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Dynamic time-cost-quality tradeoff of rockfill dam construction based on real-time monitoring*

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Abstract: Time, cost, and quality are three key control factors in rockfill dam construction, and the tradeoff among them is important. Research has focused on the construction time-cost-quality tradeoff for the planning or design phase, built on static empirical data. However, due to its intrinsic uncertainties, rockfill dam construction is a dynamic process which requires the tradeoff to adjust dynamically to changes in construction conditions. In this study, a dynamic time-cost-quality tradeoff (DTCQT) method is proposed to balance time, cost, and quality at any stage of the construction process. A time-cost-quality tradeoff model is established that considers time cost and quality cost. Time, cost, and quality are dynamically estimated based on real-time monitoring. The analytic hierarchy process (AHP) method is applied to quantify the decision preferences among time, cost, and quality as objective weights. In addition, an improved non-dominated sorting genetic algorithm (NSGA-II) coupled with the technique for order preference by similarity to ideal solution (TOPSIS) method is used to search for the optimal compromise solution. A case study project is analyzed to demonstrate the applicability of the method, and the efficiency of the proposed optimization method is compared with that of the linear weighted sum (LWS) and NSGA-II.

Key words: Dynamic time-cost-quality tradeoff; Rockfill dam construction; Real-time monitoring; Decision preferences
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1 Introduction

A rockfill dam has been widely recognized as a relatively economical type of dam. With rapid developments in the use of water resources and hydropower construction, the construction scale of rockfill dams, which now reach heights of 300 m, has increased. Due to their large scale and construction difficulty, controlling the time, quality, and cost of the construction process is increasingly important, and the time-cost-quality tradeoff (TCQT) determines a project's overall success. However, balancing time, quality, and cost simultaneously to find an optimal construction scheme presents difficulties. First, construction time, cost, and quality are typically conflicting factors. For example, taking overall construction efficiency as a constant, a decrease in time usually means reduced quality and greater cost. Second, the rockfill dam construction process consists of many sub-activities, each having several construction options with different resource allocations and construction methods. Due to this complex combination of construction options, there are many feasible construction schemes with diverse times, costs, and quality, making the selection of a compromise scheme very difficult. Given the coexistence of necessity and difficulty, it is necessary to investigate the TCQT problem for rockfill dam construction.

Because construction quality is difficult to quantify, early research focused mainly on time-cost tradeoff problems. Kelley (1961) first proposed a

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time-cost tradeoff in a critical-path planning and scheduling problem. Hindelang and Muth (1979) proposed the discrete time-cost tradeoff problem for the first time in the context of schedule control using the critical path method. The construction process was described as a node network, where a node represented an activity and an arrow represented the precedence between activities. Each node had attributes of time and cost and could be executed in several different work modes (Akkan *et al*., 2005; Peng and Wang, 2009; Sonmez and Bettemir, 2012). Because the time-cost tradeoff problem has proved to be an NP-hard problem (De *et al*., 1997), using exact algorithms such as linear programming, integer programming, and dynamic programming to solve it is relatively difficult and time-consuming (Moselhi and El-Rayes, 1993; Burns *et al*., 1996; Senouci and Eldin, 1996; Gomar *et al*., 2002). To improve the efficiency of finding solutions, researchers have investigated heuristic algorithms (Vanhoucke *et al*., 2007) and meta-heuristics (Azaron *et al*., 2005; Peng and Wang, 2009; Yang, 2011). Because construction quality has become increasingly important for the overall success of projects, recent studies have taken the quality objective into consideration, resulting in the TCQT problem. Recent studies of the TCQT problem can be grouped into three categories. Studies in the first category focused on effectively quantifying the construction quality. El-Rayes and Kandil (2005) transformed the traditional 2D time-cost tradeoff analysis into a 3D TCQT analysis and developed a multi-objective genetic algorithm to implement the optimization. Mungle *et al.* (2013) presented the analytic hierarchy process (AHP) approach to evaluate the quality of construction activity, and proposed a fuzzy clustering-based genetic algorithm to solve the TCQT problem. Zhang *et al.* (2014) built a quality model, the quality performance index, to describe system reliability and solved the TCQT using an immune genetic particle swarm optimization algorithm, which combined an immune genetic algorithm with particle swarm optimization. The second category contains studies that attempted to improve the efficiency and effectiveness of the TCQT solution algorithm. Tavana *et al.* (2014) developed a multi-objective multi-mode project TCQT model under preemption and the generalized precedence relations of activities and proved its relative superiority over the ε-constraint method. Afruzi *et al.* (2014) presented a multi-objective imperialist competitive algorithm to solve the discrete TCQT problem and evaluated it by comparison with non-dominated sorting genetic algorithm (NSGA-II), Pareto envelope-based selection algorithm-clustering (PESAII-clustering), envelope-based selection algorithm-grid based (PESAII-grid based), and strength Pareto evolutionary algorithm (SPEA2). Tran *et al.* (2015) integrated crossover operations from differential evolution with the original artificial bee colony and compared it with the NSGA-II, multiple objective particle swarm optimization (MOPSO), multiple objective differential evolution (MODE), and multiple objective artificial bee colony (MOABC) when applied to a certain TCQT problem. Studies in the third category attempted to assign weights or preferences among time, cost, and quality in the TCQT problem to search for an optimal solution. Heravi and Faeghi (2014) applied a fuzzy simple additive weighting system to describe construction quality and employed a group decision-making method to aggregate the preferences of individual decision-makers when solving the TCQT problem. Monghasemi *et al.* (2015) gave time, cost, and quality relative weights using Shannon (1948)'s entropy technique. They incorporated a multi-objective genetic algorithm based on the NSGA-II procedure with an evidential reasoning approach to identify the best Pareto solution, which can assist project managers in the planning phase of construction projects.

Although many efforts have been made to solve the TCQT problem, previous research investigated only the TCQT problem of the planning or design phase. In the planning or design phase, time, cost, and quality are estimated using empirical data from similar projects. However, every project has its own characteristics due to different construction organization conditions, which may cause estimations to deviate from real circumstances. In addition, although the construction process, especially for a long-term project such as a rockfill dam, is a dynamic procedure accompanied by randomness and uncertainty, the TCQT of the planning or design phase is built on the hypothesis that the construction process is static and the parameters used for estimation are constant. Under such conditions, even if a planning or design phase TCQT is consistent with real conditions for a time, it will lose its guiding applicability to construction management as the construction process advances and varies. In addition, most research on TCQT problems regard time, cost, and quality as equally important, which is typically uncommon in rockfill dam construction. For example, quality control outweighs time control at the beginning stage of construction because construction personnel are unfamiliar with operations and need run-in time. However, when the flood season approaches, accelerating the construction process to achieve a certain dam height becomes more important. There are distinct decision preferences at different stages of rockfill dam construction, which need to be considered dynamically by the optimization algorithm for the TCQT problem. Furthermore, most research on the TCQT problem has provided solution sets, not optimal construction schemes for the TCQT problem, which are inconveniently implemented in field construction management. These shortcomings of previous studies have created a need for a method that can dynamically balance time, cost, and quality according to real-time construction conditions.

To achieve dynamic time-cost-quality tradeoff (DTCQT), it is necessary to estimate time, quality, and cost, and optimize them with the support of real construction information from previous stages. Traditionally, it is difficult to collect construction information continuously and precisely, but with the development of real-time monitoring (RTM) technology, an innovative way to control construction process quality, it can be achieved. Real-time monitoring is an integrated technology that adopts global positioning system (GPS), ultra-wideband (UWB), radio frequency identification (RFID) or other sensor technologies to track construction equipment in real time and analyze the collected tracking data, aiding construction quality or safety control (Hildreth *et al.*, 2005; Giretti *et al.*, 2009; Zhong *et al.*, 2009; Montaser and Moselhi, 2012; Liu *et al.*, 2016). Because the monitoring data precisely record the past construction process, they can provide practical construction information for the DTCQT.

This paper focuses on dynamically solving the DTCQT problem for rockfill dam construction, to assist project managers with decision-making at any stage during the construction process. The following objectives were pursued: (1) to estimate time, cost, and quality dynamically based on information from previous construction stages instead of using subjective estimation in the planning or design phase; (2) to measure project managers' decision preferences flexibly among the time, cost, and quality of future construction stages; (3) to form an optimal construction scheme for field construction management.

In this paper, a DTCQT optimization methodology for rockfill dam construction is proposed. First, based on real-time monitoring, the time, cost, and quality of different construction options are dynamically calculated and combined to form construction schemes. Real-time monitoring technology for rockfill dam construction is applied to collect construction data that are used to extract construction parameters that reflect the construction process. The construction schedule is obtained using a dynamic rockfill dam construction simulation system, which applies construction parameters to update the simulation model. With previous construction quality information accessible by real-time monitoring, a model that relates activity quality and time is established. The influences of time and quality on cost are considered in the cost model, which includes incentive, penalty, and quality costs in addition to direct and indirect costs. Second, a decision preference analysis method is proposed based on the AHP method, which can dynamically quantify decision preferences among time, cost, and quality and assign them objective weights prior to the optimization process. Third, an improved NSGA-II is presented to obtain the Pareto solution set of the DTCQT problem, which considers objective weights during the optimization. Fourth, the technique of order preference by similarity to ideal solution (TOPSIS) is applied to search for the best compromise solution from the Pareto solution set. A flow chart of the proposed methodology is shown in Fig. 1.

2 Mathematical model

The mathematical model defines the rockfill dam construction DTCQT (Fig. 2). The model has three objective functions that are designed to minimize time and cost and to maximize quality. Eq. (1) defines the time objective, which sums the durations of all the activities in the critical path of the project network to obtain the whole project time. Eq. (2)

defines the cost objective, which includes the direct and indirect time and quality costs of all the activities when calculating the project cost. The time costs contain an incentive cost for early completion of the project and a penalty cost for late completion. Eq. (3) defines the quality objective, which estimates the overall quality of the project depending on $Q_{\min}$ (minimum quality of all selected activity alternatives), Q_{avg} (average quality of all selected alternatives for the project), and α (weight between $Q_{\min}$ and Q_{avg}). A higher value of α means a greater desire to ensure that no individual activity has a quality that is too low, whereas a lower value refers to greater attention to the overall average quality of all activities. Eq. (4) presents the definition of the quality cost, which consists of prevention, appraisal, and failure costs. The prevention cost contains the expenses of the quality tests and inspections conducted

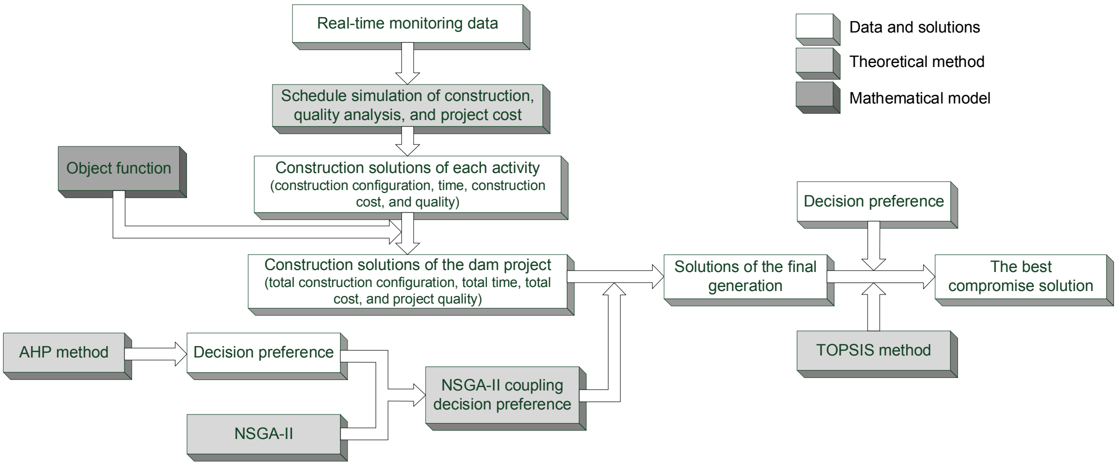
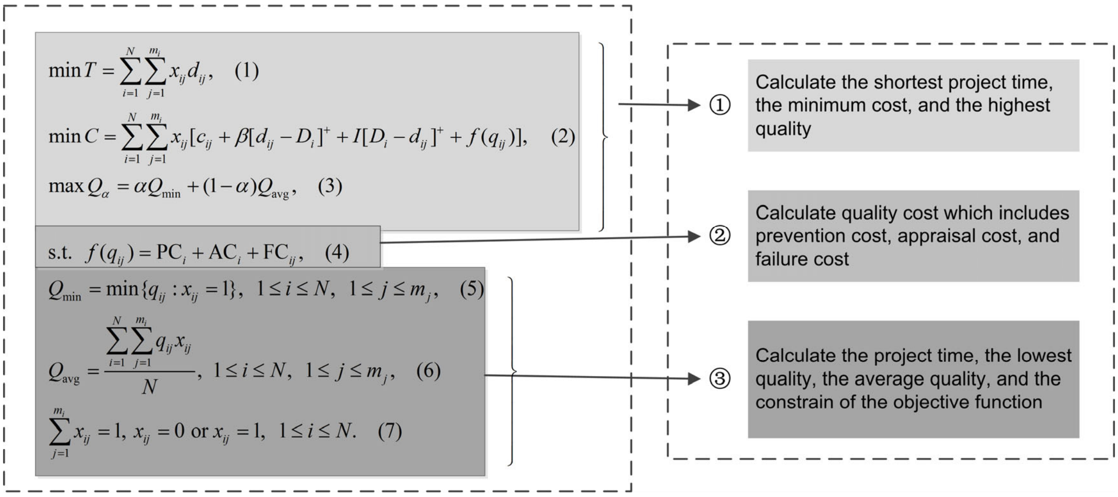


Fig. 1 Flowchart of the DTCQT for rockfill dam construction



$$\min T=\sum_{i=1}^{N}\sum_{j=1}^{m_i}x_{ij}d_{ij},\quad (1)$$

$$\min C=\sum_{i=1}^{N}\sum_{j=1}^{m_i}x_{ij}[c_{ij}+\beta[d_{ij}-D_i]^{+}+I[D_i-d_{ij}]^{+}+f(q_{ij})],\quad (2)$$

$$\max Q_{\alpha}=\alpha Q_{\min}+(1-\alpha)Q_{\text{avg}},\quad (3)$$

$$\text{s.t.}\quad f(q_{ij})=\text{PC}_i+\text{AC}_i+\text{FC}_{ij},\quad (4)$$

$$Q_{\min}=\min\{q_{ij}:x_{ij}=1\},\ 1\le i\le N,\ 1\le j\le m_j,\quad (5)$$

$$Q_{\text{avg}}=\frac{\sum_{i=1}^{N}\sum_{j=1}^{m_i}q_{ij}x_{ij}}{N},\ 1\le i\le N,\ 1\le j\le m_j,\quad (6)$$

$$\sum_{j=1}^{m_i}x_{ij}=1,\ x_{ij}=0\ \text{or}\ x_{ij}=1,\ 1\le i\le N.\quad (7)$$

Fig. 2 Mathematical model of the rockfill dam construction DTCQT

T: total duration of the project, d; C: total cost of the project, CNY; D: due-date of the project, d; N: total number of activities in the project; d_{ij}: duration for option j of activity i, for i=1, 2, …, N, j=1, 2, …, m_i, d; x_{ij}: index variable. If x_{ij}=1, activity i performs the jth option; if x_{ij}=0, activity i does not perform the jth option; c_{ij}: construction cost for the option j of activity i, including direct cost and indirect cost; m_i: number of options for activity i; β: penalty cost for tardiness of the project, CNY/d; I: incentive cost for earliness of the project, CNY/d; $f(q_{ij})$: quality cost for option j of activity i, CNY; Q_{α}: project quality, %; α: relative importance of $Q_{\min}$ and Q_{avg}; $Q_{\min}$: minimum quality of all options selected for all activities in the project, %; Q_{avg}: average quality of all options selected for all activities in the project, %; q_{ij}: quality for option j of activity i, %; PC_i, prevention cost for activity i, CNY; AC_i, appraisal cost for activity i, CNY; FC_{ij}, failure cost for option j of activity i, CNY to prevent or reduce quality related accidents. In a rockfill dam project, for example, the cost of a productive rolling experiment and the cost of purchasing, operating, and maintaining an RTM system are components of the prevention cost. The appraisal cost is the cost of evaluating whether the finished products meet the quality standards and performance requirements, and includes field test expenses, maintenance expenses and depreciation of test equipment. The failure cost refers to the loss resulting from quality related problems, and has a direct relationship with quality. Eq. (5) indicates that $Q_{\min}$ is the minimum quality for all selected activities. The average quality for all the selected activities is calculated using Eq. (6). Eq. (7) guarantees that only one machinery allocation is selected for each activity in the project.

In the above model, the time, cost, and quality of each activity still need to be quantified. Every time a DTCQT is conducted, the three decision variables are re-estimated to replace the previous model estimates. This makes the tradeoff more practical.

3 Proposed methodology

3.1 Construction quality real-time monitoring technology

The construction quality of a rockfill dam is directly related to the safety of the hydropower station and the downstream area, so the construction process should meet high quality control standards. However, conventional on-site supervision quality control methods are subject to human factor interference, which makes it difficult to achieve fine process control. Researchers at Tianjin University have conducted several studies of construction quality real-time monitoring technology (CQRMT), and successfully applied it to several rockfill dam projects in China (Zhong *et al*., 2009; 2011; Liu *et al*., 2012). CQRMT can ensure that dam construction quality is always in a real controlled state by realizing all-weather, fine and on-line monitoring of the dam construction process. In accordance with the two key links of rockfill dam construction, the major components of CQRMT for a rockfill dam are materials transportation monitoring technology and dam compaction monitoring technology. A flow diagram of CQRMT is shown in Fig. 3.

Because there are several different kinds of materials and complex roads and loading/unloading site combinations during rockfill dam construction, avoiding unloading in the wrong place is important. Materials transportation monitoring technology takes trucks as objects, and monitors the position of a truck in the whole process from the material source sites to the dam surface, and the status of loading and unloading. A GPS terminal is installed on each truck to collect the position data including latitude and longitude coordinates, altitude, and velocity. An unloading status monitoring unit (USMU) is used to identify the unloading status. A data transfer unit then transfers the collected data to the server in the control station through a general packet radio service (GPRS) network. The frequency of the above data

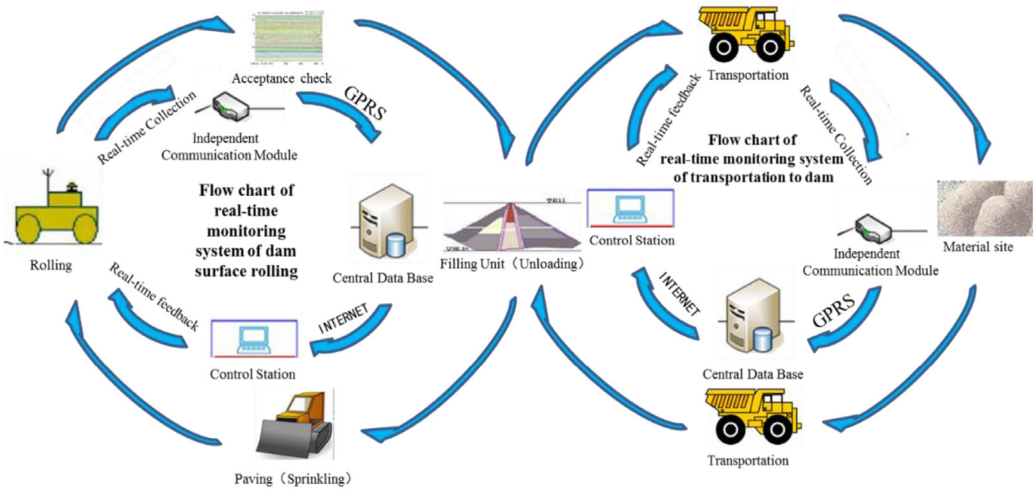


Fig. 3 Flow diagram of the CQRMT and dam construction

collection and transmission is 30 Hz. The server analyzes the operation status of the truck, and visualizes it on a digital map. When detecting unloading at an unplanned site, it will automatically send alarm information to the site personnel through a personal digital assistant (PDA).

Dam compaction monitoring technology aims to track real-time controlling compaction quality by monitoring compaction parameters including rolling speed, number of compaction passes, vibration status, and compaction thickness. When compaction parameters do not meet pre-set quality criteria, alarm information will be automatically sent to the site personnel to adjust the construction. When a construction unit is finished, graphical reports for compaction quality are provided to serve as supporting files for quality assessment. To achieve the above function, the positioning data and the vibration status data of roller compactors are collected first. Applying GPS and global navigation satellite system (GLONASS) technology, every roller compactor is installed with a satellite position receiver which collects positioning data including latitude and longitude coordinates, altitude, and velocity. The real-time kinematic (RTK) technique is also used to improve the positioning accuracy level to the order of centimeters. The vibration status data are collected by a vibration status monitoring unit (VSMU). The VSMU is connected to the vibration module of a roller compactor which automatically judges the vibration status by a high or low voltage signal. Each roller compactor is equipped with a data transfer unit (DTU). The DTU transfers the collected positioning and vibration status data to the center server through the GPRS network. The frequency of the above data collection and transmission is 1 Hz. The server calculates and analyzes compaction parameters in real-time based on collected data and visualizes the information on a client program.

The technology for dynamically collecting and displaying construction information through the PDA is also a component of the real-time monitoring technology. Material transportation and dam compaction process information can be visualized on a PDA which links to the server and the database through the GPRS network. This on-site real-time construction information display can effectively help process quality control. Field quality inspection experiment indexes including dry density and water content are uploaded to the database by the PDA through the GPRS network.

The CQRMT for a rockfill dam not only realizes process quality control, but also records massive amounts of actual construction information, which provides the data foundation for dynamic time, quality, and cost estimation.

3.2 Dynamic decision variables estimation

As mentioned earlier, the DTCQT is based on dynamically updated time, cost, and quality information using real-time monitoring data. For the first stage, due to the lack of monitoring data, the construction time, cost, and quality of a rockfill dam are estimated from empirical speculations extracted from similar projects. After a period of construction, the real-time monitoring system can gather considerable construction process data that contain information about the construction activities that have just ended. Construction parameters that are used to refine the initial simulation model can be inferred from those data. The refined simulation model is then implemented to forecast the time of the subsequent stage dynamically. With the time accessible, the cost and quality can also be dynamically estimated. The above dynamic estimation can be executed at any activity node of the TCQT problem network, making the tradeoff more convenient and suitable for construction management. The implementation process for the dynamic time, cost, and quality analysis is shown in Fig. 4.

3.2.1 Time estimation

Each stage of a rockfill dam project has multiple options with different machinery allocations. Given a machinery allocation, the duration of the stage can be determined by applying a rockfill dam construction schedule simulation system (RDC3S) based on real-time monitoring technology. The system researched by Tianjin University, China has been used in several projects that are under construction or have been completed, and the reliability and effectiveness of the system have been verified (Zhong *et al.*, 2007; Zhang, 2010).

A rockfill dam construction system can be divided into two interrelated parts: transportation subsystems and dam surface filling subsystems. A flow

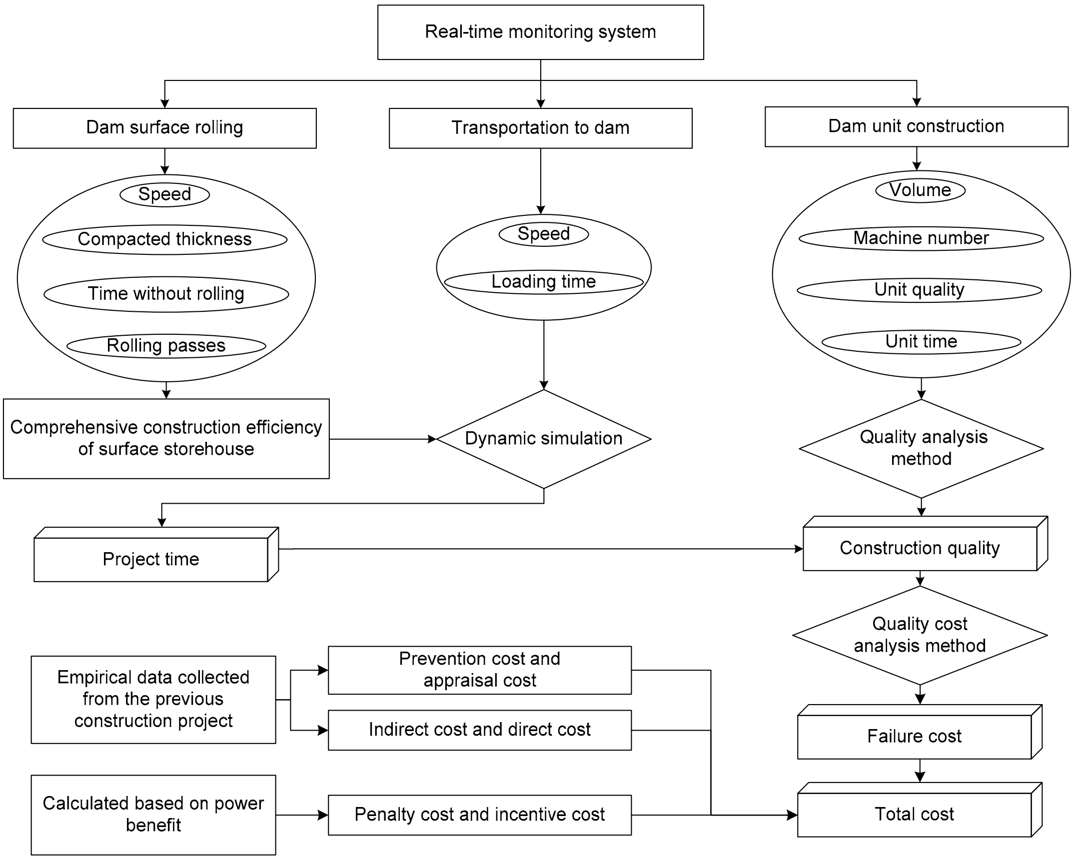


Fig. 4 Flowchart of dynamic time, quality, and cost estimation

diagram of dam construction is shown in Fig. 3. RDC3S conducts the whole process simulation on dam construction considering the contact mechanism between the two subsystems. It applies the discrete system simulation method to build a circular network model of the construction objects. In this model, the roller compactors are the control objects for the rolling process and the trucks are the control objects for the transportation process. Because there are always construction uncertainties in rockfill dam construction and their effects on future construction cannot be accurately predicted, the actual construction process may deviate from the pre-developed construction plan. To develop a reasonable construction plan for the next stage, construction uncertainties are considered in the simulation model. The uncertainty factors include loading time, speed of a loaded truck, speed of an empty truck, comprehensive construction efficiency of the dam surface, and effective working days per month. These factors are set as model input parameters and quantified using probability distributions. With this system, the construction schedule under a certain machinery allocation can be simulated. Based on the analysis of real-time monitoring data, construction parameters of an activity that has just finished are employed to update the probability distributions of simulation input parameters dynamically, making schedule simulation more consistent with real field construction.

3.2.2 Quality estimation

It is difficult to quantify the construction quality of a rockfill dam because there are numerous factors that influence the quality. The major focus of this paper is to establish the DTCQT method, and only the influence of time is therefore considered here. Related studies have shown that there is a non-linear relationship between construction quality and time (Zhang *et al.*, 2014). A quadratic function was used to describe the relation between them. This means that if the duration of an activity is shorter than a normal level, the quality will deteriorate, and the shorter the duration, the faster will be the deterioration. In rockfill dam construction, the quality will decrease as the workload on the unit roller compactor increases. However, with the application of real-time monitoring technology in rockfill dam projects, the construction quality is under strict control and will not decline as sharply as before, even for greater workloads (Zhong and Zhang, 2009). Therefore, by estimating and quantifying the activity quality of a given machinery allocation based on duration, and assuming that the relation curve between activity duration and quality is elliptical (the first quadrant), the improved formula of activity quality is

$$q_{ij} = \sqrt{a - b(V_i / (d_{ij} n_{ij}) - c)^2} - d, \tag{8}$$

where q_{ij} is the quality for option j of activity i, d_{ij} is the duration for option j of activity i, V_i is the earth volume of activity i, and n_{ij} is the number of the roller compactors for option j of activity i. a, b, c, and d are coefficients to be calculated.

For rockfill dam construction, compaction quality is the most important quality index, and is commonly quantified as compactness or dry density (Liu *et al.*, 2014). By adopting CQRMT, each time a construction unit is finished, its compaction quality index is uploaded using a PDA. Integrating the quality index with volume, time, and roller compactor number, the model can be constantly fitted. Here, only the compaction quality is considered in the quality model to demonstrate the effectiveness of the method.

3.2.3 Cost estimation

Previous research on rockfill dam construction costs considered only the cost element, neglecting the great influence of quality and time on cost. Indeed, quality and time greatly affect the economic benefit to the owner, especially the cost of maintenance based on the quality level in the operating period, which may account for a large proportion of the investment. Recent studies on the quality costs of construction projects have presented linear or non-linear relationships between quality and cost, but few studies have considered the cost of failure occurring in the operating period caused by the level of construction quality (Radziwill, 2006; Schiffauerova and Thomson, 2006; Khataie and Bulgak, 2013; Heravi and Jafari, 2014; Khaled Omar and Murgan, 2014).

The calculation of quality cost focuses on a quantitative analysis of the failure cost because prevention and appraisal costs account for a relatively stable proportion (γ) of total project investment, both of which can be acquired by analyzing relevant data from similar past projects. Combined with engineering experience, we can see that the failure cost of a project will decline gradually as quality improves. Juran (1998) proposed the traditional model of quality cost and described an approximation between failure cost and quality, and Taguchi (1986) proposed a quadratic relationship. Given that the construction quality in an actual project must be at an acceptable level and moves up and down only over a limited range under the strict control of RTMS, only the quantitative relationship between failure cost and quality over a small range at a high quality level need be considered. Therefore, this paper assumes that there is a linear relation between them, *viz.* the highest quality $q_{i\max}$ corresponds to the lowest failure cost W_1, and the lowest quality $q_{i\min}$ corresponds to the highest failure cost W_2. These values were determined by adopting expert evaluation methods. The failure cost formula is

$$\begin{aligned} \mathrm{FC}_{ij} &= \frac{q_{i\max} - q_{ij}}{q_{i\max} - q_{i\min}}(W_2 - W_1) + W_1, \\ k &= \frac{q_{i\max} - q_{ij}}{q_{i\max} - q_{i\min}}. \end{aligned} \tag{9}$$

According to Eq. (4), the quality cost for option j of activity i is obtained by

$$f(q_{ij}) = \gamma W + k(W_2 - W_1) + W_1, \tag{10}$$

where W is the total project investment.

3.3 Measurement of decision preferences

Due to the periodic variance in objective control during rockfill dam construction, it is crucial to consider decision preferences dynamically when solving a TCQT problem. The AHP method proposed by Saaty (1990) is a multi-criteria decision-making approach and is widely used in weight measurement. The AHP method divides the overall system into several subsystems to form a hierarchical structure, and the elements of each hierarchy are compared pairwise to signify the comparative weight. Here, the AHP method is applied to measure decision preferences by determining the comparative weights among time, cost, and quality.

First, a hierarchical structure is defined (Fig. 5). In this paper, the main goal is to achieve an optimal construction process, and the alternatives are time, cost, and quality control. During the rockfill dam construction process, there are several criteria that affect construction time, cost, and quality control. These criteria generally can be divided into three categories according to their effects. The first category, which emphasizes time control, includes criteria such as flood prevention and electricity generation requirements. The criteria in the second category focus on construction quality, including adaption period construction and rainy season construction. The third category gives more attention to cost control, and contains criteria such as construction method improvement. Due to the periodic characteristic of rockfill dam construction, only some of the criteria are listed in Fig. 5. Therefore, further consideration by project managers is required when conducting the DTCQT.

Second, a 1–9 preference scale proposed by Saaty (1990) is used to quantify the relative weights when making pairwise comparisons between the elements in the same hierarchy.

Third, the relative weights of alternatives being compared are derived by calculating the principal eigenvalue and the corresponding normalized eigenvector of the pairwise comparison matrices.

Fourth, a consistency index (CI) and a consistency ratio (CR) are calculated to test the consistency of each pairwise matrix. CI and CR are defined by

$$\mathrm{CI}=\frac{\lambda_{\max}-1}{n-1}, \tag{11}$$

$$\mathrm{CR}=\frac{\mathrm{CI}}{\mathrm{RI}}, \tag{12}$$

where $\lambda_{\max}$ is the largest eigenvalue of the matrixes, and n is the order of the matrix. RI (random index) represents the average consistency index over numerous random entries of same order matrices.

If CR≤0.1, the weight estimate is accepted; otherwise, a new comparison matrix is solicited until CR≤0.1.

3.4 Optimization algorithm

3.4.1 Improved NSGA-II for locating Pareto-optimal solutions

The non-dominated sorting genetic algorithm (NSGA) proposed by Srinivas and Deb (1994) is a multi-objective optimization method for locating Pareto-optimal solutions with features of simplicity, effectiveness, and minimum user interaction. Deb *et al*. (2002) further introduced NSGA-II, which adopts an elite strategy, reduces computational complexity, and does not require a sharing parameter to be chosen

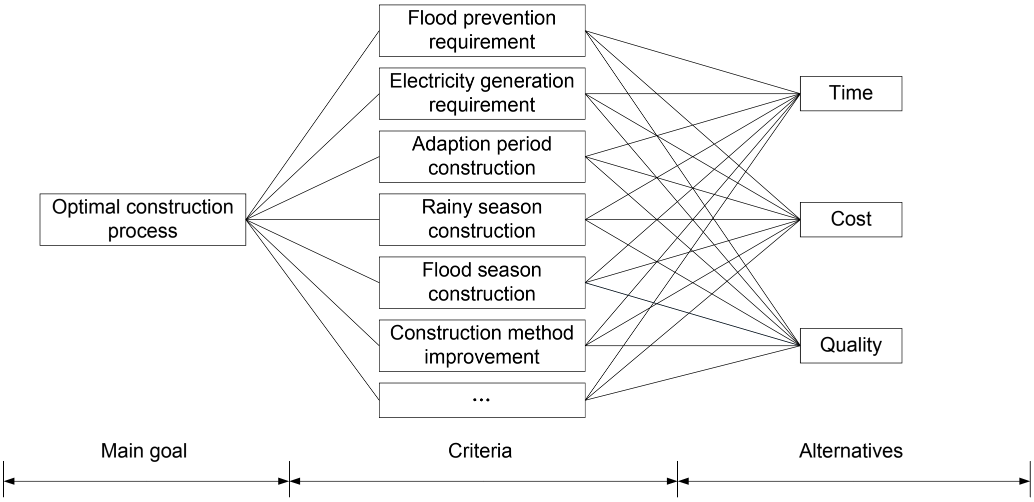


Fig. 5 Hierarchical structure of the AHP method

a priori. NSGA and NSGA-II have been applied in several studies, and their ability to solve multi-objective optimization problems has been demonstrated (Jin *et al.*, 2008; Fallah-Mehdipour *et al.*, 2012; Cheng *et al.*, 2014; 2015). The main operators of NSGA-II include fitness evaluation, non-dominated sort and rank, selection, crossover and mutation, and crowding distance calculation. The flow of the improved NSGA-II is shown in Fig. 6.

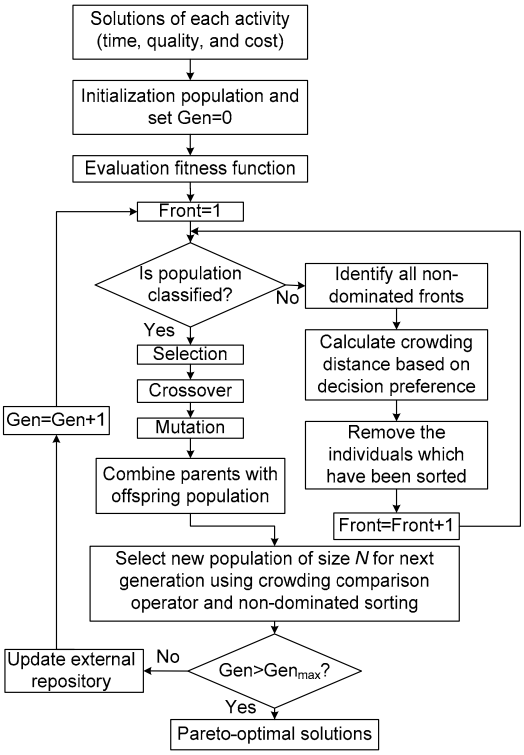


Fig. 6 Flowchart of the improved NSGA-II
Gen: evolutional generation; Front: non-dominated sorting

However, both NSGA and NSGA-II neglect the decision preferences among optimization objectives under a specific project background. There are many uncertainties when constructing rockfill dams, and managers must adopt specific objective control strategies under different circumstances, which requires decision preferences. Considering such preferences in a real construction process, we have improved NSGA-II by introducing objective weights into the crowding distance (CD) calculation step.

CD, which means the density of solutions surrounding a particular solution in the population, is typically measured by the average distance of two points on either side of that point along each of the objectives. The CD computation requires sorting the population according to each objective function value in ascending order of magnitude. For each objective function, the boundary solutions (solutions with the smallest and largest function values) are assigned an infinite distance value. All other intermediate solutions are assigned a distance value equal to the absolute normalized difference in the function values of two adjacent solutions. The overall CD value is calculated as the sum of individual distance values corresponding to each objective.

The overall CD is used as an attribute that determines the priority between solutions. If two solutions belong to the same Pareto front, then the solution with the larger overall CD value is preferred for selection into the next generation. A larger CD value can avoid solutions from crowded regions, which helps maintain population diversity. However, when calculating the overall CD, the individual CD of each objective is given the same weight. This may cause a solution with a smaller individual CD value of the main objective to be selected due to the effects of secondary objectives. Given decision preferences among objectives in rockfill dam construction, to ensure that the solution with a larger main objective individual CD has more opportunities to be selected, we propose the weighted crowding distance (WCD) method. The WCD is obtained by assigning objective weights to the corresponding individual CDs when calculating the overall CD. Eq. (13) shows the calculation of WCD.

$$D[i]=\sum_{j=1}^{N_{\mathrm{obj}}}\frac{w_j(f_{i+1}^{m}-f_{i-1}^{m})}{f_M^{\max}-f_M^{\min}}, \tag{13}$$

where $D[i]$ is the WCD of the ith solution; N_{obj} is the number of the objectives; w_j is the weight of the jth objective; f_{i+1}^{m}, f_{i-1}^{m} are the (i+1)th and the (i−1)th fitness values of the jth objective, respectively; $f_M^{\max}$, $f_M^{\min}$ are the maximum and minimum fitness values of the jth objective in population, respectively.

3.4.2 TOPSIS for searching for an optimal compromised solution

After multi-objective optimization using the improved NSGA-II, a set of Pareto-optimal solutions of the TCQT problem are obtained. However, rockfill dam project managers still need an optimal construction scheme. TOPSIS, proposed by Hwang and Yoon (1981), is used to rank the Pareto solutions obtained by NSGA-II and to obtain the optimal compromise solution. Two basic concepts are defined based on the decision preferences in TOPSIS: the positive ideal solution (S^+) and the negative ideal solution (S^-). The Pareto solution, which is the closest to S^+ and the farthest from S^-, is determined as the best compromise solution. The TOPSIS process for determining the best compromise solution is now briefly presented. A flowchart of the TOPSIS method is shown in Fig. 7.

4 Case study

The real-life rockfill dam presented in this paper is the LY dam located in eastern China. An example with eight sequential activities is used. The dam is 295 m tall, and the planned construction time was 29 months. Considering the periodic construction characteristics and the convenience of construction organization, the dam construction process was divided into eight stages, *viz.* the eight main activities. The elevations and filling volumes for each stage are shown in Fig. 8. To achieve a DTCQT based on real-time monitoring, it is necessary to extract construction parameters from the monitoring data. This task is a prerequisite for dynamic decision variable estimation. In addition, decision preferences need to be measured again when conducting the TCQT for future construction. Once a DTCQT is conducted, the decision variables and decision preferences are updated. Because the update process and subsequent optimization process are similar at each time, only the DTCQT at the end of the first activity is discussed here to demonstrate the applicability and effectiveness of the proposed method.

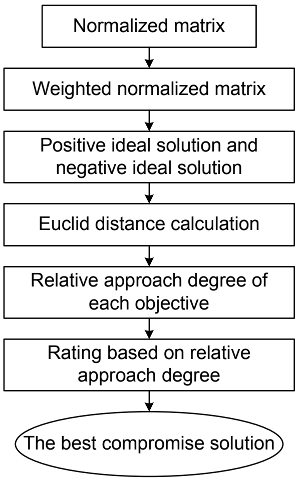


Fig. 7 Flowchart of the TOPSIS method

4.1 Time, cost, and quality estimation

After the first stage of dam construction was completed, the construction parameters were extracted using the real-time monitoring data collected by CQRMT (Table 1).

The RDC3S simulation model was updated by replacing the initial simulation parameters with the construction parameters of the first activity. Applying the updated RDC3S, the machinery allocations and construction times for subsequent activities were obtained. This process is summarized in Fig. 9.

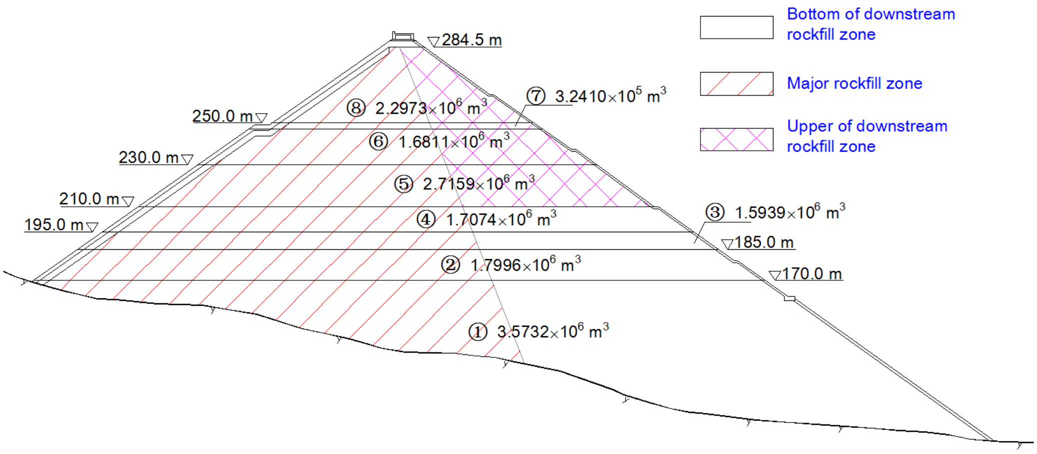
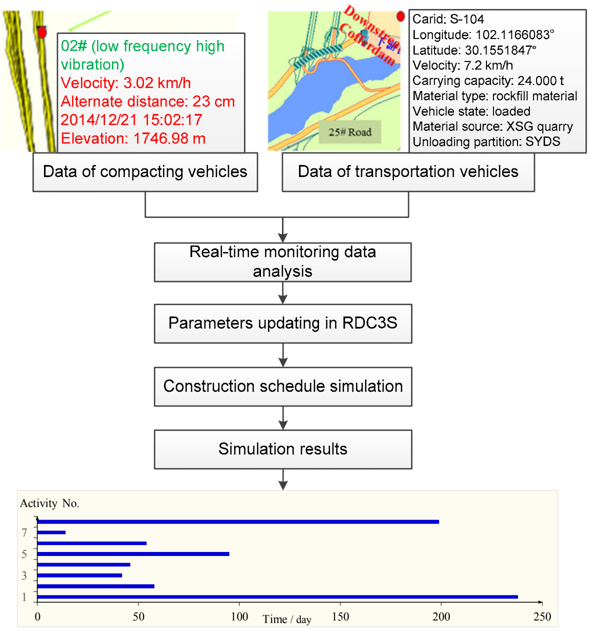


Fig. 8 Eight stages of the LY dam

Table 1 Construction parameters for the first activity

No.	Parameter	Value
1	Loading time (min)	3
2	Speed of loaded truck (km/h)	20
3	Speed of empty truck (km/h)	30
4	Hours worked per machine-team (h)	10
5	Number of machine-teams per day	2
6	Dump truck capacity (t)	40
7	Comprehensive construction efficiency of the surface storehouse (m^3/h)	520


02# (low frequency high vibration)
Velocity: 3.02 km/h
Alternate distance: 23 cm
2014/12/21 15:02:17
Elevation: 1746.98 m

Carid: S-104
Longitude: 102.1166083°
Latitude: 30.1551847°
Velocity: 7.2 km/h
Carrying capacity: 24.000 t
Material type: rockfill material
Vehicle state: loaded
Material source: XSG quarry
Unloading partition: SYDS

Fig. 9 Realization of dynamic time estimation
The top two pictures represent the visualized real-time information for the roller compactor and the truck in the RTMS

To dynamically estimate the quality, the four unknown coefficients of the activity quality function (shown in Eq. (10)) should be determined first. Given all the dam unit construction information for stage one, the data fitting method in SPSS 19.0 was used to determine the activity quality model. The relative importance of $Q_{\min}$ and Q_{avg} was set to 0.75, which means that we focused more on the minimum quality.

The indirect cost was 3400 CNY/d. The set duration for this example was taken as 630 d. The incentive cost and tardiness penalty were determined based on the benefits of the operating period during which the energy output of the hydropower station was 2×10^9 kW·h. This resulted in an incentive cost of 15000 CNY/d and a tardiness penalty of 18000 CNY/d.

After updating, the time, quality, and cost for each option were obtained (Tables 2 and 3). The machinery allocations for the first activity were (24, 4, 1, 1, 1, 5, 1), and the time, quality, and cost of the first activity were 238 d, 90%, and 3.1811×10^7 CNY, respectively.

4.2 Objective weights calculation

Before conducting the tradeoff, objective weights among time, cost, and quality should be obtained according to the managers' decision preferences for future construction stages. Here, a flood prevention requirement, construction method improvement, and rainy season construction were taken as criteria B_1, B_2, and B_3, respectively. In addition, the alternatives C_1, C_2, and C_3 correspond to cost, quality, and time, respectively. The pairwise comparison matrices for each hierarchy are

$$\boldsymbol{A}_B=\begin{bmatrix}1 & 1/9 & 1/5\\ 9 & 1 & 3\\ 5 & 1/3 & 1\end{bmatrix},\quad \boldsymbol{B}_{1C}=\begin{bmatrix}1 & 1/3 & 1/6\\ 3 & 1 & 1/2\\ 6 & 2 & 1\end{bmatrix},$$

$$\boldsymbol{B}_{2C}=\begin{bmatrix}1 & 7 & 3\\ 1/7 & 1 & 1/3\\ 1/3 & 3 & 1\end{bmatrix},\quad \boldsymbol{B}_{3C}=\begin{bmatrix}1 & 3 & 3\\ 1/3 & 1 & 1\\ 1/3 & 1 & 1\end{bmatrix},$$

where $\boldsymbol{A}_B$ is the pairwise matrix to decide the relative weights among B_1, B_2, and B_3 under the main goal A (to obtain optimal construction process); $\boldsymbol{B}_{1C}$, $\boldsymbol{B}_{2C}$, and $\boldsymbol{B}_{3C}$ are the pairwise matrices to decide the relative weights among C_1, C_2, and C_3 under B_1, B_2, and B_3, respectively.

According to the AHP method discussed above, the CRs of all the matrices satisfy CR≤0.1, including the overall CR of 0.003. The cost, quality, and time weights were 0.60, 0.15, and 0.25, respectively.

4.3 Solution optimization

In this work, the initial parameter settings of the modified algorithm, such as the exploitation or exploration rates of the search space, had a significant impact on finding a solution. As a result, it was necessary to perform a trial and error experiment to find suitable values for the initial parameters. The final parameters are shown in Table 4.

Table 2 Machinery allocations for each activity (Ac)

Ac	Allocation option				
	Option 1	Option 2	Option 3	Option 4	Option 5
2	(52, 6, 1, 1, 13, 1)	(60, 7, 1, 1, 14, 1)	(50, 6, 1, 1, 14, 1)	(44, 5, 1, 1, 13, 1)	(38, 6, 1, 1, 13, 1)
3	(52, 5, 1, 1, 17, 1)	(60, 6, 1, 1, 17, 1)	(76, 6, 1, 1, 20, 1)	(68, 6, 1, 1, 18, 1)	(72, 6, 1, 1, 19, 1)
4	(59, 6, 1, 1, 18, 1)	(83, 7, 1, 1, 21, 1)	(67, 7, 1, 1, 18, 1)	(75, 7, 1, 1, 19, 1)	(79, 7, 1, 1, 20, 1)
5	(44, 5, 1, 1, 13, 1)	(52, 6, 1, 1, 13, 1)	(61, 6, 1, 1, 15, 1)	(56, 6, 1, 1, 14, 1)	(39, 5, 1, 1, 12, 1)
6	(59, 5, 1, 1, 16, 1)	(46, 5, 1, 1, 15, 1)	(54, 5, 1, 1, 16, 1)	(50, 5, 1, 1, 15, 1)	(65, 6, 1, 1, 16, 1)
7	(39, 4, 1, 1, 10, 1)	(50, 5, 1, 1, 11, 1)	(31, 4, 1, 1, 9, 1)	(28, 3, 1, 1, 8, 1)	(35, 4, 1, 1, 9, 1)
8	(35, 5, 1, 1, 6, 1)	(28, 5, 1, 1, 6, 1)	(24, 4, 1, 1, 5, 1)	(40, 5, 1, 1, 7, 1)	(32, 4, 1, 1, 6, 1)

Note: The letters from $(n_1, n_2, n_3, n_4, n_5, n_6)$ represent the number of trucks, roller compactors, sprinklers, excavators, loaders, and bulldozers, respectively

Table 3 Activity options of the construction period

Ac	Option 1			Option 2			Option 3			Option 4			Option 5		
	t	cc	*q*	*t*	cc	*q*	*t*	cc	*q*	*t*	cc	*q*	*t*	cc	*q*
2	66	1.553169	79	57	1.551111	77	69	1.554377	87	79	1.556625	90	100	1.564193	95
3	64	1.381301	94	57	1.379910	90	43	1.375684	76	47	1.376199	80	45	1.375984	78
4	68	1.483730	96	47	1.477781	84	61	1.482233	90	51	1.478278	87	49	1.478073	85
5	128	2.363110	90	107	2.357541	80	95	2.356028	75	103	2.357756	79	140	2.365042	95
6	61	1.464443	84	81	1.470364	96	65	1.465203	86	72	1.467284	90	53	1.461717	79
7	18	0.301451	80	14	0.300539	75	28	0.304605	93	38	0.307640	99	22	0.302673	90
8	210	2.074277	85	228	2.074482	90	248	2.075337	99	200	2.075515	92	222	2.075173	95

Note: *t* represents time, d; cc represents construction cost, 10^8 CNY; *q* represents quality, %

Table 4 Values of the relevant parameters in the improved NSGA-II method

Relevant parameter	Value
Population size	50
Evolutional generation	100
Mutation probability	0.06
Crossover probability	0.8

Fig. 10 shows the performance of the improved NSGA-II over the iterations. The 3D diagrams (Figs. 10a, 10c, and 10e) express the objective values of the solutions selected over the iterations. In the 2D diagrams (Figs. 10b, 10d, and 10f), the deeper colors of the areas where the solutions are located represent smaller gaps between the practical demands. In the 3D scatter plots, the range of time was reduced from 610–735 d to 610–675 d, the qualities were improved from 86%–91% to 90%–91%, and the total costs were reduced from 1.0727×10^9–1.0759×10^9 CNY to 1.0724×10^9–1.0731×10^9 CNY. The changing trend of the selected solutions verifies the correctness of the algorithm of the program.

The solutions of the 100th generation were ordered by adopting the TOPSIS method. The first five results of the optimization are shown in Table 5.

The best compromise solutions after the first activity had finished are given in Tables 6 and 7.

As the construction of the dam continues, DTCQT optimization can be conducted at any stage, and the solution can guide the construction of the next activity and assist managers in supervising and controlling the dam filling construction. The selected solutions for each activity after the second activity are given in Table 8 (p.15).

Because the dynamic tradeoff optimizations were based on real-time monitoring data, the prediction accuracy of the activity time was improved. The above optimization process was performed after the first activity. Therefore, the selected solution for the second activity was regarded as the construction control standard. In that case, the actual time of the second activity was 77 d, whereas the time of the selected solution was 79 d. As expected, the error (2.5%) was far smaller than that of traditional methods.

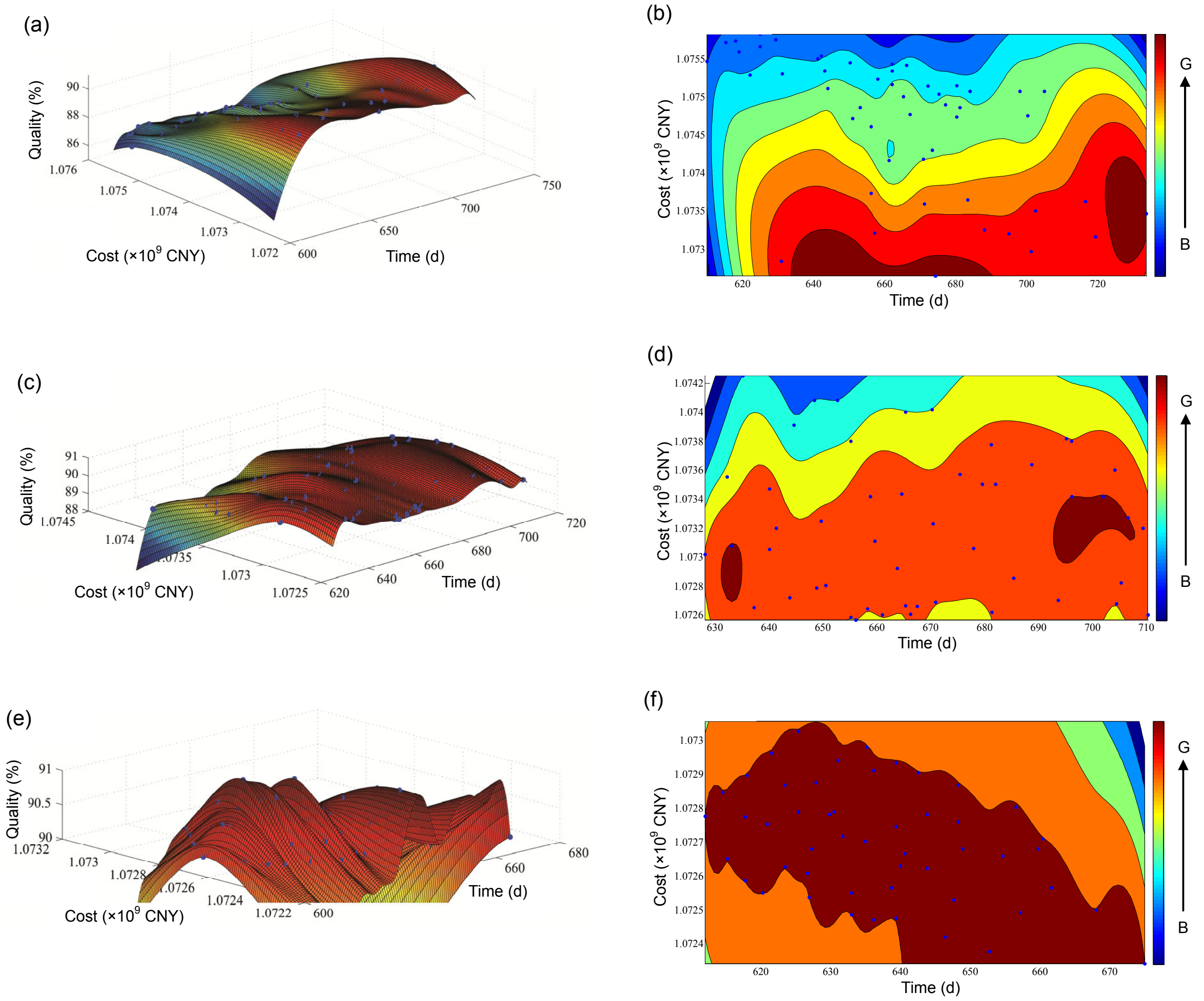


Fig. 10 Distribution diagrams of the selected solutions

Images (a), (c), and (e) are 3D distribution diagrams for the 20th, 50th, and 100th generations, respectively. Images (b), (d), and (f) are 2D distribution diagrams for the 20th, 50th, and 100th generations, respectively. The blue point means solution, and "G" and "B" represent good quality and bad quality, respectively

Table 5 The first five Pareto solutions of the optimization

Solution No.	Solution	Time (d)	Total cost (×10^9 CNY)	Quality (%)	Relative closeness	Sorting
(1)	(4, 2, 3, 1, 4, 5, 4)	619	1.0723219	89.84	0.8572	1
(2)	(4, 2, 3, 1, 2, 5, 4)	628	1.0726408	90.29	0.6113	5
(3)	(4, 2, 1, 1, 4, 5, 4)	626	1.0724416	90.29	0.7502	2
(4)	(4, 2, 3, 1, 4, 3, 4)	625	1.0725508	90.18	0.6810	4
(5)	(4, 1, 3, 1, 4, 5, 4)	626	1.0724878	90.21	0.7170	3

Note: The letters from (O_1, O_2, O_3, O_4, O_5, O_6, O_7) are the numbers of the options corresponding to activities 2 to 8

Table 6 The best compromise solutions

Solution	Time (d)	Construction cost (×10^9 CNY)	Quality (%)
(4, 2, 3, 1, 4, 5, 4)	619	1.0723219	89.84

Note: The letters from (O_1, O_2, O_3, O_4, O_5, O_6, O_7) are the numbers of the options corresponding to activities 2 to 8

4.4 Algorithm comparison

In this paper, the proposed improved NSGA-II coupled with TOPSIS aims to solve the problem of DTCQT optimization. Compared with traditional methods such as linear weighted sum (LWS) and NSGA-II, the final selected result adheres to practical engineering demands. After the first activity was finished, the above three methods were adopted to achieve the optimal compromise solution, and the LWS method was used to calculate the weighted coefficients of every solution (Table 9).

We can see from Table 9 that the weighted coefficient of our proposed method was 0.75, whereas those for the other two methods were 0.40 and 0.30. Thus, the solution selected using the proposed method was superior for decisions required for practical engineering.

The differences between the two methods (LWS and the proposed) and their computational efficiency were largely reflected in the normalization process. The LWS method was based on all the solutions (5^7=78 125), whereas our proposed method was based on the solutions of the current generation (N=50). In NSGA-II, the solutions are optimized gradually with increasing generations, which enlarges the differences among the better solutions. Therefore, the solution that meets the demands of practical engineering can be selected more accurately. The main difference between NSGA-II and the proposed method is whether the decision process is considered. The results show that considering weights can aid in the selection of an optimal construction solution.

5 Conclusions and further research

This paper has proposed a DTCQT method to implement the time, cost, and quality tradeoff dynamically during the rockfill dam construction process. A model that integrates quality and time costs is established. The time, cost, and quality are dynamically estimated with construction information accessible from a real-time monitoring system, which narrows the deviation between the construction plan and the actual construction conditions compared with using only static empirical data. In addition, considering different objective control strategies in the rockfill dam construction process, the AHP method is used to measure decision preferences dynamically.

Table 7 The best compromise machinery allocations after the first activity

Ac	Mechanical configuration	Ac	Mechanical configuration
2	$\begin{pmatrix}44, & 5, & 1\\ 1, & 13, & 1\end{pmatrix}$	6	$\begin{pmatrix}50, & 5, & 1\\ 1, & 15, & 1\end{pmatrix}$
3	$\begin{pmatrix}60, & 6, & 1\\ 1, & 17, & 1\end{pmatrix}$	7	$\begin{pmatrix}35, & 4, & 1\\ 1, & 9, & 1\end{pmatrix}$
4	$\begin{pmatrix}67, & 7, & 1\\ 1, & 18, & 1\end{pmatrix}$	8	$\begin{pmatrix}40, & 5, & 1\\ 1, & 7, & 1\end{pmatrix}$
5	$\begin{pmatrix}44, & 5, & 1\\ 1, & 13, & 1\end{pmatrix}$		

Note: n_1, n_2, n_3, n_4, n_5, and n_6 in $\begin{pmatrix}n_1, & n_2, & n_3\\ n_4, & n_5, & n_6\end{pmatrix}$ represent the number of trucks, roller compactors, sprinklers, excavators, loaders, and bulldozers, respectively

Table 8 The best compromise machinery allocations after the second activity

Ac	Mechanical configuration	Ac	Mechanical configuration
3	$\begin{pmatrix}57, & 5, & 1\\ 1, & 12, & 1\end{pmatrix}$	6	$\begin{pmatrix}45, & 4, & 1\\ 1, & 13, & 1\end{pmatrix}$
4	$\begin{pmatrix}63, & 6, & 1\\ 1, & 16, & 1\end{pmatrix}$	7	$\begin{pmatrix}30, & 3, & 1\\ 1, & 8, & 1\end{pmatrix}$
5	$\begin{pmatrix}42, & 5, & 1\\ 1, & 12, & 1\end{pmatrix}$	8	$\begin{pmatrix}35, & 4, & 1\\ 1, & 6, & 1\end{pmatrix}$

Note: n_1, n_2, n_3, n_4, n_5, and n_6 in $\begin{pmatrix}n_1, & n_2, & n_3\\ n_4, & n_5, & n_6\end{pmatrix}$ represent the number of trucks, roller compactors, sprinklers, excavators, loaders, and bulldozers, respectively

Table 9 The best compromise solution based on each algorithm

No.	Method	Option	Objective factor			LWS
			Time (d)	Total cost (×10^9 CNY)	Quality (%)	
1	LWS	(4, 2, 4, 5, 3, 3, 4)	620	1.072 437 5	89.48	0.30
2	NSGA-II	(3, 2, 3, 1, 4, 3, 4)	615	1.072 558 9	90.15	0.40
3	The proposed	(4, 2, 3, 1, 4, 5, 4)	619	1.072 321 9	89.84	0.75

Note: The letters from (O_1, O_2, O_3, O_4, O_5, O_6, O_7) are the numbers of the options corresponding to activities 2 to 8

Regarding the objective weights in the solution optimization, the improved NSGA-II and TOPSIS methods are applied to obtain optimal solutions. Compared with existing construction TCQT methods, this proposed methodology is built on real-time monitoring, which makes the tradeoff consistent with the real construction circumstances. The consistency enhances the tradeoff's applicability to construction management. In addition, the proposed method is more suitable for field construction management due to its flexibility in decision variable estimation and preference measurement. By considering a practical application, a dynamic tradeoff optimization based on real-time monitoring is realized, which improves the decision-making efficiency and increases the economic benefit of the project. The optimization results verify the feasibility of the proposed method, which provides a reliable theoretical basis and guidance for further DTCQT applications.

Based on these conclusions, further research could be carried out in the following respects:

1. A program allowing human–computer interaction could be developed. The proposed method does not yet include a program that allows human–computer interaction, which hinders its wide application to actual projects. Human–computer interaction-friendly programming would improve the flexibility and adaptability of the proposed method and help project managers to apply DTCQT easily to practical management.

2. The proposed method has good applicability and can be applied in other engineering projects. This paper illustrates the feasibility of the method using rockfill dam construction as an example, which provides effective support for its application in other projects. Applying the method to other areas remains for further study and discussion.

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中文概要

题　目：基于实时监控的面板堆石坝施工进度-成本-质量动态均衡

目　的：施工进度-成本-质量均衡是面板堆石坝工程成功的关键。目前的均衡研究建立在静态经验数据上，仅针对规划和设计阶段，难以适应施工过程的动态性和不确定性。基于面板堆石坝施工质量实时监控技术，考虑动态决策偏好，本文提出施工进度-质量-成本动态均衡方法，以实现面向过程管理的进度-质量-成本均衡。

创新点：1. 提出基于面板堆石坝施工质量实时监控技术的施工进度、质量和成本动态预测方法；2. 提出施工决策偏好动态量化方法；3. 提出施工进度-质量-成本多目标均衡求解算法。

方　法：1. 通过分析实时监控数据，更新仿真模型参数，仿真得到施工进度，再推导出质量和成本（图 4、公式（8）和（10））；2. 采用层次分析法，动态量化施工过程中的管理者决策偏好，得到进度-质量-成本三目标间的权重（图 5）；3. 采用改进的带精英策略的非支配排序遗传算法（公式（13）），求解动态均衡问题的 Pareto 解，并运用逼近理想解的排序法筛选出最优折衷方案（图 5）。

结　论：1. 基于实时监控进行施工进度、质量和成本的动态预测，提高了均衡结果与实际施工过程的一致性；2. 动态量化决策偏好，并在优化求解中予以考虑，有助于最优折衷方案的筛选；3. 在施工过程中任意阶段开展的施工进度-质量-成本动态均衡适应了施工条件的动态变化，可有效指导现场施工管理。

关键词：施工进度-成本-质量动态均衡；面板堆石坝；实时监控；决策偏好

Introducing editorial board member:

Prof. Deng-hua ZHONG is a new editorial board member of *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)* in 2017. He is the director of State Key Laboratory of Hydraulic Engineering Simulation and Safety at Tianjin University. He has been an academician of the Chinese Academy of Engineering since 2009.

Prof. ZHONG received his PhD degree from Tianjin University in 1992. He was a senior visiting scholar of Massachusetts Institute of Technology, University of Mannheim, and University of Kiel. He has been devoted to the research on hydraulic engineering construction and related theories and technologies. He has successfully presided over 10 scientific research projects, including the National Basic Research Program (973 Program) of China, the National Natural Science Foundation of China, and the National Key Technology R&D Program of China. Moreover, he is also a prolific researcher with five authored academic books and over 100 technical papers published in journals and conferences. For his outstanding achievements, Prof. ZHONG was awarded three Second Prizes of State Scientific and Technological Progress, two in 2005 and 2007 as the first Prize Winner and one in 2011 as the second Prize Winner. Besides, he was honored with several other remarkable prizes, including (1) China Youth Science and Technology Award in 2004, (2) the National Science Fund for Distinguished Young Scholars in 2005, and (3) Guanghua Engineering Science and Technology Award for Young Scientist in 2008.