Effect of Backfill Sand Density on Dynamic Response of Mechanically Stabilized Earth (MSE) Walls

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Abstract. Seismic resistant design of Mechanically Stabilized Earth (MSE) wall is essential for safe construction of these structures in earthquake-prone areas. The seismic behavior of a geogrid reinforced soil retaining wall was experimentally studied and presented here. The influence of the relative density of fine backfill sand was studied using 1-g shaking table tests. Small scale retaining wall models were constructed with two layers of geogrid on a uniaxial shaking table. The MSE wall was instrumented with accelerometers and LVDTs. Four models were tested with three increasing input peak ground acceleration (PGA) values to study the performance of these models. The face deformations and acceleration amplification factor (AAF) were estimated at different elevations for all models. Analyzing the performance of retaining structures under seismic ground shaking conditions helps in better understanding of their behavior during an earthquake and to design these structures more efficiently. The experimental results indicated that horizontal face deformations decrease as the backfill soil relative density was increased. It was also observed that AAF decreased when the base excitation was increased. This amplification is higher in dense soil backfill compared to loose soil. Hence, it was concluded that using fine sand in the dense state as fill material in retaining wall produces lower deformations in the facing wall as compared to the loose state of the sand.

Keywords: Shaking table tests; MSE wall; Geogrid; Acceleration amplification factor

1 Introduction

Mechanically stabilized earth (MSE) walls, also known as “reinforced soil,” have become a popular alternative to the traditional concrete retaining walls in many of today’s highway and bridge constructions. The cost of reinforced concrete retaining walls increases rapidly with the increase in the height of soil. Therefore, MSE walls can be a cost-effective solution compared to the conventional concrete walls. A Mechanically Stabilized Earth (MSE) retaining wall is a composite structure consisting of several layers of compacted backfill and soil reinforcement elements such as geosynthetics, polymeric or steel strips, etc., fixed to a wall facing. The stability of the wall system is derived from the interaction between the backfill and soil reinforcements, involving friction and tension. The wall facing is relatively thin, with the primary function of preventing erosion of the backfill soil. The result is a coherent gravity structure which is flexible and can carry heavy loads. The properties and materials of the three major components can vary, and an engineer must choose the most efficient combination based on the wall's design criteria. Facing elements are modular precast concrete panels, segmental blocks, etc. that can tolerate some differential movement. Each facing type offers different advantages when considering criteria such as aesthetics, durability, construction procedure, and expected settlement. Soil reinforcements are typically steel or geosynthetics, in the form of strips or ladders. All soil reinforcement options have unique characteristics for the pullout and tensile capacity, corrosion, and durability. Proper selection of Backfill material permits reliable construction and performance of the wall. The gradation, plasticity, electrochemical properties, and overall durability should be carefully analyzed.

The MSE walls can be quickly constructed, which is mostly not possible for conventional reinforced concrete walls. Curing and formwork are also not needed for these structures, hence reducing the need for support, scaffolding, and cranes as well. They also provide improved seismic performance and aesthetic benefits over conventional retaining walls [4],[12]**.** In addition to the cost reduction compared to conventional retaining walls, soil reinforcement also reduces carbon emissions and embodied energy, hence meeting the goals associated with sustainable development [6].

A series of four models with rigid facing panels reinforced with two layers of geogrid were tested using a shake table. Two of the models having vertical facing with total height 540 mm and the other two having inclined facing of 10^0 inclined towards the backfill soil with height 527.5 mm. The geogrids were kept at a spacing of 270 mm for the vertical facing models and almost the same height for the inclined facing models. Three different input motions were applied to the base with an increasing peak ground acceleration (PGA) values viz. low PGA, medium PGA, and high PGA and the effects of these motions on the facing panel were observed. The displacement of the panel was maximum at the mid portion of the facing panel, which decreased as the height increased for the vertical facings. The displacements at the top and bottom part of the panel also decreased as the sand density increased. A similar trend was also observed for the inclined facing models. It was found that the displacements for the inclined facing panels were comparatively lesser than the vertical ones. The acceleration response profiles for the panels and sand backfill were also compared. It was found that PGA value amplifies with the elevation of the backfill as the density increases for both vertical and inclined facings. The amplification factors also increase for the facing panels from lower to upper heights with an increase in the density of backfill sand.

2 Shake table test

2.1 Seismic box and Sand raining

A model of MSE wall retaining soil deposit with the dimensions of 655 mm (long) × 580 mm (wide) × 540 mm (height) was constructed within a rigid wooden box of dimensions 800 mm (long) × 580 mm (wide) × 770 mm (height) that was fixed to the shaking table. The wooden box is open at the front side. The size of the box base is slightly smaller than that of the shaking table to ensure the complete contact between them. The shaking table used in this study is designed for horizontal 1-dimensional shaking, applying sinusoidal motions only. The horizontal displacement of the shaking table is fixed, and the acceleration can be increased or decreased by changing the frequency of the motor. The dimensions of the table are 1000 mm × 700 mm equipped with 2 HP 1200 RPM motor. Fig. 1 shows the box mounted on a shake table used in the present study.
The sand was poured into the box using the sand raining system, maintaining a certain height to achieve the required relative density using a hopper. The sand was poured into the hopper attached to rods and was smoothly moved to the whole box to distribute the sand uniformly.

Fig. 1. The seismic box mounted on the shake table.

2.2 Model configurations and testing materials

The seismic responses of reduced-scaled MSE walls of 540 mm height using different backfill density were examined and compared in this study. The thickness of the facing panels was kept 25 mm for all the models. The test model configurations are shown in Table 1. Fine sand was filled at different relative densities in the wooden box which was mounted on a shaking table. The height of fall versus relative density curve was prepared for fine sand to control relative densities in the model.

Table 1. Test model configuration and parameters

Model No.	Backfill Property	Relative Density (%)	Facing	
			Toe boundary condition	Inclination
1	Loose	42	Sliding	Vertical
2	Dense	70	Sliding	Vertical
3	Loose	42	Sliding	10° inward from vertical
4	Dense	70	Sliding	10° inward from vertical

Soil

In this research, fine sand was used as backfill for all the MSE wall models with different relative densities. The specific gravity of the sand was 2.69. Other physical properties are tabulated in Table 2.

Table Error! No text of specified style in document.**.** Backfill soil physical property

Type of sand	Particle size range (mm)	Minimum density (g/cm^3)	Maximum void ratio (e_{max})	Maximum density (g/cm^3)	Minimum void ratio (e_{min})
Fine sand	0.075-0.425	1.434	0.876	1.708	0.575

Reinforcement

Two sets of biaxial geogrid have been used as reinforcing the material. It was a square shape with an aperture size 35 mm × 35 mm made up of firm polyester coated with the bituminous solvent which provides high frictional characteristics and grabbing power. The length of the geogrid was 400 mm. Reinforcement-to-wall height ratio (*L/H*) was 0.74, where '*L*' is the reinforcement length, and '*H*' is the height of the wall. This *L/H* ratio satisfies the criteria of FHWA, which recommends the length of reinforcement for MSE walls should not be less than *0.7H*.
Other properties of the geogrid reinforcement such as normal stiffness (EA) and tensile strength are 90 kN/m and 13 MPa, respectively.

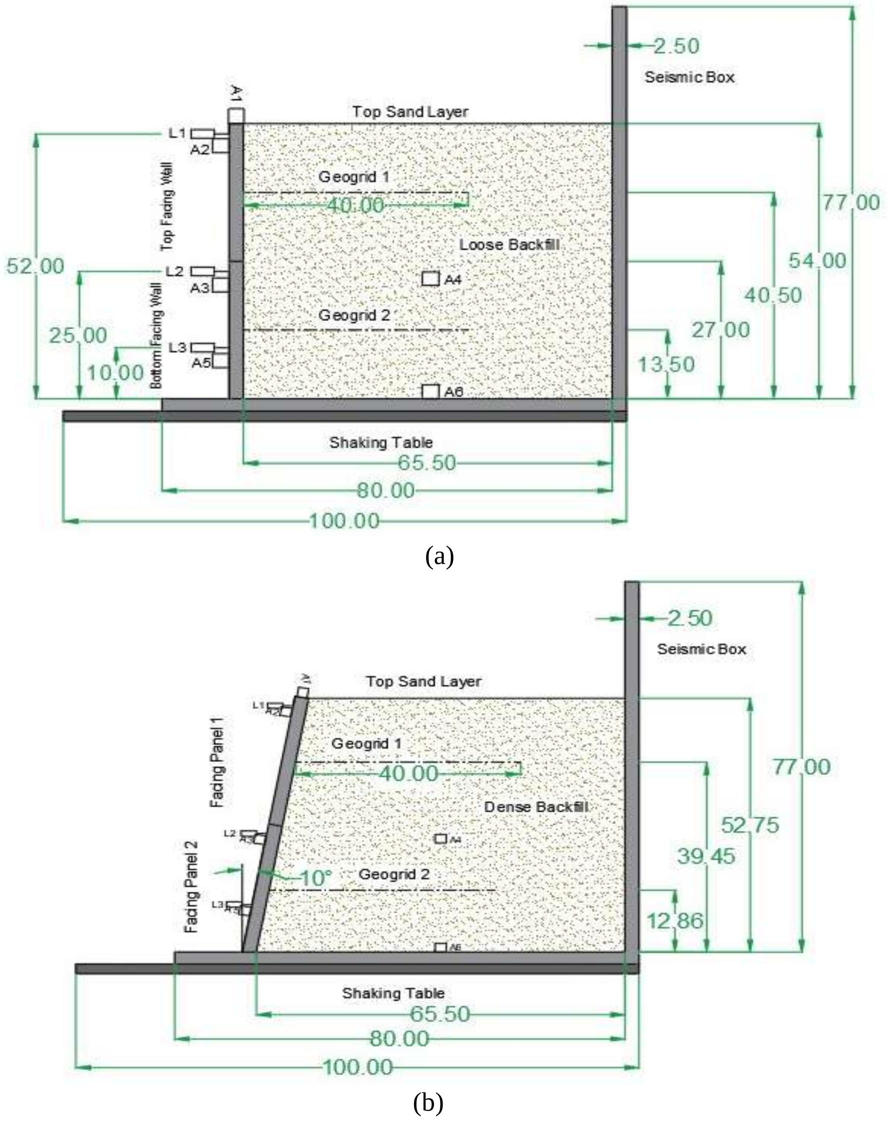

Fig. 2. Schematic representation of the shake table showing the layout of the MSE wall model (Side Elevation, all dimensions are in cm) (a) vertical facing, (b) inclined facing

2.3 Instrumentation

Modeling of MSE wall involves preparation of sand models at required relative densities and placing instruments at appropriate positions to measure its dynamic response. By fixing the wall inclination for respective MSE wall models (Table 2), the sand was filled into the box through a hopper in several layers to achieve a constant relative density. One accelerometer was fixed at the bottom of the wooden box. When sample thickness reached to a height of 135 mm, the first geogrid layer was placed and attached with the facing panel using four hook nails. After this, 135 mm of sand was filled again, and another accelerometer was placed at the center of the box. Likewise, another 135 mm of sand was filled, and the second geogrid layer was placed and attached with the facing panel using four hook nails. Then the last 135 mm of the sand layer was filled. Three accelerometers were attached at the top of the facing, middle of the facing and near the bottom where the lower geogrid was attached to the facing panel to measure the horizontal acceleration response of the facing panel. Another accelerometer was attached in the vertical direction at the top of the facing panel to measure the vertical acceleration response. Three LVDTs were placed in the facing panel at the same positions as the accelerometers to measure the horizontal deflection response of the facing panel. Schematic representation of the shake table MSE wall model is shown in Figure 2.

2.4 Base input motions

Three different sinusoidal base input motions with different peak ground acceleration (PGA), namely low PGA (PGA=0.062g), medium PGA (PGA=0.206g) and high PGA (PGA=0.369g) varying from lowest to highest were applied to the model through shake table. The input acceleration time histories are shown in Figure 3.

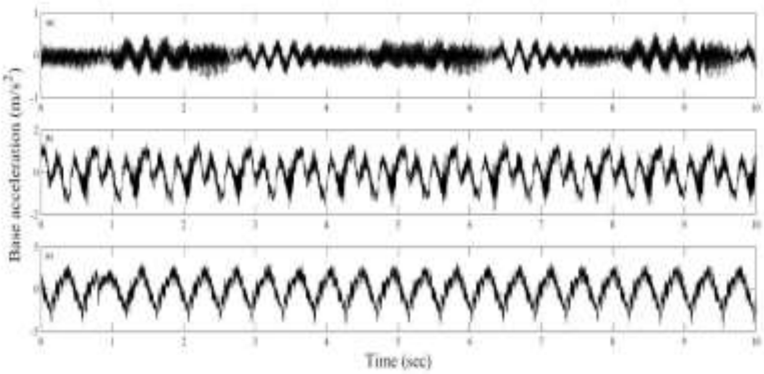

Fig. 3. Acceleration time histories (a) Low PGA, (b) Medium PGA, (c) High PGA

3 Results

3.1 Acceleration response

Acceleration response at different elevations has been presented in the form of Acceleration Amplification Factors (AAF) which is the ratio of the response acceleration value at any specific point to the corresponding value of the base input motion (Kramer 1996). Figures 4-7 shows the vertical distributions of acceleration amplification factors for three different motions (i.e., high PGA, medium PGA, and low PGA) comparing the amplification factors for the loose and dense state of soil at the facing panel and backfill sand. The black lines are showing the amplification for the loose condition, and the blue lines are showing for the dense sand. The data indicates that horizontal accelerations are amplified while transmitted through the facing panel and the backfill soil. The acceleration amplification factors for the facing panel are more nonlinear along elevation.

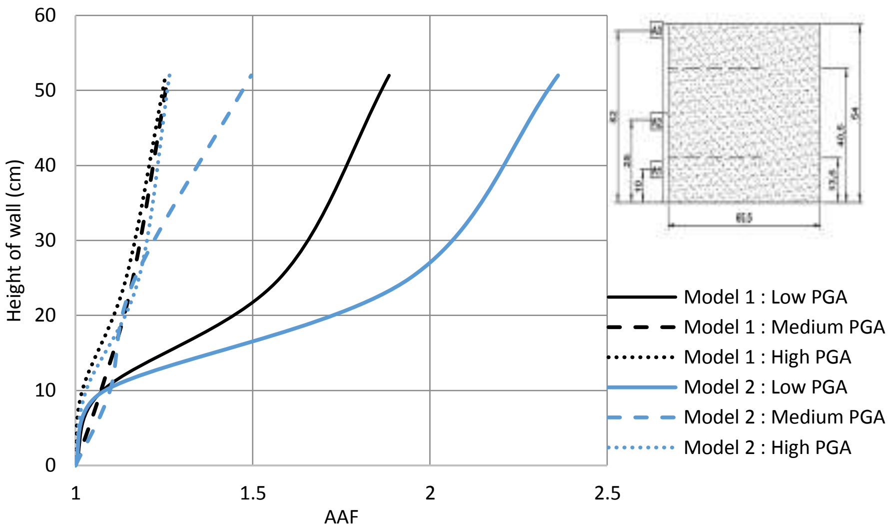

Fig. 4 Amplification of base input acceleration with height in facing panel (Models 1 and 2)

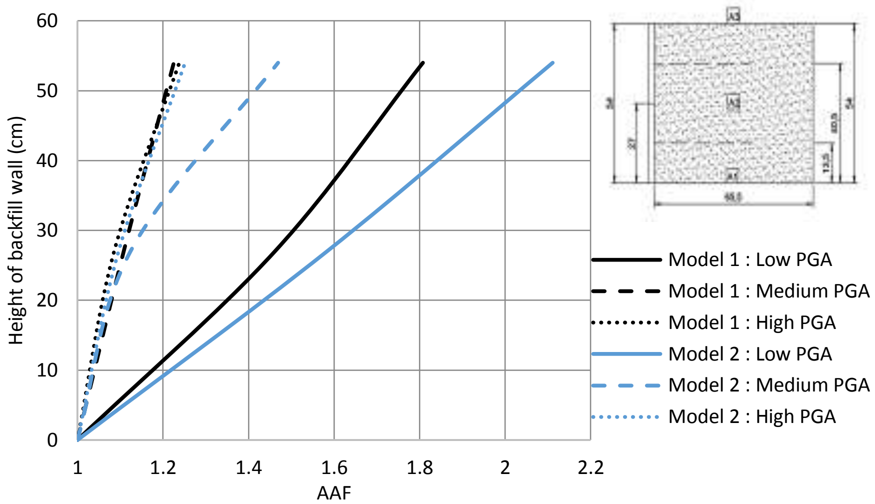

Fig. 5. Amplification of base input acceleration with height in backfill (Models 1 and 2)

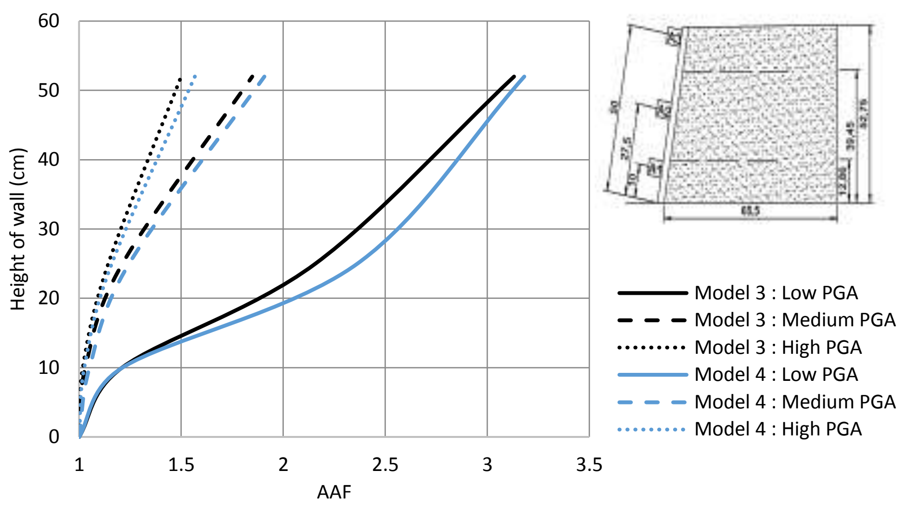

Fig. 6. Amplification of base input acceleration with height in facing panel (Models 3 and 4)

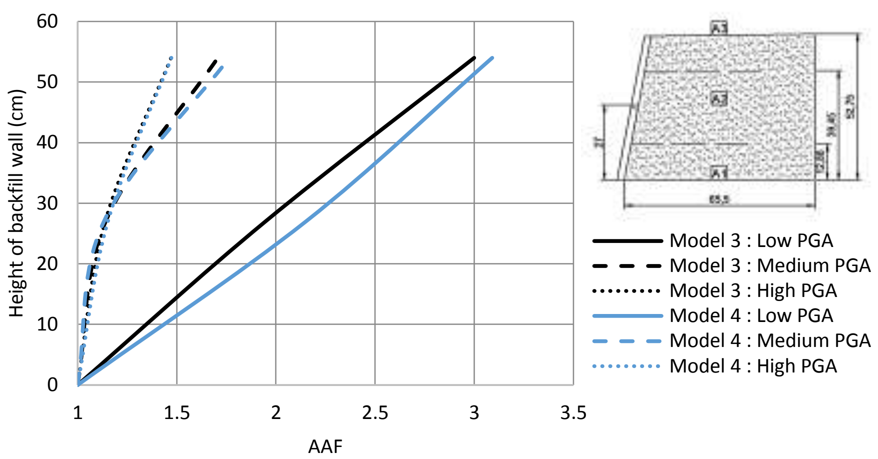

Fig. 7. Amplification of base input acceleration with height in backfill (Models 3 and 4)

The above results show a comparison of the acceleration amplification factors with an increase in the elevation in facing panels and soil backfill for both the soil conditions, i.e., loose and dense soil. The variation is found to be non-linear. The amplification of accelerations is found to be more at the top as compared to the lower elevations. These amplifications are also found to be higher for denser backfill conditions. Similar observations were obtained for both vertical and inclined facing panel.

3.2 Displacement response

The displacement response of the facing panel was observed for the three different input motions for loose and dense conditions of backfill. Figures 8-9 show the comparison of deflections of facing panel with height for vertical panel and inclined panel, respectively. The blue lines show displacement response for the loose sand model while the black lines show the same for the dense sand model.

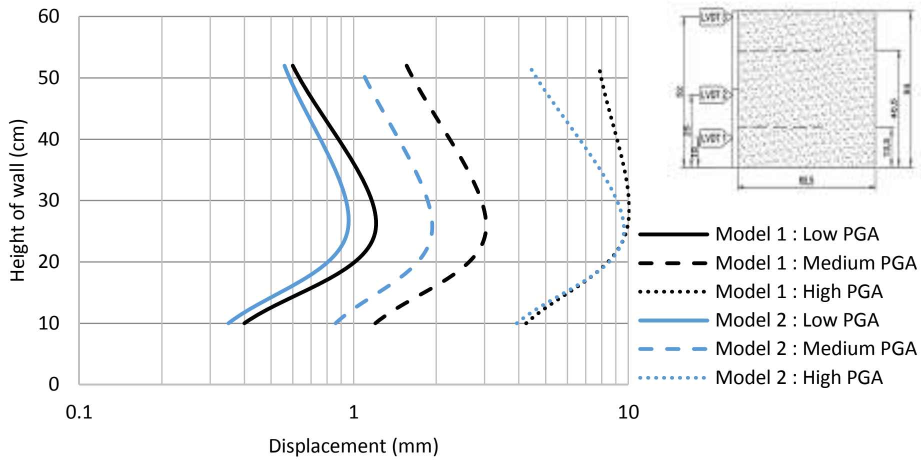

Fig. 8. Facing panel displacement response comparison for models 1 and 2

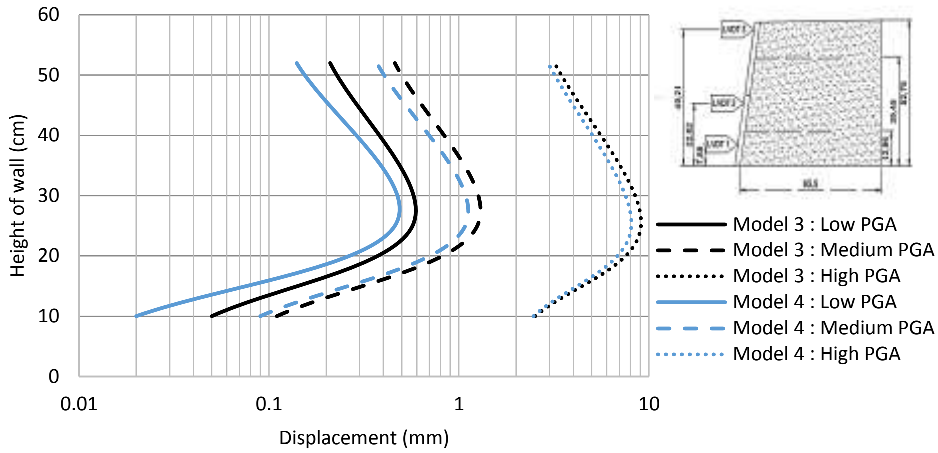

Fig. 9. Facing panel displacement response comparison for models 3 and 4

From the above graphical observations, it was observed that for all the cases, the maximum displacement was found at the mid portion of the facing panel. This could be because there were no proper connections between the facing panels. So when oscillatory motions were provided to the model, the junction got displaced the most as compared to the bottom and the top part of the facing. It was also observed that with an increase in the relative density of the backfill, the displacement got decreased for all three different input motions at the top, middle as well as the bottom part of the facing. Similar results were observed for vertical facing as well as inclined facing. However, it can be concluded from findings that the displacement reduced with the inclination of the facing. The differences between the displacements at the top and bottom portion of the facing were significant while that for the middle portion was marginal. Hence it indicated that models 3 and 4, which were 10^0 inclined with the vertical performed better than the models 1 and 2 which were vertical for the three different studied input motions.

4 Conclusions

The effects of backfill density on four different MSE wall models were tested at IIT Patna workshop to study the acceleration and deflection response for three different peak ground acceleration values in this test series. The following conclusions were drawn:

- The observed mode of deformation was a combination of bulging of the facing and rotation about the wall base with slight base sliding.
- Base accelerations generated at the foundation were amplified along with the height of facing wall and the backfill soil. The trend in amplification factors with elevation was nonlinear.
- It was observed that the acceleration amplification factors decrease with the increase in the magnitude of acceleration.
- With inclined facing towards the backfill, acceleration amplification factors were in slightly increasing nature in facing wall as well as in the backfill.
- The acceleration amplification factors for backfill soil were less than that in facing wall amplification factors.
- Using fine sand in the dense state as fill material in retaining wall produces lower deformations in the facing wall as compared to the loose state of the sand.

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