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Effects of fly ash column treatment of HP clayey soils on seismic behavior of R/C structures

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Abstract. The behavior of soil directly affects not only its stability condition but also structural response of structural systems. High-plasticity clay soil (CH) is vulnerable to volumetric swelling leading to different settlements in structural systems. Hence, it becomes indispensable to propose practical solutions to reducing this effect. In the present study, structural response of R/C frame buildings, resting on high plasticity clayey soils strengthened through the coal fly ash column technique, to earthquake motion is investigated. For this aim, the swelling behavior of high plasticity clay soil (CH) is identified with in-situ experimental tests on the regions with high swelling potential in the city of Kirikkale, Turkey. In order to reduce the swelling potential of the investigated regions, the coal fly ash column technique was implemented to the reference soil specimen with high swelling percentage of 15.6%. Experimental results obtained from the strengthened soil specimens were compared to those from the reference specimen. This comparison revealed that the coal fly ash column approach has a considerable effect on improving the swelling behavior of the high plasticity clay soil. The decrease in the volumetric swelling value is also thought to directly improve the response of a building structure settled on high plasticity clay soil. The improvement in the seismic response of existing R/C structures located in the regions with high swelling potential was identified by adopting the increased allowable bearing pressure value of the improved soil in the analyses. Based on the comparative study, structural earthquake response of R/C frame systems was investigated on the basis of the engineering parameters, including the base-shear force, base overturning moment, base axial force and settlement of foundation. The percent changes in these values showed that the base axial force and settlement of foundation were improved with the help of this strengthening application.

Keywords: fly ash column; high plasticity clay soil; earthquake performance; reinforced concrete structures, earthquake-resistant structure, time-history analysis

1. Introduction

Soil condition is underlined in many projects/studies as a significant parameter for a more accurate assessment of the structural response of civil engineering structures. Therefore, considering the soil condition in the design/analysis stage of a structural system provides more realistic solution and prevents the engineers to encounter an unexpected structural behavior. Soil swelling basically originates from the volumetric expansion of the loaded soil under different environmental and climatic conditions. Structural systems resting on clayey soils can experience unexpected significant settlements that lead to not only damages on structural elements but also serviceability problems. Taking into account its different influences, such as excessive deformations in structural systems, pavement swelling in highways and large deformations in retaining walls and site concrete, the swelling potential of soils can give rise to considerable economic losses. Hence, the need for paying attention to this critical issue in the design/analysis of civil structural systems is obvious.

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For the swelling problems of clay soils, various experimental studies and numerical solutions have been presented in literature. Among various proposed solutions, addition of mineral admixtures is the most common rehabilitation technique for clayey soils. Fly ash admixture has been regarded as the most effective solution in this respect. Therefore, many studies concentrated on the stabilization of soils with fly ash. Oral (1964) made a geotechnical evaluation on the stabilization effect of lime, cement and fly ash on Ankara clay. He clearly demonstrated that the sole use of lime was not enough for improving soil properties. Instead, the simultaneous use of fly ash and cement mixture proved to be more efficient as compared to the sole use of lime. A similar study was also done by Indraratna *et al.* (1995) on Bangkok clay. They determined that the clay mixed with 18% fly ash and 5% lime had 2-3 times higher one-dimensional compressive strength than the pure clay at the end of two-week curing duration. Lim *et al.* (2002) carried out detailed investigations on alteration of the swelling characteristics of clay samples with high swelling potential by mixing them with lime and fly ash, based on the grain size analysis through the CBR, SEM and X-ray testing. Dermatas and Meng (2003) investigated the improvement of swelling potential of clay soil subjected to heavy metal contamination using fly ash admixtures. They compared the outcomes from cured and virgin samples with

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the help of XRD testing. A similar approach of using fly ash admixture was employed by Turker and Cokca (2006) so as to depict the effects of the use of fly ash for the stabilization of clay soil. They compared the water saturation, absorption and free swelling values of the swelling clay samples cured with type F or C fly ash according to ASTM C618 (ASTM 2019). In that study, swelling characteristics of clay soil were observed to improve by adding fly ash. Besides, they experimentally proved that type C fly ash was more effective than type F in the stabilization of clays soil. The use of fly ash as an admixture was also adopted by Chugh *et al.* (2006) for a different civil engineering application. They made an investigation on the influence of different amounts of fly ash admixture on the swelling properties of construction materials and road embankments. Ramu and Hari Kishore (2007) conducted a laboratory research, and tried to determine how to utilize fly ash in soils and how to control the swelling potential of clay soils by adding it. Along with the use of fly ash for soil improvement or stabilization, adverse and physico-chemical effects of coal fly ash was stated importantly in literature. For this aim, a detailed review study was conducted by Wang *et al.* (2020). They clearly highlighted clearly physico-chemical properties of coal fly ash (CFA), adverse effects of CFA on all living creatures and directions for the use of CFA in the near future.

In the recent years, various chemical agents and fibers were used in combination with fly ash, cement or silica fume for stabilization of high plasticity clays. Researchers focused on the percentages of agents and curing durations of these applications to determine the most efficient stabilization schemes. In a related study, Rekha *et al.* (2016) used human hair fiber (HHF) in combination with fly ash for strengthening clayey soils to be used in embankments and soil reclamation works. This strengthening application was proved to have significant contributions to the unconfined compressive strength and the California bearing ratio (CBR) of the soil. Based on the SEM analyses of the treated and untreated soil samples, the change in the microstructure and the presence of hydration products in the soil were held responsible for the contribution of this treatment to the improved soil properties. Yilmaz *et al.* (2018) used a mixture of Portland cement and different chemical agents including sodium hexametaphosphate, aluminum sulfate, sodium carbonate, and sodium silicate with 0, 5, 10, and 20% concentrations for improving the unconfined compressive strength of high plasticity clayey soils. The soil samples with high concentrations of cement were observed to be very sensitive to the addition of agent. The reductions in the compressive strength reached three times the unconfined compressive strength values of the clay-agent mixtures in the presence of high concentrations of cement. Chavali and Reddy (2018) adopted Class F fly ash for treatment of black cotton soil predominant with montmorillonite and kaolin clay predominant with kaolinite in acidic environment, representing the presence of inorganic acids in industrial buildings. The use of fly ash was shown to be rather effective in reducing the swelling and compressibility of the soil samples, which was explained by the authors with the formation of aluminum phosphate cements in the presence of phosphoric acids. Alrubaye *et al.* (2018) conducted tests on Kaolin samples with a fixed percentage of silica fume and various amounts of lime. The pozzolanic reaction within the soil was found to decrease the coefficient of compressibility with increasing lime content. The increase of lime beyond 5% had an adverse effect on the coefficient of consolidation when used in combination with 6% of silica fume. Kumar and Rupali (2020) developed analytical equations for predicting the unconfined compressive strength and split tensile strength of fiber reinforced clay stabilized with grass ash, fly ash and lime. Artificial neural networks were trained with a data from tests on only Kaolin clay and clay mixed with different amounts of fly ash, grass ash, polypropylene fibers and lime. Multiple linear Regression (MLR) was used to develop the nonlinear equations, which were shown to produce accurate estimates. Bozbey et el. (2021) used hydrated lime for the stabilization of high plasticity clays. The curing duration and the percentage of lime constituted the test parameters of the study. Soaking the test samples for 10 days after curing with lime contributed to the unconfined compressive strength and the secant modulus at failure particularly in the case of fine soil pulverization. The study also depicted the significance of drainage precautions for better performances of pavements.

The studies are far from reaching concluding remarks or recommendations for the effect of improved soil properties, particularly the reduced swelling potential, on structural response of civil engineering structures. In this study, high plasticity clay soils were improved with the fly ash column method, which is very effective as compared to other mixing methods. The influences of this method on the response of superstructure were aimed to be examined. For this aim, a geotechnical study was conducted in the city of Kirikkale which possesses high plasticity clay soils. Based on one-dimensional consolidation tests on a set of soil samples from the study area, swelling values of the reference and improved specimens were obtained and later used for the estimation of the bearing capacity of these two different soils. The effect of this improvement in clay soil was then investigated on a high-rise reinforced concrete (R/C) model structure. Accordingly, seismic performance of this structure was interpreted with the help of performance parameters, including the base shear force, base moment, base axial force and vertical displacement of the building.

2. Site description and geotechnical investigation

In an effort to show the improvement in the soil characteristics of high plasticity clay using the coal fly ash column approach, the city of Kirikkale with soil class C according to NEHRP (2004) and TSCB (2018) was selected. As shown in Fig. 1, the city is at the middle of Turkey very close to the capital, Ankara. Soil class of the city was specified as C based on the recently conducted seismic hazard analysis (Sonmezer *et al.* 2018a, b, c). For geotechnical investigation on this site, drilling studies carried out within the period of 2014-2016 were utilized.

Among 484 drilling log records, 18 records were

Table 1 Index testing results

Natural Water Content (%)	Grain Size (%)		Density of particles	Atterberg limits (%)			
	Aggregate +Sand	Silt+Clay		LL	PL	PI	BL
29.2	43.8	56.2	2.7	75.2	48.62	26.58	24.5

LL: Liquid limit, PL: Plastic limit; PI: Plasticity index; BL: Bend-breaking limit (BL)

Table 2 Chemical and physical properties of the used coal fly ash

Chemical Properties	
Content	Percentage (%)
SiO2	46.59
Al2O3	12.42
Fe2O3	9.74
CaO	14.50
MgO	7.23
SiO3	5.52
Na2O	1.01
K_2O	2.28
Physical Properties	
Specific surface area (cm2/g)	2830
Specific Gravity (unitless)	2.47

Fig. 1 Location of the city of Kirikkale

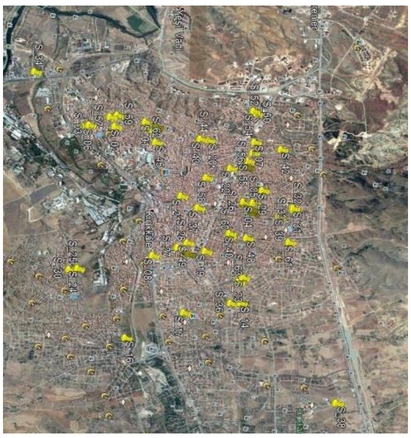


Fig. 2 High plasticity clay regions in the city of Kirikkale

selected due to their high plasticity clay (CH) potential. Based on these records, geotechnical investigation was decided to focus on the locations of these 18 records. The locations including high plasticity clays are depicted in Fig. 2. The reference soil sample without coal fly ash admixture was taken from a new construction site in one of the regions with high plasticity clay (Fig. 2). The results from the index tests on the reference sample are given in Table 1. Using these results, the activity index (A) of the reference clay sample was obtained as 1.363>1.00, which means that the considered clay soil is active.

3. Experimental study

3.1 Properties of the used coal fly ash

In the study, coal fly ash from Cayirhan coal-fired power plant in Turkey is used. The used coal fly ash has a chemical composition of SiO_2+Al_2O_3+Fe_2O_3 less than 70% and CaO higher than 10%. Hence, it is categorized as C class fly ash according to ASTM (2019). Moreover, chemical and physical properties of the used coal fly ash are given in Table 2. Due to the higher content of CaO, it also has a very good binding capability between materials. According to the given properties of the used fly ash above, the combustion conditions of the used coal, the age of the used coal fly ash, and the treatment condition of the used coal fly ash are estimated in acceptable limits to utilize the used coal fly ash for soil improvement.

The radioactivity properties of the used coal fly ash were also investigated; however, almost no radioactivity contents in the samples were obtained in terms of the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K radionuclides. The loading of the used coal fly ash was done with the conventional methods. When lignite coal is combusted, the fine particles (fly ash) are collected from the flue gases through electrostatic precipitators (ESP) or in filter fabric collectors. The collected coal fly ash particles are then transported with special conveyor belts to storage silos. The stored coal fly ash is loaded to bulk trucks by the telescopic filling handles at the loading station. Thus, the used coal fly ash with the place of Cayirhan origin is considered to be safely used for different aims of soil improvement and stabilization.

3.2 Method

After the geotechnical investigation and detailed information for the used coal fly ash, the consolidation tests were carried out on the reference and improved clay samples to determine their swelling percentage (%) that was calculated with Eq. (1). Besides, the soil specimens were compacted under normal condition with the molds of 50 cmx70 cm dimensions and 10 cm height, as shown in Fig. 3. More details for testing methods can be found in Toprak (2019).

$$S = \left(\frac{H_1 - H_0}{H_0}\right) x100 \quad (1)$$

Fig. 3 The molds for soil compaction

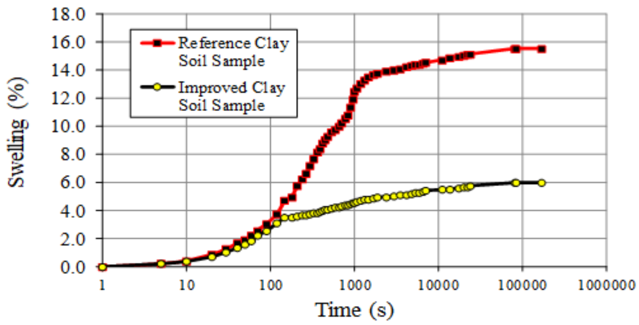


Fig. 4 Swelling-time variation of the samples

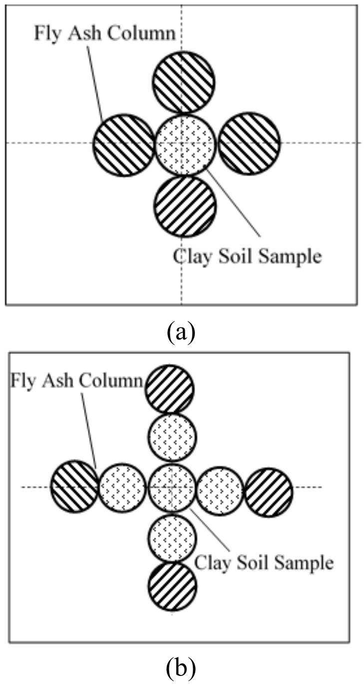
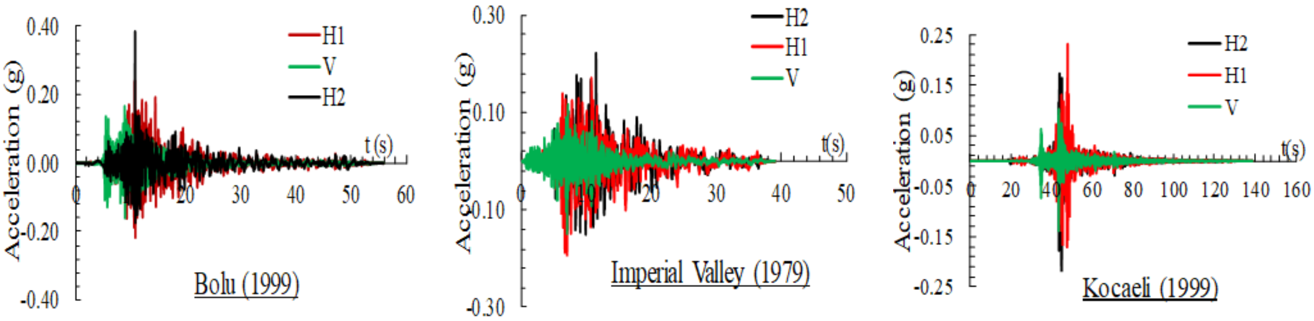


Fig. 5 Coal fly ash column method for (a) zero and (b) one-diameter clear distance patterns

where,
S: swelling percentage
H_0: initial height of the specimen
H_1: the height of the specimen after swelling

As shown in Fig. 4, swelling percentage for the reference clay soil was obtained as 15.6 %. Later, this clay reference with 15.6 % swelling was strengthened with the help of the coal fly ash column method. As depicted in Fig. 5, coal fly ash column with the same size as the reference clay sample was located right around the clayey soil sample or at a clear distance of one or two diameters in this method. In addition to the pattern of columns around the



(a) Bolu 1999 (b) Imperial valley 1979 (b) Kocaeli 1999

Fig. 6 Matched earthquake records of Bolu (1999), Imperial Valley (1979) and Kocaeli (1999)

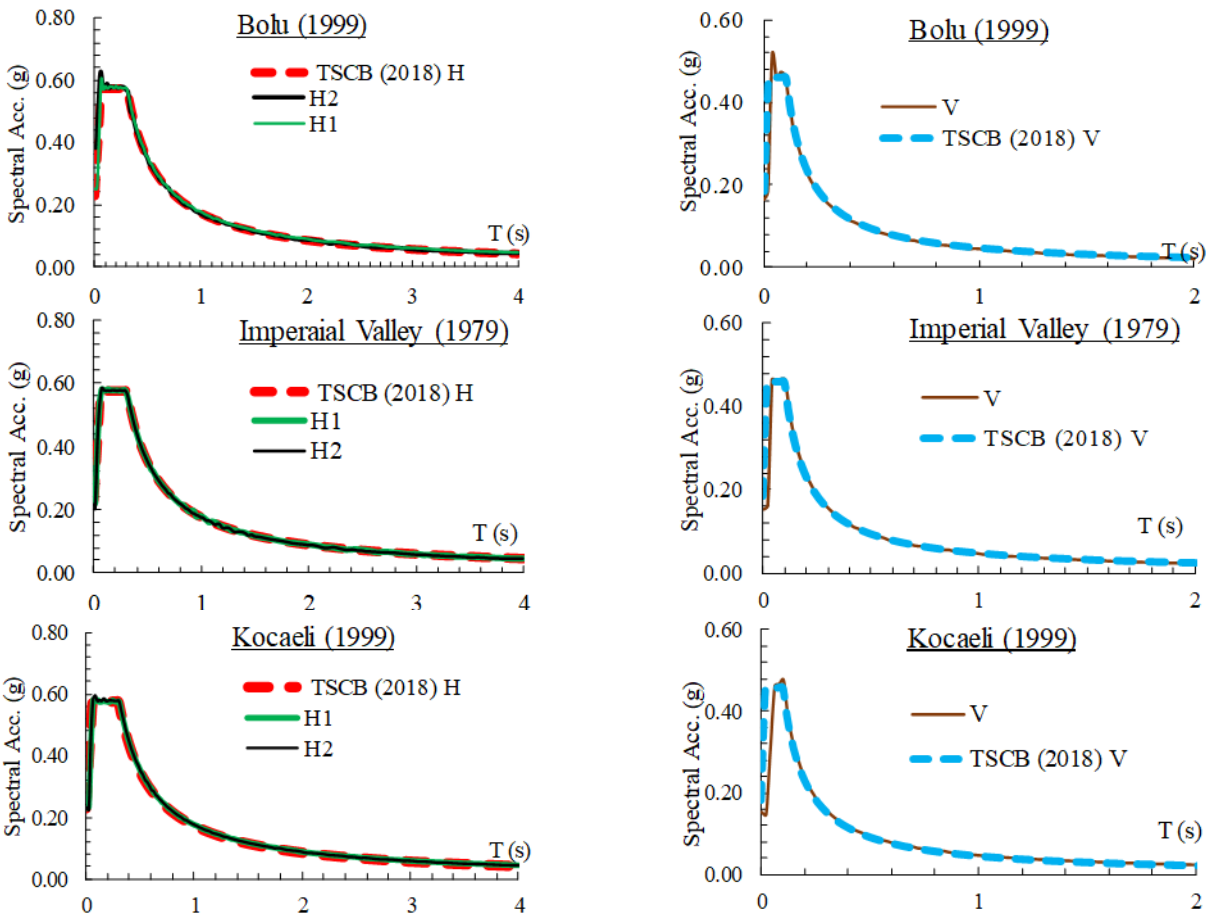


Fig. 7 Spectra of the matched records and comparison of them with design spectra given in TBDY (2018)

Fig. 8 FE model of R/C building structure

Table 3 Comparison of base shear force of the reference model with the strengthened model

EQ	Base Shear Force (kN)						
	Reference		Strengthened		Change (%)		
	Max.	Min.	Max.	Min.	Max	Min	Graphical
Duzce (1999)	11661	-12349	11776	-12055	0.99	**-2.39**	
Imperial Valley (1979)	10915	-12565	10888	-12673	-0.24	**0.86**	
Kocaeli (1999)	10882	-10727	10759	-10786	**-1.13**	0.55	

Table 4 Comparison of base overturning moment of the reference model with the strengthened model

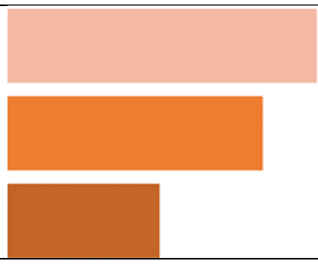
EQ	Base Overturning Moment (kNm)						
	Reference		Strengthened		Change (%)		
	Max.	Min.	Max.	Min.	Max	Min	Graphical
Duzce (1999)	220297	-226300	229094	-231509	**3.99**	2.30	
Imperial Valley (1979)	249378	-228865	256309	-221302	2.78	**-3.30**	
Kocaeli (1999)	254442	-251331	249393	-253335	**-1.98**	0.80	

Table 5 Comparison of base axial force of the reference model with the strengthened model

EQ	Base Axial Force (kN)						
	Reference		Strengthened		Change (%)		
	Max.	Min.	Max.	Min.	Max	Min	Graphical
Duzce (1999)	3229	-3592	2891	-3159	-10.48	**-12.05**	
Imperial Valley (1979)	3466	-3256	2998	-2950	**-13.51**	-9.38	
Kocaeli (1999)	3068	-3307	2689	-2908	**-12.34**	-12.07	

sample, the curing duration (30, 60, 90 days) was adopted as the second test parameter. Among different curing durations and column arrangements, the highest reduction in the swelling potential was achieved in the presence of coal fly ash columns surrounding the clay sample (zero distance) and curing duration of 90 days. In this very case, the swelling potential was 6.0 %. Fig. 4 depicts that the percent swelling value dropped by 9.6 %, implying a major enhancement in the soil resistance against swelling.

For the reference and improved clay soil samples, N_{30} values, i.e. the blow counts per 30 cm penetration of the borehole, were also estimated as $N_{30(reference)}=11$ and $N_{30(Improved)}=14$, respectively. These Standard Penetration Test (SPT) N_{30} values were then utilized to obtain the vertical soil resistance values (K_v) of the soil before and after strengthening. For this aim, the well-known equation (Eq. (2)) proposed by Das (1999) and Bowles (1997) was utilized:

$$K_v = 180 \times N_{30} \tag{2}$$

The vertical soil resistance values from this equation were then used in the seismic analyses of the model structure

4. Seismic performance analysis

From Eq. (2), the bearing resistance values of the reference and improved clay soils were determined as $K_{V\text{-}reference}=19.8 \cdot 10^5$ kN/m^2/m and $K_{V\text{-}improved}=25.2 \cdot 10^5$ kN/m^2/m, respectively. These values are considered for the TSC (2007). In the seismic analyses, the Bolu (1999), Imperial Valley (1979) and Kocaeli (1999) earthquake records were selected from the PEER NGA West-2 database. These three records were consistent with the worst earthquake scenario of the study area (Kırıkkale) in terms of earthquake magnitude, fault distance and source mechanisms. Afterwards, these raw earthquake motion histories were also scaled according to the design acceleration response spectrum of the new seismic code of Turkey, namely TSCB (2018). These new matched earthquake records, which are revealed in Fig. 6, were utilized in the linear time-history analyses. The agreement of the spectra obtained from the matched records with the design spectra given in TSCB (2018) is also demonstrated in Fig. 7.

H1, H2 and V in the figures refer to the horizontal records in two principal directions and the vertical record of each earthquake, respectively. Next, the three-dimensional finite element model of the R/C test structure was developed using different numerical elements of frame, shell, solid and link. In this model, solid elements were assigned to the mat foundation of the structure. $K_{V\text{-}reference}$= $19.8{\cdot}10^5$ kN/m^2/m and $K_{V\text{-}improved}$= $25.2{\cdot}10^5$ kN/m^2/m were considered as the stiffness values of the area spring element connected to the bottom surface of the foundation. In the model, reinforcement bars were also defined for the vertical bearing elements and beams according to as-built drawings of the building structure. For R/C slabs and mat foundation, no reinforcement was defined, which means that these elements are likely not be damaged. Totally, 800 frames, 250 areas and 7476 solid elements were used, and FE model of the structure was developed in the commercial software SAP2000 (2018). The 3-D FE model of the R/C test structure is given in Fig. 8. Table 3-5 summarize the linear time-history earthquake analyses results.

For the estimation of the effects of the improved/strengthened clay soil on the earthquake behavior of R/C structures, linear time-history analyses were realized on the model structure and the obtained results were summarized in terms of four response indicators, namely the base shear force, the base overturning moment, the base axial fore and the base settlement (Tables 3-5). Table 3 and 4 clearly indicate that the soil strengthening had no emphasized contribution to the horizontal seismic response of the structure. The lack of change in the base shear and base overturning moment, i.e. the horizontal response indicators of the analysis, with soil strengthening was associated with the absence of restraints of the mat foundation in both horizontal directions.

In future analyses, the translation of the mat foundation in two principal directions on the horizontal plane and the rotations with respect to these two axes need to be restrained for the potential variation of the horizontal response of the structure with soil strengthening applications. Instead, the settlement of the foundation was observed to decrease as expected due to high rigidity of the strengthened clay soil with the help of coal fly ash column strengthening. As demonstrated in Table 5, the settlement performance of the structure is predicted to increase as 10-15% in terms of foundation settlement. Another important result is related to base axial force which can lead to brittle behavior if not controlled. As given in Table 5, the base axial force values decrease up to 14 %. This decrease in the base axial force can be more expected when the structural system has some irregularities in plan. Normally, vertical bearing members of the structure, i.e. the columns and shear walls, are desired to be provided symmetrically about the centroidal axes of the floor plan. Since symmetric column/shear wall configuration in plan is generally not possible like the model structure of the present study, the approach presented herein can be regarded as an effective solution for the buildings resting on high plasticity clayey soils. The decrease in the base axial force also leads to decrease in the second order moments or forces in the structure. From this perspective, the reductions in the base axial force may be pertinent to the lack of different settlements in the foundation system.

5. Conclusions

In the current study, a new method for strengthening high plasticity clay soils, namely the use of coal fly ash columns around the clays, is presented and the effects of the method on seismic responses of structures were investigated. First, the most efficient coal fly ash column configuration and curing time duration were identified for this strengthening technique. Next, linear time-history analyses were conducted on a model RC structure for two different soil conditions, namely the reference and strengthened clay soils. The strengthened soil conditions in the analyses reflected the most efficient coal fly ash column configuration and curing duration. Actual earthquake records consistent with the worst earthquake scenario of the study area were used in the analyses and the geotechnical results were incorporated into the model by changing the vertical load bearing resistance under the mat foundation. The structural responses were evaluated in terms of the base shear force, base overturning moment, base axial force and foundation settlement. The following important findings were reached with the help of the experimental and numerical studies of the present research:

- The horizontal translations and rotations of the mat foundation should be restrained and the related horizontal bearing resistance of the soil should be assigned in order to evaluate the effects of soil strengthening applications on seismic response of structures. Shear forces and overturning moments in the structure and at the foundation level are directly related to these restraints.
- This strengthening technique proved to be rather effective in limiting the settlement of the foundation thanks to the significant increase in the vertical stiffness of the soil. The decrease in the settlement reached significant levels as high as 14%. These reductions in settlement can be considered to be more crucial in the structures with plan irregularities. With this strengthening, the differential settlements of the mat foundation and the related second order effects in the structure can also be reduced.
- The improvement in the vertical stiffness and strength of the soil also helped to reduce the base axial forces in the structure. These base axial forces are responsible for the severity of the second order effects in a structure during an earthquake. Hence, this strengthening application definitely improves the safety of a structure against devastating effects

of earthquakes.

• The effects of the introduction of coal fly ash columns on the soil swelling potential increases with increasing the duration of curing and decreasing the distance of the column from the core clay sample. In the present study, the decrease in the swelling values reached about 65% for ash columns right around the clay and curing time of 90 days.

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References

Alrubaye, A.J., Hasan, M., and Fattah, M.Y. (2018), "Effects of using silica fume and lime in the treatment of kaolin soft clay", *Geomech. Eng.*, **14**(3), 247-255. http://doi.org/10.12989/gae.2018.14.3.247.

ASTM (2019), Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Baran, T. (2019), "Examination of swelling potential of Kirikkale city grounds (neighborhood basis) and improvement of reducing the swelling potential of high plastics clay grounds by fly ash column method", Ph.D. Dissertation, Kirikkale University, Kirikkale, Turkey (in Turkish).

Bowles J.E. (1997), *Foundation Analysis and Design*, McGraw-Hill, U.S.A.

Bozbey, I., Kelesoglu, M.K., Oztoprak, S., Komut, M., Comez, S., Ozturk, T., Mert, A. and Ocal, K. (2021), "Effects of soaking on a lime stabilized clay and implications for pavement design", *Geomech. Eng.*, **24**(2), 115-127. https://doi.org/10.12989/gae.2021.24.2.115.

Chavali, R.V.P. and Reddy, P.H.P. (2018), "Control of phosphoric acid induced volume change in clays using fly ash", *Geomech. Eng.*, **15**(6), 1135-1141. http://doi.org/10.12989/gae.2018.15.6.1135.

Chugh, Y., Patwardhan, A., Munish, S. and Botha, F. (2006), "Development of construction materials using sulfite-rich scrubber sludge and fly ash", *Fuel*, **85**(16), 2323-2329. https://doi.org/10.1016/j.fuel.2006.01.032.

Das, B.M. (1999), *Principles of Foundation Engineering*, Cengage learning Inc., Kentucky, U.S.A.

Dermatas, D. and Meng, X. (2003), "Utilization of fly ash for stabilization/solidification of heavy metal contaminated soils", *Eng. Geol.*, **70**(3), 377-394. https://doi.org/10.1016/S0013-7952 (03)00105-4.

Indraratna, A.S., Balasubramanian, A.K. and Khan, M.J. (1995), "Effect of fly ash with lime and cement on the behavior of a soft clay", *Q. J. Eng. Geol. Hydrogeol.*, **28**(2), 131-142. https://doi.org/10.1144/gsl.qjegh.1995.028.P2.04.

Kumar, A. and Rupali, S. (2020), "Prediction of UCS and STS of kaolin clay stabilized with supplementary cementitious material using ANN and MLR", *Adv. Comput. Des.*, **5**(2), 195-207. http://doi.org/10.12989/acd.2020.5.2.195.

Lim, S., Jeon, W., Lee, J., Lee, K. and Kim, N. (2002), "Engineering properties of water/wastewater-treatment sludge modified by hydrated lime, fly ash and loess", *Water Res.*, **36**(17), 4177-4184. https://doi.org/10.1016/S0043-1354(02)00150-1.

NEHRP (2004), Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, FEMA, Washington, D.C., U.S.A.

Oral, C. (1964), "Stabilization of Ankara clay", Master Thesis, Middle East Technical University, Ankara, Turkey.

Ramu, K. and Hari Kishore, V. (2007), "A laboratory study of flyash columned bed in expansive soil", *Proceedings of the International Conference on Civil Engineering in the New Millenium: Opertunities and Chalenges*, Howrah, India.

Rekha, L.A., Keerthana, B., and Ameerlal, H. (2016), "Performance of fly ash stabilized clay reinforced with human hair fiber", *Geomech. Eng.*, **10**(5), 677-687. http://doi.org/10.12989/gae.2016.10.5.677.

SAP2000 (2018), Integrated Software for Structural Analysis and Design, Computers and Structures Inc., Walnut Creek, California, U.S.A.

Sonmezer, Y.B., Bas, S. and Akbas, S.O. (2018), "Seismic risk estimation of the Kirikkale province through street survey based rapid assessment method (SSRA)", *Earthq. Struct.*, **14**(6), 615-626. http://doi.org/10.12989/eas.2018.14.6.615.

Sonmezer, Y.B., Bas, S., Isik, N.S. and Akbas, S.O. (2018), "Linear and nonlinear site response analyses to determine dynamic soil properties of Kirikkale", *Geomech. Eng.*, **16**(4), 435-448. https://doi.org/10.12989/gae.2018.16.4.435.

Sonmezer, Y.B., Kalkan, I., Bas, S. and Akbas, S.O. (2018), "Effects of the use of the surface spectrum of a specific region on seismic performances of R/C structures", *Nat. Hazards*, **93**(3): 1203-1229. https://doi.org/10.1007/s11069-018-3347-3 .

TSC (2007), Turkish Seismic Code, Ministry of Public Work and Settlement; Ankara, Turkey.

TSCB (2018), Turkish Seismic Code for Buildings, Disaster and emergency management authority (AFAD); Ankara, Turkey.

Turker, D. and Cokca, E. (2006), *Effects of Addition of Fly Ash on Swell Potential of an Expansive Soil*, Chapter 31, Taylor & Francis, London, U.K.

Wang, N., Sun, X., Zhao, Q., Yang, Y. and Wang, P. (2020), "Leachability and adverse effects of coal fly ash: A review", *J. Hazard. Mater.*, **396**, 122725. https://doi.org/10.1016/j.jhazmat.2020.122725.

Yilmaz, Y., Eun, J., and Goren, A. (2018), "Individual and combined effect of Portland cement and chemical agents on unconfined compressive strength for high plasticity clayey soils", *Geomech. Eng.*, **16**(4), 375-384. http://doi.org/10.12989/gae.2018.16.4.375.

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