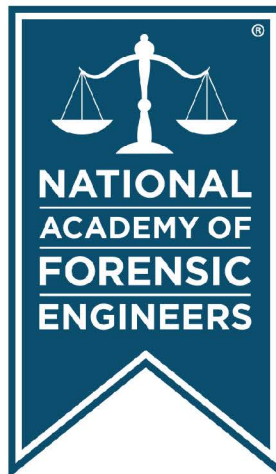


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# Beyond the Building Code — Compliance and Forensic Failure Analysis of Retaining Walls

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## Abstract

*Retaining walls are structural walls that serve to laterally restrain earth at a desired elevation in order to shape the topography of a site by managing slopes and creating usable spaces for development and construction of the built environment. Common types of retaining walls include mass/gravity walls, cantilevered walls, pile walls, and mechanically stabilized earth (MSE) walls. The design and construction of such walls are not well covered in the International Residential Code (IRC) and/or the International Building Code (IBC). As structural elements subjected to applied soil forces, retaining walls cross engineering disciplines, and a successful design often requires careful coordination between geotechnical engineers and structural engineers. In addition, successful construction often requires field verification of expected geotechnical parameters and construction oversight to ensure compliance with design specifications. This paper will explore the different stability checks (e.g., internal stability, local stability, and global stability), as well as different factors of safety, required for the proper design of a retaining wall. In addition, it will use real-world case studies to explore failures of various retaining walls, highlighting differences between compliance analysis and forensic failure analysis to identify the root cause of the failure and the responsible party.*

## Keywords

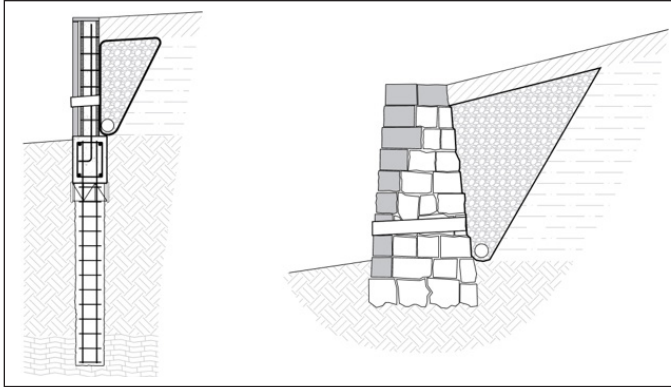
Active pressure, at-rest pressure, compliance analysis, cosmetic distress, external stability, factor of safety, failure analysis, functional distress, global stability, internal stability, local stability, mass/gravity retaining wall, mechanically stabilized earth (MSE), passive pressure, reinforced zone, safety factor, scarp

## Background and Common Types of Retaining Walls

The term “retaining wall” is a broad term that encompasses a family of structures that create vertical grade separation. In general, retaining walls fall into two categories based upon the mechanics of external resistance: gravity walls and cantilevered walls. Gravity retaining walls utilize the geometry and self-weight of the wall mass (as well as the vertical weight component of the overlying soil mass) to transfer the driving forces on the wall to vertical loads and frictional forces on the foundation soils. Cantilevered retaining walls utilize the strength/stiffness of a vertical element to transfer the driving forces on the wall to vertical loads, lateral loads, and frictional forces on the foundation soils. Both categories require the retaining wall

structure to be capable of transmitting the external loads to the foundation soils for resistance. Examples of a cantilevered retaining wall system and a gravity retaining wall system are provided in **Figure 1**.

Gravity retaining walls rely primarily on mass, width, and friction interaction with the foundation soils to resist sliding, overturning, and soil bearing failures. The basic techniques used for these walls date back thousands of years to the use of stacked stones or soils reinforced with internal layers of materials capable of resisting tension forces. Advancements in concrete and steel have led to current gravity systems such as cast-in-place concrete, mechanically stabilized earth (MSE), precast block, soil nail, and gabion basket; however, the stacked/mortared-stone



**Figure 1**

Exemplary cantilevered retaining wall (concrete masonry unit, CMU, stem on cast-in-place concrete beam on cast-in-place concrete piers, left) and gravity retaining wall (mortared stone, right).

wall is still instrumental in commercial and private development.

Common advantages of gravity walls include their relative ease of construction and control of materials. Wall components can often be placed by hand or with equipment already used for the construction of the project. The wall materials, as well as the backfill materials loading the wall, can be designed and specified by an engineer, and the foundation soils can be improved with limited additional effort. MSE, precast block, gabion, soil nail, and stacked/mortared-stone gravity retaining walls tolerate a greater degree of vertical and horizontal movement due to the fact that the components are not rigidly connected, and the individual components are relatively small with respect to the overall wall mass. For this reason, these types of gravity retaining walls are considered “flexible” in nature. The aforementioned types of gravity retaining wall structures continue to perform their intended function even with cracks/separations between elements of the wall and/or lateral/vertical movement of the wall from its original position. Challenges for gravity walls often include the width of the retaining wall mass, which can be greater than the height of the retaining wall in certain conditions, controlling the placement of fill materials and global stability.

Cantilevered retaining walls utilize relatively slender structural elements that are partially buried/embedded below grade, such that the soil at depth provides fixity for the base of the wall and the upper portion of the wall cantilevers upward to retain a mass of soil at a higher elevation. Cantilevered wall systems include reinforced concrete and/or concrete masonry unit (CMU) stem walls supported on piers, sheet pile walls, and pile walls. A cantilevered wall must be designed with adequate strength, stiffness,

and rigidity to transfer the loads from behind the wall horizontally into the soil/rock in front of the wall.

Common advantages of cantilevered retaining walls include their relatively narrow footprint and the ability for some types to be installed before mass grading or excavation. Challenges include construction costs (specialized equipment and contractors are often required), practical limitations on height (though modifications exist to address this), and limited control of soils/drainage. Some cantilevered wall systems can be utilized for groundwater cutoff; however, this is also dependent upon the soil layering.

### Governing Documents

The International Residential Code (IRC) typically governs the construction of single-family and townhouse-style residential dwelling structures as well as associated ancillary structures [1]. The International Building Code (IBC) typically governs the construction of all other structures intended for human use/occupancy (e.g., apartment complexes and commercial, industrial, educational, and institutional facilities) [2]. For the purpose of this discussion, the 2024 versions of the IRC and IBC will be considered.

Section R404.4 of the 2024 IRC includes provisions that require retaining walls to be designed in accordance with accepted engineering practice when: 1) the wall is not laterally supported at the top, and it retains in excess of 48 inches of unbalanced fill; or 2) the wall exceeds 24 inches in height and resists lateral loads, such as traffic surcharge, in addition to soil loads. In addition, the 2024 IRC explicitly requires that retaining wall designs consider stability against overturning, sliding, excessive foundation pressure, and water uplift.

Similar to the 2024 IRC, Section 1807.2.1 of the 2024 IBC explicitly requires that the design of retaining walls consider stability against overturning, sliding, excessive foundation pressure, and water uplift. Unlike the 2024 IRC, the 2024 IBC does not offer any exceptions to design/engineering requirements with respect to retaining walls that retain 48 inches or less of unbalanced fill without surcharge loads. The 2024 IBC includes prescriptive lateral soil loads that shall be used for the design of retaining walls unless such lateral loads are determined by a geotechnical investigation. Retaining walls in certain seismic locations require additional seismic loads to be applied; however, a discussion of seismic considerations is beyond the scope of this paper. Sections of the 2024

IBC applicable to the design and construction of retaining walls include Sections 1807.2, 1807.2.1, 1807.2.2, 1807.2.3, and 1807.2.4.

With respect to retaining walls, the factor of safety is defined as the load/pressure capacity of an element/component divided by the actual load/pressure applied to the element/component [3]. For example, if the sliding resistance (capacity) of a retaining wall is determined to be 12,000 pounds and the applied sliding force is determined to be 6,000 pounds, the factor of safety would be determined by dividing 12,000 pounds (capacity) by 6,000 pounds (actual load) to yield a factor of safety equal to 2.0.

The 2024 IRC specifies that retaining walls must be designed for a minimum factor of safety of 1.5 against lateral sliding and overturning. The 2024 IRC does not include minimum required factors of safety for bearing capacity of the soil or global stability. Similar to the 2024 IRC, the 2024 IBC also specifies that retaining walls must be designed for a minimum factor of safety of 1.5 against lateral sliding and overturning. The 2024 IBC also does not include a minimum required factor of safety for bearing capacity of the soil or global stability. A common factor of safety to consider for bearing capacity is 3.0, which is typically determined by the geotechnical engineer-of-record and reported in a site-specific geotechnical investigation report. A common factor of safety to consider for global stability is 1.5.

It should be noted that the 2024 IRC and the 2024 IBC do not include explicit requirements for geotechnical investigations for the design and/or construction of retaining walls. In the absence of a site-specific geotechnical investigation, a design engineer may be able to consider information and data from other sources, such as the Web Soil Survey by the United States Department of Agriculture (USDA) Natural Resources Conservation Services or data obtained from geotechnical investigations previously performed on nearby sites, if available [4].

While the IRC and IBC specify when a retaining wall must be designed in accordance with accepted engineering practice, the aforementioned codes do not provide any guidance for such engineering. Design guidance for a wide range of gravity and cantilevered wall types, including guidance for geotechnical investigations and design parameters, can be found in manuals published by the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA). The current edition of these manuals, such as

the *AASHTO LRFD Bridge Design Specifications*, Tenth Edition (2024) by AASHTO, utilizes load and resistance factor design (LRFD), which is a different methodology than the factor of safety previously described [5]. These manuals may be further adapted to specific state conditions through the state's department of transportation. Use of these design manuals and their associated construction specifications is common for state and municipal projects; however, implementation in commercial and residential projects varies based upon the engineer and contractors involved.

The *Design Manual for Segmental Retaining Walls*, 3rd Edition (Revised 2010) by the National Concrete Masonry Association (NCMA), as well as associated construction manuals, are typically used in commercial and residential projects [6]. These manuals specifically apply to walls utilizing precast facing elements with or without reinforced soils and precast modular block walls.

### Retaining Wall Terminology

To facilitate the forthcoming discussion of retaining wall design, analysis, and forensic investigation, it is necessary to define basic retaining wall terminology. For orientation purposes, the side of the wall that is exposed to the change in grade elevation (i.e., the side facing the lower grade) is considered the front of the wall. The side of the wall that is contacted by the retained soil (i.e., the side facing the retained soil) is considered the back of the wall.

The **toe** of the wall is the portion of the foundation/footing near the front of the wall. The **heel** is the portion of the foundation/footing opposite the toe. **Active pressure** is the lateral earth pressure applied to the back of a retaining wall that is allowed to deflect away from the soil/surcharge load. **At-rest pressure** is the lateral earth pressure applied to the back of a retaining wall that is not allowed to deflect away from the soil/surcharge load (e.g., basement walls that are braced at the top by a floor system). **Passive pressure** is the lateral earth pressure typically applied to the front embedded portion of a retaining wall to resist sliding.

**Backfill** is the mass of soil placed against the back of a retaining wall. The **foundation zone** is the mass of soil and/or rock below the wall or adjacent to the embedded portion of a cantilevered wall. In general, this zone extends two times the wall height below the wall and up to two times the wall height beyond the horizontal limits of the wall. The interface between the foundation zone and the bottom of the wall is where sliding is typically analyzed. The foundation zone provides resistance to sliding,

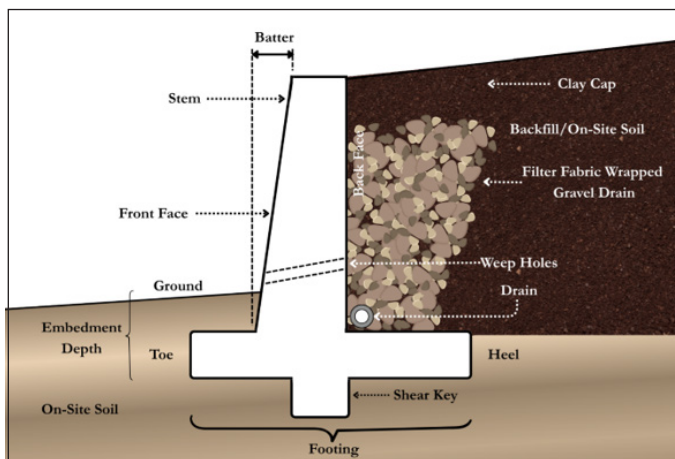
bearing, and global failures. The **retained zone** is the mass of soil and/or rock that the wall is retaining. The retained zone generally extends upward from the heel of the wall to the ground surface at an angle (generally around 45 degrees) that is dictated by the nature of the soil/material being retained. The retained zone produces or transfers the majority of the lateral forces on the wall.

**Soil reinforcements** are structural elements embedded within a soil mass in a pattern to create a cohesive soil mass known as the **reinforced zone**. **Retaining wall facing** is a structural component that transfers limited soil loading proximal to the face into the soil reinforcing elements for MSE, segmental block, and/or soil nail walls.

A retaining wall **footing** is the component of a gravity retaining wall that interfaces with the foundation zone. For MSE, soil nail, and block walls, the retaining wall footing is the base of the wall mass, including the reinforced zone. A **shear key** is often added to the footing of retaining walls in order to increase the sliding resistance of a retaining wall. A **stem** is the vertical component of a cast-in-place wall or a gravity block wall that is primarily transferring the lateral loads to the footing/foundation.

The front face of a retaining wall may be vertical or exhibit a batter. A **batter** on a retaining wall is the slope of the front face toward the backfill.

Basic retaining wall terminology for a cantilevered cast-in-place concrete gravity retaining wall is graphically illustrated in **Figure 2**. This type of wall is often referred to throughout the industry as a cantilevered retaining wall due to the fact that it incorporates a cast-in-place concrete



**Figure 2**

Basic retaining wall terminology for a typical battered cast-in-place cantilevered concrete gravity retaining wall.

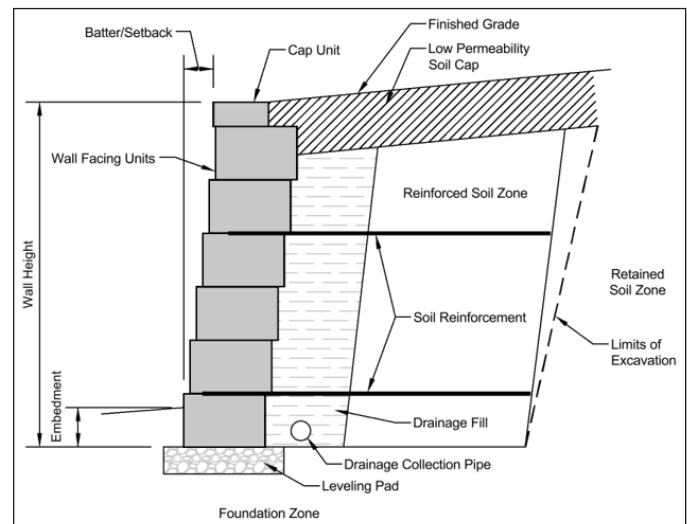
stem that is “cantilevered” from the footing; however, this type of wall is actually a gravity retaining wall system, unless it is constructed on piers, due to the fact that it relies upon the mass of the concrete wall and the vertical weight component of the soil on the footing for stability.

Basic retaining wall terminology for an MSE retaining wall is provided in **Figure 3**.

Common forensic failure terms that the reader should be familiar with include a scarp, failure wedge, and toppling. A **scarp** is a relatively steep surface produced by differential movements of soil on each side of a rupture in the ground surface [7]. A head scarp commonly develops during retaining wall failures when the retained soil rotates as a result of shear failure. A **failure wedge** is the mass of soil behind the wall that moves in response to lateral wall displacement during sliding or toppling, representing the retained zone that generates active earth pressure on the wall. **Toppling** is a rotational failure mode in which the wall rotates forward about its base; this may result in complete overturning or be limited to the upper portions of the wall failing before the entire wall mass becomes unstable.

### Design and Construction Professionals

Retaining walls are used to increase the usable footprint of a development by creating stable grade separations over relatively short distances. Because retaining walls involve multiple disciplines, their successful implementation requires careful coordination among the parties involved. The **owner** or **developer** establishes site use, operational constraints, aesthetic expectations, and performance



**Figure 3**

Basic retaining wall terminology for a typical mechanically stabilized earth (MSE) retaining wall.

expectations. The **civil engineer** and/or **landscape architect** defines the grading and drainage that establish wall location, geometry, exposed height, and adjacent conditions. The **geotechnical engineer** determines subsurface conditions and establishes appropriate soil parameters related to bearing capacity, settlement, applied soil pressures, and global stability, as well as recommendations for structural and reinforced fill materials. Using the combined information from the owner/developer, civil engineer, and geotechnical engineer, the **structural engineer** designs the wall to safely resist earth pressures, surcharge loads, and other applied forces, and to transfer those loads to the foundation soils. During construction, the **general contractor** coordinates all site activities, while the **wall subcontractor** constructs the wall and associated appurtenances. In deferred design contracts, a specialty **wall designer** provides the final structural design of proprietary wall systems. An **inspection and testing agency** observes construction and verifies that materials and workmanship comply with the approved plans and geotechnical recommendations.

Due to the fact that the responsibilities among the aforementioned parties are interdependent, coordination failures can occur during design development or construction. Common issues include retaining wall locations or heights that are not properly incorporated into the geotechnical investigation, which may result in incomplete soil data, missing settlement analyses, or missing global stability analyses. Changes in site grading may alter wall geometry or adjacent conditions and require redesign. Inadequate coordination of utilities can lead to field conflicts and differences between assumed and actual soil materials, particularly in deferred design scenarios or when fill sources change, which can compromise design assumptions if not communicated to the design team and inspection agency.

### Wall Design/Stability Checks

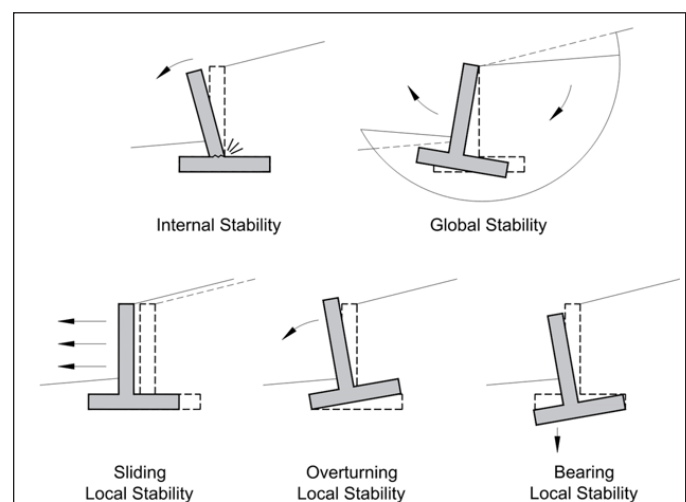
To ensure that a retained soil mass remains stable behind a retaining wall, three stability requirements must be satisfied: internal stability, local/external stability, and global stability. Internal stability refers to the stability of the wall materials with respect to internal stresses that develop from the applied loads. Internal stability considerations include material strength, flexure/bending (i.e., moment), shear, reinforcement pull-out, tension, compression, and bond strength. Local/External stability refers to the stability of the retaining wall as a unit to resist external movement from the applied loads. Local/External stability considerations include sliding, overturning, and soil bearing. Global stability refers to the overall stability of the

retaining wall system, including the retained soil mass, soil slopes, and surrounding site conditions. A global stability analysis evaluates potential slip planes that extend behind and/or below the retaining wall that may undermine the stability of the site. Refer to **Figure 4** for illustrations of different types of stability for a typical retaining wall.

### Compliance Analysis Versus Failure Analysis Compliance Analysis

A compliance analysis of a structure (e.g., retaining wall, building, pool, bridge, etc.) is an analysis that evaluates whether the structure was designed and/or constructed in accordance with the applicable requirements. A design-compliance analysis involves comparing the as-designed structure with applicable building codes, design standards, and/or geotechnical parameters. A construction-compliance analysis involves comparing the as-built structure with applicable construction documents, engineering designs, and/or industry construction standards. A design-compliance analysis may also be performed on an existing structure, in the absence of construction plans, to determine compliance with applicable provisions of a building code. In such cases, it might be possible to determine that a deficiency exists; however, it may not be possible to determine whether the deficiency constitutes a design deficiency or a construction deficiency.

With respect to retaining walls, one should consider that exact compliance with applicable building codes, construction documents, and/or industry standards may not be necessary in order to achieve a retaining wall that performs its intended function. Due to the degree of uncertainty associated with geotechnical science, in



**Figure 4**  
Different types of stability of a typical retaining wall.

conjunction with applied factors of safety, the presence of a design/construction variance relative to the applicable building codes, construction documents, and/or industry standards does not automatically equate to a retaining wall that will not perform its intended function.

When evaluating factors of safety, a value below the specified factor of safety does not establish the cause of a failure. Specifically, for failure mechanisms such as sliding, overturning, and bearing, only a factor of safety less than 1.0 suggests a potential correlation to a failure. For global stability, a factor of safety of less than 1.3 may suggest a potential correlation to failure. A compliance analysis can be performed even if a retaining wall does not exhibit any salient signs of distress or failure. This is commonly performed as a preventive measure to identify the potential presence of any latent deficiencies that could potentially affect long-term performance.

### Failure Analysis

While a compliance analysis can identify potential shortcomings in the design and/or construction of a structure for consideration as potential causes of a failure, a failure analysis of a structure is an analysis that determines the actual cause of the failure. For example, a compliance analysis may indicate that a retaining wall was designed and/or constructed to yield a factor of safety less than the specified factor of safety in soil bearing, sliding, overturning, and/or global stability; however, the actual cause of the failure may have only been associated with one of the aforementioned mechanisms. A failure analysis can be useful to identify one or more parties responsible for the failure (and resultant damage) as well as to develop an appropriate scope of remediation. A failure analysis may include gathering background information, performing visual observations of the failed retaining wall, intrusive investigations, a forensic geotechnical investigation, materials testing, and/or engineering analyses.

Gathering background information may include obtaining the original construction documents, construction records, construction materials testing (CMT) reports, maintenance records, and/or a timeline of the failure.

Visual observations should attempt to document conditions consistent with a particular type of failure mechanism, such as soil bearing, sliding, overturning, internal stability, and/or global slope stability. In addition, observations should also document the drainage conditions in proximity to the retaining wall (i.e., positive drainage, negative drainage, ponding water, etc.), soil conditions

(i.e., erosion, scour, saturated soil, dry soil, etc.), backfill conditions (i.e., drainage gravel, drainage system, general soil type, retained soil slope, etc.), measurements of wall geometry (i.e., cross-section dimensions, retained height of wall, embedment depth of wall, etc.), and measurements of movement (i.e., plumbness of wall face, plumbness of fence posts on top of the wall, relative elevations along the top of the wall, out-of-plane offset distance across cracks/separations).

Intrusive investigations may be necessary in order to obtain additional information. Test pit excavations, in which soil is removed near the toe of the wall or from behind the wall, are one form of intrusive investigation that may be necessary to determine backfill conditions and/or cross-sectional geometry of a retaining wall.

A forensic geotechnical investigation may be necessary to determine the soil properties and design parameters necessary to analyze the wall for internal stability, local/external stability, and global stability. A forensic geotechnical investigation should consider the different soil conditions that may affect the performance of a retaining wall, such as the backfill material, the material at the base of the wall, and any stratum of soil that may affect global stability.

Engineering analyses of the retaining wall should be performed utilizing information that closely resembles the state of the retaining wall and/or soil conditions at the time that the failure occurred. Typically, an analysis of the as-designed wall is beneficial to determine if the original design was acceptable, and an analysis of the as-built wall is beneficial to determine the actual cause of the failure.

### **Cosmetic Distress Versus Functional Distress**

Distress in structures (e.g., retaining walls, buildings, pools, bridges, etc.) may be classified as cosmetic distress or functional distress. Cosmetic distress is that which may affect the appearance of the structure but does not affect the structural integrity or performance of the structure. Functional distress is that which affects the structural integrity and/or performance of the structure.

With respect to retaining walls, examples of cosmetic distress include mortar cracks/separations in a mortared-stone retaining wall as well as non-structural cracks/separations causally related to differential movement in concrete or CMU. Cracks/separations in mortar, concrete, and CMU can be related to a number of mechanisms, including, but not limited to, lateral yielding from applied

earth pressure, differential soil movement, and/or thermal expansion and contraction. Mortar cracks/separations in a mortared-stone retaining wall that are causally related to thermal expansion/contraction, differential soil movement, and/or nominal rotation are considered to be cosmetic distress and typically do not adversely affect the function of the retaining wall. Remediation of cosmetic mortar cracks/separations often includes repointing mortar joints and/or resetting displaced stones. Remediation of cosmetic distress should be expected, and it is typically considered a maintenance activity. There is often-times a trade-off between initial cost of construction and subsequent maintenance. For example, a mortared-stone retaining wall typically exhibits a lower initial cost of construction relative to a cantilevered wall; however, it may require periodic maintenance to maintain a desirable aesthetic appearance, whereas a cantilevered retaining wall typically exhibits a higher initial cost but may require less maintenance to maintain a desirable aesthetic appearance.

Functional distress includes resultant distress from movement mechanisms such as sliding, rotation/overturning, and bulging of the retaining wall beyond that which is expected by the nature of the design. A retaining wall may exhibit signs of functional distress without a catastrophic failure. Retaining walls that exhibit signs of functional distress, but have not yet experienced a catastrophic failure, can often be remediated in place rather than being removed and replaced. Remediation strategies typically focus on stabilizing the retaining wall, improving drainage, reinforcing soils, and/or mitigating erosion or scour. Stabilization of mortared-stone retaining walls typically includes the addition of mortared-stone to increase the mass of the wall, which reduces pressures on the underlying soil by spreading the load across a larger footprint, thereby increasing the factor of safety against soil bearing, sliding, and rotation/overturning.

Remediation of reinforced concrete/CMU retaining walls and MSE retaining walls typically includes the installation of soil anchors, tie-backs, or dead-man anchors. Drainage improvements, such as the installation of a drainage system, weep holes, and/or gravel backfill, help relieve hydrostatic pressure and reduce lateral load. Erosion and scour control measures, such as the addition of riprap, concrete footings, vegetative cover, and/or geotextile mats, help prevent undermining and surface erosion. These combined approaches can restore performance, extend service life, and mitigate future distress without full reconstruction.

### **Case Study #1: Failure of a Mechanically Stabilized Earth (MSE) Retaining Wall**

A property located in north Texas was developed with a warehouse building as well as associated surface pavements for parking lots, driveways, and loading docks. The natural topography of the site generally sloped downward prior to construction, and development of the site required the construction of a retaining wall in order to create a more level building pad for the proposed improvements.

The retaining wall that is the subject of this matter is a mechanically stabilized earth (MSE) retaining wall comprised of dry-stacked masonry units (without mortar) connected by integrated shear keys and restrained by geosynthetic reinforcement grids (geogrid) that extend into the backfill behind the wall. The subject retaining wall is approximately 765 feet in length and ranges in height from approximately 1 foot to 20 feet tall (ground elevation differential plus footing). The ground surface behind the retaining wall (high side of wall) was specified to be graded with slopes that varied up to 1 unit vertical to 4 units horizontal (approximately 14 degrees). Approximately two-and-a-half years following completion of construction of the retaining wall, a portion of the wall, approximately 80 feet in length, failed when it translated toward the north (**Figure 5**).

The authors served as consultants for the engineer-of-record and were tasked with providing opinions regarding the design and construction of the subject retaining wall.

At the time of the initial site visit following the wall failure, scarps were observed behind the subject retaining wall (high side of wall), and portions of the subject retaining wall were observed to exhibit rotation, with the top of the wall leaning inward toward the backfill. In addition, weep mechanisms through the retaining wall were observed to be exposed by temporary excavations where they were previously blocked/occluded by soil prior to/during the failure of the retaining wall. The retaining wall exhibited the presence of bulging, with cracks in some of the blocks, and it also exhibited signs of sliding outward at the base.

### **Geotechnical Engineer-of-Record and Structural Engineer-of-Record**

According to the original-construction geotechnical report issued for development of the subject property, the geotechnical engineer-of-record was aware that retaining walls were intended to be constructed on the property, and



**Figure 5**

Google Street View image of MSE retaining wall post-failure from April 2019 [8].

geotechnical borings were specifically located and identified as being applicable for the retaining walls; however, the geotechnical engineer-of-record did not provide site-specific soil parameters for the design of retaining walls within the report. As a result, the structural engineer-of-record for the subject retaining wall reportedly based the design upon expected soil parameters. The structural engineer-of-record for the retaining wall specified that the owner's representative bear responsibility to review and verify the applicability of the expected soil parameters with respect to the actual site conditions prior to construction. In addition, the structural engineer-of-record excluded global stability analysis from its scope of services.

#### Crushed Concrete Substitution for Drainage Gravel

The contractor who constructed the subject retaining wall reportedly installed crushed concrete instead of the specified drainage gravel behind the wall. Previously demolished concrete can be crushed and recycled for use in lieu of gravel in some construction applications; however, it is not always suitable for such uses. The pH value of crushed concrete can potentially cause degradation of the geogrid over time. Also, the use of crushed concrete aggregates is not typically considered suitable for drainage applications due to the potential for cementitious particles to rehydrate and harden when mixed with water, as well as the fact that excessive fines can cause reductions in hydraulic conductivity of the system over time.

#### Reinforced Zone Soil Material

After the failure of the subject retaining wall, site-specific soil samples were obtained by investigators for

geotechnical laboratory testing. One of the aforementioned samples was obtained from the reinforced zone of the subject retaining wall. Based upon the tests of the soil obtained from the reinforced zone, it was reportedly determined that the soil exhibited a plasticity index (PI) of 25 percent and fines (material passing a No. 200 sieve) of 65.9 percent. The structural engineer-of-record for the subject retaining wall specified that the soil in the reinforced zone of the retaining wall was to exhibit a plasticity index less than or equal to 15 percent and fines less than 35 percent. As a result, the soil placed within the reinforced zone of the subject retaining wall was not compliant with the specifications for the design of the wall.

A relationship between the PI of a soil and its inherent swelling capacity was documented and qualitatively categorized by Terzaghi, Peck, and Mesri (1996) [9]. According to the plasticity index specified in the structural engineering drawings for the subject retaining wall (PI of less than 15), the shrink-swell potential of the material specified to be placed within the reinforced zone was classified as "medium." Based upon the reported plasticity index of the non-compliant soil that had actually been placed within the reinforced zone, the shrink-swell potential of the material was classified as "high." As a result, the additional swelling/expansion potential of the soil material from the addition of water would increase the lateral earth pressure applied to the retaining wall. In addition, due to the presence of an increased percentage of fines, the backfill material would not drain as easily and would not engage the geogrid as effectively as a soil material with fewer fines.

### Rain Event

The failure of the subject retaining wall occurred in early January 2019. Dallas Love Field Airport, which is located approximately 5 to 6 miles from the subject retaining wall, recorded approximately 4.42 inches of rainfall over a period of nine days shortly before the wall failed. Near the toe of the subject retaining wall was a drainage channel/swale. Due to the presence of multiple rainfall events leading up to the date of the failure, the soils exhibited a softened state with a reduced shear capacity. Softened soil is characterized by a strength reduction due to a change in the moisture content [10].

### Finished Grade Slope

The ground surface behind the retaining wall (high side of the wall) was specified by the civil engineer-of-record to be graded with slopes that varied up to approximately 14 degrees. During the investigation of the wall failure, a land surveyor performed a topographic survey, and the actual as-built slopes were found to range from 14.1 to 18.5 degrees, with an average slope of 16.2 degrees, in proximity to the portion of the subject retaining wall that experienced a failure. As a result, the finished grade at the top of the subject retaining wall exhibited a slope that was greater than the specified slope considered in the design. An increased slope of the soil behind the subject retaining wall yielded an increased lateral earth pressure applied to the retaining wall.

### Global Stability

As part of the investigation into the failure of the subject retaining wall, a global (slope) stability analysis of the “as-designed” retaining wall was performed with consideration of the expected soil parameters identified in the retaining wall design drawings. Based upon the aforementioned analysis, it was found that the wall design yielded factors of safety that were compliant with the specified factors of safety for internal stability and local/external stability; however, it was also found that the retaining wall design yielded factors of safety that were lower than the specified factors of safety for global stability. Even if the retaining wall had been constructed in perfect compliance with the structural engineering design drawings, the retaining wall would still have been at risk of a global stability failure. As previously mentioned, the structural engineer-of-record excluded global stability analysis from its scope of services.

As part of the investigation into the failure of the subject retaining wall, a global (slope) stability analysis of the “as-built” retaining wall was also performed with

consideration of the actual site-specific soil parameters as determined from the post-construction forensic geotechnical investigation following the wall failure. Based upon the aforementioned analysis, it was found that the as-built retaining wall yielded factors of safety that were generally compliant with the specified factors of safety for internal stability and local/external stability; however, it was also found that the as-built retaining wall yielded factors of safety that were lower than the specified factors of safety for global stability.

### Construction-Phase Observations

According to construction documents and contract agreements, one of the subcontractors involved in the construction of the subject retaining wall had agreed to arrange, coordinate, and obtain all construction-phase inspections for its work. According to *The Design Manual for Segmental Retaining Walls*, 3rd Edition by the NCMA [6], soil in the reinforced zone should be checked to ensure it meets specifications similar to how concrete and steel in cast-in-place concrete construction are inspected. The aforementioned document by the NCMA stated that the wall contractor is responsible for quality control of the wall installation, which includes performing necessary observation and testing to verify that work performed meets the minimum standards. Typically, construction-phase observations are performed by a representative of the structural engineer-of-record, as the structural engineer-of-record is the most familiar with the requirements of the design. It was found that the structural engineer-of-record for the subject retaining wall was never contacted during construction to perform any such construction-phase observations.

### Findings

Based upon a design-compliance analysis, consultants identified pullout of geogrid, global stability, and/or sliding as potential failure mechanisms; however, based upon the observed mode of failure, in conjunction with a failure analysis, it was found that the cause of the failure was primarily related to global stability. The global stability failure was causally related to a lack of coordination between the owner, the geotechnical engineer-of-record, and the structural engineer-of-record as well as a lack of site-specific geotechnical design values. Contributory factors to the failure included non-compliant reinforced zone backfill material, non-compliant aggregates utilized in the drainage system, increased hydrostatic pressure from rain events and reduced drainability, and a lack of adequate construction-phase observations. Based upon the investigation, remediation of the as-built retaining wall was warranted. Remediation of

the subject retaining wall included a complete rebuild of the portions of the wall that failed and the addition of tie-backs to the non-failed portions of the wall.

### Case Study #2: Evaluation and Remediation of a Mortared-Stone Retaining Wall

A residential development for hundreds of residential properties in north Texas included thousands of linear feet of mortared-stone retaining walls. The retaining walls were constructed within the subject development during the original mass grading activities on the land circa 2005 to create more-level building pads for the residential properties. According to governing documents, the owner's association for the subject development reportedly bears responsibility for maintenance and upkeep of the retaining walls. The subject retaining walls range in height from 1 foot, 0 inches to 5 foot, 6 inches tall above grade.

The authors served as consultants for the owner's association and were tasked with performing an evaluation of the retaining walls throughout the development in order to provide recommendations for remediation of the retaining walls, if necessary.

An initial site visit related to the mortared-stone retaining walls was performed on October 14, 2022. At the time of the initial site visit, portions of the subject retaining walls exhibited signs of bulging in the face of the wall, delaminated face stone, leaning/rotation/overturning, sliding, mortar separations, and separations at abutments with adjacent structures (i.e., monument sign structure, masonry column footings/pier caps, etc.).

A majority of the retaining walls were found to be performing as intended, with only signs of cosmetic distress consistent with distress that is to be expected in mortared-stone retaining wall construction. When the mass/geometry of a mortared-stone retaining wall is not being called into question, remediation of cosmetic distress in a mortared-stone retaining wall can be accomplished by having a mason clean out cracks/separations and repoint the mortar to achieve a more aesthetically pleasing appearance.

At locations where separations occurred between the mortared-stone retaining walls and adjacent structures, it was recommended to apply an elastomeric sealant to mitigate any water from flowing through the separation while still accommodating differential movement between the two structures.

Some portions of the mortared-stone retaining walls

exhibited signs of bulging that appeared to be related to delaminated face stone, as shown in **Figure 6**. The aforementioned condition is considered to be cosmetic in nature; however, it can also pose a safety hazard due to the fact that a stone can fall off the face of the retaining wall. As a result, it was recommended that such conditions be remediated by the removal and reinstallation of the face stone at such locations.

In consideration of the portions of the mortared-stone retaining walls that exhibited signs of leaning/rotation/overturning and/or sliding, the walls were evaluated on a case-by-case basis. It was recommended to monitor portions of retaining walls that exhibited an inward lean with the top leaning toward the retained soil. In addition, it was recommended to perform additional investigation for retaining walls that exhibited an outward lean, with the top leaning away from the retained soil, in order to determine contributory factors associated with the lean/rotation/overturning and to provide remedial recommendations.

Some engineering judgment may be required to determine acceptable limits/thresholds at which mortared-stone retaining walls should be remediated versus monitoring. There was only one wall that exhibited a lean/rotation of a degree, such that it exhibited a reverse batter with the top of the wall away from the soil that it was retaining (**Figure 7**). The aforementioned retaining wall varied in



Figure 6

Photographs of mortared-stone retaining wall with bulge related to delaminated face stone.



**Figure 7**

View of mortared-stone retaining wall that exhibited a reverse batter (lean/rotation with the top away from the retained soil).

height from 2 feet to 5 feet tall, and it was approximately 185 feet in length. The aforementioned retaining wall will be considered the subject retaining wall for the remainder of this case study.

Exploratory test pit excavations were performed behind the subject retaining wall, as well as near the toe of the retaining wall, in proximity to the tallest portion of the wall, to establish the as-built cross-sectional geometry of the wall such that it could be modeled and analyzed. It should also be noted that the exploratory test pit excavation revealed that the backfill soil retained by the wall appeared to consist of on-site clay soil (i.e., not imported material).

A post-construction forensic geotechnical investigation was also performed to identify the in-situ soil properties and conditions to determine the geotechnical parameters necessary for evaluation of the retaining wall design/construction. Based upon the geotechnical investigation, the geotechnical engineer specified an allowable bearing pressure of 2,000 pounds per square foot, a minimum embedment depth of 24 inches, an equivalent fluid pressure of 65 pounds per cubic foot (pcf) for active conditions of on-site soil, an equivalent fluid pressure of 40 pcf for at-rest conditions of a free-draining gravel wedge backfill, an equivalent fluid pressure of 225 pounds pcf for passive conditions of on-site soil for resistance against sliding, and a coefficient of friction of 0.3 between the base of the retaining wall and the underlying clay soil.

As previously mentioned, the subject retaining walls were constructed circa 2005, and the subject investigation began in 2022. As a result, the original engineered design drawings were not available for review as part of the investigation. As such, a design-compliance and a construction-compliance analysis with respect to any original engineered design drawings could not be performed.

A compliance analysis was performed for the as-built retaining wall with respect to code-prescribed factors of safety for sliding and rotation, as well as allowable bearing pressures for the soil based upon the aforementioned geotechnical investigation. Based upon the compliance analysis, the as-built retaining wall did not provide adequate factors of safety for sliding or overturning, and the applied pressure on the soil beneath the base of the wall exceeded the allowable bearing pressure. In addition, trees that had been planted immediately behind the subject retaining wall likely exerted additional pressure upon the wall as the root systems of the trees increased in volume over time as the trees grew.

Due to the fact that mortared-stone retaining walls utilize their mass and geometry to resist applied forces, additional mortared stone can typically be added to an existing mortared-stone retaining wall to increase the mass and/or change the geometry as necessary to achieve an acceptable design. Based upon an analysis of the subject retaining wall, additional mortared stone would be necessary to increase the mass of the wall. In addition, it was necessary to replace the existing clay soil backfill with free-draining gravel backfill in order to reduce the lateral pressure on the wall and achieve an acceptable design. In order to implement the aforementioned remediation, the soil (and trees) behind the existing retaining wall would need to be excavated such that additional mortared stone could be added to increase the cross-sectional geometry, and the excavated backfill would need to be replaced with a wedge of gravel behind the retaining wall.

### Findings

A compliance analysis determined that the as-built retaining wall did not achieve adequate/compliant factors of safety for sliding or overturning, and the applied pressure on the soil beneath the base of the wall exceeded the allowable bearing pressure. A failure analysis ruled out that the failure was causally related to sliding due to the fact that the footing/toe was restrained by a concrete sidewalk, and there were no salient signs of sliding. Based upon the mode of movement, which was rotation/overturning, a failure analysis determined that the failure

of the wall to perform as intended was causally related to lack of overturning/local stability and/or a bearing capacity failure. An analysis of the subject retaining wall found that it could be salvaged with modifications to the wall geometry and backfill; however, it was removed and replaced due to other considerations not related to the wall's performance.

### Summary

Due to the fact that retaining walls involve multiple disciplines, the successful implementation of a retaining wall requires careful coordination amongst all parties involved, including but not limited to the owner/developer, landscape architect, civil engineer, geotechnical engineer, structural engineer, general contractor, specialty wall subcontractor, wall designer (for proprietary wall system), and/or inspection/testing agency.

The first case study presented herein offered an example of a wall failure that occurred primarily due to a global (slope) stability failure associated with a lack of site-specific geotechnical design parameters and the omission of a global (slope) stability analysis during the original design, which was exacerbated by multiple construction deficiencies associated with non-compliant reinforced zone backfill material, non-compliant aggregates utilized in the drainage system, increased hydrostatic pressure from rain events and reduced drainability, and a lack of adequate construction-phase observations.

The second case study presented herein offered an example of a wall failure that occurred due to local stability failures (overturning and/or bearing capacity) associated with the as-built geometry of the wall. An analysis of the retaining wall found that it could have been salvaged with modifications to the wall geometry and backfill; however, it was removed and replaced due to other considerations not related to the wall's performance.

### Conclusion

A compliance analysis of a retaining wall is an analysis that evaluates whether the retaining wall was designed and/or constructed in accordance with the applicable requirements. While a compliance analysis can identify potential shortcomings in the design and/or construction of a retaining wall for consideration as potential causes of a failure, a failure analysis of a retaining wall is an analysis that determines the actual cause of the failure. A failure analysis of a retaining wall should be performed utilizing information that closely resembles the state of the retaining wall and/or soil conditions at the time the failure occurred.

Distress in retaining walls may be classified as cosmetic distress or functional distress. Remediation of cosmetic distress should be expected, and it is typically considered a maintenance activity. A retaining wall may exhibit signs of functional distress without a catastrophic failure. Retaining walls that exhibit signs of functional distress, but have not yet experienced a catastrophic failure, can often be remediated in place rather than being removed and replaced.

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