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Technical Letter
No. 1110-2-334

21 August 1992

Engineering and Design
DESIGN AND CONSTRUCTION OF GROUTED RIPRAP

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Errata Sheet

No. 1

ETL 1110-2-334

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28 August 1992

This errata sheet changes subparagraphs 3e and 3f on page 1 and subparagraphs 6g(3) and 6g(5) on page 5. Replace pages 1 and 5 with the enclosed pages.

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DESIGN AND CONSTRUCTION OF GROUTED RIPRAP

1. Purpose. This ETL provides guidance for the design and construction of grouted riprap. Items addressed include applications, limitations, design considerations, design requirements, construction considerations, and construction procedures.

2. Applicability. This ETL applies to all Headquarters, US Army Corps of Engineers (USACE) elements and USACE Commands having civil works responsibilities for planning, design, and operation and maintenance of civil works projects.

3. References.

a. EM 1110-2-1601, Hydraulic Design of Flood Control Channels

b. EM 1110-2-2000, Standard Practice for Concrete

c. EM 1110-2-2302, Construction With Large Stone

d. Publication No. FHWA-IP-89-016, U.S. Department of Transportation Hydraulic Engineering Circular No. 11: "Design of Riprap Revetments."

* e. CRD-C 148. Refer to: USAE Waterways Experiment Station, Handbook for Concrete and Cement, with quarterly supplements.

* f. ASTM C 94, C 685, and D 4992. Refer to: American Society for Testing and Materials, Annual Book of ASTM Standards. Available from: American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

4. Definition. Grouted riprap consists of stone bed and slope protection having voids filled with grout or concrete to form a veneer of cementitious-bonded aggregate armor. Components of a properly designed and constructed grouted riprap system include a stable and properly prepared slope, a free draining sub-base or bedding layer, and a protection layer consisting of sound, durable stone bonded by a mixture of cementitious materials, water, aggregates and admixtures. Granular filter and sub-base materials, geotextiles, sub-drains, weep-holes, cutoffs, and other special features are also included as needed.

5. Applications and Limitations.

a. Applications. Grouted riprap may be an economical alternative to (1) concrete paving, or (2) conventional riprap treatment where required stone size cannot be economically procured. Large stone is produced in relatively small amounts at most commercial quarries and is, therefore, generally more expensive. In areas where transportation costs are a significant portion of the construction cost of the riprap treatment, it may be less expensive to use grouted riprap. Typical applications include protection of bed and bank slopes in spillway entrance channels, zones of turbulence adjacent to energy dissipaters, drainage ditch linings, culvert and storm sewer outfalls, and drainways through conventional riprap. Other applications for grouted riprap include prevention of vandalism and improved pedestrian access for recreation. Grouted riprap may also be used to repair conventional riprap which has been damaged as a consequence of being subjected to water velocities exceeding design values. However, extreme caution is advised to insure that the stone displacement was indeed velocity related and not the result of slope or foundation failure.

b. Limitations.

(1) Grouted riprap must be used only on properly designed slopes. The additional expense of grouting riprap cannot be justified without providing proper slope stability. Furthermore, grouted riprap placed on a poorly designed slope can have the detrimental effect of masking progressive slope failure until it has advanced far enough to cause failure of the riprap treatment.

(2) It must be recognized that grouted riprap will crack, cracking will be irregular, and cracks will likely extend within the grout matrix and around the periphery of larger stones. Cracking may cause enhanced weathering, including aggressive chemical reactions, but should not significantly diminish the effectiveness of the treatment if the sub-base is properly designed and constructed to provide adequate drainage without loss of sub-base materials through cracks. Grouted riprap should not be used in areas where frost heave or ice in the sub-base can be expected to cause uplift failure.

(3) River-side slopes of levees should not be protected with grouted riprap. At first, it may appear that a reduction in construction cost might be realized if grouted riprap could be provided for levee protection. However, levees undergo significant settlement that cannot be accommodated by the rigid nature of grouted riprap.

(4) Applying grout to salvage a failing conventional riprap treatment without proper design to address the cause of the failure should not be undertaken. This practice most often does not provide a successful repair and results in a waste of resources. Examples are slope failures resulting from upslope surface runoff, piping-related internal erosion, down-slope riprap failure resulting from toe scour, and failures of frequently overtopped drainways and drainage ditches.

is the minimum thickness that should be applied.

(2) **Gradation.** Gradation of stone to be grouted should be as coarse as possible to allow for deeper penetration of grout. The stone should have less than five (5) percent passing a 2-inch sieve. The most important consideration is that a size and gradation be chosen that will allow for maximum grout penetration. It is important from an economic standpoint to use simple, commonly produced, and readily available gradations whenever possible.

g. **Stone Quality.** One of the most critical elements which determines success or failure of grouted riprap is the quality of stone. In general, any stone suitable for use in conventional riprap will be acceptable for use in grouted riprap. It is a mistake to suggest that a lower quality of stone may be used if the riprap is to be grouted.

(1) **Stone Characteristics.** For best results, stone used for grouted riprap should be angular for greatest resistance to movement and to provide the maximum surface area for bonding to the grout. Less angular stone may be acceptable for use in certain environments or where use of non-quarried rock provides significant economic benefits. Stone pieces with a length greater than three times their breadth or thickness should not be used.

(2) **Non-quarried Rock.** Grouted riprap may allow the use of non-quarried, appropriately sized rock, like stream-run gravel and cobbles, in place of crushed rock. It is important, however, to insure that the stone is clean, free of debris, and satisfies the gradation and stone characteristics requirements discussed above. In some instances, this could reduce costs by eliminating some processing and transportation costs.

(3) **Guidance.** EM 1110-2-2302 provides a comprehensive overview of the economic selection and evaluation of conventional riprap stone. Discussions regarding suitable laboratory tests, visual inspections, and field tests are also included in that manual. ASTM D 4992 also provides an extensive discussion.

(4) **Specifications.** Specifications should clearly list requirements for suitable quality including laboratory tests and their required results to insure satisfactory construction and to avoid conflicts and claims. Specified values should reflect minimum acceptable results of previously evaluated sources which are available for use at a particular project.

(5) **Laboratory Tests.** It is of prime importance to be sure that required tests approximate the actual field environment of the project. The most important laboratory tests used to determine durability in severe and moderate weathering regions are freezing-thawing and wetting-drying tests. Dry unit weight, petrographic characteristics, and absorption are parameters which should be determined for stone to be used in any riprap application. For lithologies susceptible to the detrimental effects of swelling clays, ethylene glycol testing (CRD-C 148) should be considered. Abrasion loss testing may also be appropriate for stone which will undergo significant handling prior to placement.

(6) **Reactive Stone.** Care should be taken to avoid stone types (for aggregate and riprap) which could have a deleterious reaction with cement. Alkali-silica and alkali-carbonate reactions are the most frequent of these reactions. Petrographic analysis should be performed to determine whether reactivity tests are indicated. Additional guidance is in EM 1110-2-2000.

h. **Grout Design.** In general, design of the grout or concrete mixture for use in grouted riprap applications should follow accepted design procedures included in EM 1110-2-2000. Typical considerations for design of the grout mixture should include strength and durability requirements.

(1) **Strength Requirements.** Strength requirements for the grout are commonly on the order of 2000 to 2500 psi. Failure of grouted riprap treatments are most often attributed to undercutting at the edges of treatment, loss of bedding and in-situ material from beneath the treatment, failures resulting from excessive hydrostatic pressure, and loads from maintenance vehicles. Experience has shown that: (a) strength of the grout will not compensate for deficiencies in other aspects of the design and (b) higher strength grout is usually unnecessary if the treatment is correctly designed.

(2) **Durability Requirements.** Grouted riprap must be designed to resist deterioration caused by environmental forces including freezing-thawing, wetting-drying, aggressive chemical reactions, and abrasion. Guidance for improving the durability of concrete materials is found in EM 1110-2-2000.

(3) **Mixture Design.** Sanded grouts commonly have a ratio of three parts of sand to one part of cement with water controlling consistency of the grout. Sanded grouts are most successful when used to prevent vandalization or removal of individual pieces of riprap stone by visitors. If conventional concrete mixture is to be used, the maximum size of aggregate should not exceed 3/4 inch and it should incorporate features to enhance placement of the concrete. Slumps on the order of 5- to 7 inches are required to allow proper pumping and placement. Water-reducing admixtures are frequently used to aid in the workability of the mixture while lowering the water demand. Air entraining admixtures are necessary to improve the freezing and thawing resistance as well as the workability of the mixture. Actual mixture proportioning should be designed in accordance with EM 1110-2-2000. If the aggregates or riprap to be used is known or suspected to be reactive to the alkalis in concrete, low alkali cement should be specified. Additional admixtures may be necessary in cases where the final color of the grouted riprap must be changed for aesthetic reasons.

(4). **Underwater Placement of Grouted Riprap.** Underwater placement of grouted riprap should be avoided. However, if site conditions make this impossible, the grout design should be similar to that for conventional underwater concrete placement. The grout or concrete mixture should be designed to withstand underwater placement without significant degradation. Anti-washout admixtures should be considered in underwater applications. Guidance on underwater concreting is included in EM 1110-2-2000.

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b. **Limitations.**

(1) Grouted riprap must be used only on properly designed slopes. The additional expense of grouting riprap cannot be justified without providing proper slope stability. Furthermore, grouted riprap placed on a poorly designed slope can have the detrimental effect of masking progressive slope failure until it has advanced far enough to cause failure of the riprap treatment.

(2) It must be recognized that grouted riprap will crack, cracking will be irregular, and cracks will likely extend within the grout matrix and around the periphery of larger stones. Cracking may cause enhanced weathering, including aggressive chemical reactions, but should not significantly diminish the effectiveness of the treatment if the sub-base is properly designed and constructed to provide adequate drainage without loss of sub-base materials through cracks. Grouted riprap should not be used in areas where frost heave or ice in the sub-base can be expected to cause uplift failure.

(3) River-side slopes of levees should not be protected with grouted riprap. At first, it may appear that a reduction in construction cost might be realized if grouted riprap could be provided for levee protection. However, levees undergo significant settlement that cannot be accommodated by the rigid nature of grouted riprap.

(4) Applying grout to salvage a failing conventional riprap treatment without proper design to address the cause of the failure should not be undertaken. This practice most often does not provide a successful repair and results in a waste of resources. Examples are slope failures resulting from upslope surface runoff, piping-related internal erosion, down-slope riprap failure resulting from toe scour, and failures of frequently overtopped drainways and drainage ditches.

6. Grouted Riprap Design. Grouted riprap treatments require special attention to the design of stable slopes, edge and toe protections, sub-base, pressure relief and drainage, stone size and gradation, stone quality, and grout design. Each of these items is discussed in the following paragraphs.

a. Design Forces. Design of grouted riprap must address the forces to which the treatment will be subjected. These forces include, but are not limited to, scouring forces of high velocity flow, pressure fluctuations inherent in highly turbulent flow, hydrostatic pressure uplift, uplift from ice in the sub-base, impact of floating ice and debris, and all the forces which affect slope stability. Grouted riprap may be designed to improve pedestrian traffic but should not be subjected to vehicular loads.

b. Slope Design. Stability of the materials to be protected by grouted riprap controls the design of slope geometry in the same manner as it would for conventional riprap protection. Successful grouted riprap treatments are most often observed on slopes which are flatter than 1 vertical on 1.5 horizontal. Information for slope design is obtained from subsurface explorations, laboratory test results, and stability analyses. In the case of limited treatments, experience gained from previous successes or failures in similar circumstances may prove adequate for design efforts. Grouted riprap is generally considered to be a rigid structure but does not possess significant strength to bridge sizeable voids or withstand uplift pressures; therefore, foundation support is critical. The foundation must have a bearing capacity sufficient to support either the dry weight of the grouted riprap structure alone, or the submerged weight of the grouted riprap plus the weight of the water beneath the maximum water surface elevation, whichever is greater.

c. Edge and Toe Design. Edge protection, or prevention of lateral undercutting, is one of the most important aspects of design for grouted riprap projects. Most grouted riprap designs include a granular sub-base and the need to confine this granular material to prevent particle migration is essential if the design is to be successful. Commonly, lateral edge protection consists of a "key transition" that is sufficiently deep to ensure that the sub-base materials will not be exposed and lost through continued failure and removal of unprotected in-situ materials. The toe of the grouted riprap is usually at or below the minimum water surface and may be subject to scouring forces during flood events which can significantly increase the potential for down-slope migration and subsequent loss of sub-base materials. Furthermore, it may be necessary to place riprap stone and grout under water which causes greater concern for toe stability. A conventional riprap berm will protect the toe and insure the integrity of the sub-base. However, the riprap berm must be sized to resist displacement of the stone by high velocity flow and thus will require larger stone. The vertical extent of grouted riprap protection should be as determined from EM 1110-2-1601 for conventional riprap treatments or as predicted from site-specific model studies. Protection should normally extend from below the anticipated level of channel bed scour to the design high water level. The top edge of the treatment requires control of surface drainage to prevent upslope runoff from flowing beneath the grouted riprap treatment. Some typical edge and toe designs are discussed in EM 1110-2-1601.

d. Sub-Base Design.

(1). **General.** Sub-base materials are required for all grouted riprap to reduce the amount of grout penetration and to protect geotextiles where necessary. Designed gradations for sub-base materials may also address granular filter requirements and particle migration of either construction materials or in-situ soils. Sub-base materials would thus provide an area drainage component to prevent buildup of excessive hydrostatic pressures. Typically a minimum of 6 inches of granular material is necessary under the grouted riprap to provide adequate drainage interception and control.

(2). **Filter Design.** The filter can consist of well-graded granular material or a uniformly-graded granular material with an underlying geotextile. The filter should be designed to provide a high degree of permeability while preventing in-situ soils or sediment deposition from penetrating the filter, causing clogging and failure. Care must also be taken to insure that grout does not penetrate through the overlying riprap stone to such an extent as to clog the filter.

e. **Pressure Relief and Drainage.** Pressure relief holes should be provided in grouted riprap to prevent buildup of hydrostatic pressure behind or beneath the treatment. Relief holes should extend through the grout and into the underlying sub-base or granular filter, or into a designed pocket of drain material. Care must be taken to insure that grout does not clog the relief hole or drain pocket. Typically, 3-inch diameter pipes spaced no more than ten feet each way should be provided for drainage. The final spacing should be based on drainage characteristics of soils being protected and on the designed granular filter layer. The buried end of the pipe must be protected with a filtering system to prevent in-situ soils or granular filter materials from migrating into the pipe. Filling the drains with pea gravel will protect against silting and vandalism. Flap valves are used when frequent overtopping is expected. If the pipe is left open, drains should be cleaned on a regular basis.

f. Stone Size and Gradation.

(1) **Top Size.** It is generally accepted that the top size of the grouted riprap stone may be smaller than that required for conventional riprap. A specific factor by which the top size of conventional riprap may be reduced, if grouted, has not been determined. One common design procedure is to evaluate the stone size requirements for conventional riprap and determine availability and cost. If the required size of stone is not readily available or is cost prohibitive, the maximum size of economically available stone may be used if grout is applied. Although this is an unscientific process to determine top stone size, experience indicates that it will provide a successful treatment if the foundation is appropriately prepared, a proper sub-base is provided and protected, adequate sub-base drainage is provided, and good construction practices are followed. Experience has shown that a 12-inch layer

is the minimum thickness that should be applied.

(2) **Gradation.** Gradation of stone to be grouted should be as coarse as possible to allow for deeper penetration of grout. The stone should have less than five (5) percent passing a 2-inch sieve. The most important consideration is that a size and gradation be chosen that will allow for maximum grout penetration. It is important from an economic standpoint to use simple, commonly produced, and readily available gradations whenever possible.

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(3) **Mixture Design.** Sanded grouts commonly have a ratio of three parts of sand to one part of cement with water controlling consistency of the grout. Sanded grouts are most successful when used to prevent vandalization or removal of individual pieces of riprap stone by visitors. If conventional concrete mixture is to be used, the maximum size of aggregate should not exceed 3/4 inch and it should incorporate features to enhance placement of the concrete. Slumps on the order of 5- to 7 inches are required to allow proper pumping and placement. Water-reducing admixtures are frequently used to aid in the workability of the mixture while lowering the water demand. Air entraining admixtures are necessary to improve the freezing and thawing resistance as well as the workability of the mixture. Actual mixture proportioning should be designed in accordance with EM 1110-2-2000. If the aggregates or riprap to be used is known or suspected to be reactive to the alkalis in concrete, low alkali cement should be specified. Additional admixtures may be necessary in cases where the final color of the grouted riprap must be changed for aesthetic reasons.

(4). **Underwater Placement of Grouted Riprap.** Underwater placement of grouted riprap should be avoided. However, if site conditions make this impossible, the grout design should be similar to that for conventional underwater concrete placement. The grout or concrete mixture should be designed to withstand underwater placement without significant degradation. Anti-washout admixtures should be considered in underwater applications. Guidance on underwater concreting is included in EM 1110-2-2000.

7. Construction Considerations. Site-specific conditions at each project must be considered to determine proper procedures for completion of all phases of grouted riprap construction. These conditions may include access to the site, types of materials and vegetation that must be excavated and removed, in-situ bed and bank materials, area to be treated, and volume of material to be placed. These factors are most important when determining the types and numbers of equipment required, scheduling of work, and phasing of construction.

8. Construction Procedures. In general, construction procedures will include: (a) bank clearing and grading, (b) foundation preparation, (c) placement of filter cover and sub-base materials, (d) placement of stone, (e) grouting of interstices, (f) placement of edge and toe protection, and (g) revegetation of disturbed areas.

a. Foundation Treatment. The site should be prepared by clearing all trees and debris, and grading the bank to a stable geometry. Care must be taken to insure that natural drainage layers or horizons within the bank, are not blocked by construction activities. Placement of the sub-base layer will generally fill local depressions. Only free draining materials should be used to fill a depression too large to fill with sub-base material. Under no circumstances should a depression be backfilled with compacted impervious material.

b. Sub-base Placement. The sub-base should be spread uniformly and placed by methods which will minimize segregation. Compaction of the sub-base layer may not be required; however, the surface should be reasonably smooth. When justified by quantities to be used, gradation tests on in-place material should be required. The graded surface should not deviate from the specified slope by more than three (3) inches unless closer tolerances are specified.

c. Stone Placement. Riprap stone should be placed to full layer thickness in one operation starting from the bottom of the slope and progressing to the top. Stone for riprap should be placed in such a manner as to minimize segregation and avoid displacing the underlying sub-base material or cause damage to the geotextile. The finished layer should be free from pockets of small stones, clusters of larger stones, and excessive voids. The riprap should be a well keyed and stable mass with adjacent stones in close contact but without alignment of longer faces so that open joints are formed. Stones should have their greatest dimension across the slope and the smaller spaces between stones would be left open to readily receive the grout. Riprap stone should be free of fines to easily facilitate grout penetration. The riprap layer thickness should never be less than 12 inches and should not deviate from the specified value by more than three inches when greater thicknesses are required. Field tests for gradation, elongation, and deleterious substances should be performed on random loads and the in-place material.

(1) Equipment and Placement Methods. Distribution of various sizes of stones should be obtained by (a) selective loading at an approved source of the material, (b) controlled dumping of successive loads during final placing, or (c) other methods which will produce proper gradation. Placement of

stone should begin at the bottom and proceed up the slope in a continuous manner. Rearranging of individual stone by mechanical equipment or by hand may be required to obtain a reasonably well-graded distribution of stone sizes. The following actions should not be permitted: placing riprap by dumping into chutes or by similar methods likely to cause segregation or disturb sub-base material; dumping at the top of the slope and rolling the stone into place; moving stone by drifting or manipulation by means of dragline bucket, dozer, or other blade equipment; and operation of crawler-type equipment on either stockpiled or in-place riprap.

(2) **Underwater Placement.** Sub-base materials and riprap stone placed underwater should meet gradation requirements in the container used for placing, and should be placed in a systematic manner assure continuous and uniform layers of well-graded stone of required thickness. Stone to be placed underwater should not be cast across the surface of the water.

(3) **Preparation of Stone.** The stone should be washed free of mud and dust to assure bonding between the grout and the stone. The stone should also be wetted and free surface water allowed to dissipate just prior to grouting. These requirements are of the utmost concern if non-quarried stone is to be used for the riprap layer.

d. Grout Placement.

(1) **Production of Grout.** Batching and mixing equipment should provide sufficient capacity to prevent cold joints and conform to the requirements of ASTM C 94 or C 685. Materials should be stockpiled and batched by methods that will prevent segregation or contamination of aggregates and insure accurate proportioning of the ingredients of the mixture. Grout should be mixed in a manner to produce a mixture having a consistency which will permit gravity flow into the interstices of the dumped riprap with limited additional effort to effect distribution. Grout should generally be used within 30 minutes after mixing. Retempering of grout should not be permitted.

(2) **Placing Grout.** Riprap should not be grouted without special protection when the ambient temperature is below 35 degrees Fahrenheit or above 85 degrees Fahrenheit, or when the grout is likely to be subjected to freezing temperature before final set has occurred. Grout placed on inverts or other nearly level areas may be placed in one course. Grout placed on slopes should be placed in successive tiers approximately ten feet in width, starting at the toe of the slope and progressing to the top. Grout should be deposited as close as possible to the final position by a positive displacement pump or by a method that will prevent segregation of aggregates or loss of mortar. Grout should be distributed over the riprapped surface by use of brooms or spades and worked into the space between stones from top to bottom with suitable spades, trowels, bars, or vibrating equipment. Some barring may be required to loosen tight pockets of riprap to aid in the penetration of grout. Adequate precautions should be taken to prevent grout from penetrating sub-base materials. Grout should be removed from the top surfaces of the upper stones and from pockets and depressions in the surface of the riprap by use of a stiff stable broom.

21 Aug 92

(3) **Placing Underwater.** When water levels prevent placement of grout in the dry, a proper method should be used to provide the least possible amount of disturbance to the grout during placement to minimize weakening of the grout mixture. This method may include placement by means of a tremie, a bottom dump bucket, or by positive displacement pumping through a suitable pipe or hose. Broom finishing should not be required for below water grouting.

(4) **Curing and Protection.** Beginning immediately after placement and continuing for at least seven (7) days, all grout should be cured and protected from premature drying, extremes in temperature, rapid temperature change, freezing, mechanical damage, flowing water, and exposure to rain. Preservation of moisture for grout surfaces can be accomplished by sprinkling, ponding, absorptive mats or sand kept continuously wet, impervious sheet material, or a membrane-forming curing compound. No workman or loads should be permitted on the grouted surface until proper strength has been developed. During cold weather placements, suitable coverings and protection should be applied in accordance with EM 1110-2-2000.

FOR THE DIRECTOR:



PAUL D. BARBER, P.E.
Chief, Engineering Division
Directorate of Civil Works