# Low-Density Cellular Concrete in MSE Structures with Steel Strip Reinforcements—Design and Construction Considerations and Case Histories

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## ABSTRACT

A mechanically stabilized earth (MSE) structure reinforced with steel soil reinforcements is a flexible coherent gravity mass, sized to resist external loads applied by the retained soil and any surcharge. The structure's high internal strength and high load-carrying ability derive from the permanent, predictable bond between reinforcements and granular backfill (the reinforced fill), assuring internal stability. The strength and flexibility of an MSE structure make it well-suited to sites where significant settlement is expected. Such sites may require foundation improvement, a costly but effective solution; a less costly solution is to reduce the load applied to the foundation soil by using a lightweight aggregate or low-density cellular concrete (LDCC) as the MSE reinforced fill. The selection of LDCC as the reinforced fill is typically made by the owner or the owner's engineer, not by the MSE supplier. Design and construction of the MSE structure must consider the properties of the selected LDCC product.

## INTRODUCTION

Mechanically Stabilized Earth (MSE) structures with inextensible steel reinforcements were introduced in the United States in 1971. This new composite material was quickly successful structurally and economically, giving rise to competing systems, expanding usage, and research and innovation. With experience and greater understanding of the flexible nature of MSE structures, engineers attempted new ways to use the technology, including on sites characterized by lower bearing capacities and a higher expectation of settlement. The use of (frequently manmade) lightweight fill materials, in lieu of either natural soils/aggregates or ground improvement methods, led to successful MSE construction on some of these poor-foundation sites. Low density cellular concrete, a flowable material, has proven to be an effective lightweight fill for MSE structures, although some design adjustments are necessary and controlled handling and installation procedures must be followed to achieve predictable performance of the resulting MSE/LDCC composite.

To provide for safe performance over the life of an MSE structure constructed with LDCC, design and construction procedures must address the unique properties of LDCC and its behavior within MSE structures. The MSE wall designer must consider its low unit weight, its angle of internal friction and pullout resistance, the resulting required soil reinforcement length and the possibility of buoyant behavior of the fill material. Contractors and installers must modify standard MSE installation practices to include proper handling and placement of LDCC during construction and the need for to fluid containment.

This case histories paper is based on experience with MSE structures using ribbed steel reinforcing strips and backfilled with low-density cellular concrete (LDCC). Two of the case histories illustrate the use of LDCC to reduce structure settlement, while a third case demonstrates the advantages of LDCC as a flowable fill. The choice to use LDCC is always made by owners or their engineers, not by the MSE suppliers who design the actual MSE structures. It is incumbent on the MSE designers, however, to set forth requirements that will assure the desired composite behavior between the MSE system components and the LDCC. This compatibility can assure predictable results throughout the required structure life.

## MSE WALL DESIGN AND CONSTRUCTION – GENERAL CONSIDERATIONS

An MSE wall using steel reinforcements is an embankment with a vertical face, comprising alternating layers of compacted granular backfill and discrete, inextensible galvanized steel soil reinforcements (strips or grids), and typically incorporating a precast concrete or wire mesh facing system (Fig. 1). The strength and stability of MSE walls derives from the permanent, predictable frictional interaction (bond) between the granular material and the reinforcements, combining the compressive and shear strengths of compacted granular fill with the tensile strength of horizontal, inextensible reinforcements. The result is a unique composite construction material having high internal strength and load-carrying ability.

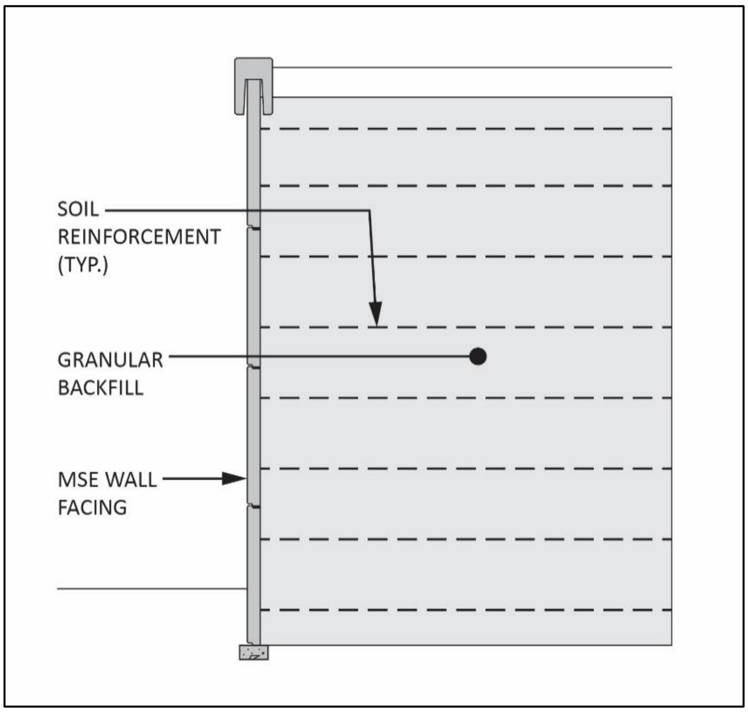


**Figure 1. Typical MSE Wall Section**

Design is performed by assuming the MSE structure behaves as a rigid body, sized to resist external loads applied by the retained soil and any surcharge, while internal stability of the reinforced soil is verified by checking reinforcement tensile rupture and pullout. This design method, derived from basic soil mechanics, is known as the Coherent Gravity Method (Anderson, P.L. et al. 2010, 2012). MSE walls typically support fill retained behind them, creating eccentric loading which produces a foundation bearing pressure that is approximately 135% of the dead weight of the mass, plus any surcharge. On sites where an unacceptable magnitude of settlement is expected, foundation improvement, or substituting a lightweight backfill or low-density cellular concrete for the granular backfill, may be a solution. No matter the backfill used, however, all MSE design principles, discussed below, must be followed to assure the finished structure is truly Mechanically Stabilized Earth.

To provide for external (gravity) stability of MSE walls with inextensible steel reinforcements, as well as to assure adequate resistance to reinforcement pullout, the assumed initial reinforcement length, L, for a wall of height H is taken as L = 0.7H (with $L_{min}$ = 8 ft.). As required by the AASHTO code (AASHTO, 2017), the assumed angle of internal friction (ϕ) of the MSE backfill is 34º (a typical value for granular materials), absent project-specific test data supporting a higher value. Calculation of internal horizontal and vertical forces is performed using ϕ and the soil unit weight (γ) but neglecting cohesion. The total horizontal force on a facing unit divided by the number of reinforcements connected to that facing unit is the reinforcement tensile load (Section 11.10.6.2.1, AASHTO 2017). Since the specific metal loss rates associated with a given MSE backfill or low-density cellular concrete are not known at the time of design, conservative metal loss rates as specified by AASHTO should be assumed in design. The AASHTO metal loss model for MSE walls (AASHTO 2017, Sect. 11.10.6.4.2a) is used to calculate the galvanized steel soil reinforcement cross-sectional area expected at the end of the service life, allowing determination of reinforcement tensile capacity.

Pullout resistance is a function of the tensile load in the reinforcement, the vertical stress on the reinforcement (calculated over both top and bottom surfaces), and the apparent coefficient of friction between backfill and reinforcements, F* (unitless). Typical values of F* have been found through extensive laboratory testing and confirmed empirically. No matter the selected backfill material, the use of both an appropriate F* and an appropriate ϕ is critical to the safe design of any MSE structure.

Since the reinforcements provide the structure tensile strength, the MSE design must provide a sufficient number and cross section of reinforcements to achieve both the expected structural performance and the required design life. When using LDCC as the MSE backfill, the conservative design approach must consider possible LDCC degradation, from a solid mass to a fractured mass having granular backfill-like properties. A conservative maximum value of the design friction angle for LDCC is 40°, which is the maximum value of this parameter specified by AASHTO Section 11.10.6.2 (AASHTO 2017) for soil backfill. Testing of the selected LDCC product may render a higher value.

Construction of an MSE wall is a repetitive process once required excavation and pouring of an unreinforced concrete leveling pad are complete. Panels are placed in an offset-alternate pattern (Fig. 2), generally raising the wall by 30 in. per row of panels and with layers of reinforcements typically also spaced 30 in. vertically. Reinforcements are connected to panels using a positive mechanical connection such as a high strength bolt through the reinforcing strip and the embedded tie strips (pictured) or interlocking loops and connecting pin (grids). Fill is compacted on top of reinforcements until reaching the next level of panels or reinforcements, then the process repeats. Geotextile glued over panel joints prevents backfill outflow through the joints. If the backfill is low-density cellular concrete, modification of both joint materials and construction procedures is necessary.

## LOW-DENSITY CELLULAR CONCRETE MSE DESIGN CONSIDERATIONS

Low-density cellular concrete is defined by the American Concrete Institute (ACI) as a concrete made with hydraulic cement, water and preformed foam to produce a hardened material with an oven dry density of 50 lbs./per cu. ft. or less (ACI 2006). During mixing and placement, LDCC is a moderately viscous fluid which can be pumped to its intended location through hoses, allowing for relatively rapid delivery. When used for MSE wall backfill, structure design must address fluid containment during construction as well as fluid pressure and leakage prior to curing. It is also necessary to limit the distance to which the LDCC flows freely from the hose, to avoid segregation or breakdown of the material (including rupturing of air cells).

**Figure 2. Offset-Alternate Panel Arrangement with Panel-to-Panel Bracing**

First used in MSE walls along Philadelphia's Schuylkill Expressway in the mid-1980s, LDCC for MSE backfill is typically supplied at a unit weight of 30-40 pcf and at a compressive strength of 140-330 psi (Aerix Industries). In an MSE application, the low unit weight of LDCC reduces the bearing pressure beneath the wall proportionate to the ratio of the unit weight of LDCC to that of granular fill, so using 40 pcf low-density cellular concrete in place of 120 pcf granular fill produces an approximately 67% reduction in applied bearing pressure. If LDCC is also placed in the retained fill zone (Fig. 3), the effect of eccentricity on bearing pressure is also reduced.

By adjusting the LDCC foam's chemical composition, the material can be produced in either an open-cell (air cells interconnect) or closed-cell form, meaning the LDCC can be designed to be permeable or impermeable, respectively. Most MSE projects have used closed-cell LDCC technology but, as will be discussed in Case History 1, an open cell structure can reduce buoyancy of the lighter-than-water mass. As with standard concrete, cellular concrete material properties and use are the subject of ACI guidance (ACI 2006), which includes cross-references to multiple ASTM standards.

When designing an MSE wall with LDCC fill, the design should follow normal MSE design procedures, including consideration of external and internal stability, tensile rupture, and pullout, to assure good performance in case of cracking or fracturing of the LDCC into a granular backfill-like mass. Shear strength testing of cured LDCC reports values exceeding typical shear strengths of granular backfills, but MSE experience and the conservative approach to MSE design, as well as the AASHTO specifications (AASHTO 2017), indicate that the design friction angle when using LDCC should be limited to $\phi = 40°$ in the absence of higher values from testing.

The apparent coefficient of friction, F*, should be determined by testing of each reinforcement type, ideally at the time of project design and using the project backfill. Testing has confirmed F* values for ribbed steel strips in granular backfills are typically between 1.5 and 4.0 at the ground surface. This value decreases linearly to tan ϕ at a depth of 20 ft. and deeper (Sect. 11.10.6.3.2, AASHTO 2017). Similarly, the F* value for low density cellular concrete must be determined from product-specific pullout tests in the selected LDCC product. Current practice, following the same provision in AASHTO, considers F* to decrease with depth from the pullout-determined value at the top to tan ϕ at 20 ft. Current practice also limits F* to 5.0 at the top to avoid over-estimating the pullout resistance and, by so doing, potentially using too few reinforcements to maintain serviceability in case of LDCC degradation.

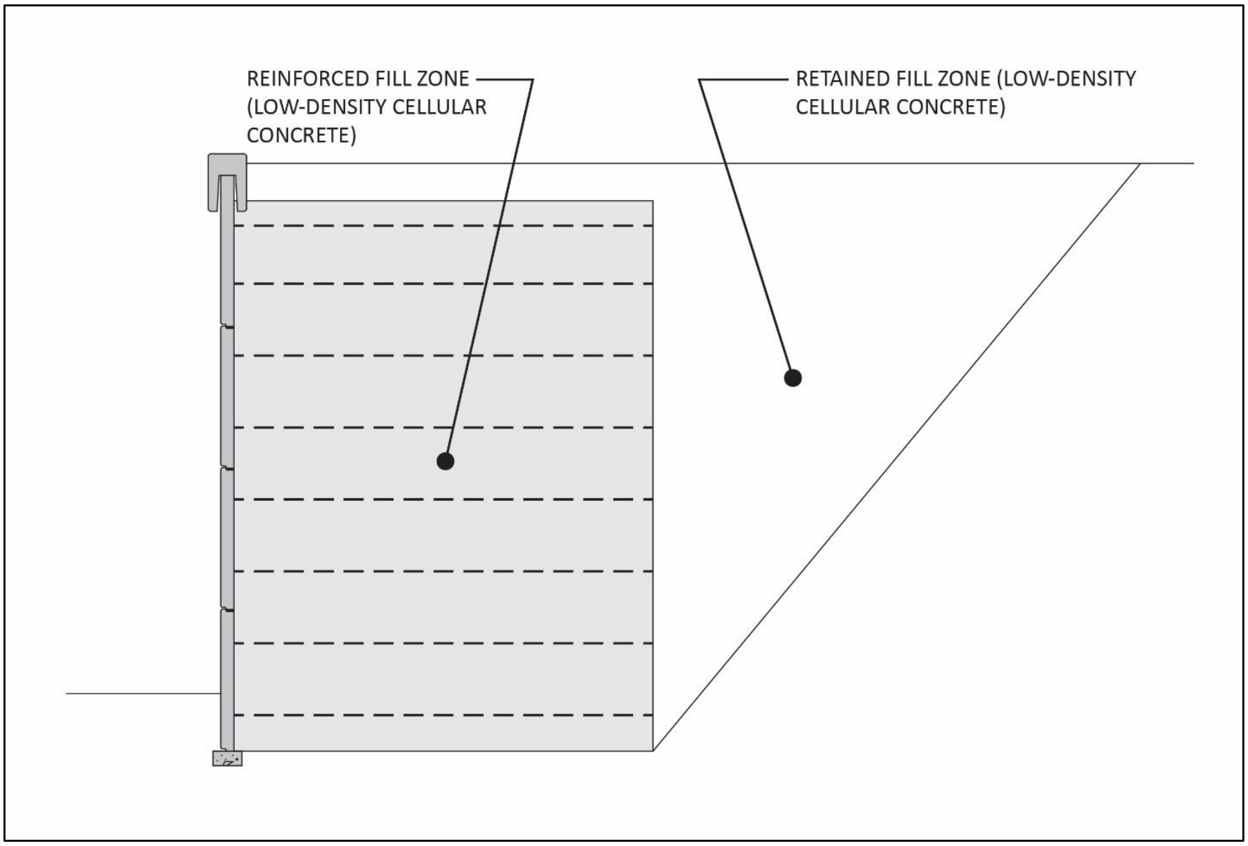


**Figure 3. MSE Wall Fill Zones**

As in the construction of any MSE wall, panels being backfilled with low-density cellular concrete must be braced to the ground (typically first row only) and to each other, or to the cured LDCC (subsequent rows, Fig. 4), to resist the fluid pressure until the LDCC has set sufficiently that bond strength and pullout resistance take over. In addition, panel joints must be covered with a separation geotextile with a small apparent opening size (AOS) to prevent material leakage, and bulkheads must be used to establish lift boundaries. Specifications regarding how far LDCC may be allowed to flow from the end of the hose to its placement position must be carefully followed to avoid mix decomposition that could result in a weaker-than-required cured layer. Since cellular concrete is a self-leveling material, each day the top lift should be finished with a slight slope away from the wall face to prevent ponding and the possibility of absorption into even closed-cell LDCC. Since each lift of LDCC must cure before installation of the next lift, a series of horizontal cold joints will be present, generally with the same vertical spacing (30 in) as the reinforcements.

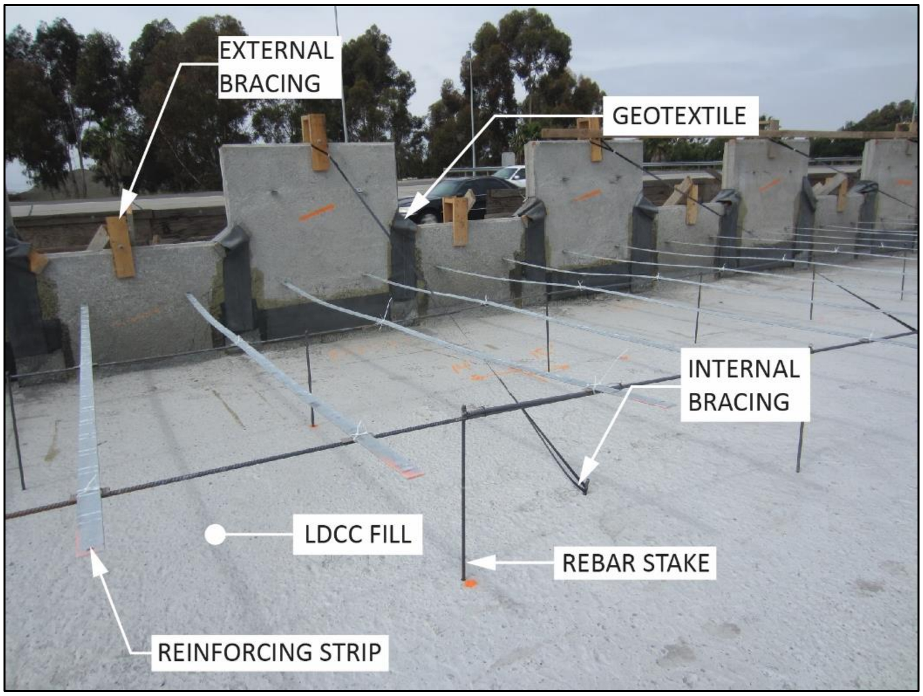


**Figure 4. Support of Reinforcing Strips in Low-Density Cellular Concrete**

Reinforcements should not rest atop cold joints to avoid possible reduction in pullout resistance. To control strip elevation within the cellular concrete lift, they must be supported in a relatively level position throughout their length. One method of reinforcement elevation control is shown in Figure 4 and Figure 5, where the contractor drove rows of vertical rebar stakes (which easily penetrate the LDCC) along lines perpendicular to the wall face and at spacing close enough to minimize reinforcement sagging. Horizontal crossbars, parallel to the wall face, are tied to the stakes to support the strips just as if they were lying on top of the backfill, while keeping them at least 6 in. above the previous day's cold joint.

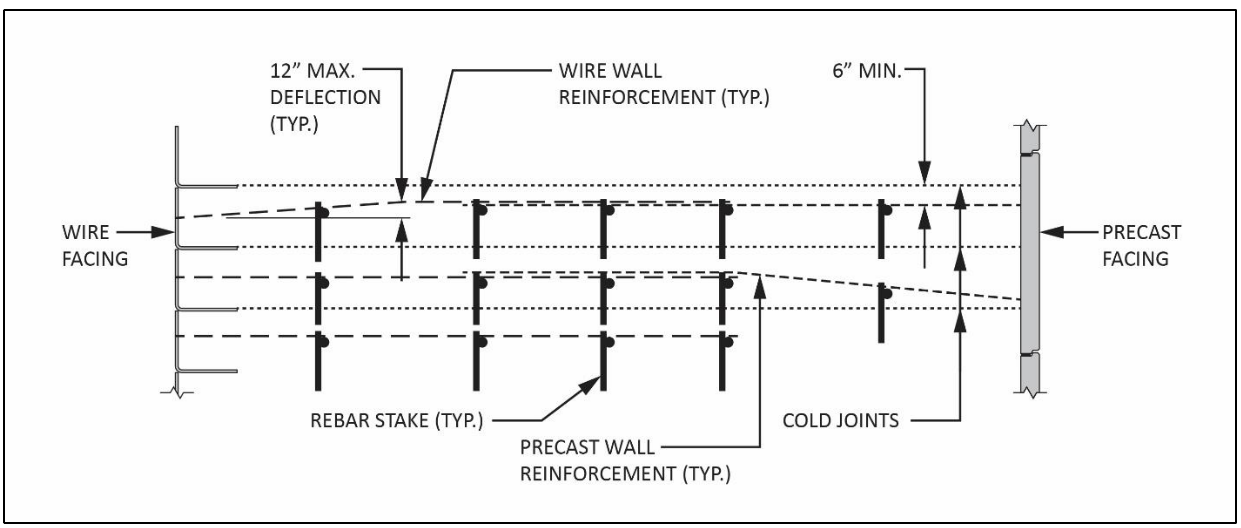


**Figure 5. Reinforcing Strip Adjustments to Avoid Cold Joints/Prevent Sagging**

Stake material should be chosen to avoid placing dissimilar metals in contact with each other (reinforcements are typically galvanized); epoxy-coated rebar satisfies this requirement. In addition, panel plumbness must always be maintained. When using LDCC backfill, plumbness may be achieved by a combination of external braces for bottom panels, with panel-to-panel clamping combined with internal ties anchored in the LDCC, for panels too high in the wall for bracing to the ground. Figure 5 illustrates these bracing options.

It is important to establish communication among the wall installer, the LDCC supplier, and the MSE wall designer/supplier to make sure that the wall installation process follows the wall installation guidelines. LDCC placement must never dictate wall construction procedures, i.e., it is never acceptable to stack panels two high, or to install multiple layers of reinforcements prior to a more-than-30-in.-deep LDCC pour. Only careful attention to proper placement of all components, including the low-density cellular concrete backfill, can assure safe MSE structure performance.

## CASE HISTORIES

### Case History 1: Illinois DOT, I-64, St. Clair County

The widening of I-64 east of St. Louis required constructing an MSE wall at the toe of an existing slope situated in the 100-year floodplain of the Mississippi River, meaning the lower portion of the wall would be periodically submerged. The Illinois DOT (IDOT) contract drawings required a permanent sheet pile wall to support the excavated embankment toe, but placement of the sheet piling left less than 70% of MSE wall height ($L < 0.7H$) available for several bottom layers of reinforcements (Fig. 6). This configuration is called a Shored MSE wall (SMSE) (FHWA, 2006), a composite system comprising a shoring wall supporting the backslope and an MSE wall constructed against and above the supported backslope. SMSEs have a design methodology that permits reinforcement lengths in the shored zone as short as 0.4-0.5H, appropriate to the limitations of this project.

The foundation beneath the proposed wall consists of fine sands and clays, with blow counts averaging less than 10 blows per foot (geotechnical investigation and design performed by IDOT). At 31 ft. tall, the structure would impose a dead load exceeding 3.7 ksf (based on 120 pcf backfill) – clearly exceeding the bearing capacity of the low blow count soil and causing unacceptable structure settlement. To address this bearing capacity deficiency, IDOT issued the contract with a requirement to use low-density cellular concrete for the MSE backfill, specifying Illinois Class IV Lightweight Cellular Concrete Fill (maximum density 37 pcf, minimum 28-day compressive strength 35 psi, resulting structure dead load of 1.1 ksf). The reduced strip lengths in the shored zone were offset by the virtually zero horizontal earth pressure due to the sheet pile wall, leaving adequate sliding resistance at the base of the wall and sufficient pullout capacity for the strips embedded in the LDCC.

In addition to the foundation considerations, design of this MSE structure had to address the possible flooding and the potential for structure buoyancy. An MSE structure with inextensible soil reinforcements and LDCC backfill behaves as a coherent gravity mass, so the effect of buoyant conditions depends on the cell structure of the LDCC. Cell structure can be open or closed; in a closed cell LDCC mass the cells do not interconnect, making the mass essentially impermeable. Due to its light weight – in an MSE application, likely less than that of water – buoyancy is a risk to structure global stability. If open-cell LDCC is used, the cells interconnect, making the mass permeable but reducing buoyancy. The type of low-density cellular concrete to be used in an MSE structure – open or closed cell – must be determined at the time of design, and the minimum required unit weight of the material must also be specified.

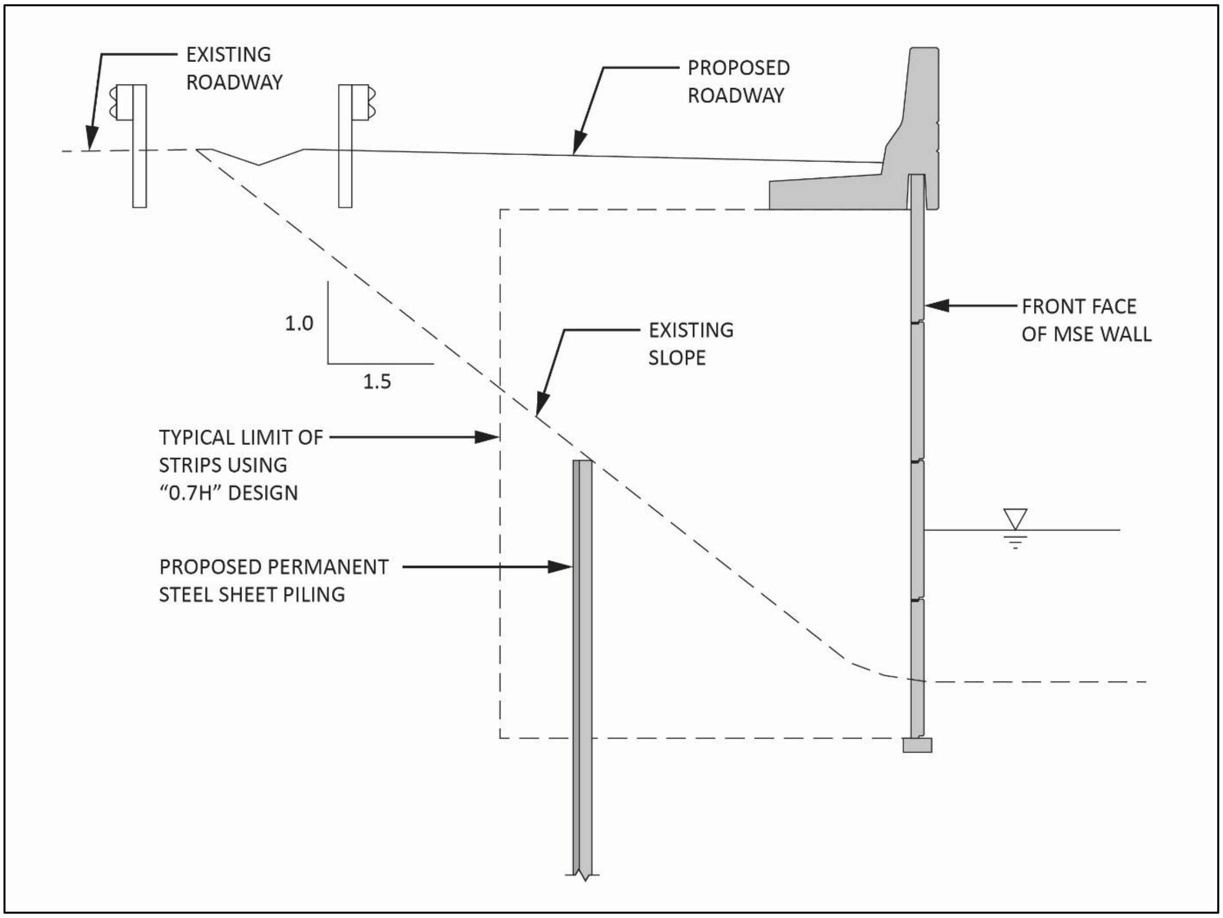


**Figure 6. Existing and Proposed Roadways**

At the time of this writing, there is no widely accepted standard for testing permeability of open-cell cellular concrete, but individual cellular concrete suppliers may provide guidance for testing the permeability of their products. For MSE structure design, open-cell LDCC material is assumed to be free-draining, like open-graded crushed stone. Further information on permeability in cellular concrete is available in ACI 523.1R-06 (ACI 2006).

## Case History 2: I-55; Cook County, Illinois

Located at the interchange between I-55 and Rte. 41 (S. Lake Shore Drive), this Illinois DOT project required construction of multiple roadway-supporting bridge approach walls, along with construction phasing to facilitate maintenance of traffic. As in Case History 1, the owner's decision to use LDCC on this project was based on weak substrata. Soil borings at the wall locations showed fill consisting of fine sands and clays with blow counts averaging less than 10 blows per foot beginning only a few feet below ground surface. (Fig. 7), suggesting the new walls would experience significant settlement and require lengthy consolidation periods if constructed of standard 120 pcf select backfill. Using LDCC would avoid this problem, so Illinois DOT specified Class II Lightweight Cellular Concrete Fill having a density range of 24-30 pcf and a 28-day minimum compressive strength of 40 psi.

The permanent MSE walls were built using precast panels, but the temporary phasing walls used a wire mesh facing because they would eventually be buried behind fill for a later phase of the project. When backfilled with soil, wire facings are typically backed by a layer of geotextile to prevent loss of backfill. By comparison, an MSE wall using LDCC in the reinforced zone requires a geotextile with the lowest possible AOS to contain the fluid LDCC until it cures. Careful overlapping and taping of seams, along with avoiding or repairing cuts, is necessary to contain the thick liquid LDCC.

As discussed earlier in this paper, reinforcements should not be placed directly on cold joints to avoid potential reduction of pullout resistance. Best practice calls for 6 in. of cover over reinforcements, meaning LDCC lifts should follow the typical 30 in. vertical reinforcement spacing. On this project, however, the wire-faced phasing walls had an 18 in. reinforcement vertical spacing so, in preplanning the sequencing of LDCC pours, the contractor had to compare the anticipated top elevation of an LDCC lift with the elevations of the strips from both the permanent and the temporary walls. Some reinforcements had to be deflected vertically to avoid them being in the plane of a cold joint (Fig. 5).

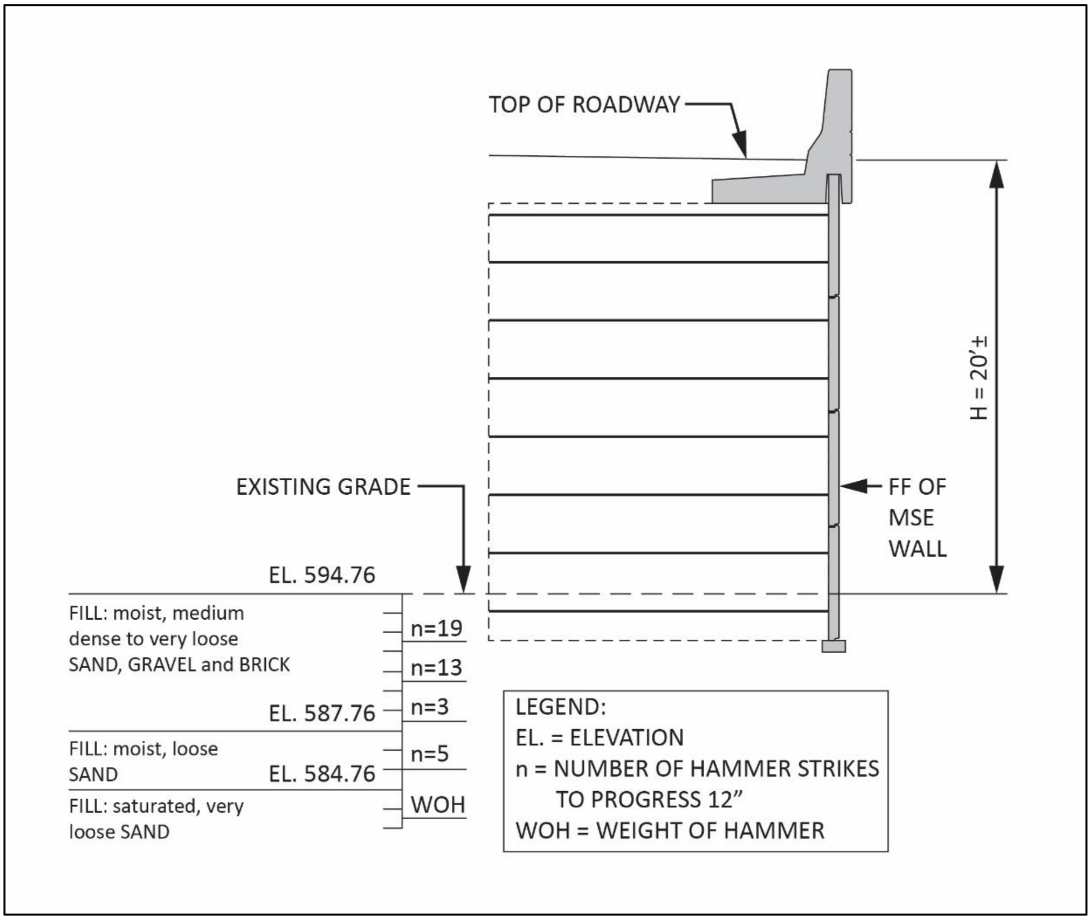


**Figure 7. New Wall atop Weak Substrata**

As occurs on this project, many MSE walls support a roadway on top of the wall. When using granular material, the top layer of backfill can be finished on a slope to parallel the roadway grade, but this cannot be accomplished with the fluid backfill that is LDCC. Instead, bulkheads are required to accomplish elevation changes that approximate the roadway grade, producing a stair-stepped top to the backfill material (Fig. 8). This stair-stepped condition leaves some MSE reinforcements exposed or with insufficient LDCC cover, so the top backfill layer should be a granular fill meeting all AASHTO MSE specifications (AASHTO 2017, Sect. 11.10.6.4.2a). A secondary benefit of this granular backfill layer is the ability to grade the top of this fill to follow roadway grade, simplifying placement of subbase, base course and pavement.

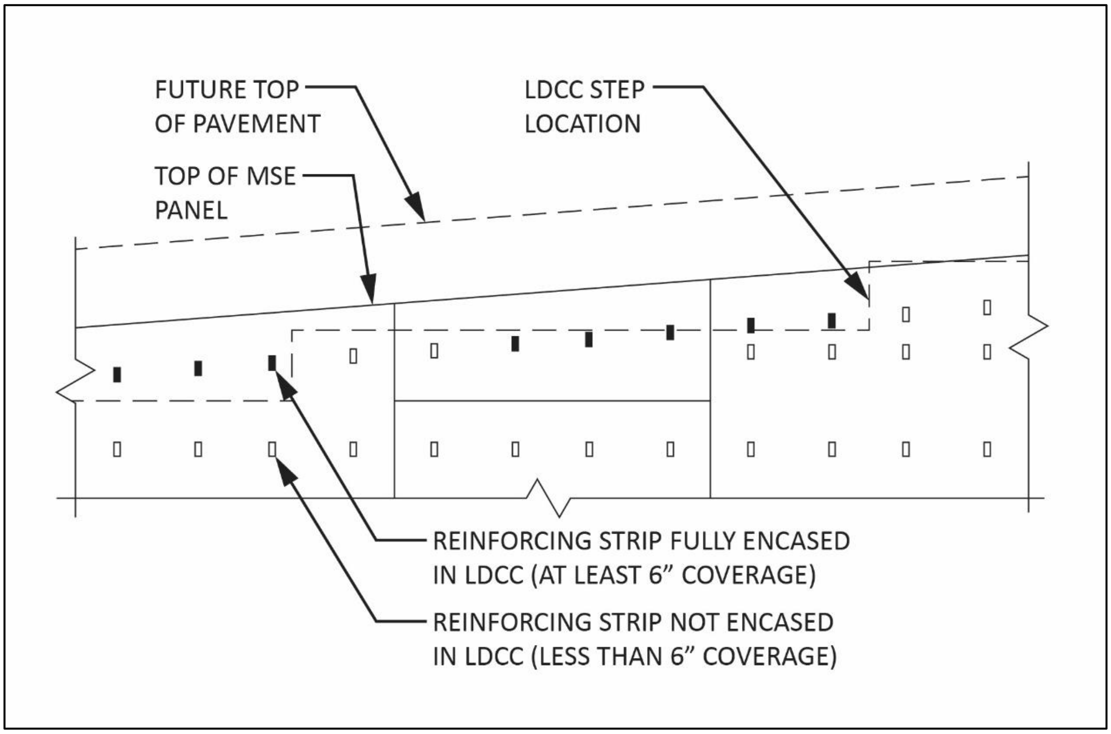


**Figure 8. Stair-Step Effect at Top of LDCC**

## Case History 3: Merchants Bridge Replacement over Mississippi River, St. Louis, MO

Merchants Bridge, constructed in 1890, is a major railroad artery across the Mississippi River, averaging 32 freight and passenger train crossings daily. Due to its age and deteriorated structural condition, the bridge has restrictions on speed, clearance and weight. Replacement spans for the river crossing will be floated into place, while onshore approach trestle downtime will be minimized by leaving the trestle in place and enclosing it in a retained fill comprising back-to-back MSE walls located just outside the existing trestle legs (Fig. 9). With trains still running, the MSE walls will be backfilled with (flowable) low-density cellular concrete to an elevation just below the top of the trestle, then trains will be stopped for removal of the track and upper portion of the trestle. L-walls, sub-ballast, ballast and new railroad tracks will complete the rehabilitation and put the reconstructed former trestle back in service, minimizing interruption of train traffic until the river spans are replaced.

With maximizing trestle availability being a major factor in design, the installation speed, small footprint and low foundation loading of Mechanically Stabilized Earth technologies made an MSE structure a clear choice for the trestle-replacement wall system. Traditional MSE construction, backfilled with granular material, would require a slow, labor-intensive process due to the limited space around the existing trestle supports, while achieving specified compaction would require use of hand-operated compaction equipment and backfill placement in thin lifts.

The use of low-density cellular concrete as the MSE backfill will not only minimize the surcharge applied to the existing trestle foundations, it will also further reduce reconstruction time since the LDCC backfill will flow into every space and requires no compactive effort, only curing time.

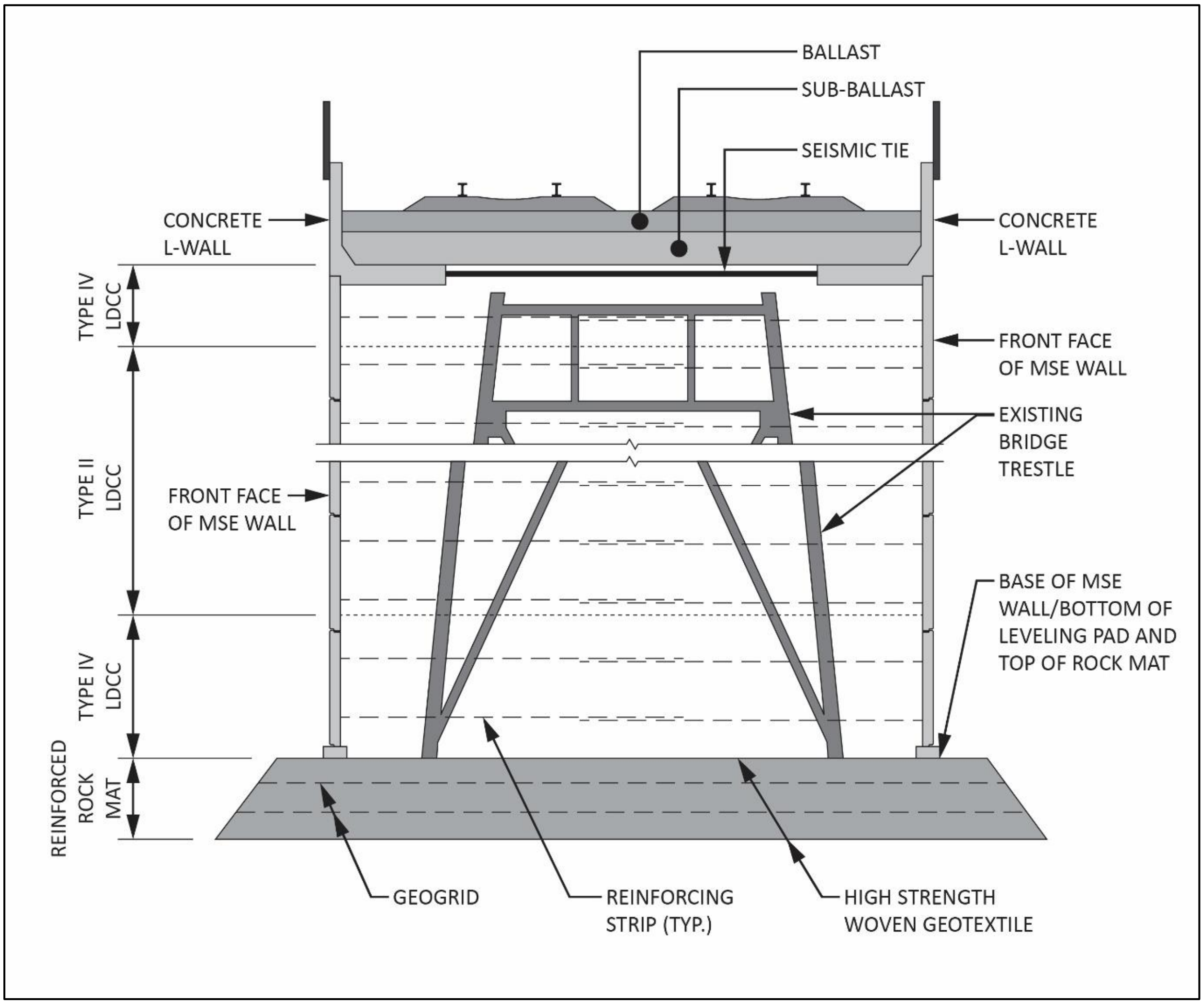


**Figure 9. Section through LDCC MSE Walls**

Designers chose to use two different classes of low-density cellular concrete in this MSE structure. Missouri DOT Type IV (42 pcf, 220 psi) was used for the bottom of the MSE fill (providing greater strength and density over the rock base) and for the top of the MSE fill just below the L-walls and ballast section (directly beneath the applied loads). The bulk of the structure, requiring less strength, was Missouri Type II, at 30 pcf and 120 psi. Design loading is Cooper E-80, roughly equivalent to a 15.5 ft high soil surcharge.

## RECOMMENDATIONS WHEN CONSIDERING USE OF LDCC IN MSE WALLS

Every MSE structure is custom-designed to meet the unique needs of a specific project. For those requiring low-density cellular concrete backfill, similar customization must go into specifying or selecting the LDCC product. Some owners, such as the DOTs of Illinois and Missouri cited above, have their own LDCC specifications and pre-select the LDCC class to be used in each structure. For first-time users or others who do not maintain a pre-established specification, a performance-based specification can be a good choice. This type of specification puts responsibility for detailed design, material selection and correct installation on the contractor and the LDCC supplier, relieving the owner of the need to research and modify specifications for every project.

Regardless of the specification type used, the owner retains overall responsibility for the project. Therefore, the owner (or owner's engineer) must understand and consider:

- Design Parameters. Specify the parameters for design of MSE structures.
- Material Properties. Select properties appropriate to project needs, such as LDCC compressive strength when planning for heavy loads such as Cooper E-80, and geotextile AOS for joints and wire facing.
- Construction Loads. Though temporary, construction loading may exceed design loads and must be considered in the design.
- Buoyancy. Evaluate buoyancy of flood-susceptible structures.
- Cracking. Evaluate cracking potential of the LDCC MSE mass due to site or loading conditions.
- Inspection. Owners must always be (or hire someone who is) knowledgeable regarding material properties and installation methods for LDCC, to be sure they receive the finished project they expect.
- Communication. The owner, the engineer, the MSE supplier, the LDCC supplier and the contractor must communicate their respective plans and requirements, to assure practicality of the design and realistic expectations regarding LDCC daily production, installation procedures and sequencing, and lift thickness relative to MSE dimensions.

## CONCLUSION

MSE walls are routinely constructed over soft foundation soils, typically using granular backfill. Where additional bearing pressure reduction is required to reduce settlement and improve structure performance, low-density cellular concrete may be used as MSE backfill in place of granular material. LDCC product selection must consider the material's unit weight and compressive strength, while normal MSE design standards must be followed. Modifications to typical MSE installation procedures address the fluid nature of LDCC by sealing joints, use of bulkheads, and supporting reinforcements to make sure they do not rest on cold joints. Attentive inspection by owners can assure correct construction practices that will lead to satisfactory long-term performance. Suppliers and owners must work together to develop more test data, to document experiences, and to build a body of knowledge about LDCC backfill in MSE walls.

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