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A critical review on the performance of column improved ground under shear and seismic loading

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ABSTRACT

This paper reviews the performance of conventional stone column improved ground under static shear conditions and seismic loading. The limitations of stone columns in resisting lateral spreading due to shear movements and ground motions are detailed from extensive literature review. Suggestions for improving the shear resistance of improved ground with alternatives to stone column are incorporated. The better performance of pervious concrete column as an alternative to stone column under static shear and seismic loading is also briefed.

1. Introduction

Stone columns are employed for improving the weak ground by enhancing the vertical load bearing capacity and controlling the settlement. These gravel columns are also used in loose sandy soils in seismically active areas. Ground improvement with stone columns mitigate liquefaction induced damages by draining excess pore water developed due to seismic shaking. In the recent past, research has been carried out for enhancing the load bearing capacity of stone columns by internally or externally reinforcing conventional stone columns by various methods. But the research focussed on shear behaviour of stone columns and modified stone columns are seldom found. The studies on seismic performance of modified stone columns are also limited. However, the liquefication mitigation potential of conventional stone columns are reported using analytical, experimental, numerical, and field studies.

In a wide embankment constructed over a stone column improved ground, the soil beneath and adjacent to the toe of the embankment can move more laterally as shown in Fig.1. This lateral movement is called lateral spreading and it reduces the support given to stone column and surrounding soil [1]. For an embankment supported by stone column system, the columns positioned in the middle are largely exposed to vertical loading. But then the columns positioned underneath the toe of the embankment is exposed to lateral loading. The failure of stone column supported embankment is shown in Fig.1.

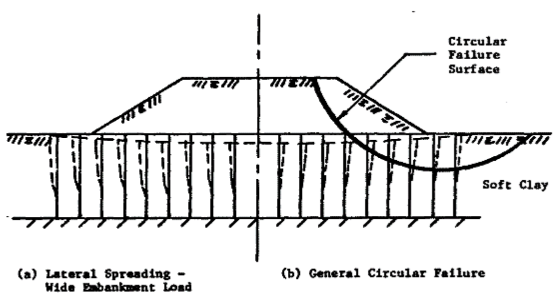

Figure 1 Failure of stone column supported embankment [1]

Kitazume and Maruyama [2] and Han [3] reported that, one of the potential column failure modes under an embankment was horizontal shear as shown in Fig.2. Utilizing Rankine's theory of active and passive earth pressures, Kitazume and Maruyama [2] assessed the internal stability of Deep Cement Mixing (DCM/DM) column improved ground due to shear. The shear failure of DCM columns is shown in Fig.3. It is reported that the shear failure mechanism in the current design methods is considered for internal stability, however the same has not been verified by experimental and/or numerical methods [2, 4].

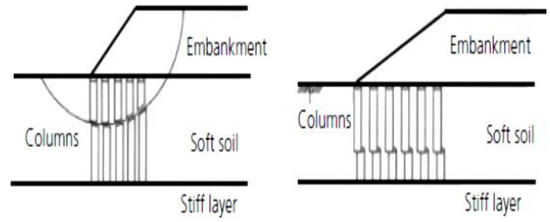

Figure 2 Possible circular and horizontal shear failure modes of columns under embankments [3]

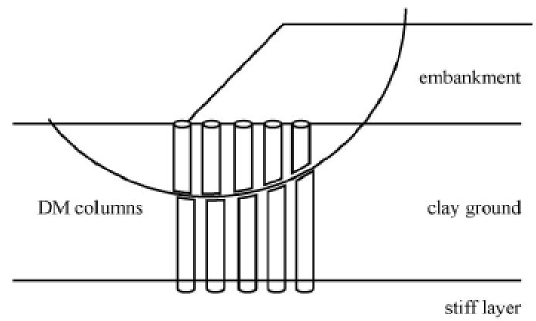

Figure 3 Shear failure of DCM/DM columns [2]

Shear strength of stone column improved ground on a sloping ground based on stability criteria was detailed by Barksdale and Bachus [1] using unit cell concept. The stability of columns was analyzed by using average shear strength method. In this method the circular arc must pass through the stone column and the shear properties of entire material is weighted. A general stone column improved ground with stone column having friction angle alone and surrounding soil with both friction and cohesion was considered.

Theoretical shear resistance (F) of stone column improved soft ground is given by,

$$F = A_c \tau_c + A_s \tau_s \quad (1)$$

F : Shear strength of improved ground

A_s : Area of soil

τ_s : Shear strength of soil

A_c : Area of stone column

τ_c : Shear strength of stone column

Noorzad et al. [5] explained the strengthening effect of partially penetrating stone columns during an earthquake and proposed a numerical model representing improved ground by a unit cell with stone column placed at the center. The model considered the following assumptions. The permeability of stone column is free draining to confirm that there is no build-up of surplus pore water pressure in the interior of the stone column during earthquakes. The horizontal component of displacement, velocity and acceleration of soil and water particles are identical during ground shaking. The stone column carries the major load imposed by the superstructure and minor load is distributed by the soil. This load remains constant during shaking. It is also assumed that there is complete connection between the stone column and the soil surrounding it.

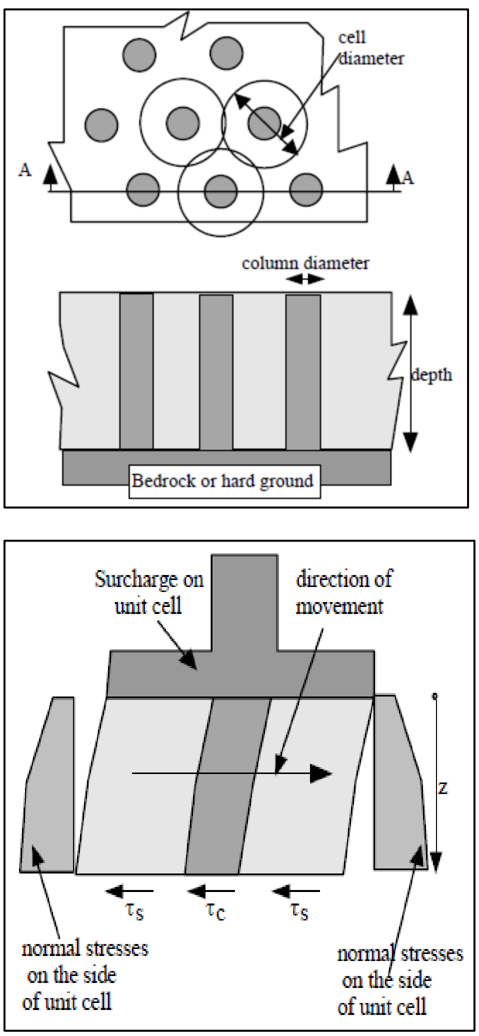

Figure 4 Stone column arrangement and FBD of unit cell block [5]

Fig.4 shows the free body diagram (FBD) of the unit cell system above the depth, *z*, by considering the dynamic equilibrium of unit cell. If W is the "weight" of the surcharge, γ_s the unit weight of the sand and γ_c the unit weight of the column Noorzad et al. [5] incorporating Equation (1), the equation for stone column arrangement when subjected to seismic loading is written as:

$$\frac{W}{g}\ddot{u}_1 + \int_0^z \left(\frac{\gamma_s}{g}A_s + \frac{\gamma_c}{g}A_c\right)\ddot{u}_\xi d\xi = F = A_s\tau_s + A_c\tau_c \quad (2)$$

where $\ddot{u}_1, A_s$ *and* A_c represents horizontal surface acceleration, cross-sectional area of sand and cross-sectional area of the column in the unit cell respectively. The average shear stress components at depth *z* are τ_s *and* τ_c respectively.

Liquefaction is a phenomenon in which saturated, or partially saturated sands and silts loses its shear strength when subjected to seismic vibrations and behaves like a liquid. The soil structure is distorted due to cyclic shear strains developed in saturated cohesionless soils due to seismic waves propagating through the soil layer. If there is no provision for the drainage of excess pore water to dissipate, the intergranular stress gets transferred to interstitial pore water. This causes soil to soften due to decreased intergranular stresses. When the intergranular stresses approach zero, that means the total soil stress is transferred to interstitial pore water, the soil behaves like liquid temporarily. This phenomenon of soil transforming from solid to liquid state is known as liquefaction[6].

Liquefaction generally occurs in loose saturated or partially saturated cohesionless soils. The liquefaction phenomenon induces ground deformation and associated ground failures. One of the ground failures due to horizontal displacement of ground is known as lateral spread. Lateral spread generally occurs in gentle slopes or in a free face adjacent to water bodies. Lateral spread occurs due to combined response of gravitation and earthquake induced inertial forces acting on soil layer[6]. The surface layers commonly break into large blocks as shown in Fig.5 due to lateral spread. These surface blocks move down the gentle slope or free face due to seismic ground shaking. This causes zones of extension with open fissures [6].

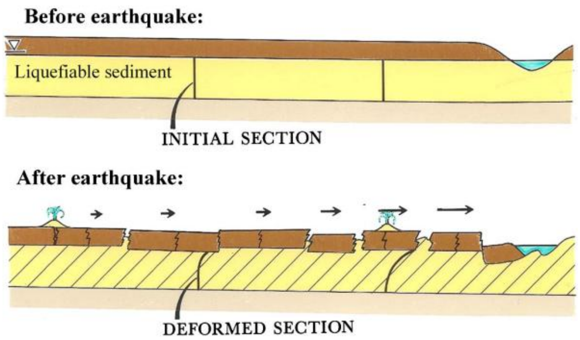

Figure 5 Lateral spread [6]

Stone columns positioned underneath huge embankment experiences considerable shear loading. This shear failure results in lateral spreading of embankments owing to the movement of subsoil. Also seismically induced liquefaction causes lateral displacements and is termed as liquefaction induced lateral spreading. The destructive effect of liquefaction is due to related lateral spreading damages. Therefore, it is important to address the liquefication mitigation potential of improved ground with emphasis on lateral spreading. Stone columns are widely used to alleviate liquefaction to a greater amount by draining excess pore water through its pores present in the stone column. Therefore, this review focussed on the performance of stone column improved ground when subjected to shear and seismic loading conditions. Though limited, the performance of encased stone columns under static loading and seismic loading is reported. It is noted that the conventional stone column ruptures and moves along with the surrounding soil under shear movements. This shows that the stone column does not offer any resistance to shear movements and indicates a need for improving the shear resistance of stone columns.

2. Literature Review

Literature review on the performance of stone column improved ground under static shear and seismic loading conditions is presented in the following sub sections.

2.1 Static shear loading

Murugesan and Rajagopal [7] performed series of direct shear tests on unreinforced stone column and reinforced stone column with geosynthetic encasement to study the behaviour of shear deformations in stone columns. They reported that the added encasement made stone column to behave as a semi rigid pile and shear load capacity was significantly improved. They also performed laboratory tests by inducing lateral soil movements in stone column treated soil and developed experimental setup to overcome the depth restriction in direct shear test. For this, large shear test tank (with an increased depth) was developed with a dimension of 1200 mm linearly, 300 mm laterally and 600 mm vertically. It is reported that the loading over the whole lateral width of the test tank (300 mm) simulates the plane strain loading under the embankment condition. From this special experimental setup, it was found that the ordinary stone columns exhibit limited resistance to shear movements. They also concluded that the geosynthetic encased stone columns offer higher shear resistance due to the confinement of aggregates provided by the encasement.

Mohapatra et al. [8] performed direct shear tests on ordinary and geosynthetic encased end bearing stone columns to study the behaviour under shear loading. They reported that the lateral load capacity of stone columns with encasement heightened with the use of encasement layer, due to the mobilization of tensile forces in the layer. The shear strength was observed to be increased with increase in area ratio for encased stone columns. They stated that the shear resistance of encased granular column increases with shear displacements up to complete rupture of encasement material. They also reported the strength reduction of encased stone column to that of plain stone column after the rupture of encasement. They conducted experiments in group of stone columns with square and triangular pattern. Tests were conducted on group arrangement of stone columns and observed to have greater shear resistance than single stone column. They concluded that the group arrangement of encased granular column offers higher shear resistance because of the confinement offered to the intervening soil. Mohapatra et al. [9] performed three-dimensional modelling of ordinary and geosynthetic encased granular columns in direct shear test model using FLAC 3D and mode of failure of encased stone column was presented. It was reported that the encased granular column tilts like a rigid body at lower normal pressures and flexural type deformation is observed at higher normal pressures at the failure plane. 3D slope stability was also carried out to simulate field conditions. From 3D slope stability analysis, it is stated that a higher Factor of safety even in very soft ground with geosynthetic encased granular columns can be mobilised.

2.2 Seismic loading

Seed and Booker [10] initially proposed the use of gravel drains in mitigating liquefaction. They developed one dimensional theory of pore water pressure generation and dissipation. They expanded this theory to three dimensions and utilized in the assessment of columnar gravel columns under a range of seismic situations. Design charts were developed from those analyses for providing convenient basis for design considerations. It was reported that the leading process in the function of a gravel drain method is of absolute horizontal drainage. A system of gravel or rock drains can be installed in liquefiable ground such that the pore water generated during earthquake vibrations may be dissipated as quickly as they are developed [10]. Baez [11] developed a mathematical model capable of modelling earthquake shear stress redistribution for evaluating improved drainage parameters and densification of liquefaction in soils ranging from clean sands to non-plastic silts. Design charts were developed for the cost-effective remediation using stone columns from SPT and CPT field tests for differing soil conditions. Based on densification mechanism, it was reported that the stone columns are more beneficial when placed at close distances (3 ft).

Ashford et al. [12] conducted full scale laterally loaded stone columns in liquefied soil. Controlled blasting was used to liquefy soil and assessed the performance before and after treatment with stone columns. Stone columns are found to improve stiffness of soil 2.5-3.5 times more than soil without stone column treatment. It was also found that the rate of excess pore pressure dissipation after blasting was significantly high due to the presence of stone columns. Adalier et al. [13] conducted centrifuge studies to assess liquefaction counter measure of densified non-plastic silty soils with stone columns. The focus of the study was on the overall stiffness of soil using stone columns rather than the drainage effectiveness of stone columns. The experiment was carried out on uniform silt ground, stone column treated ground with and without surcharge. It was reported that confinement was obtained with surcharge load and lateral displacement reduced considerably for stone column treated ground with surcharge. Elgamal et al. [14] conducted numerical modelling using OpenSeesPL on sand and silt strata with stone column and pile pinning remediation. Pile pinning was reported as effective for both sand as well as silt strata in mitigating liquefaction. However, stone column was found to be ineffective in silt strata. The ground surface displacement was reported to be less than 0.3 m using stone column remediation only when area ratio was from 20% to 30%. It was concluded that for achieving small scale deformation, area ratio greater than 40% is needed while using stone column remediation. Pile pinning with area ratio as small as 10% was observed to offer very less lateral deformation.

Krishna [15] reported the various mechanisms that contribute to the seismic performance of stone columns in mitigating liquefaction as drainage, storage, dilation and densification, and reinforcement. It was detailed that the stone columns tend to dilate during earthquake event due to shearing. The seismic forces tend to develop positive pore pressure in the soil deposit which causes an inverse effect of dilation in dense gravel columns. Design charts reported by Seed and Booker [10] were modified incorporating dilation and reinforcement effect of stone columns in mitigating liquefaction. Zhang and Zhang [16] analyzed 3 D finite element model of group of stone columns with varying diameter, spacing and length of stone columns and reported the development of excess pore water pressure developed. It is reported that the stone column parameters such as diameter, spacing between columns and depth of columns influences liquefaction. The excess pore water pressure decreased with increase in stone column diameter and excess pore water pressure was more in the deeper layer than in the top layer. Kolekar et al. [17] conducted experimental studies on stone columns installed in marine clay under cyclic loads. Unit cell concept was adopted in their study and reported that the settlement is more when compared to static loading. The settlements increased with number of cycles. They also reported that the stiffness and strength of the soil were enhanced, when the reinforced bed was given cyclic loads lower than failure loads.

Lu et al. [18] conducted high performance seismic studies on remediated ground with OpenSeesPL software. They compared seismic performance of stone column and pile–pinning case and concluded that the highly viable remediation for cellular arrangement is by using pile pinning. For pile pinning remediation, the ground lateral displacement was found to be non-existent. Liquefaction mitigation using stone column and pile pinning techniques on a liquefiable soil layer using OpenSeesPL software was studied by Asgari et al. [19]. Fully saturated sand and silt layers were considered as liquefiable layer in their study. The influence of soil and stone column permeability, ground slope inclination, diameter of column, area replacement ratio and earthquake characteristics on lateral displacement response is reported. It is stated that the presence of static shear stress component due to ground surface inclination increased the lateral displacement for grounds with higher slope angle. This behaviour was due to the increase in final lateral displacement when the soil mass inclined to move downwards owing to high slope angle. It is also specified that the low permeability of silt limited the drainage efficiency of stone column and suggested high stiffness pile pinning technique as an effective method for mitigating liquefaction in low permeability silt soils. They also reported that the stone columns tend to dilate under earthquake loading. Raju et al. [20] conducted cyclic plate load tests on black cotton soil, single stone column and group of stone columns and reported that the dynamic parameter called coefficient of elastic uniform compression, defined as the slope of load-elastic rebound graph increased with group and end bearing stone column than single and floating stone column.

Murali Krishna et al. [21] reviewed different attributes of soil improvement with stone columns on saturated sands with lower relative density. The earthquake hazard mitigation using stone columns were presented and new charts were established focussed on pore pressure generation and installation. The influence of soil fabric evolution and densification in evaluating pore pressures were added and recommended the use of combined effect in the analysis and design of gravel inclusions as liquefaction mitigating elements. They also reported that the stone column inclusions are extremely efficient in preventing liquefaction on liquefiable soils. Rayamajhi et al. [22, 23] conducted three-dimensional non-linear dynamic finite element simulations using OpenSeesPL software implementing incremental dynamic analysis. They studied the shear reinforcement mechanism of dense granular column in reducing seismic shear stresses. The seismic shear stresses provided by dense granular columns are significantly lower than those estimated based on shear strain compatibility assumption. They considered unit cell modelling approach and isolated shear reinforcement mechanism by considering hydraulic conductivity of granular column equal to that of surrounding soil. Rayamajhi et al. [26] also reported that triggering of liquefaction was not prevented with the use of dense granular columns in sloping ground, but lateral displacements were reduced. The reduction in lateral displacement is attributed to the reinforcing and strengthening effects of granular column. The drainage effectiveness of dense granular columns subjected to earthquake shaking was found to be dependent on permeability of native soil as well as granular columns.

Zhan et al. [24] conducted shake table tests on laminar shear box and reported the relation between excess pore water pressure and loading acceleration. At lower accelerations (0.030g, 0.097g and 0.161g), the excess pore water was a smaller amount at various depth of soil surrounding the piles. When the acceleration was 0.252g, the soil between piles liquefied, the pore pressure increased rapidly and reached its maximum value. It is also reported that when the loading acceleration was 0.325g, the excess pore water pressure was less than 0.252g. These results were due to the soil already been liquefied and the higher load taken by the pile and soil distributed and the effective stress of the soil surrounding the piles decreased. Tang et al. [25, 26] conducted liquefaction studies on geo-synthetic encased stone columns using unit cell modelling approach. OpenSeesPL software was used in their liquefaction study. They reported that the lateral deformation reduced while using geo-synthetic encased stone columns than conventional stone columns as mitigation method. They also reported reduction in pore pressure generation while using geo-synthetic encasement. They stated that the encased stone column developed stiffer ground remediation and amplified the seismic waves on the ground surface and the upper stratum.

Şahinkaya et al. [27] conducted parametric studies on floating stone columns, under seismic loads with maximum east-west directional acceleration value of Van Muradiye earthquake. In their study, bearing capacity and load transfer mechanism was studied under earthquake effects and reported that the bearing capacity of the soil models with stone columns under earthquake force was 1.02-3.7 times compared to the bearing capacity of the soil models without stone column. Geng et al. [28] performed numerical study using OpenSeesPL to understand the seismic performance of encased stone column. Effectiveness of encased stone column on various types of sand strata, influence of encasement length, stiffness of encasement was addressed. Relatively high and better seismic demonstration of encased granular column is reported. The optimum encasement length is found as 4 m, below which the difference in seismic performance between ordinary stone column and geosynthetic stone column is not evident. It is also reported that the effectiveness of encased granular column is dependent on the characteristics of neighbouring liquefiable soil strata.

Meshkinghalam et al. [29] carried out series of analytical modelling in FLAC 3D software. A single stone column at the centre of a cubical soil mass of 10 m was modelled. Boundary conditions applied was free field in lateral dimensions so that the plane wave transmitting upward did not have any distortion at the boundary. The modulus of elasticity of stone column was 40 times more than the surrounding soil. Interface elements were used for modelling contact between soil and stone column. Upper boundary of model and environmental boundary of stone column were defined as permeable boundary, which allowed flow to permeate from internal or external environment. They also conducted analysis in stone column group with square and triangular arrangement. Analysis without drainage was also carried out to study the effectiveness of drainage performance. The drainage function of stone columns was found to be efficient at depths of 3 m to 3.5 m from the ground surface. They reported that the rise of diameter of column enhances the drainage at a distance nearly 1 to 1.5 m from the surface, after which the column diameter does not influence drainage. It has been reported that at final cycles, the percentage increase in settlement is higher than without using stone column state. Excess pore water pressure rate rises with rise in s/d (ratio of center-to-center spacing between columns/ diameter of column). They also concluded that the column group has a better settlement reduction for center-to-center distance of 2.5 to 3.5 times column diameter. Pal and Deb (2019) reported the performance of clogged stone column using mathematical model and suggested that the peak value of excess pore water pressure ratio can increase up to 50% due to clogging. The fine sand particles migrated by seepage water blocks the hydraulic functioning of stone columns. The rate of dissipation of pore water is affected during earthquake due to clogging.

3. Modified stone columns

The conventional stone column modified with various additives applied internally and or externally for better characteristics are named as modified stone columns and the related studies are discussed in this section. Malarvizhi and Ilamparuthi [31] performed load tests on weak clay reinforced with stone column and encased stone column having numerous slenderness ratios and several types of encasements. Geogrid encased stone column resulted in elevated load carrying capacity by 1.5 times than conventional stone column regardless of end-bearing or floating columns. In their investigation, the l/d (length of column to diameter of column) ratio is found to have a lower impact on the load carrying capacity of column for the lengths (up to l/d=10) considered. With the increase in the stiffness of the encasement, the ultimate load carrying capacity of the improved column is found to improve significantly. The vertical settlement in encased stone column is found to be less significant than the ordinary stone column. The settlement is also found to decline with the rising stiffness of the encasing material. The settlement reduction ratio is found to be reduced for minor loads whereas for major loads, the settlement reduction ratio in geogrid encased stone column is found to be lesser. They also performed finite element assessment of geogrid encased stone column to replicate the investigational environments. The geogrid was modelled using the geogrid element, which can take only tensile force. They reported that for all the diameters explored, the performance of encased stone column is superior to ordinary stone column. The load carrying capacity of the reinforced bed with smaller diameter encased columns is greater than the higher diameter encased columns. The smaller diameter encased columns had greater stresses. The surge in the load carrying capacity of the encased stone column was due to the hoop stress developed in the geogrid. The hoop stresses developed in the stiffer geogrid is higher, and consequently, better is the load capacity. The dilatancy of the stones in the encasement reduces, but the combined result of the stones and the geogrid aids to the elevated stress concentration ratio of the stone columns.

Raithel et al.[32] reviewed the foundation system with geotextile encased stone column for soil improvement since 1990’s. The results of geotextile encased stone column foundation system when compared to stone columns were also detailed based on the experience gained from different installation methods. They stated that even the very weak subsoil conditions can be improved by using geotextile encased stone column foundation combined with horizontal geotextile reinforcement to act as load transfer mat.

Murugesan and Rajagopal [33] concluded that the load capacity and stiffness of the stone column can be heightened by all-round encasement by geosynthetic. The lateral bulging is minimized by the geosynthetic encasement and thus the stone columns are confined. The stiffer encasements offered higher confining pressures in the stone columns. The hoop tensile forces generated in the encasement are substantial at a depth correspond to nearly twice the diameter of the stone column. The smaller diameter encased stone column performed superior to that of larger diameter stone columns because of the utilization of greater confining stresses in encased stone column. The greater confining stress in the column indicates higher stiffness of encased smaller diameter columns. The depth up to which predominant bulging occurs should be confined sufficiently for the enhancing the stone column performance. Therefore, to significantly enhance the load carrying capacity of stone columns, it is appropriate to encase the stone column up to a depth equal to two times the diameter of stone column. It is observed that the shear strength of the surrounding soil has less influence on the load capacity of encased columns as compared to ordinary stone columns. This trend is particularly observed with stiffer encasements. Therefore, by using stiffer encasements, major embankment loads can be distributed to encased stone columns. Small scale tests were performed on stone columns modified stone columns by Black et al. [34]. The enhancements used were tubular wire mesh, a bridging rod, and a concrete plug (Cement grout with a water cement ratio of 0.5). It was concluded that the enhancement of load carrying capacity and the settlement reduction can be achieved by using these methods.

The occurrence of slippage in stone columns with stiffer encasement is reported by Wu et al. [35]. The axial strain is lower for the stiffer reinforcement when the slippage occurs. Because of this slippage, stress-strain curve is flatter and lower axial strength is observed for stiffer encased columns than with less stiffened encasement. It is reported that for a constant radius/spacing ratio, the column with smaller spacing results in stiffer behaviour in the case of reinforced stone column. The stress-strain curve is observed to be the same for reinforced columns with constant radius/spacing ratio when the slippage occurs except for the lower strain-sections. The granular material and reinforcing sheet are bonded to a greater axial strain under higher chamber pressure, which causes a rising convex stress–strain curve at high axial strain. At a constant confining pressure, encasement in the granular column, embedded in soil enhances the granular column strength than when compared to an unreinforced column.

Gniel and Bouazza [36] concentrated on exploring the behaviour of partially encased stone column with a fully encased column. Moreover, the performance of isolated encased column was evaluated with the group of encased columns. It is found that the isolated columns failed by circumferential increase beneath the encasement layer. The increased depth of encasement in the case of group of encased columns enhanced column stiffness and significantly reduced vertical strain. The percentage reduction of vertical strain by fully encased columns was 80% when compared to the unimproved soil. The length of encasement improved the load capacity of isolated stone column, and a significant enhanced capacity is observed for fully encased column. The added lateral confinement provided by the encasement resulted in preventing radial column failure and enabled the encasement to be stressed to its tensile limit. However, noticeable radial bulging was observed for partially encased group of columns beneath the encasement depth.

Samadhiya et al. [37] reported that, due to the inclusion of random fiber into the granular pile, load-settlement behaviour becomes ductile and the load carrying capacity improves and the gravel pile behaves to more elastic manner than an unreinforced granular pile. Due to random fiber, the bulging diameter reduces, and the depth of maximum bulging diameter also decreases. But total length of bulging increases due to random fiber. Wu and Hong [38] concluded that the weak clay can be improved by encapsulating the stone column with a flexible casing. This method enhances the load carrying capacity and stiffness of ordinary granular column. The governing factor that contributes to the reinforced column behaviour is the stiffness of the casing. The length of the casing required to prevent radial bulging of a granular column is found to be highly dependent on the surrounding soil properties and strength and stiffness of the flexible casing.

Shivashankar et al. [39] suggested an alternative and effective method of enhancing the performance of stone columns installed in soft soils by encasing the individual stone column with vertical circumferential nails from a series of laboratory plate load tests carried out in unit cell tanks. They concluded that the reinforced stone columns with vertical circumferential nails showed enhanced response when compared to ordinary stone columns for all the cases considered. The increase in number of nails and diameter of nails significantly improved the load carrying capacity of improved ground. However, the vertical nails with a depth of three times the diameter of the column has shown significant improvement in terms of load carrying capacity and stiffness of the improved ground. The effectiveness of vertical nails is found to be significant for lower area ratios. The load carrying capacity of reinforced ground is found to decrease with increase in diameter of stone columns, while keeping all other parameters constant. However, the bulging diameter and depth of stone column is significantly reduced with the use of vertical circumferential nails.

Fattah and Majeed [40] carried out numerical modelling on encased floating stone columns by varying different parameters such as column depth to column diameter ratio (L/d), shear strength of the intervening soil (Cu) and the area ratio (as) to study the influence on load bearing enhancement and settlement drop of the stone column. The effective L/d ratio for encased stone column is reported as 7-8. When the shear strength of the neighbouring soil (Cu) is increased, the load capacity enhancement is seen, and the settlement is reduced. The application of geogrid encasement delivers improved outcomes when shear strength of the surrounding soil is higher and increasing the value of shear strength of the surrounding soil plays an essential part in conventional stone column. A significant rise in load bearing for geogrid encased stone column is observed for L/d = 8, whereas for L/d = 4, a marginal rise in bearing enhancement at the initial phases of load application is detected and at later stages, the bearing improvement for both unimproved and encased stone columns is found to be identical. The bearing enhancement ratio of stone column improved ground is significantly influenced by area replacement ratio. The rise in area ratio (as) is further effective for bearing improvement in encased stone columns than stone columns mainly when area ratio (as) is higher than 0.25. It is also reported that the lateral displacement of geogrid encased stone column is much lesser than that of ordinary stone column.

Marto et al. [41] analyzed geogrid encased stone columns and reported that the load bearing capability of stone column is heightened by the rise of diameter of encased stone columns and axial load capability and rigidity of stone column can be enhanced by providing geogrid encasement to full depth. Ali et al. [42] conducted tests on stone columns reinforced with lateral circular discs of geotextile in the column. Experiments were conducted on end bearing and floating stone columns and the reinforcement was noticed to be effective.

Castro [43] studied the performance of groups of encased stone column beneath rigid footing. It is reported that the column arrangement has less influence on the reduction in settlement. Based on this, a new simplified approach to study group of encased stone column is proposed, by considering all the columns below footing as a single column with an equivalent area and encasement stiffness. The critical length of fully encased and partially encased column is around 2B or 3B (where B is the width of the footing). Hong et al. [46] performed numerical analysis on single encased granular column embedded in soft soil and reported that the stiffness of encasement significantly affects the bulging length of an encased column. Zhang et al [45] demonstrated that the use of Jet Grout Piles (JGP) resulted in the significant reduction of wall deflection and strut forces when used for braced excavations. The JPG was found to be more significant while excavating weak soils.

ASIRI project[46] developed a set of guidelines of composite foundation system on rigid pile foundation and having a load transfer platform (granular platform) between the superstructure and soil improved for civil engineering works. This review is focussed on the shear and seismic loading behaviour of column improved ground where hydraulic functionality is significantly used along with the improved vertical load carrying capacity. Therefore, the soil improvement using rigid pile foundation is excluded in this review paper. Although ASIRI project[46] describes the basal reinforcement improved pile foundation system, it also clarifies the conditions on which stone columns are preferred over rigid pile foundation system or any other type of soil improvement technique like dynamic compaction or vibro-floatation. It states that the cohesive soils cannot be improved by above-mentioned dynamic methods and stone columns can be used instead. It also describes that the very soft soils and organic soils cannot use stone column as a reinforcement technique and rigid inclusions like pile foundations can be adopted.

4. Rigid stone columns

Barksdale and Bachus [1] detailed the use of rigid stone columns (cement added to compacted column forming concrete rigid columns). It is reported that the rigid column is less dependent on the confinement provided by neighbouring soil. Hence, rigid columns with high load carrying capacity can be used in very soft soils than conventional stone columns. Kempfert

[47] also reported that the conventional stone columns are generally used to improve the soft soils if the undrained shear strength is more than 15kPa. Additionally, it was mentioned that the ground improvement using stone column is not suitable for sensitive or organic soils. However, the use of grouted stone column (formed by injecting grout/binder during compaction of stones/gravel) is reported as effective for soils with undrained shear strength between 8 to 15 kPa [47].

Rigid columns can be also used to strengthen an intermediate weak layer where stone columns cannot be used. The intermediate weak layer can be stabilized with rigid column and load would be transmitted to underlying stone column through rigid column. The load-settlement profile of rigid stone column is like that of a traditional pile and ultimate load carrying capability is higher than stone columns [1]. It can be also used for stabilizing stone column in vulnerable regions and also for enhancing stability of slopes. The construction of rigid stone column is carried out by vibro-displacement method and a bottom feed unit for adding cement is used. The cost of rigid stone column is also comparable with conventional stone column due to faster construction time [1].

New method of using pervious concrete pile in preference to stone column was proposed recently. The authors conducted tests on isolated columns and stated that the pervious concrete piles increased the vertical load carrying capacity 4.4 times than that of plain stone columns. Pervious concrete is mostly used in pavement applications. The suitability of using pervious concrete material as a ground improvement method is stated by Suleiman et al. [48] and Ni et al. [49]. Pervious concrete is prepared from one sized aggregate mixture with smaller quantity of fine aggregate. The mix proportion used in their study was 1:0.5:4 with a water/cement ratio of 0.21. The average compressive strength and modulus of elasticity of pervious concrete utilized in their study were 22.2 MPa and 15.4 GPa respectively. The average permeability (1.21 cm/s) and average porosity (12.5%) of pervious concrete is suitable for draining water through its pores similar to stone columns. Moreover, the load capability of pervious concrete column is not dependent on the properties of intervening soil, that makes it suitable for weak clays, organic clays and peats [48]. They also conducted fully instrumental lateral load test at the SSI facility and reported that the behaviour was similar to long concrete or steel pile when a rebar along the length was provided.

Zhen et al [50] reported that the two predominant failure mechanisms of low or high stiff piles are of shear failure and bending failure modes. This numerical study using PLAXIS 3D also established that a progressive mode of failure is more prevalent than a simultaneous failure in a rigid concrete pile supported embankment system. The stability of column supported embankment system is evaluated based on the assumption of shear failure of columns. This assumption may result in the overestimation of the stability of embankment if a bending/tensile failure occurs[51] in columns having certain bond strength. Therefore, Zhou et al. [51] developed a Multivariate Adaptive Regression Spline(MARS) model, that establishes the connection between the bending failure mechanism and parameters like thickness of clay, shear strength of clay, spacing, diameter, modulus of elasticity of columns and embankment load. The relationship between these parameters and maximum tensile stress is non-linear and multi-dimensional. Therefore, the bending failure mechanism and progressive failure mode of pervious concrete column need to be further researched.

5. Performance of modified stone column improved ground

The performance of modified stone column enhanced ground when exposed to shear and seismic loading conditions are discussed in the following sections.

5.1 Static shear loading

The stone column is reported to move further alongside neighbouring soil when exposed to shear movements [7, 52]. The shear resistance of stone columns can be improved by confining the stone column. Eg: geosynthetic encased stone column. Additionally, the shear performance of geosynthetic encased stone columns is reported as that of a semi-rigid pile when subjected to shear movements [7, 8].

The shear performance of a recently proposed alternative to stone column, pervious concrete column by Suleiman et al. [48] is numerically assessed and the behaviour is stated to be similar to a rigid pile with hydraulic functionality of stone columns [53]. The shear performance of pervious concrete column is also stated as exceptional to conventional stone column [53].

5.2 Seismic loading

Recently, the seismic performance of encased stone column improved field is reported as comparatively superior to stone column improved ground [25, 26, 28]. However, studies on seismic comportment of traditional stone column and modified stone column enhanced ground are also limited.

Elgamal et al. [14] and Asgari et al. [19] compared the seismic performance of stone columns with pile pinning technique and reported that pile pinning technique has limited lateral deformation than stone column improved ground. It is also reported that pile pinning with lower area ratio (wider spacing) is highly effective than stone columns with higher area ratio (closer spacing). Elgamal et al. [14] and Rayamajhi et al. [54] reported an amplification of ground surface acceleration due to the presence of stone columns than with unimproved sand strata.

Zhang et al. [55] reported the acceleration response and excess pore water dissipation of pervious concrete pile composite foundation in comparison with gravel pile and low-grade concrete pile numerically using FLAC. The surface acceleration amplification is found to be less for pervious concrete pile composite foundation than granular pile and low-grade concrete pile. The reduction in foundation surface acceleration indicates that the upper construction resonance can be prevented using pervious concrete pile. They have also reported obvious pressure reduction effect of pervious concrete pile composite foundation. However, detailed study on surface acceleration response needs to be further investigated.

Rashma et al. (2021a, 2021b) compared the earthquake response of improved ground with pervious concrete column as well as conventional stone column and reported that the pervious concrete column is a superior option to stone column because of its behaviour similar to rigid pile under seismic excitations. The stone column gets dilated during earthquake loading as a result of shearing. The altered gravel composition of stone column heightens the distance of the drainage route and retards the dissipation of surplus pore water developed during the trembling. Whereas the pervious concrete column composition is not altered during the seismic vibration and the pervious concrete column inclusion eases drainage route for excess pore water to disperse rapidly[57]. Consequently, the seismic shear strains established in the adjacent soil is hugely diminished. The reduced surplus pore pressure generation and comparatively elevated active confinement reduces the lateral translation of pervious concrete column improved ground substantially[56, 57]. This also indicates a superior response of pervious concrete column improved ground in alleviating liquefaction caused lateral spreading. The lateral translation of pervious concrete column is found to be similar to pile pinning technique and with hydraulic functionality of stone columns make pervious concrete column a superior option in liquefiable soils. It is observed that the surface ground acceleration of pervious concrete column improved ground amplified indicating the stiffness of improved ground than unimproved ground and stone column improved ground. It is also learned that the lateral displacement of pervious concrete column improved ground is independent of surrounding soil permeability or confinement. This shows the versatility of pervious concrete column to be used in various types of very soft soils as ground remediation.

6. Conclusions

Extensive research on the performance of column improved ground under static shear and seismic loading is summarised as follows:

(i) The conventional stone columns move along with surrounding soil under shear movements without offering any resistance. This shows the importance of confining stone columns for better shear performance or by strengthening stone columns internally and/or externally.

(ii) Encased stone column performs as having semi-rigid column behaviour when subjected to static shear loading and has relatively better performance than conventional stone column.

(iii) Stone columns dilate under seismic loading and distorts the gravel structure. The distortion of gravel structure causes lengthening of drainage path which in turn retards the dissipation of excess pore water developed. This results in the increase of shear strains in stone column improved ground and causes the surrounding sand to liquefy. This alarms a need for alternative to stone columns with better shear and seismic performance.

(iv) Pervious concrete columns are a better choice than stone columns which can perform all the functionalities of stone columns. The performance of pervious concrete column is similar to that of a rigid column under shear as well as seismic loading. Previous concrete column is also a better choice than stone column in mitigating seismically induced lateral spreading.

(v) Pervious concrete column with properties similar to normal concrete with hydraulic functionality does not get distorted like granular piles, when subjected to seismic loading. Therefore, the porous structure is still intact and allows faster dissipation of excess pore water developed owing to seismic movements. This results in the development of limited seismic shear strains in the surrounding soil and the improved ground will be having superior liquefaction mitigation capability with pervious concrete column inclusions.

(vi) The performance of stone column is dependent on the characteristics of intervening soil whereas the performance of pervious concrete column is independent of the surrounding soil. Thus, rigid columns like pervious concrete column can be employed for improving shear resistance of very soft clays and organic peat soils. Also, the pervious concrete columns can be used instead of stone columns for mitigating liquefaction and associated lateral spreading in a variety of liquefiable soil deposits.

Although pervious concrete column is a better alternative to stone column, the bending failure and progressive failure of pervious concrete column when placed below the embankment system needs to be further researched for a better understanding on the behaviour of pervious concrete column composite system.

7. Recommendations for field applications

Some recommendations for field applications from the findings of the research work are as follows:

(i) The study recommends the use of pervious concrete columns for supporting huge embankments over weak ground. This ground improvement practice increases the shear resistance of improved ground alongside hydraulic functions similar to stone columns and increased vertical load carrying capability than conventional stone columns.

(ii) The deformation of pervious concrete column is similar to that of a rigid pile. The pervious concrete columns can be employed in the site with existing installation methods used for stone column construction and this is an additional benefit. The lower requirement of fine aggregate for constructing pervious concrete column is an added economical advantage and a sustainable solution.

(iii) Results suggest that the pervious concrete columns at wider spacing can also be implemented as the pervious concrete column improved ground with an area ratio of 9% has shown significant seismic performance.

(iv) Ground improvement using pervious concrete columns is highly recommended for mitigating liquefaction in seismically active regions. Pervious concrete columns can be effectively utilized in numerous types of liquefiable soil strata.

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by first author. The first draft of the manuscript was written by first author and all authors commented and edited on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

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

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Data availability

The datasets generated during and /or analysed during the current research are available from the corresponding author on reasonable request.

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