Seismic performance of pervious concrete column improved ground in mitigating liquefaction

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Abstract. This paper investigates the performance of pervious concrete column improved ground subjected to seismic loading. The seismic performance of pervious concrete column improved ground is also compared with conventional stone column improved ground in responses of lateral displacement, excess pore pressure, ground surface acceleration, shear stress-strain behaviour and stress path. A fully saturated mildly sloping sand strata is considered as unimproved ground. OpenSeesPL software is used to analyse soil models representing unimproved ground and improved ground with stone column and pervious concrete column inclusions. It is found that the pervious concrete column improved ground has better seismic performance than stone column improved ground. The lateral displacement of ground is found to be significantly reduced while using pervious concrete column. Also the use of pervious concrete column has reduced excess pore pressure generation than stone column indicating that the improved ground with pervious concrete column inclusion is efficient in mitigating liquefaction than conventional stone column improved ground.

1. Introduction
Stone columns are widely used all over the world for reducing liquefaction. The performance of stone column is well documented during seismic events using full scale field tests, centrifuge tests and numerical modelling [1–9]. Recently, the behaviour of encased stone columns subjected to earthquake loading is reported [10,11]. The seismic performance of encased stone column treated ground is found to be relatively better than conventional stone column treated ground.

A new ground improvement method suitable for various types of soil strata like organic peat and weak clays is recently reported as pervious concrete columns [12–14]. Properties of pervious concrete columns are comparable with stone columns in terms of hydraulic functionality [13]. The strength and stiffness of pervious concrete column is reported as superior to stone columns and is independent of surrounding soil properties which makes it a better alternative to stone columns [14]. The average 28-day compressive strength of pervious concrete is 22.2 MPa with an elastic modulus of 15.4 GPa [12–14]. As per earlier studies reported, it is explained that the installation of cast-in-situ pervious concrete column is similar to the installation of displacement stone columns at site [12–14].

However, the performance of pervious concrete column improved ground under earthquake loading condition is not documented. This study focus on the seismic performance of pervious concrete column improved ground in lieu of stone column improved ground.
2. Present study

The performance of pervious concrete column (PCC) in mitigating liquefaction is addressed using unit cell modelling approach (Fig.1). The depth of strata considered is 10 m and ‘S’ represents the centre to centre spacing between stone columns. For this, the seismic performance of PCC improved ground is compared with stone column (SC) improved ground. Three criteria are used to assess the liquefaction mitigation potential of improved ground: lateral displacement reduction, excess pore pressure generation and shear stress-strain reduction. A fully saturated sand strata with mild inclination of 4° is selected as unimproved ground. Sand strata with SC and PCC inclusion is considered as improved ground. The diameter of SC and PCC is 1.2 m each. As per IS 15284 codal provisions, the centre to centre spacing between stone columns in field is 2 D to 3D (D being diameter of stone column)[15]. Hence a spacing of 2.5D is selected. The area ratio is defined as the ratio of column area to total area of unit cell considered. Therefore, the area ratio in the present case is 13%. The unimproved and improved models are subjected to El Centro 1940 ground motion with PGA of 0.32g is scaled down to 0.2g. The scaled input earthquake excitation is shown in Fig.2.

3. Numerical modelling

The validation of model generated in OpenSeesPL software is validated with experimental results of VELACS experiment model 2 in prototype scale reported by Ghasemi & Pak [16]. The VELACS experiment model 2 was conducted by Taboada & Dobry [17]using centrifuge experiment to study lateral spreading on sloping strata. Similar numerical model is employed in present study. Eight-noded brick element with u-p formulation is used for studying liquefaction behaviour for all models. The materials are modelled with PressureDependMultiYield02 (PDMY02) soil model available in OpenSeesPL software.

| Table 1. Material model parameters |
|-----------------------------------|
| Soil model Parameters             | Sand | Stone column | Pervious Concrete |
| Saturated Soil density, ρ (kN/m³) | 18   | 21           | 21.5              |
| Low strain shear modulus at reference pressure Gₘₐₓ (MPa) | 90   | 130          | 10580             |
| Bulk Modulus at reference pressure Bₘₑₚ (MPa) | 220  | 260          | 14460             |
| Shear strength at zero effective confining pressure (cohesion) (kPa) | 0    | 0            | 3000              |
| Model friction angle, same as triaxial friction angle ϕᵦₜₑ | 36°  | 42°          | 38°               |
| Phase transformation angle ϕₚₜ   | 26°  |              |                   |
| Permeability (m/s)               | 6.6 x10⁻⁵ | 0.01 | 0.01             |

Half of unit-cell model is analysed because of symmetry [4,5,7,8,10,18]. A 4° inclined sloping strata fully saturated up to ground level is modelled with stone column and pervious concrete column as shown in Fig.1. The default values available in OpenSeesPL software is used for modelling sand strata with relative density of 40%. Default values available for cohesionless sand of 75% relative density with gravel permeability is used for modelling stone column and pervious concrete column respectively. The column-surrounding soil interface is assumed to be fully bonded for simplicity [4,6–8,10,18]. As the pervious concrete properties are reported similar to concrete, values corresponding to normal concrete properties are selected as model input parameters for pervious concrete. The input parameters used for modelling sand, stone column and pervious concrete material are listed in Table.1.
4. Results
The seismic response comparison of the improved ground remediated with PCC and SC inclusion and unimproved ground are carried out based on the lateral displacement, excess pore pressure generation and variation in shear stress and shear strain.

4.1. Lateral displacement
The lateral displacement-time history plot of unimproved ground, improved ground with stone column (SC) and pervious concrete column (PCC) inclusion (labelled as sand, SC and PCC) are shown in Fig.3. The lateral displacement reduction of PCC improved ground and SC improved ground 96% and 60% respectively when compared to unimproved ground. This high reduction in lateral displacement is attributed to the presence of high stiffness of PCC.

Figure 1. Unit Cell Idealization (a) Unit Cell model (b) Discretized 3D model

Figure 2. El Centro ground motion scaled to 0.2g as input excitation
4.2. Excess pore pressure generation
The reduction in excess pore water pressure of improved ground using SC and PCC noted at the centre of finite element mesh for depths of 2m, 4m and 6m are shown in Fig.4. The excess pore pressure
values are seen to be high up to around 16 seconds of shaking and is seen to be less. Thereafter, the excess pore pressure values of PCC improved ground are the lowest for all the depths even from the start of shaking. The excess pore water pressure generation in ground with PCC inclusion is lesser than SC, which shows better performance of PCC in draining pore water than SC.

4.3. Shear stress-strain plot and stress path
Figure 5 and Fig.6 respectively shows the shear stress-strain response and stress path (shear stress-effective confinement stress plot) behaviour of surrounding soil. The soil location is around 1.0 m, farther away from the stone column location representing the surrounding soil. The reduction in shear stress-strain plot is clearly observed for improved ground with SC and PCC along with relatively higher effective confinement for PCC improved ground at 1.4 and 3.4 m depths. However at depth of...
7.4 m, the shear stress drastically increased to a higher value. The shear strain developed in the surrounding soil has significant reduction due to PCC inclusion and it in turn reduced the lateral displacement significantly.

Figure 7 represents time history plot of shear stress at the surrounding soil located at depths of 1.4m, 3.4m, 5.4 m and 7.4 m. At the time of peak acceleration, non-zero shear stress values are observed for PCC improved ground (Fig.7). At the depth of 7.4m, the shear stress drastically increased for SC improved ground. This could be due to the increase in effective confinement stress increase as shown in Fig.6.

The shear response of PCC improved ground at the centre of finite element mesh representing column centre is shown using shear stress time history plot (Fig.8). The plot at 1.4 m, 3.4m, 5.4 m and 7.4 m shows that the shear performance of PCC is better than SC and this is due to the higher rigidity of PCC.
4.4. Ground surface acceleration.
The acceleration-time history plot at the centre of finite element mesh at ground surface is shown in Fig.9. The peak ground surface acceleration is observed as 0.3g and 0.35g respectively for SC improved ground and PCC improved ground. Amplified peak acceleration to almost twice the peak input acceleration is observed in stone column improved ground [4,7,8]. The increase in peak surface acceleration value shows higher stiffness of improved ground with PCC inclusion.

5. Conclusions
The improved ground with pervious concrete columns have shown superior seismic performance than stone column improved ground. The pervious concrete columns can be considered as a better alternative to stone columns in mitigating liquefaction-induced damages based on following:

- The lateral deformation of pervious concrete column improved ground is significantly reduced than stone column improved ground.
- The excess pore pressure generation due to pervious concrete column inclusion is seen lesser than stone column inclusion, indicating the pore water being drained better with pervious concrete column inclusion.
• The shear stress-strain behaviour is seen to reduce significantly in pervious concrete column improved ground with relatively higher effective stress confinement. Also, the shear performance of pervious concrete column is better than that of stone columns.

• The peak ground surface acceleration is found to increase with stone column and pervious concrete column inclusion indicating higher stiffness of improved ground due to respective inclusions.

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