The effect of stone column area replacement ratio on seismic behaviour of foundation

I Safkan*, S Derogar, and J Anywar
Civil Eng. Department, European University of Lefke, Northern Cyprus, TR-10
*Email: isafkan@eul.edu.tr

Abstract: Tall buildings require additional foundation solutions in order to resist the applied actions on soft soil sites. Nowadays the piled foundations are often altered by stone column solutions, as a cheap alternative. Structures built on soft soil or stiff soil, generally results in different behavior under earthquakes. However, the earthquake behavior of the stone column solution on different types of soil is still unclear. This paper aims to investigate the influence of different characteristics of soil structure interaction on the seismic response of stone column mattr foundation. A reinforced concrete mattr foundation was simulated with parametric soil stiffness and area replacement ratio of stone column. An analytical method was used to model the soil profile and appropriate ground motion data were incorporated for the analyses. The comparative results were presented and highlighted in terms of soil amplification and seismic response.

1. Introduction
Structures built on soft soil or rigid soil, generally interact in a different way under earthquakes. This was first observed in the earthquake disaster occurred in Mexico on the 19th and 21st of September 1985, two earthquakes with magnitude of 8.1 and 7.5 occurred at a part of the plate boundary besides the Mexican subduction zone prior known as the Michoacan gap [1]. A large city built on soft clay soil, approximately 360 kilometers away from the epicenter region had the earthquake effects, where it has left deep scares in the economy and the daily life in the city.

Champilo et al., [2] investigated the source characteristics and propagated waves from the epicenter to the Mexico City and the authors concluded that the earthquake catastrophe of Mexico City in 1985 was due to a large local amplification, caused by the extremely soft clay layer underlying the city. The importance of these events and of their consequences has brought an increased pressure to understand the behavior of Soil-Structure Interaction, in order to improve the seismic safety of multi-story structures.

Liquefaction during an earthquake is a major reason to causes hazardous damage to the buildings. Liquefaction damage prompts the soil to excessive settlement, loss of bearing capacity, sand boils, slope failure and landslides, lateral spread, etc. Structures built in seismic active regions are susceptible to experience liquefaction of the underlying soil caused by excessive pore pressure development. The two most commonly considered soil improvement techniques in practice are stone columns and piled foundations. Among the different improvement techniques, the most popular technique adopted for liquefiable soil improvement is the installation of stone columns. Yoshimi and Kuwabara [3] suggested the use of stone columns as an improvement for liquefaction
hazards for the first time. Stone columns generally improve stiffness, permeability and strength properties of stone columns. A considerable number of research has been done regarding to the performance of stone columns to improve soil liquefaction. Seed and Booker [4] proposed a stone column model designed for liquefiable soil improvement by assuming the permeable structure of the stone column. Non dimensional charts have been introduced for the determination of the spacing of stone columns. Sasaki and Taniguchi [5] performed an experimental study for the effective area replacement ratio. Yang and KO [6] observed that the soil lacking drainage has more potential on liquefaction.

A study conducted by Asgari et al., [7], focused on stone column and pile-pinning methods, comparing the behavior of each method in retaining permanent seismic deformations. However, different stiffness properties of soil were not investigated.

This study, parametrically assess, different stiffness properties of clay on parametric stone column area replacement ratio and corresponding lateral behaviour. Relative difference in between the type or size of the foundation will be discussed in this paper.

2. Method

2.1. Modelling substructure Substructure was modeled by using the OpenSeesPL software [8]. Parametric stone column foundation models were analyzed considering different soil conditions such as loose and dense clay. Table 1 below provides the soil parameters of clay utilized in the dynamic analyses.

| Parameters | Loose clay | Medium loose clay | Medium clay | Dense |
|------------|------------|-------------------|-------------|-------|
| Mass density (ρ) (kg/m³) | 1620 | 1870 | 2090 | 2130 |
| Shear wave velocity (m/s) | 150 | 300 | 500 | 700 |
| Cohesion (c) (kPa) | 22 | 32 | 55 | 75 |

2.1.1 Stone column: The main constitutive soil modeling parameters used in this study of stone column, for: loose clay, medium loose clay, medium clay, medium dense clay and dense clay, are the main constitutive soil modeling parameters used in the study of stone column which are represented in Table 1, with the soil layer having a total depth of 10 m.

Nowadays, the stone columns are preferred as an economical solution for the stabilization of underlying soil. Stone column case utilizes dense stabilization material property for but as column shape and with different area replacement ratio (ARR). Area replacement ratio of 5%, 10%, 25%, 50% and 100% were utilized for modelling in this study.
A pressure independent multi-yield elastoplastic material model [8] was used for modelling clay material. On the other hand, the characteristics of a pressure depended multi-yield material (See Fig. 2) require modelling the regular medium dense soil by replicating drained soil conditions. For the purpose of simulating a soil under fully undrained condition, the material should either be fitted in a fluid solid porous material, or with a solid-fluid coupled element with a low permeability. For the simulation of partially drained soil behavior, the pressure dependent multi-yield material must be coupled with a solid-fluid fully integrated element with the appropriate permeability characteristics [8].

Modal response difference was obtained for the system where relatively significant difference was obtained for different stone column area replacement ratios. In total 2 strong motion data were utilized for assessing the influence of foundation type on superstructure. Table 3 gives the statistics of selected ground motions. The relatively high peak ground acceleration characteristics of these two motions are considered to influence the amplification characteristics of soil in nonlinear behavior at broader spectrum range.
Table 2. Statistics of the utilized ground motions.

| Earthquake  | Year | Length of record (s) | Magnitude |
|-------------|------|----------------------|-----------|
| El Centro   | 1940 | 31                   | 7.1       |
| Chile, Llolleo | 1985 | 116                  | 7.8       |

3. Results and discussions

The analyzed ground motions’ frequency content were especially magnified at short period range. The longer period range for the Chile earthquake was monitored to not to change in a significant manner. On the other the El Centro data was observed to damp the energy on long period range when 4m deep embedment length was considered.

Figure 3. Long period spectral acceleration amplification respect to ARR of stone column and Vs conditions.

As result of analyses, a multidimensional relationship were developed in between ARR of stone column, Vs of surrounding soil and PGA (Fig. 5) When loose soil condition (Eg. Vs< 200) was considered, significant amplification of ground acceleration was observed for ARR<25%. Although the reduction was gradual for stiffer
soil conditions, there is a jump at $V_s$: 500m/s and ARR: 20%. This may be argued as the secondary mode effects of stone column due to the specific stiffness-mass ratio. When compared with the code specified acceleration amplitudes at same period range, amplification safe region starts at 40-50% ARR range for the soft clay sites. A further study, assessing the structural behavior can be beneficial for this comparison.

Lateral maximum displacement of soil has considerably high influence on seismic demand especially on tall buildings with long period. A parametric study was conducted on clay profiles with different stiffness properties respect to different stone column area replacement ratios. The results (See Fig. 4) show insignificant difference between 50% and 100% ARR configurations. However, soil profile with 5% and 10% ARR resulted 37% more lateral displacement respect to 50% ARR profile. On the other hand insignificant difference on response was monitored for the medium and dense clay soil conditions. Furthermore, the difference in between the 50% and a100% ARR was also found to be negligible.

![Figure 4. Comparison of ground displacement respect to ARR, Chile earthquake](image)

On the other hand, no significant amplification difference was obtained for the firm soil conditions. This may be due to the insignificant difference at long period range of response spectra. Similar trend was also observed on firm soil conditions, where no amplification of acceleration characteristics were monitored.

4. Conclusion

In this study, the effect of stone column on seismic behavior of loose clay was investigated. Current practice on designing stone columns is usually limited to static bearing capacity estimates. However, the results indicate the importance of modelling stone columns based on seismic behavior. In addition, the effect of different soil types on the amplification or damping of spectral amplitudes were studied. Significantly high amplifications at longer periods were monitored for the ARR less than 25%. Finally, ARR equal to 50% was monitored to give the best response to loose soil under earthquake loading.
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