THE CONSTRUCTION OF SMALL EARTH-FILL DAMS

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Contents

Summary

This article covers the construction of small earth-fill dams less than 15 m high (the majority of small dams constructed). Planning, contracting, and preparation of site, including river diversion, are dealt with. Selection of materials and quality control are considered next. Finally, techniques of obtaining, handling, and placing suitable materials are presented, including their blending and compaction. Ancillary works, such as filters and drains, slope protection, and interfaces are described, and the role of the professional engineer in specification, control, and training is emphasized. Equipment used for construction and details of design are illustrated in the figures in the Appendices.

1. Introduction

Small earth-fill dams lower than 15 m in height comprise the majority of small dams constructed. This article provides guidelines on some important issues related to the construction of small earth-fill embankments to facilitate their improved functionality with fewer maintenance problems. Most of the basic principles are also applicable to the construction of other types of small dams, i.e. rock-fill, concrete, and masonry dams.

Constructing an earth-fill dam does not constitute merely placing earth fill. The distinction between the two is substantial, with significant implications in terms of the selection of the contractor. Appropriate experience and the right equipment are vital prerequisites. Prequalification with invitation to bid, tender, or quote, from a list of contractors with proven track records, is the advisable procedure to follow.

1.1. Contractual Relationships

Small dams are normally constructed according to one or other of the following contractual relationships:

- *Owner-designed and owner-built*, where the owner selects the site and materials, constructs to his own design, and uses his own labor and machines.
- *The owner acting as contractor* constructs the dam to designs and specifications prepared according to his own instructions. This arrangement can result in extreme difficulties if the roles are not clearly specified and responsibilities not fixed.
- *The owner/consultant/contractor relationship*, where the contract between owner and engineer is the standard form of agreement of the Association of Consulting Engineers, and that between owner and contractor is the General Conditions of Contract, which also formalizes the relationship between engineer and contractor.
- *Turnkey*, where the employer contracts a party to design and construct a dam to previously agreed-upon size and specification. Various documents, including one by the International Federation of Consulting Engineers (FIDIC), provide guidelines for preparing a contract document. The services of a professional engineer with appropriate experience are strongly urged to assist in drafting the contractual agreement.

One of the most important aspects in contract procurement is the final adjudication process. The average contractor available for construction of small earth-fill dams is relatively unsophisticated and might have priced the bid, tender, or quote without reference to the specifications. This makes it imperative that duties and responsibilities in accordance with the specifications should be clarified with the contractor before any award of contract is made.

2. Construction Planning and Programming

Proper planning of the intended construction procedure includes:

- site establishment, storage space, access roads, and provision of water to site
- methods and stages of river diversion to be used
- layout and development of construction materials borrow areas, with irrigation as required
- method statements for site clearing and stripping, excavation, foundation preparation, development of borrow areas, transportation, placing of fill, compaction, and finishing
- equipment availability and requirements (resource allocation)
- Programming the construction of a small earth-fill dam involves investigations relating to one or more of the following aspects:
- flood probability in the watercourse on which the dam is being built
- the effect of rain on earthworks operations
- availability of resources

An earth-fill dam is constructed in two distinct phases, i.e. the establishment/development phase and the placement phase. Ideally, construction should be completed during a single dry season. During the establishment phase, starting with site establishment and ending with diversion and river excavation, a number of interrelated activities take place. Planning is normally done by any one of the critical path methods, involving identification of activities and their sequencing in a logical diagram. This allows them to be scheduled and their resources allocated.

Once past the establishment/development phase, the bulk earth-fill placing phase commences, normally with fewer activities to be sequenced, and programming techniques for the production management field, such as line balancing, are more appropriate. Construction planning and programming is a specialist field.

2.1. River Diversion

The most suitable river diversion configuration depends upon site conditions, flow regime, and dam type. However, the majority of small earth-fill dams do share the following conditions, for which diversions systems have evolved as used on many dams with but slight variations:

- Small earth-fill dams are sited in either nonperennial streams or low-flow season streams.
- The construction period is relatively short, usually lasting not more than one season.
- The outlet is close to riverbed level.
- A side-channel or by-wash spillway is used.

This system is described in the following paragraphs with reference to Figure 1. The *first step* is installing the outlet pipe for the dam at a convenient level not far above the streambed level and diverting the river to this outlet by the combination of a trench and a temporary diversion.

With the riverbed exposed, the *second step* is to construct a more substantial cofferdam over the outlet pipe to a standard that allows its incorporation into the main embankment. This cofferdam usually cannot be constructed high enough to provide adequate protection against autumn floods and has to be designed for overtopping with minimal damage, i.e. with a mild downstream slope, and built from highly erosion-resistant materials. If possible, a downstream cofferdam should be avoided as this might result in a potential silt trap.

The *third step* in river diversion involves excavation of the river section; construction of an upstream section of the main embankment, as shown in Figure 1; and the excavation of a temporary by-wash or side-channel spillway (at a lower level than the main spillway and preferably on the opposite bank). The level up to which this stage should be constructed requires careful planning, taking into account time, available resources, and the intermediate spillway position.

Where the intention is to construct the dam over more than one dry season, this (third) step should be completed before the onset of the first rainy season and should provide protection against at least a 1-in-10-years flood in terms of flood absorption and spillway capacity.

The *fourth step* entails construction of the main embankment body, together with all the drains and filters and the forming of the final side-spillway. In the case of construction over more than one dry season, most of this work will have to be done during the rainy season.

Figure 1. Typical river diversion system used for small earth-fill dams

The *final step* in river diversion consists of closing the gap left by the previous step, which is risky in that overtopping can cause major damage. Consequently, it should be well timed. For a dam constructed over more than one dry period, the second dry season should be used for this operation. Throughout the construction of the dam, the object of the diversion system must be to prevent overtopping or else to minimize damage during stages where the rise in the water level does become high.

2.2. Site Preparation: Clearing and Stripping

Before commencement of work, the contractor has to clear the site, including the borrow areas, of all trees, rocks, fences, structures, and rubbish that might obstruct the work. Clearing can also include that of the dam basin if so specified. Reclamation of fences and other usable materials is usually included in the contractor's brief.

After completion of clearing operations and before commencement of excavation, the foundation area is stripped of all topsoil to a depth of between 150 mm and 300 mm, depending on site conditions. Topsoil is stockpiled for use on the downstream slope of the embankment or for site reinstatement.

2.3. Excavation and Foundation Preparation

The importance of excavation and foundation preparation cannot be overstressed. A word of warning: avoid rock foundations under small embankment dams; they are treacherous. Choose concrete dams.

2.4. Development of Materials Borrow Areas

Embankment dams ideally should be constructed from materials found in the immediate vicinity of the dam. Suitable material, therefore, has to be tested and proven during the site investigation. The design will be based on the properties of such materials. In the usual owner/consultant/contractor relationship, the contractor usually bears minimal responsibility for material selection, having only to avoid obviously unsuitable materials. Soil-testing methods are described elsewhere (see *Testing of Materials and Soils*).

The main objectives in borrow pit development are:

- to make maximum use of available materials
- to ensure minimum variation in the materials selected for any zone
- to leave behind a borrow pit that is safe, free draining, and fully reinstated

These objectives can be achieved only with careful and continuous planning.

3. Embankment Construction

The following general principles are of concern in earth-fill embankment construction.

3.1. Requirements for Construction Materials

- Use the available materials in the best way possible to ensure an acceptable end product.
- Construct the zones in the embankment as homogeneously as possible, minimizing layering as far as possible.

The importance of placing earth-fill dams at a relatively high moisture content is evident. Compaction of soil at a moisture content dry of optimum has three negative effects:

- Permeability is relatively high.
- Saturation can cause significant settlements.
- The material is stiff and brittle.

3.2. Preparation of Materials for Construction

Unfortunately, the natural moisture content of available soils in most borrow pits is far drier than optimum. The problem is exacerbated because most small-dam builders find the addition of moisture extremely troublesome, predominantly because of:

- Lack of equipment availability. Small earth dams are normally constructed using general-purpose machines that do not include the *water cart*.
- Irrigation of borrow pits causes slippery conditions where scrapers are used. Where a backactor is used, it is difficult to penetrate to a depth allowing the excavation of an adequate face.
- The number of pipelines required makes irrigation on the embankment cumbersome.
- Small dams are often built in streams that are not perennial, where water might not be available.

As a result, most small earth-fill dams tend to be constructed at a *dry-of-optimum* moisture content, with all its associated negative effects.

3.3. Materials Hauling Methods

The most economical method of hauling depends on the haulage distance. Although no agreement has been reached concerning the economical cutoff point between the various methods, there is a general consensus on the ranking of methods.

- In cut-to-fill, a bulldozer is used to move the material from the borrow pit to the fill. The protestations of the dam-building purists will never be enough to make this method unpopular. If engineers are to prevail in the business of the small earth-fill dam market, this method must be accepted and a set of rules drafted for it.
- For short hauls of up to about 200 m, the maneuverable front-end loader competes well with other methods for selection, hauling, and spreading. By careful routing, a fair degree of compaction can also be attained.
- Carry-all scrapers are suitable for most middle distances of more than 200 m and afford certain advantages over other methods, especially in production capacity and spreading ability. However, they are large and cumbersome machines and are not always suited for small dams.
- Dump trucks, operating together with front-end loaders, are ideal for long-distance hauling over several kilometers. However, they are often used over the shorter distances because of their availability and suitability for smaller dams.

3.4. Trial Embankments

Trial embankments are integral to the successful construction of an earth-fill embankment dam. Their main function is to determine the correct construction procedure for the available materials and machinery. Trial embankments are constructed during the establishment and development phase. Only equipment to be used in the construction of the actual embankment, along with the actual construction methods intended for use, should be adopted in the construction of the trial embankment. The trial embankment can normally, with good planning, be integrated into the proposed embankment.

3.5. Placing and Blending

Distribution and grading of materials in any zone should be done so that the embankment is homogeneous and remains free of lenses, pockets, streaks, and layers of materials differing markedly in density, texture, or gradation from the surrounding material.

Preparation of the top surface of each layer, prior to the placement of subsequent layers, is important. Material that has become too wet must be harrowed and left to dry to the specified moisture content or must be removed from the embankment. A compacted layer that has dried out should be ripped up, brought back to the specified moisture content, and recompacted. The upper surface of each layer should be sufficiently rough to ensure proper bonding with the subsequent layer. Scarifying of this layer is generally required, except where a pad-foot or similar roller is used. The main objective of scarifying is not bonding, but ensuring that horizontal and vertical permeabilities are as similar as possible. Hence, scarifying of all layers is almost imperative.

The earth fill is either spread by scraper or dumped in heaps on the embankment. Final spreading by motorized grader or bulldozer is required to achieve a layer of known and even thickness so as to ensure correct moisture adjustment and even compaction. After addition of final moisture, the layer has to be well mixed by means of a disc harrow. The best results are obtained where the layer is slightly overwatered and then dried to achieve the correct moisture content by harrowing. This ensures a well-mixed layer that errs on the wet side, which is considered ideal.

Construction traffic should be routed over the embankment so as not to cause areas of excessively high density or sections of the embankment that heave. Excessive compaction is often caused by hauling equipment with higher wheel loads than the actual compaction equipment. The aim is to achieve a homogeneous layer with fairly high moisture content that is adequately compacted.

3.6. Compaction

Published material on moisture control in earth dam construction dates back to 1907 when Bassel wrote: "Too much or too little (water) is equally bad and is to be avoided. It is believed that only by experience is it possible to determine just the proper quantity of water to use with different classes of materials and their varying conditions." It took a further 25 years before Proctor established the following principles for moisture and compaction control:

- For a dry material and a fixed compactive effort, the maximum dry density attained will increase with an increase in moisture content.
- For this fixed compactive effort, there is one moisture content, the optimum moisture content, which produces the maximum dry density.
- An increase in moisture above optimum moisture content results in a corresponding reduction in dry density.
- Greater compactive efforts on the same soil result in different moisture/dry density curves with optimum points occurring at lower moisture contents but

greater dry densities. The inverse is true for smaller compactive efforts.

It has been shown, both in theory and in practice, that a high dry density yields lower permeability and compressibility and higher soil strength. These advantages are offset, however, by the disadvantage of having a stiff, brittle embankment at relatively low moisture content. Economies of construction must also be taken into account.

Engineers involved in dam construction generally aim for achieving the following by means of a compromise:

- A relatively low compaction effort should approximate the standard Proctor test.
- A moisture content is achieved up to or equal to 2% above the Proctor optimum moisture content for the material.
- A density that is not lower than 5% below the Proctor density is acceptable.
- Where the engineer has to decide between higher density or higher moisture content, the higher moisture content should be chosen.

3.7. Filters and Drains

A downstream blanket and toe drain are usually included to advantage in the smallest of dams. The objective is to draw down the phreatic line as far as possible and to intercept seepage passing through the foundation of the dam. Blanket and toe drains do not pose particular construction problems apart from needing special care in the installation of perforated pipes (where required) and requiring a method of compaction that will not crush the *filter* materials.

The chimney drain is a relatively new innovation and is far more difficult to construct. A vertical chimney is usually constructed by placing three or four layers of embankment fill; excavating through these layers to expose the previously placed portion of the drain; and finally, filling the trench with filter material. This process is repeated until the chimney drain is complete. Problems in its construction are cleaning the trench before resuming placement and compacting the filter to a point where settlement is minimized. The latter problem is overcome by saturating the filter and taking it well past the full supply level so as to allow for settlement.

Subvertical (sloping) filters are extremely difficult to construct. Placing them as part of a layer is rather wasteful and disruptive where the filter is less than a full machine width. Placing a staggered series of short vertical filters is also unacceptable, as settlement of the filter material would, in all probability, result in objectionable voids in the chimney drain.

3.8. Slope Protection

The upstream slope, the crest, and the downstream slope of the dam need to be protected against wave action and erosion. Unless a suitable source is readily available that can be exploited without the use of explosives, the provision of riprap as protection on the upstream slope of small earth-fill dams is uneconomical and should not be specified. A more appropriate solution would be to flatten the upstream slope to at least

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Biographical Sketches

Louis Hattingh is a civil engineer with bachelor’s and master’s degrees from Stellenbosch University, South Africa, who works in the field of dam engineering and numerical modeling. His experience in the fields of dam safety evaluation and dam monitoring is extensive. He has also been actively involved in performing transient seepage analysis in earth-fill dams, correlating numerical results with physical measurements. His career experience was with the Department of Water Affairs and Forestry and the Water Division of BKS (Consultants) (Pty) Ltd., in South Africa.

Heinrich Grimsehl is a registered professional engineer with bachelor’s and MBA degrees from the University of Pretoria and an M.S. (Eng.) from Georgia Institute of Technology, US. His experience includes planning, design, and construction of earth-fill, rock-fill, concrete-gravity, and arch dams, including roller-compacted concrete structures. Design experience covers foundations, internal drainage systems, spillways, outlet works, and main structures of dams. He has wide experience in preparing bidding and contract documents and has been appointed specialist review consultant on project evaluation. Responsibilities include training, management, and investigation assignments. He has 33 years of experience with, among others, the Department of Water Affairs and Forestry and BKS (Consultants) (Pty) Ltd. in South Africa, and in Lesotho.