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Seismic Analysis of Subsea Cable in Longitudinal Direction

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***Abstract*— In the underground structure, it is difficult to cause relative vibration to the surrounding ground. Therefore, the displacement of the ground caused by the earthquake is an important factor in seismic design of underground structures. Generally, the Equivalent Static Method (ESM) which computes pipe seismic response quantities using idealized models describing the interaction of the hazard, soil and pipe is widely used. In this study, the longitudinal displacement profile is developed from spatially variable ground motion time histories. The longitudinal displacement profile is used to perform a series of three dimensional finite element analyses. The results are compared with the design method. The site natural period can be used to predict the predominant period of acceleration, but it can't be used to predict the predominant period of displacement. If accurate information on the wavelength of the displacement is provided, the design method for the harmonic wave is highly accurate and applicable to the design.**

***Keywords*—Subsea cable, Axial strain, Wavelength, Equivalent static method, 3D time history analysis**

I. INTRODUCTION

As offshore developments extend into deeper waters located further from shore, pipelines and cables represent an increasingly important part of the development infrastructure.

In the case of a structure such as a flexible pipelines with a long longitudinal length and a high flexural strength, it is reported that the damage caused by the shear deformation is small, unlike the tunnel, while the axial deformation causes a large damage[1].

In general, the axial strain induced in a straight continuous pipeline depends on the ground strain, the wavelength of the traveling waves and the interaction forces at the pipe-soil interface. For small to moderate ground motion, one may simply assume that pipe strain is equal to ground strain. This assumption results in the aforementioned upper bound relation. However, for large ground motion, slippage typically occurs at the pipe-soil interface, resulting in pipe strain somewhat less than the ground strain[2]. [3] evaluated the seismic response of the buried pipeline through the analysis using a 3D shell-spring model. However, it is not practically possible to apply it to all sections in the design of a very long buried pipe. In general, the seismic response of the buried pipe is calculated by applying the empirically estimated wavelength and interpretation of harmonic waves.

In this study, the accuracy of the seismic design process described above was evaluated. First, a series of ground response analyzes were performed to numerically calculate wavelengths and the results were compared with empirical methods to assess their suitability. Secondly, the accuracy of the analytical solution was evaluated by comparing the analytical results of the 3D time history analysis with the harmonic analysis.

II. SEISMIC DESIGN OF BURIED PIPELINES

A. *Equivalent static method*

Simplified procedures for assessing pipe response due to wave propagation were first developed by [4]. Newmark's approach is based on three assumptions. The first assumption is that ground motion at two points along the propagation path are assumed to differ only by a time lag. The second assumption is that the pipeline inertia terms are small and may be neglected. Experimental evidence from Japan[5], as well as analytical studies [6, 7], indicate that this is a reasonable engineering approximation. The third assumption is that there is no relative movement at the pipe-soil interface and, hence, the pipe strain equals the ground strain.

Fig. 1 shows a pipeline subject to S-wave propagation in a vertical plane having an angle of incidence γ_s with respect to the vertical. For this case, the ground strain parallel to the pipe axis is:

$$\varepsilon_g = \frac{V_{max}}{V_s} \sin\gamma_s \cos\gamma_s \qquad (1)$$

where V_{max} is the peak ground velocity and V_S is the shear wave velocity.

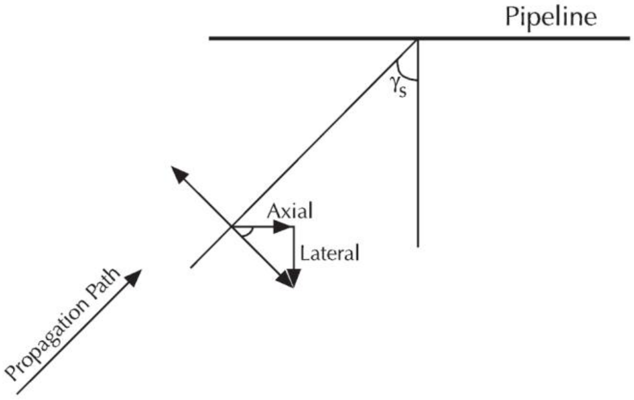

Fig. 1. S-Wave Propagation and Pipeline [8]

In relation to Newmark's assumption regarding no relative displacement at the pipe-soil interface, [2] proposed the maximum axial strain induced in continuous pipe by wave propagation as follows.

$$\varepsilon_p = smaller\ of \begin{cases} \varepsilon_g \\ \frac{t_u \lambda}{4AE} \end{cases} \qquad (2)$$

where t_u is the maximum frictional resistance and λ is wavelength and A is cross-sectional area and E is modulus of elasticity of the pipe.

The axial strain in a pipeline depends on the wavelength and the ground strain. However, there is uncertainty in the prediction of site wavelength.

B. Finite element method

To predict the seismic response of the subsea cable, 3D time history analyses were performed using Zeus NL[9]. The soil layer and cable were simulated with elastic spring and beam model, respectively. The ground motion is the displacement - time history at the depth of the cable extracted through the 1D site response analysis. The wavelength length L and the displacement amplitude A were estimated from 1D site response analysis. The displacement - time history and the shear wave profile were applied to calculate the longitudinal displacement profile. Finally, numerical analysis results and analytical solutions were compared.

The numerical model applied to the analysis is shown in Fig. 2. The soil springs are modelled to follow the elasto-plastic load-deflection curves presented in ALA[10]. They suggest, for the purpose of analysis, idealized elasto-plastic models

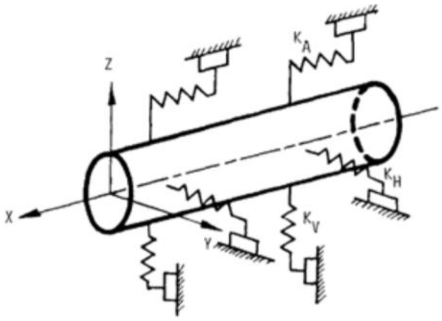

Fig. 2. Finite element model

The measured shear wave velocity profiles used in the analyses are shown in Fig. 3. The profiles 1~4 are homogeneous and the profiles 5~7 are based on site investigations performed in Korea. The diameter of the cable is 0.15m and the buried depth is 2.5m. The properties of soil and cable are summarized in Table 1 and Table 2.

The spring spacing is 10m and the cable length is 1km. The values of the spring coefficients are listed in Table 3. Note that the elasto-plastic model is fully characterized by two parameters: 1) the maximum resistance t_u, p_u or q_u in the axial, transverse-horizontal and transverse-vertical directions, respectively, and 2) the maximum elastic deformation x_u, y_u or z_u.

TABLE 1
SOIL PROPERTIES

Soil type	Specific weight (kN/m^3)	Friction angle (°)	Average shear wave velocity (m/s)
Profile 1	17	28	165
Profile 2	18	30	230
Profile 3	19	32	270
Profile 4	20	34	300
Profile 5	18	30	225
Profile 6	19	32	250
Profile 7	18	30	230

TABLE 2
MATERIAL PROPERTIES

Cable type	**Diameter (mm)**	**Elastic modulus (GPa)**	**Yield strength (MPa)**
Infield array	150	200	350

In a longitudinal structure such as a cable, a time lag occurs when the seismic load reaches each point. Therefore, the analysis was performed by simulating the time difference of the earthquake load at each point on the cable.

III. COMPARISON OF EQUIVALENT STATIC METHOD AND FINITE ELEMENT METHOD

A. 1D site response analysis

Three motions are used in the analyses, as shown in Fig. 4.

Each of the selected motions has been scaled to match the PGA of seismic zone I, with return periods of 1000 years. Note that the acceleration time histories and Fourier spectra of the input motions shown in Fig. 4 are scaled to a PGA of 0.154 g. Even though the motions are representative of the ground motions at rock outcrop, the frequency characteristics show distinct variation.

The equivalent linear analyses are also performed using Deepsoil[11]. In performing an equivalent linear analysis, the dynamic soil behavior is modeled using shear modulus reduction and damping curves. The shear modulus reduction and damping curves selected for the analyses are shown in Fig. 5.

The acceleration - time history at 2.5m, the depth of the cable, was calculated and the displacement - time history was derived through integration.

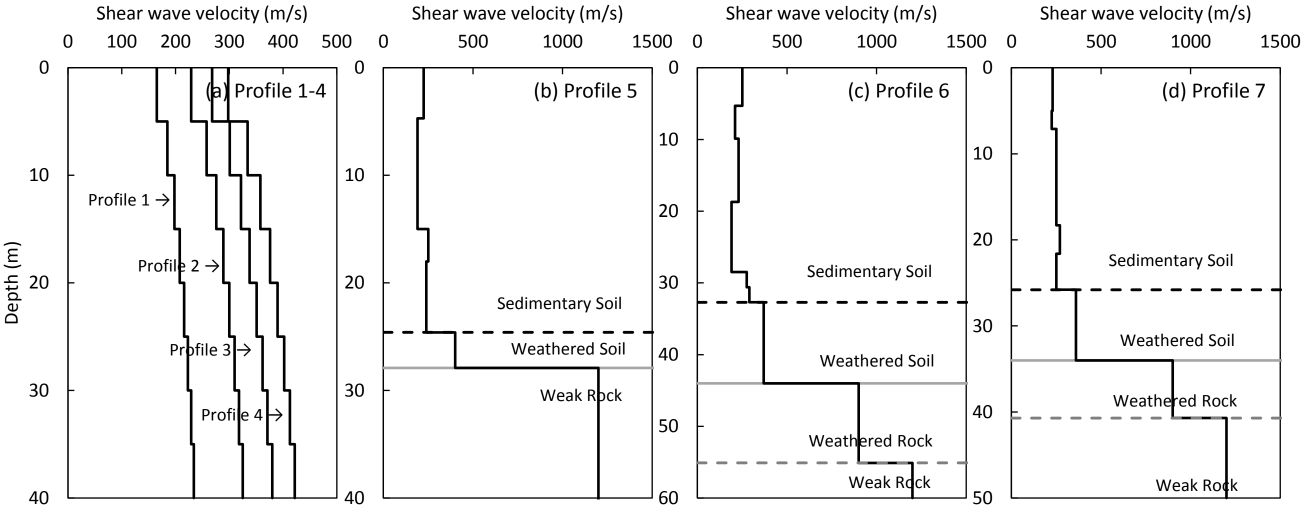

FIG. 3. SHEAR WAVE VELOCITY PROFILES

TABLE 3
SPRING COEFFICIENTS

	Axial direction		Transverse-horizontal direction		Transvers-vertical direction			
					Upward		Downward	
	t_u (kN/m)	x_u (mm)	p_u (kN/m)	y_u (mm)	q_u (kN/m)	z_u (mm)	q_u (kN/m)	z_u (mm)
Profile 1	2.5	2.5	40.3	22.5	23.4	37.5	26.3	257.5
Profile 2	3.1	2.5	55.6	22.5	28.8	37.5	42	128.8
Profile 3	3.7	2.5	76.6	22.5	35.1	37.5	57.4	128.8
Profile 4	4.4	2.5	104.6	22.5	42	37.5	75	77.3
Profile 5	3.1	2.5	55.6	22.5	28.8	37.5	42	128.8
Profile 6	3.7	2.5	76.6	22.5	35.1	37.5	57.4	128.8
Profile 7	3.1	2.5	55.6	22.5	28.8	37.5	42	128.8

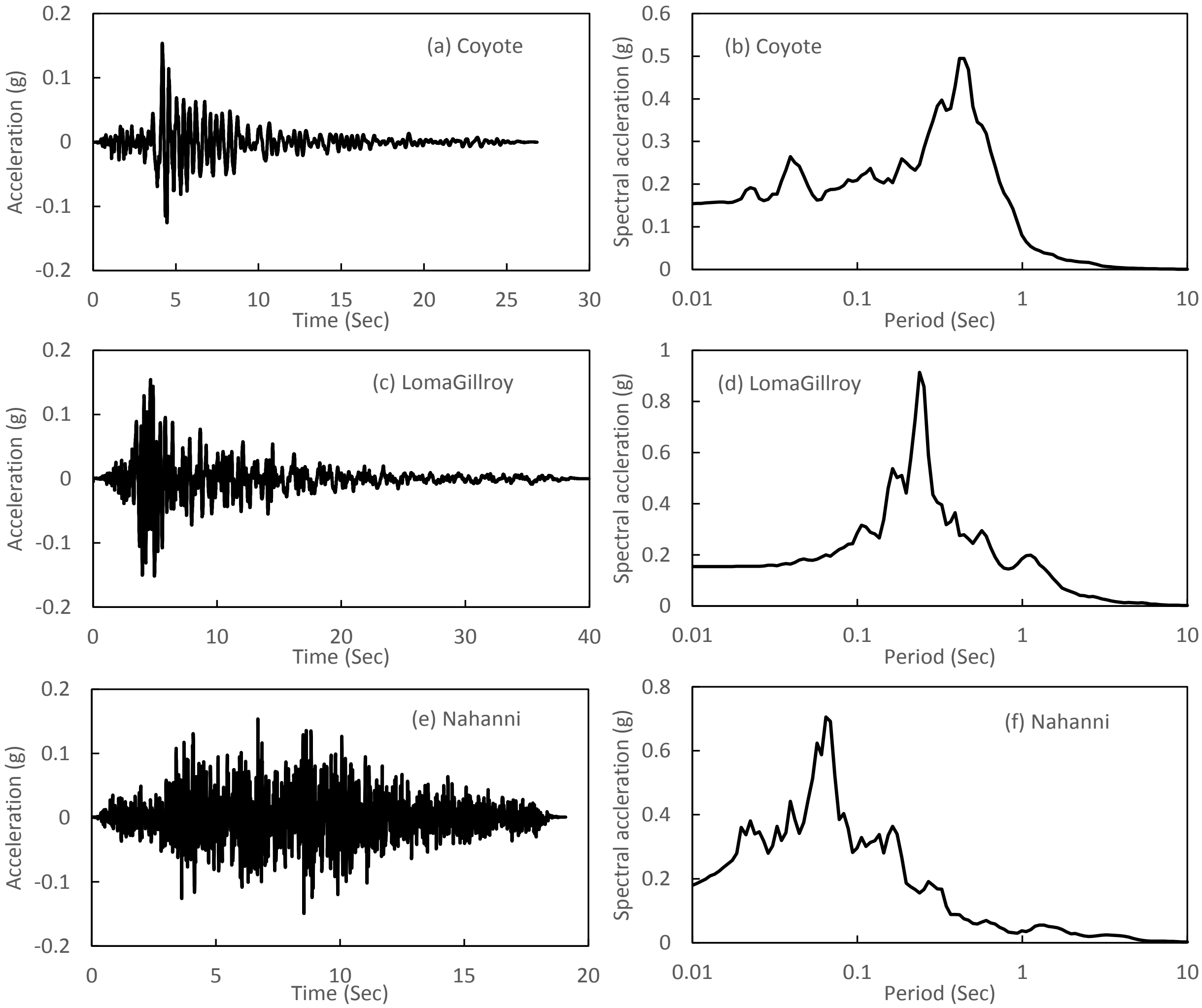

Fig. 4. Time histories and Fourier spectra of the input motions

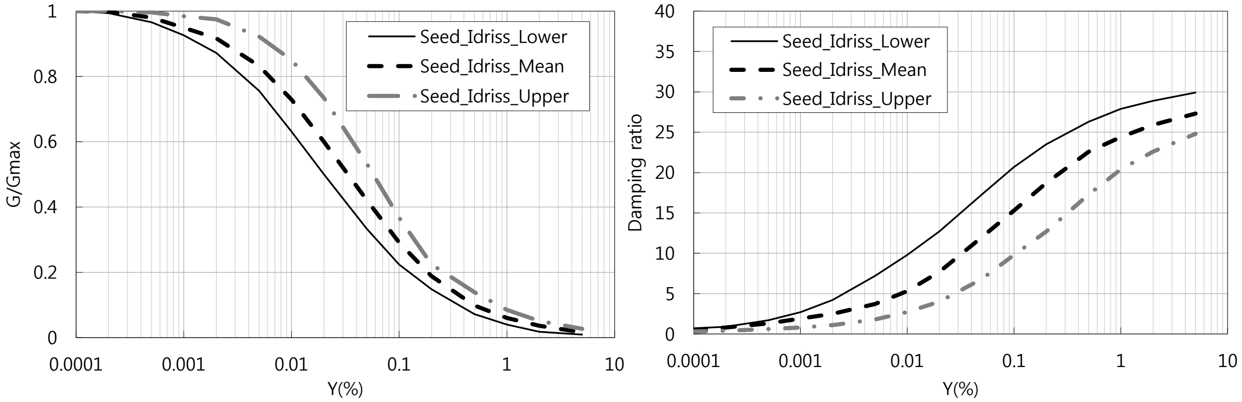

Fig. 5.The shear modulus and damping curves

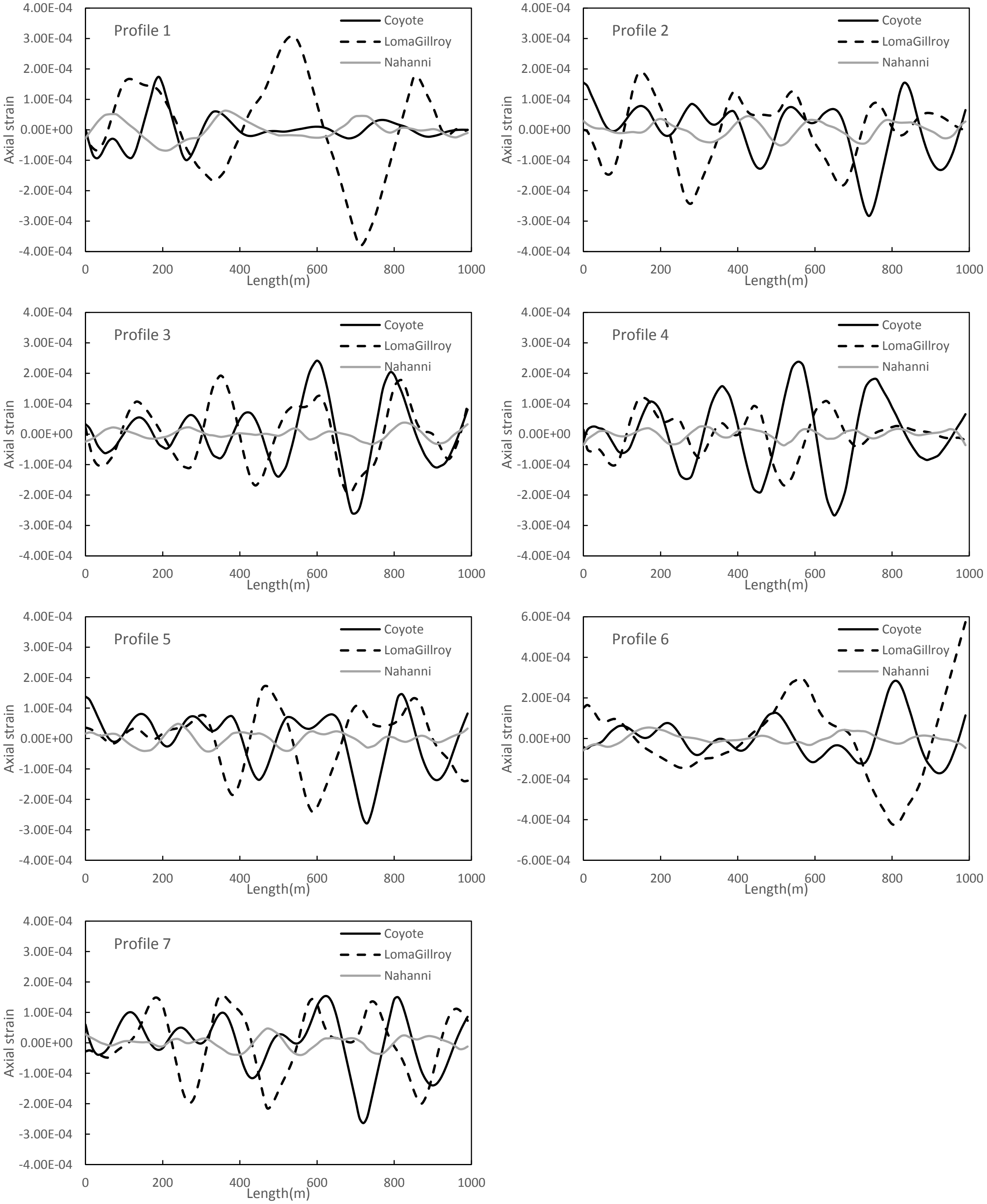

Fig. 6. Longitudinal displacement profile

B. 3D time history analysis

Fig. 6 shows the longitudinal displacement profile at the time of maximum displacement was calculated by the 1D site response analysis. The ground motion is assumed to be incident at an angle of 45 ° to the cable axis direction. From the calculated longitudinal displacement profiles, the wavelength at maximum displacement was calculated.

As described above, to estimate the longitudinal response of a cable using equivalent static method, the wavelength and amplitude must be estimated. In this study, the displacement amplitude was used as the result of the ground response analysis. The accuracy of interpretation was evaluated.

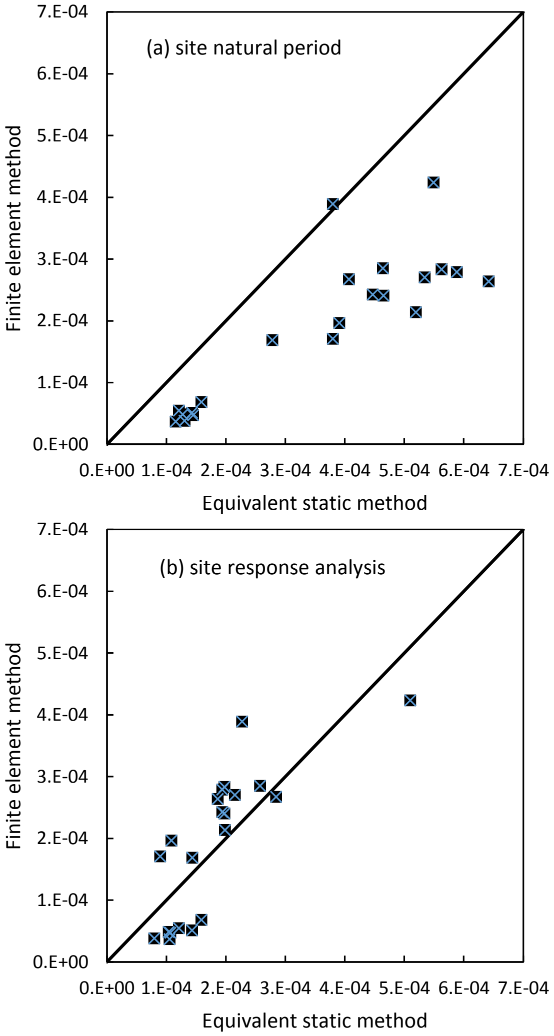

Fig. 7. Comparison of the ESM and FEM

Fig. 7 (a) compares the predicted strain with the wave length calculated from the natural period of the ground and the calculated result from the 3D time history analysis. It can be seen that the empirically estimated wavelength is very small compared with the result calculated from the numerical analysis, so that the calculated response is also very large. If the wavelength is not accurately predicted, it can be confirmed that the strain is largely overestimated. The results of applying the equivalent static method to the harmonic motion and the numerical analysis results are shown in Fig. 7 (b). When used in analysis, the wavelengths were calculated from the 1D site response analysis. Even if the response to earthquake records without actual harmonic motion is predicted, it is possible to obtain similar results to the 3D time history analysis by accurately predicting the wavelength from the ground response analysis.

IV. CONCLUSIONS

In this study, 3D time history analysis method and equivalent static method were compared by applying various seismic loads.

Displacement - time histories were extracted by performing 1D site response analysis and the calculated displacement - time histories were applied to 3D time history analysis. The conclusion of this study is as follows.

Previously, the wavelength was calculated by multiplying the natural period of the soil layer by the shear wave velocity. However, this predicts the actual wavelength to be very small. Therefore, in order to predict the wavelength, the displacement-time history should be calculated and applied from the site response analysis.

[2] proposed the maximum axial strain induced in continuous pipe with elastic behavior. As a result of comparing the results calculated by the finite element method with the equivalent static method, in the case of predicting the wavelength considering the displacement - time history, ground shear wave velocity and incident angle calculated by the ground response analysis, the equivalent static method accurately predicted the response of the cable.

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