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Research paper

The Experimental Design of Stone Columns' Modelling using Small-Scale Unit Cells: A Review

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Abstract

This paper presents a review of the experimental design of the small-scale single stone column that adopts the unit cell concept. Materials and methods used in experiments along with their effects and implication have been appraised. The reviewed cases showed that clayey soils were often used to construct the host ground. Steel cylindrical tanks were used with diameters ranging from 15 to 60 cm and heights ranging from 20 to 120 cm. For such scale, the used stone size is 2 to 10 mm. Plates load test can be carried out on the entire tank or on the stone column. The load has been imposed at a constant settlement rate of 1 to 1.25 mm/min in order to simulate the stage immediately after construction. The review shows that remoulding and replacement have been often practised for the construction of the host ground and the stone column, respectively.

Keywords: *Clay; Geosynthetics; Physical models; Stone column; Unit cell*

List of Abbreviations

SC	Stone column	F	Floating stone column
l	Stone column length	A_r	Area replacement ratio
d	Stone column diameter	L_L	Liquid limit
s	Stone column spacing	D_r	Relative density
EB	End bearing stone column	G_s	Specific gravity
P_L	Plastic limit	D_e	Effective diameter
HG	Host ground		

1. Introduction

One of the well-established methods for improving the behaviour of the soft soil is the stone columns (SCs). The main benefits of this method are increasing the bearing capacity and reducing the settlement [1]. The SCs can mitigate the liquefaction effects and increase the stability of the structure. Simplicity in construction and cost reduction can be achieved. Not to mention the wide range of application and the environmental benefits.

There are no specific guidelines for designing the stone columns, and the current practise is based on empirical data [2]. The research is still on-going in order to perceive the intricate behaviour of this combination of soil in order to understand the nature of such composite ground. It is known that the common failure mechanism of a singly-loaded SC is the bulging of the top portion of the SC when the length (l) is more than 4 times the diameter (d) [3]. The bulging occurs because of the granular nature of the stone, and it is obvious when the SC is loaded alone because of the formation of a conical failure surface directly under the loaded area. In practice, the SCs are constructed in a uniform grid having a certain pattern. Each SC and the soil that surrounds it can closely be approximated into an equivalent circular area having the same total area as shown in Figure 1. The unit cell is the equivalent cylinder that contains an SC at its centre and the tributary ground surrounding it. The pattern of the grid governs the area of the unit cell [3,4]. The effective diameter (D_e) is the equivalent diameter of the circle that encloses the cell and is equal to 1.05s for an equilateral triangular pattern, and 1.13s, where s is the Spacing of SCs.

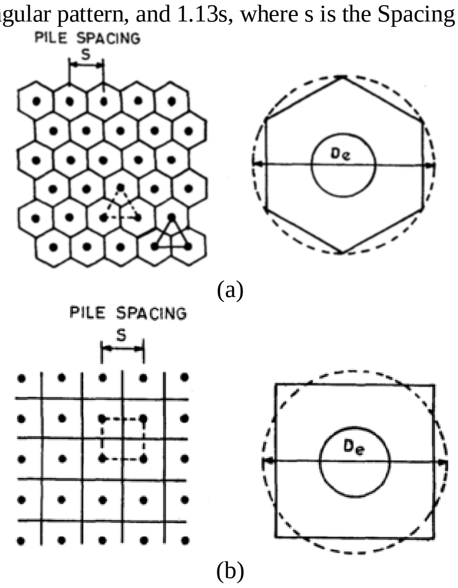

Fig. 1: The common patterns of SCs: (a) the triangular pattern, and (b) the square pattern [3]

The behaviour of the SC has widely been studied by adopting the unit cell concept. Furthermore, the small-scale modelling has been advantageous because many parameters can be considered without the limitations of size, effort, and cost. Many studies follow a systematic methodology in order to model the behaviour of the single SCs that are embedded in soft host ground (HG). By establishing the behaviour, the effects of the considered parameters can be investigated and the improvement contributed by the SC can be established. This is achieved by establishing the load-settlement response and the deformed shape of the SC. The SC can be made stronger by reinforcement. Several reinforcement methods can be investigated through the unit cell modelling. The unit cell concept can be used to model the behaviour of the SC numerically by taking advantage of the axisymmetry. The 2D axisymmetric modelling of the unit cell is shown in Figure 2. According to the unit cell concept, the HG is free to move along the external vertical boundaries, which means that the inner vertical surface of the testing tank should be frictionless.

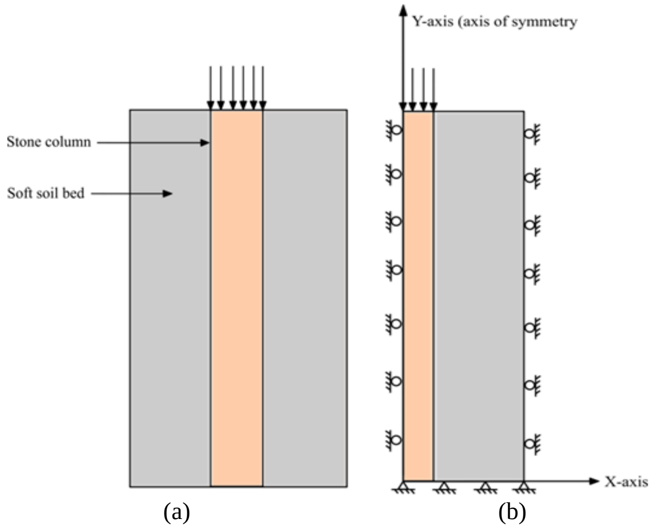

Fig. 2: Schematics of a unit cell: (a) section, and (b) axisymmetric

There is no unified guide or precise methodology necessary to be adopted for designing such experiments; it is based on the experience in satisfying the criteria of the unit cell concept. Different authors adopt different approaches in the design and execution of their experiments. The small-scale physical modelling has not been sufficiently discussed in the literature. Because the small-scale physical modelling of the single SCs has widely been adopted in the previous studies, it has become increasingly challenging to keep track of all the methodologies, materials, construction and reinforcement methods, and test setups along with their implications.
The physical small-scale modelling of single SCs using the unit cell concept is presented in this review. The materials and methods used in the experimental work, as well as SC reinforcement methods, have been compiled and discussed to highlight their effects and implications. This review can serve as a quick guide for the upcoming researchers to keep track of the current practices and technical aspects in this field. The study comprises a description of the materials used, the methods used for the construction of the unit cell and their effects, the testing conditions and the post-testing procedure.

2. Test Setup

The plate loading test was carried out on the area of the stone column only, or the total or partial area of the unit cell. Circular loading plates were used with sufficient thickness in order to ensure uniform stress distribution on the loaded area. The typical test setup is shown in Figure 3. The diameter of the loading plates that were used by different authors can be found in Table 1.
The testing tank, as well as the loading and measurement equipment, were accommodated within a loading frame. The advantages of the use of the load frame are to facilitate load imposition at a certain rate and to ensure the stability during the test which leads to uniformity and accuracy of measurement.

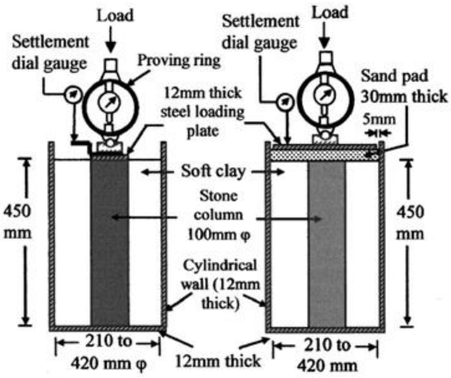

Fig. 3: The physical test setup that was adopted by Ambily and Gandhi [5]

The tri-axial loading frames were frequently used for that purpose because the small-scale unit cell can be well accommodated, and settlement at a constant rate can be applied by using such frames. The load was usually measured as settlement progressed at a constant rate. This approach was adopted frequently because usually, the allowable settlement is predefined and the interval of settlement is small as compared to load interval. This approach has led to clearer progression in load against settlement in smaller time as compared to applying increments of the load. Alternatively, few studies adopted the approach of imposing load and measuring the corresponding settlement. Proving rings or load cells were used to measure load and dial gauges or linear variable displacement transducers were used to measure the settlement. Electronic measurement equipment can be connected to a data logger and the data can be saved in a computer for improved accuracy.

2.1. The scale of the Unit Cell

In order to model the behaviour of a full-size SC on a small scale, the dimensions of the unit cell components are reduced. This reduction in scale saves time, resources and effort consumption; this facilitates the testing procedure to incorporate more case studies. The dimensional scaling is described as the similitude ratio; it is the ratio of any linear dimension of the full-scale model to that of the small-scale one as in the works of Ali et al. [6] and Debnath and Dey [7].
In practice, d varies from 0.6 to 1m, similitude ratios of 8 to 13 can be adopted. In order to develop bulging, the SC should have a minimum l/d ratio of 4 [3, 4]. In practice, l/d ratio ranges from 4.5 to 20. The range of stone size (k) that is usually used in the field is 2 to 75mm [3], also, d/k typically ranges from 8 to 550 [8]. Malarvizhi and Ilamparuthi [9] referred to a study that suggested that the maximum k/d should not exceed 1/6 to 1/7. As for the reinforcement, in practice, the axial stiffness of the geosynthetic fabrics can vary from 1000 to 4000 kN/m. The axial stiffness can be reduced by multiplying it by a reduction factor, as was adopted by Hasan and Samadhiya [8].

2.2. Testing Tank

Cylindrical tanks made of steel were used to simulate the external boundary of the unit cell. The diameter of the cylinder represents the effective diameter of the unit cell. The effective diameter is set based on the spacing of the SCs and the pattern of construction, as given in mentioned earlier. The diameter and the height of the tank are also set based on the diameter, length and end condition of the SC. The SC dimensions affect the area replacement ratio, l/d ratio, s/d ratio. The effects of the aforementioned parameters on the behaviour of the SC have been frequently studied, and were found to control the behaviour of the column.
The unit cell height, which is equal to the height of the HG, can be equal to or less than the testing cylinder's height. The dimensions of the tanks and the heights of the unit cell, are given in Table 1. The tank dimensions should not interfere with the formation of the failure mechanism [9, 10]. The failure zone reaches a radial dis-

tance of about 1.5d and a depth about 2d from the periphery of the SC [11].

Due to the symmetric loading condition, horizontal deformation is not allowed outside the boundary of the unit cell [4]. The load is imposed on, and should remain within, the unit cell [12]. A thin coat of lubricant is applied to the inner vertical surface of the tank in order to simulate the free movement by reducing the friction between the inner surface of the tank and the HG. It should be noted that some friction will take place, but the comparison with finite element results shows that this friction is insignificant [8, 13]. The inner bottom surface of the tank, however, is left without lubrication to simulate the fixed boundary condition. The load is imposed on the unit cell by using circular thick plates. Table 1 shows the diameter of the loading plates used in some studies.

Although the column diameter and the unit cell diameter can affect the Ar, the studies with variable D_e values concentrated on the effect of SC spacing, while those with variable d values concentrated on the effect of the SC diameter.

Table 1: The testing tanks dimensions, HG height, and foundation plate diameter that were adopted in the literature

Author	Testing tank		Clay bed height (mm)	Diameter of the loading plate (mm)
	Diameter (mm)	Height (mm)		
Akhitha and Aswathy [14]	400	500	450	2d
Ali et al. [6]	300	600	550	d
Ambily and Gandhi [13]	210, 315, 420	500	450	d, D
Ambily and Gandhi [5]	210,420	500	450	d, D
Anju and Leander [15]	500	500	—	—
Aza-gnandji and Kalumba [16]	300	550	400	d
Babu et al [17]	237	780	750	D
Balan et al. [18]	250	500	450	2 d
Beena [19]	500	500	500	243
Dehariya et al. [20]	180	400	400	d
Demir and Sarici [21]	600	600	250	d
Gniel and Bouazza [22]	143	550		51
Hasan and Samadhiya [23]	200	525-630	525, 630	D, d
Hasan and Samadhiya [24]	200	525	525	d
Hasan and Samadhiya [8]	200	525	525	D, d
Isaac and Girish [25]	210	270	250	D
Kumar and Jain [26]	157.5, 204.75, 252	250, 325, 400	—	d
Kumar and Jain [27]	105, 157.5, 204.75, 210, 252	250, 325, 400	250, 325, 400	d
Malarvizhi and Ilamparuthi [9]	300	280	280	2.3 d
Malarvizhi and Ilamparuthi [10]	300	300	—	2.3 d
Malekpoor and Poorebrahim [28]	160-470	300-1200	300-1200	D
Mohanty and Samanta [29]	185	600	600	d, D
Murugesan and Rajagopal [30]	210	500	500	d
Murugesan and Rajagopal [31]	210	500	500	d
Parihar and Ahuja [32]	180	260	260	d
Pivarč [33]	125, 253	600	600	d, D
Sarici et al. [34]	300, 250, 200, 150	—	—	d
Sarvaiya and Solanki [35]	300	600	600	d
Sharma et al. [36]	300	>350	300	d, 2d
Shivashankar et al. [12]	237	780	720	d, D
Shivashankar et al. [37]	158, 283	750	720	D, d
Subramaniyan and Masoodhu [38]	280	310	310	60
Sudheer et al. [39]	210	280	210	50
Suriya et al. [40]	150	220	220	—
Tallapragada et al.,2011 [41]	100	300	300	—

3. Materials

3.1. HG Soil

The parameters compiled in Table 2 show the main properties of the HG soils. The HG soils are usually obtained from the river and the lake beds[15, 18, 30], marine clay of coastal areas [10, 39, 42], where the fines form the largest portion of such soils.

Such sources contain soils having a low strength, namely, clay and silt, and can be improved by using the SCs. The obtained soil is then processed usually by air-drying, pulverizing, and then sieving the soil in order to discard lumps and unwanted objects, as well as to facilitate the mixing and hydration. The processing is done to produce a specimen having uniform characteristics and controllable properties [5, 13]. The particle size distribution using sieve analysis and hydrometer analysis, specific gravity, and Atterberg's limits are common to determine the properties of the soil. The unified soil classification system is adopted to classify the soil. From Table 2, it can be seen that the clay is widely used followed by a rare use of silt and organic soils, since SCs can be used to reclaim landfills [43, 44]. The black cotton soil was also used in some studies [26, 32, 38, 41].

3.2. SC Materials

Different types of granular materials were used to construct the SCs. The granite chips are one of the frequently used materials [9, 10, 30, 31]. The reason behind using granite is the high strength, which prevents crushing [8, 23, 24]. Basic tests such as sieve analysis, direct shear, and specific gravity are common to determine the properties of the SC materials. The key properties of the SC materials are compiled in Table 3. It can be noted that stone ranging in size between 2-10 mm was frequently used. It is suggested that the particle size of the column material should be in the range of 1/6 to 1/7 times the diameter of the column [9] and most of the selected materials fall within that range. The selected material should possess uniform properties and characteristics.

The type and size of the SC materials play an important role in governing the load-settlement behaviour of the SC stone since they affect the strength parameters. The impact of using alternative materials to constructs SC's was appraised in several studies [14, 25, 28, 38, 50, 53]. The stronger the material, the better the performance of the SC. Alternative materials are also used, because they are cheap, abundantly available, and have properties similar to natural stone, such as industrial waste and concrete debris; this also has a good impact on the environment due to waste recycling. The alternative materials are tested in a similar manner to that of natural stone.

Table 2: The properties of the HG soils that were used in the literature

Author	Soil classification	L_L (%)	P_L (%)	PI (%)	G_s	Silt content (%)	Clay content (%)
Akhitha and Aswathy [14]	CL	34.9	23.4	11.5	2.61	42	53
Ali et al.[6]	—	54	23	31	2.64	—	—
Ali et al.[45, 46]	—	54	23	31	2.64	—	—
Ali [47]	—	54	23	31	2.64	35	55
Ambily and Gandhi [13]	CH	52	21	31	2.492	45	25
Ambily and Gandhi [5]	CH	52	21	—	2.6	—	—
Anju and Leander [15]	MH or OH	64.50	36.49	28.01	2	49.43	38.97
Aza-gnandji and Kalumba [16]	CL	43	26	—	2.7	—	—
Babu et al. [17]	MH	68	32	—	2.62	—	—
Balan et al. [18]	MH	112	62	50	2.36	—	—
Beena [19]	—	59	27	32	2.74	61	12
Chandrawanshi et al. [48]	CL	27.23	17.64	9.59	2.62	73	27
Dehariya et al. [20]	CH	55	30	25	2.66	—	—
Demir and Sarici [21]	CH	55	22	33	—	—	—
Demir et al. [49]	CH	55	22	33	2.6	—	—
Gniel and Bouazza [22]	—	62	29	33	2.64	—	—
Hasan & Samadhiya [8, 23, 24]	CI	48	18	30	2.73	—	—
Isaac and Girish [25]	—	78.5	48.8	—	2.72	—	—
Khan et al.[50]	CH	51	28	23	2.56	40	60
Kumar and Jain [26]	CH	55	30	25	2.6	—	—
Kumar and Jain [27]	CH	55	27	28	2.74	74.5	25.4
Malarvizhi and Ilamparuthi [9]	CH	55	37	—	—	—	44
Malarvizhi and Ilamparuthi [10]	CH	55	18	37	2.68	27	65
Malekpoor and Poorebrahim [28]	CL	42	21.5	20.5	2.72	—	—
Mohanty and Samanta [29]	CI-MI	42	31	11	2.7	—	—
Murugesan and Rajagopal [30]	CL	49	17	32	2.59	—	—
Murugesan and Rajagopal [31]	CH	49	17	32	2.59	—	—
Parihar and Ahuja [32]	CH	54	31	23	2.64	—	—
Sarici et al.[34]	CH	55	22	33	2.6	—	—
Sarvaiya and Solanki [35]	CL	45	20	25	2.6	60	35
Sharma et al.[36]	CL-CH	50	22	28	2.6	41.5	36
Shivashankar et al.[37]	ML	47	34	13	2.6	—	—
Shivashankar et al.[12]	MH, ML	68, 47	32, 34	36, 13	2.62, 2.6	—	—
Subramaniyan and Masoodhu [38]	CH	57.6	31.58	26.02	2.7	—	—
Sudheer et al.[39]	Bintonite	—	52	—	2.68	18	80
Suriya et al.[40]	—	71	36.13	34.87	2.63	—	—
Tallapragada et al.[41]	CH	67	21	46	—	—	—
Tandel et al.[51]	CL	49	20	29	2.56	—	—
Tandel et al.[52]	CL	46	17	29	2.56	—	—

3.3. Reinforcement Materials

Due to the low lateral confinement provided by the surrounding HG to the SC, bulging occurs at the top portion of the column. Such bulging limits the ability of the column to carry the load. Several reinforcement methods can be applied to the SC to provide extra lateral confinement to reduce the bulging. The application of reinforcemnt increases the load capacity and stiffness of the SC. The encasement of SC, by using sleeves made of geosynthetic fabrics, is one of the widely used and investigated methods. Introducing discs made from geosynthetic fabrics laterally within the column at constant spacing in order to provide increased friction has also been considered. The full and partial length was considered. The reinforcement methods are presented in Table 3. A combination of horizontal and lateral reinforcement provides even better performance as reported by Hasan and Samadhiya [8, 23]. Inserting nails vertically along the perimeter of the SC is suggested as a form of reinforcement [17, 37].

For the geosynthetic fabrics, the tensile strength, the aperture size, the thickness and, the weight per unit length can usually be provided by the manufacturer. When sleeves are made for the purpose of encasing the SC the strength of the formed joint should be tested in order to ensure that the failure is not going to take place at that section. The strength and the stiffness of the reinforcing material should follow the scale of the experiment in order to obtain better behaviour prediction [6].

4. Unit Cell Construction

4.1. HG Construction

Two methods were recognised for the construction of the HG. Those methods are aimed towards constructing an HG of uniform and repeatable properties. Those methods have been presented as given in Table 4 and can be outlined as follows:

1- The remoulding method, whereby the HG soil is mixed with a certain amount of water and kneaded in order to produce a uniform paste having a certain moisture content. A series of unconfined compression tests are carried out and the moisture content corresponding to the required strength is used to prepare the soil paste. This soil is then placed in sealed containers, in order to avoid the loss of moisture, for a period of time. The moisture content is checked afterwards, and if there is any loss of moisture, water is added to compensate. This paste is placed to form a layer then placed in layers having 50 or 100 mm thickness inside the testing tank up to the required height. Each layer is uniformly compacted by gently tapping the layer using a tamper, usually a wooden plank, to achieve a uniform density and minimize the voids that contain air within the soft soil layers. The compaction and the moisture content must be uniform and specified in order to achieve a HG having a uniform strength. Care must be taken in order to achieve uniform layers. The vane shear test, the unconfined compressive test, or the pocket penetrometer can be used to measure the strength for the remoulded ground [34]. In the case of constructing a floating SC, it is common that HG below the SC is constructed first and then, a casing pipe having a diameter equal to the SC is placed at the centre and the HG is constructed around it. [9]. For the purpose of compaction, Aza-gnandji and Kalumba [16] used a wood panel and a hammer while Subramaniyan and Masoodhu [52] used the proctor's hammer. Many others used a wooden plank or compacted by hand.

Table 3: The properties of SC material that were used in the literature

Study	Size (mm)	φ (°)	C_c	C_u	D_r%	E (MPa)
Akhitha and Aswathy [14]	10	—	—	—	—	—
Ali et al. [6]	1-4.75	40	—	—	—	—
Ali et al. [45]	2-4.75	45	—	—	60	—
Ali et al. [46]	2-4.75	42	—	—	60	—
Ambily and Gandhi [13]	2-10	42	1.125	2	—	48
Ambily and Gandhi [5]	2-10	43	—	—	—	55
Anju and Leander [15]	4.75>	—	1.18	1.37	70	—
Aza-gnandji and Kalumba [16]	1.18-9.50	48	1.04	1.46	—	—
Babu et al. [17]	2-10	—	—	—	—	—
Balan et al. [18]	>4.75	38	—	—	—	—
Beena [19]	0.041-4.6	37	5.6-0.93	3.85-1.4	—	—
Chandrawanshi et al. [48]	—	—	—	—	74	—
Dehariya et al. [20]	—	35	1.23	1.79	—	—
Demir and Sarici [21]	2-10	—	—	—	—	—
Demir et al. [49]	2-10	42	1	2.78	—	—
Gniel and Bouazza [22]	1-4	35	—	—	90	—
Hasan and Samadhiya [8, 23, 24]	2–6.3	43	—	—	70	—
Isaac and Girish [25]	10>	38-43	0.9-1.37	1.37-2.52	—	12-60
Khan et al. [50]	2-10	41			—	—
Kumar and Jain [26]	—	40.82	1.22	1.76	65	—
Kumar and Jain [27]	0.008-6	38.5	1.22	1.76	65	—
Malarvizhi and Ilamparuthi [9]	5-10	—	—	—	—	—
Malarvizhi and Ilamparuthi [10]	2-6.35	46	—	—	—	—
Mohanty and Samanta [29]	1.18-10	42	—	—	—	—
Murugesan and Rajagopal [30]	2-10	41.5	—	—	60	—
Murugesan and Rajagopal [31]	2-10	41.5	—	—	—	—
Parihar and Ahuja [32]	—	—	1.22	1.74	—	—
Pivarč [33]	2-5	45	—	—	—	45
Sarvaiya and Solanki [35]	2-10	42	1.25	2	—	—
Sharma et al. [36]	2.36-4.75	38	0.96	1.52	60	—
Shivashankar et al. [37]	2-10	—	—	—	—	—
Shivashankar et al. [12]	2-10	—	—	—	—	—
Subramaniyan and Masoodhu [38]	10-12	—	—	—	—	—
Sudheer et al. [39]	2-6 0.6-4.75	—	—	—	—	—
Tandel et al. [54]	0.2-4.75	30	0.72	3.56	—	—
Tandel et al. [51]	1-4.75	30	0.72	3.56	—	21
Tandel et al. [52]	0.2- 4.75	30	0.72	3.56	—	—

2- The consolidation method, whereby the HG soil is mixed with water and kneaded thoroughly to form a slurry free of any lumps and previous consolidation. This slurry is filled into the testing tank and pressure is applied in order to consolidate it. The settlements that occur in the soil bed are monitored by dial gauges. Two-way drainage is permitted from the top and the bottom of this soil bed by placing layers of sand. The consolidation process takes a few days until the rate of settlement diminishes. After the construction of the HG, the top surface is trimmed and levelled.

4.2. SC Construction

End-bearing (EB) as well as floating (F) columns can be tested using the unit cell concept. As presented in Table 4, three methods were used to construct the SCs. Those methods are outlined as follows:

1- The replacement method, whereby an open-ended casing pipe with an outer diameter equal d is inserted manually into the HG from the top in certain increments, 5 cm usually. The HG within the pipe is removed with each increment using a helical auger to avoid the suction effect and friction that can disturb the HG. After total removal of soil, the casing is partially lifted, and SC's material is charged and compacted in layers keeping an overlap between the casing and the layer in order to avoid necking and bulging [30]. The properties of tampers that are used to compact the SC's materials are shown in Table 5. A gentle compaction effort is applied to the SC's material in order to avoid disturbing the surrounding HG and to ensure that the layer is packed without significant voids, also, to avoid breaking the stone. The compaction using minimum effort was suggested by [12, 52, 50]. The following layers are constructed in a similar manner until the full column length is achieved.

2- The displacement method, whereby a casing pipe, with its lower end sealed using a base plate, is pushed manually into the HG from the top. Then, the SC is constructed by adopting the same abovementioned method. The base plate is left within the HG as the casing pipe is lifted. The excess soil protruding from the top surface of the HG, due to the displacement effect, is trimmed back to its original level.

3- The fixed pipe method, whereby the casing pipe is fixed, centred and levelled at the bottom of the testing tank when the SC is end-bearing, or on the HG when the SC is floating. The HG is constructed in layers around the casing pipe. The SC is constructed in the same afore-mentioned method simultaneously with the layers of the HG, or after the full construction of the HG. Table 4 shows that this method is preferred when floating SCs are constructed.

Table 4: The details of the SCs that were adopted in literature

Study	SC		Construction method		Column end condition
	L (mm)	d (mm)	HG	SC	
Akhitha and Aswathy [14]	450	50	Remoulding	Fixed pipe	F, EB
Ambily and Gandhi [13]	450	100	Remoulding	Replacement	EB
Ambily and Gandhi [5]	450	100	Remoulding	Replacement	EB
Anju and Leander [15]	100, 200, 300, 400	—	—	Replacement	F
Aza-gnandji and Kalumba [16]	400	70, 100	Remoulding	Replacement	EB
Babu et al [17]	540	90	Remoulding	Replacement	F
Balan et al [18]	350	50	Consolidation+ remoulding	Fixed pipe	F
Beena [19]	500	110	Remoulding	Fixed pipe	EB
Chandrawanshi et al.[48]	194	25.4, 76.2	Consolidation	Replacement	EB
Demir and Sarici [21]	250	50	Remoulding	—	EB
Demir et al.[49]	300	50, 100	Remoulding	Fixed pipe	EB
Gniel and Bouazza [22]	—	50.5	Consolidation	Replacement	EB
Hasan and Samadhiya [23]	5d F,7d EB	75, 90	Remoulding	Replacement	F, EB
Hasan and Samadhiya [24]	5d	75	Remoulding	Replacement	F
Hasan and Samadhiya [8]	5d F,7d EB	75	Remoulding	Replacement	F, EB
Isaac and Girish [25]	250	50	Remoulding	Fixed piped	EB
Khan et al. [50]	148, 203.5, 259	37	Remoulding	Replacement	F
Kumar and Jain [26]	50, 65, 80		Replacement	—	EB
Kumar and Jain [27]		50, 65, 80	Remoulding	Replacement	EB
Malarvizhi and Ilamparuthi [9]	variable	30	Remoulding	Fixed pipe	F,EB
Malarvizhi and Ilamparuthi [10]	150, 225, 300	30	Remoulding	Fixed pipe	F,EB
Malekpoor and Poorebrahim [28]	300-900 EB, (400-1200-2d) F	100-150	Remoulding	Fixed pipe	F, EB
Mohanty and Samanta [29]	600	88	Remoulding	Replacement	EB
Murugesan and Rajagopal [31]	500	50,75,100	Consolidation	Displacement	EB
Parihar and Ahuja [32]	260	57	Remoulding	Replacement	—
Sarici et al.[34]	250	50	Remoulding	Replacement	—
Sarvaiya and Solanki [35]	300	45, 50, 55, 60	Remoulding	Displacement	F
Sharma et al. [36]	300	60	Remoulding	Fixed pipe	EB
Shivashankar et al. [37]	540	60, 75, 90	Remoulding	Fixed pipe	F
Shivashankar et al. [12]	540	90	Remoulding	Replacement	F
Subramaniyan and Masoodhun [38]	200	26	—	Replacement	F
Sudheer et al. [39]	150	25	Remoulding	Displacement	F
Suriya et al. [40]	220	25	—	Replacement	—
Tallapragada et al. [41]	200, 225, 300	15, 20, 25	Remoulding	Replacement	F, EB
Tandel et al. [54]	450	50,75,100	Remoulding	Displacement	EB
Tandel et al. [51]	—	50,75,100	—	Displacement	EB
Tandel et al. [52]	variable	50, 75	Remoulding	Displacement	F, EB

In all methods, the columns should be vertical and centred. A lubricant can be applied to the casing pipe in order to reduce the friction with the HG and avoid disturbance, also, to facilitate the penetration and the extraction of the casing pipe. The unit weight of the SC is determined by determining the weight of the material and the volume of the SC. Some authors suggested that the column's material should be moistened before construction to prevent the absorption of moisture from the surrounding HG.

Table 5: The specification of the steel tampers that were used to compact the SCs in several studies

Study	diameter (mm)	length (mm)	Weight (kg)	Falling distance (mm)	Number of blows
Ali et al. [6]	—	—	2	100	10
Ambily and Gandhi [5]	—	—	2	100	10
Aza-gnandji and Kalumba [16]	—	—	2	180	12
Babu et al. and Shivashankar et al. [17, 37]	—	—	2	100	10
Hasan and Samadhiya [8, 23]	—	—	2.5	150	5
Khan et al.[50]	—	—	1.25	100	15
Kumar and Jain [26]	—	—	2	100	10
Kumar and Jain [27]	—	—	—	100	10
Malekpoor and Poorebrahim [28]	—	—	4.5	—	—
Murugesan and Rajagopal [30]	10	1000	2	250	25
Sarvaiya and Solanki [55]	—	—	2	100	10
Shivashankar et al. [12]	—	100	2	—	10
Tandel et al. [52, 54]	—	—	1.3	150	12

The replacement method is preferred to the displacement method because the displacement method is difficult to practice in small-scale models [23]. In the case of constructing an encased column, the encasement sleeve can be fixed outside or inside the casing pipe before placing the SC's material. In the case of horizontal reinforcement, the circular discs can be placed horizontally between the layers as the column is constructed. A uniform pressure of 2.5 or 5 kN/m^2 is occasionally applied to the top surface of the unit cell after the construction of both of the HG and the SC for a period of one or two days in order to ensure proper contact between ground and the SC also, to ensure the gain of strength for the disturbed soil [9].

5. Testing Procedure

The test is carried out using a loading frame which facilitates the accommodation of the testing tank, the load imposing equipment, and the load and settlement measurement equipment. During the test, the loading plate can be set to settle at a prescribed settlement rate, and the corresponding load is measured. This approach has widely been adopted because the failure load can clearly be determined. Alternatively, the load can be applied at a certain rate and the settlement can be determined, although, this approach has rarely been adopted. Usually, the test continues until failure, which is when no load gain takes place as settlement increases. Table 6 shows the loading rate and the maximum displacement adopted by several authors.

Table 6: The settlement rate and the final settlement adopted by various studies

Study	Settlement rate (mm/min)	Settlement limit (mm)
Akhitha and Aswathy [14]	—	25
Ali et al. [6]	1	50 or failure
Ali et al. [45]	1	60
Ali et al. [46]	1	60
Ambily and Gandhi [13]	1.2	14
Ambily and Gandhi [5]	0.0625	>10
Aza-gnandji and Kalumba [16]	0.0625	37.5
Babu et al. [17]	0.0625	10
Balan et al. [18]	1.25	50
Beena [19]	1.2	—
Dehariya et al. [20]	1.25	12.5 (10%d)
Hasan and Samadhiya [23]	1.2	35 or failure d, 25 D
Hasan and Samadhiya [24]	1.2	35
Isaac and Girish [25]	0.048	7
Khan et al. [50]	—	25, 30
Kumar and Jain [26]	1.25	0.2 d
Kumar and Jain [27]	1.25	10
Malekpoor and Poorebrahim [28]	0.7	15
Mohanty and Samanta [29]	—	20
Murugesan and Rajagopal [30]	1.2	50
Murugesan and Rajagopal [31]	1.2	—
Pivarč [33]	5	—
Sarici et al. [34]	2.33	—
Sarvaiya and Solanki [35]	0.24	40
Shivashankar et al. [37]	1.2	10 D, 40d
Shivashankar et al. [12]	0.0625	10, 40
Subramaniyan and Masoodhu [38]	—	5
Sudheer et al. [39]	1.25	10
Suriya et al. [40]	0.025	25
Tandel et al. [54]	1.25	50
Tandel et al. [51]	—	30
Tandel et al. [52]	1.25	50

Table 6 shows that two settlement rates were generally adopted; the settlement rate that was usually adopted was fast enough to simulate the undrained condition, which represents the stage directly after construction. Few authors have adopted the slow rate of settlement to simulate the medium or the long-term behaviour.

Before starting the test, all of the load imposing and the measurement equipment must be calibrated. A sand blanket 20-30mm thick can be placed below the loading plate for better stress distribution; this was preferred when the load was imposed over the entire area of the unit cell [5, 12, 13, 17, 29]. Care should be taken while levelling and positioning both of the tank and the measurement equipment in order to ensure accurate data collection. HGs with no SCs were loaded for the purpose of comparison and establishing the improvement contributed by the construction of the SC [12, 20].

The measurement equipment can be connected to a data acquisition device which is in turn connected to a computer having a software that is specialized in recording the measured data accurately. For the purpose of measuring the settlement, dial gauges are used and fixed diametrically on opposite sides of the loading plate to capture the differential settlement of the loading plate. Also, the settlement can be measured using a linear variable displacement transducer (LVDT).

The improvement contributed by the construction of SC was evaluated by comparing the load carrying capacity of a treated and an untreated HG [9] also, some studies evaluated the improvement in the settlement, similarly. Instead of direct loading, Chandrawanshi et al. [48] subjected the unit cell to consolidation under a constant pressure and evaluated the settlement.

6. Post-Testing Procedure

Figure 4 shows the deformed shape of columns tested by Hasan and Samadhiya [8]. In addition to the load-settlement behaviour, the deformed shape of the SC can be established [8, 5, 12, 45, 23, 37, 52].

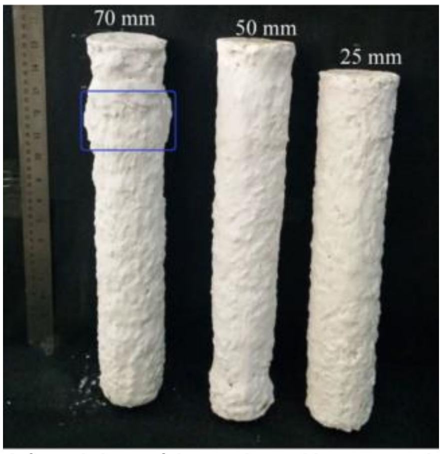

Fig. 4: The deformed shape of the SC obtained by Hasan and Samadhiyea [23]

After the loading test is finished, the SC's material is removed carefully without disturbing the HG. The cavity is then filled using a paste made of plaster of Paris because it forms a thick paste when mixed with water and does not stick to the clay due to the high viscosity, also, it can harden in a short time [5]. Cement mortar can also be used, although it can take longer to harden. After hardening, the HG is carefully removed and the deformed shape of the SC is obtained and can be examined, measured and, analysed. It was observed that bulging occurs at the top part of the SC with a maximum value at d/2 to d [12, 13]. It was also observed that in the case of partially reinforced SC, bulging takes place directly under the reinforced part [22].

7. Concluding Remarks

The experimental design of small-scale single stone columns by adopting the unit cell concept was reviewed. The materials and methods used in such experiments along with the discussion of their effects and implication were presented. The following remarks can be drawn from the review:

1- The unit cell is a robust concept that was frequently used to investigate the behaviour of single SCs. Many materials, methods of construction, methods of SC reinforcement, testing and post-testing procedures can be tested. Also, various geometry aspects such as the spacing, the diameter and the end condition of the SC can be considered.
2- Several measures should be taken to ensure the uniformity of unit cell construction to ensure repeatability of the test results. Care must be taken for scaling the unit cell to ensure correct behaviour simulation.
3- The HG strength parameters can be controlled by adjusting the moisture content. The compaction of the HG during construction should be uniform to ensure a uniform HG strength.
4- A combination of construction of HG by remoulding and SC by replacement is preferred with fast loading rate because such methodology is rapid, consistent and accurate. Also, rapid loading simulates the stage in directly after construction in which, the soil is weakest and thus, considered the critical case.
5- The reviewed cases revealed clay was mostly used as a HG material as compared to other types of soil.
6- Even though in theory, the inner vertical surface of the testing tank should be frictionless, the friction cannot be totally eliminated physically. However, comparison with finite element solutions shows that the friction has an insignificant effect on the SC behaviour.
7- Bulging is the dominant mechanism if the stone column is only loaded. The bulging is reduced as the area of the loading plate increases to cover the surrounding V.
8- The deformed shape of the SC can be successfully established by exhumation technique. It is found that the bulging of an unreinforced SC occurs at the top, while the bulging of partially reinforced SC occurs below the reinforced part.

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