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RESEARCH PAPER

Geotechnical Challenges in Slope Stability: Experimental Investigation of Coconut Fiber Reinforcement Under Seismic Loading

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Abstract
Geotechnical challenges in contemporary engineering necessitate the construction of structures on poor soils and vulnerable slopes due to limited land availability. The stability of soil slopes under seismic conditions is crucial for designing safe infrastructures. Conventional slope reinforcement techniques, such as geosynthetics, are effective but costly. This study explores the use of coconut fibers as a cost-effective, temporary reinforcement for improving slope stability under seismic loading. The research involved horizontal and vertical shake table tests on slopes of varying heights and angles, both with and without surcharge loads. Coconut fibers were mixed into the soil at different percentages to assess their effectiveness in reducing displacements and settlements during seismic events. Linear Variable Differential Transformers (LVDTs) measured displacements at various heights on the slopes. Results indicate that slopes reinforced with coconut fibers exhibit significantly reduced vertical and horizontal displacements compared to unreinforced slopes under both vertical and horizontal seismic loading. The reinforced slopes showed improved stability, particularly under higher surcharge loads and increased shaking frequencies. This study demonstrates that coconut fibers can serve as an effective, eco-friendly reinforcement method for temporary slope stabilization, offering a sustainable alternative to synthetic materials. The findings contribute to the broader understanding of natural fiber applications in geotechnical engineering, especially for regions prone to seismic activities.

Keywords Coconut fibres · Seismic loading · Shake table · Surcharge load · Slope stability

1 Introduction

Slopes are generally classified into two types namely naturally occurring slopes and manmade slopes (Karir et al. 2022). Natural slopes are formed by various physical processes, such as plate tectonics, and material deposition from the weathering of rock formations (Paliwal et al. 2022). Artificially made slopes are established to facilitate infrastructure projects such as embankments, earth dams and road cuttings. The loss of shear strength of the slope geomaterial causes the slope to fail. Several natural and anthropogenic factors can trigger a slope failure. Among these, seismic excitation is one of the most important factors leaving a slope vulnerable to failure (Noroozi et al. 2015; Giri et al. 2010a, b; Kumsar et al. 2000; Guo et al. 2011). Numerous landslides of different types were generated during the Chamoli earthquake in 1999, the Kashmir earthquake in 2005, the Wenchuan earthquake in 2008, the Lushan earthquake in 2013, the Ludian earthquake in 2014 and the Jiuzhaigou earthquake in 2017. Soil slope failure accounted for a large proportion of these earthquake-induced landslides. In

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addition, soil slopes are widely distributed throughout the major mountain ranges around the world. However, determining the seismic response of a soil slope remains a challenge for researchers worldwide (Fan et al. 2016; Su et al 2021; Lin et al. 2015).

Geotechnical engineers are interested in using soil reinforcement to improve slope performance, reduce deformations, and build steeper slopes in less space. Researchers have extensively investigated the static stability of reinforced soil slopes (Ray et al. 2020). During earthquakes, even stable soil slopes can collapse due to ground shaking, liquefaction, and reduced safety factors (Madhavi Latha et al. 2014; Srilatha et al. 2017; Hazari et al. 2020). Understanding how reinforcement stabilizes soil slopes during seismic shaking is crucial for designing safe slopes in seismically active zones. Researchers used experimental, field, and numerical techniques to study the response of reinforced soil slopes to seismic loading conditions. There is extensive literature available on the seismic response of reinforced soil slopes using shake table tests (Giri et al. 2010a, b; Srilatha et al. 2013; Lin et al. 2015). Grasso et al. (2005) carried out experiments in which the performances of reinforced soil slopes with overload were investigated under dynamic conditions using a shake table test in which polypropylene geogrid was used as reinforcement. It was found that the presence of a surcharge decreases the displacement and the presence of a surcharge showed two wedge failures. Wartman et al. (2005) carried out experiments on physical models to investigate the permanent deformations which were seismically induced in slopes and to evaluate the accuracy and applicability of the Newmark sliding block procedure. It was found that the permanent deformations were induced due to the strong vibrations, the deformation being larger near the

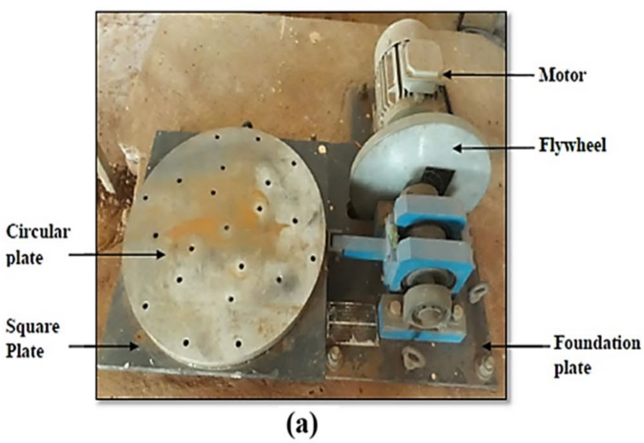


Fig. 1 Shake Tables (**a**) Horizontal, and (**b**) Vertical shake table

Fig. 2 Particle Size Distribution Curve

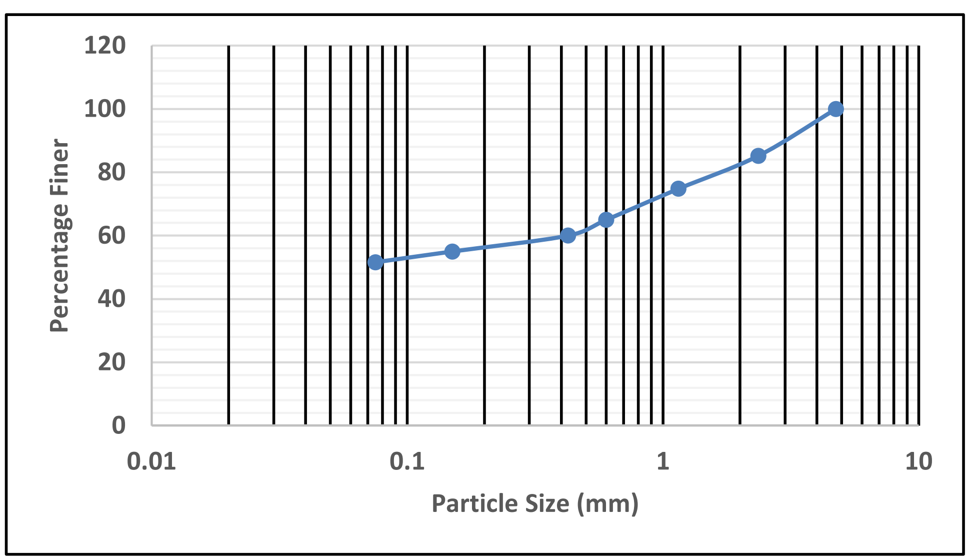


Table 1 Properties of soil

Particulars	Notations	Results	IS Codes
Specific Gravity	Gs	2.54	IS 2720- Part III
Percentage of Gravel	–	14.8%	IS 2720- Part IV
Percentage of Sand	–	33.6%	IS 2720- Part IV
Percentage of fine (silt and clay)	–	51.6%	IS 2720- Part IV
Liquid Limit	W_L	37%	IS 2720- Part V
Plastic Limit	Wp	20.13%	IS 2720- Part V
Plasticity Index	Ip	17.87%	-
Natural Water content	w	15.76%	IS 2720- Part II
Field Density	γ_d	14.22 kN/m^3	IS 2720- Part II
Cohesion (Without Fibres)	C	13.72 kN/m^2	IS 2720- Part XIII
Angle of Internal Friction (Without Fibres)	ϕ	30^0	IS 2720- Part XIII
Cohesion (With Fibres)	C	33.80 kN/m^2	IS 2720- Part XIII
Angle of Internal Friction (With Fibres)	ϕ	38^0	IS 2720- Part XIII
Type of Soil	CI	Clay with intermediate plasticity	–

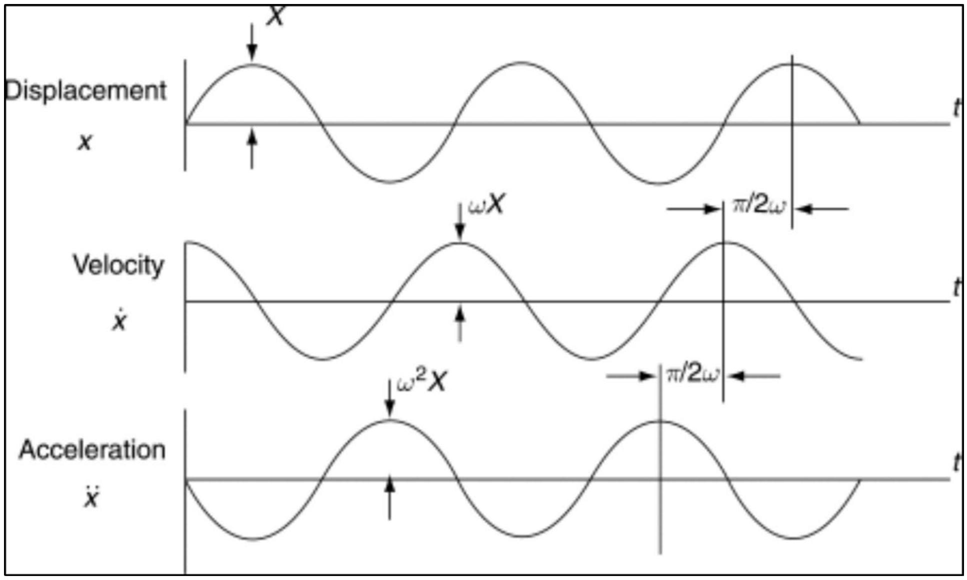
Table 2 Properties of Coconut Fibres (Source: Panarese et al 1991)

Properties	Values
Diameter	0.004–0.016 (inches)
Specific Gravity	1.12–1.15
Tensile Strength (MPa)	120–200
Elastic Modulus (MPa)	19000–25000
Strain at Failure (%)	10–25

toe. Madhavi Latha et al. (2016) carried out experiments to investigate the effect of reinforcement type and quantity on the behaviour of model slopes under a seismic loading condition in which the biaxial geogrid and geotextile were used as reinforcement. The study showed that the reinforced slopes performed better than unreinforced slopes and geotextile reinforcement gave better stability than that of geogrids. Srilatha et al. (2017) conducted experiments to study the effect of slope angle on the dynamic behaviour of unreinforced slope and reinforced slope with geogrids using shake table tests. The results showed that there was an increase in acceleration, amplification factor and displacement with the increase in angle of slope and displacement decreased by the addition of geogrids. Edinçliler and Toksoy (2017) studied the behaviour of embankment reinforced with geotextile using the shake table test. It was concluded that an increase in frequency level increases the horizontal displacements and geotextile application plays an important role in reducing the displacement and settlement. Wang et al. (2020) utilized a combination of large-scale shake table tests and 3D finite element numerical simulations to assess the seismic stability of high steep loess slopes under the combined effects of building and seismic loads. Su et al. (2021) carried out a large-scale shaking table test with a 1:15 scale to distinguish the seismic response of slopes with different natural densities. Bao et al. (2021) investigated the dynamic response and failure mechanism of slope subjected to near-fault ground motion using shake table tests. Mathane et al. (2022) carried out shake table tests which provide a 1-D constant state of motion to examine the stability of soil slopes under seismic loading.

In the past, researchers have carried out works on slope models of different heights and angles subjected to different frequencies. To study the dynamic response of reinforced slope models, various geo-synthetics like geogrids, geomembrane, and geotextile are used as reinforcement in these studies. However, very limited studies were carried out on slope reinforced using natural fibres and their percentage addition as reinforcement. Also research on the seismic behaviour of a laboratory scale slope under varying surcharge loads is rarely available. Therefore, this work tends to study the seismic behaviour of a natural fibre-reinforced slope by using shaking table tests on soil slopes reinforced with coconut fibres under varying surcharge loads to understand the influence of frequency of base shaking, geometry of the slope and reinforcement on the behaviour of the slope subjected to dynamic loading by assessing the displacement and settlement.

Fig. 3 Illustration of Sinusoidal Vibratory load (Source: Thorby 2008)



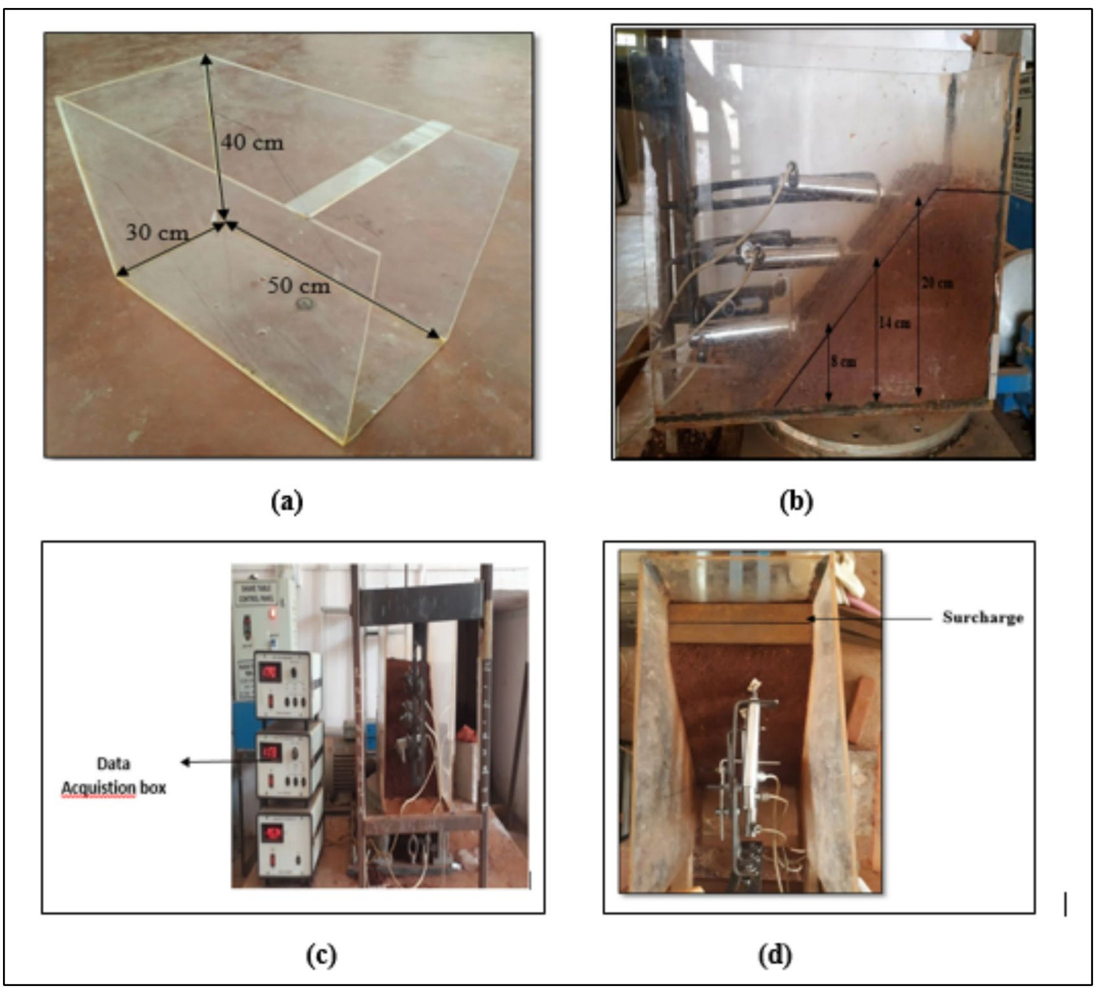


Fig. 4 Experimental setup (**a**) Model Box, (**b**) Slope model showing the position of LVDT (**c**) Front View of slope model with Data Acquisition Box and (**d**) Top View of slope with surcharge.

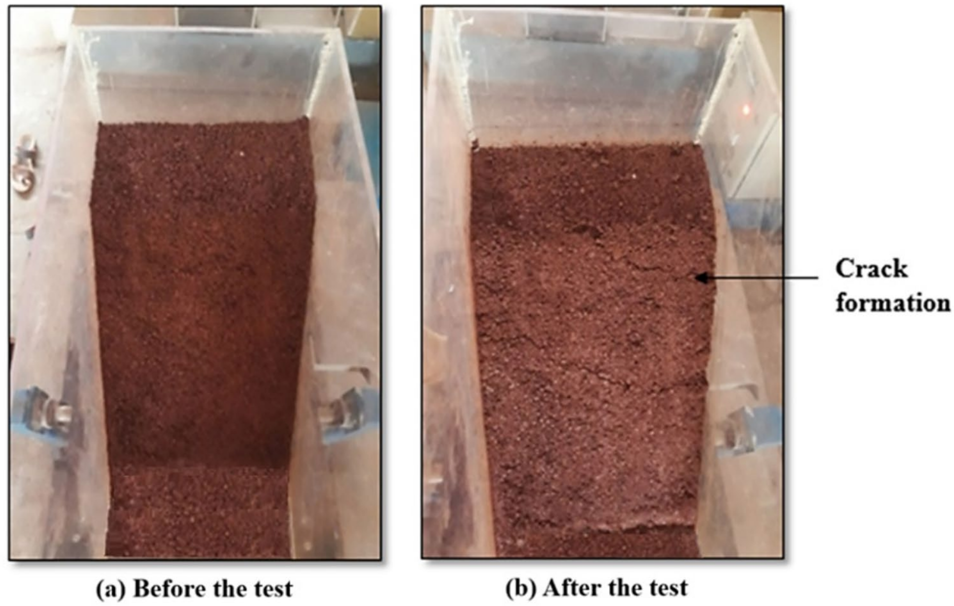


Fig. 5 Picture showing the slope model in horizontal shake table

2 Instrumentation and Materials

2.1 Shake Table

A shake table is used to test the resistance of structure and embankment slopes to seismic shaking. This instrument can generate the vibrations of the desired frequency and amplitude as that is produced during an earthquake in one direction i.e. unidirectional. In the present study, horizontal and vertical shake table is used. The shake table square plate has a dimension of 400 mm x 400 mm. The circular plate with an angular scale is mounted on the square plate. This circular plate has drilled holes in it which are used to fix the various experimental model boxes. The shake table is driven by a motor. This motor is connected to the control panel which controls the input frequency and amplitude. The horizontal shake table has a payload capacity of 50 kg and the vertical shake table has a payload capacity of 80 kg. The maximum operating frequency and amplitude are 25 Hz and 10 mm respectively. Figure 1 shows the horizontal and vertical shake table used in the study.

2.2 Linear Displacement Measurement

Linear Variable Differential Transformers (LVDTs) of $\pm$ 12 mm run are used to measure the displacement of

Table 3 Test results of slope 25 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
25	40	0	3	24	7.20	8.23	10.32	4320
			4	20	8.80	9.80	11.80	4800
			5	17	9.10	10.24	12.84	5100
		10	3	22	8.50	9.50	11.48	3960
			4	20	9.00	10.27	12.18	4800
			5	18	10.27	11.87	13.57	5400
		20	3	16	9.20	10.37	12.56	2880
			4	15	9.48	11.28	13.70	3600
			5	14	11.02	12.58	14.69	4200
		30	3	15	10.27	11.65	13.57	2700
			4	13	11.26	12.37	14.29	3120
			5	11	12.48	13.57	15.28	3300

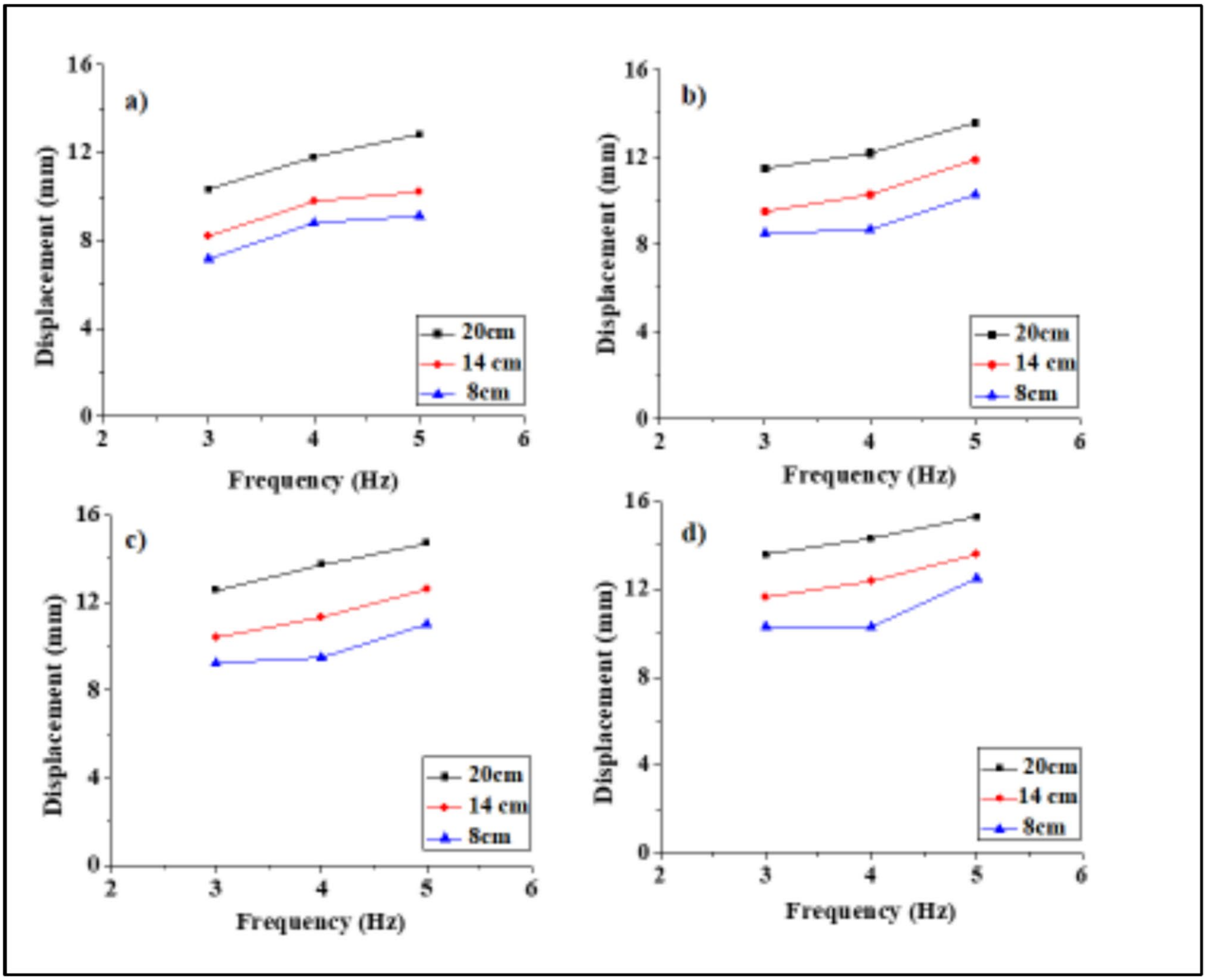


Fig. 6 Variation of displacement with a horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of a slope of 25 cm height and 40° slope angle (**a**) without surcharge and with surcharge load of (**b**)10N, (**c**) 20N, and (**d**) 30N

Table 4 Test results of slope 25 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
25	45	0	3	28	8.08	9.26	11.50	5040
			4	26	9.23	10.52	12.38	6240
			5	22	10.10	11.37	13.61	6600
		10	3	26	9.20	10.49	12.80	4680
			4	24	10.10	11.27	13.49	5760
			5	20	11.25	12.67	14.57	6000
		20	3	23	10.59	11.57	13.75	4140
			4	21	11.27	12.38	14.37	5040
			5	19	12.07	13.24	15.57	5700
		30	3	20	11.28	12.62	14.95	3600
			4	18	12.22	13.29	15.28	4320
			5	16	13.08	14.52	16.68	4800

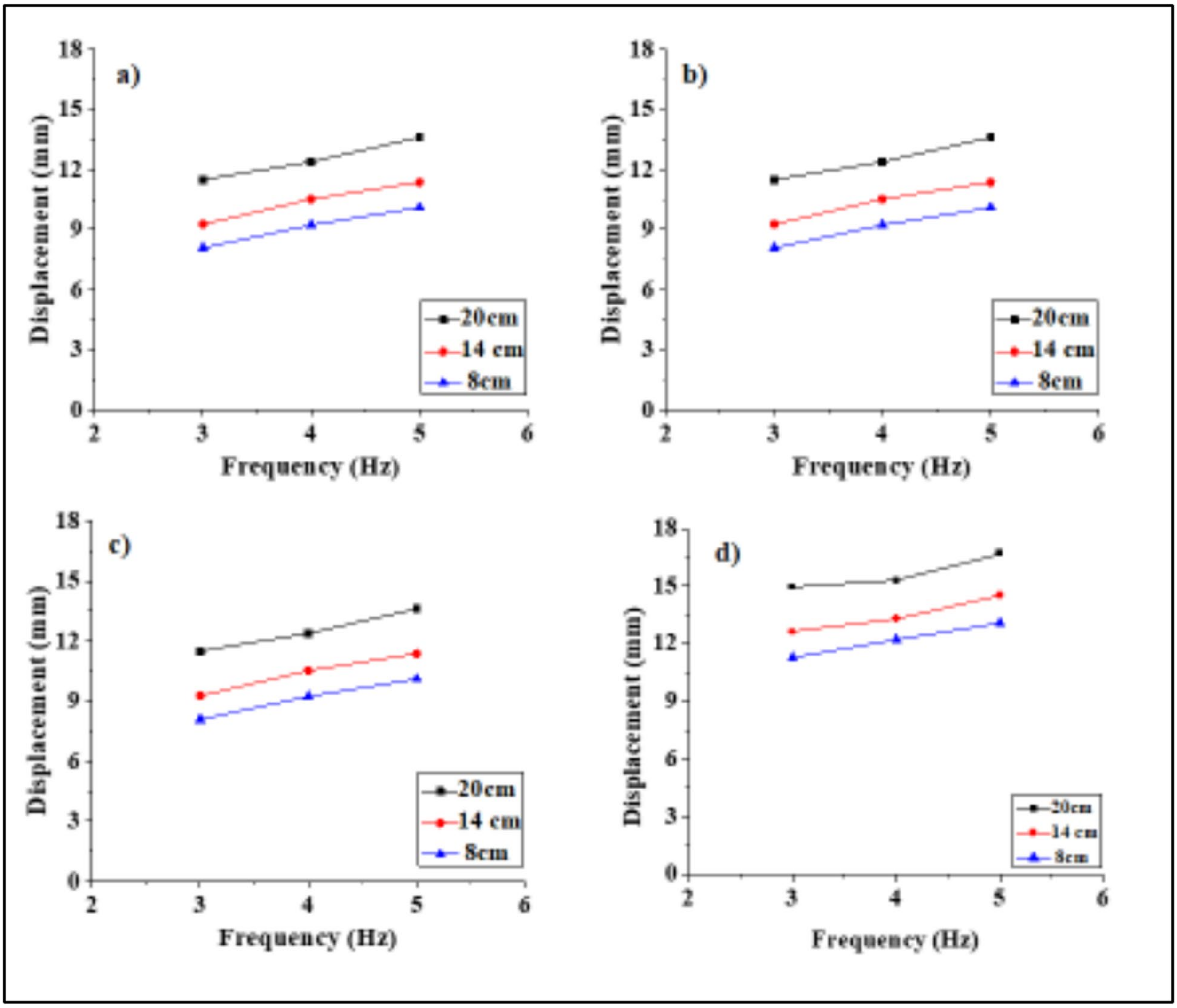


Fig. 7 Variation of displacement with a horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of a slope of 25 cm height and 45° slope angle (**a**) without surcharge and with surcharge load of (**b**)10N, (**c**) 20N, and (**d**) 30N

Table 5 Test results of slope 27 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
27	40	0	3	27	9.758	10.62	12.72	4860
			4	25	10.68	11.75	13.31	6000
			5	22	11.25	12.26	14.42	6600
		10	3	25	10.28	11.29	13.28	4500
			4	23	12.05	13.33	14.66	5520
			5	21	12.08	13.68	15.87	6300
		20	3	23	11.22	12.28	14.25	4140
			4	21	12.05	14.33	15.66	5040
			5	18	13.05	15.28	16.80	5400
		30	3	21	12.08	13.56	15.08	3780
			4	19	13.09	14.55	16.08	4560
			5	17	14.01	16.23	17.54	5100

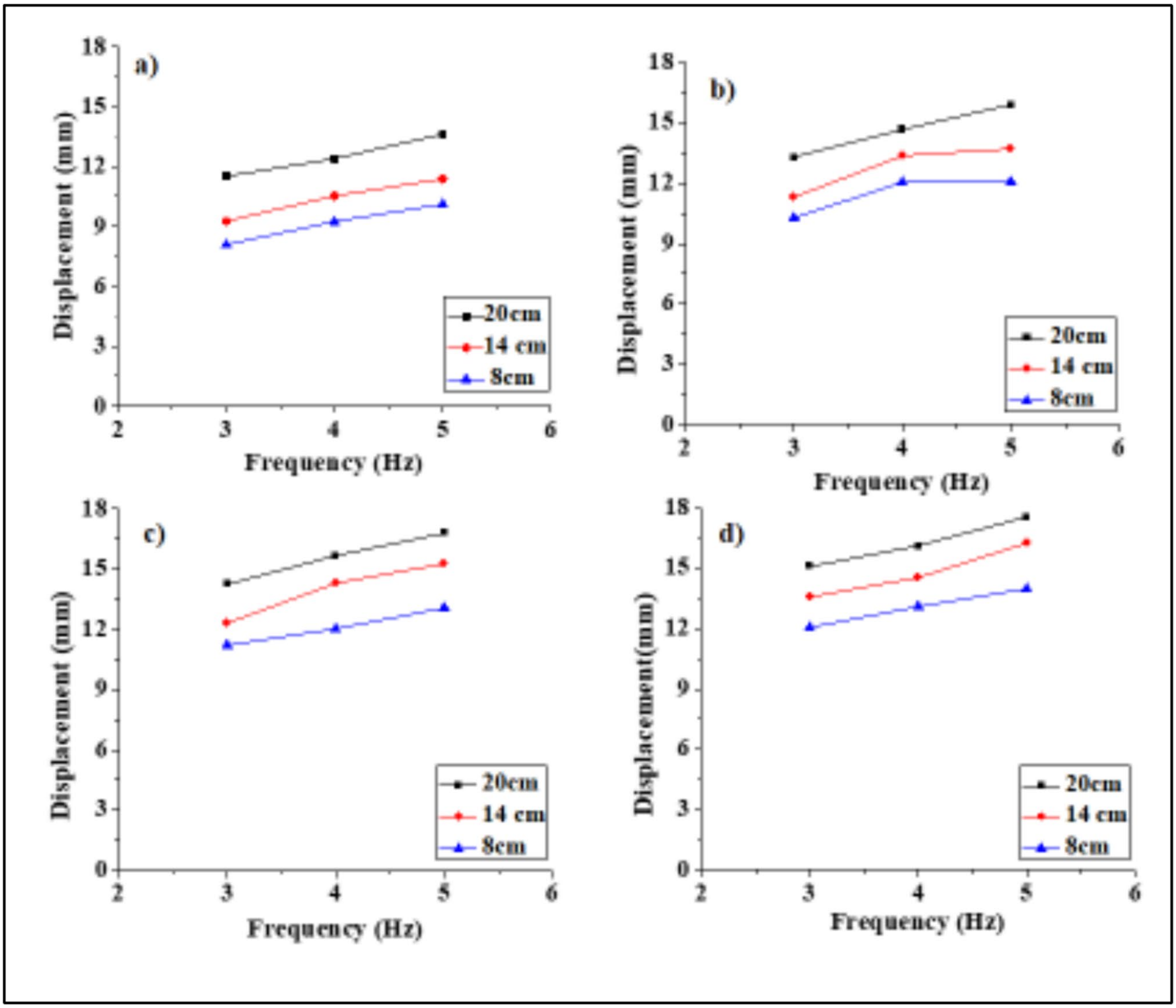


Fig. 8 Variation of displacement with a horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of a slope of 27 cm height and 40° slope angle (**a**) without surcharge and with surcharge load of (**b**)10N, (**c**) 20N, and (**d**) 30N

slope models when subjected to horizontal and vertical shaking. In this experimental study, three LVDTs are used, placed on the slope surface at a height of 8 cm, 14 cm and 20 cm from the toe of the slope. These LVDTs are connected to a data logger which records and displays the displacements.

2.3 Soil

The soil used for the development of model slopes in this experimental study is collected from the Eastern Ghat mountain range of Tirupathur District, Tamil Nadu, India. Various tests are conducted on the soil to determine the different basic properties of soil as per the Indian Standard Code (IS) -2720. The Particle Size Distribution Curve is given in

Table 6 Test results of slope 27 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
27	45	0	3	32	10.72	11.92	13.50	5760
			4	28	11.08	12.45	14.28	6720
			5	25	12.08	13.68	15.87	7500
		10	3	27	11.89	12.96	14.97	4860
			4	25	12.09	13.57	15.35	6000
			5	24	13.08	14.75	16.92	7200
		20	3	24	12.73	13.98	15.99	4320
			4	22	13.21	14.66	16.47	5280
			5	20	14.02	15.78	17.52	6000
		30	3	21	13.08	14.97	16.98	3780
			4	19	14.02	15.78	17.54	4560
			5	17	15.02	16.87	18.66	5100

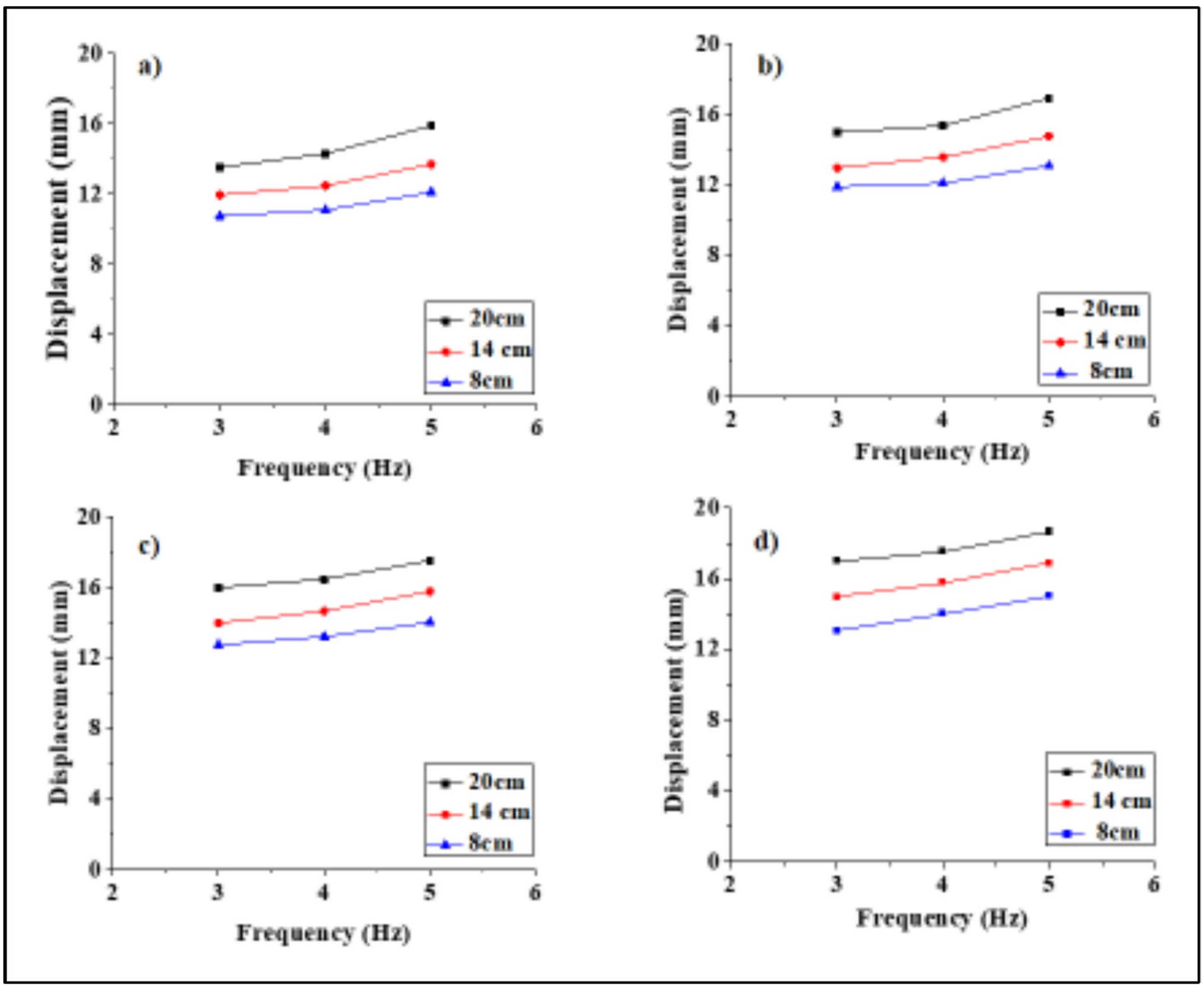


Fig. 9 Variation of displacement with a horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of a slope of 27 cm height and 45° slope angle (**a**) without surcharge and with surcharge load of (**b**)10N, (**c**) 20N, and (**d**) 30N

Table 7 Test results of slope 30 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
30	40	0	3	31	11.28	12.57	14.85	5580
			4	28	12.08	13.58	15.95	6720
			5	24	13.30	14.57	16.08	7200
		10	3	29	12.35	13.64	15.85	5220
			4	26	13.09	14.67	16.85	6240
			5	25	15.27	16.87	18.80	7500
		20	3	27	13.27	14.28	16.58	4860
			4	25	14.39	15.57	17.69	6000
			5	23	16.02	18.02	19.02	6900
		30	3	27	14.51	15.26	17.25	4860
			4	24	15.29	16.68	18.66	5760
			5	21	16.42	18.67	19.57	6300

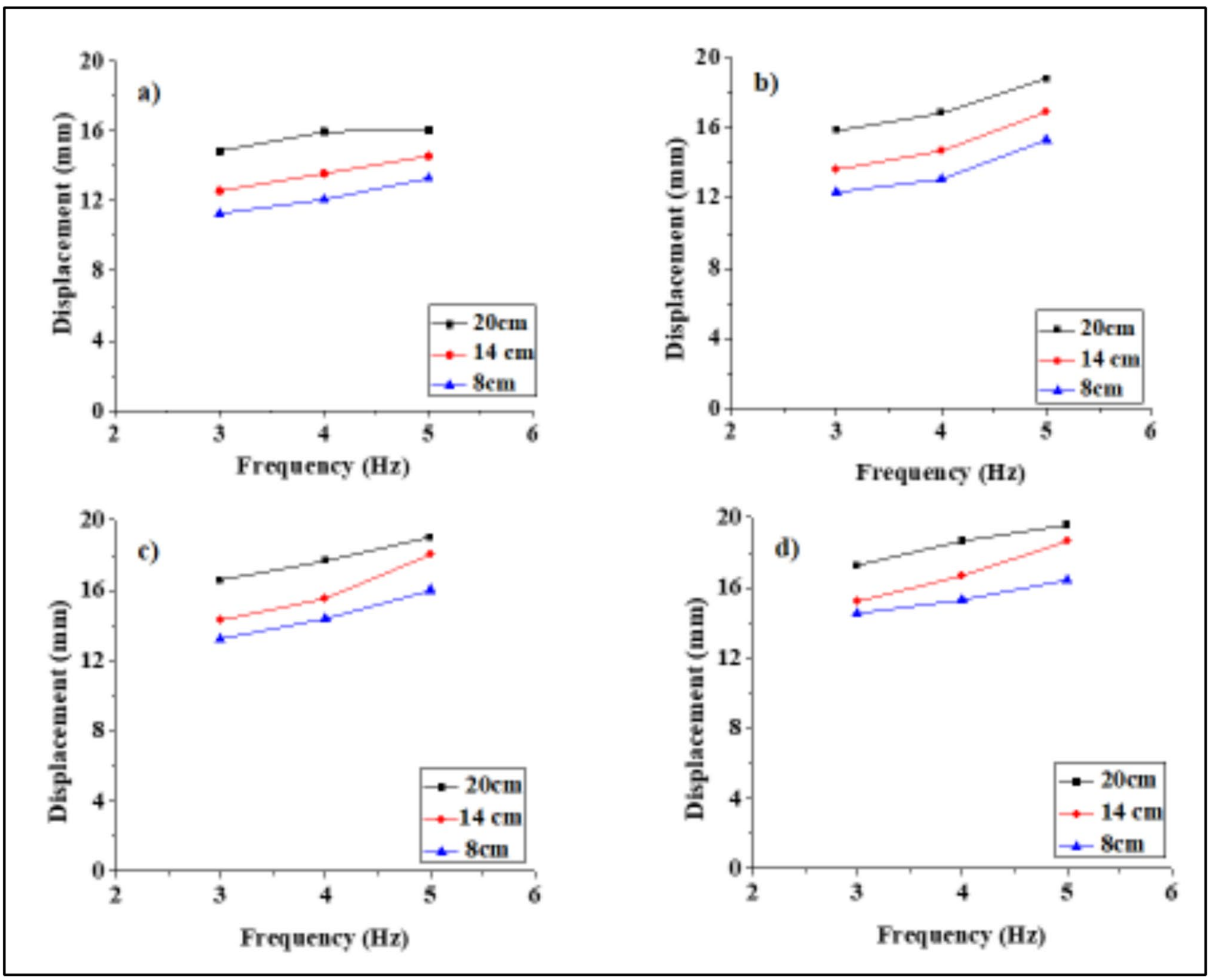


Fig. 10 Variation of displacement with a horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of a slope of 30 cm height and 40° slope angle (**a**) without surcharge and with surcharge load of (**b**)10N, (**c**) 20N, and (**d**) 30N

Table 8 Test results of slope 27 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
30	45	0	3	34	12.58	13.87	15.76	6120
			4	30	13.08	14.28	16.70	7200
			5	27	14.28	15.82	17.80	8100
		10	3	31	13.05	14.26	16.22	5580
			4	28	14.02	15.23	17.85	6720
			5	25	15.75	16.94	18.76	7500
		20	3	29	13.02	15.02	17.25	5220
			4	26	15.09	16.52	18.92	6240
			5	23	16.98	17.58	19.67	6900
		30	3	27	14.05	16.25	18.26	4860
			4	25	16.08	17.98	19.95	6000
			5	22	17.28	18.52	20.27	6600

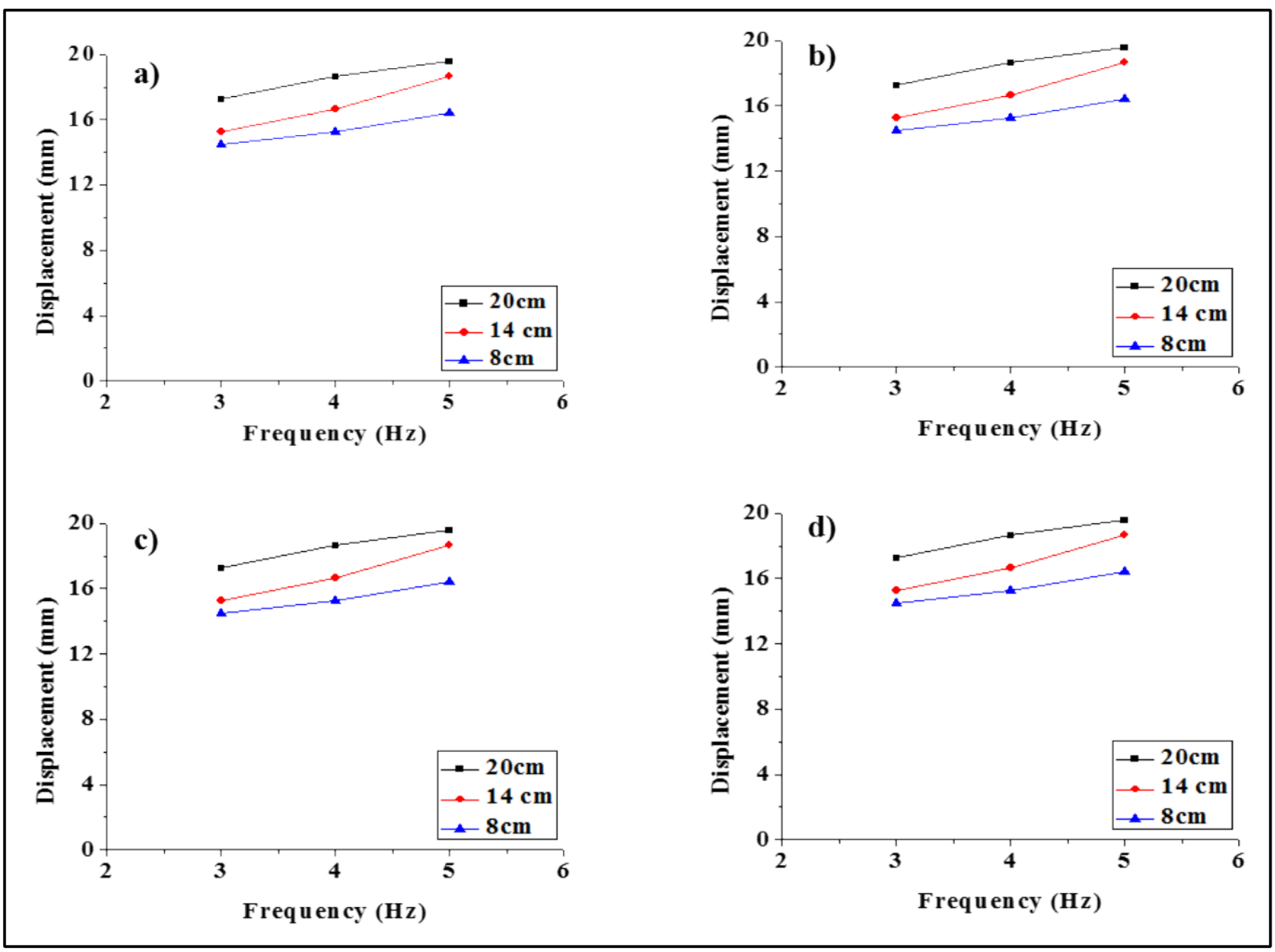


Fig. 11 Variation of displacement with a horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of a slope of 30 cm height and 45° slope angle (**a**) without surcharge and with surcharge load of (**b**)10N, (**c**) 20N, and (**d**) 30N

Table 9 Test results of slope 25 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm)			No. of cycles
					8 cm	14 cm	20 cm	
25	40	0	3	35	5.13	5.90	7.36	6300
			4	33	6.24	6.95	8.37	7920
			5	30	6.45	7.26	9.10	9000
		10	3	39	4.87	5.60	6.99	7020
			4	36	5.93	6.60	7.95	8640
			5	34	6.13	6.89	8.65	10200
		20	3	43	4.35	5.02	6.26	7740
			4	40	5.31	5.89	7.12	9600
			5	37	5.48	6.17	7.76	11100
		30	3	47	4.08	4.69	5.86	8460
			4	44	4.96	5.50	6.67	10560
			5	41	5.14	5.77	7.02	12300

Table 10 Test results of slope 25 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm)			No. of cycles
					8 cm	14 cm	20 cm	
25	40	0	3	45	3.86	4.63	5.65	8100
			4	42	4.18	5.23	6.21	10080
			5	38	4.30	5.60	6.45	11400
		10	3	49	3.27	3.91	4.78	8820
			4	46	3.52	4.41	5.47	11040
			5	44	3.54	5.25	6.41	13200
		20	3	53	2.89	3.46	4.21	9540
			4	49	2.93	3.90	4.92	11760
			5	46	3.19	4.64	5.68	13800
		30	3	55	1.98	2.99	3.61	9900
			4	52	2.50	3.33	4.18	12480
			5	56	2.72	3.97	4.83	16800

Fig. 2. The results obtained from basic tests are briefed in Table 1.

2.4 Reinforcement

Coconut fibres as reinforcement are used in this study. Coconut fibres are natural fibres that are pulled out from the hard-core shell of coconut seed. The coconut fibres being organic material are vulnerable to deterioration due to microbial activities and pest attacks. There are some physical and chemical treatment methods such as washing and boiling, alkaline treatment with sodium hydroxide, potassium hydroxide and calcium hydroxide and acidic treatment with acetic acid. In alkali treatment, the alkali chemicals are mixed with distilled water in a certain percentage and the fibres are submerged in the solution for 5 to 6 h. After the treatment, the fibres are washed and dried (Shoeb et al. 2024). These fibres are available in lengths of 10 cm to 30 cm. For the experimental purpose of enabling

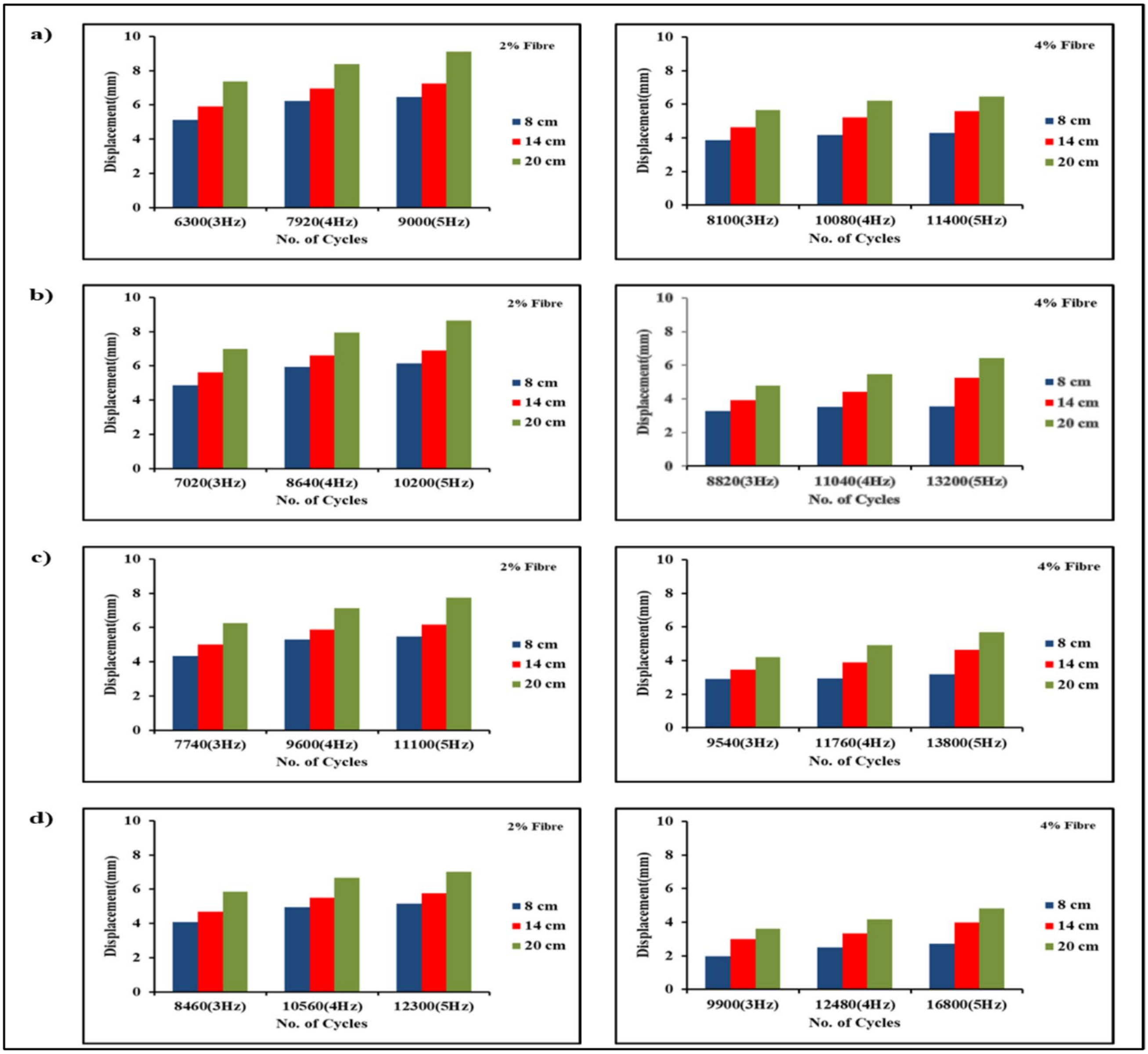


Fig. 12 Variation of displacement with No. of cycles and horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 25 cm height and 40° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge load

random distribution of fibres and easy mixing, these fibres are trimmed to the length of 2.5 cm to 3 cm and mixed in the soil with varying percentages. The properties of coconut fibre are given in Table 2.

2.5 Steel Plates Used as Surcharge Load

The steel plates of 24.5 cm in length 3 cm in width and 0.9 cm thick, each weighing 5N (500 g) are used to act as surcharge load on the top of the slope in this study (Fig. 2). The steel plates are placed on the top surface of the soil slope varying from 10 to 30N.

Table 11 Test results of slope 25 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
25	45	0	3	38	5.71	6.55	8.16	6840
			4	35	6.52	7.43	9.62	8400
			5	32	7.62	8.03	10.85	9600
		10	3	42	5.42	6.22	7.75	7560
			4	37	6.19	7.05	8.05	8880
			5	34	7.20	7.62	9.14	10200
		20	3	45	4.61	5.29	6.58	8100
			4	42	5.50	6.31	7.22	10080
			5	38	6.45	6.79	8.13	11400
		30	3	49	4.54	5.21	6.21	8820
			4	46	5.19	5.93	6.95	11040
			5	43	6.32	6.40	7.67	12900

Table 12 Test results of slope 25 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
25	45	0	3	46	4.18	6.27	7.66	8280
			4	44	6.33	7.96	8.54	10560
			5	41	7.09	8.29	9.37	12300
		10	3	50	3.54	5.32	6.58	9000
			4	49	5.36	6.75	7.22	11760
			5	46	6.00	7.02	8.06	13800
		20	3	55	3.14	4.70	6.03	9900
			4	53	4.71	5.93	6.21	12720
			5	49	5.29	6.22	7.09	14700
		30	3	58	2.64	4.002	5.12	10440
			4	56	3.98	5.03	5.27	13440
			5	52	4.47	5.27	6.02	15600

3 Methodology

The model box is made of transparent acrylic fibre sheets of 6 mm thickness. It has a length of 50 cm, a width of 30 cm and a height of 40 cm. The model box is designed to fit the soil slope model of the required dimension such that the load coming on the shake table does not exceed the maximum payload capacity of a shake table. The soil slope models of height 25 cm, 27 cm, and 30 cm with slope angles of 40° and 45° are constructed by mixing soil with natural water content. The soil is placed in three layers and compacted to a required height and density. After compacting, the soil is trimmed to the required slope to achieve the slope angle accurately. In reinforced soil slope, the fibres are distributed arbitrarily with varying percentages of 2% and 4% by mass of soil and then mixed in the soil. The model slopes are subjected to the sinusoidal vibratory unidirectional motion of frequencies 3 Hz, 4 Hz, and 5 Hz with a constant amplitude of 4 mm. The illustration of sinusoidal vibratory load is shown in Fig. 3. The frequency range was selected based on the studies by Srilatha et al. (2013, 2016, 2017) and Hazari et al. (2020). Each slope is tested with a surcharge load of mass 10N, 20N and 30N.

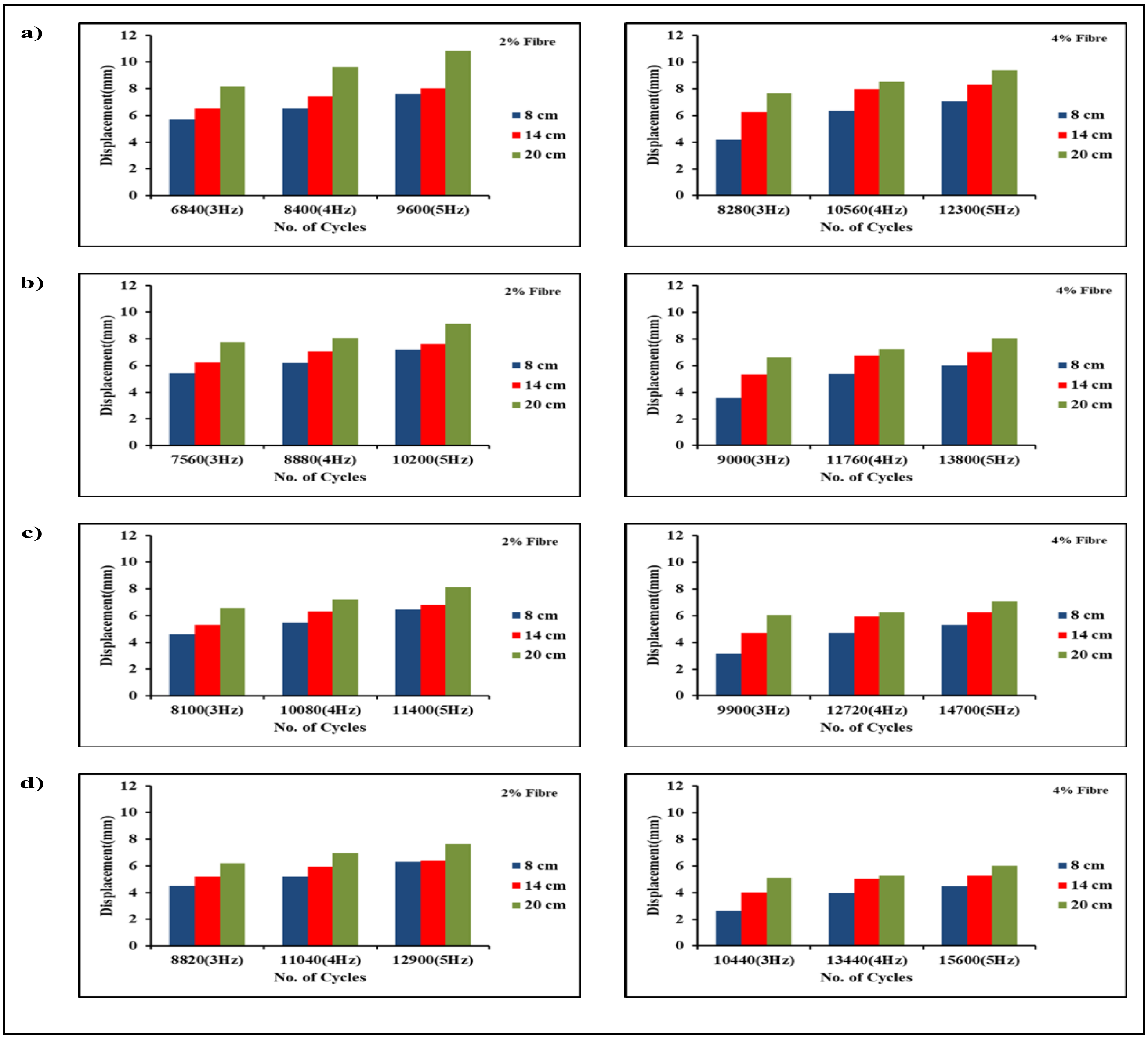


Fig. 13 Variation of displacement with No. of cycles and horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 25 cm height and 45° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge load

The model box, side view, front view and top view of the slope loaded with a surcharge of 10N of the instrumental set-up are shown in Fig. 4.

The appearance of hairline cracks on the surface of the slope is considered as the failure of the slope. Therefore, the test is terminated when the hairline cracks appear on the surface. The time against horizontal displacement of the slope is recorded by the Data Acquisition (DAQ) system till the failure. For reinforced soil slope, the fibres are mixed randomly with different percentages and the same procedure is followed as above. The response of slope is recorded in terms of displacement at different elevations and settlements. Figure 5

Table 13 Test results of slope 27 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
27	40	0	3	39	7.02	7.64	9.16	7020
			4	35	7.69	8.46	9.58	8400
			5	32	8.1	8.83	10.38	9600
		10	3	43	6.67	7.26	8.73	7740
			4	38	7.30	8.04	9.10	9120
			5	34	7.69	8.38	9.86	10200
		20	3	46	5.93	6.44	7.74	8280
			4	43	6.51	7.15	8.09	10320
			5	40	6.84	7.46	8.82	12000
		30	3	51	5.59	6.05	7.28	9180
			4	48	6.11	6.75	7.62	11520
			5	45	6.46	7.25	8.29	13500

Table 14 Test results of slope 27 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
27	40	0	3	49	4.19	5.02	6.10	8820
			4	43	4.83	5.98	7.03	10320
			5	40	6.08	7.13	8.02	12000
		10	3	53	3.55	4.02	4.93	9540
			4	47	4.03	4.86	5.96	11280
			5	43	4.93	5.98	6.78	12900
		20	3	57	3.12	3.53	4.52	10260
			4	52	3.54	4.27	5.25	12480
			5	48	4.37	5.28	6.01	14400
		30	3	62	2.54	3.00	3.96	11160
			4	58	2.99	3.60	4.44	13920
			5	54	3.68	4.46	5.08	16200

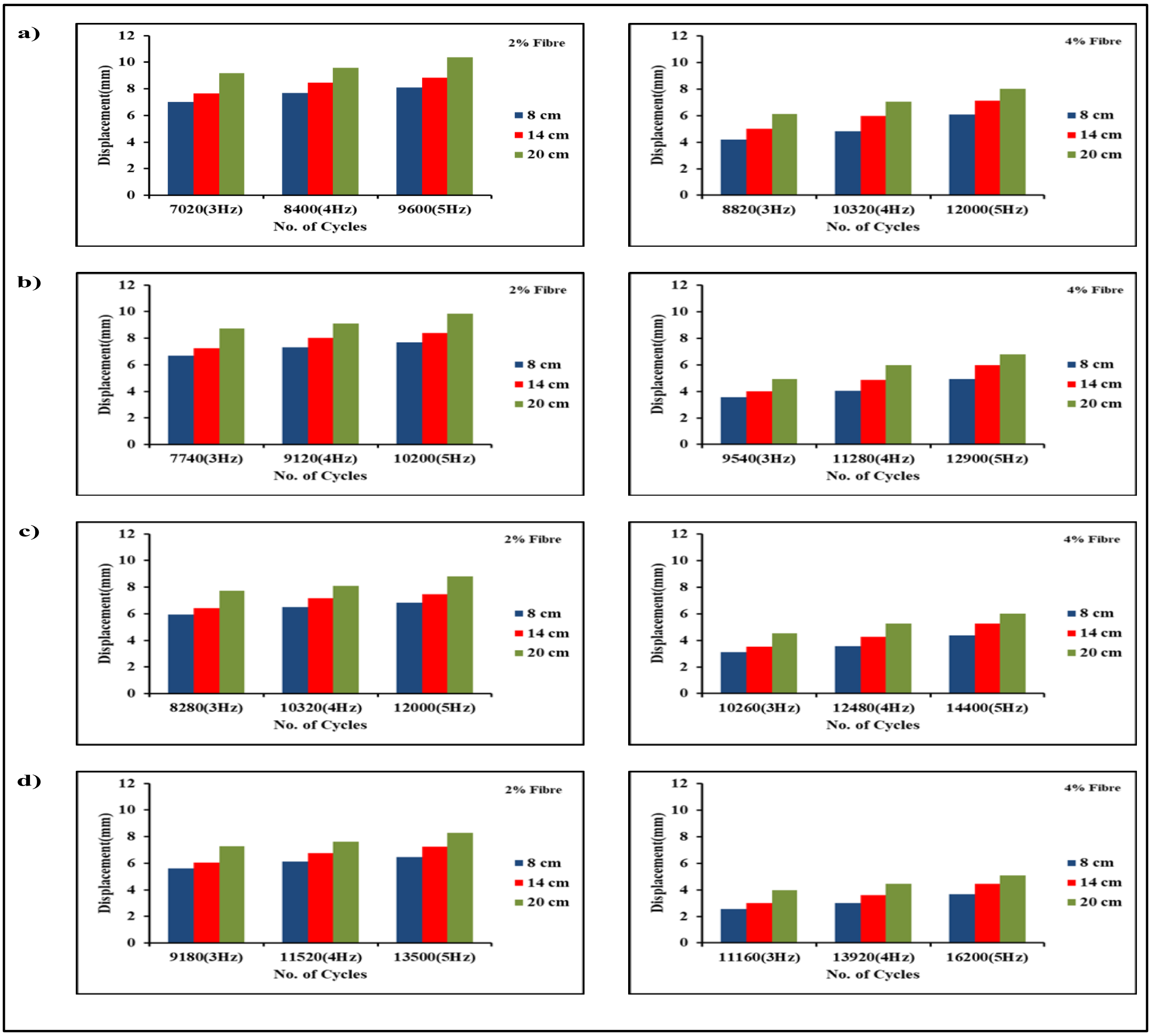


Fig. 14 Variation of displacement with No. of cycles and horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 27 cm height and 40° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge load

Table 15 Test results of slope 27 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
27	45	0	3	44	7.72	8.58	9.72	7920
			4	40	7.97	8.96	10.28	9600
			5	37	8.69	9.84	11.83	11100
		10	3	48	7.33	8.151	9.23	8640
			4	45	7.57	8.51	10.07	10800
			5	43	8.25	9.35	11.23	12900
		20	3	51	6.54	7.27	8.219	9180
			4	47	6.74	7.59	8.71	11280
			5	44	7.36	8.31	9.99	13200
		30	3	56	6.07	6.82	7.76	10080
			4	53	6.34	7.13	8.15	12720
			5	49	6.99	7.92	9.47	14700

Table 16 Test results of slope 27 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
27	45	0	3	52	4.97	5.51	6.99	9360
			4	45	5.84	6.92	8.06	10800
			5	43	7.36	8.03	9.01	12900
		10	3	54	3.85	4.65	5.92	9720
			4	49	4.95	5.85	6.79	11760
			5	46	5.91	6.78	7.62	13800
		20	3	59	3.41	4.12	5.24	10620
			4	55	4.35	5.16	6.02	13200
			5	53	4.52	5.96	7.42	15900
		30	3	64	2.89	3.47	4.42	11520
			4	60	3.66	4.33	5.09	14400
			5	58	3.81	5.00	6.27	17400

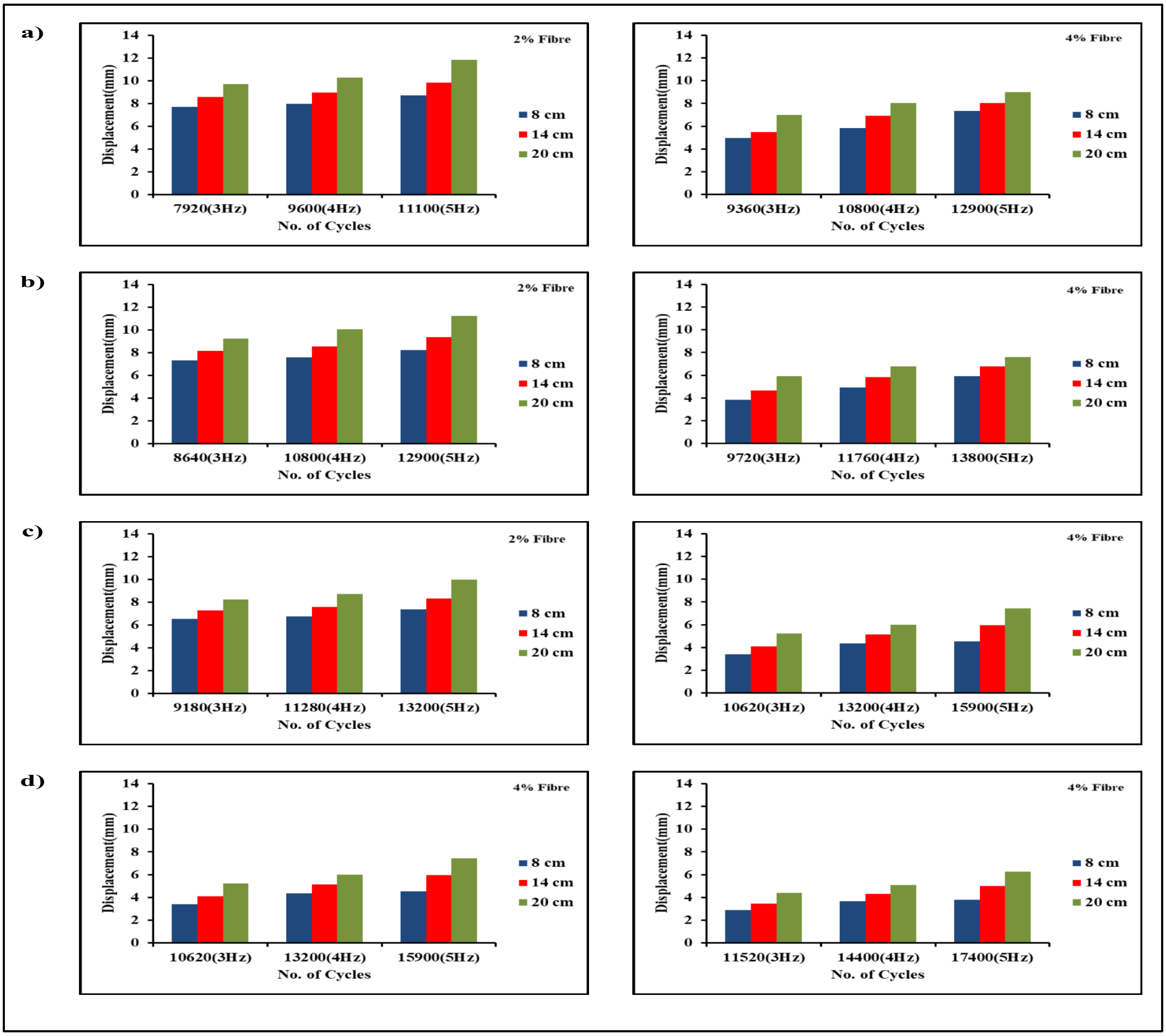


Fig. 15 Variation of displacement with No. of cycles and horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 27 cm height and 45° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge load

Table 17 Test results of slope 30 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm) at			No. of cycles
					8 cm	14 cm	20 cm	
30	40	0	3	45	8.12	9.05	10.69	8100
			4	42	8.69	9.77	11.48	10080
			5	40	9.57	10.49	12.57	12000
		10	3	50	7.71	8.59	10.15	9000
			4	47	8.25	9.28	10.90	11280
			5	45	9.10	9.96	11.94	13500
		20	3	53	6.88	7.67	9.02	9540
			4	48	7.29	8.22	9.67	11520
			5	46	8.09	9.56	10.64	13800
		30	3	57	6.47	8.2	8.50	10260
			4	53	6.92	8.65	9.13	12720
			5	48	7.64	9.02	9.97	14400

Table 18 Test results of slope 30 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm)			No. of cycles
					8 cm	14 cm	20 cm	
30	40	0	3	54	5.17	6.2	7.36	9720
			4	48	6.17	7.3	8.92	11520
			5	43	7.21	8.85	9.98	12900
		10	3	58	4.35	5.22	6.21	10440
			4	52	5.21	6.16	7.54	12480
			5	47	6.09	7.48	8.43	14100
		20	3	63	3.81	4.59	5.5	11340
			4	57	4.59	5.44	6.67	13680
			5	52	5.37	6.58	7.46	15600
		30	3	67	3.22	3.85	4.65	12060
			4	62	3.87	4.57	5.64	14880
			5	56	4.19	5.63	6.26	16800

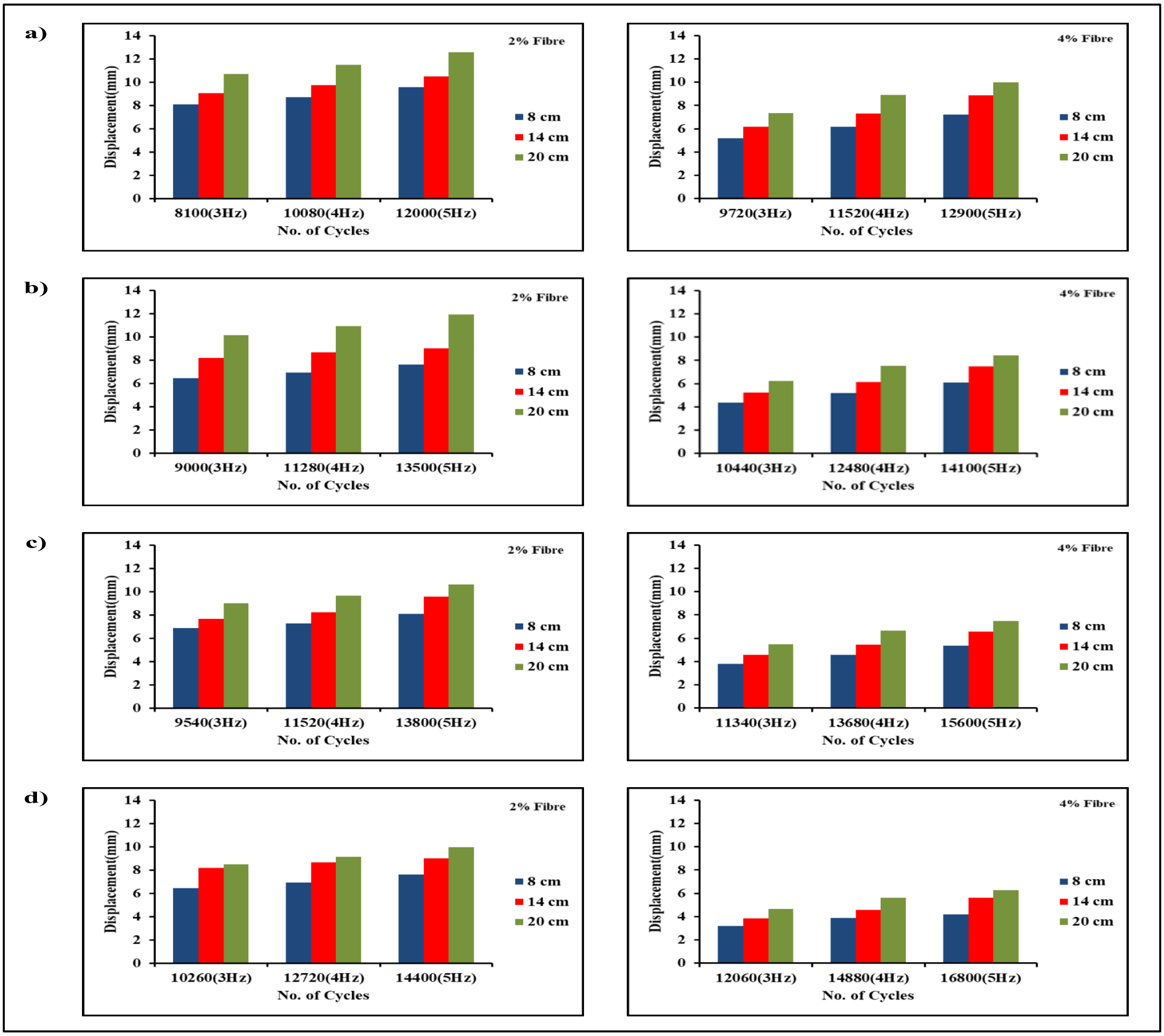


Fig. 16 Variation of displacement with No. of cycles and horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 30 cm height and 40° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge load

Table 19 Test results of slope 30 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (kg)	Frequency (Hz)	Time (min)	Displacement (mm)			No. of cycles
					8 cm	14 cm	20 cm	
30	45	0	3	48	11.34	9.98	9.05	8640
			4	45	12.02	10.28	9.41	10800
			5	42	12.81	11.39	10.28	12600
		10	3	52	10.79	9.5	8.62	9360
			4	49	11.42	9.79	8.95	11760
			5	46	12.21	10.85	9.78	13800
		20	3	56	9.68	8.44	7.65	10080
			4	53	10.18	8.69	7.97	12720
			5	50	10.83	9.60	8.72	15000
		30	3	61	9.03	7.94	7.21	10980
			4	58	9.55	8.19	7.92	13920
			5	55	8.03	7.16	6.03	16500

Table 20 Test results of slope 30 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a horizontal frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (min)	Displacement (mm)			No. of cycles
					8 cm	14 cm	20 cm	
30	45	0	3	55	6.03	7.20	8.55	9900
			4	52	7.16	8.16	9.32	12480
			5	49	8.17	9.34	10.29	14700
		10	3	60	5.08	6.14	7.20	10800
			4	56	6.05	6.89	7.90	13440
			5	53	6.94	7.89	8.70	15900
		20	3	64	4.45	5.39	6.37	11520
			4	58	5.29	6.03	6.92	13920
			5	55	6.05	6.93	7.57	16500
		30	3	70	3.817	4.63	5.48	12600
			4	65	4.56	5.16	6.00	15600
			5	62	5.18	5.99	6.57	18600

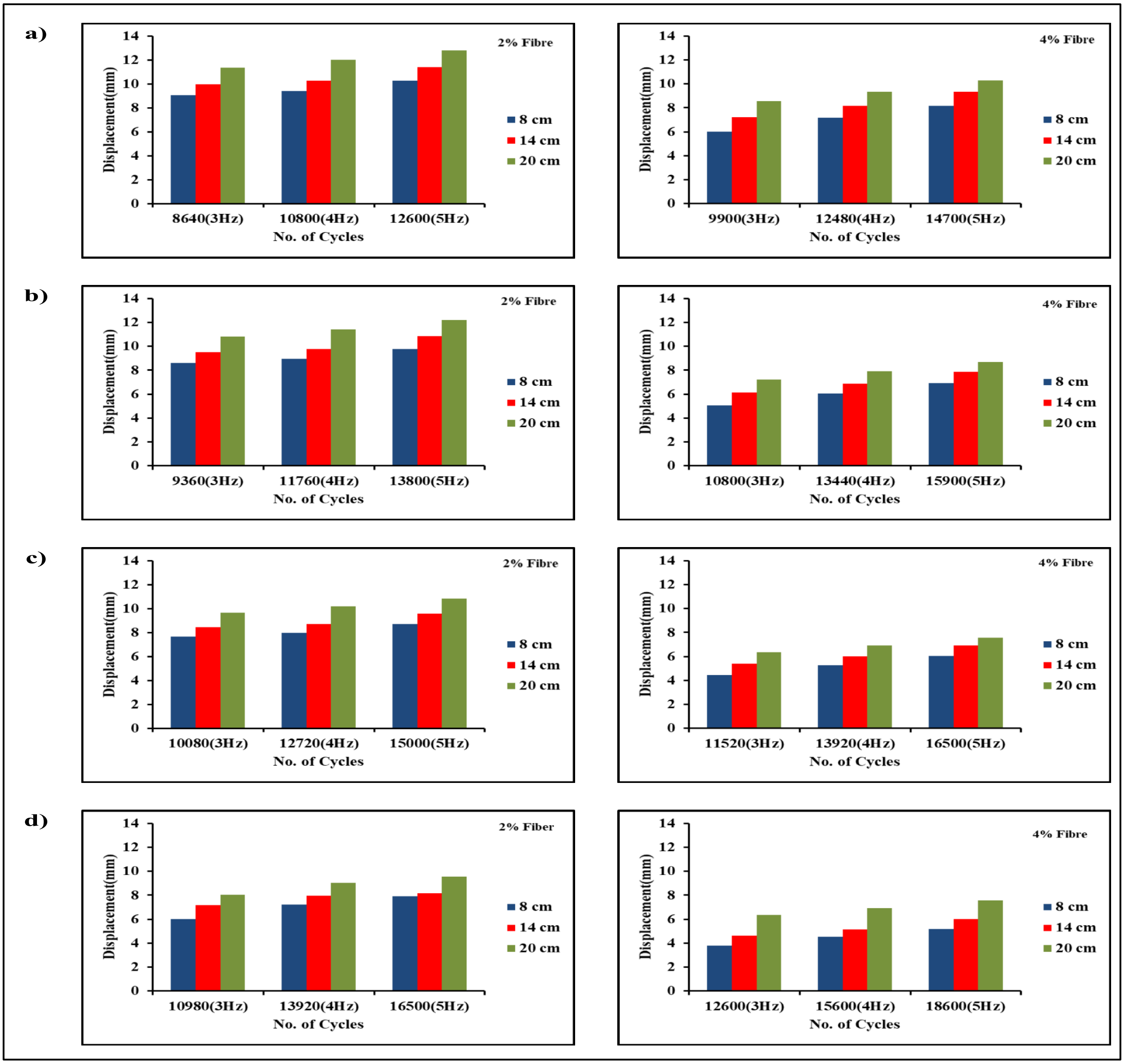


Fig. 17 Variation of displacement with No. of cycles and horizontal frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 30 cm height and 45° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge load

Table 21 Test results of slope 27 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
27	40	0	3	35	26	21	15	25	105
			4	27	30	25	19	31	108
			5	24	33	26	23	36	120
		10	3	29	29	23	17	30	87
			4	23	33	27	22	35	92
			5	19	35	28	25	42	95
		20	3	25	32	25	19	32	75
			4	20	35	30	23	37	80
			5	17	37	31	27	44	85
		30	3	22	35	25	18	33	66
			4	17	36	31	25	38	68
			5	14	39	32	29	46	70

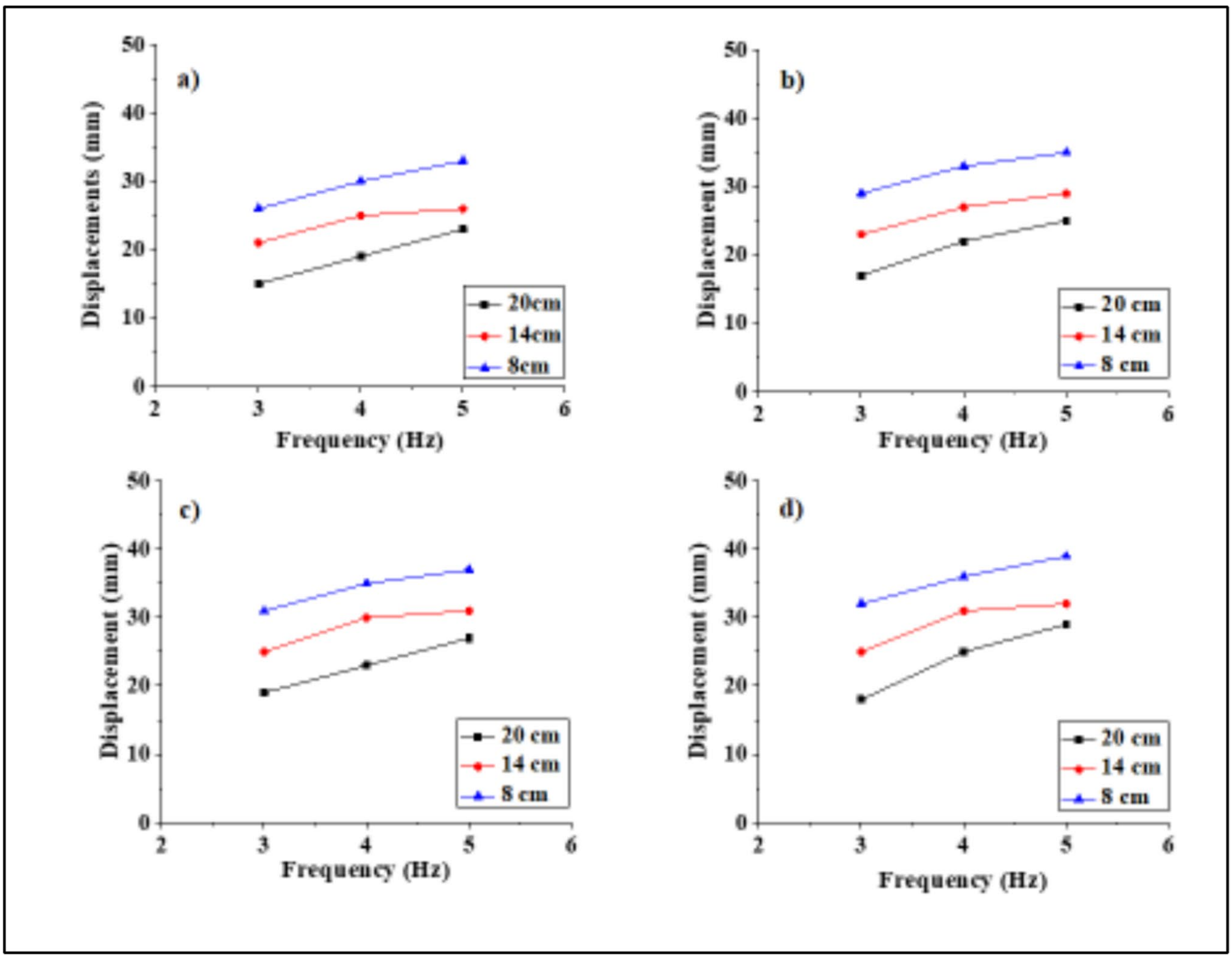


Fig. 18 Variation of displacement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of slope 27 cm height and slope angle of 40° (**a**) without surcharge load and with surcharge load of mass (**b**) 10N, (**c**) 20N, and (**d**) 30N

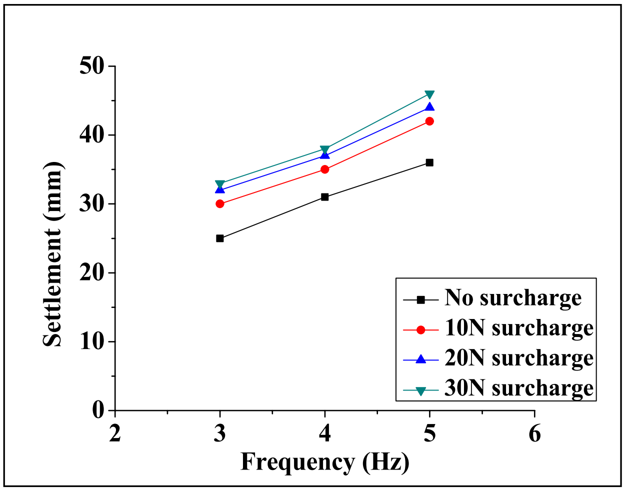


Fig. 19 Variation of settlement with vertical frequency of 3 Hz, 4 Hz and 5 Hz of slope 27 cm height and slope angle of 40° with surcharge load of mass 10N, 20N and 30N

shows the slope before and after (at failure) subjecting to horizontal shaking respectively.

4 Results

4.1 Seismic Response of Unreinforced Slope Using Horizontal Shake Table Test

The slopes of varying height and angle with surcharge loads are subjected to horizontal shaking of frequency 3 Hz, 4 Hz and 5 Hz and a constant amplitude of 4 mm. The time taken for the failure of the slope is recorded and the number of cycles is evaluated for each test. Table 3 shows the results that are obtained from testing the slope model of height 25 cm and angle 40° subjected to frequencies of 3 Hz, 4 Hz and 5 Hz with a constant amplitude of 4 mm. The model slope is tested without surcharge and

Table 22 Test results of slope 27 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
27	45	0	3	37	29	26	21	22	111
			4	29	33	29	25	29	116
			5	24	37	35	31	34	120
		10	3	30	33	28	25	26	90
			4	25	36	31	27	32	100
			5	23	38	36	33	38	115
		20	3	27	34	29	27	28	81
			4	22	38	33	30	34	88
			5	20	41	36	35	39	100
		30	3	25	35	31	30	29	75
			4	20	38	35	31	35	80
			5	18	43	38	36	40	90

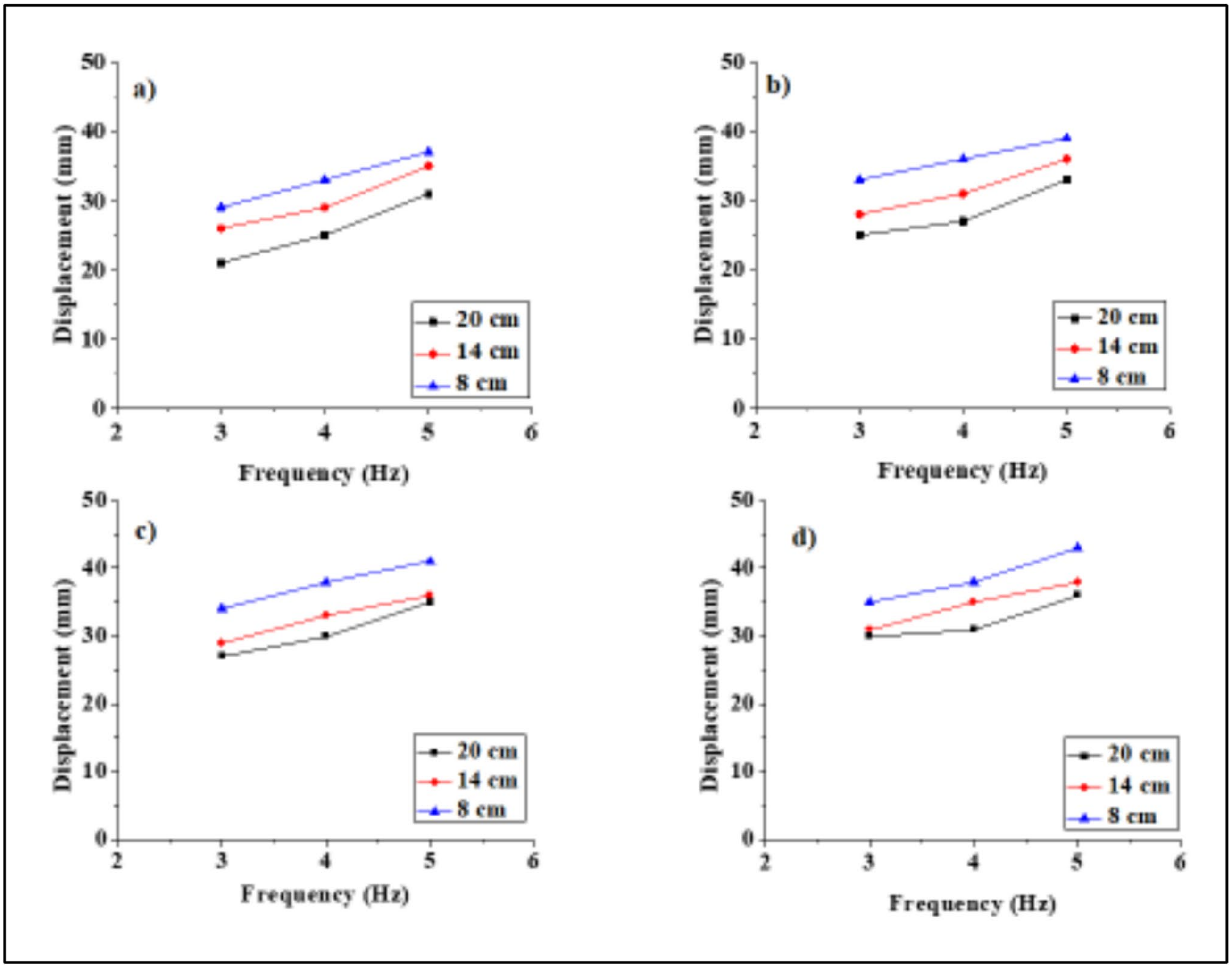


Fig. 20 Variation of displacement with the vertical frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the bottom of slope 27 cm height and slope angle of 45° (**a**) without surcharge load and with surcharge load of mass (**b**)10N, (**c**) 20N, and (**d**) 30N

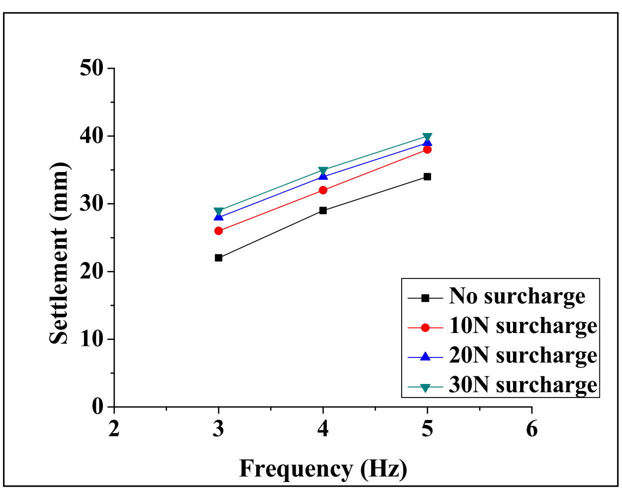


Fig. 21 Variation of settlement with vertical frequency of 3 Hz, 4 Hz and 5 Hz of slope 27 cm height and slope angle of 45° with surcharge load of mass 10N, 20N and 30N

Table 23 Test results of slope 30 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
30	40	0	3	40	21	16	11	23	120
			4	31	25	21	17	25	124
			5	26	28	24	20	33	130
		10	3	33	23	18	12	25	99
			4	27	27	23	20	27	108
			5	25	30	26	22	34	125
		20	3	30	24	20	14	26	90
			4	24	30	25	22	28	96
			5	21	32	27	24	36	105
		30	3	27	26	22	16	28	81
			4	23	31	28	22	30	92
			5	19	33	29	25	38	95

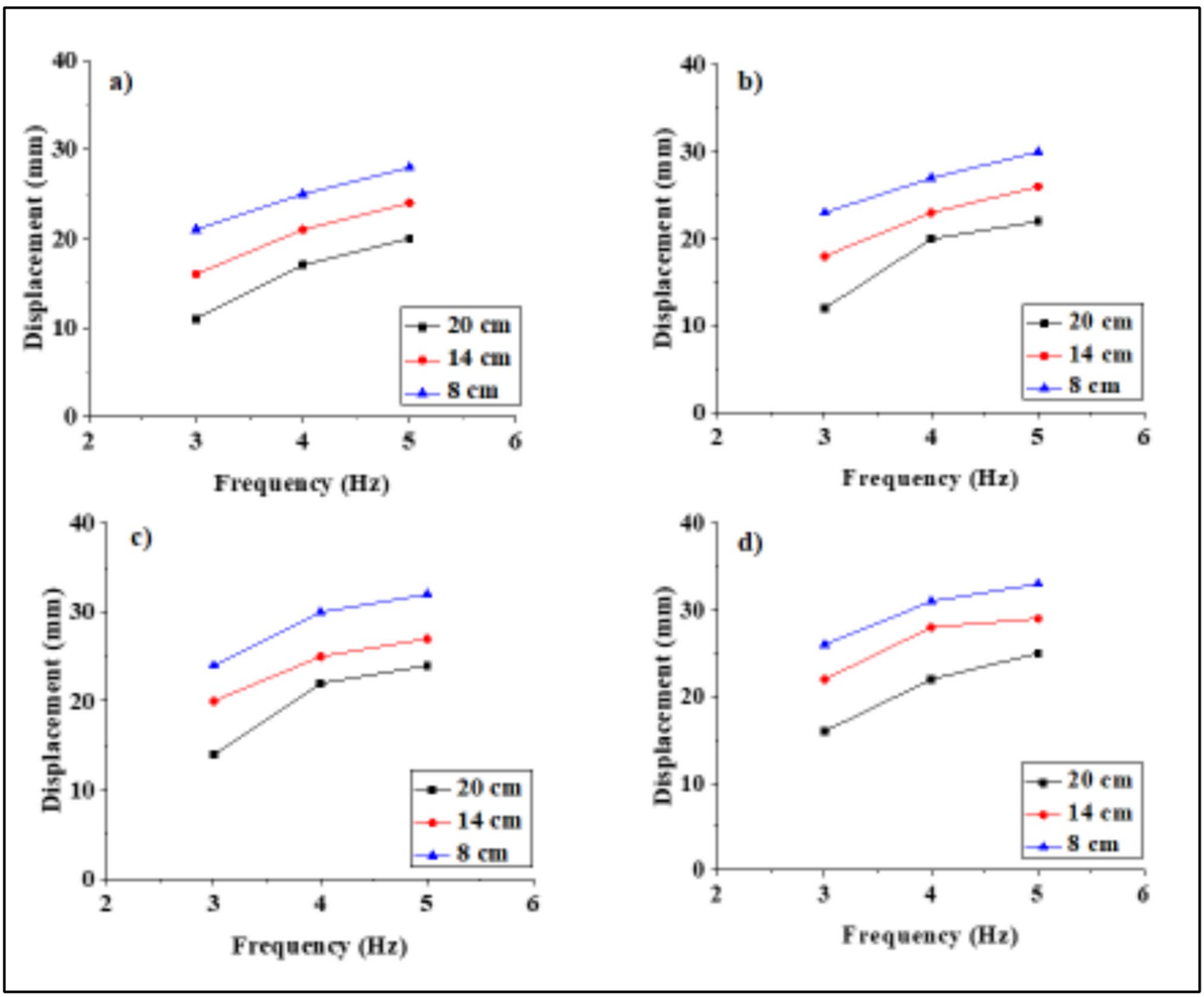


Fig. 22 Variation of displacement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of slope 30 cm height and slope angle of 40° (**a**) without surcharge load and with a surcharge of mass (**b**)10 N, (**c**) 20N, and (**d**) 30N

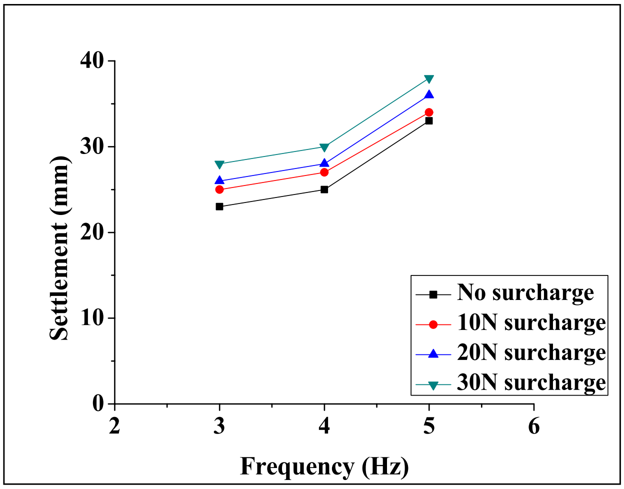


Fig. 23 Variation of settlement with vertical frequency of 3 Hz, 4 Hz and 5 Hz of slope 30 cm height and slope angle of 40° with surcharge load of mass 10N, 20N and 30N

with a surcharge load of mass 10N, 20N and 30N. The variation of displacement with the time is recorded. The variation of displacement with the frequency of slope without surcharge and with surcharges is given in Fig. 6. Similarly, the horizontal response of unreinforced slopes of height 25 cm and angle 45°; 27 cm and angle 40°; 27 cm and angle 45°; 30 cm and angle 40°; and 30 cm and angle 45° is given in Table 4 and Fig. 7; Table 5 and Fig. 8; Table 6 and Fig. 9; Table 7 and Fig. 10; and Table 8 and Fig. 11 respectively.

4.2 Seismic Response of Reinforced Slope Using Horizontal Shake Table Test

The slope of height 25 cm and angle of 40° is reinforced with coconut fibres of 2% and 4% is subjected to frequencies of 3 Hz, 4 Hz and 5 Hz at constant amplitude of 4 mm. The slope is tested without surcharge and with a surcharge load of mass 10N, 20N and 30N. The displacements are measured at heights of 8 cm, 14 cm and 20 cm from the toe

Table 24 Test results of slope 30 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
30	45	0	3	47	24	20	16	20	141
			4	38	29	25	21	24	152
			5	30	34	30	26	28	150
		10	3	40	26	22	18	22	120
			4	32	31	27	23	24	128
			5	27	36	32	28	31	135
		20	3	33	28	23	20	23	99
			4	26	33	30	25	25	104
			5	25	38	34	29	33	125
		30	3	30	29	25	22	25	90
			4	25	36	31	24	26	100
			5	24	38	35	31	35	120

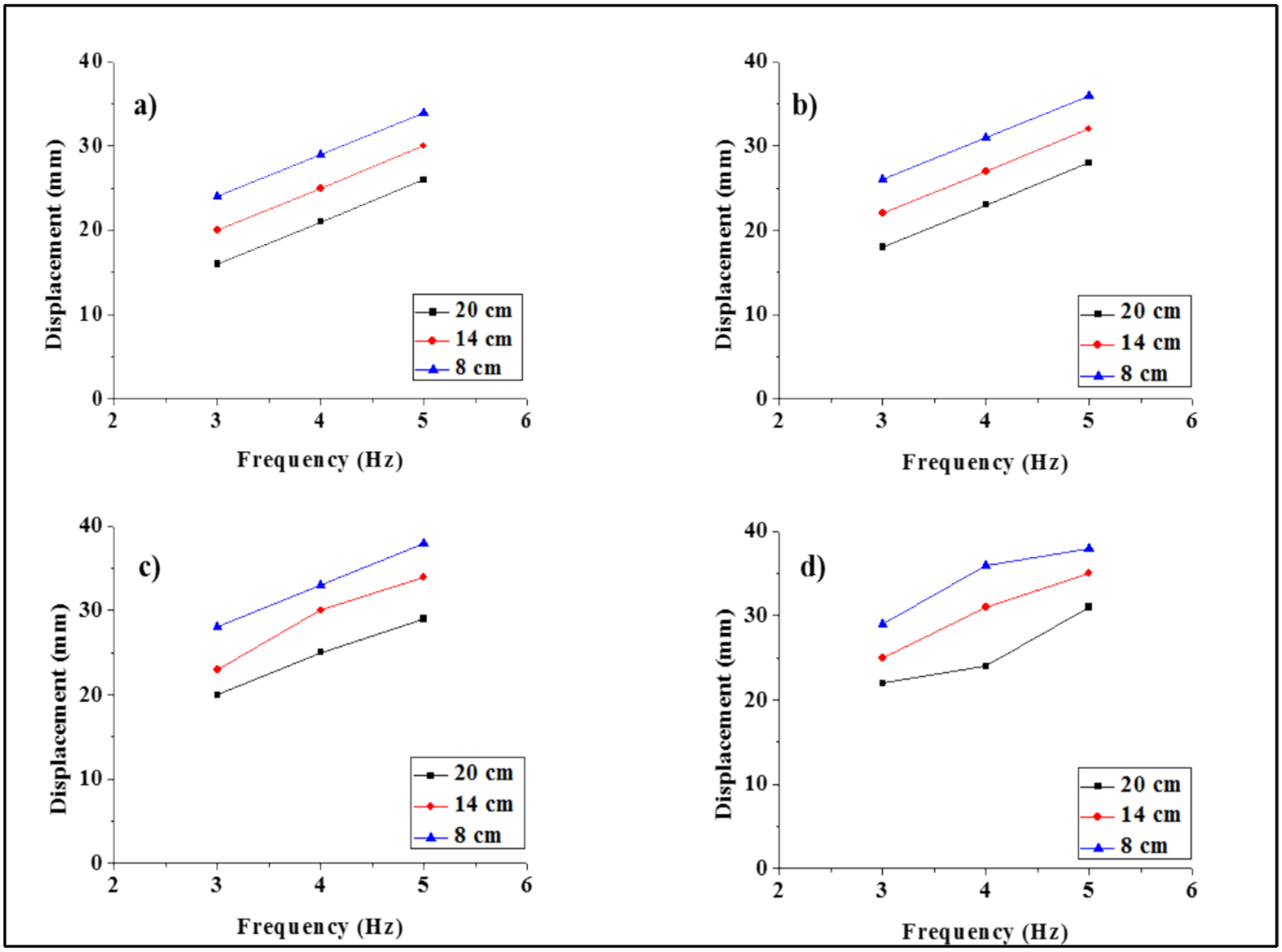


Fig. 24 Variation of displacement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of slope 30 cm height and slope angle of 45° (**a**) without surcharge load and with a surcharge of mass (**b**)10N, (**c**) 20N, and (**d**) 30N

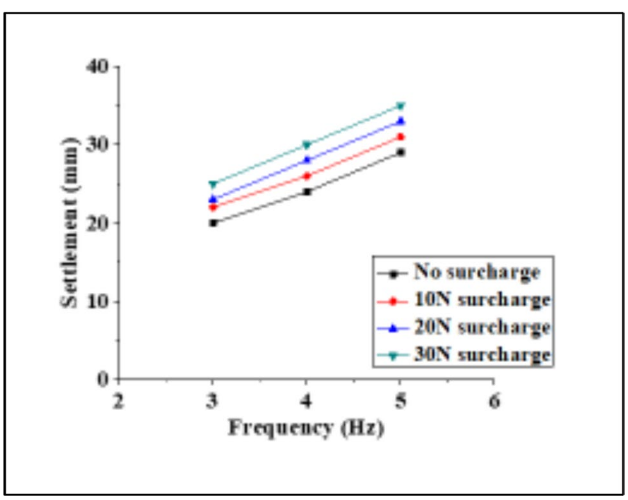


Fig. 25 Variation of settlement with vertical frequency of 3 Hz, 4 Hz and 5 Hz of slope 30 cm height and slope angle of 45^0 with surcharge load of mass 10N, 20N, and 30N

Table 25 Test results of slope 27 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of Coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
27	40	0	3	39	20	16	12	22	117
			4	30	24	20	16	28	120
			5	26	29	26	23	32	130
		10	3	31	18	14	11	20	93
			4	22	23	19	14	24	88
			5	17	27	24	22	28	85
		20	3	36	15	13	9	18	108
			4	30	20	17	12	20	120
			5	26	25	22	20	24	130
		30	3	40	14	11	7	15	120
			4	33	18	14	10	17	132
			5	29	23	20	18	22	145

Table 26 Test results of slope 27 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
27	40	0	3	43	17	15	10	18	129
			4	34	21	18	14	23	136
			5	29	27	24	21	29	145
		10	3	46	15	13	8	17	138
			4	38	18	15	11	21	152
			5	35	25	22	18	27	175
		20	3	48	13	10	6	15	144
			4	40	15	12	9	18	160
			5	37	23	20	14	25	185
		30	3	52	10	8	5	12	156
			4	45	13	10	8	15	180
			5	42	20	18	11	23	210

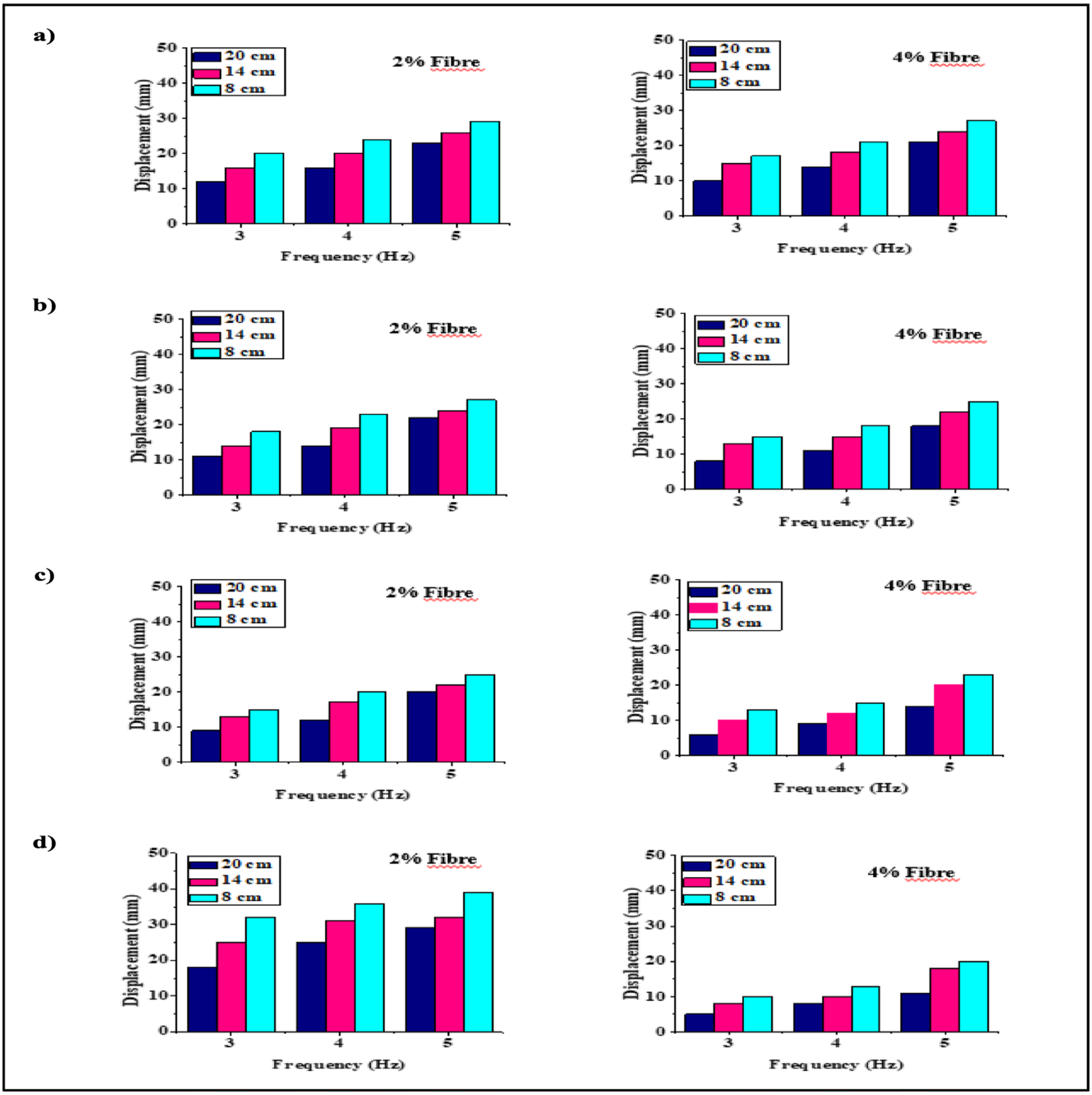


Fig. 26 Variation of displacement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 27 cm height and 40° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge

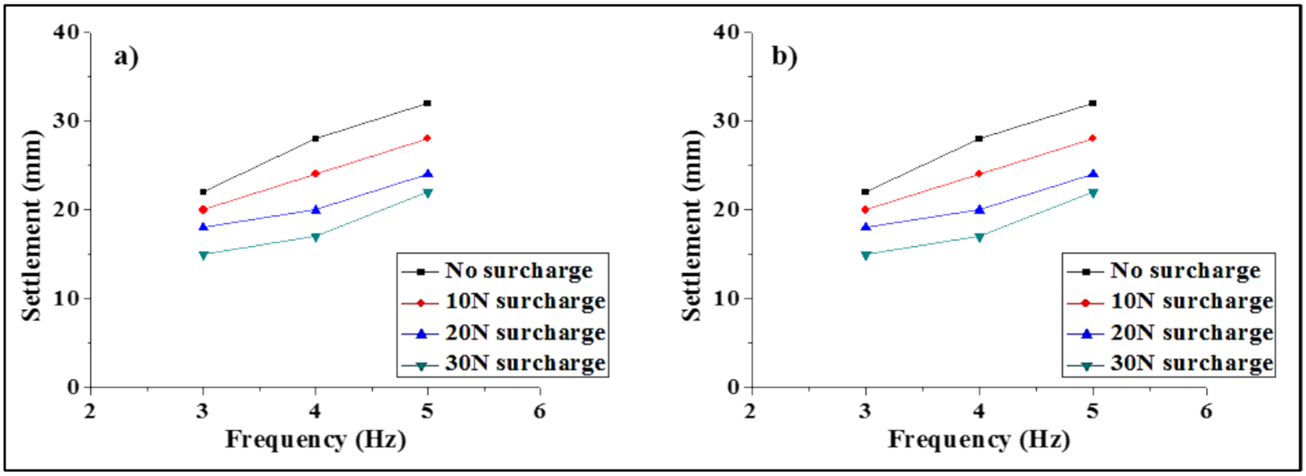


Fig. 27 Variation of settlement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz of slope 27 cm height and slope angle of 40° reinforced with (**a**) 2% of coconut fibres and (**b**) 4% of coconut fibres with surcharge load of mass 10N, 20N and 30N

Table 27 Test results of slope 27 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
27	45	0	3	43	23	18	15	18	129
			4	34	28	24	20	25	136
			5	29	33	28	23	30	145
		10	3	34	21	16	14	15	102
			4	25	25	22	19	23	100
			5	21	30	25	21	27	105
		20	3	39	19	14	11	14	117
			4	30	24	18	15	21	120
			5	28	27	23	18	25	140
		30	3	42	17	11	9	12	126
			4	35	22	16	13	20	140
			5	30	25	21	16	24	150

Table 28 Test results of slope 27 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
27	45	0	3	48	19	15	12	14	144
			4	38	25	21	17	21	152
			5	34	29	24	20	26	170
		10	3	53	17	13	10	12	159
			4	42	22	19	15	19	168
			5	38	27	22	18	25	190
		20	3	56	15	10	8	9	168
			4	45	20	16	13	16	180
			5	40	25	20	16	23	200
		30	3	60	13	8	7	7	180
			4	49	17	14	10	13	196
			5	43	20	18	14	20	215

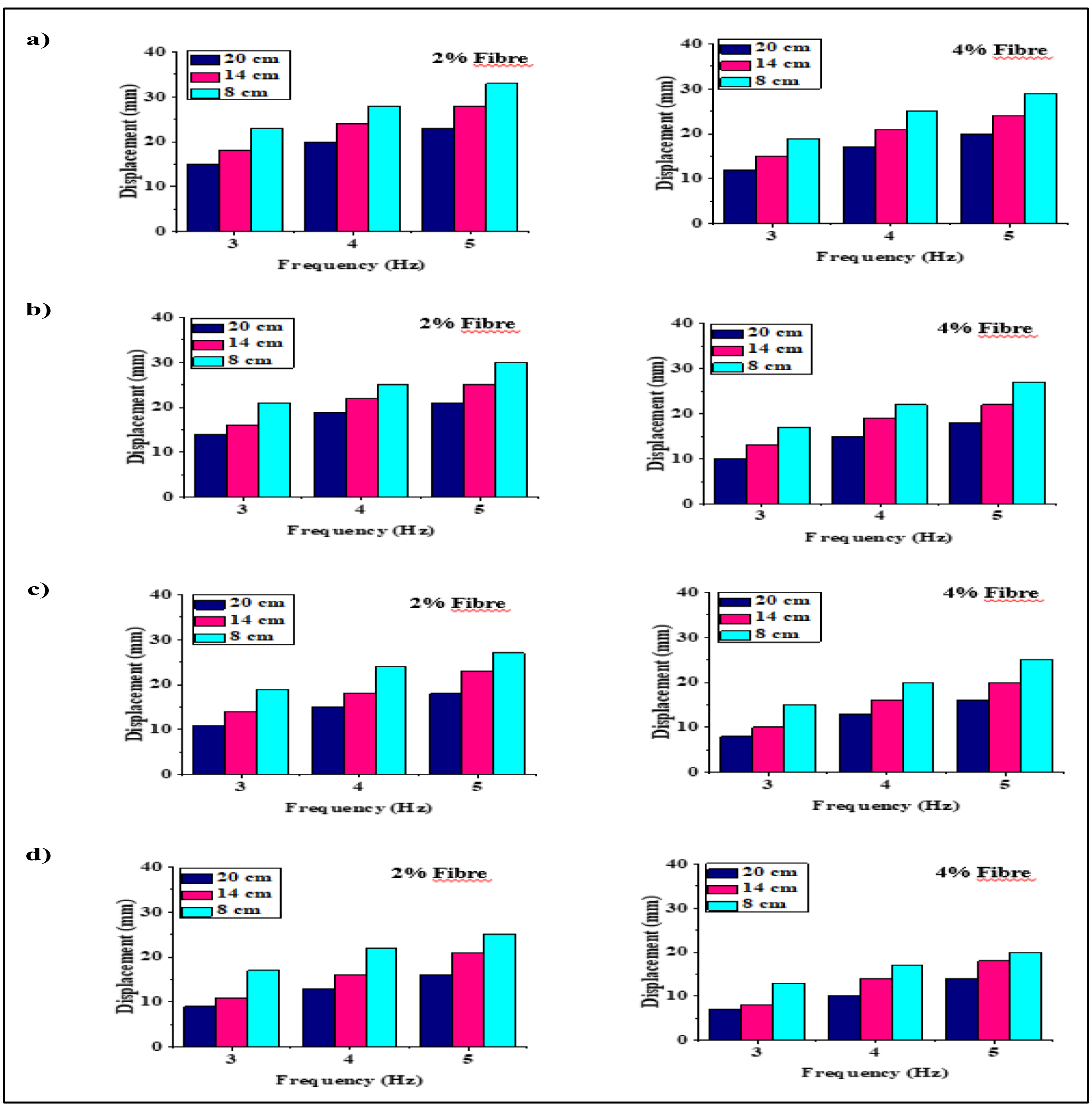


Fig. 28 Variation of displacement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 27 cm height and 45° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge

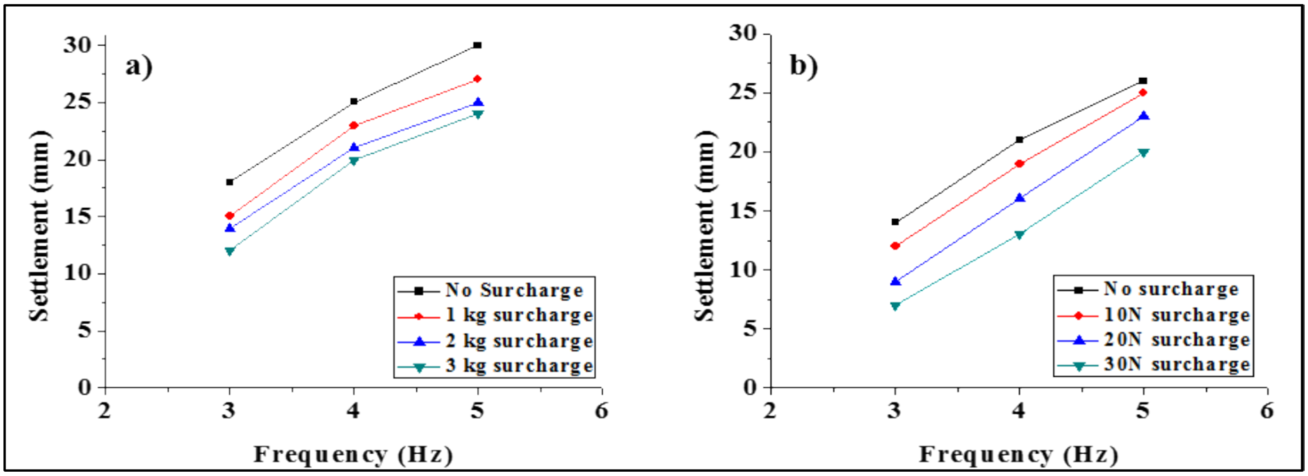


Fig. 29 Variation of settlement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz of slope 27 cm height and slope angle of 45° reinforced with (**a**) 2% of coconut fibres and (**b**) 4% of coconut fibres with surcharge load of mass 10N, 20N and 30N

Table 29 Test results of slope 30 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
30	40	0	3	45	17	13	11	18	135
			4	36	20	17	14	21	144
			5	31	24	21	17	29	155
		10	3	50	15	11	10	16	150
			4	40	18	16	13	19	160
			5	35	24	20	16	27	175
		20	3	55	13	9	8	14	165
			4	45	15	14	11	17	180
			5	40	22	18	15	25	200
		30	3	59	11	9	7	12	177
			4	46	15	13	10	16	184
			5	43	20	15	14	22	215

Table 30 Test results of slope 30 cm height and angle of 40° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
30	40	0	3	49	15	11	8	14	147
			4	40	19	14	12	18	160
			5	36	22	18	14	25	180
		10	3	53	12	9	7	12	159
			4	45	16	12	10	15	180
			5	40	20	16	12	26	200
		20	3	56	10	7	5	10	168
			4	49	14	10	8	14	196
			5	43	18	13	10	24	215
		30	3	60	8	6	4	8	180
			4	52	12	8	6	12	208
			5	47	15	11	8	22	235

and the time taken by slope to fail is recorded. The Number of cycles is evaluated for frequencies of 3 Hz, 4 Hz and 5 Hz. The results are tabulated in Tables 9 and 10. The variation of displacement with the number of cycles of slope without surcharge load and with surcharge loads is given in Fig. 12.

Similarly, the horizontal response of reinforced slopes of height 25 cm and angle 45°; 27 cm and angle 40°; 27 cm and angle 45°; 30 cm and angle 40°; and 30 cm and angle 45° is given in Tables 11 and 12 and Fig. 13; Tables 13 and 14 and Fig. 14; Tables 15 and 16 and Fig. 15; Tables 17 and 18 and Fig. 16; and Tables 19 and 20 and Fig. 17 respectively.

4.3 Seismic Response of Unreinforced Slope Using Vertical Shake Table Test

The vertical shake table tests are conducted on slopes of height 27 cm and 30 cm with slope angles of 40° and 45°. The slope of height 27 cm and angle 40° is tested without surcharge and with surcharge load of mass 10N, 20N, and 30N. The slope is subjected to frequencies of 3 Hz, 4 Hz and 5 Hz with a constant amplitude of 4 mm. The displacements are measured at heights of 8 cm, 14 cm, and 20 cm from the toe and the settlement is measured at the end of the test (appearance of hairline cracks). The time taken by the slope to fail is recorded for each frequency. The results are tabulated in Table 21. The variation of displacement with frequencies of 3 Hz, 4 Hz and 5 Hz of slope without surcharge and with surcharge load of mass 10N, 20N, and 30N is given in Fig. 18 and the variation of settlement with frequency is given in Fig. 19.

Similarly, the vertical response of unreinforced slopes of height 27 cm and angle 45°; 30 cm and angle 40°; and 30 cm and angle 45° is given in Table 22 and Figs. 20 and 21; Table 23 and Figs. 22 and 23; and Table 24 and Figs. 24 and 25 respectively.

4.4 Seismic Response of Reinforced Slope Using Vertical Shake Table Test

Vertical shake table tests are conducted on slopes reinforced with coconut fibres added in different percentages. The slope of height 27 cm and angle of 40° reinforced with coconut fibres of 2% and 4% is subjected to frequencies of 3 Hz, 4 Hz and 5 Hz at a constant amplitude of 4 mm. The slope is tested without surcharge and with a surcharge load of mass 10N, 20N and 30N. The displacements are measured at heights of 8 cm, 14 cm and 20 cm from the toe and the time taken by slope to fail is recorded. The Numbers of cycles are evaluated for frequencies of 3 Hz, 4 Hz and 5 Hz. The results are tabulated in Tables 25 and 26. The result table shows the shaking time taken by the slope to fail and the displacements measured at heights of 8 cm, 14 cm and 20 cm from the toe. The variation of displacement with frequency of slope without surcharge load and with surcharge loads is given in Fig. 26. The variation of settlement with frequency of slope is given in Fig. 27.

Similarly, the vertical response of reinforced slopes of height 27 cm and angle 45°; 30 cm and angle 40°; and 30 cm and angle 45° is given in Tables 27 and 28 and Figs. 28 and 29; Tables 29 and 30 and Figs. 30 and 31; and Tables 31 and 32 and Figs. 32 and 33 respectively.

5 Discussions

5.1 Horizontal Shake Table Tests

5.1.1 Effect of Slope Angle on the Response of Slope

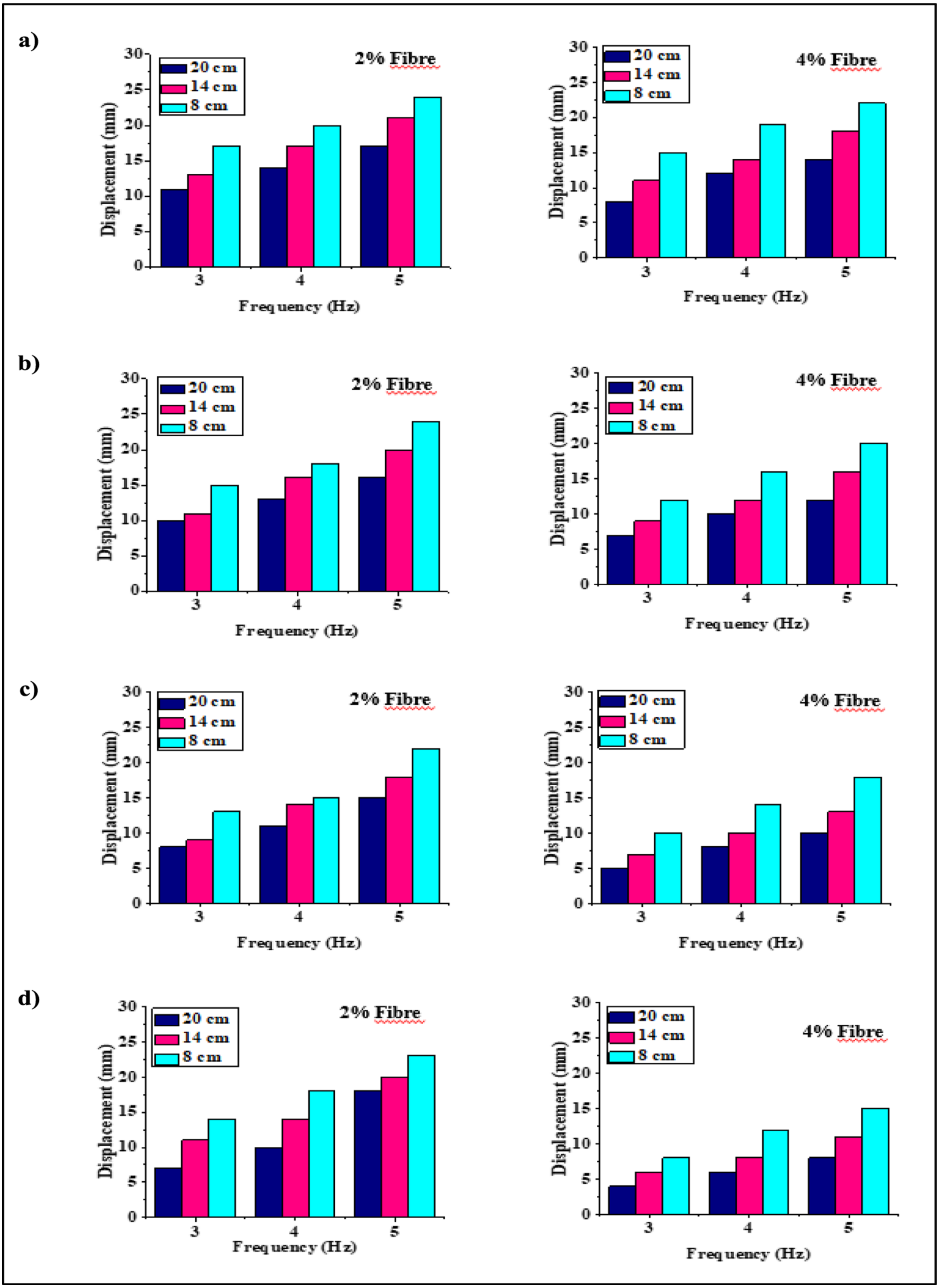
The displacement increases with an increase in the slope angle in the case of both reinforced and unreinforced slopes i.e. the steeper slopes show larger displacements in horizontal shaking. The comparison results are shown in Fig 34. This could happen if the slope gets too steep for shear strength to counteract shear stress, beyond the angle of repose resulting in mass movement. These results are similar to those computed by Srilatha et al. (2017).

5.1.2 Effect of the Addition of Coconut Fibres as Reinforcement

From the results, it is observed that the reinforced slopes show lesser displacement compared to those of unreinforced slopes. Fig 35 illustrate the decrease in the displacement in the reinforced slope. This is because the friction that the addition of coconut fibres as reinforcement has caused between the soil and the reinforcement has enhanced the shear strength of the soil material. This can be validated by C and ϕ values obtained for soil with fibres. These results are like those computed by Srilatha et al. (2013).

5.1.3 Effect of Surcharge Load on Unreinforced and Reinforced Slope Models

It is seen that in unreinforced slopes the displacement that occurred is less in the case of slope without surcharge load i.e. the displacement increases with an increase in surcharge load. But in the case of reinforced slopes, the displacement is more in the slope without surcharge i.e. the displacement decreases with an increase in surcharge load. This results from the surcharge load increasing the interfacial resistance between the reinforcement and the soil. These findings align with the


a)
2% Fibre
4% Fibre
b)
2% Fibre
4% Fibre
c)
2% Fibre
4% Fibre
d)
2% Fibre
4% Fibre
20 cm
14 cm
8 cm
Displacement (mm)
Frequency (Hz)

◂**Fig. 30** Variation of displacement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 30 cm height and 40° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge

calculations made by Lo Grasso et al. (2005). The variation of displacements with surcharge load of reinforced and unreinforced slopes is shown in Fig 36.

5.1.4 Effect of Frequency on Slope Models

The way that slopes respond to seismic stimulation changes with elevation rather than being constant along the slope. The reaction of both reinforced and unreinforced slopes increased as the frequency of shaking increased which is illustrated in Figs 6, 7, 8, 9, 10 and 11.

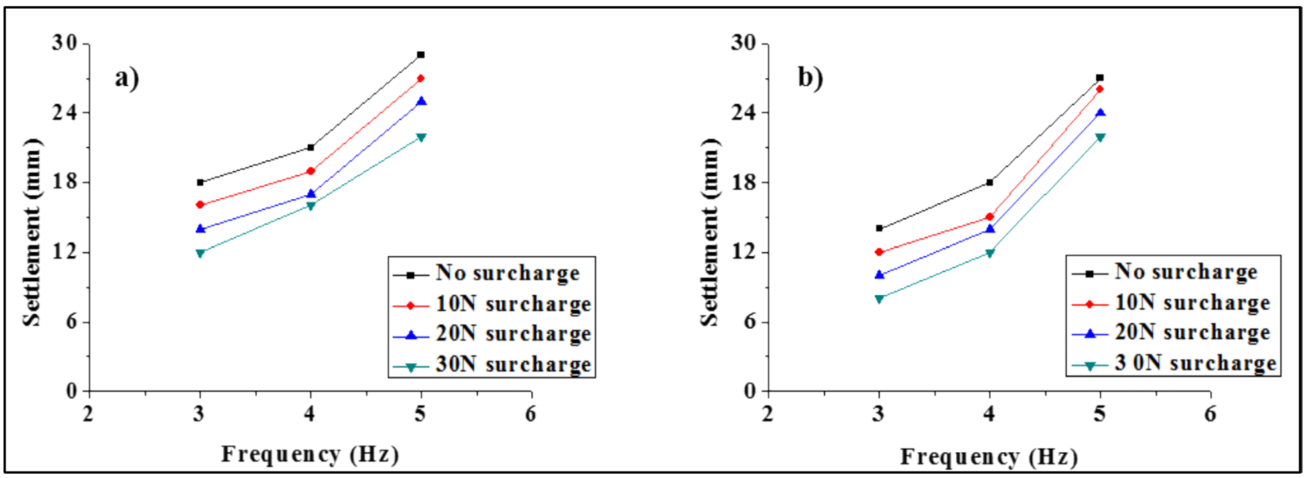


Fig. 31 Variation of settlement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz of slope 30 cm height and slope angle of 40° reinforced with (a) 2% of coconut fibres and (b) 4% of coconut fibres with surcharge load of mass 10N, 20N and 30N

Table 31 Test results of slope 30 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 2% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
30	45	0	3	52	21	16	12	17	156
			4	43	24	20	17	20	172
			5	38	28	25	21	27	190
		10	3	56	19	15	12	14	168
			4	50	22	18	17	18	200
			5	45	26	23	20	25	225
		20	3	60	17	12	10	12	180
			4	56	22	16	14	15	224
			5	50	24	20	18	23	250
		30	3	62	15	11	8	10	186
			4	60	20	14	13	12	240
			5	54	22	18	16	20	270

Table 32 Test results of slope 30 cm height and angle of 45° without surcharge and with a surcharge of mass 10N, 20N, and 30N subjected to a vertical frequency of 3 Hz, 4 Hz and 5 Hz reinforced with 4% of coconut fibres

Height (cm)	Angle (Degree)	Surcharge (N)	Frequency (Hz)	Time (sec)	Displacement (mm)			Settlement (mm)	No. of cycles
					8 cm	14 cm	20 cm		
30	45	0	3	57	19	13	10	13	171
			4	48	21	18	14	16	192
			5	40	25	22	19	23	200
		10	3	63	17	15	11	11	189
			4	53	21	18	17	13	212
			5	45	23	21	20	23	225
		20	3	60	14	13	9	9	180
			4	57	18	14	15	11	228
			5	49	21	18	16	20	245
		30	3	63	12	10	7	7	189
			4	60	15	13	11	9	240
			5	53	18	16	14	18	265

5.2 Vertical Shake Table Tests

5.2.1 Comparison of Displacements and Settlements of Reinforced and Unreinforced Slope Models

From the results, it is seen that the displacement and settlements decrease with the addition of reinforcement. This is due to the friction that is developed due to the addition of coconut fibres as reinforcement which increases the shear strength of the soil slope. The comparison of variation of settlements of unreinforced with reinforced slope is shown in Fig 37.

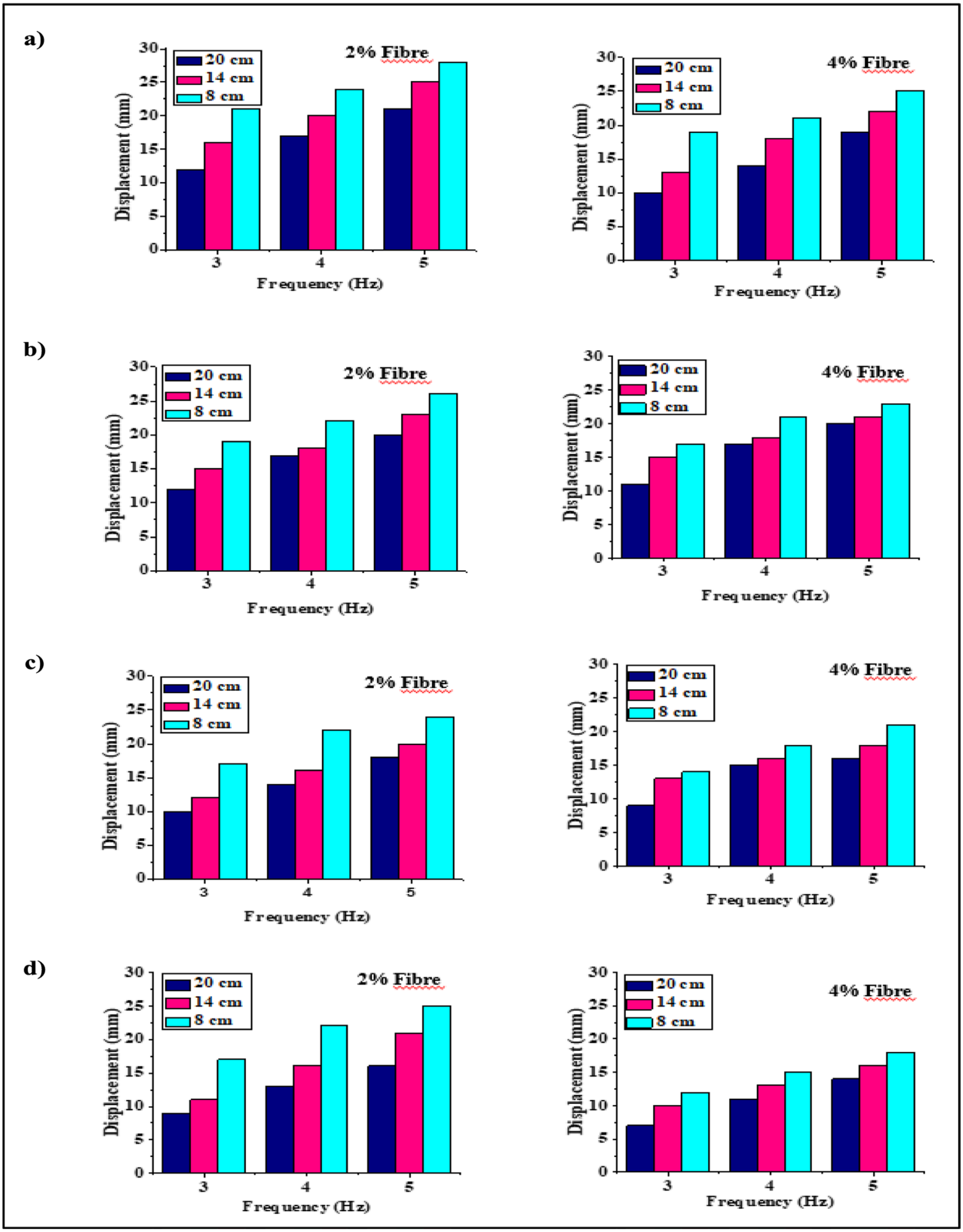
5.2.2 Effect of Surcharge

It is observed that in unreinforced slopes, the displacement occurs less in the case of a slope without a surcharge load, whereas the displacement increases with a surcharge load. However, in the case of reinforced slopes, the displacement is greater in the slope without surcharge, indicating that the displacement decreases as the surcharge load increases. This occurs because the surcharge load increases the interfacial resistance between the reinforcement and the soil. The variation of displacements with surcharge load of reinforced and unreinforced slopes is shown in Fig 38.

6 Conclusions

Dynamic studies on slopes reinforced with fibres have received increasing attention due to higher demands for developmental activities in recent times. However, investigations on the use of natural fibres like coconut fibres in slope stability are still limited so far. To develop a better understanding of the effectiveness of reinforced slopes using

Fig. 32 Variation of displacement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz at heights of 8 cm, 14 cm and 20 cm from the toe of reinforced slope 30 cm height and 45° slope angle (**a**) without surcharge load, (**b**) 10N surcharge load, (**c**) 20N surcharge load, and (**d**) 30N surcharge ▶


a)
b)
c)
d)
2% Fibre
4% Fibre
20 cm
14 cm
8 cm
Displacement (mm)
Frequency (Hz)

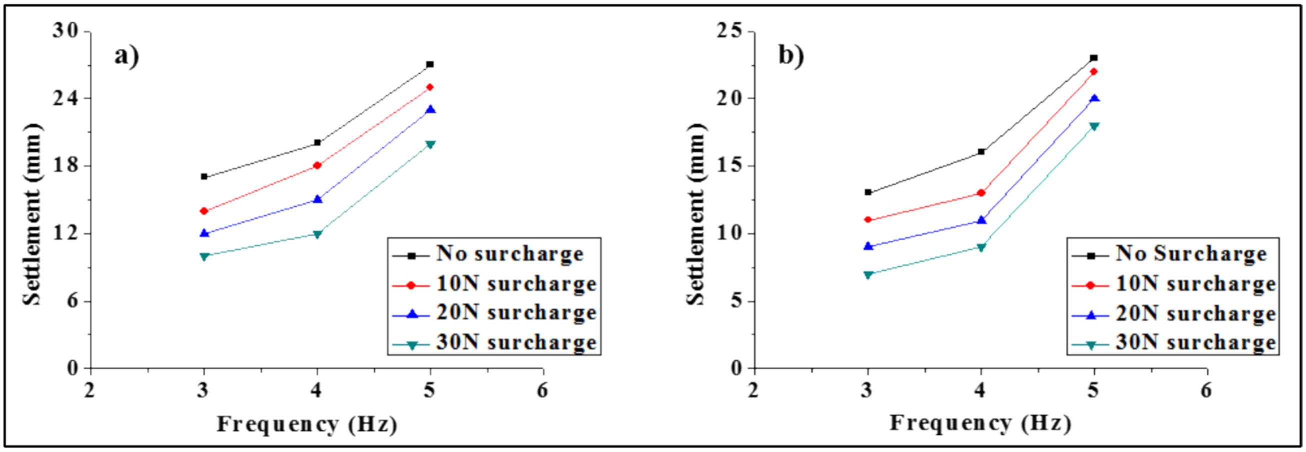


Fig. 33 Variation of settlement with a vertical frequency of 3 Hz, 4 Hz and 5 Hz of slope 30 cm height and slope angle of 45° reinforced with (**a**) 2% of coconut fibres and (**b**) 4% of coconut fibres with surcharge load of mass 10N, 20N and 30N

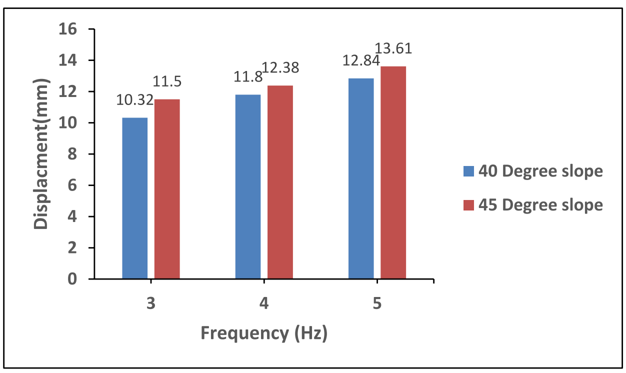


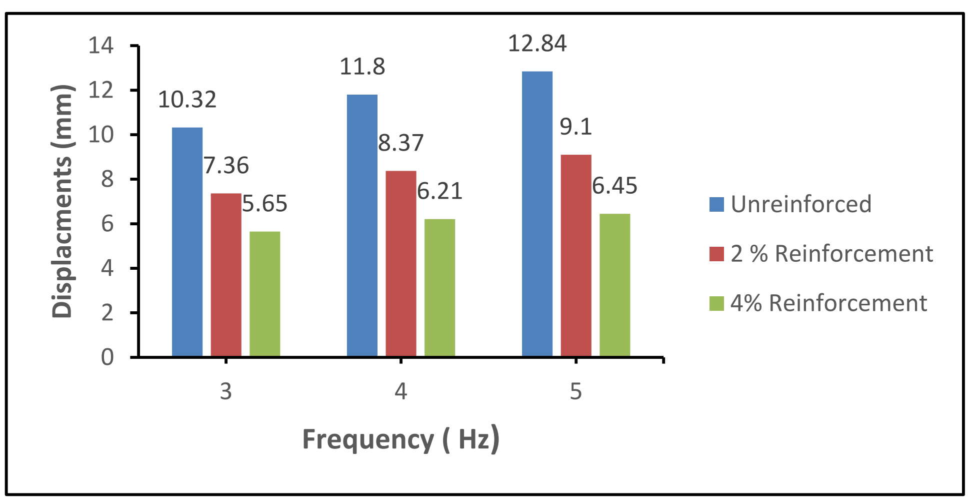
Fig. 34 Displacements occurred at a height of 20 cm in an unreinforced slope of 25 cm height with a slope angle of 40 and 45 degrees without surcharge load at frequencies of 3 Hz, 4 Hz, and 5 Hz

natural coconut fibres, shaking table tests were conducted on a series of laboratory-scale artificial slopes, where the influence of height, the slope angle and the amount of fibre reinforcement was considered. Besides, the behaviour of the fibre-reinforced and unreinforced slope is studied without surcharge and with surcharge of varying loads. The following conclusions were drawn from the study:

6.1 Effect of Using Coconut Fibres as Reinforcement

i. The addition of coconut fibres as reinforcement has significantly reduced the displacement under earthquake loading. For slopes of 40° and 45°, the displacements have reduced from 28 to 79% when subjected to horizontal shaking and 20 to 75% when subjected

Fig. 35 Displacements occurred at a height of 20 cm in an unreinforced and reinforced slope of 25 cm Height without surcharge load at frequencies of 3 Hz, 4 Hz, and 5 Hz



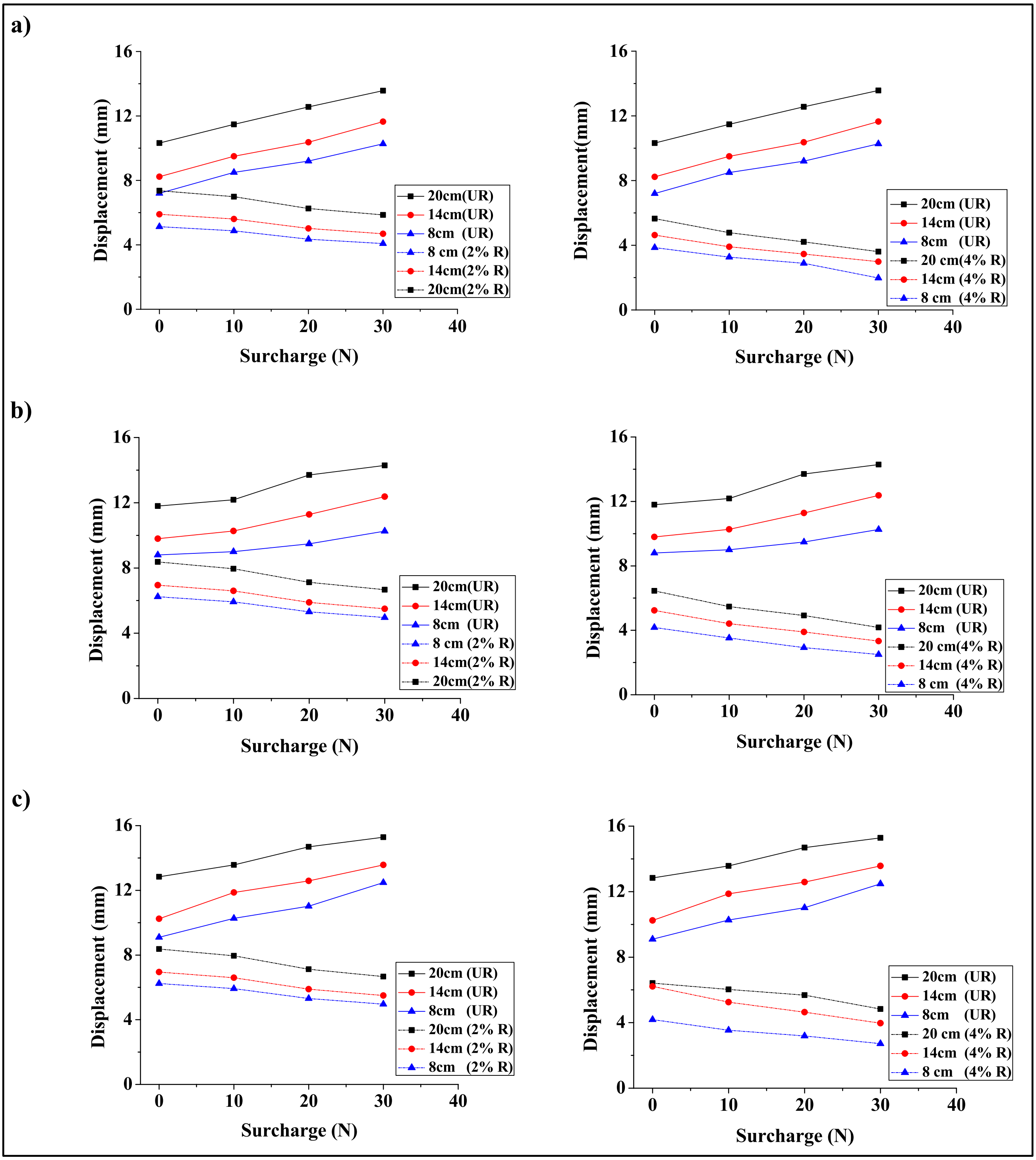


Fig. 36 Comparison of variation of displacement with surcharge load of an unreinforced slope and with a reinforced slope of 25 cm height and 40° angles at a frequency of (**a**) 3 Hz, (**b**) 4 Hz, and (**c**) 5 Hz subjected to horizontal shaking

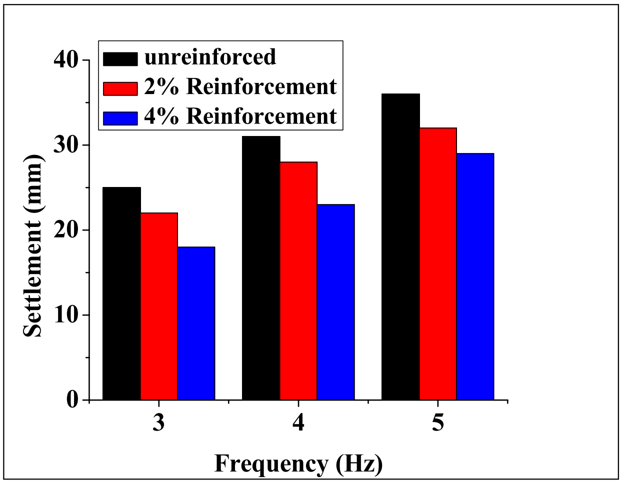


Fig. 37 Comparison of variation of settlement of unreinforced with a reinforced slope of slope 27 cm height and 40° angles without surcharge subjected to a frequency of 3 Hz, 4 Hz and 5 Hz in vertical shake table test

to vertical shaking at a higher fibre content of 4% and larger slope height of 30 cm.

ii. In reinforced slopes, the settlement reduced up to 70% underscoring the effect of coconut fibres in stabilizing the slope.

6.2 Effect of Surcharge Load

i. In unreinforced slope, with the increase in surcharge load, the displacement increased up to 28% and up to 45% when subjected to horizontal and vertical shaking respectively for a surcharge load of 30N.

ii. In the reinforced slope, a decrease in displacement was observed with increasing surcharge load. The displacements were reduced up to 35% during horizontal shaking and 45% during vertical shaking for 4% coconut fibre content showing the load distribution capacity of reinforcement.

7 Recommendation and Future Scope

a. Optimizing Fibre Content

The study showed that the addition of coconut fibres reduced the displacements and settlements of the slope. In the present study, the coconut fibre content was increased up to 4% only, hence higher fibre content was not evaluated. Therefore it is recommended to evaluate the slope stability for higher fibre content so that optimal fibre content can be determined and understand the effectiveness and practical limitation of higher fibre content.

b. Real-Time Application

Considering the significant advantages observed, coconut fibres can be considered a cost-effective and sustainable solution for enhancing the stability of slopes under seismic conditions.

8 Future Scope

Investigation of the long-term durability of coconut fibres under varying environmental conditions can be carried out. Coconut fibres combined with other reinforcement methods can be explored for further enhancement of stability. The study can be extended to a larger scale slope and more complex seismic loading scenarios for better applicability to field conditions.

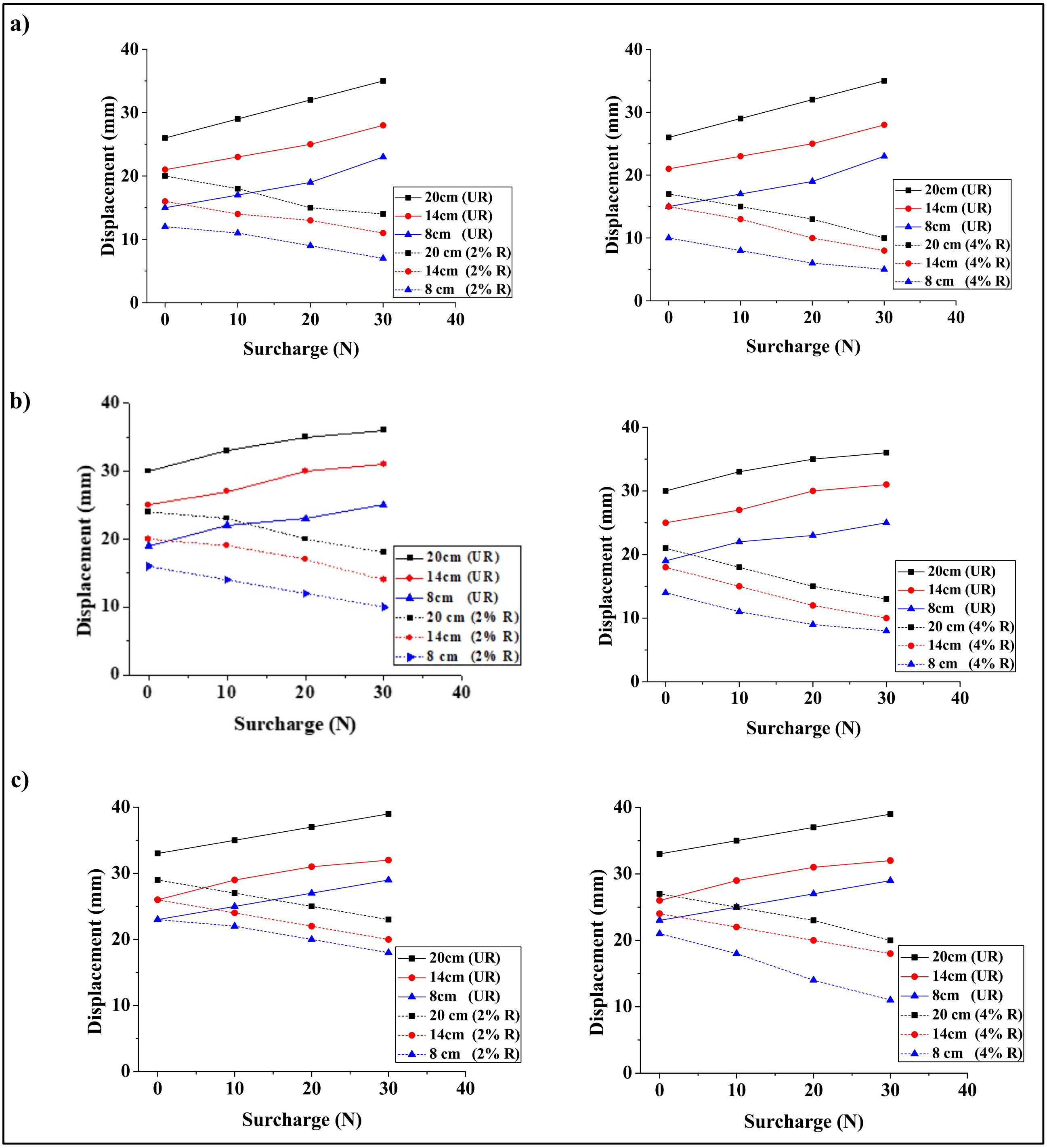


Fig. 38 Comparison of variation of displacement with surcharge load of an unreinforced slope and with a reinforced slope of 27 cm height and 40° angles at a frequency of (**a**) 3 Hz, (**b**) 4 Hz, and (**c**) 5 Hz subjected to vertical shaking

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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