Effects of soil, structure and seismic parameters on the natural frequency of retaining structures

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ABSTRACT

As an extension of the analytical model proposed and developed by the authors this paper studies the effects of soil, structure and seismic parameters on the natural frequency of retaining structures. The backfill soil behind the retaining structure modeled realistically by Coulomb and Mononobe Okabe failure wedges. Backfill material is considered in the analysis as cohesionless. The natural frequency increases with the increase of the values of soil backfill parameters and decreases with the increase of structure parameters and intensity of ground motion. Each variation of retaining structure, soil backfill and seismic accelerations changed the system and naturally the natural frequency.

Keywords: natural frequency; retaining structures; soil parameters; structure parameters; seismic parameters.

1. Introduction

An adequate determination of the natural frequency of retaining structures plays a primordial role in the study of its dynamic behavior in earthquake prone regions. Many researchers have developed several methods to determine the natural frequency of retaining structures. The natural frequency is often calculated by the elastic wave theory and based on two parameters namely height of the backfill and the soil shear wave velocity. Matsuo and Ohara (1960) obtained an approximate elastic solution using a two dimensional analytical model using two limiting boundaries where they believed the real solution lied within. They assumed zero vertical displacement in the soil mass. Wood (1973) provided a one of the more important analytical contribution to understanding and solving the problem of rigid structures retaining an isotropic homogeneous elastic soil material backfill, with a smooth contact soil-structure, subjected to harmonic excitation. However, Wood’s solution is mathematically complicated to apply in engineering practice and is limited to harmonic input motions. Wood (1973) suggested an approximate static solution that gave very good estimates of the peak seismic thrust for harmonic excitation when dynamic amplification effects in the wall-soil system were negligible. He found dynamic amplification to be negligible.
when the frequency ratio, of harmonic motion and of the first shear mode of the backfill, is less 0.5. It should be noted that the model used by Wood (1973) does not incorporate any effect of the inertial response of a superstructure connected to the top of the wall. Scott (1973) used a one dimensional elastic shear beam linked to the wall by Winkler springs to model the seismic effects of the backfill and to easily obtain the natural frequency of a rigid retaining wall by dotting a representative value of the Winkler spring constant. Veletsos and Younan (1994) concluded that Scott’s model does not adequately describe the response of the system and may lead to large errors. Ortiz et al (1983) investigated using the centrifuge modeling technique the behavior of flexible cantilever walls retaining a cohesionless soil subjected to dynamic excitations, and determined experimentally in prototype scale the fundamental frequency of the wall-soil by an examination of the Fourier Amplitude Spectra of the accelerograms recorded at the top and bottom of the wall. Based on these investigations it concluded that: the two walls of 18 feet and 20 feet had fundamental frequencies of 2.6 Hz and 2.5 Hz with the soil employed.

Alampalli and Elgamal (1997) studied in-situ dynamic response characteristics of a long reinforced cantilever wall-soil systems supporting an elevated backfill using an in-situ harmonic shaker. The results of this study showed that long wall-backfill systems of various heights display resonances with motion variation along the length, which may be of significance in seismic studies. Wu (1994) developed a modified shear beam model applicable to both finite and semi-finite backfills. This model validates the exact solution of Wood (1973). Wu and Finn (1999) used an approximate method based on a modified shear beam model to develop design charts of seismic thrusts against rigid walls under earthquake excitations for uniform and non-uniform soil backfills. A closed-form solution of the modified shear beam model has been used to compute the thrusts for uniform soil profiles. The design seismic thrusts are given as functions of the fundamental frequency of the soil-wall system.

Hatami and Bathurst (1999) studied the effects of: wall’s height, backfill width, stiffness and length of reinforcements, soil’s angle of friction, conditions of the toe’s abutment and magnitude of the earth movement. Hatami and Bathurst (2000) study showed that the principle frequency of the modeled reinforced retaining walls can be estimated using the elastic wave theory and the shear wave velocity in backfill with sufficient width and the wall height. Ghanbari et al (2013) modeled in their analysis the soil as a series of linear springs and presented an analytical formulation to calculating the natural frequency of retaining walls, this formula considers the change of the vertical cross sectional width, hence enables to calculate the natural frequency of retaining walls with different type of backfill. The geometrical properties and bending rigidity of the retaining walls together with the soil’s elasticity properties are the only used parameters. Nevertheless, the effect of the properties of earth pressures didn’t get any attention till today. In this paper, a complete analysis is carried out to study the effects of soil, structure and seismic parameters on the natural frequency of retaining structures analytically in a more general way by introducing the Coulomb and Mononobe Okabe active failure wedge.
2. Overview of the proposed and used model

The attractive aspect of the proposed model is its ability to consider soil, structure and seismic parameters in determining of natural frequency of retaining structures by failure wedge. The active failure wedge is commonly calculated by the critical active failure surface.

Recently, Ismeik and Shaqour (2015) proposed a new analytical formulation for estimating magnitude and lateral earth pressure distribution on a retaining wall subjected to seismic loads, the solution accounts for failure wedge inclination and horizontal and vertical seismic ground accelerations.

![Fig. 1 A schematic system of retaining structure with considering the active failure wedge.](image)

The static and seismic active failure wedge was estimated using the Coulomb’s sliding wedge theory (1776) and its extension Mononobe-Okabe (1926, 1929). The extension of the method for including failure wedge is not presented. A detailed model is already reported in (Guechi et Belkacemi. 2018). The proposed model takes into account changes in soil wedge geometry and was used in the analysis given below.

In order to study the effects of soil, structure and seismic parameters on the natural frequency of retaining structure, the range of parameters for presenting the results of figures. 2-9, are as follows, for retaining structure, soil backfill and seismic load:

- **H**: 3 m, 5 m, 7 m, 9 m, 12 m, 15 m.
- **e**: 0.1 m, 0.2 m, 0.4 m, 0.5 m, 1 m, 2 m.
- **E_{str}**: 15 MPa, 30 MPa, 60 MPa, 2.6 GPa, 26 GPa, 260 GPa.
- **ρ_{str}**: 1600 kg/m³, 1900 kg/m³, 2320 kg/m³, 2700 kg/m³, 7850 kg/m³.
- **E_{soil}**: 15 MPa, 30 MPa, 60 MPa, 90 MPa, 120 MPa, 240 MPa.
- **ρ_{soil}**: 1600 kg/m³, 1800 kg/m³, 1900 kg/m³, 2100 kg/m³, 2300 kg/m³, 2320 kg/m³.
- **υ_{soil}**: 0, 0.1, 0.2, 0.3, 0.4, 0.5.
- **φ_{soil}**: [0-55]° for static case and [25-45]° under seismic conditions ‘to avoid the phenomenon of shear fluidization, i.e., the plastic flow of the material at a finite effective stress’ (Choudhury and Nimbalkar 2006).

The combination of seismic load (a_h=0.3, a_v=0.5a_h) was considered for each case.
The effect of all parameters on the natural circular frequency is discussed in the following sections. Results are presented in graphical form for circular natural frequency. The material properties and the geometry of the retaining structures system are given in each graph.

3. Effect of soil parameters

A parametric analysis is conducted to evaluate the effects of soil backfill parameters on the natural frequency of retaining structures.

Figure 2 shows the variation of natural angular frequency (ω) in static case (Fig 2.a) and seismic condition (Fig 2.b) for different values of backfill friction angle (φ) and soil density material ρ_{soil} with u_{soil}=0.2, E_{soil}=15 MPa, E_{str}=26 GPa, e=0.4 m, ρ_{str}=2320 kg/m^3, H=7 m and a_h=0.3, a_v=0.5a_h. It is seen that as ρ_{soil} increases, the natural angular frequency decreases. The decrease is less for static system (12.20% for Coulomb wedge and 15.64% for Mononobe Okabe wedge in φ=30°).

Likewise, Figure 3 shows the influence of backfill Young modulus (E_{soil}) on the values of natural angular frequency (ω) in static case (Fig 3.a) and seismic condition (Fig 3.b). The natural frequency shows significant increase with the increase in the value of backfill friction angle and Young modulus. For φ =30°, when E_{soil} changes from 15 MPa to 240 MPa, circular natural frequency increases by about 300% in both static and seismic, circular natural frequency increases by about 300%. It is seen that as φ increases, natural angular frequency also increases for all values of E_{soil}.

Variations of natural angular frequency (ω) in static case (Fig 4.a) and seismic conditions (Fig 4.b) with Poisson ratio (υ_{soil}) for different values of backfill friction angle (φ) show that the natural frequency (ω) is not very sensitive to υ_{soil}. For φ=30°, the natural frequency (ω) increases by 15.22% in static and by 13.47% under seismic conditions when υ_{soil} change from 0.0 to 0.5.
4. Effect of structure parameters

To investigate the effects of structure parameters on the natural frequency of retaining structures, a parametric analysis was performed using varying values of each structure parameter.

As indicated in Figures 5a and 5b, the values of natural angular frequency (ω) increases with reduction of structure’s height in Coulomb wedge (a) and Mononobe Okabe wedge (b) for different values of backfill friction angle (φ). It is seen that for the same value of φ and H the natural angular frequency in static case ‘Coulomb wedge’ is greater than under seismic conditions. When H changes from 3 to 15 m, natural angular frequency decreases by about 121.41% for φ=30° in static and 174.45% under seismic conditions.
Figure 5 shows the angular natural frequency for different values of backfill friction angle and height of structure in Coulomb and Mononobe Okabe Models. Figure 6 shows the effect of thickness of wall (e) on the natural angular frequency (ω) in Coulomb wedge (Fig 6.a) and Mononobe Okabe wedge (Fig 6.b) for different values of backfill friction angle (φ) with $\mu_{\text{soil}}=0.2$, $E_{\text{soil}}=15 \text{ MPa}$, $E_{\text{str}}=26 \text{ GPa}$, $\rho_{\text{soil}}=1900 \text{ kg/m}^3$, $\rho_{\text{str}}=2320 \text{ kg/m}^3$, $H=7 \text{ m}$ and $a_{h}=0.3$, $a_{v}=0.5a_{h}$. From the plot, it may be seen that the natural angular frequency decreases with increase in wall thickness and the rate of decrease is larger for higher values of backfill friction angle. For $\phi=30^\circ$, the circular natural frequency of the system decreases by 33.21% in static and 18.599% in seismic when thickness changes from 0.1 to 2 m. Thus, the present study reveals the significant influence of wall thickness on the natural frequency of retaining structures system.

Likewise, Figure 7 shows the influence of Young’s Modulus of structure ($E_{\text{str}}$) on the natural angular frequency in static case (Fig 7.a) and seismic conditions (Fig 7.b) for different values of backfill friction angle (φ). The natural angular frequency (ω) shows...
no significant decrease with the increase in the values of Young’s Modulus of structure ($E_{str}$). When $E_{str}$ changes from $1.5 \times 10^{-4}$ GPa to 2.6 $\times 10^{-2}$ GPa, natural angular frequency decreases by about 0.04% in static and 0.358% under seismic conditions for $\phi=30^\circ$.

Similarly, Figure 8 shows the influence of the material density of structure ($\rho_{str}$) on the circular natural frequency of retaining structures for different values of $\phi$ in static and seismic conditions. The circular natural frequency decreases with the increase in ($\rho_{str}$). For $\phi = 30^\circ$, when $\rho_{str}$ changes from 2320 kg/m$^3$ ‘concrete’ to 7850 kg/m$^3$ ‘steel’, natural circular frequency decreases by about 38.34% in static system. Also in seismic system, when $\rho_{str}$ change from 2320 kg/m$^3$ to 7850 kg/m$^3$, natural circular frequency decreases by about 17.35%. It is seen that as $\phi$ increases, natural angular frequency also increases for all values of $E_{str}$. 

![Diagram](image1.png)

Fig. 7 Angular natural frequency for different values of backfill friction angle and Young’s Modulus of structure in Coulomb and Mononobe Okabe Models.

![Diagram](image2.png)

Fig. 8 Angular natural frequency for different values of backfill friction angle and mass density of abutment structure material in Coulomb and Mononobe Okabe Models.
5. Effect of seismic accelerations

Whenever possible five values of horizontal acceleration $a_h$ are used in combination with four values of the ratio $a_v/a_h$ (0, 0.5, 1 and -1). This parametric analysis is done for values of $\phi_{soil} > \phi_{failure}$.

Fig. 9 shows the natural angular frequency ($\omega$) versus backfill friction angle and seismic vertical and horizontal accelerations. This Figure shows that the values of the natural circular frequency are decreasing with the increase in both the horizontal and vertical seismic accelerations. It is interesting to observe that both the horizontal and vertical accelerations affect the results significantly and as showed by Nian et al (2014) for dynamic active earth pressure a combination of downward and towards-the-wall seismic inertia forces causes a maximum active thrust. With increase of seismic accelerations, failure wedge is increase and natural frequency would depend on other system.

![Fig. 9 Signification of horizontal seismic acceleration and vertical seismic accelerations](image-url)
6. Conclusions

In this research, by considering the failure wedge in the soil backfill behind retaining structures the natural frequency of retaining structures obtained. An analytical model using the Coulomb and Mononobe-Okabe failure wedges, to determine the natural frequency of retaining structures, is used. In addition to the consideration of horizontal and vertical seismic acceleration coefficients, height and thickness of structure, Young modulus and density of the soil and the structure material and also Poisson ratio and friction angle of soil backfill are considered. Both static and seismic active thrusts are considered and it is found that values of natural frequency increases with the increase in the values of: Young modulus, Poisson ratio and friction angle of backfill soil (E_{soil}, \upsilon_{soil} and \phi_{soil}) but decreases with increase in the value of: structural components (E_{str}, H and e) and intensity of ground motion a_h, a_v.

The natural frequency is highly sensitive to E_{soil}, \phi_{soil}, e and H, but comparatively less sensitive to the \rho_{str} and \upsilon_{soil}. Unlike, the E_{str} and \rho_{soil} do not significantly affect the natural frequency of retaining structure.

The consideration of failure wedge plays an important role in determining the natural frequency of retaining structures, each variation of soil backfill and seismic accelerations changed the system and naturally the natural frequency.

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REFERENCES


