

Quality Control and Quality Assurance Methods for Cutoff Walls in Dams and Levees

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ABSTRACT: Detailed performance assessments of many existing dams and levees have demonstrated a need to install cutoff walls to reduce seepage quantities and provide protection against internal erosion and piping. Cutoff walls can be constructed by removal and replacement technologies or by in-situ mixing technologies. In either case, a high level of quality control (QC) by the construction contractor is necessary to produce an effective barrier, and sound quality assurance (QA) activities are necessary to provide the owner with confidence that the result will perform as intended. This paper provides descriptions of different cutoff wall construction technologies and appropriate QC/QA activities to accompany each. The principal objectives of QC/QA programs are to produce and verify cutoff walls with the necessary geometry, homogeneity, integrity, permeability, strength, and deformability. QC/QA programs include component material certifications and tests, construction process observations, construction process records, observations and tests of samples from the completed cutoff wall, and tests of completed cutoff wall performance at specific locations. Appropriate application and details of these QC/QA components differ in important ways for the different types of cutoff wall. This paper provides guidance regarding QC/QA methods and data interpretation.

INTRODUCTION

A substantial effort is underway by governmental agencies throughout the US to assess the safety of existing dams and levees. In many cases, these assessments have resulted in remedial measures to mitigate the potential for seepage, piping, and erosion through embankments and foundations of dams and levees. Mitigation techniques include upstream blankets, downstream pressure relief wells, and cutoff walls.

Cutoff walls will be effective only if they are properly designed and constructed. Appropriate construction quality control (QC) and quality assurance (QA) programs are essential to verify that the cutoff wall is constructed as designed. QC/QA programs should be developed with a thorough understanding of the purpose of the cutoff wall and the method of construction of the cutoff wall. Inappropriate specification requirements for QC/QA activities can result in inadequate verification of cutoff walls construction and/or in unnecessary costs or contract disputes.

The content of this paper is presented in these main sections: Definitions; Objectives of Cutoff Wall Construction and Cutoff Wall QC/QA Programs; Key Elements of Successful QC/QA Programs; QC/QA Observations, Measurements, and Tests; and Concluding Remarks.

DEFINITIONS

Several terms are defined for use in this paper. Cutoff walls are categorized by type of construction (Bruce and Sills 2009):

- Category 1 cutoff walls are constructed by removing the in-situ materials and replacing them with an engineering material with controlled performance characteristics. Excavation is generally done under slurry with long-reach excavators, clamshells, or hydromill equipment. The backfill material can be plastic concrete, self-hardening slurry, soil-bentonite, or soil-cement-bentonite.
- Category 2 cutoff walls are constructed by in-situ mixing of the existing soils with fluid grout, generally by some variation of the deep mixing method (DMM), such as vertical axis DMM, cutter soil mixing (CSM), or chain-saw type mixing equipment (TRD).

Cutoff walls can also be constructed by jet-grouting. Depending on the amount of replacement involved, jet-grouting transitions from Category 1, when the end-result is a mixture of the in-situ soils and the grout, to Category 2, when the jet-grouting is executed to achieve nearly complete replacement of the in-situ soils with grout. Seepage barriers can be constructed by grouting fissures in rock and by permeation grouting in soils, but those technologies are not addressed in this paper.

QC and QA are defined as follows:

- Quality Control (QC) activities are performed by the construction contractor to control the quality of the finished product. Such activities include providing, measuring, observing, testing, and documenting the necessary materials, equipment, and processes to achieve the specified end product. Many QC activities that document construction processes occur on a continuous basis and cover virtually 100% of the constructed work.
- Quality Assurance (QA) activities are performed by the owner, the owner's engineer, and/or the construction contractor to verify that the specified end product is achieved. Such activities include observations of construction and measurements and tests performed on completed construction. QA observations may occur during most or all of the construction process. However, in contrast to continuous QC monitoring of all construction processes, QA measurements and tests are generally performed on a small percentage of the completed work.

As will be discussed in more detail later, an important part of the philosophy of QC/QA is that a high level of QC by the contractor, using materials and methods that have been verified in a field test program, constitutes the primary means by which the owner can have confidence that the specified end result is obtained. QA measurements and tests are spot checks that provide additional assurance that the QC activities are producing the specified end product.

Another important characteristic of QC/QA is that these activities take place while the construction contract is in effect. This is distinct from assessment of the in-service

performance of a cutoff wall, which is normally a long-term effort based on monitoring instrumentation during various operational and climatic conditions. In some cases, it may be years after construction until the design hydrogeologic loadings are applied. This difference highlights the importance of QC/QA activities because the best opportunity to achieve the specified end product is through careful evaluation of QC/QA information while the contractor is actively engaged in on-site construction.

OBJECTIVES OF CUTOFF WALL CONSTRUCTION AND CUTOFF WALL QC/QA PROGRAMS

Cutoff walls can be installed in the embankments and foundations of dams and levees to reduce seepage quantities, reduce pore water pressures downstream of the wall to improve slope stability, and/or to prevent erosion and piping of soils in the embankment and foundation. If the design objective is to dramatically reduce seepage quantities, then low permeability is an important goal. However, if the design objective is primarily to prevent erosion and piping, then low permeability and avoidance of hairline cracks become less important than stability and continuity of the cutoff wall. Accordingly, the QC/QA program should be based on a clear understanding of the design objectives.

Objectives of the QC/QA program generally include establishing that some or all of the following parameters satisfy specification requirements:

1. Geometry. This includes plan-view location (position), width, depth, and verticality.
2. Homogeneity and integrity. This includes limitations on voids, inclusions of untreated materials, and other defects.
3. Material properties. These may include hydraulic conductivity, strength, and deformability.

KEY ELEMENTS OF SUCCESSFUL QC/QA PROGRAMS

Based on our experience with numerous cutoff wall projects, we observed that the following elements are invariably necessary for successful QC/QA programs

- Clear and complete specifications. Without clearly written specifications, the contractor will not be able to determine what QC/QA activities and submittals are required. Similarly, the specifications must be complete because it is simply unfair to expect the contractor to perform QC/QA activities that are not identified in the specifications. In addition, it is equally important that the specifications establish requirements that are based on the design objectives of the cutoff wall and consistent with the cutoff wall technologies that the specifications allow. If unnecessary requirements are specified, the construction cost may be unnecessarily increased. Furthermore, QC/QA requirements should be compatible with the technologies permitted. For example, it is not realistic to require coring as a sampling method for soft backfill materials. Specifications for QC/QA programs should be tailored to the unique objectives, subsurface conditions, and construction technologies permitted for each individual project.
- Appropriate organizational structures and qualified personnel. For both the

Owner/Engineer and the Contractor, project teams generally include home office personnel, field personnel, and laboratory personnel. All personnel involved should have the necessary training and experience. On virtually all cutoff wall projects, the contractor must employ a full-time Quality Manager. On medium to large projects, there should also be a dedicated CADD/GIS/IT specialist to manage the data. Materials specialists, engineers, geologists, and technicians may also be necessary, depending on the size and complexity of the project. Owners and Contractors may engage the services of Technical Review Boards, which afford independent technical insights at the highest levels for the benefit of the project and all parties involved. Such boards can resolve problems that frequently arise regarding unanticipated subsurface conditions and unexpected construction problems, as well as resolve questions that can only be addressed by experienced professional judgment.

- Communication. There should be close collaboration between the contractors QC personnel and the owner/engineer QA personnel, including rapid and complete sharing of observations and data. Early identification of problems enables immediate corrective actions to be taken, which is the least expensive time to make corrections and avoid building substantial sections of cutoff wall with ineffective parameters. Interactions between the contractors and owners QC/QA personnel should be collaborative rather than confrontational, with frequent meetings in person. All team members share a common goal of completing the project to achieve the specified end result. Communication flows should be open and rapid, not only horizontally, but also vertically, such that managers, home office personnel, and review boards have rapid access to essential information.
- Instrumentation monitoring plan and emergency action plan. Depending on the type of project, changing hydraulic loading conditions during construction, as well as effects of the construction itself, can trigger the need for emergency actions. Potentially adverse conditions should be anticipated, appropriate instrumentation installed with redundancy, an instrumentation monitoring plan developed, action levels established, and emergency action plans developed.
- Bench-scale tests. These tests are conducted in the laboratory, and they are used to determine and demonstrate the capability of materials to achieve the desired engineering property values under idealized laboratory mixing conditions.
- Field trials. These trials are conducted using the field equipment that will be used for the production cutoff wall. Ideally, the field trials are conducted after the bench-scale tests indicate which materials and proportions can effectively and economically achieve the specified end result. Schedule requirements sometimes dictate that the timing of bench-scale testing and field trials overlap. There are so many benefits to field trials that they are virtually essential. Field construction is not the same as laboratory sample preparation, so the field trials provide an opportunity for the contractor to demonstrate that the field equipment and processes are capable of producing the specified end result. Field trial sections of cutoff wall are subject to a much higher level of testing than production cutoff wall, with the idea being to develop field construction parameters that can reliably produce the specified result. Then, if the Contractor

controls and documents those parameters during production cutoff wall construction, the Owner can have a high level of confidence that the production cutoff wall will satisfy the design intent. Additional assurance is achieved by QA testing on a small percentage of the production cutoff wall volume. Other important benefits of the field trials are that QC/QA procedures can be demonstrated and all parties can develop a common understanding of construction methods, test procedures, and communication protocols.

- Continuous monitoring of construction processes. In modern cutoff wall construction, many parameters are monitored continuously. For example, in Category 2 walls, continuously monitored parameters include grout delivery rate, penetration rate of the mixing tools, rotation rate of the mixing tools, advance rate of trench mixers, etc. Plots of continuously monitored data enable timely review, identification of deviations, and rapid application of remedial measures.
- Data management and review. A large volume of QC/QA data is generated on cutoff wall projects. This data must be communicated swiftly in an easy to understand form. The data must be properly archived and remain accessible. Deviations from targets and from limiting values must be flagged. The data should be reviewed immediately and appropriate actions taken. Adequate staffing to perform these functions on a timely basis is necessary.
- Checklists. There are enough unique details on every cutoff wall projects that checklists become extremely useful. Checklists can be prepared for observations, measurements, tests, reviews, and every other activity related to construction and QC/QA.

QC/QA OBSERVATIONS, MEASUREMENTS, AND TESTS

Discussion of QC/QA observations, measurements, and tests are organized according to the following objectives: geometry, homogeneity, integrity, and property values.

Geometry

Key characteristics of cutoff wall geometry include position, depth, width, and verticality.

Position

The plan view position of a cutoff wall includes the position of each element for a wall constructed using vertical shaft mixing equipment, clamshells, and hydromill equipment, as well as the overall alignment and length of the entire cutoff wall for walls constructed using any type of equipment.

Category 1 walls constructed using clamshells or hydromills are usually constructed between concrete guidewalls that position and align the excavating tool. The position of cutoff walls constructed using excavators and deep mixing equipment are generally established by accurately locating the equipment. In both cases, optical surveying can be applied, but more recently, GPS instruments located on the construction equipment can provide real time location information.

Position is particularly important when a cutoff wall is constructed using overlapping elements, such as for vertical axis DMM. Position can be specified and controlled to within 3 inches of the planned location with modern equipment.

Depth

Cutoff wall depth is an important parameter that should be recorded for every set-up of equipment that makes a vertical stroke and frequently, e.g., every 30 ft, for cutoff walls constructed using excavators. For equipment that makes a vertical stroke, continuous automatic monitoring of depth is typically employed. For Category 1 walls excavated under slurry, soundings can be made with a heavily weighted wire using small and large bearing surfaces to determine whether solids settle out of the slurry.

For cutoff walls that penetrate into an aquitard, the depth of penetration into the aquitard can be an important performance parameter. This depth can be determined by comparing the tool depth measurement to the depth to the top of the aquitard based on a nearby boring. If the aquitard is more resistant to penetration than the overlying materials, measures of penetration rate or power consumption can sometimes be correlated with penetration into the aquitard. Such measures can serve as alternate means to determine adequate cutoff wall depth, but they need to be calibrated on a project specific basis.

Simple observations of marks on tooling should also be made periodically for comparison with the recorded depths of cutoff wall penetration.

Width

For Category 2 walls, which involve various types of mixing in place, the cutoff wall width is determined by the equipment dimensions, which can be easily measured while the mixing tools are at the ground surface. For vertical axis DMM, the average wall width is affected by the overlap between columns. The average width, b , can be expressed in terms of the overlap distance, e , and the column diameter, d , as follows:

$$\alpha = 2 \arccos \left(1 - \frac{e}{d} \right) \quad a_e = \frac{\alpha - \sin \alpha}{\pi} \quad b = \frac{\pi d^2 (1 - a_e)}{4(1 - e)}$$

where the intermediate values are α = the angle (radians) encompassing the common chord of the two overlapping columns and a_e = the dimensionless overlap area ratio = the overlap area common to two adjacent columns divided by the area of a single column. Misalignment can affect the average wall width, but it can also have more serious consequences, such as creating a defect in the cutoff wall. Consequently, controlling positioning and verticality of adjacent columns is especially important when cutoff walls are constructed from overlapping columns.

For Category 1 walls, the slurry properties need to be sufficient and compatible with the native soils to prevent collapse prior to backfilling. The potential for slurry trench stability is discussed by Filz et al. (2004), Fox (2004), and others. Free movement of the excavation tool over the entire depth and length of each cutoff wall element is a useful indicator that the cutoff wall is at least as wide as the tool. Additional

assurance that the minimum width is achieved can be provided by:

- An ultrasonic scanner.
- A sonic caliper.
- Volume calculations comparing backfill and theoretical excavation volumes.

The geophysical methods for measuring cutoff wall width require that the slurry have a low enough unit weight, e.g., less than 75 pcf, for the readings to be reliable.

Verticality

Although a high degree of accuracy is not generally necessary for the overall verticality of a cutoff wall, accurate control of verticality is important when overlapping elements are used to construct a cutoff wall extending to depth, with the most important factor being that adjacent elements are constructed at the same inclination to maintain the design overlap over the full depth of the cutoff wall. Generally this is accomplished by specifying a fine tolerance for deviation from vertical for each individual element, e.g., within 0.1% of plumb. Verticality can be controlled by (1) proper initial set-up of the construction equipment, (2) use of stiff, multi-auger equipment for vertical shaft deep mixing, (3) steering controls for hydromill equipment, and (4) use of an alternating primary-secondary construction sequence for individual elements. Verticality can and should be continuously monitored by inclinometers on the construction equipment.

For walls constructed using a continuous construction technique, such as backhoe slurry trenches and TRD, fine tolerances on verticality are not generally necessary.

Homogeneity

For Category 1 walls, in which the native soils are replaced with a backfill material that is prepared at the ground surface, a high level of homogeneity is expected, without any inclusions of foreign material, particularly for walls filled with plastic concrete or self-hardening slurry. When the backfill is soil-bentonite or soil-cement-bentonite blended at the ground surface, the expected level of homogeneity is not as high as for self-hardening slurries or plastic concrete, but it should still be completely free of clumps of unblended material larger than 3 inches, and the backfill material in the cutoff wall should have the same composition as the well-blended material at the ground surface.

Category 2 walls, for which mixing is done in-situ, should be free of inclusions or other defects larger than 3 inches. Depending on the soil types, water-to-binder ratio of the slurry, and equipment configuration, this may require double-stroking over the entire cutoff wall depth for vertical axis DMM. Double-stroking is ordinarily done at the bottom of the cutoff wall in any case to make sure the bottom is properly treated.

For cutoff walls that have an unconfined compressive strength of 60 psi or more, full-depth coring is the standard method for verifying homogeneity. Recovery requirements for each core run should be based on the specified unconfined compressive strength because weak materials are more difficult to core than strong materials. For a specified minimum unconfined compressive strength of 60 psi, a required core recovery of 80% may be appropriate, provided that a 20% lack of

recovery can be rationalized as not being representative of a major void or untreated inclusion, but rather as a result of the coring process in weak backfill. For a specified minimum unconfined compressive strength of 120 psi, a required core recovery of 95% might be appropriate for Category 1 walls, and a required core recovery of 90% might be appropriate for Category 2 walls. Core holes that deviate outside the cutoff wall must be re-done.

Core should be at least 2¼ inches in diameter, and individual core runs should not be more than 10 ft long. Triple tube coring is generally most effective at achieving good recovery in weakly cemented materials. Core holes are backfilled with grout that is compatible with the cutoff wall material.

Inspection of recovered cores can be supplemented with optical logging to give a 360-degree image of the core-hole wall. This technique can provide invaluable information about cutoff wall homogeneity when the coring process produces low recovery in weakly cemented materials.

Cores can be drilled at joints between elements to attempt to verify connection quality at the joint. Alignment of the core hole with the joint can be challenging, and large diameter core combined with precision control of the position and verticality of the core hole can help. Core holes at joints should be subject to optical logging.

An issue that deserves special consideration in connection with coring in cutoff walls is that the coring process itself can produce cracks in the wall. Tensile stress may be induced in the core-hole wall by differences between lateral and longitudinal stresses in the cutoff wall, combined with drilling fluid pressures, as well as shrinkage of the cutoff wall due to curing processes and/or temperature changes. Shear and normal stresses induced in the core-hole wall by the action of the drilling tool can also contribute to tensile stresses that can cause cracking. Evidence of cracking induced by coring is provided if optical logging shows vertical cracks in the core-hole wall that are not present in the recovered core at the same elevation. It may be possible to reduce coring-induced cracking by reducing the drilling fluid pressure, using foam instead of water as a drilling fluid, and keeping the slurry temperature low. It is as yet unclear how best to control strength and stiffness to reduce coring-induced cracking. Stronger materials tend to have higher tensile strengths, but they may also be brittle.

Hairline cracks induced by the coring process can be repaired by properly grouting the core hole. However, such cracks do artificially increase the permeability determined from slug tests performed in the core holes. If optical logging demonstrates that a crack in a core hole was produced by the coring process, a slug test result that exceeds the specified value should not be considered a failure by the contractor to construct a satisfactory wall.

Integrity

Cutoff wall integrity refers to the overall continuity of the cutoff wall, and it encompasses prevention of gaps due to misalignment of individual elements, inhomogeneities large enough to compromise the cutoff wall function, cracks large enough to pass particles or significant water flow through the wall, inadequate keys into aquitards, and other defects. The primary means to achieve cutoff wall integrity is the contractor's construction quality control operations. QC and QA activities that

support cutoff wall integrity are discussed throughout this paper, but the topic is given separate mention here to encourage designers to carefully consider all factors that could affect cutoff wall integrity for a particular project, and to prepare the wall design and the contract documents, including QC/QA requirements to address such factors.

Material Properties

The most important material property for cutoff walls is permeability (hydraulic conductivity), but strength and deformability can also be important.

Permeability

Cutoff walls are constructed to reduce seepage, so permeability is of primary importance. Permeability tests can be performed on specimens prepared by hand from “wet” samples of the cutoff wall material or by slug tests (also known as single-well tests) in core holes. Permeability tests are not normally performed on core samples because the coring process can produce cracks in the core that artificially increase the measured hydraulic conductivity.

Permeability tests on laboratory prepared specimens are ordinarily conducted in flexible-wall permeameters with back-pressure saturation. For appropriate mix designs, such tests generally produce low values of permeability, but they do not fully represent in-situ conditions of mixing, placement, and curing, or of larger scale features that may exist in the cutoff wall. Consequently, in-situ slug tests are generally performed in core holes spaced at 100 to 200 ft intervals along the cutoff wall alignment. Slug tests can be performed using the rising head or falling head method, but several precautions should be observed, including:

- Core holes should be drilled with care to prevent damaging the cutoff wall. The alignment of core holes should be carefully controlled to prevent the core hole from approaching or passing through the sides of the cutoff wall.
- The core hole should not be drilled with bentonite slurry, and completed holes should be flushed with water several times to clean the hole prior to testing.
- Slug tests that fail to pass the permeability criterion can be inspected with an optical logger to check for coring-induced cracking.
- Slug tests in cutoff walls establish a three-dimensional flow regime, and the data should be reduced with an appropriate method, such as described by Britton et al. (2002, 2005) or Choi and Daniel (2006). The Hvorslev (1951) method should not be used because it overestimates the permeability of cutoff walls in aquifers.

Strength and Deformability

Minimum and maximum values of unconfined compressive strength are sometimes specified to provide a cutoff wall material with sufficient durability and compatibility with the surrounding ground. Rather than specifying absolute minimum and maximum values, it is recommended that a statistically based specification should be applied to appropriately recognize the natural variability in strength of cutoff wall materials. Information about statistically based strength specifications is presented by

Filz and Navin (2010). Both the low end (durability) and high end (deformability) values of specified strength are often based on engineering judgment instead of quantitative analysis. Designers are encouraged to provide a relatively wide range of target strength values to avoid unnecessary difficulties for the contractor.

Sampling for strength testing can be done at the surface for Category 1 walls, by wet grab sampling for Category 2 walls, and by coring for Category 1 and Category 2 walls. Samples from sufficiently fluid Category 2 walls can also be obtained by using a double concentric tube system with grease between the tubes. The system is inserted open-ended, initial set is reached, the inner tube is withdrawn, the outer tube remains in place, and hole is filled with grout.

CONCLUDING REMARKS

Successful cutoff walls require especially careful attention to design and construction QC/QA because cutoff walls are typically large features for which even a single large defect could compromise performance. Nevertheless, the authors contend that, with diligence and cooperation by all parties, successful cutoff walls can be constructed. At the same time, the real objectives of the cutoff wall, as well as the realities of cutoff wall construction, should be kept in mind to avoid establishing requirements that unnecessarily complicate construction and verification.

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