Increased Use of MSE Abutments

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ABSTRACT:

Reinforced Earth® structures, introduced in the US in 1971, were initially used primarily for retaining walls, yet many early structures supported heavy and concentrated loads for railways, industrial structures and highway bridges. Success spawned competing systems, the generic name Mechanically Stabilized Earth (MSE), and a new industry. In spite of initial reluctance by some bridge engineers, Reinforced Earth and MSE abutments are now widely accepted; more than one thousand bridges are currently supported by this technology.

INTRODUCTION

Reinforced Earth® was invented in 1957 by the French engineer and architect Henri Vidal, who first published results of his research in 1963.[1] After a brief period of skepticism by practicing engineers, the first significant structures were constructed in Europe in 1967. The new, patented technology was so versatile and cost effective that its use spread rapidly in the early 1970s to more than 30 countries throughout the world.

Vidal brought his technology to the United States in 1971, at the invitation of the Federal Highway Administration (FHWA), to solve a difficult landslide problem. With the encouragement of financial support from a Federal Highway demonstration project,[2] states constructed additional Reinforced Earth structures as slide buttresses and slide repair walls in mountainous areas, as a bridge abutment, as high retaining walls, and even as a foundation reinforcement slab over a sinkhole-prone area. From these first experiences, it was recognized that this material, with its unique high strength and flexibility, could be used to support extremely heavy loads, even on marginal foundation conditions.

In addition to retaining walls for all imaginable applications, early Reinforced Earth structures supported the heavy loads of quarry and mining vehicles and carried Cooper E-80 railway loading. Constructed in France in 1969 and in the United States in 1974, the first Reinforced Earth bridge abutments were "true" abutments, meaning the bridge beams rested on a spread footing-type beam seat bearing directly on the reinforced backfill (by comparison, "mixed" abutments have a row of piles supporting the beam seat). One of the first true abutments in France carried a 250-foot span, while the first American true abutment spanned a comparatively small 70 feet.

As is typical of successful new technologies, competitive systems developed and, by the early 80s, a new industry had been created. The generic name Mechanically Stabilized Earth, often shortened to MSE, was coined, and the use of MSE structures increased dramatically through the last two decades of the 20th century and to the present. Today there are several companies designing and supplying MSE structures in the United States for highway, industrial, military, forestry, commercial and residential applications.

To better understand the mechanism of an MSE bridge abutment, further discussion of the materials and their behavior is required.

BASIC MECHANICS OF REINFORCED EARTH

As explained by McKittrick in 1978,[3] "The basic mechanics of Reinforced Earth were well understood by Vidal and were explained in detail in his early publications. A simplification of these basic mechanics can be illustrated by Figure 1. As shown in Figure 1a, an axial load on a sample of granular material will result in lateral expansion in dense materials. Because of dilation, the lateral strain is more than one-half the axial strain. However, if inextensible horizontal reinforcing elements are placed within the soil mass, as shown in Figure 1b, these reinforcements will prevent lateral strain because of friction between the reinforcing elements and the soil, and the behavior will be as if a lateral restraining force or load had been imposed on the element. This equivalent lateral load on the soil element is equal to the earth pressure at rest ($K_o\sigma_v$). Each element of the soil mass is acted upon by a lateral stress equal $K_o\sigma_{v.}$ Therefore, as the vertical stresses increase, the horizontal restraining stresses or lateral forces also increase in direct proportion." Reinforced Earth is, therefore, a composite material, combining the compressive and shear strength of compacted granular fill with the tensile strength of horizontal, inextensible reinforcements.

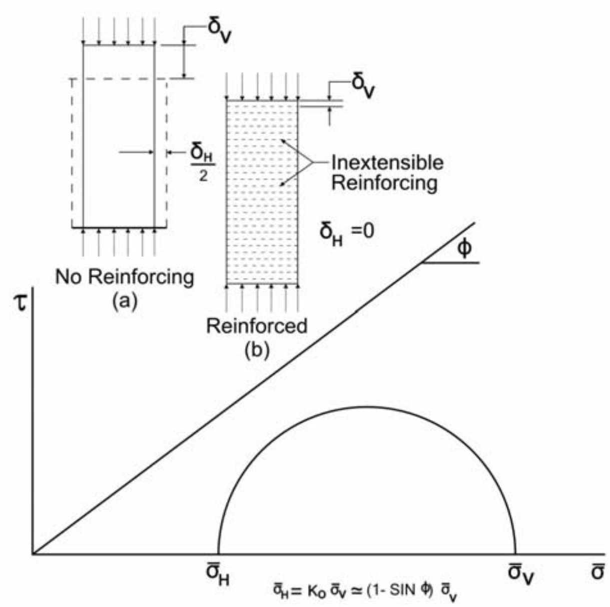

Figure 1 – Basic Mechanics of Reinforced Earth

In practical terms, the larger the surcharge put atop a Reinforced Earth structure, the stronger the material becomes. Thus, understanding Reinforced Earth's basic mechanics and its resulting inherent strength and flexibility, and with the addition of a facing system, this composite material was well suited for use as bridge abutments and other heavily loaded structures. The combination of facing, reinforcement and granular backfill has performed successfully, in an ever-increasing number of abutments and other structures, for over three decades.

MATERIALS

FACING – Originally conceived of as a "skin," the facing of an MSE structure forms the physical and visual front of the structure and provides both localized soil retention and stress continuity between reinforcement layers. Early Reinforced Earth walls and abutments in France truly had a skin, as the facing panels were 0.12 inch thick, galvanized, rolled steel sections, 1 foot high by 33 feet long and elliptical in cross section.[4] These panels were also used for the first Reinforced Earth wall constructed in the United States in 1971, a massive landslide repair and buttress structure on Highway 39 in the Angeles National Forest near Los Angeles.[2] Still in service today, this structure is a testament to the durability of galvanized steel in MSE structures. Precast concrete facing panels, introduced in the early 70s and offering a rapid, simple construction process and a wide range of architectural possibilities, were used for most of the early FHWA demonstration project structures and are now the facing of choice for owners, engineers and architects. Square, rectangular and proprietary shapes are now the industry standard for MSE walls supporting embankments, ramps and bridges along America's highways and for numerous non-highway applications as well.

REINFORCEMENT – The two basic types of MSE soil reinforcements are inextensible (steel) and extensible (polymeric). Inextensible steel reinforcements are either flat ribbed strips or welded wire mats, both of which are hot dip galvanized (except for temporary structures). Since inextensible reinforcements do not stretch under design loading, they are the preferred MSE reinforcement type for highway structures in general and for critical structures such as bridge abutments in particular, where deformation control is crucial to structural performance of both the superstructure and the abutment.[5] Inextensible reinforcements have been used successfully in MSE bridge abutment structures for thirty-five years, while research is still underway trying to develop an extensible reinforcement that will perform adequately in bridge abutment applications.

Extensible reinforcements, by comparison, stretch, often to the extent that the strain in the reinforcement is equal to the strain in the soil mass, accompanied by considerable lateral movement of the retained fill and facing. Well-suited for applications such as reinforced slopes, basal reinforcement, temporary walls for staged construction and surcharging, and for modular block faced walls, extensible reinforcements are used primarily in commercial and residential applications where the possible elongation of the reinforcement and resulting lateral deformation can be tolerated.

GRANULAR BACKFILL – The backfill used in MSE structures is granular material with a 4 inch maximum size and less than 15% fines content (Table 1), as required by the AASHTO Standard Specifications For Highway Bridges.[6] Additional requirements for plasticity index (PI), internal friction angle (ϕ), soundness and electrochemical properties are also specified. Some states vary the gradation limits or reduce the allowable fines content based on local material characteristics.

U.S. Sieve Size	Percent Passing
4 inches	100
No. 40	0-60
No. 200	0-15

Table 1 – Gradation Limits per AASHTO

For a period in the early 80s, the FHWA specification for MSE walls allowed up to 25% fines, and many structures were constructed in the United States with these finer materials. Quality control was a problem, however, with many backfills significantly exceeding the 25% limit, making wall facing alignment problematic for contractors. As a result, to reduce the incidence of backfill-induced wall deformations, gradation limits were made more restrictive; these limits remain in force today.

BEHAVIOR OF MSE STRUCTURES

Bridges may be designed to last for 100 years, requiring predictable performance from all structural components. For engineers to use Reinforced Earth or other MSE systems as abutments, they must have confidence that the material's behavior is both appropriate for the application and predictable throughout the bridge's design life. Given the well-understood inherent strength and flexibility of MSE structures and the established design methodology, the areas in which confidence is needed are service life, settlement, and seismic performance.

SERVICE LIFE – The service life of an MSE structure is defined as the period of time during which the tensile stress in the soil reinforcements will be less than or equal to the allowable stress for the steel. MSE retaining walls are routinely designed for a 75-year service life, while structures supporting bridges are designed for a 100-year service life. The primary factor determining the service life of an MSE structure is corrosion of the reinforcements which, for a metallic reinforcement material, is closely related to backfill electrochemical properties.

Research on buried galvanized steel, conducted by the National Bureau of Standards, Terre Armee Internationale, FHWA, and several state DOTs, confirms that the metal loss rates (Table 2) used in the design of MSE structures are conservative for steel soil reinforcements galvanized with 2 ounces per square foot of zinc and buried in backfill meeting the electrochemical requirements in Table 3.[7]

Material	Loss Rate
Zinc (first 2 years)	15 μm/yr
Zinc (subsequent years to depletion)	4 μm/yr
Carbon steel (after zinc depletion)	12 μm/yr

Table 2 – Metal Loss Rates

Backfill	Electrochemical Requirements
Resistivity	≥ 3000 ohm-cm at saturation
pH	Range 5-10
Chlorides	≤ 100 ppm
Sulfates	≤ 200 ppm

Table 3 - Electrochemical Requirements

The carbon steel loss rate in Table 2 is twice the average loss of steel based on weight, so that the calculated loss is in proportion to the loss of tensile strength based on rupture of corroded samples.[8] Since it is necessary to maintain the reinforcement in an allowable stress condition at the end of the service life, the loss rates in Table 2 determine the sacrificial thickness of steel which must be added to the load-carrying cross section to produce the design cross section. At the end of the service life, the remaining steel will have a factor of safety of 1.8 against yield and 2.2 against rupture.

SETTLEMENT PERFORMANCE – The ability of MSE walls and abutments to withstand extreme settlements is a well-recognized benefit of this construction technology. MSE structures have accommodated total settlements of nearly 3 feet, as well as differential settlements greater than 1 foot in 100 feet (1%), without loss of structural function and without showing facing panel distress. Thus, at sites where down-drag forces could overload piles beneath a traditional abutment or require heavier pile sections to carry the added load, MSE abutments will be virtually unaffected by the settlement, built at lower cost, and will require less maintenance during the bridge's service life.

Mechanically Stabilized Earth is frequently used for abutments on compressible foundation soils. If primary settlement can be hastened by preloading, the MSE abutments and approach walls (if any) may be constructed atop the in situ soil and serve as a surcharge load, with an additional surcharge placed atop the constructed MSE walls and abutments if heavier preloading is required. After primary settlement is complete, any additional surcharge is removed, the top rows of panels are installed, and the bridge seats and deck structure are constructed.

Post-construction settlement of a bridge can be more damaging to the superstructure than to the substructure, but studies have shown that bridges founded on medium-dense granular soils will tolerate as much as 2-4 inches of such settlement.[9] Since only 0.25 inches of compression settlement is expected within the granular fill of a typical 25-foot high MSE abutment wall following construction of the deck,[10] it is clear that long-term performance of the bridge is enhanced when settlement of the foundation soils is essentially complete prior to superstructure construction.

<u>Settlement Example: B & M Railroad over US Rte 1</u> – One of the earliest MSE abutments subjected to extreme settlement was a 103-foot single span bridge constructed in 1980 to carry US Route 1 over the Boston & Maine Railroad in Wells, Maine.[11] Situated on foundation soils consisting of 150 feet of loose to medium sands and clay, this bridge was expected to, and did, experience over 2 feet of settlement at the abutments.

The approach embankments, abutment walls and wing walls were constructed and surcharged prior to installation of the bridge seats, with the resulting load producing 8.5 inches of settlement. After removing the preload and constructing the seat and superstructure, an additional 6.5 inches of settlement occurred within the first two years of service, with approximately 12 inches of additional settlement experienced over the next ten years. Because settlement of this magnitude was expected, provisions were made in the design to allow for the installation of jacks to raise the bridge to maintain both the highway profile and the clearance over the railroad. Gages installed to monitor lateral movement of the wall facing panels recorded virtually no lateral movement in spite of the massive settlement the walls experienced. Based on bid tabulations, this single span bridge, including its Reinforced Earth abutments and wing walls and jacking provisions, cost 32% less than the three-span pile-supported alternate design.

<u>Settlement Example: McNeil Generating Station</u> – In another example of extreme MSE abutment settlement, a pair of Reinforced Earth abutments in Vermont was expected to settle approximately 6 inches due to the 35 feet of loose sandy silt underlying the site. Supporting a railroad-unloading trestle at the Joseph C. McNeil Generating Station in Burlington, one of the abutments actually settled over 16 inches prior to girder placement, but the contractor was able to adjust the elevations of the bridge pedestals to compensate for the settlement. The selection of Reinforced Earth abutments for this project was based not only on basic construction economy, but also on the simplicity and economy of a design that could perform without distress over this highly compressible foundation material.[12]

<u>Dealing With Settlement Using Two-Stage Construction</u> – In recent years a new technique, originally created to deal with sites where total settlement in excess of 3 feet is expected, has erroneously come to be treated as the ultimate answer to all MSE structure settlement issues. So-called "two-stage" construction of MSE walls consists of two major steps. The complete wall is built first, utilizing a flexible wire facing backed by geotextile, and the wall is allowed to settle (with or without surcharge). In the second step, the permanent precast concrete facing is attached, leaving a void between the precast and wire facings that must be filled with either soil or flowable fill. A recent problem with facing panels popping off two-stage walls in which this void was not filled confirms the

need to fill the space between the wire and concrete facings.

While two-stage construction can be a valuable technique in limited and specific circumstances involving extreme settlement, it is unnecessary and costly at sites where anticipated total settlement is less than 3 feet and/or where expected differential settlement is less than 1% – settlement behavior well within the normal capabilities of any properly designed MSE wall. In fact, thousands of MSE structures were constructed on compressible foundation soils, many experiencing settlements as large as 2-3 feet, before this technique even existed, making the rush to use it on projects anticipating as little as a few inches of settlement contrary to all logic. Simply stated, two-stage construction should be reserved for sites where anticipated settlement exceeds 3 feet, and should be used only after careful evaluation of the foundation conditions and in consultation with the MSE wall supplier. Dealing with extreme settlement using foundation improvement methods, as discussed by Anderson,[13] is a cost-effective and preferred alternative to using two-stage construction.

SEISMIC PERFORMANCE – Around the world, structure performance during earthquakes is a critical design consideration. Reinforced Earth walls and abutments have performed exceptionally well during recent earthquakes. The following are two of many documented examples:

- Twenty-one Reinforced Earth walls and two Reinforced Earth abutments experienced the 6.7 Richter magnitude Northridge earthquake in 1994, in the densely populated San Fernando Valley 20 miles northwest of Los Angeles. Buildings, bridges and freeways all suffered severe damage, yet all Reinforced Earth structures performed extremely well, with only superficial damage to a few facing panels of one wall.[14]

- Three abutments and several high retaining walls, within 2 miles of the epicenter of the 1983 5.0 Richter magnitude earthquake in Liege, Belgium, suffered no damage or deformation.

As these examples demonstrate, the seismic performance capabilities of MSE abutments make them an ideal choice for bridges in earthquake-prone regions.

MSE ABUTMENTS IN THE USA

The first MSE abutments in the United States were constructed in 1974 on I-80 near Lovelock, Nevada.[15] These true abutments carry four lanes of traffic on a 70-foot span crossing Big Meadow Ranch Road northeast of Reno. The Reinforced Earth abutments were selected by the Nevada Department of Transportation not only because they saved money, but also because they improved the design. The site is underlain by deep, weak foundation soils that would have subjected piles to large negative skin friction forces, greatly increasing the cost of a pile-supported design. The Reinforced Earth true abutment design used no piles, dramatically reducing the cost of the abutments.

An additional benefit was realized on this project that is typical of all true MSE abutments. The approach embankment leading up to an MSE abutment is continuous with the compacted granular fill on which the bridge seat rests. Therefore, if the embankment settles due to settlement within the foundation soils, the bridge seat moves with it rather than being rigidly fixed in position by piles. The "bump at the end of the bridge" is eliminated, with resulting reduced maintenance cost.

ABUTMENTS TYPES – There are two types of MSE abutments – true and mixed. In a true abutment, the bridge beams are supported on a spread footing bearing directly on the MSE structure (Figure 2). To prevent overstressing the soil of a true abutment, the beam seat is sized so the centerline of bearing is at least 3 feet behind the MSE wall face and the bearing pressure on the reinforced soil is no more than 4 kips per square foot. The bearing stresses beneath the seat are distributed into the reinforced soil, so soil reinforcement density is higher near the top of the structure and decreases with depth as the bearing stresses dissipate.

A mixed abutment, by comparison, has piles supporting the bridge seat (Figure 3), with the MSE walls retaining the fill beneath and adjacent to the end of the bridge. In some cases a portion of the lateral load on the pile-supported seat is transmitted to the MSE fill. This load can be resisted by MSE reinforcements in the wall or by reinforcements extending from the backwall of the seat.

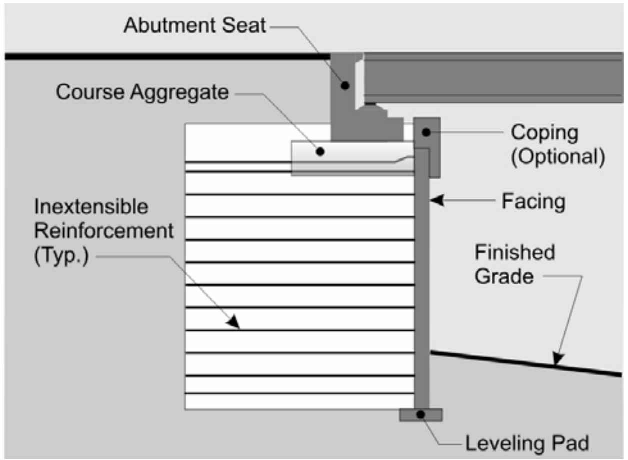

Figure 2 – True MSE Abutment

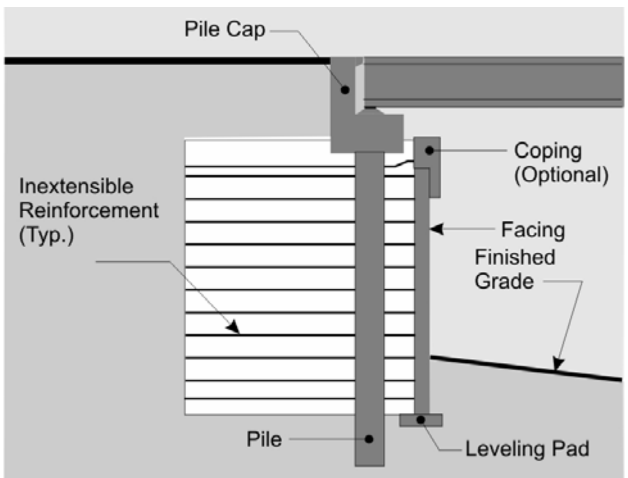

Figure 3 – Mixed Abutment

INTEGRAL ABUTMENTS AND MSE STRUCTURES – Both true and mixed MSE abutments are used for bridges with integral abutments as well as for conventional bridges. Integral bridge abutments, having neither joints nor bearings, are becoming popular in the United States. Since repair of joints and bearings on traditional bridges is costly and disruptive to traffic, a goal of integral bridge design is reduced maintenance, with nearly maintenance-free substructures. Integral bridges are generally supported on piles, so pile deflection caused by thermal movements of the superstructure must be accommodated by the reinforced soil of the MSE structure.

The additional horizontal forces due to the deflection of the piles can be accommodated in the design of the soil reinforcement. Per FHWA Demonstration Project 82,[5] design details associated with the combination of integral abutments and MSE walls are:

- Provide a clear horizontal distance of 0.5 meters between the back of the panels and the front edge of the piles.
- When significant negative skin friction is anticipated, provide a casing around each pile extending through the reinforced fill.
- Where pile locations interfere with reinforcements, specific methods for installation must be developed. Simple cutting of reinforcements is not permissible.

The provision for 0.5 meters clear between the piles and the back of the facing not only permits pile deflection and lateral stress transfer to the reinforced soil, it also enables small compaction equipment to be used between the piles and the MSE wall facing. Strip-type MSE reinforcements with bolted connections may simply be skewed around the piles, while systems utilizing welded wire mats require special details to transfer the reinforcements and their load around the piles. These design details are applicable to traditional (non-integral) pile supported MSE abutments as well.

DESIGN OF MSE ABUTMENTS

MSE Abutments – both true and mixed – should be designed according to the coherent gravity design method outlined in Chapters 5 and 7, Design, of the 1996 AASHTO Standard Specifications for Highway Bridges,[16] The coherent gravity method, which accounts for externally-applied loads and the structure's eccentricity, was first applied to MSE walls in the 1970s and is still used today. This design method, documented by the National Cooperative Highway Research Program in its Report 290,[17] has been used by the MSE wall industry to design walls and abutments for more than 25 years. The method was fully developed by Terre Armee Internationale based on a decade of research on model scale and full-scale structures, supplemented by numerical modeling.[18,19,20] These studies included complex geometries and loads typical of both MSE abutments and mixed abutments.

The simplified method, developed in the 1990s (AASHTO interim 1997 and subsequent), should not be used for the design of structures with complex geometries. The simplified method for MSE design was developed to eliminate the need to calculate, at each reinforcement level, the eccentricity of the structure caused by externally applied loads. The method was intended for level top-of-wall conditions and was calibrated to give the same (or very similar) results as the coherent gravity method for the level top condition. Since the simplified method ignores the effect of externally applied loads on internal stresses, the method should not be used for structures supporting sloping surcharges, abutments, tiered walls, or for MSE structures supporting significant surcharges behind the MSE volume.

A section on MSE wall design has recently been added to the 2004 AASHTO LRFD Bridge Design Specifications.[21] To date, however, very few abutments have been designed according to this methodology, in part because the applicable load and resistance factors require additional research to quantify load prediction bias and uncertainty. This concern is explained in the commentary to Section 11.10.6.2.1, on page 11-44 of the specifications, as follows:

> "…EV is not directly applicable to internal reinforcement loads in MSE walls, since the calibration of EV was not performed with internal stability of a reinforced system in mind. The use of EV for the load factor in this case should be considered an interim measure until research is completed to quantify load prediction bias and uncertainty."

INCREASED USE OF MSE ABUTMENTS – SUMMARY AND BENEFITS

MSE abutment usage has increased rapidly in recent years (Figure 4) as more and more owners and engineers become familiar with and develop confidence in this technology. After a long period of building only a few dozen MSE abutments per year, the current US rate is approximately 600 abutments (300 bridges) annually, 75% being mixed and 25% being true abutments supported directly on the MSE reinforced volume. The main reason for this growth is that MSE abutments generally cost substantially less than conventional concrete abutments,

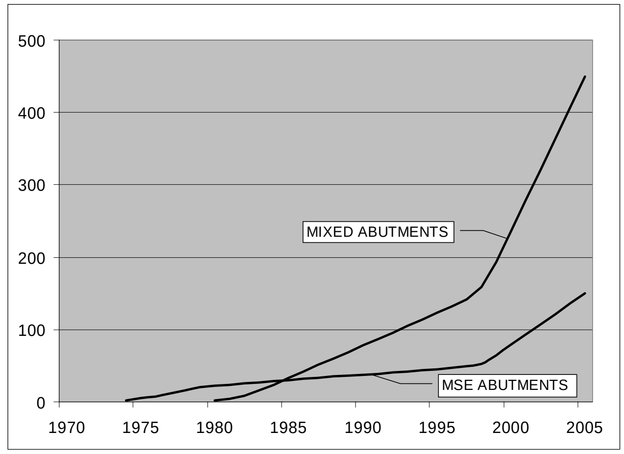

Figure 4 – Number of Abutments Annually

especially at sites underlain by weak or compressible soils where piles are eliminated by true MSE abutments. True abutments offer additional savings through reduced maintenance by eliminating the bump at the end of the bridge. These performance and cost advantages, particularly of true abutments, offer a significant opportunity to stretch highway construction budgets by reducing structure costs and shortening project schedules.

CONCLUSIONS

- The simple, rapid and predictable construction process utilizes precast concrete facing panels, galvanized steel reinforcements and compacted granular backfill.
- The basic mechanics of MSE abutments is well understood, the service life is predictable and the behavior in seismic events is well documented and superior to that of rigid structures.
- MSE abutments handle large total and differential settlements without significant distress or loss of function. Two-stage construction (precast facing attached in second stage) is unnecessary on most foundations; the rare exception occurs if total settlement exceeding 3 feet is expected, especially if in conjunction with differential settlement in excess of 1%. In such cases, foundation improvement methods are preferred and should be evaluated.
- True MSE abutments should be considered for most bridges, especially if constructed on compressible foundation soils.
- True MSE abutments eliminate the bump at the end of the bridge and its associated maintenance costs.

- MSE true abutments (no piles) are more cost-effective than mixed abutments (piles under the bridge seat). Both are economical compared to conventional concrete abutments and dramatically economical in place of concrete abutments on piles.

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