TPF-5(433) Behavior of Reinforced and Unreinforced Lightweight Cellular Concrete (LCC) For Retaining Walls

Interim Report on Test 3 of MSE Wall with Lightweight Cellular Concrete Backfill

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Background

This test is the third MSE wall test conducted with reinforced lightweight cellular concrete (LCC) backfill under Transportation Pooled Fund Study TPF-5(433). Previous tests were performed using (1) unreinforced LCC backfill behind a reinforced concrete cantilever (RCC) wall, (2) reinforced LCC backfill behind a mechanically stabilized earth (MSE) wall, and (3) reinforced LCC backfill on a soil slope behind a MSE wall. This test was intended to be a repeat of the first MSE wall test but at a lower LCC strength. Comparisons between the two tests are discussed subsequently in this report.

Test Set-up

Schematic plan and profile drawings for the reinforced LCC test are shown in Fig. 1. The test box is nominally 10 ft tall x 12.5 ft long x 10 ft wide. The MSE wall panels were nominally 5 ft tall by 10 ft wide and 0.5 ft thick. Reinforcements consisted of galvanized ribbed strips that were 50 mm wide and 5 mm thick, provided by Reinforced Earth Company (RECo). The LCC had a wet unit weight of 28 lbs/ft^3 and an unconfined compressive strength (UCS) of about 73 psi at the time of the load test. The LCC was placed in 2.5-foot thick lifts to a height of 10 feet behind the MSE wall panels over a four-day period (one pour per day). The three steel braced walls (show in red) were stiff enough to constrain lateral movements to less than 0.15 inch at the maximum expected surcharge load of about 64 psi (7200 psf) based on SAP2000 analyses of the steel frame. The test box was designed so that we could apply load independently to six stiff concrete beams (2 ft wide by 10 ft long) using independently activated hydraulic jacks with load cells.

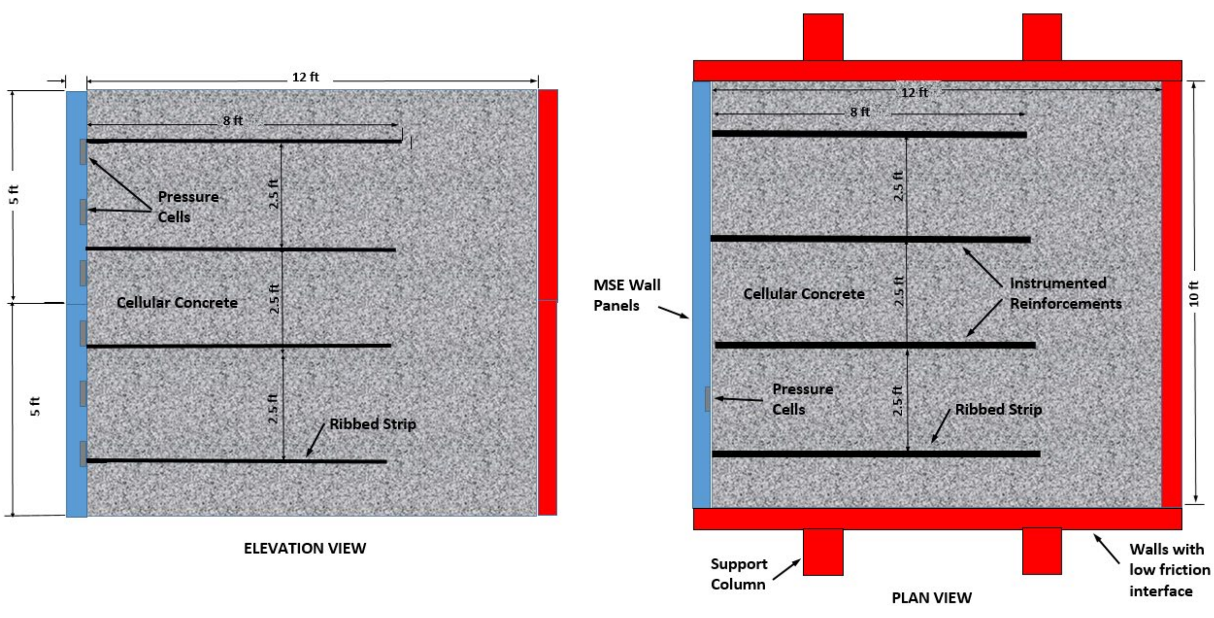


Fig. 1. Schematic plan and profile drawings of the test with reinforced LCC behind two 5'x 10' MSE wall panels

Six Geokon pressure cells were placed at approximately 1.5 ft vertical intervals on the back face of the MSE wall panels to monitor interface pressure on the wall during the backfill placement, curing, and surcharge loading.

Deformation of the retaining wall, the LCC backfill and the test box was monitored using a series of string potentiometers from fill placement to failure that were connected to a data acquisition system. A digital image correlation (DIC) system was also used to monitor the deflection of the MSE wall panels to create a color contour map of wall displacements. Sondex pipes were installed at three depths within the LCC backfill and measured before and after tests to identify potential failure plane development during surcharge loading. Finally, at the conclusion of the test, the sides of the box and the surcharge panels were removed to identify shear planes and crack patterns in the LCC.

Loading Procedure

Photographs of the test box are provided in Fig. 2. For each test, we applied the surcharge load incrementally at 25,000 lbs to 50,000 lbs load increments or 2.8 psi to 5.5 psi pressure increments. For the test on the MSE retaining wall, load was applied to the first three surcharge blocks (6 ft) adjacent to the MSE wall as illustrated schematically in Fig. 3(a). For the test against the free face, with no retaining wall, load was applied to the first three surcharge blocks (6 ft) adjacent to the free face as illustrated schematically in Fig. 3(b). The load was quite uniformly distributed over the three blocks in each case, but settlement under each block could be different. Displacement of each block was monitored with three string potentiometers attached to an independent reference frame.

(a) (b)

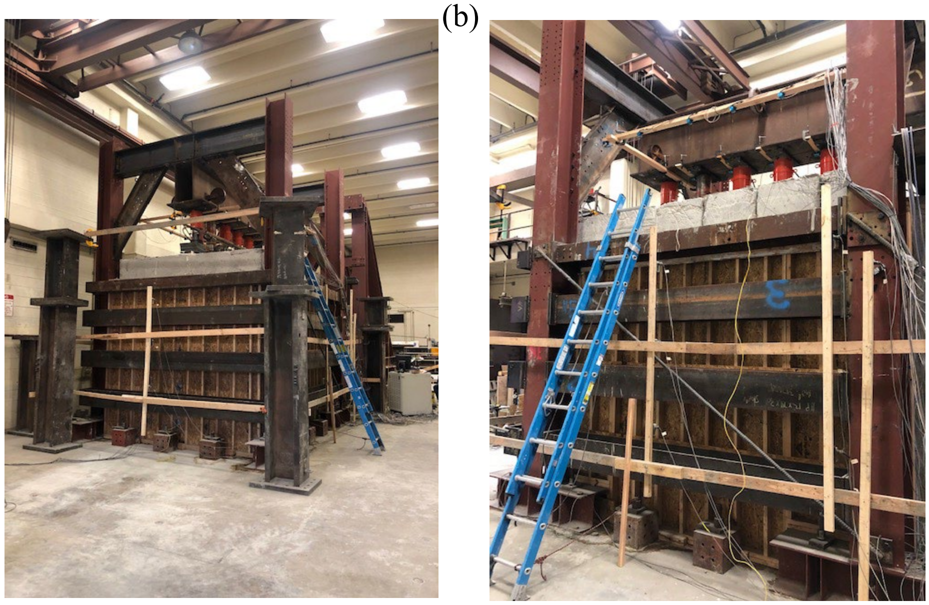
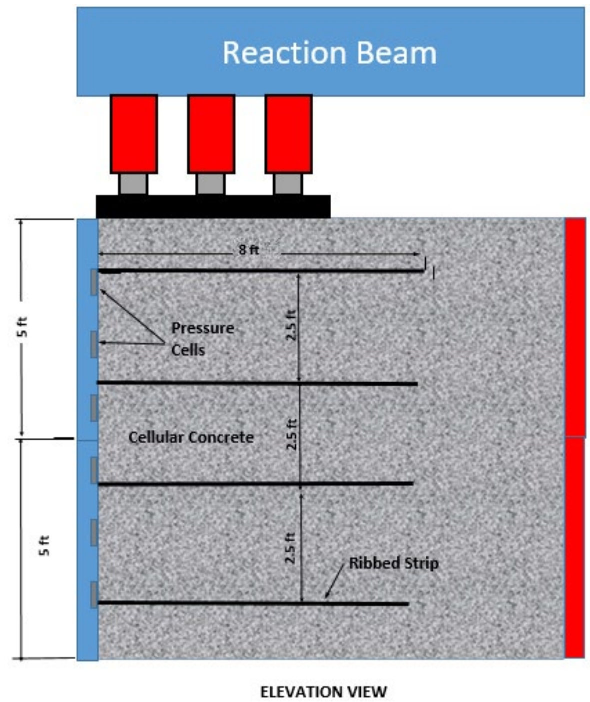


Fig. 2 Photographs showing: (a) the test box from the short side opposite from the retaining wall and (b) the test box from the long side with the concrete surcharge blocks and hydraulic jacks reacting against a longitudinal beam consisting of two deep beams.

(a)



(b)

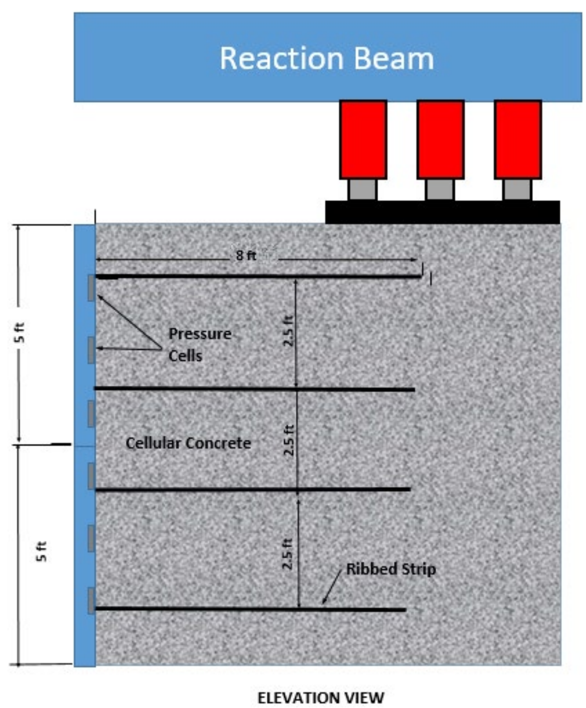


Fig. 3. Schematic drawings illustrating the surcharge load application for (a) the MSE wall test and (b) the free face test.

Test Results

A plot of the applied surcharge pressure versus axial displacement is provided in Fig. 4. The stiffness of the MSE wall and the free face were initially the same. However, at a surcharge pressure of about 32 psi, the axial settlement near the free face increased rapidly and the surcharge pressure decreased as the LCC lost about 30% of its strength after reaching its peak strength. In contrast, the test near the MSE wall continued to carry higher surcharge pressures up to a value of about 67 psi, where settlement increases to over 2.5 inches with a small decrease in surcharge pressure. Failure of the MSE wall exhibits relatively ductile behavior, while the free face does not.

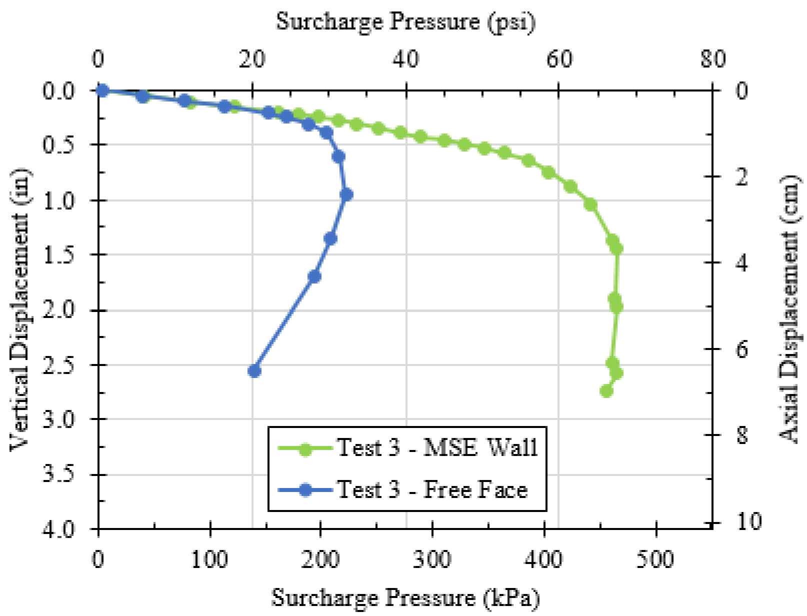


Fig. 4. Applied surcharge pressure versus axial displacement in the LCC for MSE wall and free face tests.

Fig. 5 shows plots of surcharge pressure vs. axial strain for both wall tests. Strain was computed by dividing the vertical settlement by the height of the wall. The curves show that failure occurred at axial strains of 0.8% and 1.2% for the free face and MSE wall tests, respectively.

A plot of applied surcharge pressure vs. lateral wall displacement is provided in Fig. 6 for both walls. The pressure vs. displacement curves were very similar until a pressure of 30 psi suggesting that the strength of the LCC provided most of the resistance to this point. At pressures just about 30 psi, the curve for the free face experiences significant lateral displacement as the strength decreases by 30%. In contrast, the surcharge pressure vs. lateral displacement curve for the MSE wall continues to show an increase in resistance that must come primarily from the strength of the wall system. There is a significant reduction in stiffness at a surcharge pressure of about 61 psi and failure of the retaining wall occurs at a surcharge pressure of about 67 psi when the wall begins to deform significantly without an increase in applied pressure. Once again the stress-strain curve for the free face test is brittle while the curve for the reinforced LCC is ductile.

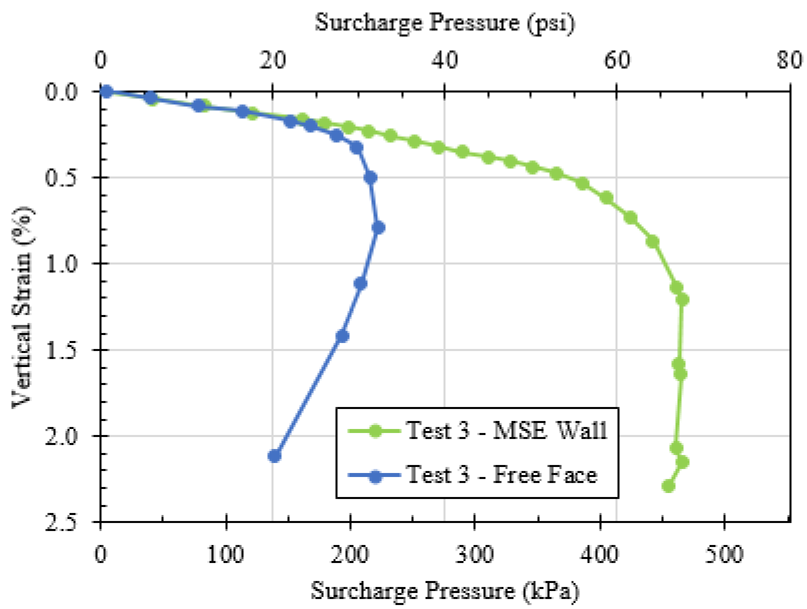


Fig. 5 Applied surcharge pressure versus axial strain in the LCC for MSE wall and free face.

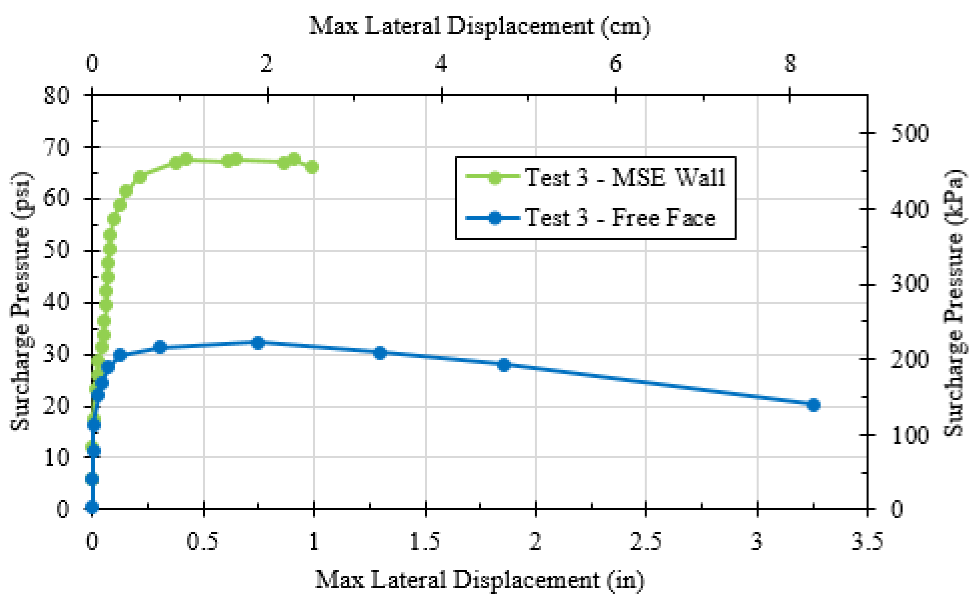


Fig. 6. Applied surcharge pressure vs. lateral wall displacement in the LCC for MSE wall and free face tests.

Fig. 7 provides a comparison of the surcharge pressure vs. lateral wall displacement for MSE wall tests 1 and 3. The unconfined compressive strength (UCS) for MSE wall tests 1 and 3 were approximately 144 psi and 73 psi, respectively. The surcharge area adjacent to the walls, 6 feet, was the same in both tests. Despite the difference in UCS, the wall deflection begins to develop at a surcharge pressure of about 17 psi for both tests. The displacement for both tests is linear up to about 17 psi. After 17 psi, the rate of displacement increases, and test 3 increases faster than test 1. At 67 psi both tests fail (displacement increases with no increase in strength). The failure surcharge pressures in both tests are considerably lower than the LCC unconfined compressive strength.

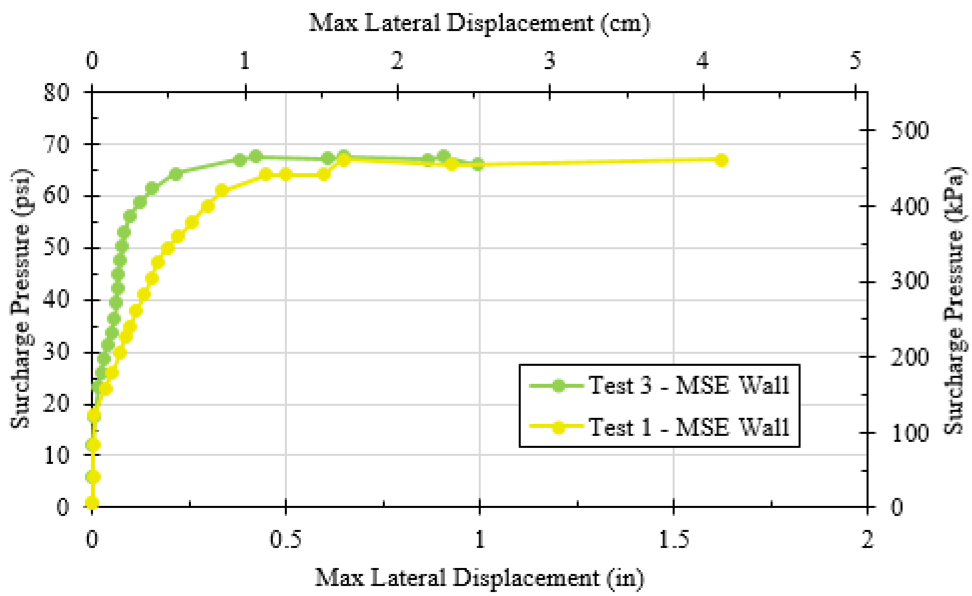


Fig. 7. Applied surcharge pressure vs. lateral wall displacement for MSE wall tests 1 and 3.

Fig. 8 provides a comparison of the surcharge pressure vs. lateral wall displacement for the free face tests associated with MSE wall tests 1 and 3. The surcharge area adjacent to the walls, 6 feet, was the same in both tests.

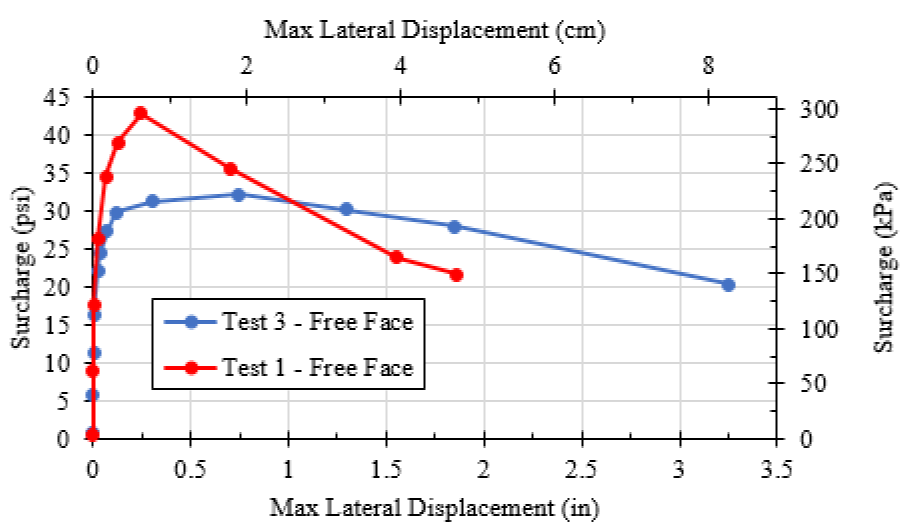


Fig. 8. Applied surcharge pressure vs. lateral wall displacement for free face tests 1 and 3.

Despite the surcharge area, the failure surface initiated at a distance of 2 feet behind the wall in both cases. Both tests behave the same up to about 27 psi. Test 1, with the higher UCS, fails at a surcharge pressure of about 44 psi while Test 3 fails at about 33 psi. Test 1, with the higher strength, also experiences much more brittle behavior than Test 3. Test 1 loses about 50% of its strength post-peak, while Test 3 only loses about 30%.

Fig. 9 provides a plot of horizontal pressure on the MSE wall vs. height for selected applied surcharge pressures during loading as measured by the Geokon pressure plates for Test 3. The pressure plate measurements had to be zeroed the start of the test, and as such, any existing pressure was removed from the data. Thus, the recorded pressures represent the increase in pressure during the surcharge test.

Recent investigations by Tiwari et al. (2018) and Black (2018) have concluded that the shear strength of LCC can be approximated using a friction angle (ϕ) of 34° and a cohesion ranging from 700 to 1000 (Black 2018) or 700 to 1600 psf (Tiwari et al. 2018). If this strength model is adopted, then the horizontal pressure (σ_h) versus depth on the wall due to the LCC during surcharge loading can be computed using the equation

$$\sigma_h = \gamma z K + qK - 2cK^{0.5} \qquad (1)$$

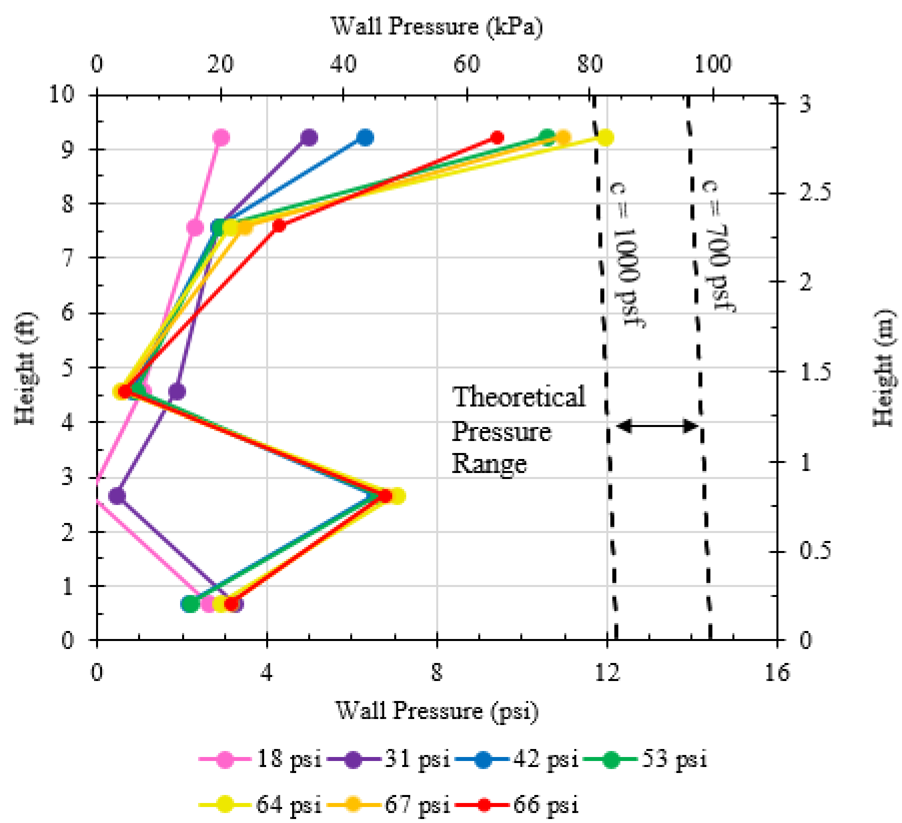


Fig. 9. Horizontal pressure on the MSE wall vs. height curves for selected applied surcharge pressure values near the wall during MSE test 3 as measured by Geokon pressure plates.

where ϕ = 34º, K_a= $\tan^2(45\text{-}\phi/2) = 0.28$, c = 700 to 1000 psf, $\gamma = 27$ lbs/ft^3, q = surcharge pressure = 67 psi, and z = depth below the LCC surface. The range of theoretical horizontal pressures (c = 700 to 1000 psf) on the cantilever wall computed using Equation 1 is plotted relative to the measured horizontals pressure in Fig. 9. The pressures on the MSE wall panels were generally less than the pressure predicted by the theoretical equation. Because lateral resistance for an MSE wall is largely designed to be resisted by the reinforcements, not the wall, this result is consistent with expectations for the system.

Based on the string potentiometer measurements on the front face of the MSE wall panels, horizontal wall deflection has been plotted as a function of height above the base of the wall for selected surcharge pressures in Fig. 10. The string pots were located at the height of the MSE reinforcement connections. All displacement were less than about 0.1 inch for surcharge pressures up to 53 psi. At the peak surcharge pressure of 67 psi, wall deflection exceeded 0.40 inch at the top of the wall with deflection of about 0.1 inch at the bottom. As the strength decreased post-peak, the displacement of the MSE wall panels accelerated with the maximum value ultimately occurring at the joint between the two wall panels (5 ft height). Overall, displacements of the top panel were greater than those on the bottom panel.

(a)

(b)

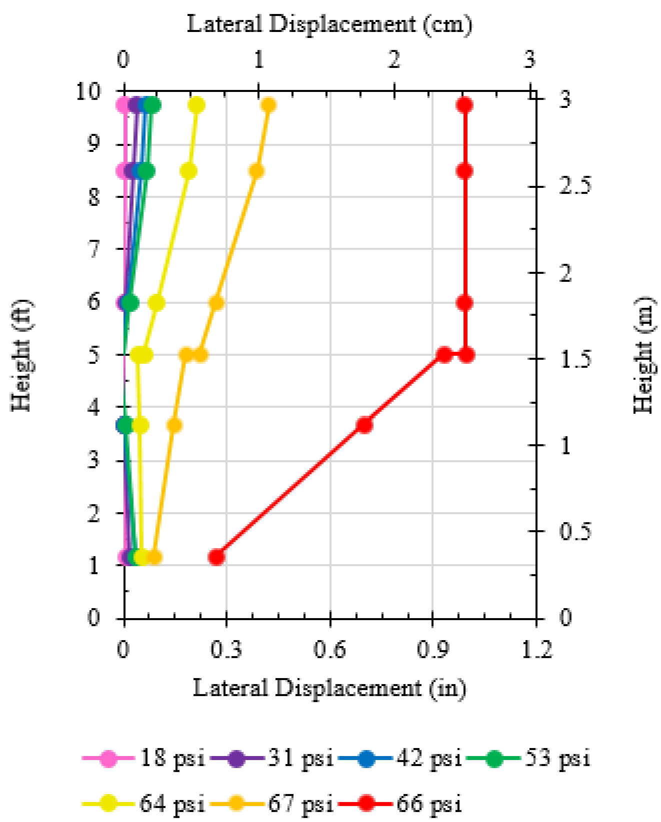


Fig. 10 Photograph of (a) MSE wall panel deflection after the test, and (b) measured horizontal deflection of the wall versus height above the base of the wall for selected surcharge pressures.

At the completion of the test, one side wall and the back wall (free face) were both removed to provide a view of the crack patterns produced by the load testing. Drones were also used to photograph the LCC block from multiple angles to produce a 3D point cloud model of the deformed geometry using structure from motion software. Fig. 11 provides a photograph from the side of the LLC block while Fig. 12 provides 3D point cloud representations of the crack patterns in the LCC block. The cracks painted in green likely developed during loading near the MSE wall, while the cracks painted in blue likely developed during loading near the free face with no wall.

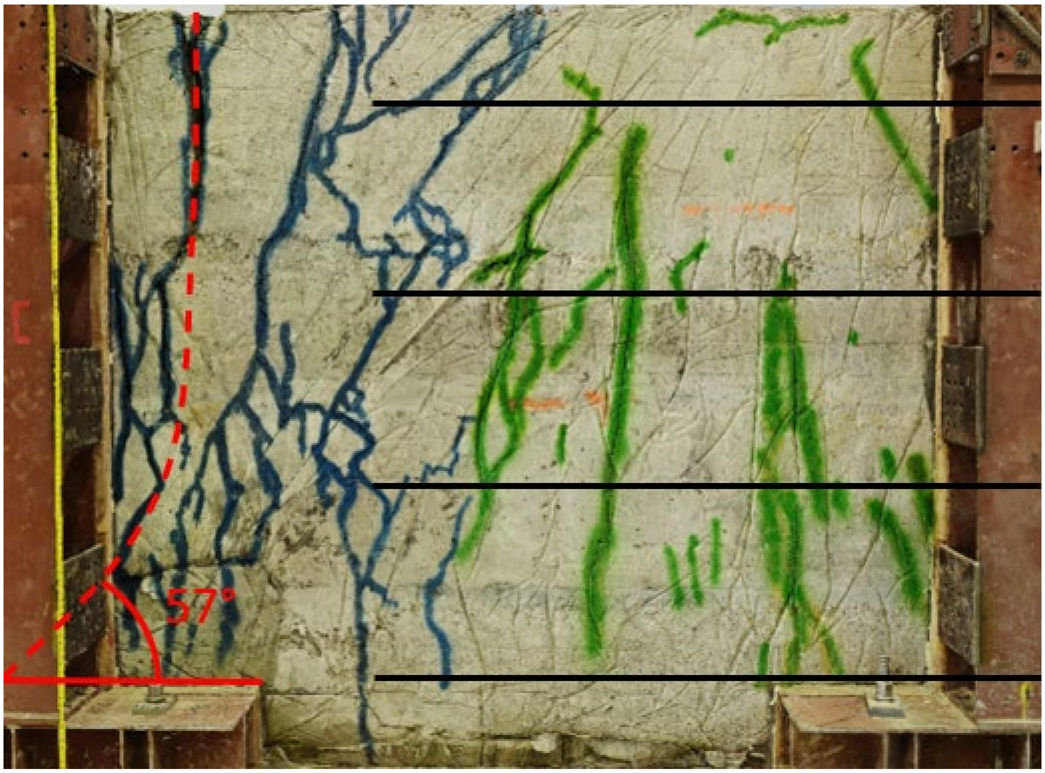


Fig. 11. Photo showing the green crack patterns adjacent to the MSE wall with the six-foot wide surcharge load adjacent to the MSE wall. Blue crack patterns are for a second test with six-foot wide surcharge load adjacent to free face. Reinforcement locations are shown by horizontal black lines.

The green cracks show no apparent sign of a shear failure plane. This indicates that the MSE wall may have failed in reinforcement pullout. On the blue free face side, a relatively uniform surcharge pressure was applied to a distance of six feet from the free face, but a shear plane developed in the LCC just behind the first surcharge block at a distance of two feet behind the wall. A significant crack was observed across the top of the LCC block in Fig. 12 (a). The shear cracks form a log spiral failure plane that is nearly vertically to a depth of about 6 ft, then slopes down to about 1 ft above the base of the wall at an angle that appears to be about 57° relative to the horizontal as shown in Fig. 11.

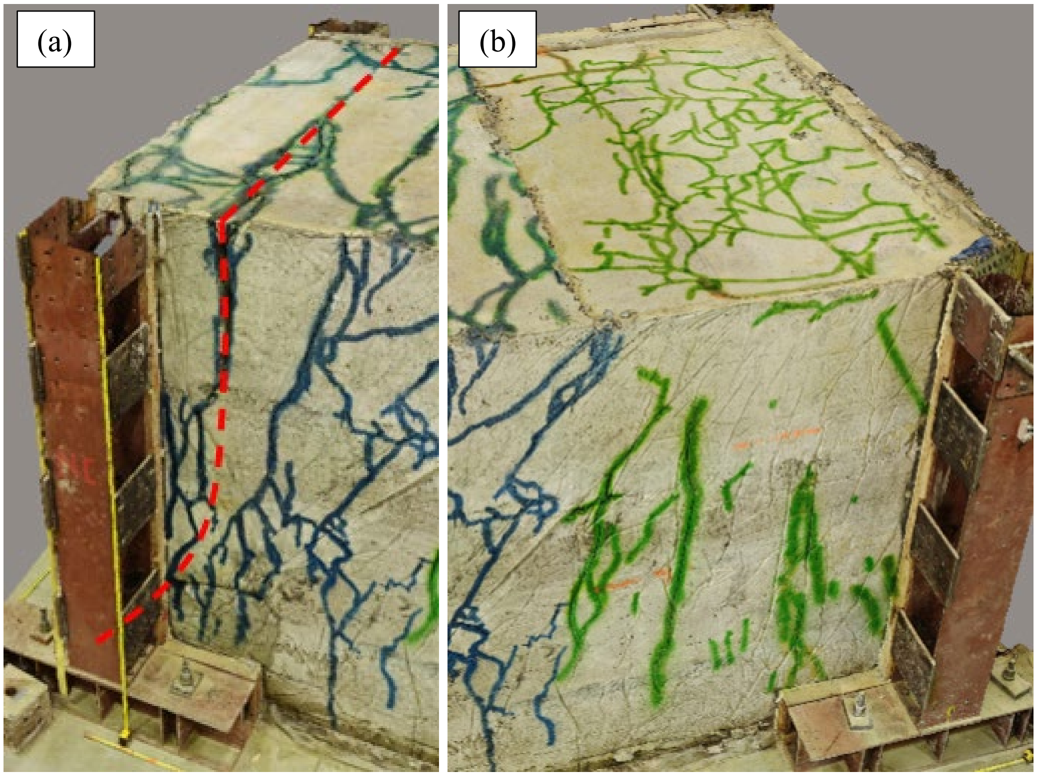


Fig. 12. Three-dimensional point cloud models of (a) crack patterns due to surcharge loading near the free face without a wall and (b) crack patterns due to surcharge loading near the MSE wall. (URL for interactive 3D point cloud models).

If the angle of inclination of the failure slope is assumed to be equal to 45 + ϕ/2, as would be the case of an active earth pressure failure, then the back-calculated friction angle is 24°, which is smaller than the friction angle that has been recommended for LCC, as discussed previously (Tiwari et al. 2018, Black 2018).

A photograph of the free face at the completion of the surcharge loading adjacent to the free face is shown in Fig. 13. All the cracks were spray painted to highlight their location, and all the paint was intended to be blue. The cracks consist of both vertical, horizontal, and inclined cracks. The large horizontal crack 1 ft to 1.5 ft above the bottom of the free face appears to be where the log spiral failure plane surfaced. Surcharge loading was halted to prevent the failing LCC from damaging the instrumentation and steel box.

Fig. 13. Photograph of the crack pattern in the LCC on the free face opposite to the MSE wall side.

Preliminary Conclusions

1. LCC free face walls can successfully withstand significant surcharge loadings with limited axial and lateral deformations. However, failure or excessive displacement occurs at surcharge pressure much less than the unconfined compressive strength (UCS).

2. The presence of an MSE wall significantly increased the strength of the LCC block and led to a more ductile rather than a brittle failure with a significant loss of strength. This result strongly demonstrates the improved performance produced by the MSE wall reinforcement.

3. Measured horizontal pressures at the back of the MSE wall panels were generally less than what would be expected using Rankine earth pressure theory using a friction

angle (ϕ) of 34° and with expected cohesion range. Assuming no cohesion would lead to significant overestimation of the measured wall pressures. This result is expected because the MSE reinforcements are expected to resist the lateral pressure rather than the wall panels.

4. The MSE wall cracks showed no signs of a failure shear plane. The failure surface for the free face wall with unreinforced LCC resembled a log spiral failure. The failure surface in the lower half of the wall was generally consistent with a Rankine active earth pressure with a friction angle of 24°.