Research Article

Response of Slope Made Up of Soil and Other Waste Materials under Sinusoidal Motion

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Performance of small scale embankment slopes under dynamic loading is experimentally evaluated in the present work conducting shake table test. Model slopes are made up of soil and soil dust mixtures at various water level conditions. Material dust types as taken in the experiment are saw dust, stone dust, brick dust, and building demolish dust. Shear strength of soil such as cohesion and internal friction angle increases on an average 25% and 23%, respectively, when soil is mixed with 30% building demolish dust at different water content. Similarly other dust materials also enhance shear strength of soil. Responses of model slope on the basis of laboratory test have been observed and presented. At base frequency 5 Hz and 6% water content condition RMSA decreases up to 57% when slope material is changed from soil to “S + 30% DD” for slope with inclination 45° and at the same condition slope shows better stability which is reflected from reduction of base displacement as well as crest deformation up to 89% and 58%, respectively. Analytical solution of slope considering planer rupture surface is done using pseudodynamic method and results are compared with experimental observation. It is seen that when soil is mixed with 30% stone dust, sliding displacement of slope with inclination 45° is 7.5 mm at shake table test which is very closer to the analytical result. Stability of slope is maximum when “soil and building demolish dust” mixture is used and gradually reduces when slope material changes from “soil and brick dust,” “soil and stone dust,” “soil and saw dust” mixture, and ultimately soil. Thus, different material dust which we treat as waste can be used at various field conditions to enhance stability of embankment slope.

1. Introduction

Safety evaluation of slope against devastation under seismic loading condition is one of the most trending research areas in the field of geotechnical engineering as well as in transportation engineering. Study on slope stability and monitoring of slope movement is done many a time by researchers (Taylor [1, 2], Fellenius [3], and Newmark [4]). Slope shows a stable behaviour under static condition which can simply collapse under seismic loading condition due to the development of seismic inertia forces which acts along with weight of the potential soil mass leading decrease in the strength parameters of soil. The vulnerability of earth structure to ground motion is clearly understood after devastation caused due to different earthquakes recorded during past years. Slope in the form of embankment or cutting many times undergoes severe distress (example Bhuj earthquake in India [5]) and performance of these embankments during

earthquake can be analysed by doing instrumentation and monitoring these actual embankments. However, due to different barrier in reality model tests in the laboratory are the only way to study the seismic behaviour of these embankments. To understand the behaviour of embankment slope under dynamic condition model test can be conducted on shake table. Clough and Pirtz [6] are the first to study the performance of slope using shake table. Furthermore, Seed and Clough [7], Goodman and Seed [8], and Arango and Seed [9] used shaking table test and observed response of embankments and dams. Response of soil, pile, and fluid interaction during earthquake was studied by Iai [10] by using shake table. A series of shake table tests were done by Koga and Matsuo [11] to see the response of earthen embankment founded on saturated sand under earthquake loading and they observed that slumps and cracks were formed due to softening of underlying ground. Recently Wartman et al. [12–14] conducted small scale shake table

tests to study slope deformations during seismic condition and to assess the applicability of Newmark's sliding block method of analysis and observed largest deformation due to shaking being near the toe of slopes. A 0.5 m high 30° inclined sandy slope was analysed by Lin and Wang [15] and they observed that responses of slope became nonlinear after 0.5 g loading. Prasad et al. [16] used laminar shear box to enhance the accuracy in assessing ground behaviour and reported calibration and testing of slopes.

Apart from all the experimental works theoretical analysis of slope was done by many researchers to obtain safety factor of slope (Ling et al. [17], Ling et al. [18]) using pseudo-static method where inertia forces were calculated as product of seismic coefficients recommended by researchers (Terzaghi [19]) and weight of the failure wedge does not depend on time and is unable to show the dynamic nature of earthquake loading. The limitation of pseudo-static method was sorted out by Steedman and Zeng [20] and pseudodynamic method is introduced which is able to show the influence of the phase and amplitude variations of earthquake acceleration with depth, velocity of seismic waves, and the period of lateral shaking. Factor of safety of homogeneous slope has been analysed by Chanda et al. [21] using the pseudodynamic method and shows effects of seismic forces and soil strength parameters on the factor of safety of slope.

All these studies give very positive indication to conduct more research to observe response of embankment slopes under seismic condition. Therefore in the present work a series of shake table tests is conducted to study the response of model slope made up of soil and soil with other waste materials under dynamic loading. Four types of waste materials such as saw dust, stone dust, brick dust, and building demolish dust are mixed with soil to enhance the strength parameters, that is, cohesion and angle of internal friction of soil, and model slopes made up of these mixtures are tested under dynamic loading using shake table. Responses of model slopes are presented in terms of RMSA along slope height, displacement at base of slope, and crest deformation of model slopes under dynamic loading at different water content. As the pattern of failure surface in shake table test result is found to be almost linear, an analytical solution of slope using pseudodynamic method has been carried out considering planer rupture surface. Results obtained from shake table test on model slope in terms of sliding displacement are compared with evaluated sliding displacement from analytical solution.

2. Test Set-Up and Method of Experiment

2.1. Shaking Table. The uniaxial shaking table experimental set-up in the laboratory consists of a 1.0 m × 1.0 m base plate (table) fitted with smooth wheels at the bottom which allow sliding in a horizontal direction on two parallel rails. A slotted disc made up of mild steel is bolted to another circular disc of the same size. The supported disc is connected to the shaft of the motor. A steel crank shaft is connected to the slotted disc by bolts. The end of the crank shaft is connected to a reciprocating rod which has maximum stroke length of 150 mm and a peak frequency of 50 Hz. The amplitude of the sinusoidal motion can be varied by changing the position of

the crank shaft in the calibrated slot of the disc. The other end of the reciprocating rod is connected to the shaking table base plate. The reciprocating shaft with the help of slotted disk is fitted with 7.5 H.P. reciprocating motor which can run with speed near about 1400 rpm. The frequency of the input motion is adjusted by using an electrical variant. Figure 1(a) shows the experimental set-up in the laboratory. A 12 mm thick Perspex box of size 80 cm × 58 cm × 35 cm ($l \times b \times h$) is used to conduct test on model slope using that shake table as shown in Figures 1(b) and 1(c) because the deformation of slopes from sides can be easily visible through Perspex glass sheets. The front side of the box is marked with light colour ink so that all deformations after test can be measured manually. Sides of the box were fixed rigidly with steel angles to prevent any movement. It has been observed by Whitman and Lambe [22] that soil located in close proximity to rigid boundary walls responded differently than soil near the middle of the model; besides that, reasonably correct physical model test data can be obtained in rigid wall containers. Analysis of soil structure in most of the cases is done by modeling the structure consisting of rigid boundary condition. Therefore, in the present study a rigid wall box was selected the boundary condition of which matches with analytical model. The three inner sides of the Perspex glass box are glued with 10 mm thick sponge sheets to minimize the boundary effects such as reflection of waves during shaking. Soil particles were glued to the inner bottom surface of the model box to generate surface roughness to control slippage between the base of the model slope and bottom surface of the container during shaking. Acceleration responses of the base plate, container and the model slopes during shaking were measured using B & K 4507001 type accelerometers. The Bruel & Kjaer Pulse 6.1 frontend system was used for the data acquisitions. Performance of the experimental set-up before starting test on model slopes was checked by system calibration by assuring amplification produced by the system is negligible.

2.2. Material for Slope Model. Soil procured from National Institute of Technology Agartala campus is the main ingredient used to prepare model slopes. The soil is classified as silty sand according to the Indian standard soil classification system. The grain size distribution and mineral composition of soil are presented in Figures 2(a) and 2(b). To enhance the strength of the soil four types of dust are used as shown in Figure 2(c). These dust types are saw dust, stone dust, brick dust, and building demolish dust. The surface structure of different materials used to construct model slope is analysed and SEM images along with variation in elemental composition detected by EDX study are presented in Figure 3. Gradation and basic properties of stone dust, brick dust, and building demolish dust are given in Tables 1(a) and 1(b). Each material is mixed as 10% and 30% of total soil weight, respectively. Properties of soil and these soil dust mixtures are also given in Table 1(c). In the table "S + 10% WD" is used to denote soil mix with 10% saw dust. Similarly, "S + 10% SD," "S + 10% BD," "S + 10% DD," "S + 30% WD," "S + 30% SD," "S + 30% BD," and "S + 30% DD" are used to denote soil mix with 10% stone dust, soil mix with 10% brick dust, soil mix with

FIGURE 1: Instrumentation and preparation of slope model.

FIGURE 2: (a) Particle size distribution of soil; (b) XRD diagram of soil used in the present study; (c) Waste dust used to enhance soil strength.

FIGURE 3: (a)–(e) SEM images of soil, brick dust, stone dust, building demolish dust, and saw dust, respectively, and (f)–(j) EDX patterns of soil, brick dust, stone dust, building demolish dust, and saw dust, respectively.

TABLE 1

(a) Gradation of different dust mixed with soil

Weight of sample taken			Cumulative percentage retained	Percentage passing	Remarks
IS sieve size	Weight retained (gm)	Percentage retained			
Stone dust					
4.75 mm	0	0	0	100.0	The gradation of stone dust is zone IV as per IS: 383-1970
2.36 mm	0	0	0	100.0	
1.18 mm	04	0.4	0.4	99.6	
425 μ	456	45.6	46	53.6	
300 μ	428	42.8	88.8	11.2	
150 μ	100	10	98.8	1.2	
75 μ	10	1	99.8	0.2	
Pan	02	0.2	100	0	
Brick dust					
4.75 mm	0	0	0	100.0	The gradation of brick dust is zone IV as per IS: 383-1970
2.36 mm	0	0	0	100.0	
1.18 mm	02	0.2	0.2	99.8	
425 μ	454	45.4	45.6	54.4	
300 μ	426	42.6	88.2	11.8	
150 μ	100	10	98.2	1.8	
75 μ	10	1	99.2	0.8	
Pan	08	0.8	100	0	
Building demolish dust					
4.75 mm	0	0	0	100.0	The gradation of building demolish dust is zone IV as per IS: 383-1970
2.36 mm	0	0	0	100.0	
1.18 mm	06	0.6	0.6	99.6	
425 μ	454	45.4	46	53.6	
300 μ	429	42.9	88.9	11.2	
150 μ	98	9.8	98.7	1.2	
75 μ	8	0.8	99.5	0.2	
Pan	05	0.5	100	0	

(b) Physical properties of dust types mixed with soil

Tests performed	Test results		
	Stone dust	Brick dust	Building demolish dust
Specific gravity	2.7	1.89	2.2
Bulk density	18.1 kN/m ³	13.7 kN/m ³	15.5 kN/m ³
Water absorption	2.6%	6.67%	3.8%

(c) Properties of slope material

Slope material	Material Property						
	Liquid limit	Plastic limit	Shrinkage limit	Unit weight (kN/m ³)	Optimum moisture content (OMC)	Cohesion (kN/m ²)	Internal friction angle
Soil	33%	24%	16%	19.5	18%	18	16°
S + 10% WD	33.2%	24.4%	16.2%	20.5	17.6%	20	16.2°
S + 10% SD	33.5%	24.8%	16.28%	19.1	15%	18.2	18°
S + 10% BD	33.8%	25%	16.29%	18.6	14.6%	18.35	18.5°
S + 10% DD	34%	25.3%	17%	18.3	14.2%	18.5	19.3°

(c) Continued.

Slope material	Material Property						
	Liquid limit	Plastic limit	Shrinkage limit	Unit weight (kN/m^3)	Optimum moisture content (OMC)	Cohesion (kN/m^2)	Internal friction angle
S + 30% WD	34.8%	25.4%	17.3%	18	13.8%	22	17°
S + 30% SD	35%	25.6%	17.6%	17.4	13.6%	20.6	21.4°
S + 30% BD	35.3%	25.7%	17.8%	16	13%	21.5	22.5°
S + 30% DD	35.8%	26%	18%	15	12.5%	21.8	25°

FIGURE 4: Shear strength parameters of soil and soil dust mixtures at different water content.

10% building demolish dust, soil mix with 30% saw dust, soil mix with 30% stone dust, soil mix with 30% brick dust, and soil mix with 30% building demolish dust, respectively. Shear strength parameters of soil mixture with various dust types at different water content are presented in Figure 4.

2.3. Model Construction and Testing. Slope models are constructed with the soil and soil dust composition as given in Table 1(c) at three different water level conditions for each model such as (1) air dried, (2) at 3% water content, and (3) at 6% water content. To maintain the slope geometry for all model slopes the densities of filled slope material composed of “soil,” “S + 10% SD,” “S + 10% BD,” “S + 10% DD,” “S + 30% SD,” “S + 30% BD,” and “S + 30% DD” are found to be 10 kN/m^3 , 11 kN/m^3 , and 12 kN/m^3 at air dried condition, at 3% water content, and at 6% water content, respectively. As saw dust has more volume in comparison to other dust types for a particular weight, densities for slope material composed of “S + 10% WD” are found to be 8 kN/m^3 , 9 kN/m^3 , and 10 kN/m^3 and for slope material composed of “S + 30% WD” are found to be 6 kN/m^3 , 7 kN/m^3 , and 8 kN/m^3 , at air dried condition, at 3% water content,

and at 6% water content, respectively, for construction of model slopes having predefined geometry. Slope models with slope inclination angles 30° , 45° , and 60° are prepared using each mixture separately. A rainfall falling system is used for uniform filling of soil in the Perspex box and model slopes are prepared. A rectangular mixture model is first prepared pouring the mixture in three layers from the hopper. First layer of soil is filled in the box and compacted lightly over the surface to maintain the layer thickness uniform. Similarly second layer and third layer filling are done. After that, one side of the rectangular soil wedge which is supported by a wooden board is slightly removed and slope with desired angle is constructed. To maintain the uniform sloping face and leveled top surface the tamping of the sloping face and top surface is done using wooden block of negligible weight. It is assumed that due to the tamping there is no change in the density and other related parameters of the filled up soil and soil dust mixture.

For convenience the Perspex glass sheet box is marked so that it can represent a graph sheet with origin at extreme right bottom corner and according to the precalculated dimension slope models are shaped with base width “ $B = 60 \text{ cm}$,” height

FIGURE 5: Schematic diagram of typical slope with instrumentation.

“ $H = 25$ cm,” and top width “ $W = 17$ cm” for model slope having inclination 30° ; “ $B = 45$ cm,” “ $H = 25$ cm,” and “ $W = 20$ cm” for model slope having 45° inclination; and “ $B = 45$ cm,” “ $H = 25$ cm,” and “ $W = 30$ cm” for model slope having 60° with the help of trowel. Accelerometers are of analog voltage output type with full scale acceleration range of $\pm 1g$ along both the x - and y -axes, with sensitivity of $0.001g$ placed along the model slope height at distances $H/3$, $2H/3$, and H from base as shown in Figure 5. After modeling the whole set-up horizontal sinusoidal input motion at two different frequencies is generated to observe responses of each model slope. First, input motion with 2 Hz frequency and base acceleration $0.2g$ is imposed for duration of 10 second on each model slope and responses are observed. After that, input motion with 5 Hz frequency and base acceleration $0.2g$ is generated and responses of slope models are observed. Slope models are prepared with soil and soil dust mixtures at different water content and subjected to sinusoidal horizontal input motion at two different frequencies to conduct the study and responses are observed. These tests are devised to understand the effects of acceleration and frequency of base shaking, geometry of the slope, and slope material on the performance of the slope during seismic excitation. The frequency of motion varied from 2 Hz to 5 Hz keeping a constant base acceleration of $0.2g$. Table 2 shows various test parameters used for different tests.

3. Pseudodynamic Analysis of Slope

It has been observed from these entire tests that model slopes deform after the loading duration and the failure surface is almost planer failure surface. Therefore, pseudodynamic analysis of slope assuming planer failure surface is done to evaluate the sliding displacement of base of slope and is compared to observe horizontal displacements of model slope for different condition.

A slope model of c - ϕ soil of height H and slope angle i as shown in Figure 6 is considered. Seismic inertia forces acting on the slope are $Q_h(t)$ in the horizontal direction and $Q_v(t)$ in vertical direction. AB is the planar failure wedge inclined at an angle α with the horizontal. R is the reaction acting on failure wedge at an angle ϕ_m with the normal of the failure

FIGURE 6: Forces on soil wedge.

wedge. $c = c_m L$ is the mobilized cohesion acting along the face AB (length L) and ϕ_m is the mobilized internal friction angle.

Weight of the wedge is as follows:

$$W = \frac{\gamma \times H^2 (\cot \alpha - \cot i)}{2}. \quad (1)$$

The mass of a thin element of wedge at depth z of thickness dz is given by

$$m(z) = \frac{\gamma}{g} \times (\cot \alpha - \cot i) \times (H - z) \times dz. \quad (2)$$

For a sinusoidal base shaking subjected to both horizontal and vertical earthquake acceleration with amplitude $k_h g$ and $k_v g$, the horizontal and vertical acceleration, respectively, at any depth z below the ground surface at time “ t ” can be expressed as

$$\begin{aligned} a_h(z, t) &= k_h \times \sin \omega \left(t - \frac{H - z}{V_s} \right) \\ a_v(z, t) &= k_v \times \sin \omega \left(t - \frac{H - z}{V_p} \right). \end{aligned} \quad (3)$$

TABLE 2: Parameters in shaking table test of slope models.

Sl number	Test code	Frequency (Hz)	Slope material	Water content (%)	Slope inclination
(1)	Soil	2, 5	Soil	Air dried, 3, 6	30°, 45°, 60°
(2)	S + 10% WD	2, 5	Soil and 10% saw dust of soil weight	Air dried, 3, 6	30°, 45°, 60°
(3)	S + 10% SD	2, 5	Soil and 10% stone dust of soil weight	Air dried, 3, 6	30°, 45°, 60°
(4)	S + 10% BD	2, 5	Soil and 10% brick dust of soil weight	Air dried, 3, 6	30°, 45°, 60°
(5)	S + 10% DD	2, 5	Soil and 10% building demolish dust of soil weight	Air dried, 3, 6	30°, 45°, 60°
(6)	S + 30% WD	2, 5	Soil and 30% saw dust of soil weight	Air dried, 3, 6	30°, 45°, 60°
(7)	S + 30% SD	2, 5	Soil and 30% stone dust of soil weight	Air dried, 3, 6	30°, 45°, 60°
(8)	S + 30% BD	2, 5	Soil and 30% brick dust of soil weight	Air dried, 3, 6	30°, 45°, 60°
(9)	S + 30% DD	2, 5	Soil and 30% building demolish dust of soil weight	Air dried, 3, 6	30°, 45°, 60°

Horizontal seismic inertia force acting on soil wedge is

$$Q_h(t) = \int_0^H m(z) \cdot a_h(z, t) dz$$

$$Q_h(t) = \frac{k_h \gamma \lambda H (\cot \alpha - \cot i)}{4\pi^2} \left[2\pi \cos 2\pi \left(\frac{t}{T} - \frac{H}{\lambda} \right) + \frac{\lambda}{H} \left\{ \sin 2\pi \left(\frac{t}{T} - \frac{H}{\lambda} \right) - \sin 2\pi \frac{t}{T} \right\} \right] \quad (4)$$

Similarly vertical seismic inertia force is

$$Q_v(t) = \int_0^H m(z) \cdot a_v(z, t) dz \quad (5)$$

$$Q_v(t) = \frac{k_v \gamma \eta H (\cot \alpha - \cot i)}{4\pi^2} \left[2\pi \cos 2\pi \left(\frac{t}{T} - \frac{H}{\eta} \right) + \frac{\eta}{H} \left\{ \sin 2\pi \left(\frac{t}{T} - \frac{H}{\eta} \right) - \sin 2\pi \frac{t}{T} \right\} \right] \quad (6)$$

The resultant weight which makes an angle ψ' with vertical and is given as

$$\psi' = \tan^{-1} \frac{k_h}{(1 \pm k_v)} \quad (7)$$

Using sine rule:

$$\frac{W'}{\sin(90^\circ + \phi_m)} = \frac{c_m}{\sin(\alpha + \psi' - \phi_m)} \quad (8)$$

$$= \frac{R}{\sin(90^\circ - \alpha - \psi')}.$$

Solving (6) we get

$$S_n = \frac{c_m}{\gamma H} = \frac{\sin \alpha \sin(\alpha + \varphi - \phi_m) (\cot \alpha - \cot i)}{2 \cos \phi_m} \times \left[1 \pm \frac{\eta k_v}{H \pi^2} \left\{ 2\pi \cos \omega \varepsilon + \frac{\eta}{H} (\sin \omega \varepsilon - \sin \omega t) \right\} + \frac{\lambda^2 k_h^2}{4\pi^4 H^2} \left\{ 2\pi \cos \omega \xi + \frac{\lambda}{H} (\sin \omega \xi - \sin \omega t) \right\}^2 + \frac{\eta^2 k_v^2}{4\pi^4 H^2} \left\{ 2\pi \cos \omega \varepsilon + \frac{\eta}{H} (\sin \omega \varepsilon - \sin \omega t) \right\}^2 \right]^{1/2}, \quad (9)$$

where $\varepsilon = t - H/V_p$, $\xi = t - H/V_s$.

Normal force (N) and shear force (S) acting on the soil wedge are expressed as

$$N = (W \pm Q_v(t) + (0.5\gamma H^2)) \cos \alpha - Q_h(t) \sin \alpha \quad (10)$$

$$S = (C + N \tan \phi).$$

And shear force $S = (C + N \tan \phi)$ along the failure plane.

Horizontal forces acting on the soil wedge are $S \cos \alpha$, $N \sin \alpha$, and $Q_h(t)$.

Factor of safety for unreinforced earth slope is the ratio of resisting force and driving force acting on soil wedge and it is formulated as

$$\text{Fos} = \frac{(C + N \tan \phi) \cos \alpha}{N \sin \alpha + Q_h(t)}. \quad (11)$$

When the slope is on the verge of failure factor of safety is reduced to unity and the acceleration which reduces this factor of safety is termed as yield acceleration k_y as discussed by Chanda et al. [23]. k_y is determined for different slope inclination and soil friction angle by equating factor of safety to one and k_y is formulated by substituting all terms in (11) and is expressed as

$$k_{y1} = \frac{m_3}{m_4} \quad (12)$$

$$\text{or } k_{y2} = \frac{m_3}{m_5}.$$

k_{y1} and k_{y2} are evaluated by MATLAB 2012 (a) optimization program which yields lesser value termed as k_y .

In these expressions

$$\begin{aligned}
 m_1 &= \frac{\gamma \lambda H (\cot \alpha - \cot i)}{4\pi^2} \left[2\pi \cos 2\pi \left(\frac{t}{T} - \frac{H}{\lambda} \right) \right. \\
 &\quad \left. + \frac{\lambda}{H} \left\{ \sin 2\pi \left(\frac{t}{T} - \frac{H}{\lambda} \right) - \sin 2\pi \frac{t}{T} \right\} \right] \\
 m_2 &= \frac{\gamma \eta H (\cot \alpha - \cot i)}{4\pi^2} \left[2\pi \cos 2\pi \left(\frac{t}{T} - \frac{H}{\eta} \right) \right. \\
 &\quad \left. + \frac{\eta}{H} \left\{ \sin 2\pi \left(\frac{t}{T} - \frac{H}{\eta} \right) - \sin 2\pi \frac{t}{T} \right\} \right] \\
 m_3 &= \left\{ \cos \alpha (\sin \alpha - \tan \phi \cos \alpha) (W + 0.5\gamma H^2) \right\} - c \\
 &\quad \cdot \cos \alpha \\
 m_4 &= (m_1 \\
 &\quad + (a_c m_2 \cos \alpha - m_1 \sin \alpha) (\sin \alpha - \tan \phi \cos \alpha)) \\
 m_5 &= (m_1 \\
 &\quad - (a_c m_2 \cos \alpha - m_1 \sin \alpha) (\sin \alpha - \tan \phi \cos \alpha)) .
 \end{aligned} \tag{13}$$

$H/\lambda = 0.25$ and $H/\eta = 0.09$, $a_c = k_v/k_h$ for horizontal motion only, and $a_c = 0$ and while applied acceleration is more than yield acceleration the sliding displacement of slope is obtained by double integrating the difference of the applied acceleration and the yield acceleration over time of earthquake excitation and is expressed as

$$SD = \int_0^t \int_0^t (k_h - k_y) g dt. \tag{14}$$

In the present analysis applied acceleration is assumed to be $k_h = 0.2g$ as all the model slope in test is subjected to a horizontal base shaking of $0.2g$ acceleration. Strength parameter of model slope material is taken from Figure 4 and for each slope the sliding displacement using pseudodynamic method is determined.

4. Results and Discussions

4.1. Acceleration Response on Slopes Subjected to Dynamic Loading. Acceleration-time history plot of 4 accelerometers placed at different elevations of a typical model test is shown in Figure 7. It has been observed that for a typical model slope with 45° inclination and made up of S + 10% SD at 3% water content, the acceleration at different elevation along the slope height (A2, A3 and A4) is on an average about 1.15, 1.4, and 1.55 times the base acceleration (A1), respectively.

Plots presented in Figure 8 show acceleration responses of all model slopes for different slope material, slope inclination angle, and frequency of input motion at air dried condition. For simplification the abscissa in these plots represents the normalized elevation (h/H) and axis represents RMSA amplification factor. Root mean square acceleration (RMSA)

FIGURE 7: Acceleration history of accelerometers placed at different elevation of a typical soil slope with 45° inclination, frequency 5 Hz.

amplification factor is the ratio of response acceleration value in the soil to that of the corresponding value of the base acceleration (Kramer, 1996, ML). The RMSA value seen in these plots corresponds to the state at the end of 2 Hz and 5 Hz shaking for duration of 10 seconds. These plots depict that acceleration amplification at top is to be the most and the values are highly dependent on slope material. As the material strength increases the acceleration RMSA amplification value decreases for a typical slope at typical frequency of input motion. Figures 8(a)–8(f) depict that “RMSA amplification factor” value decreases up to 35.42%, 36.36%, 33.89%, 35.71%, 32.31%, and 28.98%, respectively, when the slope material is changed from soil to “S + 30% DD” at normalized elevation. Similarly the pattern is also observed for other model slopes under sinusoidal motion and these responses are presented in Table 3. Tabulated result also shows that responses of slope material with higher densities are better than slope material with lower densities for a typical slope at a particular frequency of input motion.

4.2. Horizontal Displacement of Base due to the Effect of Dynamic Loading on Model Slope. Horizontal sinusoidal input motion caused sliding displacement of base. The displacement base ratio (D/B) of model slopes made up of various material mixtures at different water content is presented in tabular form. For three different water content unit weights of slope mass are different and it is reflected from Table 4 that “ D/B ” is decreasing with increase in water content of the mixture. The table depicts that “ D/B ” ratio is different for different mixtures. S + 30% DD mixture has maximum strength and due to this reason for a particular water content and nature of input motion the “ D/B ” value is minimum when slope is made up of this material. It has been observed from the table that, for slope inclination 30° , “ D/B ” value decreases up to 96%, when the slope material is changed from soil to “S + 30% DD” at 6% water content and frequency of input motion 2 Hz. Similarly, other results presented in the table reflect that slope made up soil shows adverse response against dynamic loading and the performance of slope improves gradually from soil to “S + 30% DD” along with increase in water content of slope material.

4.3. Crest Deformation of Model Slope after Loading. Vertical deformation at crest on all slope models has been observed when the input motion is imposed for certain duration. The crest deformation to slope height ratio (h/H) against water content for different mixtures is observed and presented in

FIGURE 8: Response of slope made up of soil and soil dust mixtures at frequency of input motion 2 Hz and 5 Hz for air dried material.

TABLE 3: Response of slope made up of soil and soil dust mixtures at frequency of input motion 2 Hz and 5 Hz at different water content.

Slope material	Normalized elevation	RMSA amplification factor											
		3% water content						6% water content					
		2 Hz frequency		5 Hz frequency		2 Hz frequency		5 Hz frequency		2 Hz frequency		5 Hz frequency	
		Slope angle in degree		Slope angle in degree		Slope angle in degree		Slope angle in degree		Slope angle in degree		Slope angle in degree	
		30	45	60	75	30	45	60	75	30	45	60	75
Soil	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	3.8	4.24	4.9	4.2	4.58	5.5	5.5	2.8	3.2	3.2	3.5	4.5
	0.66	5.8	6.3	6.9	6.2	6.9	7.5	7.5	4.8	5.2	5.2	5.5	6.5
	1	6.9	7.4	7.9	7.3	7.9	8.9	8.9	5.9	6.3	6.3	6.6	7.5
S + 10% WD	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	3.7	4.1	4.8	4	4.4	5.4	5.4	2.6	3	3	3.4	4.1
	0.66	5.7	6.2	6.5	6	6.8	7.2	7.2	4.6	5	5	5.3	6.2
	1	6.8	7.1	7.5	7.2	7.8	8.6	8.6	5.8	6.2	6.2	6.5	7.1
S + 10% SD	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	3.4	3.9	4.3	3.8	4.3	5.2	5.2	2.4	2.8	2.8	3.1	3.9
	0.66	5.5	6.1	6.3	5.9	6.4	6.9	6.9	4.5	4.9	4.9	5.2	5.9
	1	6.7	7.2	7.3	7.1	7.6	8.1	8.1	5.7	6.1	6.1	6.4	6.9
S + 10% BD	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	2.9	3.3	3.8	3.3	3.7	4.8	4.8	1.9	2.3	2.3	2.6	3.4
	0.66	5.1	5.5	5.6	5.5	5.8	6.4	6.4	4.1	4.5	4.5	4.8	5.3
	1	6.4	6.8	6.9	6.8	7.3	7.7	7.7	5.4	5.8	5.8	6.1	6.6
S + 10% DD	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	2.7	3.2	3.7	3.1	3.4	4.7	4.7	1.7	2.1	2.1	2.4	3.3
	0.66	4.9	5.3	5.5	5.3	5.6	6.1	6.1	3.9	4.3	4.3	4.6	5.1
	1	6.1	6.5	6.7	6.5	6.9	7.4	7.4	5.1	5.5	5.5	5.8	6.3
S + 30% WD	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	2.6	3.1	3.6	3	3.3	4.4	4.4	1.6	2	2	2.3	3.2
	0.66	4.8	5.1	5.3	5.2	5.5	5.9	5.9	3.8	4.1	4.2	4.5	4.9
	1	6	6.3	6.6	6.4	6.8	7.3	7.3	5	5.4	5.5	5.7	6.2
S + 30% SD	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	2.5	2.9	3.4	2.9	3.1	4.1	4.1	1.5	1.9	1.9	2.2	3
	0.66	4.5	4.9	5.2	4.9	5.4	5.5	5.5	3.5	3.9	3.9	4.2	4.5
	1	5.9	6.2	6.5	6.3	6.7	7.2	7.2	4.9	5.3	5.3	5.6	6.1
S + 30% BD	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	2.3	2.7	3.1	2.7	2.9	3.8	3.8	1.3	1.7	1.7	2	2.7
	0.66	4.1	4.4	4.6	4.5	4.9	5.1	5.1	3.1	3.5	3.5	3.8	4.2
	1	5.7	5.9	6.4	6	6.3	7	7	4.7	5.1	5.4	5.4	6
S + 30% DD	0	1	1	1	1	1	1	1	1	1	1	1	1
	0.33	2.1	2.5	2.9	2.5	2.7	3.2	3.2	1.1	1.5	1.5	1.8	2.5
	0.66	3.8	4.1	4.3	4.2	4.3	4.8	4.8	2.8	3.2	3.2	3.5	3.9
	1	5.3	5.8	6	5.8	6	6.8	6.8	4.3	4.7	4.8	5	5.6

TABLE 4: Response of slope made up of soil and soil dust mixtures in terms of base displacement at frequency of input motion 2 Hz and 5 Hz.

Slope material	Water content	Displacement base ratio (D/B)					
		2 Hz frequency			5 Hz frequency		
		Slope angle in degree			Slope angle in degree		
		30	45	60	30	45	60
Soil	0	0.16	0.23	0.28	0.17	0.26	0.31
	3	0.12	0.19	0.19	0.14	0.21	0.22
	6	0.1	0.15	0.16	0.11	0.17	0.18
S + 10% WD	0	0.15	0.21	0.26	0.16	0.25	0.29
	3	0.11	0.17	0.16	0.12	0.19	0.19
	6	0.09	0.13	0.15	0.1	0.15	0.171
S + 10% SD	0	0.13	0.2	0.24	0.16	0.25	0.28
	3	0.1	0.15	0.16	0.12	0.19	0.185
	6	0.08	0.12	0.14	0.09	0.15	0.165
S + 10% BD	0	0.11	0.17	0.2	0.15	0.22	0.25
	3	0.08	0.104	0.12	0.11	0.14	0.156
	6	0.06	0.08	0.1	0.09	0.11	0.125
S + 10% DD	0	0.08	0.13	0.15	0.13	0.19	0.203
	3	0.06	0.075	0.09	0.08	0.11	0.119
	6	0.04	0.05	0.064	0.05	0.08	0.085
S + 30% WD	0	0.07	0.11	0.13	0.11	0.18	0.18
	3	0.05	0.061	0.08	0.07	0.098	0.105
	6	0.02	0.04	0.04	0.03	0.054	0.064
S + 30% SD	0	0.06	0.09	0.11	0.10	0.17	0.16
	3	0.04	0.048	0.05	0.07	0.096	0.0747
	6	0.013	0.02	0.02	0.02	0.04	0.034
S + 30% BD	0	0.04	0.07	0.08	0.08	0.16	0.12
	3	0.02	0.03	0.04	0.04	0.075	0.061
	6	0.009	0.013	0.02	0.02	0.025	0.024
S + 30% DD	0	0.03	0.05	0.07	0.07	0.134	0.117
	3	0.01	0.017	0.02	0.02	0.064	0.033
	6	0.004	0.01	0.01	0.01	0.018	0.016

Table 5. It has been seen from table that “ h/H ” ratio decreases about 46% when the slope material is changed from soil to “S + 30% DD” at air dried condition for a slope inclination 30° . Similarly the gradual increase of strength from soil to different soil mixtures for a particular water content and nature of input motion has also depicted from the tabulated result.

4.4. Evaluation of Critical Angle of Failure Plane with Horizontal from Pseudodynamic Analysis of Slope. For a stable condition the stability number of slope must be low. Eqn. (9) is solved using MATLAB 2012(a) and the critical α value (α_c), that is, inclination of failure surface with horizontal corresponding to maximum stability number for each slope at different soil condition, is evaluated. Table 6 shows the value of α_c and S_n for a model slope made up of S + 10% WD

at different slope inclination and internal friction angle of mixture.

5. Comparison

The deformed slope geometry after both experimental and analytical studies subjected to horizontal sinusoidal vibration for slope material made up of soil and 30% stone dust at 6% water content is presented in Figure 9 and it has been observed that the failure line in experimental study is slightly lower than analytical one. The reason may be the limitations of small model test in laboratory under certain boundary condition.

Solving (14) sliding displacement of model slope by pseudodynamic method is evaluated and compared with sliding displacement observed on model slope under shake table test. Table 7 shows the analytical and experimental

TABLE 5: Response of slope made up of soil and soil dust mixtures in terms of crest deformation at frequency of input motion 2 Hz and 5 Hz.

Slope material	Water content	Crest deformation to slope height ratio (h/H)					
		2 Hz frequency			5 Hz frequency		
		Slope angle in degree			Slope angle in degree		
		30	45	60	30	45	60
Soil	0	0.26	0.3	0.36	0.3	0.34	0.4
	3	0.215	0.26	0.32	0.24	0.3	0.36
	6	0.16	0.2	0.26	0.2	0.24	0.3
S + 10% WD	0	0.25	0.29	0.35	0.29	0.33	0.39
	3	0.2	0.25	0.31	0.22	0.29	0.35
	6	0.15	0.19	0.245	0.19	0.23	0.29
S + 10% SD	0	0.24	0.28	0.34	0.28	0.32	0.38
	3	0.193	0.24	0.3	0.215	0.28	0.34
	6	0.14	0.18	0.24	0.18	0.22	0.28
S + 10% BD	0	0.225	0.26	0.32	0.26	0.3	0.36
	3	0.175	0.22	0.28	0.19	0.26	0.32
	6	0.12	0.16	0.22	0.16	0.2	0.26
S + 10% DD	0	0.2	0.24	0.3	0.24	0.28	0.34
	3	0.16	0.2	0.26	0.175	0.24	0.3
	6	0.11	0.14	0.2	0.14	0.18	0.24
S + 30% WD	0	0.19	0.22	0.28	0.23	0.26	0.32
	3	0.14	0.18	0.24	0.155	0.22	0.28
	6	0.105	0.12	0.18	0.13	0.15	0.22
S + 30% SD	0	0.16	0.2	0.26	0.2	0.24	0.3
	3	0.13	0.16	0.22	0.13	0.2	0.26
	6	0.1	0.1	0.16	0.1	0.14	0.2
S + 30% BD	0	0.14	0.18	0.24	0.18	0.22	0.28
	3	0.11	0.14	0.2	0.12	0.18	0.24
	6	0.08	0.08	0.14	0.08	0.12	0.18
S + 30% DD	0	0.12	0.16	0.22	0.16	0.2	0.26
	3	0.09	0.12	0.18	0.1	0.16	0.22
	6	0.04	0.06	0.12	0.072	0.1	0.16

TABLE 6: Critical angle and stability number of slope made up of soil + 10% saw dust.

i	S_n at $\phi = 10^\circ$	α_c (°)	$K_h = 0.2, K_v = 0$		S_n at $\phi = 12.5^\circ$	α_c (°)
			S_n at $\phi = 11.5^\circ$	α_c (°)		
10°	0.0288	7.2	0.026	8	0.023	8.1
20°	0.051	17.5	0.048	18	0.046	18.4
30°	0.075	25.6	0.073	26	0.071	26.5
40°	0.1	36.5	0.092	37	0.089	37.52
50°	0.126	46.2	0.11	47	0.092	47.4
60°	0.155	56.2	0.14	57	0.12	57.3

results for sliding displacement under horizontal sinusoidal vibration for different model at different water content and unit weight for slope material made up of soil and 30% stone dust.

6. Conclusions

In this present paper an attempt is made to conduct experiment on model slopes made up of soil and soil dust

mixtures. An analytical work using pseudodynamic method considering planer rupture surface is also carried out. On the basis of analysis of results in the present investigation, the following conclusions are drawn:

(1) Recorded responses of accelerometers placed at different elevation along slope height reflect that water content of slope material affects slope safety. At normalized elevation 0.33 and frequency of input motion 2 Hz response of slope with inclination 60° in terms of RMSA decreases up to 20.4%

FIGURE 9: Deformation of model slope measured and pattern of failure surface during shake table test and pseudodynamic analysis of slope made up of S + 30% SD for frequency 2 Hz and 5 Hz at water content 6%.

TABLE 7: Sliding displacement of slope made up of S + 30% BD from experimental result and pseudodynamic analysis.

Water content (%)	Slope angle	Sliding displacement (mm)			
		2 Hz frequency		5 Hz frequency	
		Experimental result	Analytical result	Experimental result	Analytical result
0	30°	8	7.64	9	9.3
	45°	8.5	8.68	10.4	9.89
	60°	10	9.86	11	10.64
3	30°	7.3	7.42	7.9	7.83
	45°	7.5	7.49	8.5	8.2
	60°	8.4	8.32	9.1	8.96
6	30°	6.5	6.54	7	7.26
	45°	7.1	7.21	7.8	7.86
	60°	8	8.13	8.5	8.54

when water content of soil changes from 3% to 6% and the similar pattern is also observed for other slope materials also. In addition results also depict stability of slope is highly dependent on slope material. At same normalized elevation and base shaking frequency RMSA decreases up to 20.8%, 22.4%, 29.3%, and 34.5% when slope material changes from “soil” to “S + 30% WD,” “S + 30% SD,” “S + 30% BD,” and “S + 30% DD,” respectively, for model slope with 30° inclination at 3% water content.

(2) Displacement of base due to seismic excitation is observed in each model slope after test and it has been clearly visible that when input motion is generated with frequency 2 Hz for a duration of 10 sec on slope with 45° inclination at water content 3% the “D/B” ratio is highest for slope made up of soil and decreases up to 10.5%, 21%, 45%, and 63% when slope material changes from “soil” to “S + 10% WD,” “S + 10% SD,” “S + 10% BD,” and “S + 10% DD,” respectively. Similar pattern is also observed for response of slope when measured in terms of crest deformation and the “h/H” ratio is reduces up to 3.8%, 7.7%, 15.4%, and 23% when slope material changes from “soil” to “S + 10% WD,” “S + 10% SD,” “S + 10% BD,” and “S + 10% DD,” respectively. Also slope model constructed with soil dust mixtures is observed to be more stable when water content of the material mixture changes from 3% to 6%.

(3) Stability number critical angle of failure surface α_c of a model slope has been evaluated by pseudodynamic method. Horizontal sliding displacement of a slope in a particular soil and seismic condition is determined analytically and compared with base displacement of model slope observed in the shake table test. The pattern of failure for both analytical and experimental investigation is also presented.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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