DESIGN OF STREAMBANK STABILIZATION WITH GEOGRID REINFORCED EARTH SYSTEMS

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ABSTRACT

Reinforced earthen slopes through mechanically stabilized earth (MSE) utilizing **Geogrid** is an effective and innovative channel stabilization measure which can eliminate requirements for highly visible structural control measures, particularly when difficult environmental or physical site constraints are involved. Current advances in new construction material have resulted in soil retention systems through reinforced earth construction, which offer a new application for flood control and streambank protection control measures. Most conventional applications of reinforced earth systems have primarily involved earthwork slope stabilization or roadway projects. However, reinforced earth systems offer numerous advantages over conventional streambank stabilization techniques which include: structural reinforcement of the earthen streambank, ease of construction with normal fill operations, low costs, and an inert mattress that becomes an integral matrix with the earthen bank. Geogrids are typically manufactured of high-density polyethylene (HDPE) resins that resist elongation when subjected to high load for long periods of time. The geogrids can carry large tensile load applied in one or two directions, and their open structure interlocks with the natural earthen fill material. The geogrid installation results in a structurally stable embankment, which reacts similar to a gravity wall. In addition, the geogrid constructed streambanks can provide a steeper than normal slope face which can be naturally landscaped and provides an aesthetic alternative to conventional streambank revetments. Geogrid slope stabilization technology offers a new form of "bioengineering" with unique long-term engineering properties and avoids common failure mechanisms. In addition, there are a variety of proprietary industry systems that combine with the use of geogrid that have potential flood control and erosion protection applications. Comprehensive design procedures are reviewed for applied designs utilizing geogrid material for reinforced earth stabilization of channel banks, including the hydraulic and structural evaluation steps involved in the design of this type of system. Several unique flood control projects utilizing geogrid technology are evaluated, focusing on the different applications and constraints for each project.

INTRODUCTION AND GENERAL BACKGROUND

Streambank erosion from both natural and induced erosion is a continual physiographic process associated with alluvial rivers and streams requiring the effective design of protective countermeasures. Conventional river engineering protective measures have included slope revetments to provide armoring through rigid, flexible, and biotechnical means which resist the hydraulic forces. However, current restrictive environmental regulations and community awareness of aesthetics often limit these available options, in addition to the physical constraints and other evolving stringent design criteria. Common limitations of standard slope revetment materials include (1) limitations of slope geometry, (2) unattractive, (3) limited velocity or tractive force resistance, (4) limited earth retaining and structural capacity, (5) foundation requirements, (6) no slope stabilization only erosion protection, (7) lack of seismic load resistance. MSE wall systems also offer a suitable replacement alternative for the standard rigid reinforced concrete channel. systems

Introduction of new soil stabilization technology through the application of mechnically stabilized earth (MSE) through geogrid systems offer unique erosion protection solutions which can avoid many of the current issues and provide a substantial economic benefit over conventional measures. A major drawkback of standard bank protection methods is that the primary design function is to provide erosion protection and assist in little in structural soil stabilization or retention. Control measures which incorporate features to resist soil loads will generally result in costly facilities and large structural elements. Earth retaining structures typically utilize cast-in-place reinforced concrete cantilever walls or even gabions for economical solutions of low-walls. Soil reinforcement techniques offer sot effective solution for earth retaining system extending over ten-feet in height. The conventional flexible erosion protection systems for streambanks such as rock rip-rap, cabled concrete, however, are limited to a maximum slope angle which is generally controlled by the angle of repose of the native bank material or the natural stability of the bank. This requirement can impose a serious physical constraint in attempting to apply these measures.

BASIC THEORY OF RETAINED EARTH SYSTEMS

The fundamental principle of retained earth system lies in the mobilization of the bearing pressure of the soil. The stability of a soil reinforced retaining systems is derived from the composite action of the horizontal reinforcing elements which extend within the reinforced soil mass behind the slope or wall face. The resulting structure behaves as a unit with the reinforcing elements providing tensile strength to the soil mass. A retained earth wall system can be thought of as a gravity dam supporting itself and the earth behind it. The earth within the area of reinforcement acts as a homogeneous unit for resistance. Soil reinforcing elements are designed and positioned within the compacted backfill to give the composite structure tensile strength. The mechanism of soil to reinforcing stress transfer is through the bearing pressure of the soil onto the mesh of the buried grid panels or reinforcing elements. The bearing pressure is developed along the projected area of the geogrid and is in turn transferred from the soil mass to the longitudinal axis of the geogrid web, resulting in the development of tensile forces in this portion of the geogrid. The horizontal earth pressure within the reinforced earth zone is based upon a modified trapezoidal failure surface or plane, which is different, and reduced from the natural circular failure for the native soil embankment. The assumed failure surface, at a horizontal distance of 0.3H, defines the geometry of the active pressure earth zone developing the tension load transferred to the mattress.

The passive or resistive earth pressure zone is on the opposite side of the failure surface and is the area that the force is transferred.

Three primary materials have been utilized for the buried soil reinforcement panels which include: (1) high-density polyethelene (HDPE) extruded meshes such as Tensar materials, (2) metallic strips or welded wire mesh, and (3) high strength woven geotextile fabrics. The disadvantages of the various materials include: (1) metal wire meshes and steel strips have limited durability from corrosion and long anchorage lengths are required, and (2) geotextile have reduced durability by fine filaments and difficult to connect to the slope facing system.

Earth retention systems for bank stabilization utilizing MSE for water applications generally require and incorporate some form of slope revetment or facing which is generally part of the structural member, but provides the necessary erosion protection of the slope. “Segmental walls” involve separate precast concrete panels or block which are interlocking and transfer the horizontal soil loading to the reinforcing geogrids with a vertical face if required. Another type of proprietary system is the Sierra® Slope System by Tensar and is different since it allows a vegetative slope face. This system involves applying soil retention material at the slope face, such as a geotextile fabric, between the horizontal layers of the geogrid and results in a very steep stabilized slope face.

GEOGRID MATERIAL PROPERTIES

Geogrids are high strength polymer grid structures that form an extremely efficient reinforcing by performing as a network of distributed anchors within a soil matrix. One of the leading manufacturers of geogrid in the United States is Tensar® and they offer HDPE geogrids either biaxial or uniaxial. Some inherent attributes of the polymeric geogrid material include: (1) the load transfer by which structural forces are transferred to the geogrid, (2) working load capacity of the geogrid, (3) structural integrity of the geogrid to deforming forces, and (4) resistance of the geogrid to degradation or long term environmental stress. The manufacturing process involves punching a linear hole pattern into a polymer sheet which is then heated and drawn in the machine direction to produce either “uniaxial” product or feedstock for subsequent stretching into “biaxial” product. The uniaxial geogrid is used as the primary reinforcement for load transfer because of is high tensile strength and the biaxial geogrids are used for secondary slope reinforcement which provides resistance to surficial slope sloughing.

The characteristic material properties associated with the HDPE Tensar geogrid include: (1) resistance to biological degradation or attack, (2) chemical resistance, (3) weathering resistance from UV degradation through incorporating additive of carbon black, (4) resistance to aging from oxidation since much of the material incorporates antioxidants, and (5) environmental stress cracking will not effect their performance. The manufacturing process for the Tensar geogrids causes a molecular orientation along the axial alignment of the geogrid which is responsible for the improvement to its mechanical properties. Long-term strength of the geogrids needs only to include allowances for: (1) potential onsite damage during construction, (2) outdoor weathering on parts that will remain exposed for many years, and (3) inherent safety factor for the particular structure design.

COMPARISON TO TRADITIONAL STREAMBANK PROTECTION SYSTEMS

Traditional streambank armoring or revetment provides artificial surfacing of the side slope to resist erosion and scour, but results in limited geotechnical stabilization or structural earth retention capabilities. Conventional armoring methods can be classified as "rigid" or "flexible" systems. Representative types of rigid revetment systems include cantilevered concrete retaining walls, concrete slope paving, grouted stone, and sheet piles. Similar types of flexible systems include gabions, articulating concrete block mattress, loose rock rip-rap, and gabions. All these systems have various inherent physical constraints and result in specific limitations for a particular application. One of the most serious limitations is the maximum bank slope which the system can be applied and this is generally governed by the natural geotechnical stability of the bank or the hydraulic stability of the armor unit. Cantilevered retaining walls are the only rigid type system which can resist the horizontal soil loads from increase streambank slopes, but increasing wall heights cause larger structural systems with increasing costs. Cantilevered concrete walls are utilized extensively in flood control works such as intake structures, headworks, outlet facilities, and channelization. Current seismic loading requirements eliminate concrete walls as a cost effective solution and many times it is difficult to achieve the desired safety factor because of these conditions. Foundation stability is another factor which is critical to the long term performance of many rigid revetment systems and is difficult to achieve, particularly in a riverine environment.

MSE systems offer inherent advantages to many of the common constraints and issues encountered with the traditional streambank revetment systems. An important consideration in seismically active zones is the exceptional performance when subjected to seismic loads because of their flexibility and inherent energy absorption capacity of the earth system. MSE walls may become the only feasible alternative for an extremely high wall height such as an intake structure or spillway training wall, when compared to a conventional cantilevered concrete retaining wall. Another restriction encountered in many streambank protection projects is the environmental regulatory restrictions which limit the amount of encroachment into the floodplain. MSE streambank system offer the advantage of being able to utilize steeper slopes, up to vertical, and potentially avoiding this issue. Foundation stability is not as critical with the MSE system since the load carrying capacity is transferred to the earthen backfill and differential settlements higher than those allowed in reinforced concrete retaining walls can be tolerated.

STREAMBANK RIVER ENGINEERING APPLICATIONS FOR MSE SYSTEMS

The potential applications for MSE systems in river streambank protection provide a wide range of opportunities and offer improved long term performance of the structure while assisting to avoid many difficult design constraints. Several actual design applications which will be reviewed in more detail include: (1) flood control reservoir intake training wall, (2) channelization, and (3) alluvial streambank protection. Additional applications can include hydraulic structures, spillway walls, outlet works retaining systems, floodwalls / levee protection, and drop structures. MSE system also offer the potential to provide improved stability to conventional water bioenigneering techniques. Some of the MSE systems, such as the Sierra® System, provide the opportunity to incorporate bioengineering techniques into the slope facing which promote riparian enhancement, while conventional bioengineering have limits on erosion protection effectiveness. The feasibility for the application of the MSE system must be carefully evaluated based upon satisfying the field conditions, long term stability, and economic justification compared to conventional systems.

Hydraulic Design Issues

The standard hydraulic design requirements for conventional bank armoring are also applicable to bank stabilization utilizing any of the geogrid earth retention systems. The system can be applied to both alluvial or moveable streambeds and fixed channel inverts. The common design elements of concern for bank protection include: (1) depth of toe protection if an alluvial streambed, (2) maximum height of revetment, (3) alignment, (4) erosion resistance of armored surface, (5) providing for tributary drainage outlets, (6) geotechnical slope stability, (7) subdrainage and foundation protection, and (8) protection at the termination points through tiebacks to prevent flanking. The most common failure of rigid streambank revetments in alluvial channels is inadequate toe protection depth which resulted in undermining from scour. The design of the streambank revetment in an alluvial stream must ensure adequate toe-down protection is provided below the anticipated scour depths to account for dynamic changes in the streambed. Toe-down depth of the streambank revetment system must consider potential vertical adjustments from (1) general streambed degradation, (2) bedform height, (3) local scour, (4) bed scour, and (5) low-flow entrenchment.

Particular items which must be addressed for the geogrid system are the erosion resistance capabilities of the armored slope facing system and the potential hydraulic migration of subgrade or retained earth backfill material. The MSE segmental wall systems with concrete wall facing segments can essentially function similar to traditional reinforced concrete channels and have the capability of conveying high velocity flows. The potential limitations of higher velocity flows adjacent to the MSE wall system include the potential pressure differential at each wall segement joint and the loss of material through the panel joint. Much of the potential problem can be alleviated through providing a free draining backfill material for the reinforced earth volume and installing a geotextile fabric to reduce migration of the fines from the backfill. These features will also assist in mitigating a rapid drawdown condition which must also be evaluated as part of the structural design analysis. Hydraulic limitations of the MSE systems are generally not a concern for low-velocity flows.

Erosion resistance of the MSE slope face is a function of the slope facing material incorporated in the design of the wall system. Erosion or abrasion should not a serious consideration for the wall systems utilizing concrete facing panels. Erosion resistance of systems which utilize an erosion mattress will have reduced velocity resistance capabilities based upon the performance characteristics of the fabric.

Structural Design Requirements

MSE retaining systems fail in two principle modes. One is the breakage of the reinforcing strips and the other is the pullout of the reinforcing strips from the backfill. The structural design procedure for a retained earth MSE wall system is a two fold analysis. The first concerns the external stability of the structure which includes sliding at the base, punching of the foundation soil, and differential settlements, and general sliding within the existing soil. The second deals with the internal stability of the structure or the pulling out and or breaking of the reinforcing elements. The basic outline of the structural design procedure includes:

1. Check the external stability for a given geometry
    a. Safety factor against overturning
    b. Safety factor against sliding
2. Calculate the maximum bearing pressure at toe of wall
    a. Check eccentricity of the reinforced earth mass
3. Calculate the horizontal earth pressure at each reinforcing grid level
4. Check safety factor in bond or anchorage at each level
5. Check reinforcing grid stress at each level

The length of reinforcing grid is determined by analyzing the pullout resistance. The pullout length is the sum of the distance required to develop sufficient frictional force to resist the pullout and the distance required to extend the strips beyond the failure wedge.

where FS_p is the factor of safety against pullout, K is the earth pressure coefficient, is the area of the facing panel, N is the grids on the wall panel, w is the width of the grid, and φ_u is the soil-geogrid friction angle.

MECHANICALLY STABILIZED EARTH (MSE) WALL

Mechanically stabilized earth systems encompass a broad range of soil retaining structures which utilize buried horizontal reinforcing mattress systems to transfer and distribute soil loads. Common systems which have streambank stabilization applications are reviewed including unique proprietary systems.

Segmental Wall - MSE retaining wall system with face constructed of precast concrete panels which interlock to form a complete vertical wall. The panels transfers the full horizontal load to the reinforcing grids.

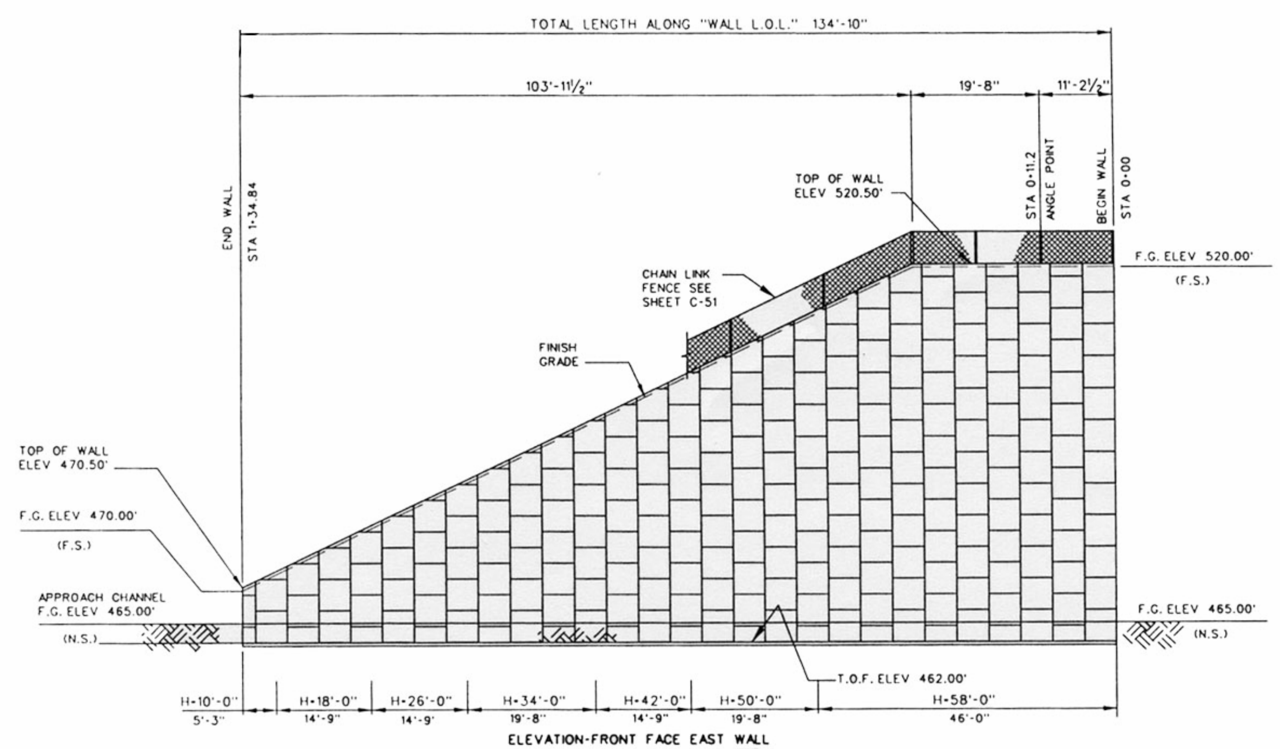
Pin Connected Block (PCB) Wall - Precast concrete block wall which anchors the geogrid into the facing block units. Each individual block is interconnected vertically with pins to the adjacent blocks, while the geogrids mats are installed at vertical intervals based on the structural requirements.

Sierra® Slope Retention System - This unique and proprietary form of MSE retention system is manufactured by Tensar® and provides the potential for vegetation on a oversteepened slope face while having all the properties of the conventional MSE system. A modified system includes welded wire facing elements which can be installed vertically to maintain a uniform alignment of the geotextile fabric. The Sierra® system is comprised of (1) Tensar uniaxial geogrids which provide the primary slope reinforcement, (2) biaxial geogrids for secondary slope reinforcement to ensure surficial stability, and (3) slope facing material. Slopes from 26^{o} to 70^{o} can be generated with this system.

PROJECT APPLICATION NO.1 - PRADO DAM INTAKE WINGWALL (CORONA, CA)

Prado Dam in Corona, California is a major existing regional flood control reservoir which was completed by the Army Corps of Engineers in 1941. The dam can no longer provide the required level of flood protection to the downstream communities and requires modifications. The project consists of enlarging the reservoir capacity by raising the spillway crest 20 feet and the top of the dam by 28 feet. A new gated outlet capable of releasing 30,000 cfs would be provided compared to the current available release by the existing outlet of 9,000 cfs. One of the elements of this design includes the training walls or wing walls which extend a maximum of 55-feet in height within the reservoir to the gated intake structure.

Another unique structural are the downstream stilling basin walls which dissipates the hydraulic energy from the double 22 feet wide by 23 feet high regulating outlet conduit prior to the runout

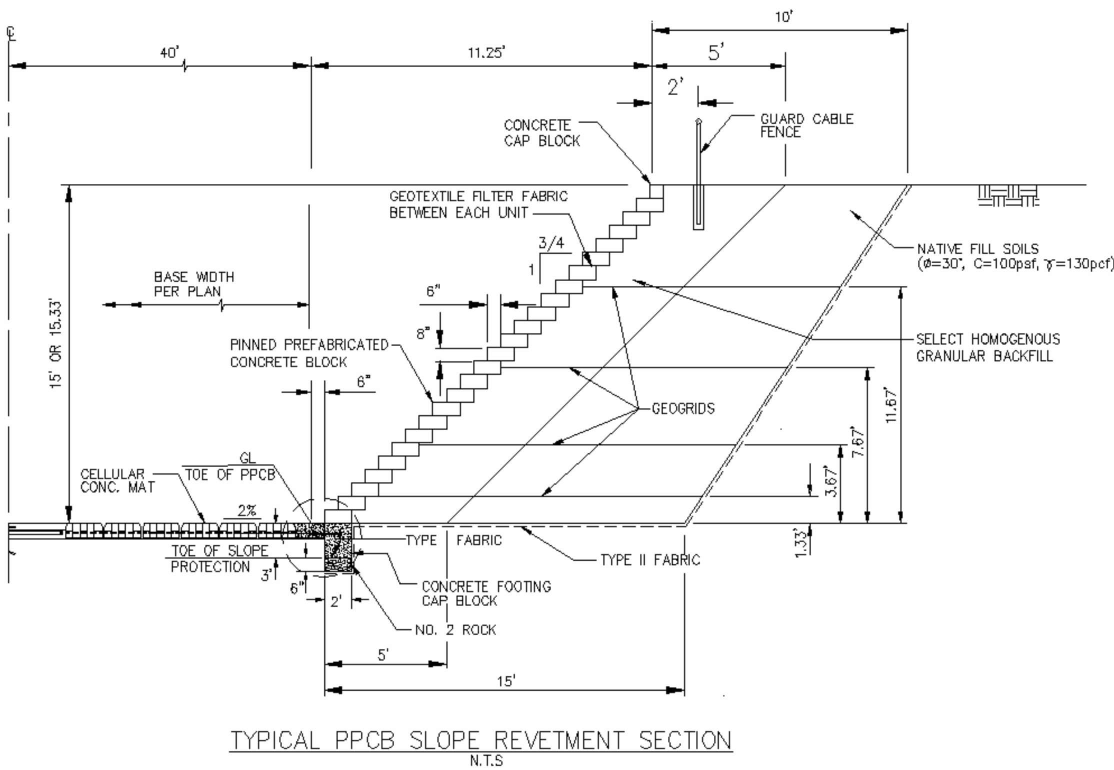


channel. These particular walls extend to a maximum of 50-feet vertically. The original design concept for the stilling basin walls and intake wing walls evaluated concrete gravity and cantilevered retaining walls, however, the seismic loads from the 0.7g ground acceleration resulted in wall heights resulted in extremely massive structural elements so a segmental MSE wall was utilized. The stilling basin wing walls will be subjected to extremely high velocities from the outlet conduit on the order of 40 fps and significant turbulence. The MSE system design resulted in a segmental wall with earth reinforcing strip which extended a maximum of 64 feet horizontally and the concrete slab for the stilling basin functioned independently of the wall. The earth reinforcing for the intake tower wingwalls in the reservoir required earth reinforcing strips which extended a maximum of 72-feet horizontally. The proposed MSE segmental wall system resulted in a cost effective solution and only alternative which could achieve the desired safety of factor for the seimic loading conditions.

PROJECT APPLICATION NO. 2 - SAND DIEGO CREEK CHANNELIZATION (IRVINE, CA)

The flood control improvements associated with the San Diego Creek project in Irvine, California involved channelization of approximately 5,350 lineal feet of natural floodplain between existing upstream and downstream channelized portions of San Diego Creek. An adjacent arterial roadway extension, in addition to the flood control improvements, were constructed as part of a residential development by the Irvine Community Development Company. The San Diego Creek watershed at this location has approximately 33.9 square miles tributary, with an estimated ultimate100-year design flow of 17,400 cfs. The proposed channel geometry consisted of an average 80-feet wide and 16-feet deep trapezoidal section within a fully urbanized portion of the community. The construction materials selected for the flood control improvements included a combination of cabled cellular concrete mattress for the channel bottom and pin connected block (PCB) walls with geogrids for the channel side slopes utilizing the Keystone® system. The concrete mattress in the channel invert provided erosion protection to prevent vertical movement of the streambed and minimize the foundation depth of the PCB channel wall. The PCB wall was installed with a 0.75 horizontal to 1.0 vertical side slope and the primary objective of utilizing this material was to enhance the aesthetics for the community. The structural analysis of the keystone block design required 4 different layers or levels of geogrids embedded approximately 15-feet beyond the face of the channel wall. The proposed improvements resulted in a full channelization of the existing creek, but provided a relatively pervious invert to allow vegetive growth and an aesthetic appearance for the public utilizing the adjacent trail system. The reinforced earth system incorporated in the PCB wall allowed an oversteepened slope of 3/4:1 which maximized the adjacent land for residential development. The hydraulic characteristics for this portion of the channel reflect a relatively high velocity associated with the longitudinal slope $S_o = 0.0055$. The average velocity associated with the design flowrate yields approximately 17 fps. An eight-foot zone of select granular material was installed directly behind the wall face, in addition to a geotextile fabric at the interface between the reinforced earth prism and the native material. Unique features of this installation include (1) the connection interface between the concrete mattress invert and the keystone block, (2) curved channel horizontal alignment, (3) concrete foundation for the PCB wall system to ensure consistent alignment of the blocks.

PROJECT APPLICATION NO. 3 - ALISO CREEK STREAMBANK (LAKE FOREST, CA)



TYPICAL PPCB SLOPE REVETMENT SECTION

N.T.S

El Toro Road is a major existing arterial roadway, in southern Orange County, California, that is located on a steep hillside immediately above the Aliso Creek natural floodplain. A portion of the roadway was constructed in an ancient landslide and the stabilizing buttress material at the toe of the slope has been slowly eroded by the creek which has activated the landslide. This portion of the roadway must be reconstructed and the landslide stabilized in order to protect the community. The height and steep nature of the slope from the roadway to the creek provide a significant design constraint, in addition to the need to protect the reconstructed embankment to prevent lateral erosion of the buttress. However, another issue of the project was avoiding environmental regulatory permitting requirements by eliminating any construction within the floodplain. In order to achieve this solution the Sierra® slope retention with the welded wire reinforced face was selected for the embankment protection adjacent to the creek. The proposed construction presented numerous obstacles including the construction of the new buttress to stabilize the landslide. The shear key for the buttress had to be excavated approximately twenty-feet below the existing channel invert and would be reconstructed utilizing geogrid reinforcement when slopes exceeded 2:1. The Sierra® system was selected in order to ensure erosion protection of the new buttress face and extend slope revetment to the anticipated scour depth of the alluvial channel. A near vertical wall system was required in order to satisfy the construction excavation geometry without encroaching into the floodplain and initiating environmental regulatory permits.

The general characteristics for this portion of the Aliso Creek floodplain include a very active streambed which has migrated in a relatively narrow canyon and developed some deeper incised locations. The estimate 100-year discharge associated with this portion of the watershed is approximately 4,400 cfs and hydraulic analysis indicated the average velocities varied from 15 fps to 20 fps. Estimates of the maximum scour depth ranged from 8 to 9 feet which was utilized to embed the limits of the MSE wall. Loose rock revetment will be installed at the base of the MSE wall system to minimize the scour adjacent to the wall. The wall height did not extend to the maximum vertical limits of the 100-year flood elevation, so articulated concrete mattress was incorporated from to top of wall to protect the buttress fill from erosion during maximum flood events. The proposed Sierra® system also has the advantage in this particular application to apply introduction of some bioengineering vegetative techniques to restore the natural elements of the existing floodplain.