Analysis of Stone Columns Reinforced Weak Soil under Harmonic Vibrations

Photo graph of Prese

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Abstract

The construction of stone columns is a relatively efficient technique and is a classic solution for soft and loose ground improvement. This method is usually a replacement of weak soil with granular course material to increase load carrying capacities of weak foundation soils, reduced excessive settlement, liquefaction remediation, and provide the shortest drainage path to the excess pore water. In some projects, dynamic loads may be exerted to the foundation soil due to, for example, operating industrial machines, earthquake, wind, waves, etc. In such cases, dynamic analysis of soil-foundation system with the presence of stone columns as reinforcing objects is necessary. In this paper, an approximate analytical solution is presented for the vertical dynamic response of stone columns. For this purpose, an element stone column is considered and reaction of the soil on loading the column is modeled using a one-dimensional simulation. The governing differential equation of the stone column-soil element is derived. For this purpose, the stone column is divided to series of lumped masses connected by springs and dashpots. The springs simulate the axial stiffness of the column material and the dashpots reflect the material damping properties of the stone column material. The reaction of the surrounding soil is taken into account by attaching some springs and dashpots. The former simulates the dynamic soil stiffness and the latter simulates the geometric damping due to wave propagation within the surrounding soil. The results show that with increasing the slenderness ration of stone column, the stiffness and damping parameters of soil-stone column system increase and vibration amplitude of stone column decreases. In addition, with increasing the dimensionless frequency a_0, the stiffness of the system tends to decrease while damping of the system tends to increase. Further data extracted from analysis will also be presented.

Key words: Stone Column, Harmonic Vibrations, Material Damping, springs and dashpots

1. Introduction

The soil improvement techniques of gravel stone column have been commonly utilized in last few decades. The cause of improving soft soil with stone column can be generally expressed as following reasons: (a) enhancement of loose soil stiffness due to replacing with stiffer stone column material (Balaam and Booker, 1981; Poorooshasb and Meyerhof, 1997) and compaction effect of stone column installation (Wattes et al, 2000; Vautrain, 1980) (b) the pore water pressure dissipation which results in increasing effective stress (c) damping effects of stone column during earthquake and reduction in deformation.

In fact the dynamic interaction between stone column and surrounding soil which can significantly modify free-field motion reduces transmitted seismic excitation to the superstructures.

Analysis methods of soil-pile interaction under vertical harmonic vibration which may be utilized for stone columns classified into numerical approaches such as FEM and BEM and also Winkler methods.

The finite element method which has been used for simulating soil-pile interaction presented by Wu and Finn (1997), Cai et al. (2000), Kimura and Zhang (2000) and Maheshwari et al. (2004). In general FEM technique is one of the most powerful numerical methods in simulation nonlinear problems. However this method is more complicated since it needs appropriate radiation-damping boundary condition in case of dynamic analysis.

Boundary element technique is another method which represented by many researchers (Kaynia and Kausel, 1982; Mamoon and Banerjee, 1990; Cairo and Dente, 2007). In This method by means of discretization of interfaces and wave propagation towards infinity, satisfying condition is achieved. However because of solving the problem in frequency domain the material behavior in this technique should be limited to linear.

The time saving technique of Winkler foundation model is firstly presented by Novak (1974), Nogami and Novak (1976) Novak (1977), Flores-Berrones and Whitman (1982) and Kavvadas and Gazetas (1993). In this approach, the pile is modeled as a series of distinct lumped mass connected to surrounding soil by some springs and dashpots. Later Boulanger et al. (1999), El Naggar et al. (2005), Maheshwari and Watanabe (2006) and Cairo et al. (2008) expanded the method by solving the problem in frequency domain while the behavior of the soil considered being nonlinear.

2. **Data and Material**

In order to study the differences between concrete pile and stone column in displacement, stiffness and damping of soil-column system, the range of stone column material properties are chosen according to Table 1 (Iowa State University, ISU). In this table, ρ_c, l, r, υ_c, E_c, and G_c stand for mass density, length, radius, Poisson's ratio, elasticity modulus, and shear modulus of the pile, respectively.

ρ_c (kg/m^3)	l (m)	r (m)	υ_c	E_c (Mpa)	G_c (MPa)
2100	2-30	0.3-0.75	0.25	30-70	12-28

Table 1. Variation of Stone column properties

The surrounding soil is assumed clay and the normalized properties of soil-stone column system are shown in Table 2.

ρ/ρ_c	ρ_b/ρ	V_s/V_c	V_b/V_c	l/r	a_0	υ_c/υ
0.92	1	0.15-0.25	1	4-15	0.1-1.4	0.5

Table 2. The normalized properties of soil versus stone column

In Table 2, ρ, ρ_b, V_s, V_c and a_0 denote soil mass density, soil mass density of the soil at the stone toe, shear wave velocity in soil, longitudinal wave velocity in stone column, and dimensionless frequency, respectively.
It should be mentioned, the normalized parameters of soil-concrete pile system for comparing with stone column system are chosen according to Novak (1977).

3. Analysis Method

The problem studied in this paper is a single stone column in a homogeneous soil under vertical seismic excitation (Fig.1). The harmonic compressional waves applied as vertical seismic excitation at the base of the layer. In addition the effect of axial stiffness and material damping properties of the stone column is specified by a series of springs and dashpots. The effect of surrounding soil is also defined by attaching some springs and dashpots. Therefore, the stone column is discretized into lumped masses connected at mentioned spring and dashpots.

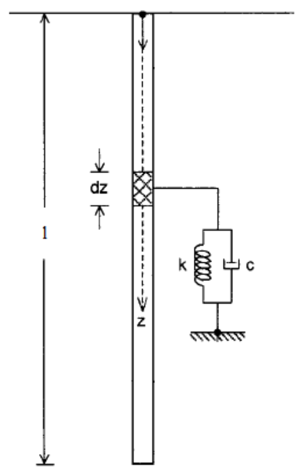

Fig 1: Wave equation model

The motion equation of elementary stone column segment is written as Eq. 1 according to Novak (1977):

$$\mu \frac{\partial^2 w(z,t)}{\partial^2 t} + c\frac{\partial w(z,t)}{\partial t} - E_c A \frac{\partial^2 w(z,t)}{\partial^2 z} + G(S_{w1} + iS_{w2})w(z,t) = 0 \tag{1}$$

Where $w(z,t) =$ displacement of column in depth (z) and time (t), $\mu =$ mass of the stone column per unite length, $c =$ stone column damping, $A =$ area of stone column cross section and S_{w1} and S_{w2} are parameters of the distributed soil springs and dashpots, $G =$ shear modulus of soil.

The axial stone column force is entered the equation as $\frac{\partial p}{\partial z} = E_p A \frac{\partial^2 w(z,t)}{\partial^2 z}$ and the harmonic vibrations is considered by assuming $w(z,t) = w(z,t)e^{i\omega t}$.

By solving the ordinary differential equation and using boundary condition, the motion amplitude at a given depth can be computed. For simulating the boundary condition at the stone column tip, it is assumed stone column acts as a rigid disk on the surface of a homogeneous elastic half space. This reaction can be written as:

$$R = G_b r\,(C_{w1} + C_{w2})W(l) \tag{2}$$

Where $G_b =$ is shear modulus of soil beneath the tip, $W(l) =$ displacement of stone column at depth l and C_{w1}, C_{w2} are parameters proposed by Bycroft (1956).
At the stone column head, the amount of amplitude for the harmonic motion is assumed unit. The solution of differential equation results in following equation:

$$w(z) = w_1 + iw_2 \tag{3}$$

Which the real value of amplitude is obtained from absolute amount of $w(z)$.

4. Results

In this section, the effect of slenderness and dimensionless frequency on real amplitude is shown in Figs. 2 and 3. Moreover, the effect of slenderness and dimensionless frequency on stiffness (f_{w1}) and damping (f_{w2}) of soil-column system is presented in Figs. 4 and 5.

4.1. Effect of l/r_0 and a_0 on $|W|$

Fig. 2 shows that increasing the length of pile results in decreasing displacement. Also the amount of displacement along the stone column length with week surrounding soil is considerably less than that of a concrete pile. In this case, the ratio of soil improvement with stone column to concrete pile in limiting amplitude is near to 2.7. Furthermore, by increasing V_s/V_c, the vibration amplitude decreases.

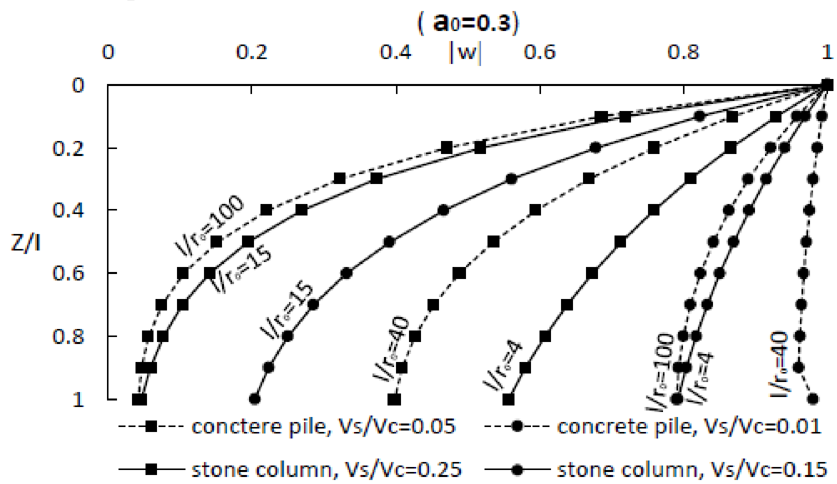

Fig 2: Variation of stone column and pile displacements with depth for a_0=0.3

Fig. 2 shows that damping of system relates to length, materials of column and surrounding soil. It must be noted in some curves the displacement of concrete pile is less than that of stone column. The choice of either of these depends on site conditions and soil parameters. Also by increasing the dimensionless frequency from 0.3 to 0.9, the displacement of stone column is negligible.

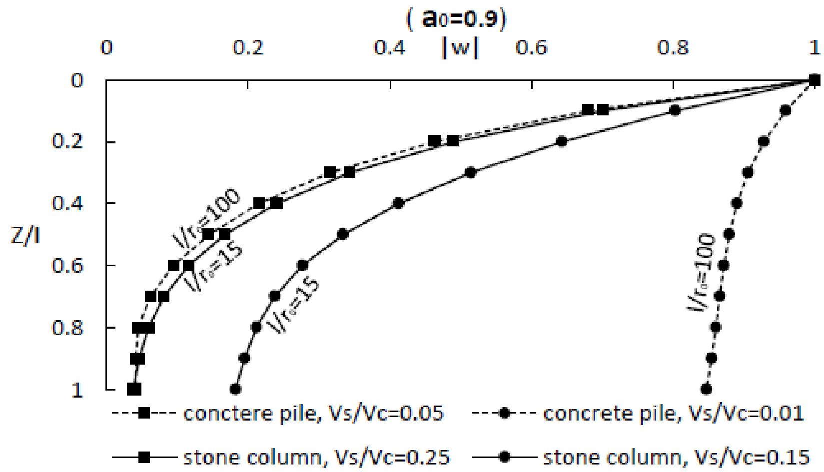

Fig 3: Variation of stone column and pile displacements with depth for a_0=0.9

4.2. Effect of l/r_0 and a_0 on f_{w1} and f_{w2}

Fig. 4 shows that with increasing the dimensionless frequency, damping parameters of soil-stone column first decrease to $a_0 = 0.5$ and then increase continuously. The stiffness of system increases with increasing a_0. However, the gradients of stiffness and damping variation is significant for a_0 smaller than 0.3. Also the variation of f_{w1} and f_{w2} is smooth. Further damping of system with short stone columns and low frequencies is less than long stone columns at the same frequency. In contrast, the damping of short stone columns in moderate and large frequencies is greater than that of long stone columns.

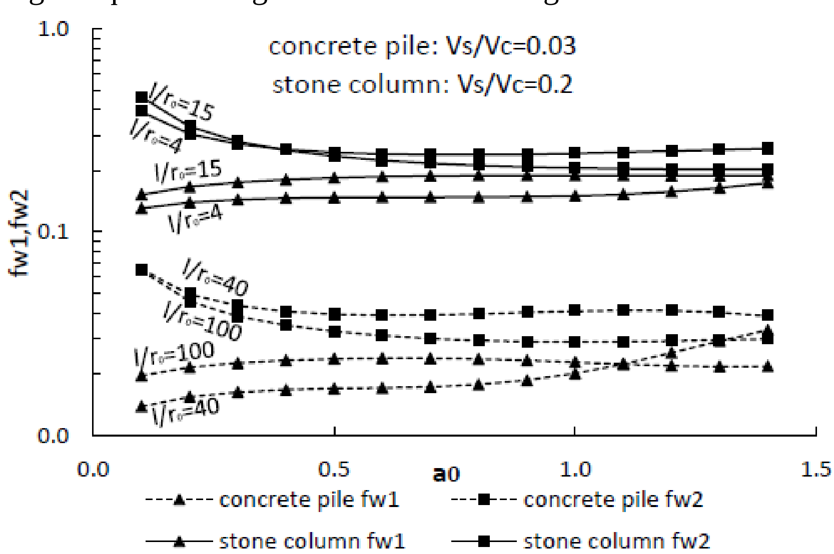

Fig 4: Variation of stiffness and damping parameters with frequency

In Fig. 4, a comparison between results for concrete pile and stone column shows that the amount of f_{w1}, f_{w2} of soil-stone column system is approximately 9.1 and 6.6 times the stiffness and damping of soil-concrete pile system, respectively.

According to Fig. 5, with increasing the slenderness ratio, f_{w1} and f_{w2} values increase. This shows that longer stone columns have greater effect on stiffness and damping of system.

Furthermore, the values of f_{w1}, f_{w2} for stone column is 9 and 7 times the stiffness and damping of concrete pile, respectively. Also with comparing Figs. 4 and 5, it can be seen that the variation of f_{w1}, f_{w2} in Fig. 4 is between 0.15 and 0.46 while in Fig. 5 it is between 0.14 and 0.27 .Thereby, the effect of slenderness ratio variation on stiffness and damping at a given frequency is less than the effect of frequency variation in a constant slenderness ratio. In other words, the effect of frequency variation on f_{w1}, f_{w2} is greater than slenderness ratio.

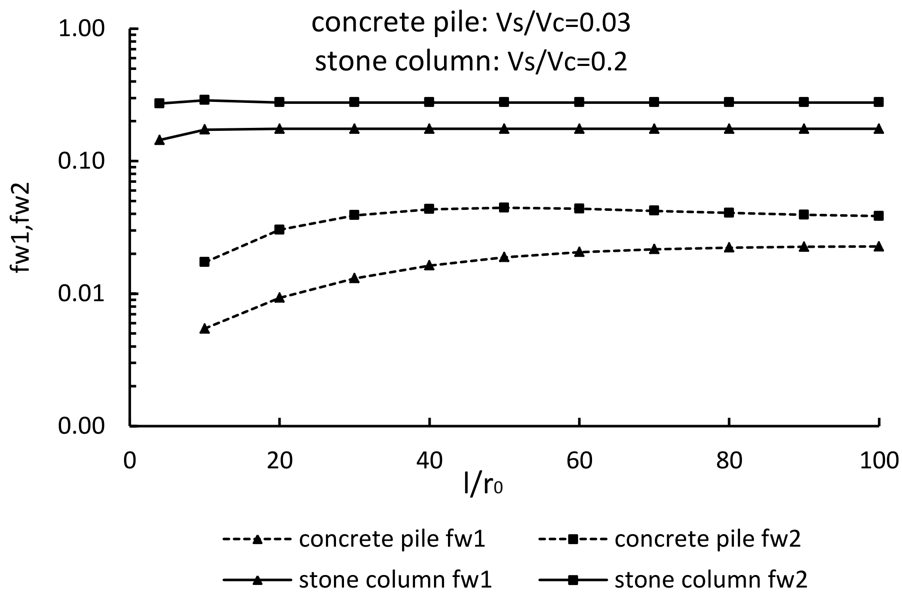

Fig.5. Variation of stiffness and damping parameters with slenderness (a_0=0.3)

It must be noted values of l/r_0 greater than 15 are unrealistic for stone columns, though the variation of f_{w1} and f_{w2} values for further amounts is negligible.

5. Conclusions

From the analyses carried out in this paper, it may be said that:

- With increasing mechanical properties of stone column and its length, the vibration amplitude decreases.
- For small V_s/V_c , a stone column has better operation than concrete pile.
- The effect of dimensionless frequency variation on stone column amplitude is negligible.
- In soil-stone column system, the stiffness and damping related to change of a_0 is respectively 9.1 and 6.6 times greater than that of soil-concrete pile system.
- In soil-stone column system, the stiffness and damping related to change in slenderness ratio is respectively 9 and 7 times greater than that of soil-concrete pile system.
- The effect of frequency on variation of stiffness and damping of stone columns is more than that slenderness ratio.

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