's behavior is considered to be linear. Further verification should be conducted for nonlinear structures.

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