Experimental evaluation of lime column as a ground improvement method in soft soils

Shabir Hussain¹ · Muhammad Fahim¹ · Fasih Ahmed Khan¹ · Saeed Zaman¹

Received: 15 June 2020 / Accepted: 30 August 2021

Published online: 08 September 2021

© The Author(s) 2021

Abstract

Lime column (LC) is an effective method for ground improvement which causes reduction in settlement and enhancement in bearing capacity of soft soils, subsequently resulting in economical foundations. This study investigates the effects of LC on soft soil with the help of laboratory tests. Firstly, basic laboratory tests are performed on natural soil followed by load deformation tests on untreated and LC treated soils. LC effects on natural soil are studied by changing various parameters like shear strength of soil (54 kPa, 32 kPa, 14 kPa), slenderness ratio (4, 5.5, and 7) and spacing to diameter ratio (2, 3). Experimental results show that LC significantly increases load carrying capacity and stiffness for soils having higher shear strength. For soil samples of 54 kPa and 32 kPa, the load carrying capacity increases by 48 and 21% respectively whereas 75% increase in average stiffness ($\beta = 1.75$) is observed. However, LC are found to be ineffective at very low shear strength of 14 kPa. In case of group LC, increasing column spacing from 2 to 3D (D: diameter of LC) significantly decreases load carrying capacity of treated soil. It is also observed that increase in LC slenderness ratio causes a decrease in ultimate load carrying capacity.

Article highlights

- Lime columns can be used to increase load carrying capacity of soft soils, especially in soils having relatively higher shear strength.
- In case of group columns, the spacing should not be more than two times the diameter of the column.
- The length of the lime columns should not be more than four times the diameter for better results.

Keywords Ground improvement · Lime columns · Soft soil · Shear strength

1 Introduction

Civil engineering structures resting directly on, in or against problematic soils have experienced significant damages throughout history resulting in heavy casualties and huge capital loss. The challenges that problematic soft soils present to geotechnical engineers are inappropriate

engineering properties of these soils like swelling, shrinkage, high compressibility, low shear strength, and low bearing capacity [1]. Swelling and shrinkage in these soils are primarily due to their grain size distribution (presence of large quantity of clay size fraction) and their mineralogical composition i.e. presence of active clay minerals like Montmorillonite (a very soft group of phyllosilicate

✉ Muhammad Fahim, drmfahim@uetpeshawar.edu.pk; Shabir Hussain, shabirhussain@uetpeshawar.edu.pk; Fasih Ahmed Khan, fasihahmad@uetpeshawar.edu.pk; Saeed Zaman, saeedzaman@uetpeshawar.edu.pk | ¹Department of Civil Engineering, University of Engineering and Technology, Peshawar, Pakistan.

minerals). Soft soils with such minerals have the so called “double water layer” clung to the soil particles which makes them shrink as well as swell upon decrease and increase of moisture content. Various reinforcing techniques are currently employed e.g. stone columns [2–4], sand compaction piles [4, 5], fiber-reinforcement [6, 7], chemical admixtures [8], chemical stabilization using cement and lime [9], and lime column/piles [10–12].

The terms lime piles and lime columns are used interchangeably in the literature. An overview of the two techniques shows that there are three basic procedures used in different countries for installation of lime columns/piles. The first method was developed in Sweden by Broms and Boman [13] in which lime is mixed thoroughly with clay by a deep mixing auger. This method was also used for soft ground stabilization in China, Japan, Singapore and many other countries of the world with little or no variation. Lime pressurized slurry injection is the second technique in which lime slurry is injected under pressure in the sloping ground by relatively small but specialized equipment. This method was used in United States of America by Blacklock and Wright [14]. The third method is the lime column/pile technique in which holes are drilled in the soft soil deposits and are filled with quick lime and then compacted. Extensive research on lime piles method has been carried out by Rogers and Glendinning [15] in UK while lime piles field installation method was shown by Ingles and Metcalf [16]. Lime column/pile can be used as an effective stabilization technique for weak foundation soil and weak sub-grade soil. It can also be used as a slope stabilization technique for highway embankments, water retaining structures, breakwater, sea wall and also for bracing of excavation support systems.

The first developments in deep mixing technology were made in 1954 in the United States. However, lime column method was originated and used practically in the field in mid-1970's in Sweden by Broms and Boman [13] and in Japan by Okumura and Terashi in 1975 [17]. The technique soon became popular all over the world due to its effectiveness and high growth potential. Various researchers have worked on lime columns/piles in different regions of the world like Austria [18], Sweden [13], Italy [19], and Japan [20]. In developed countries like UK and US, lime pile/column is used as deep soil stabilization and slope stabilization method. Notable research on lime pile/column as a deep soil stabilization and also as a slope stabilizing mechanism is carried out in UK by Rogers and Glendinning [15, 21] and in the US by Handy and Williams [22], and Blacklock and Wright [14]. Lime columns/piles are also used in certain Asian countries like China, Singapore, Japan, and Thailand [23].

Baker [24] showed that stiffness of the stabilized soil using lime column/pile increased significantly than that of

lime-cement column. Wong [25] worked on various case studies and theoretical studies and concluded that lime columns/piles increase strength and stiffness of in situ soils and the resulting increase in shear strength with lime columns was higher than the theoretical prediction. Malekpoor and Poorebrahim [26] concluded that compacted lime-well graded soil columns reduces the settlement and increases the load carrying capacity of the surrounding soil. It was also concluded that the variations in stiffness become negligible with column diameters greater than 100 mm so the results can be extrapolate for predicting the behavior of full size columns. Hozatlioglu and Yilmaz [27] compared shallow mixing and column performances of gypsum, fly ash, and lime in swelling soils and concluded that the greatest reductions (99.8% for shallow mixing and 51.9% for column technique) were produced by lime. Numerical studies using various finite element based software packages like PLAXIS, Phase 2, ANSYS and ABAQUS have also been carried out by various researchers [28, 29]. Poorooshasb and Meyerhof [10] studied the effectiveness of end bearing lime columns for reducing settlement/differential settlement. Moghal et al. [30] studied expansive semiarid soils treated with lime under a range of loading periods and concluded that the compressibility behavior is significantly reduced with the addition of lime.

This paper presents the results of laboratory tests on small-scale models of lime column treated soil specimens. Five different parameters which are necessary for evaluation of lime column efficiency and performance in the field were considered and testing was conducted accordingly. These include variation in number of columns (single or group), undrained shear strength of soil, L/D ratio of columns, S/D ratio of columns, and loading pattern i.e. entire area loading and column only loading. The findings of the study will help practicing engineers in deciding the efficient use of lime column for improving the performance of soft soils. The experimental setup is discussed in the following section which includes material properties, preparation of soil sample and lime columns, and testing procedure. This is followed by discussion on the results for soil samples treated with single lime column and group lime columns. Finally, important conclusions are drawn from the results and recommendations are given for future research.

2 Experimental setup

A series of laboratory tests on untreated and LC treated soft soils were performed to investigate the performance of lime columns in enhancing the strength of soft soils. The clay bed was prepared in locally assembled steel mould having height of 360 mm, internal diameter of

Fig. 1 Particle size distribution of soft soil specimen

Fig. 2 Moisture density relationship of soft soil

300 mm and wall thickness of 6 mm. A compression testing machine was used for loading of treated and untreated soil samples.

2.1 Properties of materials

2.1.1 Natural soil

Natural high plastic soil/soft soil used in this study was obtained from Jahangira in district Swabi, province of KPK, Pakistan. The soil samples were pulverized in the laboratory before conducting tests for Atterberg's limits, moisture content, unconfined compressive strength, grain size distribution (Fig. 1), optimum moisture content and maximum dry density (Fig. 2). All the tests were performed as per standard ASTM and AASHTO procedures as shown in Table 1. The physical properties indicate that the natural soil used in this research is high plastic clay (CH) with a high percentage of fines due to which the soil has high volume compressibility and low bearing capacity problems, which needs improvement.

2.1.2 Quick lime (Column Material)

The lime used in this research was local quick lime (CaO) collected from Islamabad Pakistan. Quick lime used for making lime columns was oven dried, pulverized and passed through standard Sieve No. 4 (4.75 mm) before using as a column material. The properties of lime used in this research are summarized in Table 2.

2.1.3 Relationship between shear strength (S_u) and moisture content (w) of natural soil

Unconfined compression tests were performed on cylindrical soil samples for developing relationship between shear strength (S_u) and moisture content before the preparation of clay bed. Figure 3 illustrates the change in S_u of natural soil with addition of water. Optimum moisture content (OMC) is considered as a compaction control parameter in most of real life field compaction projects for ensuring efficient compaction. However, in certain field

Table 1 Physical properties of natural soil

Property	Procedure	Results
Standard proctor test (OMC %)	(ASTM D698 / AASHTO T99)	31
Modified proctor test (OMC %)	(ASTM D1557/ AASHTO T180-D)	24
Liquid limit (%)	ASTM D 4318	51
Plastic limit (%)	ASTM D 4318	28
Plasticity index	ASTM D 4318	23
Shrinkage limits (%)	ASTM D427-04	26.43
Specific gravity	ASTM D-854	2.65
Passing no. 200 sieve (%)	ASTM D6913/D6913M	100
Silt contents (%)	ASTM D6913/D6913M	40
Clay contents (%)	ASTM D6913/D6913M	60
Classification according to USCS	ASTM D2487-17	CH

Table 2 Engineering properties of lime (column material)

Property	Procedure	Results
Lime type	–	Quick lime
Specific gravity	ASTM D-854	2.61
Dry unit weight	ASTM D-1556–64	18 KN/m ³
Angle of internal friction	ASTM D-3080–90	25°
Un-drained shear strength	ASTM D-2166	100 KN/m ²
Modulus of elasticity	ASTM D-2435	15 MPA

Fig. 3 Undrained shear strength (S_u) and moisture content (w) relationship

scenarios moisture content encountered is greater than OMC which can reduce bearing capacity of soft. So in this study treated and untreated soil samples were compacted and tested at OMC and also above OMC to simulate the actual field conditions. The OMC obtained from standard proctor test for the natural soil used in this study was 31%. Three moisture contents (31% = OMC), 35% = OMC + 4%, 39% = OMC + 8%) were selected for preparing natural soil bed. The undrained shear strengths were calculated as 54 kPa, 32 kPa and 14 kPa at these moisture contents, respectively.

2.2 Soil sample preparation

For preparation of each soil bed, natural soil was first oven dried and then required amount of water was added and thoroughly mixed with soil to obtain desired undrained shear strength. The total height of the soil sample was 300 mm (six layers of 50 mm thickness) in the container after compaction. Each layer was compacted by giving 70 blows of a 10 kg tamper dropped from a height of 300 mm Fig. 4a, b. This corresponds to a compaction energy as provided in Standard Proctor Test (12,375 ft-lb/ft³). The compacted soil in the steel mould was properly covered with the plastic sheet and left for four days curing period Fig. 4c.

(a) Compaction of clay in layers **(b)** Compacted clay sample **(c)** Soil sample covered in plastic sheet during curing period **Fig. 4** Process of sample preparation

2.3 Construction of lime columns

Replacement method was used for the construction of lime columns after the preparation of soil bed (Fig. 5). A hole was made in the soil bed up to the required depth with the help of an open-ended steel pipe having 37 mm outer diameter and 1 mm wall thickness. The outer surface of the steel pipe was made smooth with the help of some grease to ensure smooth penetration and withdrawal. The column material was then fed into the hole in six layers, each having depth of 50 mm. Each layer was compacted with 15 blows of a 1.25 kg circular steel tamper dropping from a height of 100 mm. The soil samples were covered with plastic sheets for four days curing period to ensure uniform moisture distribution. It should be noted that in this study lime columns are considered as inclusions like micro piles, meant to increase the stiffness of the soil, the clay-lime mixing is not done which generally cause clay-lime chemical reactions like cation exchange, flocculation, aggregation and carbonation. The LC installation technique used in this study permits clay-lime reactions only on the periphery of the columns.

Fig. 5 Specimen preparation process and failure patterns

(a) Compaction of soil

(b) Hole for lime column

(c) Single LC

(d) Sample covered with plastic sheet during curing period

(e) Model in compression testing machine

(f) Failed LC

(g) Holes for group lime columns $S = 2D$

(h) Group lime columns

(i) Failed Lime Columns

2.4 Load-deformation testing procedure

A compression testing machine was used to apply compressive load on the surface both untreated and treated samples to develop load-deformation relationships. A round steel plate of 200 mm diameter and 100 mm thickness was placed at the centre of steel container to transfer the load uniformly to the soil samples. Deformation gauges were attached to the upper plate to constantly monitor the settlement. The load was applied at a constant loading rate and settlement was recorded. Load was applied continuously until failure of sample or excessive settlement of 30 mm (10% strain) was reached. The termination strain was selected as 10% due to high plasticity of soft soil samples (10–20% termination strain is the failure

criteria followed in most of the soil shear strength tests i.e. triaxial compression test (ASTM D 4767), Unconfined compression test (ASTM D 5102–96)). The stepwise procedure of lime column construction and load deformation testing by compression testing machine for both entire area loading and axial column loading are shown in Figs. 5 and 6

2.5 Testing program

After four days of curing, load-deformation tests were performed on untreated and LC treated soil samples to investigate the effect of lime columns on load carrying capacity of soft soil. Five different parameters which are necessary for evaluation of lime column efficiency and performance in the field were considered and testing was

Fig. 6 Test arrangement **a** Column alone loading **b** Equivalent entire area loading

conducted accordingly. These include variation in number of columns (single or group), undrained shear strength of soil, L/D ratio of columns, S/D ratio of columns, and loading pattern i.e. entire area loading and column only loading. The details of the testing program are given in Table 3.

3 Results and discussion

3.1 Soil samples treated with single lime column (Entire Area Loaded)

The results for soil samples treated with single LC having slenderness ratio of 4 and entire area under load are shown in Fig. 7. The ultimate load carrying capacity of treated samples compacted at OMC and 4% above OMC having S_u of 54 kPa and 32 kPa was increased by 48% and 21%, respectively. However, treated soil samples compacted at 8% above OMC having relatively low S_u of 14 kPa, showed a decrease in load carrying capacity. This indicates that LC effectiveness decreases as moisture content is increased beyond OMC, which is also in accordance with Proctor compaction test. The single LC with $L = 4D$ became ineffective as shown in Fig. 7 for specimens compacted at OMC + 8% (39%). This behaviour is attributed to the fact that if moisture content is as high as 39% and curing period is short (four days in this case), so slaking of lime occurs which converts lime into

Fig. 7 Comparison of untreated and treated soil for $L/D = 4$

slurry and makes it unsuitable for increasing the load carrying capacity of soft soils.

Stiffness improvement factor (β) was calculated as a ratio of stiffness of treated soil ($L/D = 4$) to stiffness of untreated soil. Figure 8 shows the effect of undrained shear strength on average stiffness as shown by stiffness improvement factor. Since no improvement was observed with single lime column ($L = 4D$) inclusion in relatively high moisture content (39%) and low undrained shear strength (14 kPa) so stiffness improvement factor was reported to be less than unity. However, the stiffness improvement factor is independent of the undrained shear strength at 32 and 54 kPa as 75% increase in average stiffness was calculated for both cases. For stone columns, the stiffness improvement factor is also reported to be independent of shear strength [2].

Figure 9 shows effect of slenderness (L/D) ratio of lime columns on soft soil. The load carrying capacity is maximum at L/D ratio of 4 and decreases with increase in L/D ratio from 5 to 7. A similar type of response has been reported for compacted lime soil columns and stone columns by [2, 26]. The bearing capacity failures were observed beyond critical column length (L) of $4D$ which decreases load carrying capacity of treated soil, so increasing column length beyond critical column length is counterproductive.

Table 3 Type of tests conducted

S. No	No. of columns	Undrained shear strength (kPa)	L/D ratio	S/D ratio	Loading
1	Single	54, 32, 14	4	N/A	Entire area
2	Single	32	4, 5.5, 7	N/A	Entire area
3	Group of three	32	5.5	3, 2	Entire area
4	Single	54, 32, 14	4	N/A	Column only
5	Single	32	4, 5.5, 7	N/A	Column only

Fig. 8 Effect of shear strength on stiffness improvement factor

Fig. 9 Effect of length to diameter ratio (L/D)

3.2 Samples with group lime columns (Entire Area Loaded)

A group of three columns in triangular pattern were installed in a soft soil ($S_u = 32$) where column spacing to diameter ratio (S/D) was 2 and 3 and L/D was kept as 5.5. Treated soil with group of LC having $S = 2D$ has shown 100% improvement in load carrying capacity and soil treated with LC group having $S = 3D$ has shown 48% improvement at 30 mm settlement. The ultimate load carrying capacity of sample with $S/D = 2$ is 52% higher as compared to that of $S/D = 3$ at 30 mm settlement as shown in Fig. 10. Venkatanarayana et al. [20], also reported that smaller spacing between lime piles show greater degree of improvement. The group efficiency is observed to be greater at closer spacing while it becomes negligible at $S/D > 2$. The load carrying capacity of group columns also validate that single lime column at centre of mould with same area ratio simulates the behaviour of a column at the centre of multiple columns.

Fig. 10 Comparison of single lime column and group lime columns

Fig. 11 Effect of shear strength on axial capacity of lime columns

3.3 Samples with single lime column (only column loaded)

Figure 11 shows the effect of S_u on axial capacity of lime columns. It can be observed that as S_u decreases, the axial load carrying capacity of lime column decreases. The reason being the decrease of lateral resistance from the surrounding soil as S_u of soil decreases.

The effect of length to diameter ratio (L/D) on lime column load carrying capacity is shown in Fig. 12. The load carrying capacity is found to be maximum at $L/D = 4$ and decreases with increase in L/D ratio. It has also been reported by [31] that no significant increase in load carrying capacity has been observed beyond $L/D = 5$. In this research, critical column length was observed to be $4D$ in both entire area as well as axially column loaded cases. Increasing column length beyond critical length causes bulging in the upper region of the column which decreases along column depth as shown in Fig. 13b. Handy and Williams [22] reported that bulging depth varies from 2 to 3 times diameter of the column in slender stone columns. However, bulging was observed when only column

Fig. 12 Effect of slenderness (L/D) ratio on axially loaded lime column

Fig. 13 a Loading of LC b Bulging of axially loaded LC (L/D = 7)

was loaded. In entire area loading case, bearing capacity failure was observed for both single and group columns.

4 Conclusions

This study investigates the effects of lime columns on soft soil with the help of laboratory tests. Five different parameters; namely shear strength of soil (54 kPa, 32 kPa, 14 kPa), slenderness ratio (4, 5.5, and 7), spacing to diameter ratio (2, 3), number of columns (single or group), and loading pattern i.e. entire area loading and column only loading are considered. In case of undrained loading, the lime columns are more effective in soft soils (CH) compacted at OMC. The load bearing capacity of lime columns significantly decreases with the increase of moisture beyond OMC and becomes ineffective when installed in soft soils compacted at OMC + 8%. Similarly, in case of undrained loading, the load bearing capacity of compacted soft soils treated with lime columns decreases with the decrease of undrained shear strength (S_u) of soil.

The load bearing capacity of soft soil treated with lime columns decreases with increasing slenderness (L/D) ratio of lime columns. This response was observed for entire soil area loaded as well as column only loaded cases. The critical column length (L) is found out to be 4D beyond which increasing column length was counterproductive. Increasing lime columns spacing from 2 to 3D causes a significant decrease of 52% in load carrying capacity of treated soil. Stiffness improvement factor (β) was found to be constant at undrained shear strengths of 54 and 32 kPa (independent of S_u). However it falls below unity at $S_u = 14$ kPa and $w = \text{OMC} + 8\%$ because complete slaking of lime occurs at such high moisture which is counterproductive. Axially loaded lime columns show bulging in the top region where axial stress is maximum, but it decreased continuously with increasing depth of the column. In the entire soil area loaded cases, columns showed no bulging and bearing capacity failures were observed.

This study was conducted on small scale specimens so both large scale laboratory testing and field testing of lime column treated soils may be carried out to supplement the findings of this study. Lime may also be used in combination with other materials e.g. sand, stones, cement, etc. for treating soft soils. Future study may also investigate the effects of other parameters such as chemical reaction between lime columns and soil, strain rate, method of LC installation, curing time and temperature, etc.

Acknowledgements The first author is grateful to the Civil Engineering Department at National University of Sciences and Technology (NUST), Pakistan for facilitating the lab work.

Funding None.

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Onyelowe K et al (2019) Sorptivity, swelling, shrinkage, compression and durability of quarry dust treated soft soils for moisture bound pavement geotechnics. *J Market Res* 8(4):3529–3538
2. Ambily AP, Gandhi SR (2007) Behavior of stone columns based on experimental and FEM analysis. *J Geotech Geoenvironmental Eng* 133(4):405–415
3. Barksdale RD, RC. Bachus RC (1993), Design and Construction of Stone Columns, F.H. Administration, Editor. 1993, School of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia
4. Malekpoor MR, Tonfigh MM (2010) Laboratory study of soft soil improvement using lime mortar-(Well Graded) soil columns. *Geotech Test J* 33(3):225–235
5. Naseer S et al (2019) Laboratory and numerical based analysis of floating sand columns in clayey soil. *Int J Geo-Eng* 10(1):10
6. Soltani A, Deng A, Taheri A (2018) Swell compression characteristics of a fiber-reinforced expansive soil. *Geotext Geomembr* 46(2):183–189
7. Rafalko SD et al (2007) Fiber reinforcement for rapid stabilization of soft clay soils. *Transp Res Rec* 2026:21–29
8. Shen Z, Cao Y, Fang L (2017) Experimental investigation of rapid stabilization of soft clay soils using chemical admixtures. *Soil Mech Found Eng* 54(3):202–210
9. Rafalko SD et al (2007) Rapid chemical stabilization of soft clay soils. *Transp Res Rec* 2026:39–46
10. Poorooshasb HB, Meyerhof GG (1997) Analysis of behavior of stone columns and lime columns. *Comput Geotech* 20(1):47–70
11. Zhou C, Yin JH, Ming JP (2002) Bearing capacity and settlement of weak fly ash ground improved using lime-fly ash or stone columns. *Can Geotech J* 39(3):585–596
12. Malekpoor M, Poorebrahim G (2014) Comparative study on the behavior of lime-soil columns and other types of stone columns. *Geomech Eng* 7(2):133–148
13. Broms BB, Boman P (1975) Lime Stabilized Column. In: *Proceedings 5th Asian regional conference on soil mechanics and foundation engineering*. pp. 227–234
14. Blacklock JR, Wright PJ (1987) Injection stabilization of failed highway embankments. *transportation research board*. pp. 7–18
15. Rogers CDF, Glendinning S (1997) Improvement of clay soils in situ using lime piles in the UK. *Eng Geol* 47(3):243–257
16. Ingles OG, Metcalf JB (1972) *Soil stabilization principles and practice*. Butterworths, Sydney
17. Engan K, Gijutsu K (2002) *The deep mixing method: principle, design, and construction*. CRC Press, Boca Raton
18. Brandl H (1973) Stabilization of slippage-prone slopes by lime injections. In: *8th International conference on soil mechanics and foundations engineering*. Moscow.. Vol. 4.3: pp. 300–301
19. Paviani A, Pagotto G (1991) New technological developments in soil consolidation by means of mechanical mixing, implemented in Italy for the ENEL power plant in Pietrafitta. In: *Proceedings of X ECSMFE*. 1991. pp. 511–516
20. Terashi M (1997) Deep mixing method -brief state of the art. In: *Proceeding of 17th international conference on soil mechanics and foundation engineering*. Hamburg, Germany
21. Rogers C, Glendinning S (1994) Deep-slope stabilization using lime piles. In: *Transportation Research Record 1440*, Transportation Research Board, National Research Council, Washington DC, USA. pp. 63–70
22. Handy RL, Williams WW (1967) Chemical stabilization of an active landslide. *Civ Eng* 37(8):62–65
23. Ruenkairergsa T, Pimsarn T (1982) Deep hole lime stabilization for unstable clay shale embankment. In: *Proceedings of the seventh S E Asia geo-technics conference*. Hong Kong
24. Baker S (2000) Deformation behavior of lime/cement column stabilized clay. *Swedish Deep Stabilization Research Centre*, Sweden, pp 1–203
25. Wong P (2004) Ground improvement case studies chemical lime piles and dynamic replacement. *Austr Geo Mech Soc J* 39 (2)
26. Malekpoor MR, Poorebrahim G (2015) Behavior of compacted lime — (Well-graded) soil columns: large scale tests and numerical modelling. *KSCE J Civ Eng* 19(4):893–903
27. Hozatlıoğlu DT, Yılmaz I (2021) Shallow mixing and column performances of lime, fly ash and gypsum on the stabilization of swelling soils. *Eng Geol* 280:105931
28. Salem T, Mashhour M, Hassan R (2012) Stabilizing piles of soft cohesive slopes: a case history. *Electron J Geotech Eng* 17:3803–3820
29. Amutha K, Satheeskumar V (2017) Experimental and numerical modeling of composite piled raft with cushion. In: *International conference on geotechniques for infrastructure projects*
30. Moghal A et al (2015) Compressibility and durability characteristics of lime treated expansive semiarid soils. *J Test Eval* 43(2):1–9
31. Samadhiya NK et al (2008) Load settlement characteristics of granular piles with randomly mixed fibers. *Indian Geotech J* 38(3):345–354

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.