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STABILITY ANALYSIS OF STEEP NAILED SLOPES IN SEISMIC CONDITIONS: NUMERICAL APPROACH

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Abstract. *In this paper an attempt has been made to understand the seismic behavior and deformation characteristics of model steep nailed soil slopes by numerical studies. A two-dimensional plane-strain numerical model has been developed to simulate steep nailed slopes by finite element software, MIDAS GTS. The real time-history analyses are carried out to study the seismic response of nailed-soil slopes. The effect of various influencing parameters such as the nail inclinations and the slope angles on the seismic resistance and failure mechanism of the nailed slopes are studied in details. The numerical model developed has been used to examine the shaking table test results of steep nailed slopes [1]. The nailed soil slopes are modeled in FE analysis as per the geometry of shake table testing and the numerical analysis are carried out for different seismic excitations. The numerical results such as maximum lateral displacements at various heights of the facing are compared with the test results for various slopes angles, nail inclinations and peak amplitude of accelerations. The failure pattern of nailed soil slopes for different seismic conditions obtained from the numerical analysis are studied and compared with the experimental failure patterns. A reasonable agreement between the finite element analysis and shaking table test results are obtained.*

1 INTRODUCTION

The use of soil nailing method for the in-situ stabilization of existing slopes and excavations has now covered a wider part of the world. Soil nailing for improving the stability of slopes started in Versailles (France) for the first time in 1972 [2]. The fundamental concept of soil nailing method consists of placing of closely spaced passive inclusions in the ground to restrain the displacements and limit decompression of soils during and after excavation. A factor, which makes soil nailing technique more desirable than the other earth reinforcing techniques when performed on cuttings or excavations, is its easy and flexible top-down construction. Hence the soil-nailing method is a better in-situ reinforcement technique than others. It has also been proved in the literature [1], that the performance of nailed soil slopes is quite excellent than the gravity retaining structures under earthquake conditions. The literature survey on the nailed soil structures reveals that lots of work has been done on the design and construction methodologies, laboratory modeling and numerical modeling of nailed slopes and excavations under static load condition [3, 4, 5, 6, 7, 8, 9, 10]. Hong et al. [1] investigated the performance of nailed soil slopes under dynamic condition in the laboratory. Lou and Ye [11] and Sabahit et al. [12] studied theoretically the performance of such structures under seismic conditions. The failure or distress reported in the literature [13] due to Earthquakes showed how vulnerable these structures are to ground motions. Hence more research is required to properly understand the behavior of nailed soil structures under seismic conditions.

A series of laboratory shaking table tests were conducted on five model nailed soil slopes with various nail and slope arrangements [1]. In this paper, an attempt is made to back-analyze the three models out of the five models [1] for three input peak amplitude of accelerations (g) such as 0.474g, 0.598g and 0.818g which are summarized in table 1. The numerical models using finite element software, MIDAS GTS are developed to examine the effect of nail inclination and the slope angle on the seismic response of steep nailed soil slopes.

2 DETAILS OF THE NUMERICAL MODEL

Two-dimensional plain-strain model slopes with different slope angles and nail inclinations are developed using the same geometry as per the dimensions of the laboratory shaking table test [1]. The nails are modeled as one-dimensional linear elastic structures and the facing plate is modeled as two-dimensional plain-strain elastic structure. The dimensions of PMMA tubes (Nails) and PMMA plate (Facing) used in FE analysis are considered as per the reported literature [1]. The Mohr-Coulomb model is adopted for soil to simulate the elasto-plastic behavior of soil. The water table is assumed to be at great depth. The material parameters of soil, nail and facing plate are also considered same as those adopted for the shake table testing. The schematic diagram of geometry and generated mesh of the model no. 2 is shown in Figure 1.

Model No.	Slope angle (˚)	Nail length (m)	Nail inclination (˚)	Frequency amplification factor	Input peak amplitude of accelerations (g)
1	80	0.4	0	5.0	0.5952
2	80	0.4	30	5.0	0.8281
3	90	0.4	0	5.0	0.4784

Table 1. Summary of numerically developed model slope arrangements

In FE analysis, the meshing has been done using 8-noded quadrilateral elements. Since the meshing type chosen for soil elements and nail elements are quadratic and linear respectively, the connection between these two different type of elements are made by extracting the line (nail) elements and merging their nodes with the surrounding nodes of quadratic (soil) elements after dividing each linear element in to two. The interface elements are created around the nail elements by calculating the normal stiffness modulus, shear stiffness modulus, cohesion, internal friction angle and strength reduction factor from the material properties to provide the interface between soil and nail. Similarly interface elements are also created between the facing plate and the soil. In the FE analysis, the locations where the displacements are measured at various heights of the facing in the test [1] are marked by creating points on the facing as shown in Figure 1. The other two models are also developed similar to this model by adopting the same mesh type as well as same element size.

Then the boundary conditions have been provided. The Bottom soil boundary nodes are considered as fixed against displacement in both horizontal and vertical directions while at the side soil boundary nodes, displacement is restrained in horizontal direction and is allowed in vertical direction.

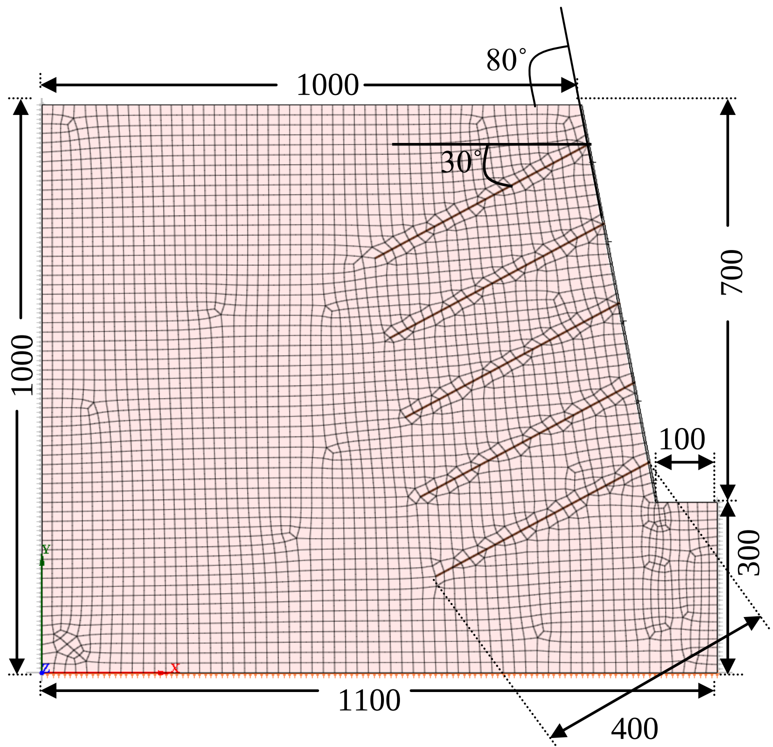


Figure 1. The mesh and boundary conditions used for the FE analysis for model 2. All dimensions are in millimeters.

All the three models developed using the finite element method with different slope and nail arrangements are analyzed with the respective input peak amplitude of accelerations (*g*) as per the shaking table test. The time history analyses are carried out on the developed FE model slopes using the inbuilt earthquake histories in the finite element software, MIDAS GTS. Figure 2 is a plot of the time history of the acceleration for all the three input peak amplitude of accelerations (*g*) with frequency amplification factor = 5.0 which are chosen for the finite element analysis. These data are used in finite element analysis to provide unidirectional (horizontal) seismic excitation which is similar to the laboratory shaking table test.

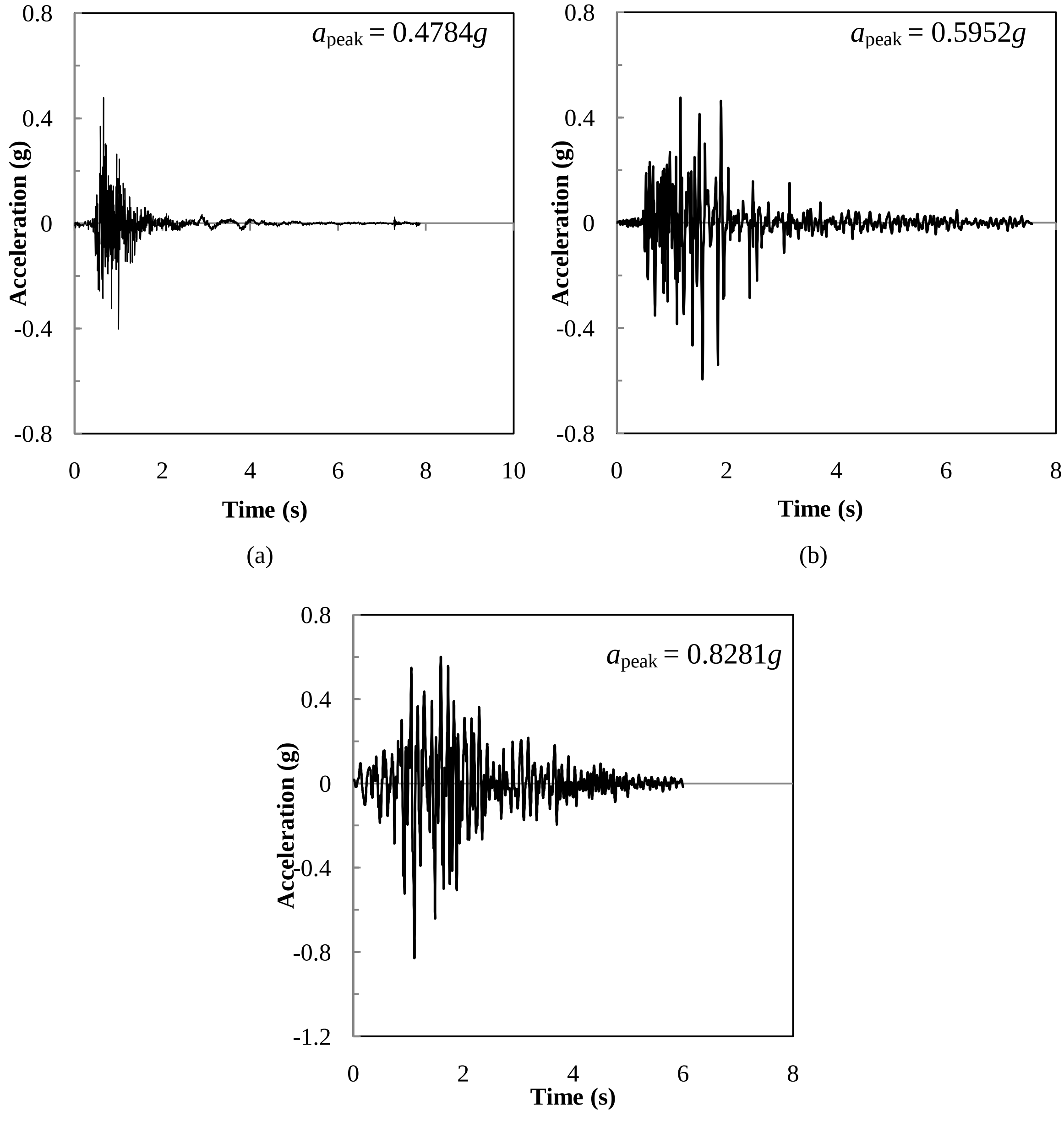


Figure 2. History of acceleration: (a) 1979, James RD. El Centro, Up ; (b) 1979, Bonds Corner El Centro, 310 Deg ; (c) T2-I-1 (1995, HYOUGOKEN South, NS)

In the numerical analysis, the peak amplitude of accelerations (g) are 0.4784g, 0.5952g, 0.8281g in place of 0.474g, 0.598g and 0.818g respectively and these values are adopted as per the available inbuilt earthquake histories. The input peak amplitude of accelerations (g) considered in shaking table test and the numerical analysis are nearly equal for the respective model slopes.

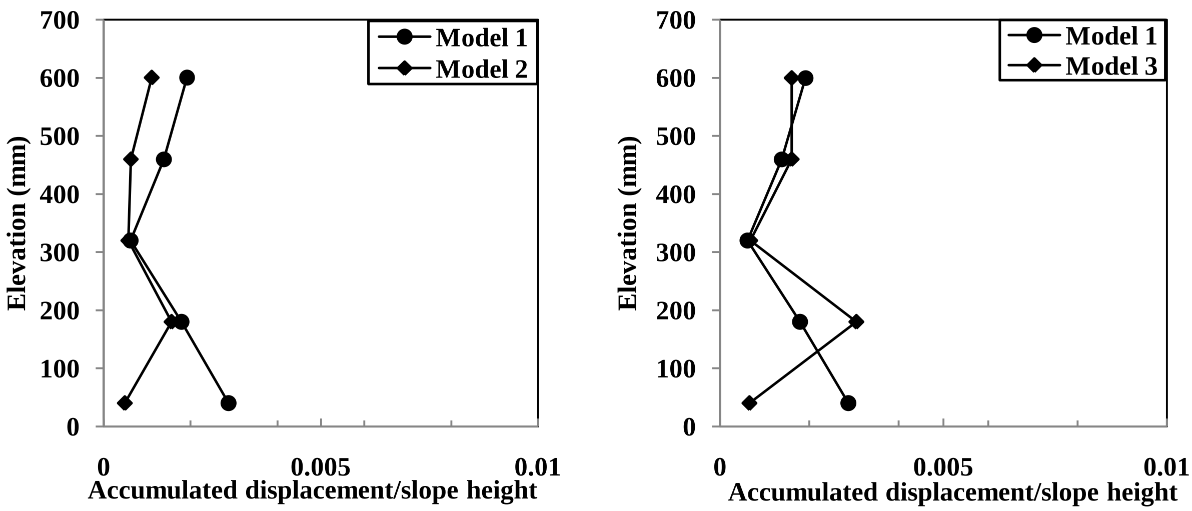
3 RESULTS AND DISCUSSIONS

The normalized accumulated displacements of the facing at the end of the seismic sequence is shown in Figure 3(a, b) for all the models with $a_{peak} = 0.5952g$.

3.1 Effect of nail inclination

The effect of nail inclination on the seismic response of slopes is studied for model 1 and model 2 having two different nail inclinations (0˚ and 30˚) keeping other parameters as constant and the variation of the response for various slope angles is shown in Figure 3. It can be seen from the plot that the outward movement of the toe of model 1 is greater than that of model 2 which shows translation of the entire slope mass in case of the slope with nail inclination of 0˚. The nature of movement of soil for the upper soil mass and the lower soil mass are just reverse of each other for model 1 as well as for model 2. For model 2, the upper soil mass exhibits greater outward movement than the lower soil mass which indicates the rocking of the slope with nail inclination of 30˚.

Hence it can be concluded from this plot that the translational movement is more predominant with a little rocking in case of the slope having nail inclination of 0˚. In case of the slope having nail inclination of 30˚, there is a combination of translational and rocking movement with lesser translational and rocking movement than model 1 (nail inclination of 0˚). The magnitude of facing displacement at all the measured points is also greater in case of horizontally placed nails than that of inclined nails. Therefore the inclined nail for steep slopes is better option than the horizontally placed nails.



(a) (b)

Figure 3. Normalized accumulated displacements of the facing at the end of the seismic sequence ($a_{peak} = 0.5952g$): (a) model 1 and model 2; (b) model 1 and model 3.

3.2 Effect of slope angle

The effect of slope angle on the seismic response of two model slopes such as model 1 and model 3 having slope angle of 80˚ and 90˚ respectively keeping other parameters same is shown in Figure 3(b). Though the upper part of the soil mass in both the cases follows the same pattern of movement, the translational movement is more predominant for model 1 than model 3. However, there is a combination of translation and rocking for model 3.

3.3 FE Analysis Vs Shake table test

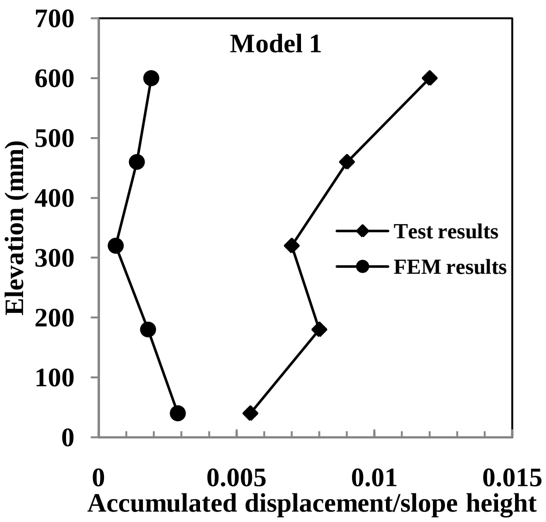
The comparison of test results with the FEM results from the plot between the normalized accumulated displacements of the facing with the slope height at every measured location for all the three models is shown in Figure 4.

In the plot of Figure 4(a) for model 1, the pattern of facing movement at all the measured points except at the toe of the slope are similar in both the cases i.e., FE analysis and the shaking table test. The combination of translation and rocking movement are found in both the cases. The magnitude of facing displacement at all the measured points is found greater in case of shaking table test than the FE analysis.

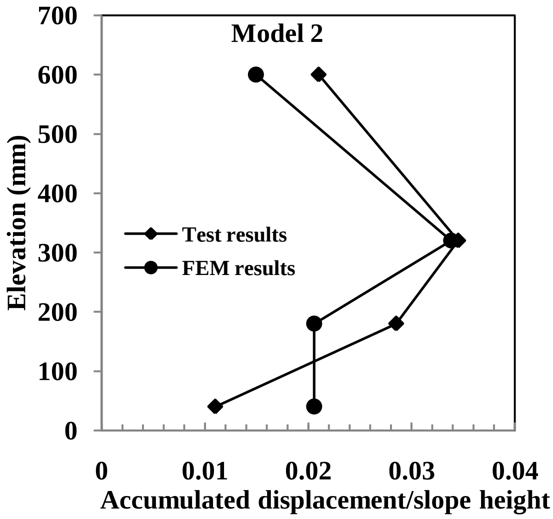
It can be seen from Figure 4(b) for model 2, the pattern of facing movement at all the measured points are similar for both the test and analysis. The combination of translation and rocking movement are found in both the cases. The magnitude of facing displacement at all the measured points is found greater in case of shaking table test than the FE analysis for this model. The model also exhibits a greater horizontal displacement in the middle part of the facing than in other parts for both the cases and hence proved to have a significant tendency of outward convex displacement.

In the plot of Figure 4(c) for model 3, the movement pattern at the middle part of the facing is similar in case of shaking table test and numerical analysis. Similar to other models, the combination of translation and rocking movement are found. The magnitude of facing displacement at all the measured points except at the toe and crest points are greater in case of shaking table test than the FE analysis. This model exhibits a significant tendency of outward convex displacement for both the cases.

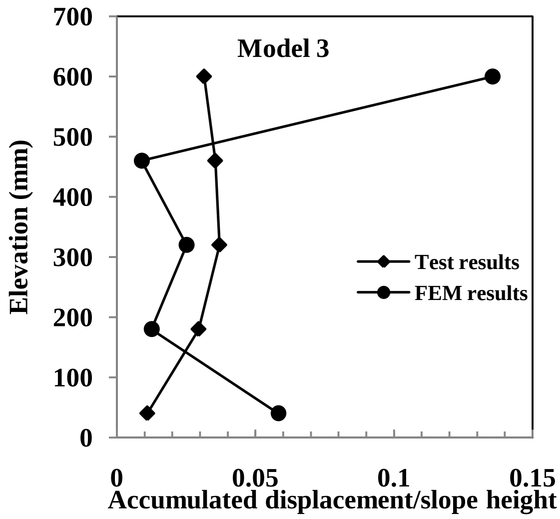
It has been shown in the results of finite element modeling [14, 15] that the seismic response of reinforced soil walls is a function of peak ground acceleration, peak velocity, duration of the ground motion, frequency content, distance from the source, and other factors. For the current numerical analysis, only one site characteristic (i.e., peak horizontal ground acceleration) has been considered. Hence the variation in the results of shake table test and the FE analysis may be due to the variation of acceleration history, earthquake duration and frequency of excitation considered in FE analysis and shake table testing.



(a)



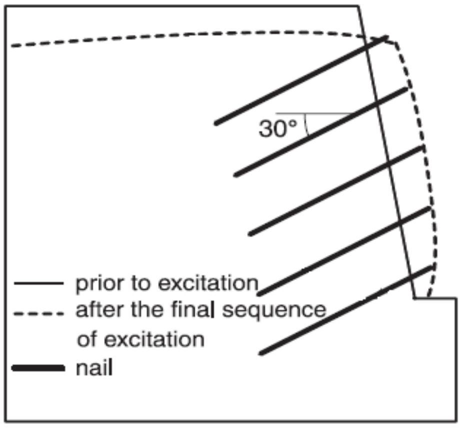
(b)



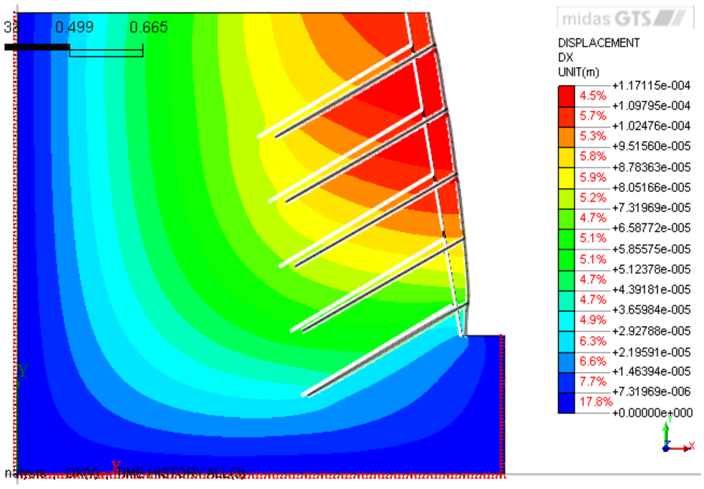
(c)

Figure 4. Normalized accumulated displacements of the facing at the end of each seismic sequence: (a) model 1; (b) model 2; (c) model 3.

The initial and final displacement diagram of model 2 at the end of the seismic sequence having $a_{\text{peak}} = 0.8281g$ has been depicted schematically in Figures 5(a) and (b) for shake table test and FE analysis respectively. The critical amplitude of acceleration for the model 2 at the end of a range of seismic sequences has already been found as $0.805g$ from the shaking table test. In the FE analysis, the peak amplitude of acceleration is considered as $a_{\text{peak}} = 0.8281g$ which is greater than the critical amplitude of acceleration ($0.805g$) obtained from the test. This may be the reason for higher deformation of the slope obtained in FE analysis.



(a)



(b)

Figure 5. Initial and final displacement diagram of model 2 at the end of the seismic sequence having a_{peak} = 0.8281g (a) Shake table test; (b) FE analysis.

4 CONCLUSIONS

The FE analysis has been conducted on the nailed soil slope models as per the geometry as well as the material parameters adopted in shaking table test [1]. The effect of angle of nails and the angle of slopes on the seismic resistance and failure mechanism of nailed soil slopes are analyzed by FE analysis corresponding to the three model slopes of the shaking table test. Some of the important conclusions drawn on the basis of the results obtained from the FE analysis and comparison with the shaking table test results are as follows:

- The effect of nail inclination on the seismic resistance of nailed soil slopes is very little though there is a substantial variation in the nature and magnitude of facing movement due to any particular earthquake loading. The magnitude of facing displacement is greater in case of horizontally placed nails than that of inclined nails. The translational movement is found more predominant in case of horizontally placed nails. The inclined nails exhibit a combination of translation and rocking and hence the inclined nails are better than the horizontally placed nails.

- The effect of slope angle on the seismic resistance of nailed soil slopes is quite significant as the magnitude of facing displacement is found high due under earthquake loading. The magnitude of facing displacement is greater in case of a slope having slope angle of 90˚ than the slope angle of 80˚. The translational movement is found more predominant in case of the 80˚ slope. A combination of translation and rocking is found for slope angle of 90˚.
- The deformation patterns in both the cases i.e., FE analysis and the shaking table test are found similar. The variation in magnitude of facing displacement at all the measured points as well as the movement pattern may be due to the chosen earthquake histories and their variation from the respective model tests.

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