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

Interim Report on Test of MSE Wall with Lightweight Cellular Concrete Backfill and Welded-Wire Reinforcement

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Background

This test is the fourth mechanically stabilized earth (MSE) wall test conducted with reinforced lightweight cellular concrete (LCC) backfill under Transportation Pooled Fund Study TPF-5(433). This test involved welded-wire reinforcements. Previous tests were performed using unreinforced LCC backfill behind a reinforced concrete cantilever (RCC) wall and ribbed-strip reinforced LCC backfill behind an MSE wall. Comparisons to the unreinforced backfill tests are discussed subsequently.

Test Set-up

Schematic plan and profile drawings for the reinforced LCC test are shown in Figure 1. The test box is 10 feet tall x 12 feet long x 10 feet wide. The MSE wall panels were nominally 5 feet tall by 10 feet wide and 0.5 feet thick. Reinforcements consisted of welded-wire reinforcements that were 3/8 of an inch thick x 30 inches wide x 8 feet long, provided by SSL, LLC. The grid pattern consisted of W11 bars with 4 longitudinal bars spaced 8 inches transversely center to center and 8 cross bars spaced 12 inches longitudinally center to center. Dimensions are shown in Figure 2. On the free-face wall, 12 welded-wire reinforcements for pull-out testing were placed in three layers with four reinforcements spaced at 2.5 feet vertically. All 12 reinforcements had two longitudinal W11 bars spaced 8 inches transversely center to center and cross bars spaced 12 inches longitudinally center to center. Six reinforcements were 3.5 feet long with 3 W11 cross bars and six were 4.5 feet long with 4 W11. All cross bars were 14 inches long. Dimensions are shown in Figure 3.

The cellular concrete had an average unit weight of 27.7 lbs/ft^3 and an average unconfined compressive strength (UCS) of about 70 psi at the time of the load test. The cellular concrete 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 in Figure 1) 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 feet wide by 10 feet long) using independently activated hydraulic jacks with load cells.

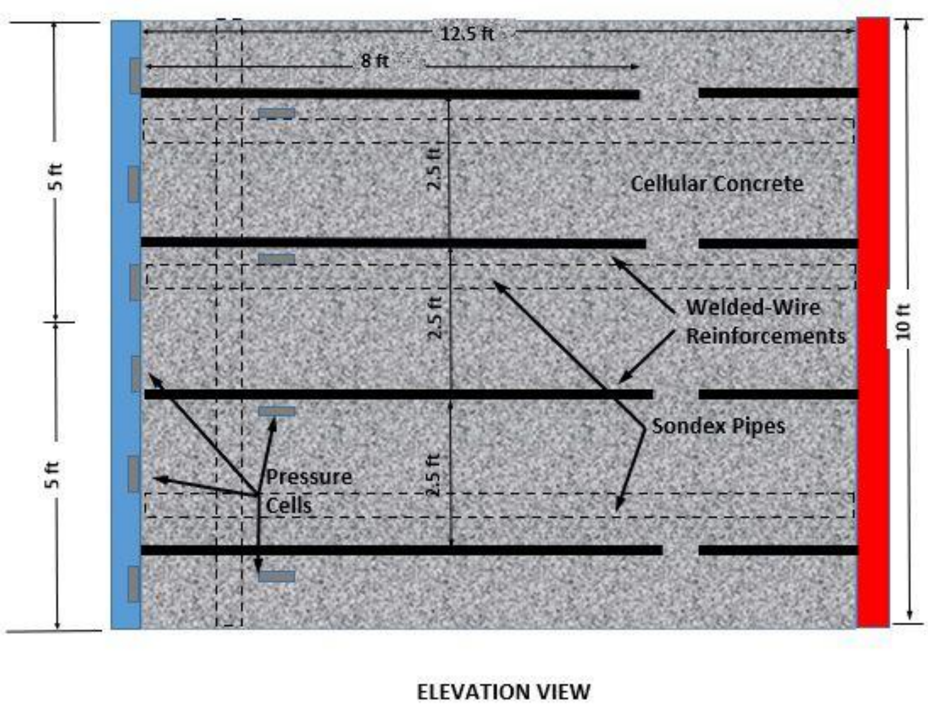
Six Geokon pressure cells were placed at approximately 1.5 feet vertical intervals on the back face of the MSE wall panels to monitor interface pressure on the wall during the backfill placement, curing, and surcharge loading. Four Geokon pressure cells were also placed horizontally at 2.5 feet intervals to monitor surcharge pressure distribution down the profile of the LCC.

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 retaining wall face to create a color contour map of wall displacements. One vertical and three horizontal corrugated plastic Sondex pipes were installed in the backfill, as shown in Figure 1. These pipes made it possible to monitor lateral and vertical displacements within the backfill at 0.5 feet intervals. Finally, at the conclusion of the test, the sides of the box and the surcharge panels were removed to identify shear plane and crack patterns in the LCC.

Loading Procedure

Photographs of the test box just prior to testing the MSE wall are provided in Figure 4. For each test, we applied the surcharge load incrementally at 25,000 lbs to 50,000 lbs load increments or 2.75 to 5.5 psi pressure increments. For the test on the MSE retaining wall, load was applied to the first three surcharge blocks (6 feet) adjacent to the MSE wall as illustrated schematically in Figure 5 (a). For the test against the free face, with no retaining wall, load was applied to the first three surcharge blocks (6 feet) adjacent to the free face as illustrated schematically in Figure 5 (b). The load was quite uniformly distributed over the three blocks in each case, but settlement under the load could be different. Displacement of each block was monitored with three string potentiometers attached to an independent reference frame.

(a)



(b)

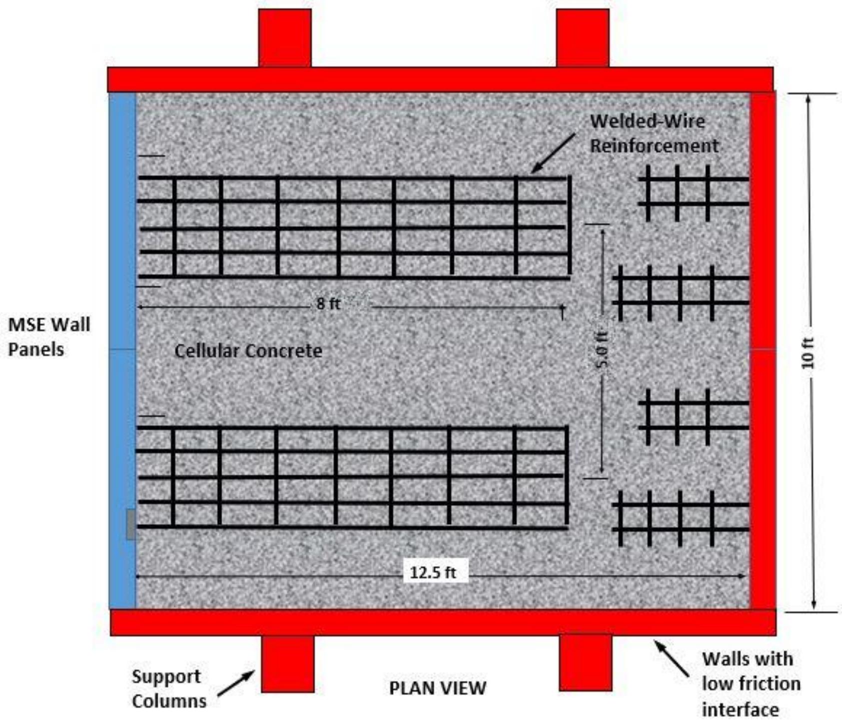


Figure 1: Profile drawings of the test with reinforced LCC behind two 5 feet x 10 feet MSE wall panels (a) Elevation view and (b) Plan view.

(a)

(b)

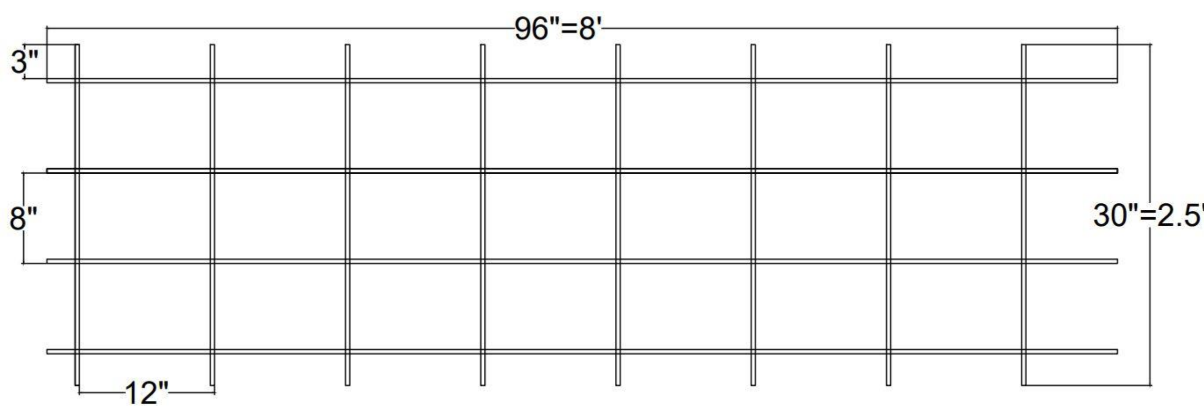


Figure 2: Auto CAD drawings showing: (a) front view of the welded wire grid dimensions and (b) plan view of the welded wire grid dimensions.

(a)

(b)

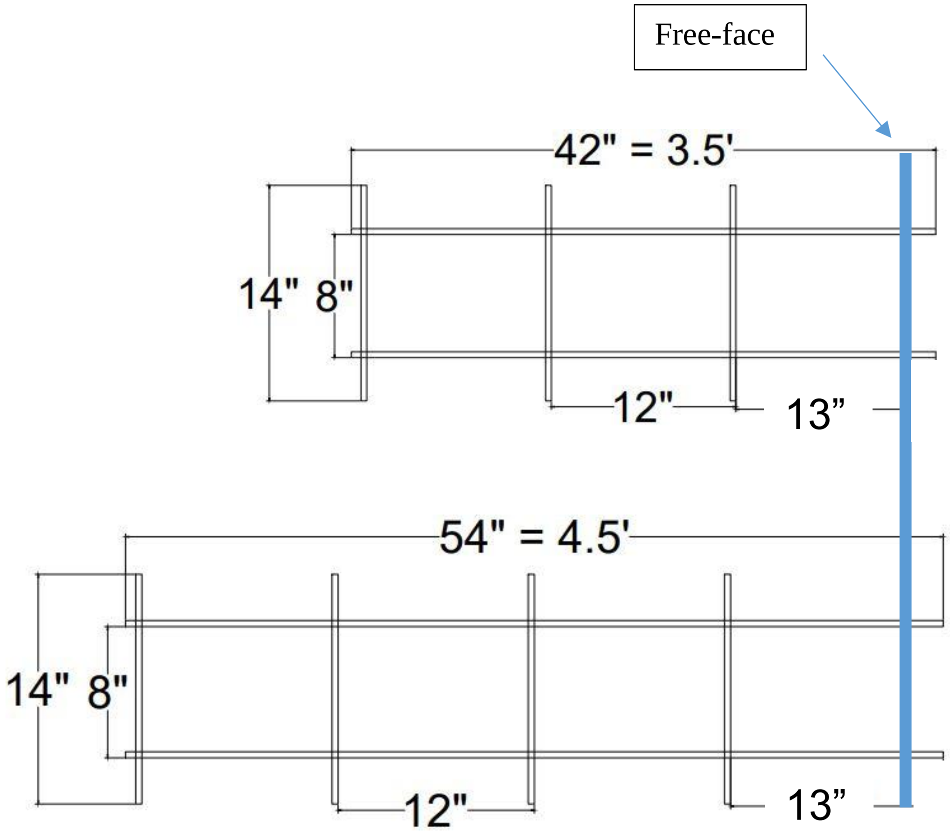


Figure 3: Auto CAD drawings showing: (a) plan view of 3.5-foot reinforcements and (b) 4.5-foot reinforcements on free face wall.

(a) (b)

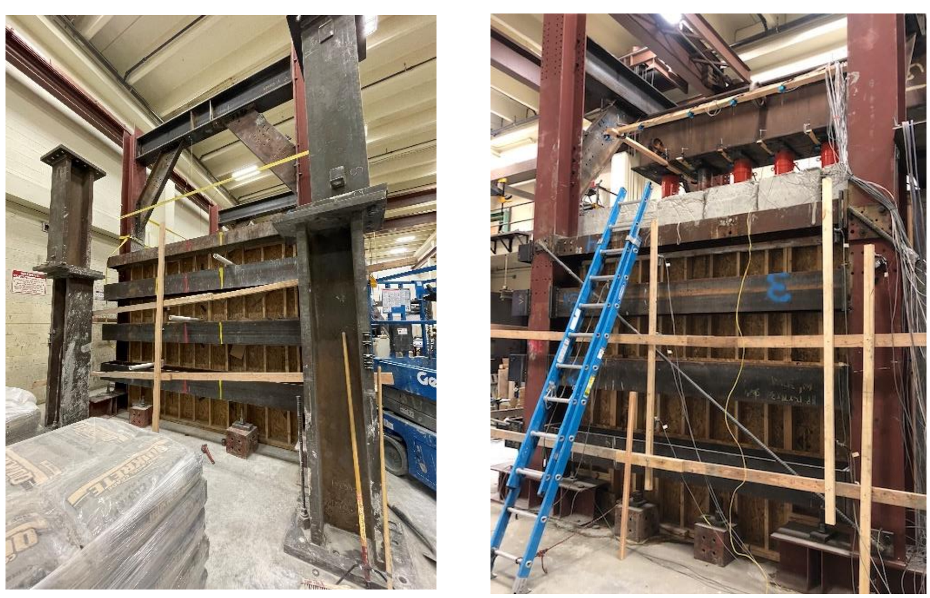
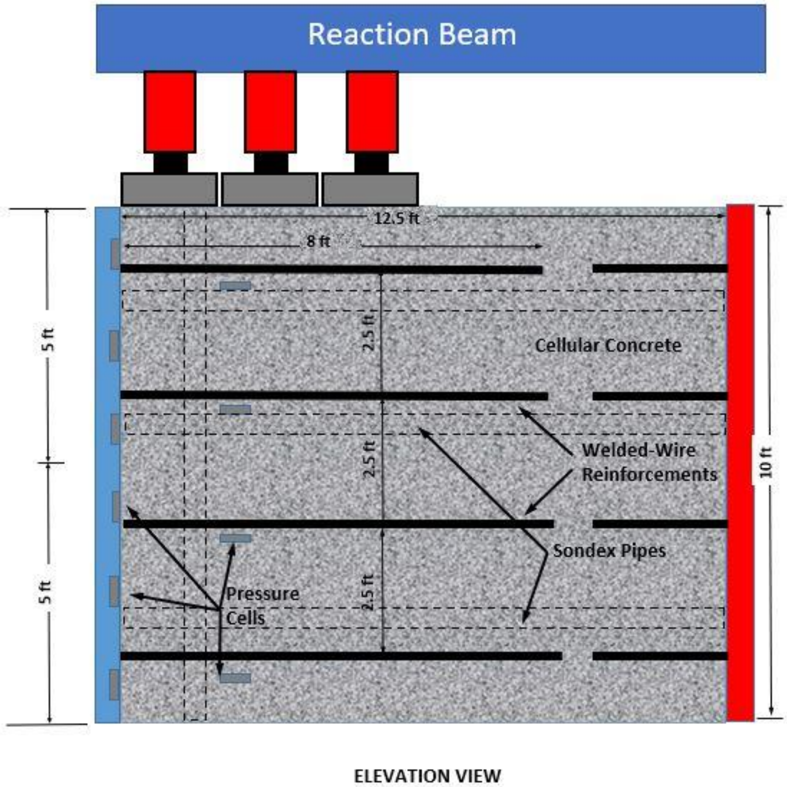


Figure 4: Photographs showing: (a) the test box from the short side opposite from the retaining wall and (b) the test box from the long side with the concrete surcharge blocks and hydraulic jacks reacting against a longitudinal beam consisting of two deep beams.

(a)



(b)

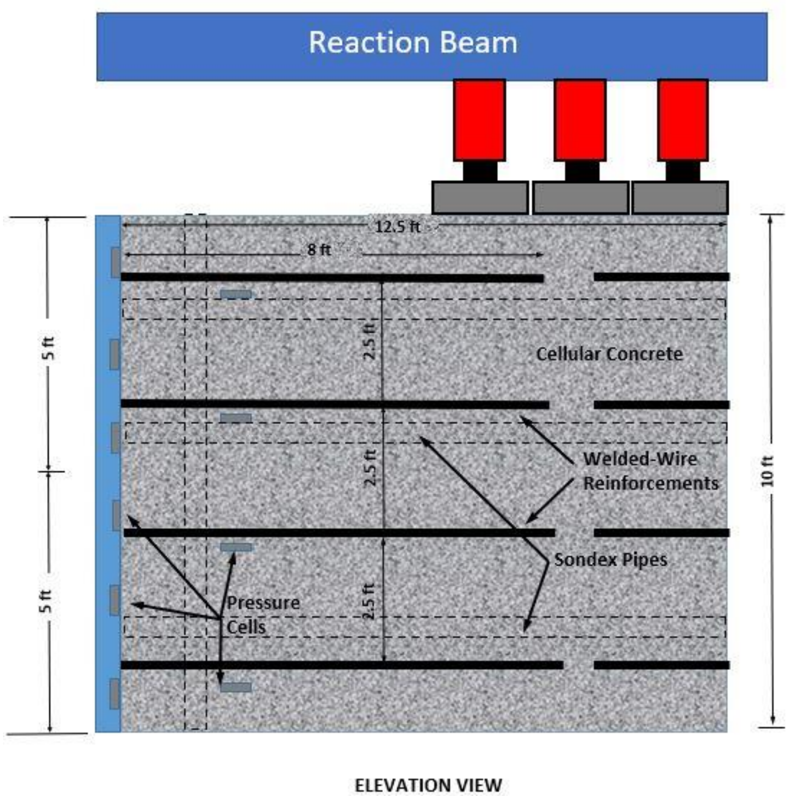


Figure 5: Schematic drawings illustrating the surcharge load application for (a) the MSE wall test and (b) the free face wall test.

Test Results

A plot of the applied surcharge pressure versus axial displacement is provided in Figure 6. The stiffness of the curve near the MSE wall is similar to that for the free face. However, at a surcharge pressure of about 32 psi, the axial settlement near the wall increases rapidly and the surcharge pressure decreases as the LCC loses strength after reaching its peak strength. In contrast, the test near the MSE wall continues to carry higher surcharge pressures up to a value of about 69 psi, where settlement increases to about 1.4 inches with a small decrease in surcharge pressure. At 69 psi, the MSE wall was approaching failure but did not reach a point where it was deforming under constant pressure. This was the maximum pressure applied by the load frame. The trend of the MSE wall exhibits relatively ductile behavior, while the free face does not.

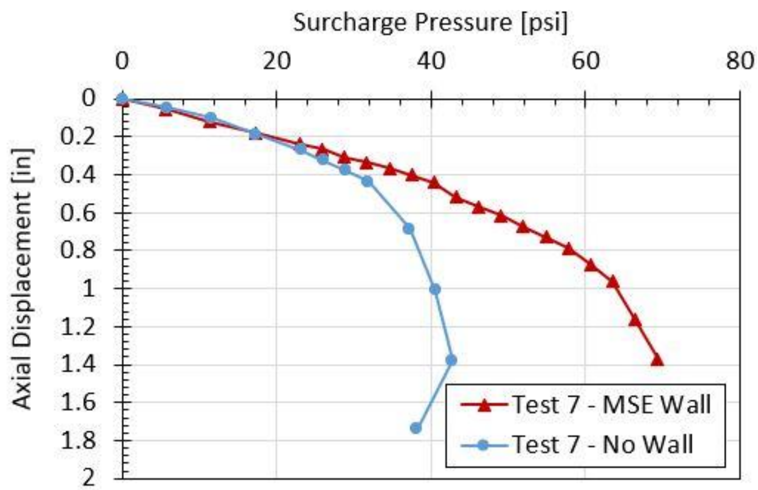


Figure 6: Applied surcharge pressure versus axial displacement in the LCC for tests with and without MSE wall.

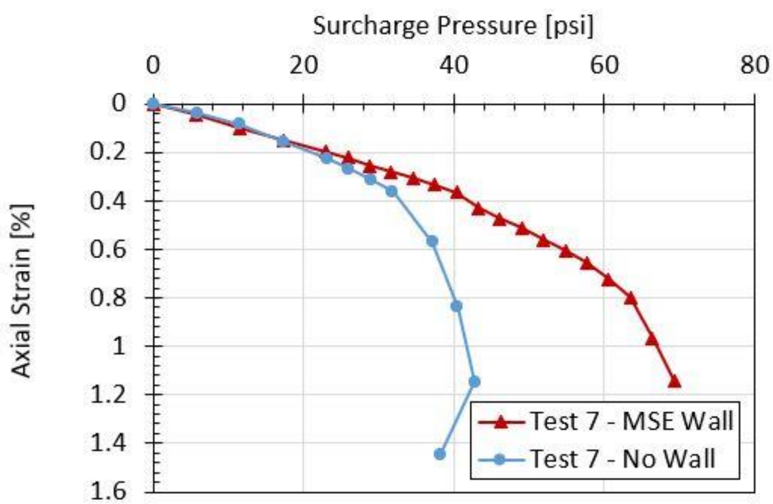


Figure 7: Applied surcharge pressure versus axial strain in the LCC for tests with and without MSE wall.

Figure 7 shows plots of surcharge pressure vs. axial strain for both wall tests. The free-face curve shows that failure occurred at axial strains of 1.15%, whereas the MSE wall showed a significant change in slope at an axial strain of 0.8% but did not entirely fail.

A plot of applied surcharge pressure vs. lateral wall displacement is provided in Figure 8 for both walls. The pressure vs. displacement curves are very similar until a pressure of 32 psi suggesting that the strength of the LCC provided most of the resistance to this point. At higher pressures, the curve for the free face experiences significant lateral displacement as surcharge pressure decreases. In contrast, the pressure vs. lateral displacement curve near the MSE wall continues to show an increase in resistance that must come primarily from the strength of the wall system. Again, the MSE wall did not reach complete failure as explained previously.

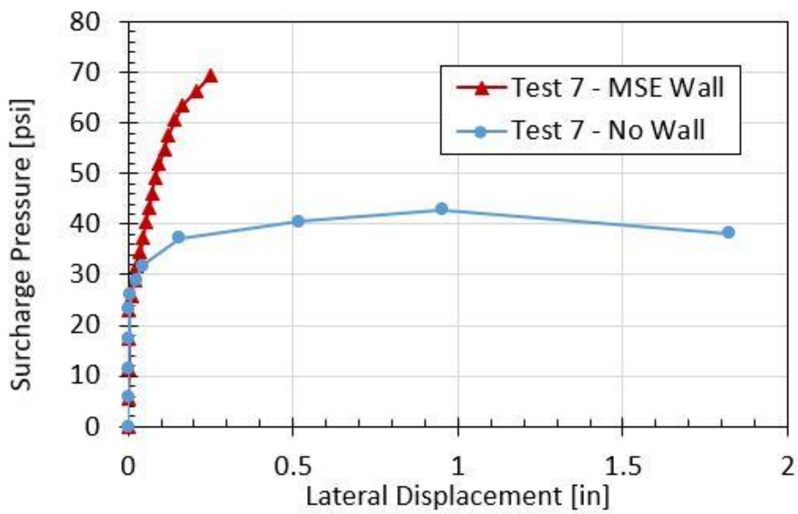


Figure 8: Applied surcharge pressure vs. lateral wall displacement in the LCC for tests with and without MSE wall for reinforced LLC test 7.

Figure 9 provides a comparison of the surcharge pressure vs. lateral wall displacement for tests 2 (RCC wall), test 3 (MSE with ribbed strips), and test 7 (MSE with welded-wire). The unconfined compressive strength for test 7 was approximately 70 psi for the MSE wall and 90 psi for the free-face wall. The unconfined compressive strength for tests 2 and 3 was approximately 100 psi. In addition, the surcharge area of 6 feet adjacent to the walls was the same in all tests. The initial pressure vs. displacement curves are remarkably similar for all the tests. Wall deflection begins to develop at a surcharge pressure of about 25 psi and the stiffness for all tests is linear up to a surcharge pressure of about 50 psi. At this point, the RCC wall for test 2 begins to displace more rapidly. Whereas, for test 3 and 7, the MSE walls begin displacing more at a surcharge pressure of 60 psi. Test 2 reaches a peak strength at a surcharge pressure of 63 psi where failure occurs (displacement increases with no increase in strength) and test 3 reaches a peak strength at a surcharge pressure of 67 psi. In contrast, the MSE wall in test 7 develops additional resistance up to a peak of 69 psi and does not completely reach failure due to the limit capacity of the frame. The failure pressure for test 7 was close to the unconfined compressive strength whereas the failure pressures in both test 2 and 3 are considerably lower than the unconfined compressive strength.

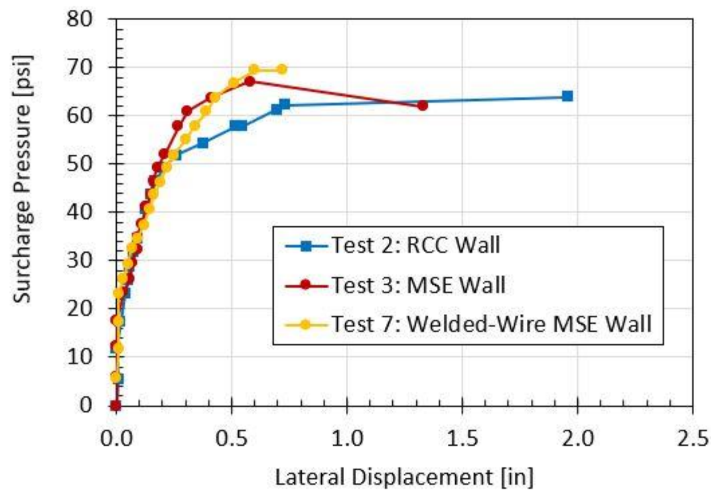


Figure 9: Applied surcharge pressure vs. lateral wall displacement with MSE retaining wall for reinforced LCC tests 2, 3, and 7.

Figure 10 provides a comparison of the surcharge pressure vs. lateral wall displacement for tests 2, 3, and 7 adjacent to the free face (no retaining wall). For the unreinforced LCC (test 2) and the welded-wire MSE (test 7) tests the surcharge pressure was applied over an area 6 feet back from the wall face, while the surcharge pressure was only applied over an area of 4 feet for the MSE wall (test 3) test. Despite the smaller surcharge area, the failure surface initiated at a distance of 2 feet behind the wall in all cases. The pressure vs. lateral displacement curves for tests 2 and 3 are nearly identical, in terms of initial stiffness, failure pressure, and post-peak strength reduction. Post-peak strength reduction was approximately 50%. However, test 7 shows a different result. Around 25 psi the wall displacement begins to accelerate until the surcharge pressure reaches a peak of 42 psi. The post-peak strength vs. displacement curve is much more ductile and only experiences a strength reduction of about 14%. This increase ductility is likely due to the limited reinforcing used for the pull-out tests prior to loading the free-face wall.

Figure 11 provides plots of horizontal pressure on the MSE wall vs. depth for selected applied surcharge pressures during loading as measured by the Geokon pressure plates. As the surcharge pressure increases, the pressures on the wall increase, but then appears to stabilize, for the most part, throughout the remainder of the test. We speculate that the initial horizontal pressure produced enough wall deflection to mobilize the resistance of the reinforcements which then picked up the additional load on the MSE wall panels. The higher pressures near the surface may be due to shorter curing times of the top lift of the LCC.

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

$$\sigma_h = \gamma z K_a + q K_a - 2cK_a^{0.5} \tag{1}$$

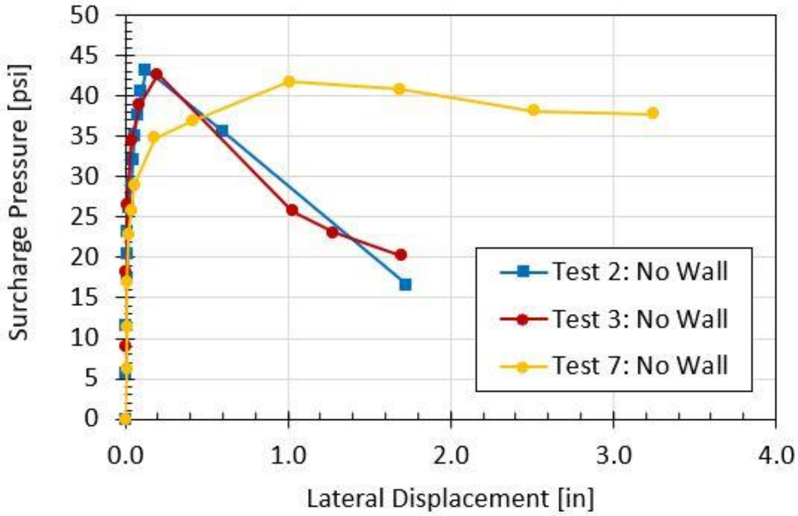


Figure 10: Applied surcharge pressure vs. lateral wall displacement with no retaining wall (free face) for unreinforced LCC tests 2, 3, and 7.

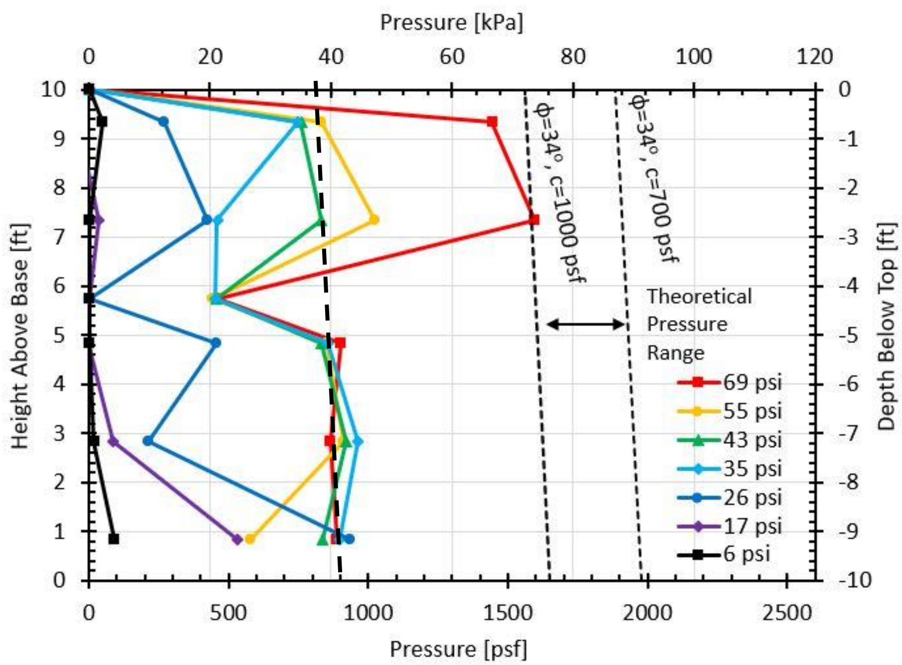


Figure 11: Horizontal pressure on the welded-wire MSE wall versus depth curves for selected applied surcharge pressure values near the wall during test 7 as measured by Geokon pressure plates.

where $K_a=\tan^2(45-\phi/2)$, $\phi=34^{\circ}$, c=700 to 1000 psf, $\gamma=27$ lbs/ft^3, q=surcharge pressure, and z=depth below the ground surface. The range of theoretical horizontal pressures (c = 700 to 1000 psf) on the MSE wall computed using Equation 1 is plotted relative to the measured horizontals pressure in Figure 11. In the LCC test seven with the welded-wire MSE wall, the pressures on the retaining wall approached the limits of the theoretical pressure curves.

However, for the MSE wall test, the pressures on the MSE wall panels were typically about half of the pressure on the MSE wall, given by the dotted line in Figure 11. Because lateral resistance for an MSE wall is largely designed to be produced 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, horizontal wall deflection has been plotted as a function of height above the base of the wall for selected surcharge pressures in Figure 12. The string pots were located at the height of the MSE reinforcement connections. All displacement were less than about 0.30 inch for surcharge pressures up to 55 psi. At the peak surcharge pressure of 64 psi, wall deflection exceeded 0.40 inch with the maximum value at the top of the wall with deflection of about 0.15 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 top of the two wall panels (10 ft). Overall, displacements of the top panel were greater than those on the bottom panel.

(a) (b)

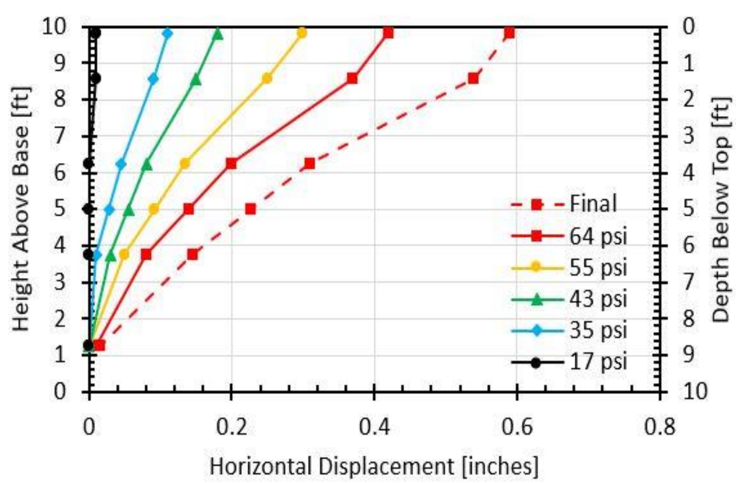


Figure 12: (a) photograph of MSE wall panel deflection at failure, and (b) measured horizontal deflection of the wall versus height above the base of the wall for selected surcharge pressures.

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. Figure 13 provides a photograph from the side of the LLC block. The cracks painted in blue likely developed during loading near the MSE wall, while the cracks painted in green likely developed during loading near the free face with no wall. The green cracks indicate that a nearly vertical shear plane developed at the back side of the third surcharge block (6 feet behind the wall), due to the 3-inch offset at the top of the LCC block, and propagated to a depth of about 5 feet (mid-height).

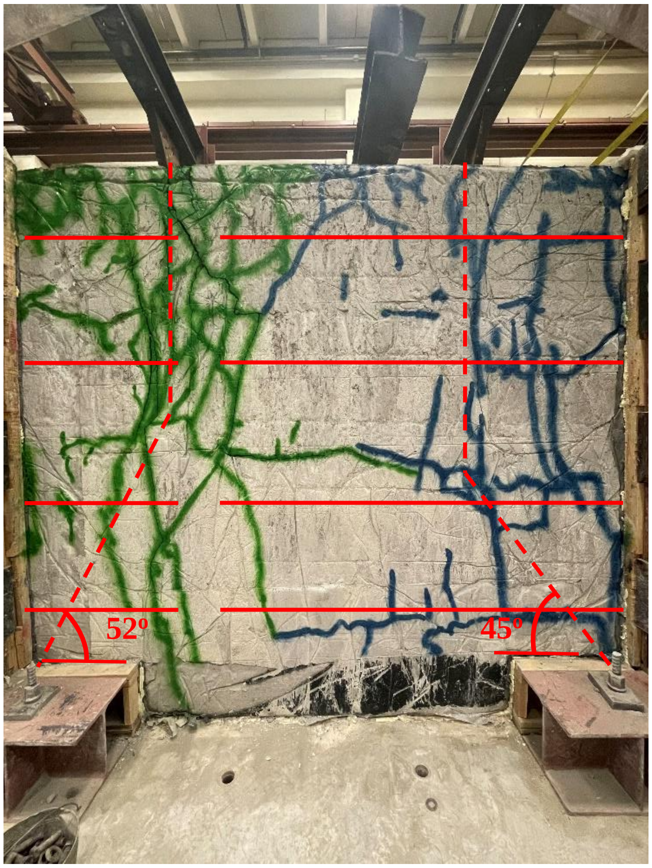


Figure 13: Photo showing the blue crack patterns adjacent to the MSE wall with the six-foot wide surcharge load at the surface. Green crack patterns are for a second test with four-foot wide surcharge adjacent to free-face without MSE wall. Reinforcement locations are shown by horizontal black lines.

This failure surface is similar to what would be expected for an MSE wall where the failure wedge extends vertically downward at a distance of 0.3H (3 feet) behind the wall to a depth of 0.5H (5 feet) and then slopes to the base of the MSE wall. However, the vertical plane develops further back from the wall, about 4 feet, and the sloped section is steeper, in this case.

In the absence of a retaining wall, the pattern of shear planes and cracks develops much closer to the free face than was observed near the MSE wall. Although a relatively uniform surcharge pressure was applied to a distance of six feet from the wall, a shear plane developed in the LCC just behind the second surcharge block and the reinforcements at a distance of four feet behind the wall. A significant vertical offset is observed across the top of the LCC block in Figure 13. The shear crack propagates nearly vertically to a depth of about 5 feet (mid-height of the wall), then slopes down to the base of the wall at an angle of 52° from the horizontal as shown in Figure 13. This failure angle is obviously steeper than was observed in the LCC behind the MSE wall. In previous tests with no reinforcement behind the free face the failure plane typically reached the ground surface at about two feet behind the face. Even though the reinforcements for the pull-out tests were relatively minimal, they were apparently sufficient to force the failure surface further back into the LCC and produce a more ductile surcharge pressure vs. lateral displacement curve.

A photograph of the free face at the completion of the surcharge loading adjacent to the free face is shown in Figure 14. The cracks were spray-painted with blue paint to highlight their locations. The cracks consist of both vertical and horizontal or inclined cracks. Visual observations at the time that the wall was failing indicated that the top half of the wall appeared to be moving as an intact block that was sliding downward on top of the underlying shear planes. Surcharge loading was halted to prevent the sliding mass from reaching complete failure. Nevertheless, some blocks of LCC toppled to the floor once the surcharge pressure exceeded 42 psi.

Figure 14: Photograph of the crack pattern in the LCC on the free face opposite to the MSE retaining wall side.

Preliminary Conclusions

1. LCC walls can successfully withstand significant surcharge loadings with limited axial and lateral deformations. With MSE reinforcements the surcharge pressure at failure was about equal to the unconfined compressive strength (UCS). However, for the free-face test the surcharge pressure at failure was about 57% of the 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 only about half of what would be expected using Rankine earth pressure theory using a friction angle (ϕ) of 34° and a cohesion of 700 to 1000 psf. This result is expected because the MSE reinforcements are expected to carry the lateral pressure rather than the wall panels.

4. The failure surface for the free face wall with limited reinforcement was steeper and shallower than those supported by the MSE wall. The limited reinforcement was sufficient to prevent a brittle failure of the wall, but was unable to increase the surcharge pressure at failure relative to the MSE wall. The surcharge pressure at failure was similar to that for other surcharge tests with unreinforced LCC.

5. The failure surface for the LCC behind the MSE wall panels show a bi-linear shape typical of soil backfill with MSE wall reinforcements that provide an effective cohesion. The composite failure surface is vertical to about 50% of the wall height and then inclines towards the base of the wall.