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Quality Performance Evaluation of Embankment Dam Construction Projects

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Abstract

Quality management is one of the most important areas in project management, especially in the field of infrastructure construction industry. To better manage and control the quality of a construction project, the role of quality evaluation is critical. But it has been always a challenging task due to its complexity and the varying factors during construction phase. Quality evaluation or quantifying the quality performance of heavy construction projects such as embankment dams consists of the following main stages: 1) identifying quality indicators related to different project activities; 2) determining the factors affecting quality performance of indicators; 3) aggregating quality performance of quality indicators to gain the overall quality level of the project. This paper seeks to distinguish these quality indicators and factors, as well as evaluate each indicator. Furthermore, the weight and the relative importance of each indicator and each activity are established by eliciting the views of experts with experience in the field of dam design and construction using conference method. Consequently the overall quality at the project level is calculated by using a defined function which accumulates quality performances at activity levels. The results of this study can be used in quality-based contactor prequalification systems.

Keywords

Construction quality evaluation, Quality indicator, Quality performance, Earth dam project, Rock-fill dam project

1. Introduction

Time, cost and Quality are three major factors that have undeniable effects on planning, scheduling and controlling construction projects, especially in the field of heavy and infrastructure construction projects. Regarding the large amounts of cost included in these types of projects and considering their significant role in today's societies, quality evaluation is a necessity. Dams as infrastructure projects are always subjected to sophisticated loads, thus their quality and efficiency must be adequate. Earth-fill and rock-fill dams because of material availability and their convenient way of construction, are highly regarded. Heavy construction projects such as dams require that project managers or engineers be aware of cost, productivity and quality performances of: 1) different types of construction methods that can be applied to a project, 2) different types of heavy construction plant and equipment (Vanegas et al. 1993) and their performances. A planner must prepare a plan that is economically, financially, and timely feasible and may result in a highly qualitative completed project.

Although the term “quality” is often considered as an attribute, it can be evaluated and quantified (Minchin and Smith 2001). Providing a framework which can create a link between these two concepts is of great importance. In recent years, interest in the quantification of quality has increased and some methods have been provided in which the quantifying of quality and qualification of contractors is regarded. The main focus of early researches in categorizing and quantifying quality performance in industrial construction was on the amount of rework on a project and tracking the source of the rework (Minchin and Smith 2001). On the other hand, quantifying quality was based on cost data. While many research studies have provided great contributions to this field, little research has concentrated on the area of quantifying quality in order to plan and schedule construction projects. In order to deal with quality performance data and analyze them, quantification is necessary so a decision maker can conveniently make a compromise among cost, time and quality in the planning process of a project. In 2005, El-Rayes and Kandil suggested a method for measuring quality performance for highway construction based on quality-based contractor qualification systems, which was the basis of a time-cost-quality trade-off multi-objective optimization model.

This paper provides a framework to evaluate quality in earth-fill and rock-fill dam construction projects, in which critical quality indicators related to each activity are investigated and identified. Also some important technical factors that may affect the quality of the project as well as time and cost, are determined for each activity. This research also illustrates the utility of quality control data to measure the quality performance of each indicator and subsequently the quality performance in activity level and project level by introducing a simple weighted approach quality function.

2. Embankment Dams

Depending on the dominant fill materials used, there are two main types of embankment dams: 1) Earth-fill dams, and 2) Rock-fill dams. When basically only one impervious material is available and the dam is of relatively low height, a homogenous dam with an internal filter may be used. For dams with high height and when the borrow materials do not supply sufficient impervious materials, a dam with an impervious core and with a shell which constitutes the structural function and provides stability of dam, is designed (USACE 1995, Das 2008).

3. Quality Indicators of Embankment Dams

In order to facilitate the evaluation of construction quality, some significant indicators are investigated and identified in this research. Indicators are measures of the quality performance of the end product of each activity. In this section the embankment dams are divided into three main components:

1) **Impervious and semi-impervious zone, such as a clay core, is the main barrier of flow of water.** This zone is comprised of impervious material but no compacted fill is utterly impervious. Impervious materials include clays of high and low plasticity (CH and CL), clayey sand or gravel (SC and GC), and clayey silt (CL-ML). Semi-pervious materials include silts (ML), silty sands, and gravel (SM and GM) (USACE 2004).
2) **Pervious zone, such as filters and rock-filled shells.** Pervious fill material is defined as free-draining cohesion-less sand and/or gravel, containing less than approximately 5 percent passing the No. 200 sieve (USACE 2004). The primary function of the pervious zone is to support the core. Also this zone provides favorable hydraulic conditions, and acts as a transition zone between materials with wide variation in grain size.
3) **Slope protection.** Because upstream face of a dam is probably subjected to damage as a result of wave action, weathering, ice damage, and damage due to floating debris, slope protection is furnished. Upstream slope protection usually consists of riprap, but when riprap was not economically justifiable, soil cement, concrete paving, and asphalt paving have occasionally been used. Riprap is the most common type of upstream protection. It is a relatively thin layer of graded rocks which

secures protection against wave action for embankment material. (USACE 1995) A bedding layer also must be utilized between riprap layer and embankment material.

The key point that must be considered is that these indicators are determined in a way that they could be objectively and practically measurable (El-Rayes and Kandil 2005). Table 1 illustrates critical quality indicators designated for above-mentioned zones.

Table 1: Quality indicators of impervious and semi-impervious zones of embankment dams (USACE 2004, USACE 1995, USBR small dams, Das 2008, Minchin and Smith 200, Anderson and Russell 2001)

Zone	Indicators		Comments
Impervious and semi-impervious zone		Density/Compaction	Shear strength, permeability, and deformation characteristics are the main properties of embankment fill which vary with the density and water content of the compacted fill. Therefore, soil must be compacted as specified. Both requirements must be satisfied. If the water content is outside its specified range, even though the desired density is obtained, the soil must be reworked. The desired density must be about 90 percent to 95 percent of in-situ maximum dry density. Plasticity of soil is a significant feature which makes the soil able to bear different deformations without crack generation.
		Water content	
		Plasticity index	
Pervious zone		Gradation	Controls during construction of pervious fill are conducted to ensure that: 1) the material are compacted homogenously, 2) the fill is free draining, 3) consolidation will not occur due to superimposed fill, and 4) the angle of friction of soil is high. The permeability and workability of this zone is very important, and controls must focus on gradation and presence of fine particles (e.g. clay or silt), and relative density to secure above-mentioned issues. The amount of included fines must be inspected, since the presence of excessive fines can lead to can cause excessive post-construction settlements when the reservoir is filled.
		Relative density	
		Percent of fine particles	
	Rock-fill	Maximum permissible size	For rocks gradation is not usually determined but the maximum permissible size is normally specified.
		Relative density	
		Percent of fine particles	
Slope protection		Gradation	Loads from the quarry should provide a good mixture of different sizes within the specified gradation. Placing also should perform in a way that provides a uniform distribution of different sizes without segregation. Therefore gradation should be checked. Bedding layer material must be large enough to prevent being washed out due to water currents and waves. Thus, it is a necessity for Bedding material to meet specifications concerning gradation and layer thickness.
		Layer thickness	

4. Quality Factors

Quality of the end product depends on some controllable factors during the construction phase. In order to obtain the desired performance, construction management should focus on these factors. Disregarding these factors may lead to deficiency, and consequently, additional costs related to those deficiencies and reworks. These factors vary for every alternative of feasible resource utilization. Available resources for activities consist of machinery, material, and labor. Each of these resource components has its own parameters to alter the outcome.

For instance, compaction is the principle part of embankment dam construction. Achieving optimal compaction depends on three main factors which are: 1) base factors of the soil, 2) Roller factors, and 3) treatment factors (Sminiati and Hren 2008). Each of these factors is consisting of some sub factors dependent on the nature of a construction activity, as shown in Table 2.

Table 2: Possible construction activity-related quality factors (USACE 2004, USACE 1995, USBR small dams, Sminiati and Hren 2008)

Zone	Factors	Sub-Factors
Impervious and semi-pervious zone	Base parameters of soil	Type of the soil, structure granulation, layer stiffness, layer thickness and structure and stiffness of lower layers.
	Roller factors	Force sense, exciter frequency, roller drum amplitude, drum diameter, roller weight, roller weight/ drum weight ratio, drum geometry, type of roller (drag or self-propelled).
	Treatment factors	Number of passes, velocity and its direction and the shape, slope and smoothness of surface, water content.
Pervious zone	Base factors of fill material	Type of the material, structure granulation, layer stiffness, layer thickness and structure and stiffness of lower layers
	Roller factors	Force sense, exciter frequency, roller drum amplitude, drum diameter, roller weight, roller weight/ drum weight ratio, drum geometry, type of roller (drag or self-propelled).
	Treatment factors	Number of passes, velocity and its direction and the shape, slope and smoothness of surface, water content. Water content: if Gravel; no water content control is required, if Sand; it is required.
Slope protection zone	Material factors	Aggregate quality.
	Treatment factors	Dumping techniques.

5. Quality Evaluation Model Development

In previous sections, quality indicators are determined and categorized to evaluate the quality performance of the project. Measuring the quality performance of indicators depends closely on the inspections during construction phase. In the evaluation process, the defined approach is based on quality control data and actual records. Therefore in the proposed approach there must be two critical requirements in order to achieve reliable and acceptable results: the quality of sampling and the quality of testing (Zaniewski and Adams 2005).

5.1 Embankment Dam Quality Control

Quality control testing and collecting samples of completed activity are conducted for two main reasons, to ensure adaptation with design requirements and to provide a report of as-built conditions of the embankment dam. Devising a systematic plan for sampling and testing is necessary during construction. Control tests are designated as routine tests and performed at assigned locations. Additional tests are performed where the inspector is doubtful about the adaptation to the desired requirements (USACE 2004). When the field test results are obtained they should be compared to the acceptable ranges. Obviously, if the results don’t satisfy the technical specifications correction is needed.

5.2 Measuring the quality level of indicators

Indicators shown in Table 1 can be easily tested and measured using standard test methods like ASTM and AASHTO. Appropriate control limits for each test is established by laboratory tests, and particularly in the case of soil it depends on the type of soil (Iowa DOT Project 2002). For example, tolerable range (the upper and the lower limits) water content, which is one of the quality indicators, is determined based on compaction tests results accomplished and analyzed in the laboratory. Water content-density tests can be conducted according to AASHTO T99 and T180 tests. Based on the obtained results and according to the density requirements the acceptable range for water content and the standard deviation from optimum water content can be established.

It should be noted that the measurement results for indicators are reported in different units. Because of this reason, it is required to transform them to a unified system of measurement which can be used to evaluate the performance of different quality indicators. In order to illustrate the level of satisfaction according to designed specifications, in this model, the results of quality control tests of different indicators are transformed to a value that ranges from 0 to 100% (El-Rayes and Kandil 2005). The quality of each indicator can be expressed by linguistic terms which are indicated by a range of quality percent, such as: the lowest (0, 20), very low (20, 30), low (30, 40), relatively low (40, 50) medium (50, 60), relatively high (60, 70), high (70, 80), very high (80, 90), and the highest (90, 100). For example, if the average amount of all data gathered from compaction test results of both accepted and reworked samples falls in the range from 80 to 90 percent it can be said that the quality level is very high.

5.3 Quality Performance Evaluation Function

In order to estimate the overall quality of a project, it is first needed to estimate the quality in activity level. In the next step, aggregating the quality performance of activities by calculating the quality performance in the project level will be available. For this purpose a simple weighted approach function was proposed by El-Rayes and Kandil (2005):

$$\text{Overall Quality} = \sum_{i=1}^{l} wt_i \sum_{k=1}^{k} wt_{i,k} \times Q_{i,k}^{n}$$

where $Q^n_{i,k}$= performance of quality indicator k in activity (zone) i, $wt_{i,k}$ = weight of quality indicator k compared to other indicators in activity (zone) i representing the relative importance of this indicator to others, and wt_i= the weight of activity (zone) i compared to other activities in the project illustrating the importance and contribution of the quality of this activity (zone) to the overall quality of the project (El-Rayes et al. 2005, San Cristóbel 2009). Therefore, according to the suggested function, the weight of each activity and subsequently the weight of each indicator in a given activity is required.

5.4 Weights of Activities (zones) and Quality Indicators

The next step is to determine the degree of importance of indicators and activities. It should be noted that the degree of importance of every element of an embankment dam varies by different conditions in the dam's life cycle. In the designing phase considered conditions are: 1) Stability during construction and the end of construction, 2) Steady-State Seepage conditions, 3) Sudden drawdown stability, 4) Partial pool condition. For instance, at the end of construction, a short period of time after construction before ponding, the role of the core and the shell are very critical in dam safety because they secure the dam's stability, but the filter and the slope protection zones are of less significance. Authors attributed linguistic terms to these different zones related to above conditions, regarding upstream and downstream slopes. These terms are obtained based on the views of highly experienced experts in the field of dam design and construction (Table 3). Experts were asked to participate in a conference and discuss the indicators and their relative importance. The overall level of relative weights of indicators and zones are elicited from each participant's ranking for indicators and zones as shown in Table 4.

Table 3: Attributed linguistic terms to embankment dam zones based on expert judgment

Zone	Steady state seepage		Partial pool		Rapid drawdown		End of construction		Quality indicator	Weight of indicator
	US*	DS**	US	DS	US	DS	US	DS		
Impervious and semi-pervious zone	VH		VH		L		VH		Density/Compaction	VH
									Water content	H
									Plasticity index	M
Pervious zone (Filter)	L	H	L	H	VH	VL	VL	VL	Gradation	H
									Relative density	VH
									Percent of fine particles	L
Pervious zone (Shell)	L	H	M	H	VH	VL	VL	VL	Gradation	H
									Relative density	VH
									Percent of fine particles	L
Slope protection	L	L	VL	VL	VL	VL	VL	VL	Gradation	H
									Layer thickness	H

*US=Upstream
**DS=Downstream

Table 4: Determined overall weights' of zones and indicators based on expert judgment

Zone	Weight of zone	Quality indicator	Weight of indicator
Impervious and semi-pervious zone (clay-core)	40%	Density/Compaction	45%
		Water content	35%
		Plasticity index	20%
Pervious zone (Filter)	20%	Gradation	40%
		Relative density	50%
		Percent of fine particles	10%
Pervious zone (shell)	30%	Gradation	40%
		Relative density	50%
		Percent of fine particles	10%
Slope protection	10% (Rip-rap: 6% / Bedding Layer: 4%)	Gradation	50%
		Layer thickness	50%

6. Sensitivity Analysis

In this section, a sensitivity analysis is performed to examine the impact of changes in quality levels of each zone on the model's results. For this purpose four scenarios are introduced. In each scenario the quality level of the three zones of the dam are regarded to be constant and to be in stable condition until the project completion (the medium quality level condition is considered as the stable condition). But the fourth one varies. Table 5 summarizes the considered scenarios. For example, in the first scenario, the level of quality of the filter, shell, and riprap are assumed to be medium and will be stable until the completion of dam construction. Sensitivity analysis illustrates the influence of the core zone's quality performance variation on the project's overall quality performance. Similarly the influence of the filter, shell, and riprap zones respectively are considered in the scenarios 2 through 4. In order to perform sensitivity analysis the scores of 2, 3, 4, 5, 6, 7, 8, 9, and 10 assigned to the linguistic terms of the lowest, very low, low, relatively low, medium, relatively high, high, very high, and the highest, respectively. The results of sensitivity analysis are shown in Figure 1.

As shown in the Figure 1, the gradient of the curve related to the core zone (Sc-1) is higher than the other zones, thus the overall quality performance is more susceptible to the quality level of the core zone. Also described in Table 4 the impervious or semi-impervious zone with the weight of 40% and the pervious zone of the shell with the weight of 30% have higher weights than other zones, therefore their influence is more remarkable. As such, a two-way sensitivity analysis is performed to examine the relationship between these two parameters changing simultaneously while the quality level of the two other parameters are assumed to be at the level of very high (score of 9). The results are presented in Figure 2.

Table 5: Different scenarios for sensitivity analysis

Zones / Scenario	Core	Filter	Shell	Riprap
Sc-1	Variable	Constant	Constant	Constant
Sc-2	Constant	Variable	Constant	Constant
Sc-3	Constant	Constant	Variable	Constant
Sc-4	Constant	Constant	Constant	Variable

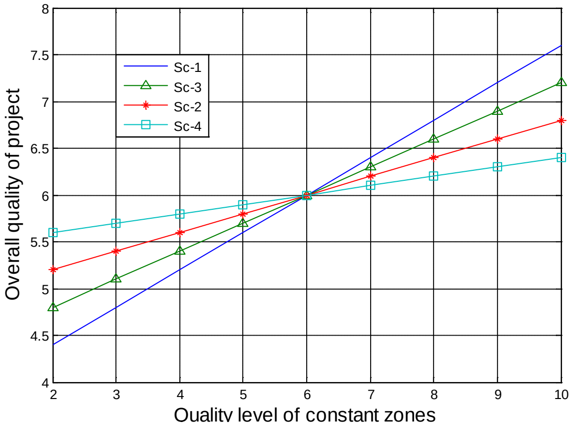

Figure 1: Sensitivity curves for medium quality condition

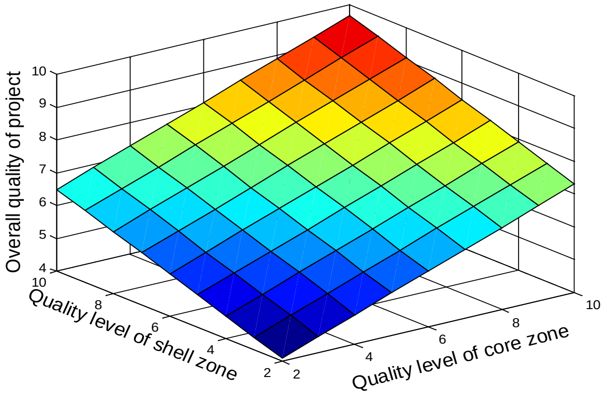

Figure 2: Two-way sensitivity analysis results

7. Application

In this section, the above developed model is applied to an example. Table 7 indicates different zones of a simple embankment dam, their obtained quality levels, and the overall quality level of the project.

Table 7: Quantifying the quality of an example by using proposed model

Zone	Weight of zone	Indicator 1		Indicator 2		Indicator 3		Quality level of zone	
		Weight	Quality level	Weight	Quality level	Weight	Quality level	Percentage	Score
Clay core	40%	45%	80%	35%	76%	20%	79%	78.4%	8
Filter	20%	40%	72%	50%	81%	10%	83%	77.6%	8
Shell	30%	40%	92%	50%	85%	10%	90%	88.3%	9
Riprap	10%	50%	68%	50%	96%	--	--	84%	9
Project's overall quality								74.21%	8

8. Conclusions

In this research a framework to evaluate the quality performance of embankment dams is introduced. Some critical quality factors related to these projects according to the nature of each element and activity are studied. The suggested method measures identified quality indicators based on quality control data.

Authors utilized a simple weighted approach function to measure the quality performance in activity level and consequently in project level which depends on determining the weights of quality indicators and the weights of activities (zones). These weights are determined based on expert judgment utilizing conference technique. By taking all above mentioned arguments into consideration, it should be noted that it is worth paying more attention to record and collect quality control data related to earth-fill and rock-fill dams. Thus it will be more feasible to estimate the quality performance of different and available recourses in scheduling phase. Moreover some significant factors according to crew formations consisting of machinery, equipment and labor are determined in this paper. Sensitivity analysis is also implemented to analyze the impact of quality performance on each element of the dam on the overall quality level of the whole project.

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