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Seismic response of vertical shafts in multi-layered soil using dynamic and pseudo-static analyses

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Abstract. In this study, numerical analyses were conducted to investigate the load transfer mechanisms and dynamic responses between the vertical shaft and the surrounding soil using a dynamic analysis method and a pseudo-static method (called response displacement method, RDM). Numerical solutions were verified against data from the literature. A series of parametric studies was performed with three different transient motions and various surrounding soils. The results showed that the soil stratigraphy and excitation motions significantly influenced the dynamic behavior of the vertical shaft. Maximum values of the shear force and bending moment occurred near an interface between the soil layers. In addition, deformations and load distributions of the vertical shaft were highly influenced by the amplified seismic waves on the vertical shaft constructed in multi-layered soils. Throughout the comparison results between the dynamic analysis method and the RDM, the results from the dynamic analyses showed good agreement with those from the RDM calculated by a double-cosine method.

Keywords: vertical shaft; underground structure; multi-layered soil; seismic design; dynamic analysis; response displacement method (RDM)

1. Introduction

Underground structures are in integral part of infrastructures and have been widely constructed in urban areas. There is a great demand for the development of underground space including subways, tunnels, and underground storages. In this regard, varying widely in shape and size, underground structures can be classified into two groups; the first one is a laterally long or wide underground structure (i.e., horizontal tunnel); another is a vertically long underground structure (i.e., vertical shaft). These underground structures are necessary to be constructed in deeper locations to avoid existing structures (e.g., deep foundations and tunnels). For this reason, a number of vertical shafts has been increasingly constructed in urban areas as ventilation systems, working spaces, and vertical access areas connected to deep horizontal tunnels (Jeong *et al*. 2010, Kim *et al*. 2013, Lee *et al*. 2016). Therefore, vertical shafts have a higher risk under seismic loading as compared to horizontal tunnels since the vertical shaft is vertically constructed in the multi-layered soil that is likely to experience a severe deformation due to an amplified seismic wave (Wong and Kaiser 1988).

A seismic design of underground structures is characterized in terms of a dynamic deformations and stress-strain relationship on the structure due to a fundamental deformation of surrounding soils (kinematic interaction) during earthquakes (Akagi 2004, Gazetas *et al*. 2005, Hashash *et al*. 2005, Kwak *et al.* 2018, Liu *et al*. 2018). For a vertical shaft, the special attention is given to the deformation of the surrounding soil and the ground motion parameters (e.g., peak acceleration, peak velocity, target response spectra, and ground motion). In addition, it is necessary to investigate the influence of layered soils and wave conditions on the vertical shaft since there exist some uncertainties. In general, there are two basic approaches for the seismic design of vertical shafts (Gioda and Swoboda 1999). The first approach is to carry out a dynamic analysis using a finite element method. The second approach assumes that seismic ground motions induce a pseudo-static loading condition on the structure, which is called a response displacement method (RDM). The latter allows the development of analytical solutions to evaluate the magnitude of seismically induced strains in underground structures (Penzien 2000 and Hashash *et al*. 2001). These relations are based on the premise that the vertical shaft subjected to seismic loads tend to deform with the surrounding soil, and thus the structure is designed to accommodate the free field deformation without loss of itself structural integrity (John and Zahrah 1987, Kaizu 1990, Uenishi and Sakurai 2000).

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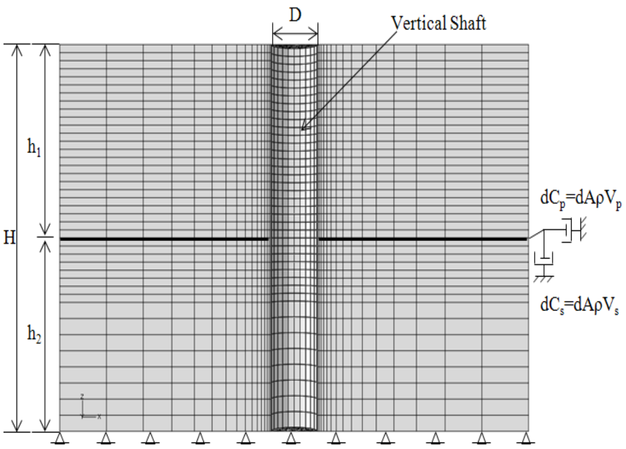
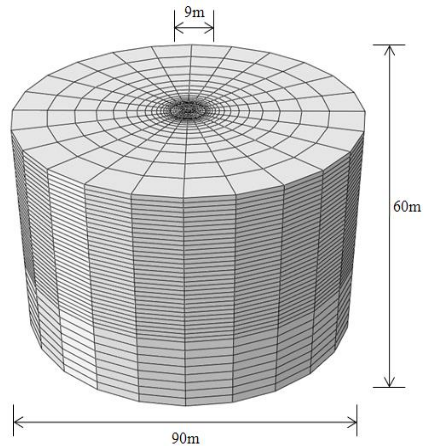
Table 1 Material properties used in dynamic analyses

		Model	Thickness (m)	γ_{sat} (kN/m^3)	E_s (MPa)	V_s (m/s)	c_u (kPa)	ϕ (deg)	υ	Earthquake Wave
Vertical Shaft	Side wall	Elastic	0.6	25	28,000	-	-	-	0.2	-
	Top/bottom slab	Elastic	0.5/1.0	25	28,000	-	-	-	0.2	-
Case A	h_1	M-C*	20	18	41	180	100	30	0.4	Ofunato Hachinohe Artificial
	h_2	M-C	40	21	807	760	0	40	0.3	
Case B	h_1	M-C	30	18	41	180	100	30	0.4	
	h_2	M-C	30	21	807	760	0	40	0.3	
Case C	h_1	M-C	40	18	41	180	100	30	0.4	
	h_2	M-C	20	21	807	760	0	40	0.3	

*Mohr-Coulomb, Damping ratio of the layered soils: 5%



(a) Plane view (x-z direction)



(b) 3D view (x-y-z direction)

Fig. 1 Finite element mesh and boundary condition of the vertical shaft and surrounding soil

Some attempts have been conducted to study the seismic behavior of underground structures in laboratory tests and numerical simulations (An *et al*. 1997, Hashash *et al*. 2001, Ortlepp 2001, Makovicka and Makovicka 2005, Huo *et al*. 2006, Huo *et al*. 2005, Kawashima 2006, Zhang *et al*. 2017, Lim and Jeong 2018, Sun *et al*. 2019). Nevertheless, it can be pointed out that most works have focused on the behavior of horizontal tunnels and structure performances that are limited to site-specific characteristics. Despite a growing interest in the construction of vertical shafts, very few studies have considered the structure that constructed in the multi-layered ground because the vertical shaft is assumed to be a minor structure in the field (Jeong *et al*. 2010).

In this study, numerical analyses were conducted to investigate the load transfer mechanisms and dynamic responses of the vertical shaft in layered soils using a three-dimensional dynamic analysis method and a response displacement method (RDM). Numerical solutions were verified against data from the literature. A series of parametric studies was performed with three different excitation motions, various surrounding soils. Results of dynamic analyses were compared with those from the RDM in terms of the maximum shear force and bending moment of the vertical shaft. In combination of finite element method, the observation gives the insight to understand the behavior of the vertical shaft in multi-layered soils under seismic loading.

2. Finite element model

Three-Dimensional dynamic finite element analyses were carried out using the commercial software ABAQUS version 2012 (ABAQUS Inc. 2012). A finite element mesh consisting of the three-dimensional element was developed, in which the surrounding soil and vertical shaft were modeled, respectively, by eight-node hexahedra elements. The cross-section of the vertical shaft was represented by cylindrical shell elements with a specified thickness. The vertical shaft element was assumed to remain elastic at all time, while the surrounding ground was idealized as a linear elastic material first and then as an elasto-plastic material. A hysteretic nonlinear model was incorporated in the dynamic analysis (Huo *et al*. 2005). The model captures the behavior of shear modulus degradation and damping increase with strain. All analyses were performed considering a 60 m in height and a 9 m in outer diameter of the vertical shaft. The material properties of the reinforced concrete are modulus of elasticity (E) of 28 MN/m^2, Poisson's ratio (v) of 0.2, and mass density equal to 2500 kg/m^3. The surrounding soil consists of a two-layer system. As shown in Fig. 1, total depth (H), in a vertical layer is 60 m. The soil layer (h_1) and the bedrock layer (h_2) were varied from 20 m to 40 m. Material properties and ground conditions for numerical analyses are summarized in Table 1, where the parameters

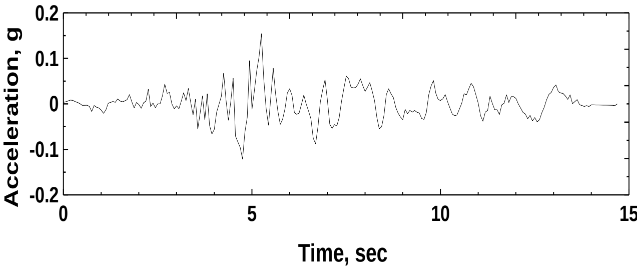
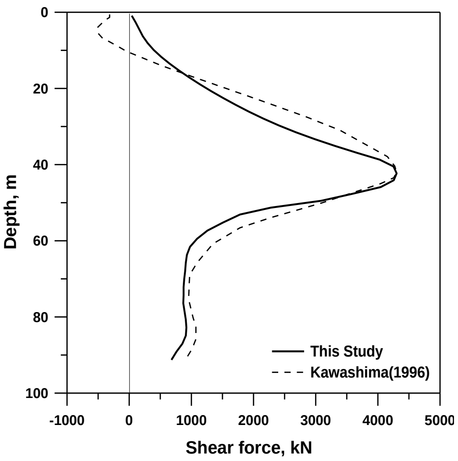
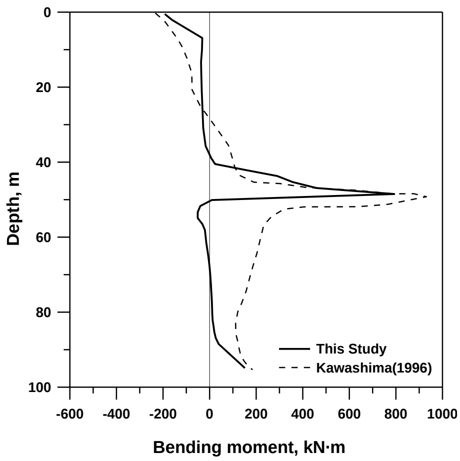


Fig. 2 Input ground motion



(a) Shear force versus depth



(b) Bending moment versus depth

Fig. 3 Comparisons between this study and literature

are listed: unit weight (γ), soil and structure modulus (E), mean shear wave velocity (V_s), cohesion (c), internal friction angle (ϕ), Poisson's ratio (v).

In dynamic analysis, both the structure and the surrounding ground were modeled by three-dimensional of finite element method. An issue is the effect of the location and nature of the lateral boundaries on the response of the soil-structure system. This is needed because the model of the continuum requires the existence of a finite domain with well-defined boundaries. If the lateral boundaries are created artificially, it becomes necessary to determine appropriate conditions that simulate the physical behavior on the actual system. The appropriate boundary conditions should work as energy sinks rather than energy reflectors in the sense that the energy transmitted to the lateral boundary through the soil media should not be reflected back to the structure. Otherwise, the solution would be affected by the reflected energy between the structure and boundaries of the ground which does not exist in reality. In this paper, viscous damper boundaries were placed on the outer boundary of the mesh. It is based on the absorbing boundaries in order to simulate the radiation of energy. The viscous dashpot boundary was achieved using horizontal and vertical viscous dashpots, which absorb the radiated energy from the P and S waves, respectively. The efficiency of the viscous dashpots is quite acceptable, but as it depends strongly on the angle of incidence of the impinging waves the dashpots were placed at the boundaries to improve the accuracy of the simulation. This study assumed that the viscous damping was determined based on Rayleigh damping formulation and the damping ratio was assumed to be 5 % (Ahmadi *et al.* 2015).

The interface between the structure and the ground were modeled as a frictional surface. The contact can open if there is tensile normal stress or it can slip if the magnitude of the applied shear stress is larger than the shear strength, which is assumed to follow the Coulomb friction law. A coefficient of friction (μ) equal to 0.35 was assumed which corresponds to a friction angle and no cohesion between structure and ground was used. Note that the interface properties inferred from the soil properties and the friction coefficient exhibited no significant influence on the lateral behavior of the vertical shaft in the preliminary analyses. Similar results concerning the effect of interface properties were founded previously by Kim and Jeong (2011).

Special attention was paid to the initial stress field of soil. In ABAQUS program, at first, the initial stress was established in soil through initial condition command and adding the gravity of the soil. In the actual application for soil, the stress is induced from the soil weight over the calculation point is considered as the vertical stress and the horizontal stress is obtained through the vertical stress multiplied by the lateral pressure coefficient K_0. In this paper, the initial horizontal stresses in the soil were set up according to a K_0 value of 0.5.

The ground motions imposed at the bottom of the model for the numerical analyses are the motions registered at the Hachinohe and Ofunato in Japan. In addition, an artificial earthquake was made as a ground motion to evaluate the behavior of the vertical shaft. The input accelerations are specified on the bottom of the soil and at rock level in order to account for the amplification effects of the soil layer and its influence on the results.

3. Validation

The validity of the three-dimensional finite element model was tested by comparing the results of the existing study by Kawashima (1996). A vertical shaft consisted of a circular reinforced concrete structure with 20 m in diameter and 95 m in height and with lining thickness of 2 m. The concrete in the structure was modeled as an elastic material with unit weight (γ_{sat}) of 25 kN/m^3, Poisson's ratio (v) of 0.17 and Young's modulus (E_s) of 27 GPa. The vertical shaft was placed on a soft clay layer with SPT *N*-values of 0-10 and shear wave velocity of 0-172 m/s from 0 to 50m depth. Below the soft clay was a medium sandy gravel layer with *N*-values of about 50 and shear wave velocity 295 m/s from 50 to 90 m depth.

The surrounding soils were modeled as an elasto-plastic material; Young's modulus of 140 MPa, Poisson's ratio of 0.45, cohesion of 5 kPa and friction angle of 30° in the soft clay. A medium sandy gravel layer was modeled with Young's modulus of 420 MPa, Poisson's ratio of 0.35, and friction angle of 40°. The external ground motions imposed at the bottom surface of the medium sandy gravel layer. Fig. 2 shows the applied ground motion, which has a maximum horizontal acceleration about 0.154 g. The results of shear force and bending moment on the vertical shaft obtained from numerical analyses were compared with those from the literature conducted by Kawashima (1996) in Fig. 3. The result from Kawashima (1996) is based on the two-dimensional finite element approach. The comparison results of shear force and bending moment of the vertical shaft along the depth were shown that present analysis results were in a good agreement with previous results. It is the best way to verify the numerical model since there is a lack of sufficient data or observations on the vertical shaft.

4. Parametric study

The dynamic behavior of a vertical shaft in multi-layered soils is influenced by the soil stratigraphy when seismic loads are induced. This is referred to as the site effect. A major parameter influencing the site effect is the composition of soil layers. In 1985, Mexican earthquake in Mexico clearly showed this influence through the damaged underground structures such as tunnel, utility pipe conduit. Another parameter influencing the site effect is the input motion such as frequency content, amplitude, duration time. To obtain detailed information on the dynamic behavior of the vertical shaft, a series of numerical analyses on the vertical shaft was performed for different soil conditions and input motions. Total depth (H) in a vertical soil layer is 60 m. The first layer (h_1) and second layer (h_2) of soil were varied from 20 m to 40 m. The applied accelerations at the bottom of the vertical shaft are plotted in Fig. 4. In order for the accelerations to eliminate the accumulated errors, the baseline correction was carried out. Material properties and ground conditions for numerical analyses are summarized in Table 1. The soil properties were inferred from the shear wave velocity at the site.

In addition to comparison with dynamic analysis results, the response displacement method (RDM) analysis was performed based on a pseudo-static approach. In this method, the displacements of surrounding soils were evaluated using a single cosine method, double cosine method, and one-dimensional seismic response analysis method (i.e., Proshake). The distribution of soil displacement along the vertical direction using the single and double cosine methods can be calculated as follows, respectively:

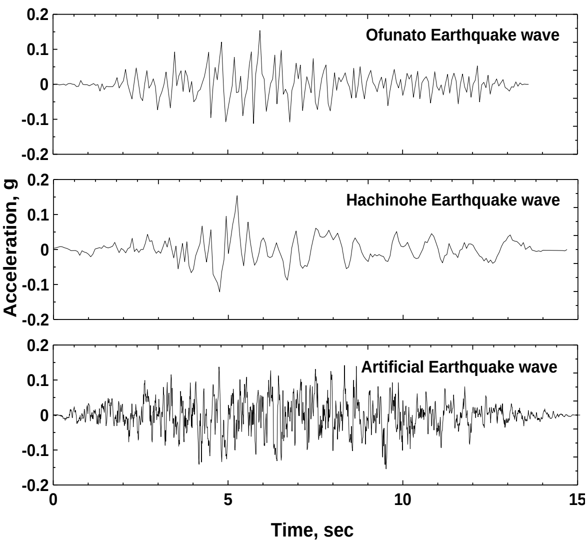


Fig. 4 Three earthquake waves used in parametric studies

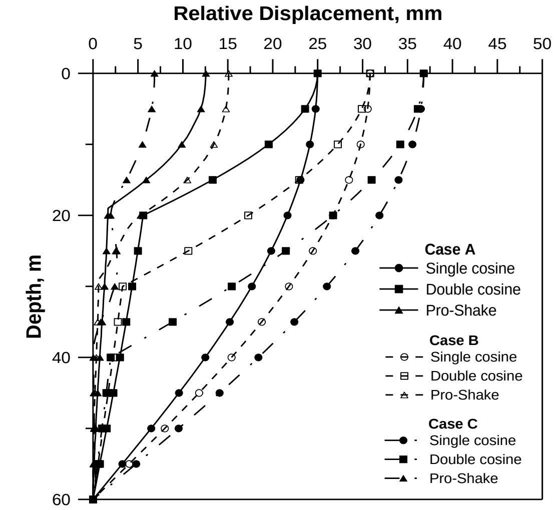


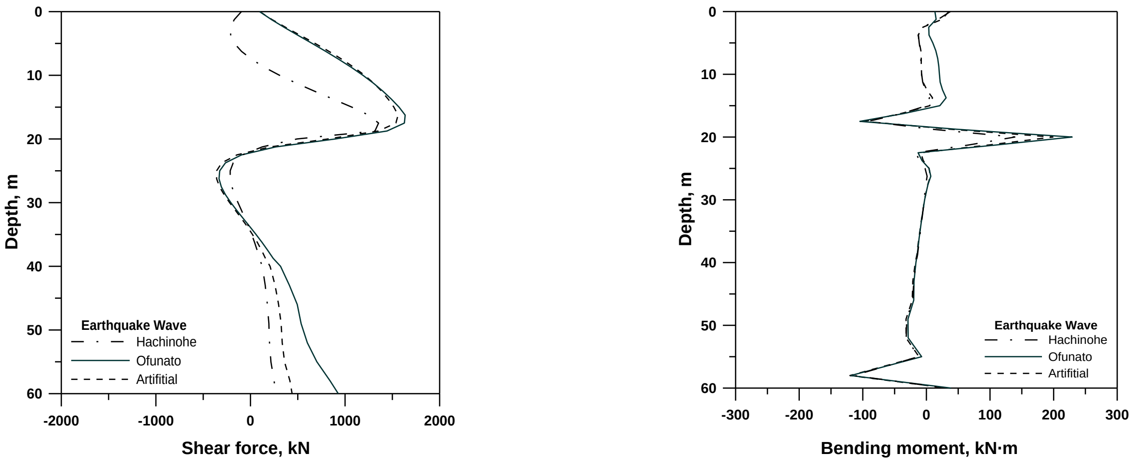
Fig. 5 Relative displacements from single cosine, double cosine, and proshake methods

$$U_h(z) = \frac{2}{\pi^2} S_v T_G \cos\left(\frac{\pi z}{2H_2}\right) \quad (1)$$

$$U_{h1}(z) = \frac{2}{\pi^2} S_v T_G \cos\left(\frac{\pi z_1}{V_{s1}}\right) \quad (2)$$

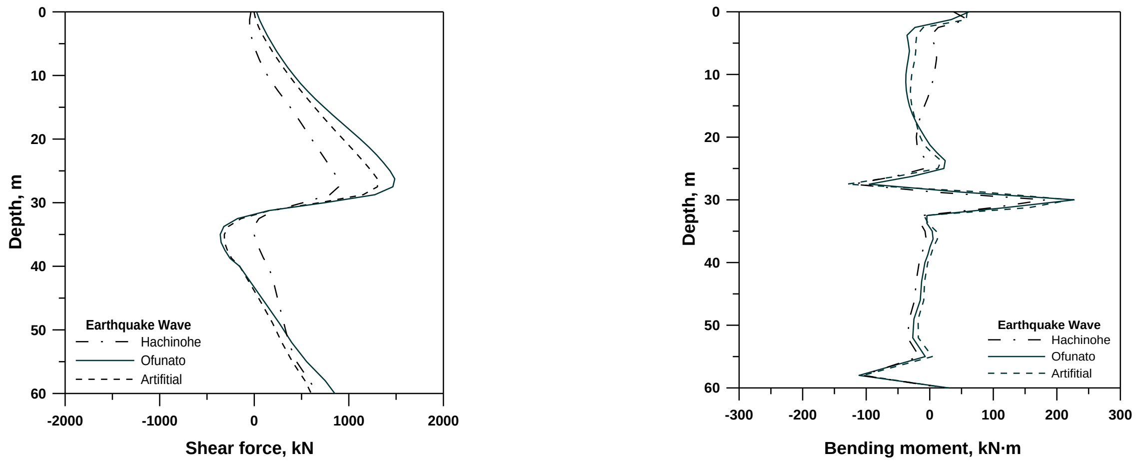
$$U_{h2}(z) = \frac{2}{\pi^2} S_v T_G \cos\left(\frac{\omega H_1}{V_{s1}}\right) \cos\left(\frac{\omega z_2}{V_{s2}} - \frac{\sin\frac{\omega z_2}{V_{s2}}}{\tan\frac{\omega H_2}{V_{s2}}}\right) \quad (3)$$

Here, $U_h(z)$, $U_{h1}(z)$, $U_{h2}(z)$ are the displacement of



(a) Shear force versus depth (b) Bending moment versus depth

Fig. 6 Comparison of shear force and bending moment of the vertical shaft (case A)



(a) Shear force versus depth (b) Bending moment versus depth

Fig. 7 Comparison of shear force and bending moment of the vertical shaft (case B)

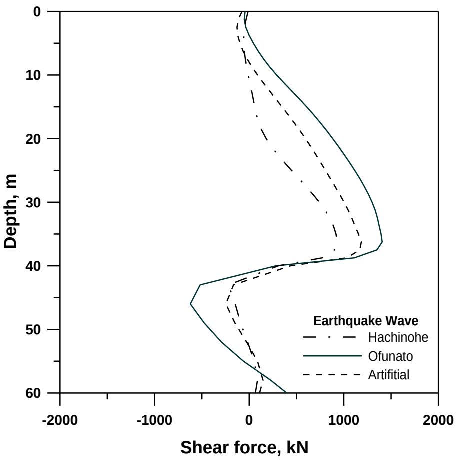
entire soil, surface (first), and subsurface (second) layers in the horizontal direction at a certain depth z from the ground surface, respectively; S_v is the velocity response spectrum; T_G is the first natural period of surface ground. The coefficient $2S_vT_G/\pi^2$ indicates amplitude of ground surface displacement; H_s, H_1, H_2 are the thickness of entire soil, surface, and subsurface layers, respectively; V_{s1}, V_{s2} are the mean shear wave velocity in surface and subsurface layers, respectively; ω is the natural frequency of soil. The comparisons for the distribution of relative displacements among the three methods were plotted in Fig. 5. In this section, these three methods were incorporated in the comparison study to investigate the effect of each method in determining the shear force and bending moment.

5. Results and discussion

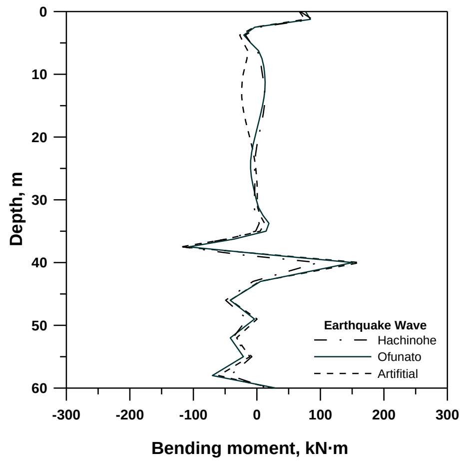
Figs. 6-8 show the shear force and bending moment distributions of vertical shafts in case A, case B and case C, respectively. In soil profiles where the transition between layers is sharp, the bending moments in the vertical shaft have been found to be significant, especially near interfaces of layers with highly contrasting stiffness where a stress peak arises. Figs. 6-8 show the bending moments and the shear force profile obtained for a two-layered soil profile with a sharp change of properties between the upper and the lower layers. The figures represent the maximum values at a certain time along with the depth. It can be observed that the shear force and bending moment of vertical shafts exhibit maximum values at the interface between the soil layers. This is attributed to relative displacement between the two soil layers; a displacement of upper soil is relatively larger than lower soil. In addition, the maximum shear force and the bending moment were obtained by applying the Ofunato earthquake. All results (case A, B and C) show a similar tendency in developing maximum values. Consequently, input motions and ground conditions may affect the seismic response of the vertical shaft.

Fig. 9 shows the comparison of maximum shear force and bending moment of the vertical shaft with respect to different surrounding soil conditions. It can be observed that the largest shear force and bending moment occurred in the case A, and then the smallest value was in the case C.

These results could be attributed to the amplification of earthquake waves. The amplification ratio in case A is much

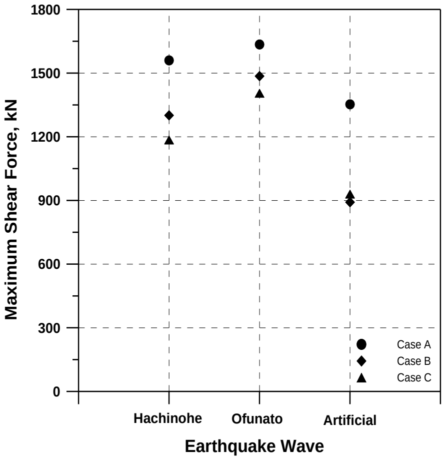


(a) Shear force versus depth

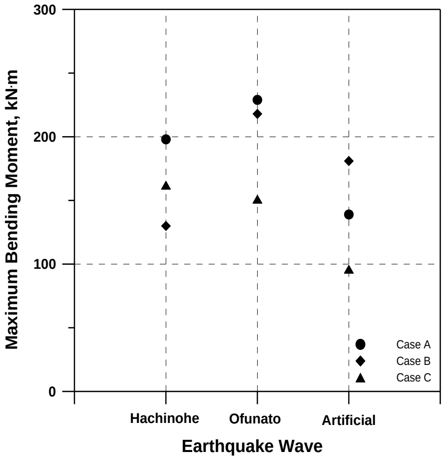


(b) Bending moment versus depth

Fig. 8 Comparison of shear force and bending moment of the vertical shaft (case C)

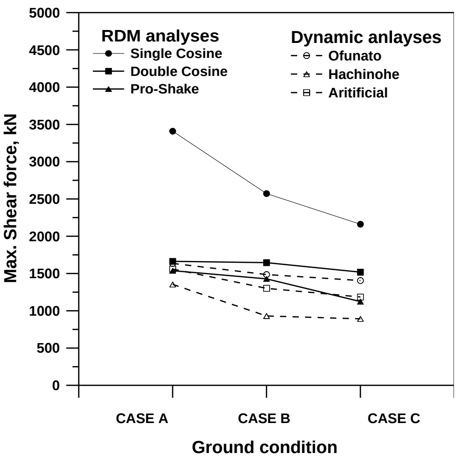


(a) Maximum shear force versus earthquake wave

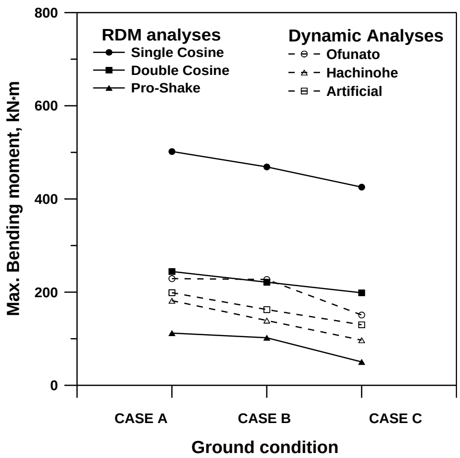


(b) Maximum bending moment versus earthquake wave

Fig. 9 Comparison of maximum shear force and bending moment of the vertical shaft



(a) Maximum shear force

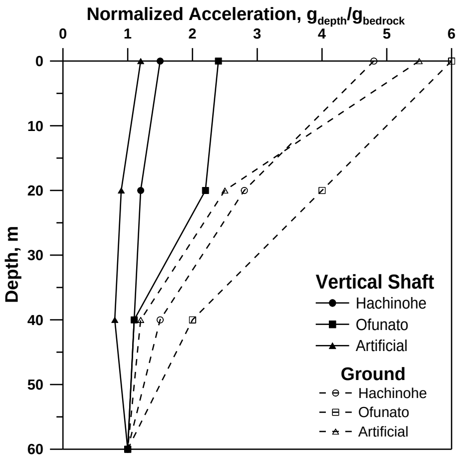


(b) Maximum bending moment

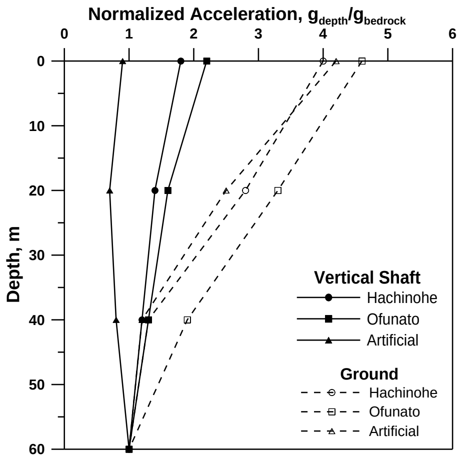
Fig. 10 Comparison of maximum shear force and bending moment between dynamic and RDM analysis

higher than others because the bottom layer with higher soil stiffness may transfer earthquake energy to the upper layer without energy loss.

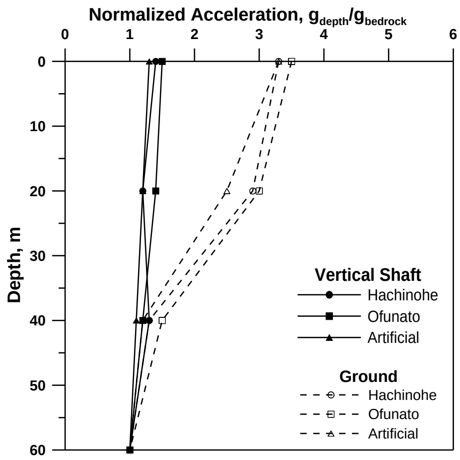
Fig. 10 shows the maximum shear force and the bending moment of the vertical shaft in case A, case B and case C, respectively. This figure shows comparison results between the dynamic analysis method and RDM method. The results obtained from RDM method showed that the maximum shear force and bending moment of the vertical shaft tend to increase as the stiff layer depth increases. This result



(a) Case A



(b) Case B



(c) Case C

Fig. 11 Normalized acceleration amplitude ratio between vertical shaft and surrounding soil for three earthquakes

indicates that the pseudo-static approach can capture the amplification of the earthquake wave indirectly. On the other hand, the results of the RDM analysis overestimated the shear force and bending moment when a single cosine method is applied to estimate the relative displacement of the soil because the relative displacement of soils calculated by the single cosine method exhibits the largest value among other methods (Fig. 5). However, when the double cosine method and the Pro-Shake method are considered as an evaluation method of the relative displacement of surrounding soils, the results obtained from the RDM analysis were in a good agreement with those from the dynamic analysis results.

The influence of the ground conditions on the dynamic behavior of the vertical shaft in response to the three earthquake waves was investigated through analyses conducted for a constant acceleration of input motions (a_{max}=0.154 g). Fig. 11 shows the amplification characteristics of vertical shafts and surrounding soils under seismic loading. The amplitude ratio at each point in the surrounding soils and the vertical shafts correspond to the maximum acceleration of an earthquake motion obtained at points 0 m, 20 m, 40 m and 60 m respectively.

It can be observed that the amplitude ratio of the vertical shaft is smaller than that of the surrounding soil in three ground cases. These results are based on characteristics of underground structure which tends to deform with the surrounding soil. Especially, maximum acceleration amplitude was estimated in case A because earthquake wave was amplified through a layered soil.

6. Conclusions

This paper presents the seismic analysis of vertical shafts to study the load transfer mechanism between the vertical shaft and the surrounding soil. Numerical solutions were verified against the literature data. A series of dynamic finite element analyses were conducted to determine the shear force and bending moment of the vertical shaft under seismic loading. In combination of finite element analyses, the observation gives the insight to understand the seismic behavior of vertical shafts in multi-layered soils. Based on the findings of this study, the following conclusions can be drawn:

- Based on the results, it is shown that the dynamic behavior of the vertical shaft is significantly influenced by the soil stratigraphy and input motion.
- The peak values of the bending moment and shear force in the vertical shaft occur at the interface between the soil layers because of stiffness contrast between layers. It is important to note that the maximum values predominantly

near the interface between the soil layers.

• The response displacement method (RDM) analysis is dependent on the method of estimating relative displacements. Therefore, the commonly used method for calculating the relative displacement could be the double cosine method, which is in a good agreement with the results of dynamic analyses.

• The deformation and loading on the vertical shaft and surrounding soil are highly influenced by the amplitude of earthquake for the case of vertical shafts constructed in multi-layered soils.

Acknowledgments

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