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Behavior of eccentrically inclined loaded footing resting on fiber reinforced soil

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Abstract. A total of 104 laboratory model tests on a square footing subjected to eccentrically inclined loads supported by sand reinforced with randomly distributed polypropylene fibers were conducted in order to compare the results with those obtained from unreinforced sand and with each other. For conducting the model tests, uniform sand was compacted in a test box at one particular relative density of compaction. The effect of percentage of reinforcement used, thickness of the reinforced layer, angle of inclination of load to vertical and eccentricity of load applied on various prominent factors such as ultimate load, vertical settlement, horizontal deformation and tilt were investigated. An improvement in ultimate load, vertical settlement, horizontal deformation and tilt of foundation was observed with an increase in the percentage of fibers used and thickness of reinforced sand layer under different inclinations and eccentricities of load. A statistical model using non-linear regression analysis based on present experimental data for predicting the vertical settlement (s_p), horizontal deformation (hd_p) and tilt (t_p) of square footing on reinforced sand at any load applied was done where the dependent variable was predicted settlement (s_p), horizontal deformation (hd_p) and tilt (t_p) respectively.

Keywords: geosynthetics; eccentrically inclined loading; fiber reinforced sand; model tests; ultimate load; tilt

1. Introduction

In geotechnical engineering problem, field tests on full-scale prototype foundations are the only method to get realistic and representative results. But due to practical difficulties as well as economical and time considerations, field tests cannot usually be conducted. In such cases carefully conducted model tests, which are less expensive and also provide useful qualitative data, and which can subsequently be used to study the effect of important parameters in prototype tests, could be utilized.

Several laboratory model test results have been published in past related to the improvement of load bearing capacity of shallow foundations supported by sand reinforced with various materials such as metal strips (Binquet and Lee 1975, Fragaszy and Lawton 1984), rope fibers (Akinmusuru

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and Akinbolande 1981), geotextiles (Guido *et al*. 1985, Sadoglu *et al*. 2009, Lovisa *et al*. 2010), geogrid (Guido *et al*. 1986, Khing *et al*. 1993, 1994, Omar *et al*. 1993, Yetimoglu *et al*. 1994, Latha and Somwanshi 2009, Abu-Farsakh *et al*. 2013). Randomly distributed fiber reinforced soil (RDFS) is among the latest techniques in which fibers of desired type and quantity are added in the soil, mixed and laid in position. The main advantage of randomly placed fibers is the absence of potential planes of weakness that can develop parallel to the oriented reinforcement. Very little work is reported in past relating to the model footing test on sand reinforced with randomly distributed fibers (Consoli *et al*. 2003, Kumar *et al*. 2011, Kumar and Kaur 2012, Wasti and Butun 1996).

But in all of these tests performed, the test footing was subjected to concentric loading. For designing foundations subjected to earthquake forces, adopting appropriate values of horizontal and vertical seismic coefficients, equivalent seismic forces can be conveniently evaluated. These forces in combination with static forces make the foundations subjected to eccentric inclined loads. A number of experimental studies on subject of inclined loading have been conducted by several researchers using different types of reinforcement (Wong 1982, Andrawes *et al*. 1985, Patra *et al*. 2006, Saran and Aggarwal 1991, Saran *et al*. 2008). Out of these Wong (1982), Andrawes *et al.* (1985) and Saran *et al*. (2008) studied the effect on footing subjected to eccentrically inclined loadings. Little work is reported in literature on problem of footings subjected to eccentrically inclined loads.

In the present study, large scale model tests were performed on unreinforced soil and soil reinforced with randomly distributed polypropylene fibers to study the behavior of square footing subjected to eccentrically inclined loading. Here the effect of thickness of reinforced soil layer, fiber percentage, angle of inclination of load and eccentricity of load on ultimate load, vertical settlement, horizontal deformation and tilt were studied in detail.

2. Model testing program

2.1 Soil used

The sand classified as a poorly graded sand (SP) according to the Unified soil classification system with a minimum and maximum density of 13.8 kN/m^3 and 17.09 kN/m^3 respectively, a C_u

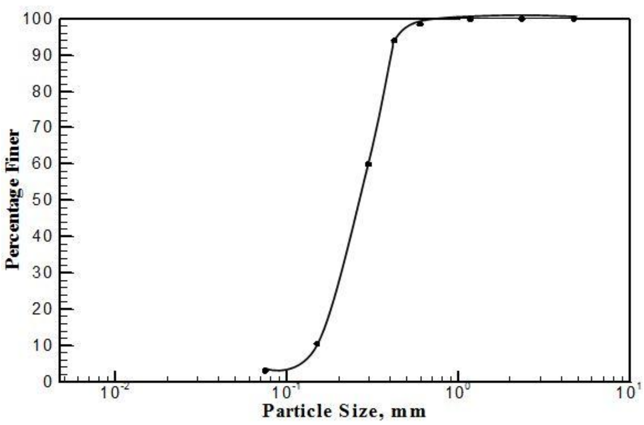

Fig. 1 Grain size distribution curve

Table 1 Detail of model tests conducted

Test no.	Conditions					
	Tank conditions	h_1	h_2	Angle of inclination to the vertical	Eccentricity ratio (e/B)	Percentage of fibers used
1-8	Only sand	0	3B	0°, 5°, 10°,15°	0.1 and 0.2	0
9-32	Sand + Sheet	0.5B, 0.75B, 1B	2.5B, 2.25B, 2B	0°, 5°, 10°,15°	0.1 and 0.2	0
33-104	Sand + Sheet + Fibers	0.5B, 0.75B, 1B	2.5B, 2.25B, 2B	0°, 5°, 10°,15°	0.1 and 0.2	0.5%, 0.75%, 1%

and C_c of 2.09 and 0.98, respectively and a specific gravity of 2.61. Fig. 1 shows the "Grain size distribution curve".

2.2 Reinforcement used

Corrugated polypropylene fibers "ENDURO HPP 45" with a length of 45mm and diameter of 0.95mm, were used as reinforcement throughout this investigation. The specific gravity, tensile strength and E-modulus of fiber was 0.91, 400 N/mm^2 and 9 GPa, respectively.

A plastic fabric sheet with a maximum tensile strength of 8.46 kN/m at 7.25% strain was also placed at an interface of the reinforced and unreinforced layer to act as a separator which also acted as reinforcing material.

2.3 Test series description

A total of 104 stress controlled model tests, as described in Table 1, were conducted on a square footing resting on unreinforced and reinforced sand subjected to eccentrically inclined loading.

The testing was conducted in three phases. Phase I comprised eight tests conducted on totally unreinforced sand (Only sand with no plastic fabric sheet and no fibers) at four different inclination angles (*i*) of 0°, 5°,10° and 15° with the vertical and 0.1B and 0.2B eccentricity of load applied compacted at 25% relative density. Phase II (24 tests) was designed to examine the effect and strength contribution of plastic fabric sheet placed at interface of two different layers of unreinforced sand at three different thicknesses of sand layers (0.5B, 0.75B and 1B) on ultimate load. Here the load was applied at four different inclination angles of 0°, 5°, 10° and 15° with 0.1B and 0.2B eccentricity and the layers above and below the plastic fabric sheet were compacted at same relative density of 25%. Phase III involved 72 tests conducted on a sand bed with top layer of sand reinforced with three different fiber percentages by weight of sand (0.5%, 0.75% and 1%) subjected to eccentrically inclined loading with eccentricity 0.1B and 0.2B and load inclined at 0°, 5°, 10° and 15° to the vertical. All the reinforced and unreinforced sand layers were compacted at same relative density of 25% with plastic fabric sheet placed at interface of reinforced and unreinforced sand at the different thicknesses of reinforced layer (0.5B, 0.75B and 1B).

2.4 Test set up and testing procedure

2.4.1 Testing tank

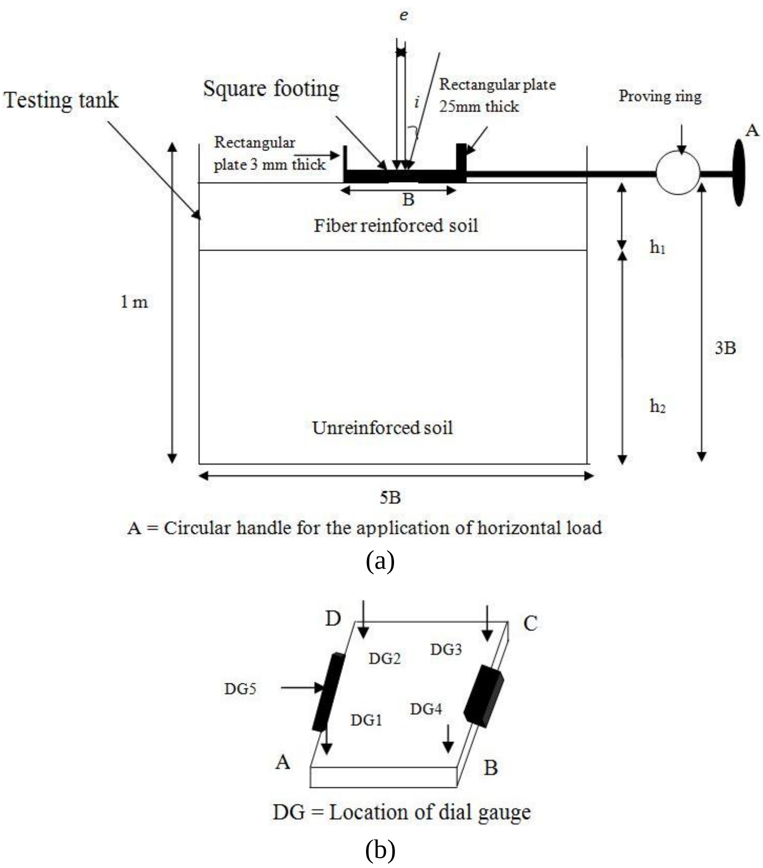

Fig. 2 (a) Arrangement of model footing tests; (b) arrangement of dial gauges on model footing subjected to axially oblique loading

All the model loading tests were conducted in a cubical steel tank of size 1.5m by 1.5m in plane and 1m in depth. The size of the tank was taken as 5 times the size of plate keeping in view the size of footing and zone of influence (IS: 1888 1982). The size of tank for conducting the model tests was decided by the size of footing and zone of influence. A hole was made in one side of tank to allow the passage of a horizontal steel rod for the application of horizontal load (Fig. 2(a)).

2.4.2 Footings

A model square footing made up of mild steel plate of size 300 mm by 300 mm and thickness 25mm was used. Various standards have recommended a plate size varying from 300 mm to 750 mm for conducting the footing tests (IS: 1888 1982, BS 1377: Part9 1990, ASTM D 1194 94 YEAR). A rectangular plate of 4mm thickness was welded to one edge of footing for fixing a dial gauge to record horizontal deformation and another rectangular plate of 25 mm thickness was welded to opposite edge of footing for the application of horizontal load (Fig. 2(b)).

2.4.3 Loading assembly and load application

Vertical load (*V*) was applied to the model footing by a hydraulic jack of capacity 250 kN. A horizontal load (*H*) was applied simultaneously with the help of a horizontal steel rod which was displaced by rotating the circular handle with which it was attached (Fig. 2(b)). A proving ring of capacity 50 kN was fixed in between the horizontal steel rod and circular handle. As the load applied is eccentric, the collar which was originally in centre was moved in the *x*-direction with the help of a pulley system to the desired eccentricity from the centre. For the angle of inclination i, the horizontal load to be applied was calculated as H = V tan i. After the application of each load increment, the cumulative load was maintained for a time interval of 15 minutes or until the vertical settlement ceased or the rate of vertical settlement was reduced to a value of 0.02 mm/min (ASTM D 1194 94 YEAR, IS: 1888 1982).

2.4.4 Preparation of test bed

The test bed was prepared by placing the sand and fiber mixed sand in layers, each layer of 10 cm thickness and compacted with the help of wooden rammer to a relative density of 25%. To achieve the desired density, the weight of sand and fiber mixed sand was calculated for 10 cm thick layer using the unit weight of sand and fiber mixed sand. The unit weight 'γ' of fiber reinforced soil mixture was taken as $(W_f + W_s)/V_m$ which indicates that when fibers are added some sand is removed to keep the overall unit weight constant. Here W_f is the weight of fiber; W_s is the weight of sand, γ is unit weight of fiber reinforced soil mixture and V_m is the corresponding volume of mixture.

Before starting a new test, the sand in the tank (from the previous test) was removed to the depth of about three times the footing width and then test bed was prepared in the same manner as explained above.

2.4.5 Measurement of vertical settlement, horizontal deformation and tilt

Vertical settlement, horizontal deformation and tilt of the footing for each increment of the load applied were measured using dial gauges. In order to record the vertical settlement of the footing for each increment of load applied, four sensitive dial gauges were placed at each corner of the square footing (Fig. 2(b)) and their average was taken. The dial gauges were fixed to a reference beam and supported on external rods. The vertical load was applied in equal increments. To record the horizontal deformation of footing for each increment of load applied, a sensitive dial gauge was used. The plunger of the dial gauge rested on the rectangular plate of width 4mm welded to the edge of the footing to record the horizontal deformation. To record the value of tilt the difference of average of dial gauges (1 and 2) and (3 and 4) were taken. For each load increment, measurement of vertical settlement, horizontal deformation and tilt was made.

2.4.6 Testing procedure

The test bed was prepared for various conditions as explained in Section 2.3. Then, the footing was placed on the surface of the leveled sand/sand-fiber mixture. A proving ring was fixed to the horizontal rod which was further attached to the circular handle and this assembly was allowed to just touch the rectangular plate of 25 mm thickness. The hydraulic jack was placed on the footing and the collar rested on the top of hydraulic jack and, if required, some adjusting plates were also placed. The eccentricity of load was applied by moving the collar to the desired eccentricity. The vertical settlement, horizontal deformation and tilt were recorded for each load increment.

3. Model test results

Model test results were presented as load versus vertical settlement, load versus horizontal

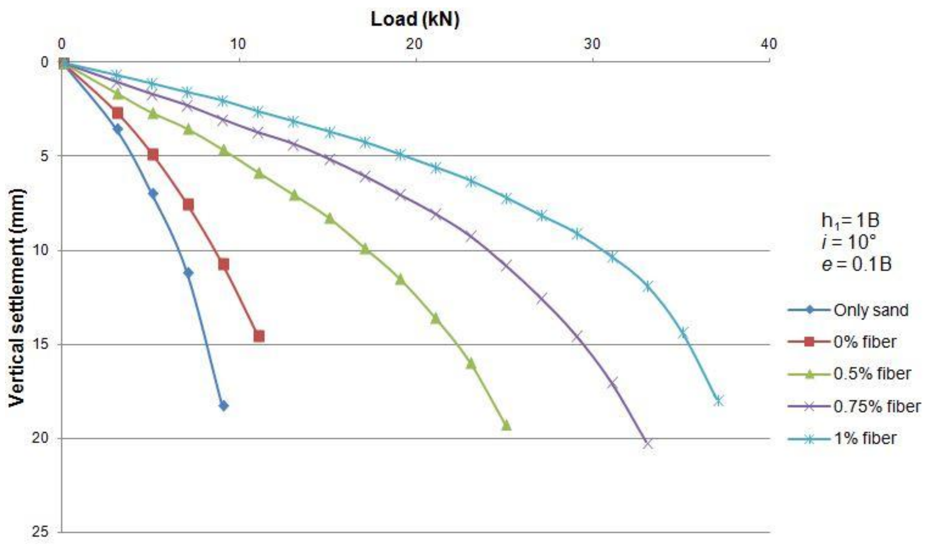

Fig. 3 Load versus vertical settlement for the soil reinforced when h_1 = 1B

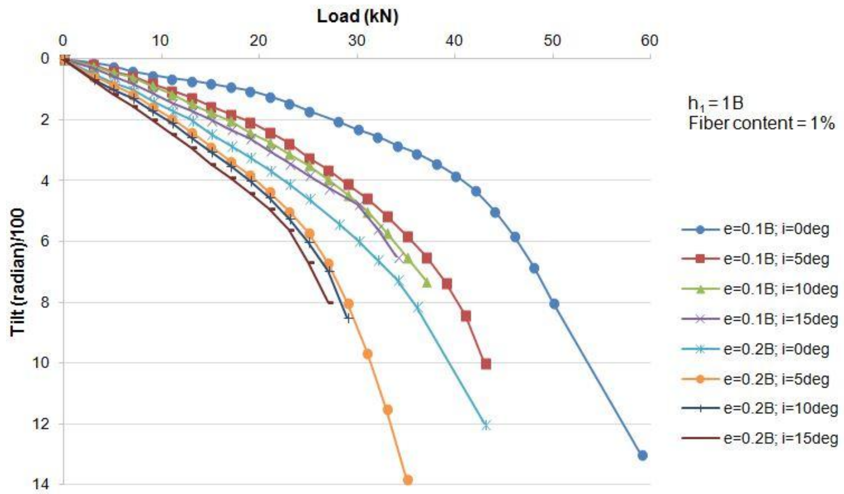

Fig. 4 Load versus tilt for the soil reinforced with 1% fibers (h_1 = 1B) for various values of 'i' and 'e'

deformation and load versus tilt curves. Typical curves are shown in Figs. 3-4.

The discussion on test results is presented in following sections and to express the data four terms Ultimate load ratio (ULR), Vertical settlement ratio (VSR), Horizontal deformation ratio (HDR) and Tilt ratio (TR) have been used which are defined as follows

$$\text{ULR} = \frac{\text{Ultimate load of reinforced soil}}{\text{Ultimate load of unreinforced soil}} \quad (1)$$

$$\text{VSR} = \frac{\text{Vertical Settlement corresponding to the Ultimate load of reinforced soil}}{\text{Vertical Settlement corresponding to the Ultimate load of unreinforced soil}} \quad (2)$$

$$\mathrm{HDR} = \frac{\text{Horizontal Deformation corresponding to the Ultimate load of reinforced soil}}{\text{Horizontal Deformation corresponding to the Ultimate load of unreinforced soil}} \quad (3)$$

$$\mathrm{TR} = \frac{\text{Tilt value corresponding to the Ultimate load of reinforced soil}}{\text{Tilt value corresponding to the Ultimate load of unreinforced soil}} \quad (4)$$

Load versus vertical settlement, load versus horizontal deformation and load versus tilt curves were plotted for various setups and the ultimate load values were calculated from the load versus vertical settlement curves using the double tangent method. The effect of various parameters on ultimate load, vertical settlement, horizontal deformation and tilt are discussed in this section.

3.1 Effect on ultimate load

With the increase in thickness of reinforced sand layer, experimental result analysis revealed that value of the ultimate load and ultimate load ratio increased but the rate of increase of ultimate load is perhaps little less between 0.75% and 1% than it is between 0.5% and 0.75%. In addition, Figs. 5-6 and Tables 2-3 clearly show this trend. With 0.1B eccentricity, the ultimate loads of the totally unreinforced layer at 0°, 5°, 10° and 15° was found to be 7.7 kN, 6.9 kN, 6.3 kN and 4.5 kN, respectively. In the case of 0.2B eccentricity, the ultimate loads of totally unreinforced layer at 0°, 5°, 10° and 15° was found to be 5.7 kN, 4.9 kN, 4.1 kN and 2.7 kN, respectively. When reinforced with 1% fibers, under eccentrically inclined loading conditions with 0.1B eccentricity and 10° inclination to the vertical, there was an approximately 2.7, 4.1 and 5 times increase in ultimate load, with increase in thickness of the reinforced soil layer for 0.5B, 0.75B and 1B in comparison to the unreinforced soil (Table 2).

Table 2 Ultimate load ratio for 0.1B eccentricity of load

Fiber content	i = 0°			i = 5°			i = 10°			i = 15°		
	ULR at h_1/B =			ULR at h_1/B =			ULR at h_1/B =			ULR at h_1/B =		
	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0
0% (only fabric sheet)	1.5	1.6	1.6	1.4	1.5	1.4	1.2	1.4	1.1	1.2	1.2	1.1
0.5%	2.3	3	3.6	1.9	2.7	3.4	1.6	2.5	3.2	1.8	3	4.1
0.75%	3	3.6	4.4	2.7	3.6	4.2	2.4	3.6	4.2	2.2	4.5	5.5
1%	3.5	4.3	5.2	3.2	4	4.9	2.7	4.1	5	3.4	5.3	6.5

Table 3 Ultimate load ratio for 0.2B eccentricity of load

Fiber content	i = 0°			i = 5°			i = 10°			i = 15°		
	ULR at h_1/B =			ULR at h_1/B =			ULR at h_1/B =			ULR at h_1/B =		
	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0
0% (only fabric sheet)	1.7	1.9	1.8	1.5	1.8	1.7	1.3	1.7	1.4	1.5	1.8	1.6
0.5%	2.8	3.6	4.6	2.5	3.7	4.8	2.3	4	4.4	2.7	5.5	6.2
0.75%	3.4	4.4	5.1	3.4	4.3	4.9	3.2	4.8	5.4	3.4	6.7	7.5
1%	3.9	5.2	5.7	3.8	5.2	5.6	3.9	5.7	6.1	4.8	7.7	8.8

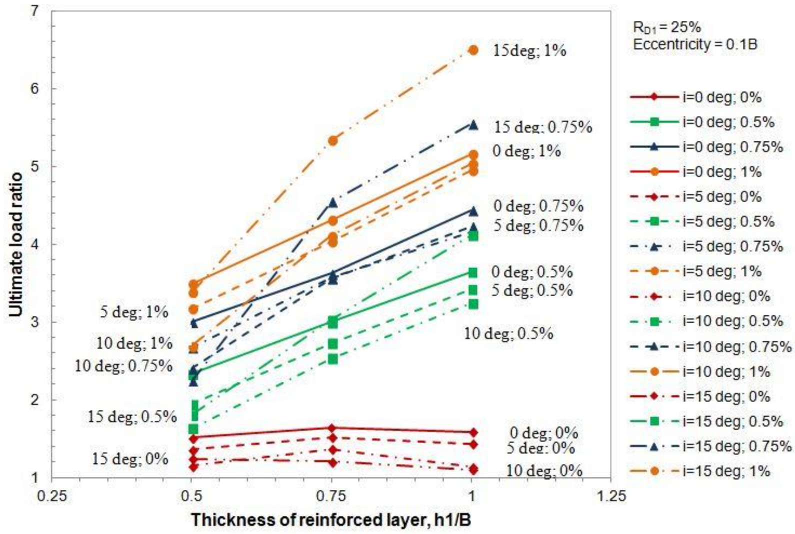

Fig. 5 Ultimate load ratio versus thickness of reinforced layer

As the poorly graded sand was reinforced with two types of reinforcement (fibers of different percentages and plastic fabric sheet), therefore, it was necessary to study the effect of the reinforcements both individually and together with each other. The fibers were added to the sand for the purpose of only reinforcing the material thus increasing its strength but the plastic fabric sheet fulfilled two purposes; one as a reinforcement and other as a separator to separate the reinforced layer from the unreinforced layer so as to maintain the percentage of fibers in reinforced layer to the desired content. The top layer of poorly graded sand was reinforced with 0.5%, 0.75% and 1.0% randomly distributed fibers at different thicknesses and model footing tests were conducted on the footing resting on reinforced sand overlying poorly graded sand. For the reinforced sand case, the ultimate load calculated from these was the combined effect of plastic fabric sheet and percentage fiber. The individual contribution of fibers is computed from Eq. (7).

Now

$$ULR(T) = ULR(PFS) * ULR(Fibers) \tag{5}$$

$$ULR(Fibers) = ULR(T) / ULR(PFS) \tag{6}$$

Therefore

$$q_{u(Fibers)} = ULR(Fibers) * q_{u(OnlySand)} \tag{7}$$

Where,

ULR (T) = Ultimate load ratio of soil reinforced with randomly distributed fibers and plastic fabric sheet at the interface,

ULR (Fiber) = Ultimate load ratio of soil reinforced with randomly distributed fibers only,

ULR (PFS) = Ultimate load ratio of soil reinforced with plastic fabric sheet only,

$q_{u(Fiber)}$ = Ultimate load of soil reinforced with randomly distributed fibers only,

$q_{u(Only\ sand)}$ = Ultimate load of totally unreinforced soil.

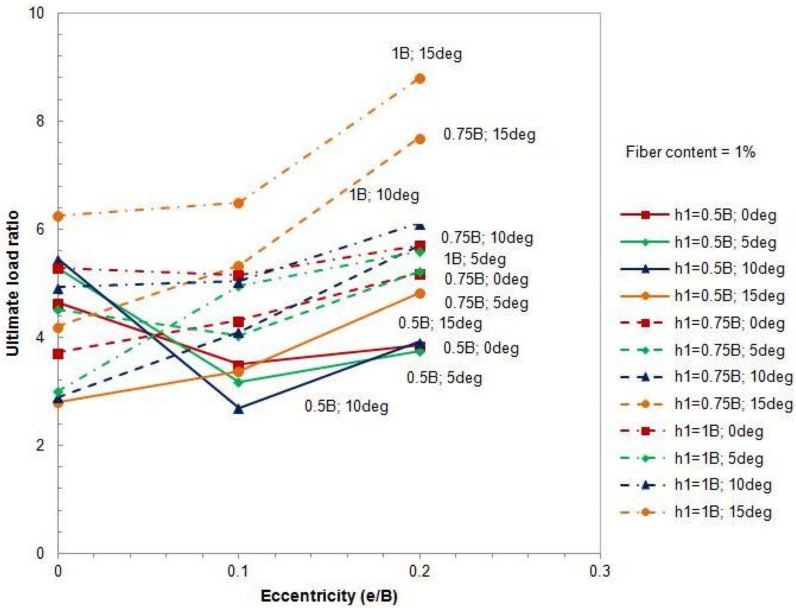

Fig. 6 Ultimate load ratio versus e/B

With increase in percentage of fibers and keeping all other parameters same, the experimental results reveal that there is increase in value of ultimate load (thus ultimate load ratio). This effect is clear from Fig. 3 which shows the graphical representation of model test results when the thickness of top reinforced layer is taken as 1B and the load applied is inclined at 10° with 0.1B eccentricity. For 1B thickness of reinforced layer under eccentrically inclined load with 0.1B eccentricity and 10° inclination to the vertical and considering the effect of only fibers, there is about 184%, 270.7% and 342.4% increase in the ultimate load if the percentage fiber is increased to 0.5%, 0.75% and 1% respectively in comparison to totally unreinforced soil (Fig. 5). Further, some model footing tests under eccentrically inclined loading conditions (e = 0.1B eccentricity and i = 5°) were conducted without providing plastic fabric sheet at the interface of reinforced and unreinforced layers. The test results showed that the addition of fibers to soil was more effective if the fiber reinforced soil layer is separated from the unreinforced soil with a plastic fabric sheet (Table 4).

The load-vertical settlement, load-horizontal deformation and load-tilt curves were plotted after reinforcing the soil with a fabric sheet only for different depths of placement of plastic fabric sheet (0.5 B, 0.75 B and 1.0 B). From the results it is evident that the ultimate load increased with an increase in the depth of plastic fabric sheet up to depths of 0.75B. However, beyond 0.75B depth, with an increase in the depth of placement of the plastic fabric sheet there was a decrease in the ultimate load and thus the ultimate load ratio (Tables 2-3). Similar results were observed by Consoli *et al*. (2003), Kumar *et al*. (2011), Kumar and Kaur (2012) and Kaur and Kumar (2013).

Analysis of the model test results revealed that with an increase in the load inclination there was an improvement in the ultimate load, vertical settlement and tilt value. Similar findings were reported by Saran *et al*. (2008).

With an increase in the angle of inclination to the vertical, the ultimate load decreased but the ultimate load ratio increased in most of the cases (Figs. 5-6 and Tables 2-3). The reason behind this

Table 4 Ultimate load results showing the effect of fabric sheet at the interface of reinforced and unreinforced soil

Test condition	Relative density of reinforced soil layer	$q_{u(Fiber)}$ (kN)	
		$q_{u(Fiber)}$ = ULR $_{(Fibers)}$ * $q_{u(Only\ Sand)}$	$q_{u(Fiber)}$ from tests conducted without fabric sheet
Soil reinforced with 0.75% fibers up to 0.75B depth	25%	16.6	15
Soil reinforced with 0.75% fibers up to 1.0B depth	25%	20.7	20.1
Soil reinforced with 1.0% fibers up to 0.75B depth	25%	18.4	15.9
Soil reinforced with 1.0% fibers up to 1.0B depth	25%	24.2	22.4

finding is that the ultimate load of totally unreinforced soil decreases with an increase in the angle of inclination so the dividing factor to compute the ultimate load ratio was different for different angle of inclination of load and it decreased with an increase in the angle of inclination. For example, under an eccentrically inclined load with eccentricity 0.1B when the top 0.3 m (1B) thick layer was reinforced with 1% fibers, the ultimate load decreased from 39.7 kN to 34.4 kN, 34.4 kN to 31.7 kN and 31.8 kN to 29.2 kN and the ultimate load ratio changed from 5.2 to 4.9, 4.9 to 5 and 5 to 6.5 when angle of inclination increases from 0° to 5°, 5° to 10° and 10° to 15°, respectively (Figs. 5-6 and Table 2).

The model footing tests were conducted on footing resting on reinforced sand and the load applied was eccentrically inclined with an eccentricity 0.1B and 0.2B. It is clear from the results discussed in Figs. 4 and 7 that with an increase in the eccentricity of the load applied there was

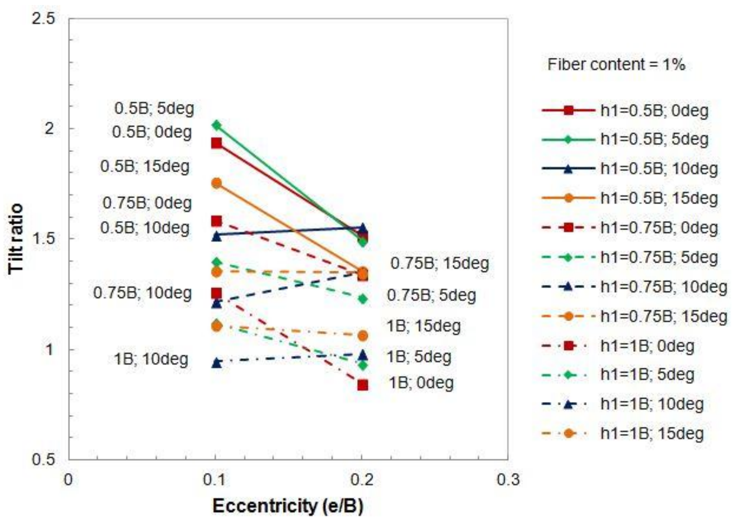

Fig. 7 Tilt ratio versus e/B

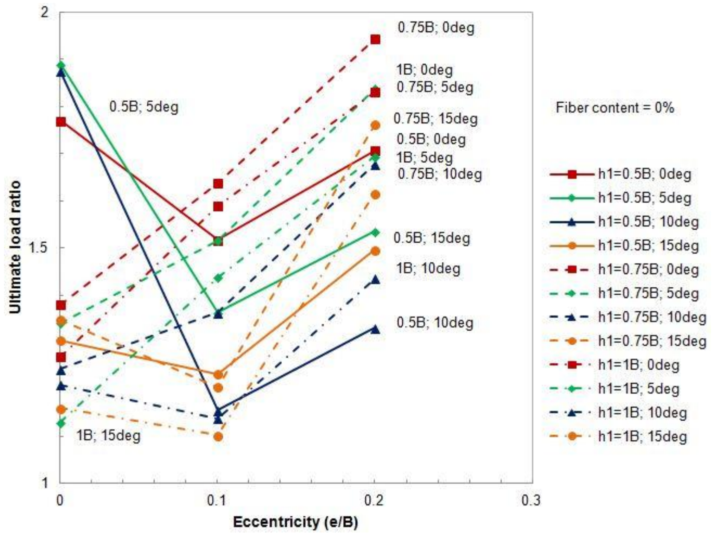

Fig. 8 Ultimate load ratio versus e/B when soil layer reinforced with only fabric sheet

increase in the value of tilt. Figs. 6 and 8 and Table 2 and 3 clearly reveal that with an increase in the eccentricity of the load applied, the ultimate load decreased but ultimate load ratio increased in some cases.

The reason behind decrease in the ultimate load ratio is that the dividing factor was different for different angles of inclinations and eccentricity values. For the comparison, the results for zero eccentricity were plotted in the figures. If the top 1B thick layer was reinforced with 1% of fibers and an eccentrically inclined load was applied at 10° to the vertical, the ultimate load decreased from 31.7 kN to 24.9 kN with increase in eccentricity from 0.1B to 0.2B but ultimate load ratio increased from 5 to 6.1 with an increase in eccentricity from 0.1B to 0.2B, respectively. Al-Samadi (1998), Manjunath and Dewaikar (1996), Mutgi *et al*. (2001), Singh (1984), Shaw (1985) observed similar trends in their investigations regarding the behavior of footings resting on reinforced sand.

3.2 Effect on vertical settlement

The vertical settlement decreased with an increase in thickness of reinforced layer, percentage of fibers, angle of inclination of load to the vertical and eccentricity of load applied. There was about 23.5% and 19.3% decrease in vertical settlement ratio when the thickness of top 1% fiber reinforced layer increased from 0.5B to 0.75B and 0.75B to 1B, respectively with 0.1B eccentricity and 10° inclination of load to the vertical (Figs. 9- 10 and Table 5).

With the increase in eccentricity from 0.1B to 0.2B, the vertical settlement ratio reduced by a factor of two in most of the cases (Fig. 10 and Table 5).

3.3 Effect on horizontal deformation

With the increase in thickness of reinforced layer, percentage of fibers and eccentricity of load applied there was decrease in horizontal deformation (and thus horizontal deformation ratio) but

Table 5 Vertical settlement ratio for 0.1B eccentricity of load

Fiber content	i = 0°			i = 5°			i = 10°			i = 15°		
	VSR at h_1/B =			VSR at h_1/B =			VSR at h_1/B =			VSR at h_1/B =		
	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0
0% (only fabric sheet)	1.1	1	0.8	1.0	0.9	0.8	1.2	1.1	0.8	1.2	1.0	0.8
0.5%	2.1	1.7	1.4	2.0	1.4	1.1	2	1.7	1.3	2.1	1.8	1.3
0.75%	1.9	1.5	1.2	1.6	1.3	1	1.9	1.5	1.2	2	1.5	1.2
1%	1.8	1.4	1.1	1.5	1.2	0.9	1.8	1.4	1.1	1.9	1.4	1.2

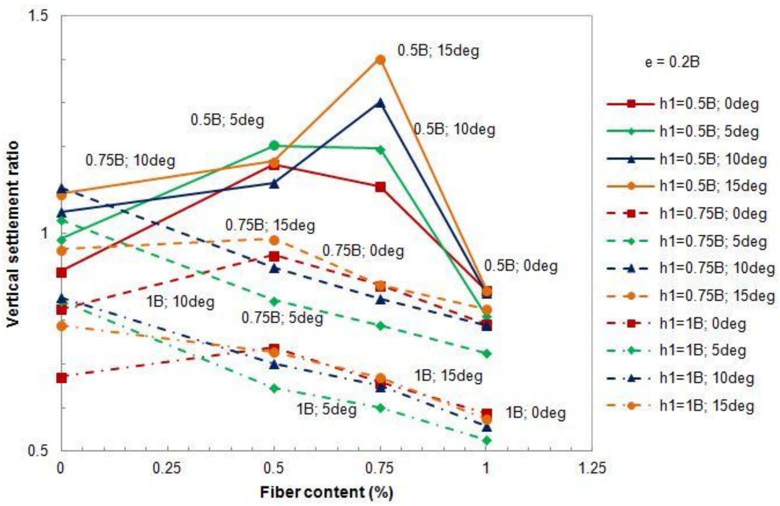

Fig. 9 Vertical Settlement ratio versus fiber content

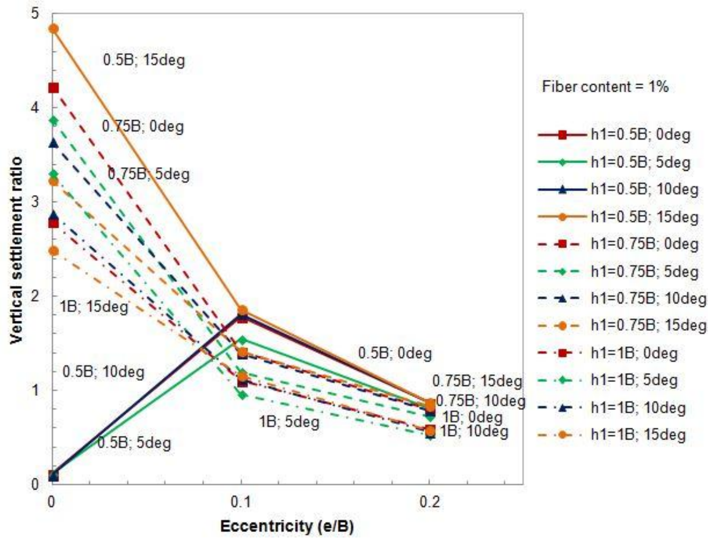

Fig. 10 Vertical Settlement ratio versus e/B

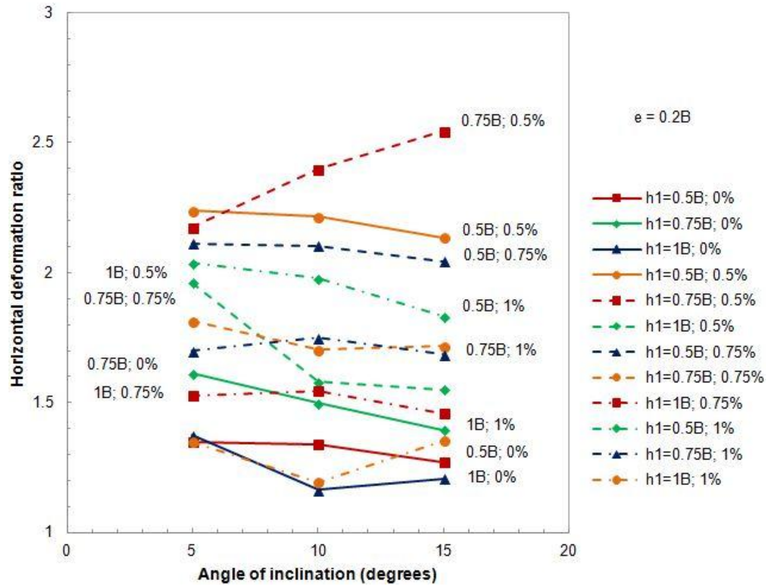

Fig. 11 Horizontal deformation ratio versus angle of inclination

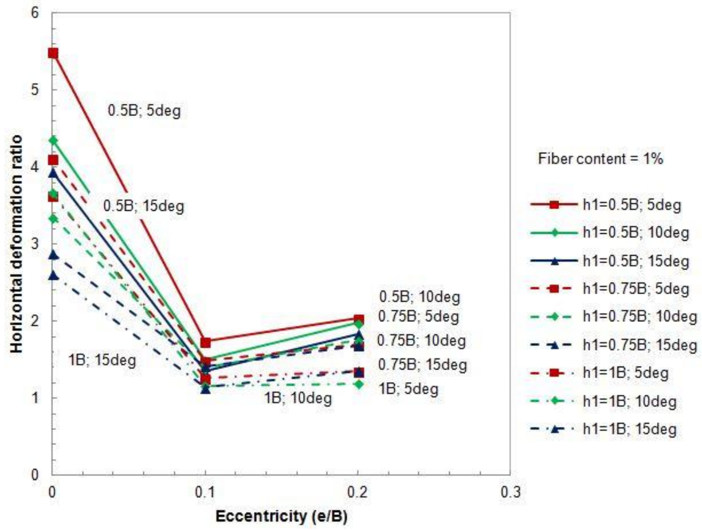

Fig. 12 Horizontal deformation ratio versus e/B

there were some cases, as shown in Table 6, where the horizontal deformation ratio increased. The reason behind this is that the dividing factor was different for different angles of inclinations and eccentricity values.

When a top reinforced layer of 1B thick and applied load inclined at 10° to the vertical and eccentricity of 0.2B, there was about a 1.58, 1.55 and 1.2 times decrease in the horizontal deformation ratio when the percentage fiber is increased to 0.5%, 0.75% and 1%, respectively, in comparison to the totally unreinforced case (Fig. 11).

The results for zero eccentricity were also plotted and it is evident that there is a remarkable decrease in horizontal deformation ratio when eccentricity is increased from 0 to 0.1B (Fig. 12).

With the increase in the angle of inclination, there was an increase in the horizontal deformation but decrease in the horizontal deformation ratio in some cases. This effect is clearly revealed in Figs. 11-12 and Table 6.

Table 6 Horizontal deformation ratio for 0.1B eccentricity of load

Fiber content	i = 5°			i = 10°			i = 15°		
	HDR at h_1/B =			HDR at h_1/B =			HDR at h_1/B =		
	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0
0% (only fabric sheet)	1.25	1.45	1.3	1.15	1.39	1.02	1.16	1.13	0.86
0.5%	1.92	1.63	1.4	1.8	1.59	1.3	1.77	1.56	1.35
0.75%	1.82	1.55	1.35	1.7	1.48	1.23	1.68	1.47	1.27
1%	1.75	1.48	1.26	1.7	1.4	1.16	1.35	1.41	1.14

Table 7 Tilt ratio for 0.1B eccentricity of load

Fiber content	i = 0°			i = 5°			i = 10°			i = 15°		
	TR at h_1/B =			TR at h_1/B =			TR at h_1/B =			TR at h_1/B =		
	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0	0.5	0.75	1.0
0% (only fabric sheet)	1.35	1.23	0.9	1.52	1.6	1.4	1.2	1.1	0.7	1.2	1	0.8
0.5%	2.26	2.19	1.4	2.26	1.92	0.9	1.8	1.48	0.7	1.7	1.4	0.9
0.75%	2.1	1.68	1.4	2.22	1.81	0.8	1.7	1.37	1	1.6	1.6	1.3
1%	1.94	1.58	1.2	2.02	1.4	1.1	1.5	1.22	0.9	1.7	1.4	1.1

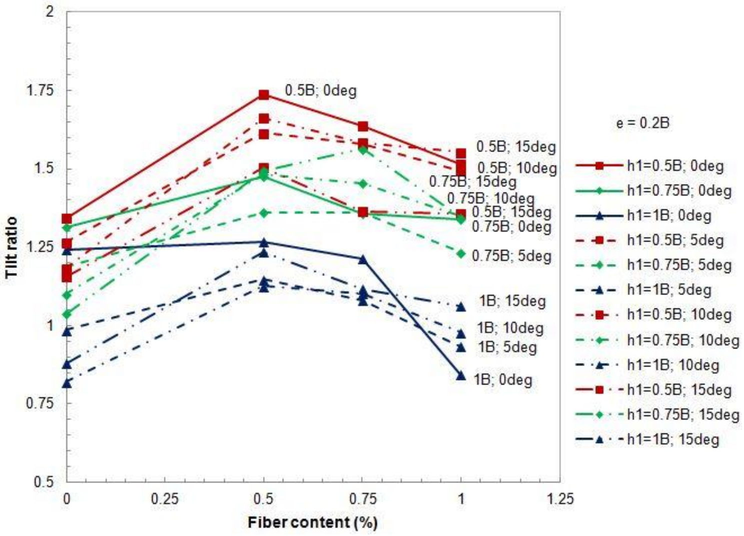

Fig. 13 Tilt ratio versus fiber content

3.4 Effect on tilt

There was a decrease in the tilt ratio with an increase in the thickness of the reinforced layer, percentage of fibers and angle of inclination of load to the vertical. The tilt ratio decreased with an increase in the thickness of the top reinforced layer and this decrease was more pronounced with an increase in the thickness of the reinforced layer from 0.75B to 1B (Figs. 7 and 13, Table 7).

With an increase in the percentage of fiber, the tilt value (and thus tilt ratio) decreased and in most of the cases this decrease was more when the fiber percentage increased from 0.75% to 1%.

Examinations of the experimental results revealed that with an increase in the eccentricity of the load applied, there was an increase in tilt value and tilt ratio, but in some cases, there was a decrease in the tilt ratio (Figs. 7 and 13, Table 7).

4. Statistical model results

A statistical model has been developed based on present experimental data for predicting the vertical settlement (s_p), horizontal deformation (hd_p) and tilt (t_p) of square footings on reinforced sand at any load applied. Multiple non-linear regression analysis was done three times where the dependent variable predicted vertical settlement (s_p), horizontal deformation (hd_p) and tilt (t_p) are calculated. The various independent variables considered for regression analysis were as follows:

(i) Settlement of square footing on unreinforced sand at any load in mm (s_u)
(ii) Horizontal deformation of square footing on unreinforced sand at any load in mm (hd_u)
(iii) Tilt of square footing on unreinforced sand at any load in mm (t_u)
(iv) Various load values in kN (l)
(v) Thickness of reinforced layer per unit width (h_1/B)
(vi) Eccentricity per unit width (e/B)
(vii) Percentage of fibers used (p_f)
(viii) Angle of inclination of load applied (i)
(ix) Bond stress angle between RDFS and plastic fabric sheet (δ_1)
(x) Bond stress angle between unreinforced sand and plastic fabric sheet (δ_2)

The equation for predicted settlement values (s_p), predicted horizontal deformation values (hd_p) and predicted tilt values (t_p) obtained is given below

$$s_p = -0.275 + \Big[0.015 * (s_u)^{0.031} * (l)^{1.3} * (2.94 - (h_1/B))^{4.53} * (e/B)^{0.27} * \big(1 - (0.717 * p_f)\big)^{0.85} * (1 - \tan(i))^{-1.66} * (1 - \tan(\delta_1))^{-0.42} * (1 - \tan(\delta_2))^{-0.018}\Big] \quad (8)$$

$$hd_p = 0.713 + \Big[0.0018 * (s_u)^{0.19} * (l)^{1.41} * (3.16 - (h_1/B))^{6.01} * (e/B)^{0.024} * \big(1 - (0.0632 * p_f)\big)^{-18.54} * (\sin(\mathrm{i}))^{0.58} * (1 - \tan(\delta_1))^{3.35} * (1 - \tan(\delta_2))^{-4.6}\Big] \quad (9)$$

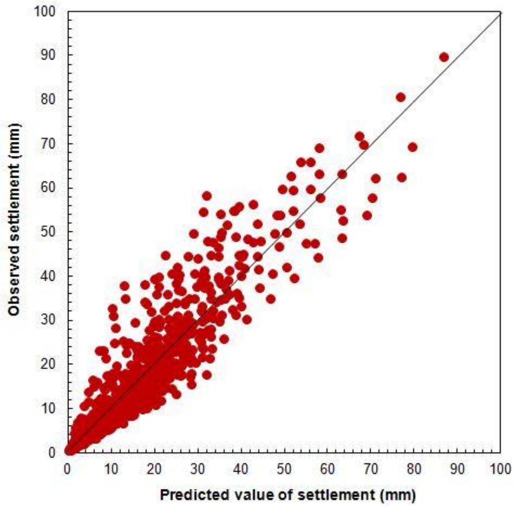

Fig. 14 Scatter diagram showing the comparison between observed and predicted values of vertical settlement

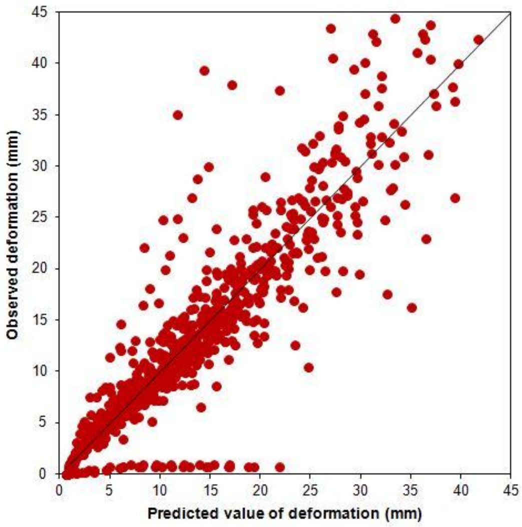

Fig. 15 Scatter diagram showing the comparison between observed and predicted values of horizontal deformation

$$t_p = 0.32 + \left[5.18 * 10^{-5} * (s_u)^{0.1} * (l)^{1.33} * (4.64 - (h_1/B))^{6.97} * (e/B)^{1.02} * \left(1 - (0.0189 * p_f)\right)^{43.24} * (1 - \tan(i))^{-1.27} * (1 - \tan(\delta_1))^{4.06} * (1 - \tan(\delta_2))^{-4.8}\right] \quad (10)$$

For Eqs. (8)-(10), the value of R^2 was found to be 0.86, 0.83 and 0.88, respectively. The scatter diagram using the Eqs. (8)-(10) is shown in Figs. 14-16 respectively, which shows that the observed and predicted values match very well.

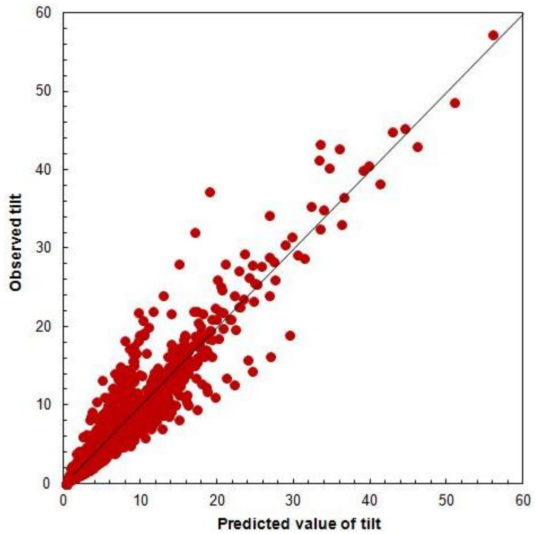

Fig. 16 Scatter diagram showing the comparison between observed and predicted values of tilt

5. Conclusions

After the analysis of 104 large scale model tests conducted under different loading conditions the following conclusions were drawn:

- The ULR increased with an increase in the thickness of the reinforced layer but the rate of increase of ultimate load was perhaps a little less between 0.75% and 1% than it was between 0.5% and 0.75%.
- With an increase in the percentage of fibers, and keeping all other parameters same, there was an improvement in terms of ULR, VSR, HDR and TR.
- The addition of fibers to soil was more effective if the fiber reinforced soil layer was separated from the unreinforced soil with a plastic fabric sheet.
- The vertical settlement ratio decreased by up to half when the eccentricity of the load applied increased from 0.1B to 0.2B and it also decreased with an increase in the thickness of the reinforced layer. This rate of decrease was more pronounced when the thickness of the reinforced sand layer was 0.75B.
- There was a remarkable decrease in the horizontal deformation ratio when the eccentricity of load applied was increased from 0 to 0.1B.
- The decrease in tilt ratio was more when the fiber reinforcement was increased from 0.75% to 1% and it also decreased with an increase in thickness of reinforced sand layer and there was much improvement in terms of tilt ratio when thickness was increased from 0.75B to 1B.
- There was a remarkable decrease in the ultimate load values with an increase in the angle of inclination from 0° to 15°. This variation depends on the thickness of the reinforced soil layer and percentage of fibers used.
- A statistical model using multiple non-linear regression analysis based on present experimental data for predicting the vertical settlement (s_p), horizontal deformation (hd_p) and tilt (t_p) of square footing shows that the observed and predicted values match very well.

5.1 Limitations

- As model tests were used to draw qualitative conclusions for various factors that were investigated, the stress levels are not the same as those for prototype foundations.
- Conclusions and equations drawn are applicable to only one type of dry soil with one density (very loose case) on which the tests were actually performed.

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CC

Nomenclature

B	Width of the footing (m)
C_c	Coefficient of curvature (dimensionless)
C_u	Coefficient of uniformity (dimensionless)
e	Eccentricity (mm)
H	Horizontal load (N)
HDR	Horizontal deformation ratio (dimensionless)
h_1	Thickness of reinforced sand bed (m)
h_2	Thickness of unreinforced sand bed (m)
hd_p	Predicted horizontal deformation (mm)
hd_u	Horizontal deformation of square footing on unreinforced sand at any load (mm)
i	Angle of inclination to the vertical (degree)
l	Various load values (kN)
p_f	Percentage of fibers used (%)
$q_{u(T)}$	Ultimate load of soil reinforced with randomly distributed fibers and plastic fabric sheet at the interface (N)
$q_{u(Only\ Sand)}$	Ultimate load of totally unreinforced soil (N)

$q_{u(Fiber)}$	Ultimate load of soil reinforced with randomly distributed fibers only (N)
RDFS	Randomly distributed fiber reinforced soil
s_u	Settlement of square footing on unreinforced sand at any load (mm)
s_p	Predicted settlement (mm)
TR	Tilt ratio (dimensionless)
t_p	Predicted tilt (radians)
t_u	Tilt of square footing on unreinforced sand at any load (mm)
ULR	Ultimate load ratio (dimensionless)
ULR (*Fiber*)	Ultimate load ratio of soil reinforced with randomly distributed fibers only (dimensionless)
ULR (*PFS*)	Ultimate load ratio of soil reinforced with plastic fabric sheet only (dimensionless)
ULR (*T*)	Ultimate load ratio of soil reinforced with randomly distributed fibers and plastic fabric sheet at the interface (dimensionless)
VSR	Vertical settlement ratio (dimensionless)
V	Vertical load (N)
V_m	Volume of mixture (m^3)
W_f	Weight of fiber (N)
W_s	Weight of sand (N)
δ_1	Bond stress angle between RDFS and plastic fabric sheet (degree)
δ_2	Bond stress angle between unreinforced sand and plastic fabric sheet (degree)
γ	Unit weight of fiber reinforced soil mixture (N/m^3)