

# A decision support system for substage-zoning filling design of rock-fill dams based on particle swarm optimization

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**Abstract** In this paper, we studied a substage-zoning filling design problem, which is considered as a complex problem with numerous tasks such as construction planning, dam access road and borrow placement, workspace filling, and construction project management. In analyzing workflows and the mechanism of substage-zoning filling, not only the above-mentioned tasks are considered, but also the environmental factors such as rainfall and hydrology characteristic temperature are taken into account. In this study, an optimization model for dam filling which aimed at reducing the disequilibrium degree of filling intensity was proposed; in addition, a technique based on particle swarm optimization was introduced as the basis of a decision support system for rock-fill dams. The system has been employed in a water conservancy and hydropower project which shows that the system is able to provide quality decision support and facilitate the rock-fill dam construction effectively.

**Keywords** Substage-zoning filling design · Rock-fill dam · Decision support system · Particle swarm optimization · Leveling of production

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## 1 Introduction

As an infrastructure and basic industry, water conservancy and hydropower projects have enjoyed continuous development in China, and valuable design and construction experience have been accumulated in recent years [1]. Among all hydropower projects, the rock-fill dams are in general given a higher priority. The description of rock-fill dam in the Wikipedia is that rock-fill dams are embankments of compacted free-draining granular earth with an impervious zone.

The term rock-fill is used because there are a large percentage of large particles which are contained in the earth utilized by the dam. The impervious zone which is made of masonry, concrete, plastic membrane, steel sheet piles, timber or other material may be on the upstream face. The impervious zone is referred as a core when it is within the embankment. The dam is referred to as a composite dam in which case the impervious material contains clay. A filter is used to separate the core to prevent internal erosion of clay into the rock fill due to seepage forces. The migration of fine grain soil particles is prevented by the grading of the soil which is the ingredient of filters. To reduce the transportation cost of material during construction, the rock-fill dam can make full use of material which is suitable and at hand. The rock-fill dam is economical due to the use of cheap local materials. ([http://en.wikipedia.org/wiki/Dam#Rock-fill\\_dams](http://en.wikipedia.org/wiki/Dam#Rock-fill_dams)).

The lack of earth of acceptable quality and plentiful supply of sound rock at hand entail the adoption of rock-fill dam. Soil and rock are the materials used to construct rock-fill dams. Soil is classified by particle size. Silt is also suitable for the construction. Sand is ranged by granularity. It can be constructed in the wet and cold weather. Even it permits continuous work under weather conditions that

would not permit earth or concrete construction. The constructions of the rock-fill dam can be very rapid because of the simultaneous operation of filling and other separates compaction like rolling. In recent years, many large-scale rock-fill dam hydropower junctions with a filling volume of more than 10 million squares with the duration of construction of a couple years are appearing, such as the Waterfall Gully Hydropower Station at the Dadu River Basin Station, and Nuozhadu Hydropower Station on the Lancang River.

A rational plan for quantities of each filling stage is an important aspect of the construction to increase the speed of project completion, ensuring construction quality, and reducing the cost [1]. In rock-fill dam construction, the planning of the quantities of the material to fill and the construction visage of each stage of a rock-fill dam is called substage-zoning filling design of the rock-fill dam. The results of substage-zoning filling design of the rock-fill dam are directly related to the dam's construction quality and stability, construction schedule, and project cost control. The substage-zoning filling design of rock-fill dams involves many complex tasks such as construction scheduling, placement of access roads to dam site, material planning, construction organization method, construction space, construction machinery, and environment issues. In order to promote the economic efficiency of the project and shorten construction time, substage-zoning filling design of dams has been studied focusing on the aspect of construction decision-making and has attracted attention from many scholars. Huang et al. predict that the crack problem of the concrete faced rock-fill dam of Hongjiadu Hydropower Station is minor through repeated scheme comparison and computation regarding concrete faced rock-fill dam, based on the experience and lessons learn from Tianshengqiao Hydropower Station [2]. An effort has been made by Ozkan to summarize the methods used in assessing the dynamic behavior and safety of earth and rock-fill dams under seismic shaking from the soil engineer's point of view [3]. Cetin et al. study the settlement and slaking problems of the world's fourth largest rock-fill dam, the Ataturk Dam in Turkey [4]. Li et al. describe the main technical issues in the filling of dam body, the arrangement of access roads to dam crest, and the research results on the construction design of the NuoZhadu Hydropower Station [5]. Complex systems are studied and defined in existing literature [6–8]. The construction process of large rock-fill dam is a complex system. It involves many factors such as construction scheduling, placement of dam access roads, filling workspace, arrangement of borrows, construction organization of workforce and machines. In such a dynamic environment, flexibility becomes an intrinsic part of the planning process. Hence, simulating a construction operation should include the ability to capture

a set of dynamic strategies and represent them with a good plan [9].

The development effort for complex systems applications featuring such sophisticated behavior is increasing and the complexity grows even further [10–15]. Decision support systems have been widely applied to decision problems which involve a large quantity of complex factors [16–21]. Feng et al. provided a comprehensive evaluation on the overall development of urban systems and proposed a DSS based on fuzzy, multi-criteria, multilayer evaluation model [22]. Ogryczak et al. presented a system named DINAS for solving various multi-objective transshipment problems [23]. Many complex decisions are needed to be made in the concurrent product development process. As a result, complex concurrent engineering design problems require decision aids such as decision support systems [24–26]. Given the nature of decision support problems, the research emphasis of decision support systems development has been focused on modeling aspects. Xu et al. presented a fuzzy sets approach to evaluating design alternatives and developed a decision support system to provide support for multi-stage decision making [25]. Kannan et al. present a framework for the integration of project-level and process-level simulations with the dynamic strategies that form the core of the plan [9]. Hastak et al. presented a system to assist construction managers systematically for evaluating construction process [27]. Kumaraswamy and Dissanayaka developed a system for building project procurement [28]. Zavadskas et al. developed a multiple criteria on-line system for real estate [29]. Zeng et al. created an information system for machine arrangement for filling construction of rock-fill dams [30]. Al-Khaiat and Fereig introduced computer applications in the Kuwaiti construction industry [31]. There are so many factors in construction design that each of them should be taken into account; meanwhile, there are so many design alternatives that have been generated in different design stages that need to be evaluated. Obviously, the impact of decisions from one stage to another is critical. Zhao et al. found that a decision for the current stage depends on the decisions result from the previous stage, and the final design is reached through the evolution of a design process stage by stage [24]. Jackie et al. introduced a genetic algorithm approach to group decision support systems and proposed groups using GDSS to address certain tasks [32]. Zhang and Xia established a material flow equilibrium system (EDMFES) that is applicable to embankment dam engineering [1]. Luo et al. implemented a flood decision support system which combined the wireless sensor network for data acquisition and software agent technology for legacy system integration [33]. Feng et al. presented a decision support system for assessing the social-economic impact of China's

South-to-North Water Transfer project which is one of the four largest trans-century projects in China and seeks to promote Northern China's economic growth by relaxing water constraints in a region facing severe water shortage [34]. Zhou et al. described how to use dynamic recurrent neural networks to provide the model base of a hybrid intelligent system for the metallurgical industry with a quality control model which has been developed into a fuzzy decision support system and integrated with a number of existing decision support systems [35–37].

However, the following two issues remain unresolved in the existing literature. Although it is known that there are many factors including rain and hydrology characteristic temperature which can influence the design of the substage-zoning filling, a scientific analysis of the influencing mechanism is still not available. The substage-zoning filling design of dams is an important way to reduce the cost of the project and ensure completing the project successfully, providing decision support for reducing the disequilibrium degree of filling; however, there are few decision support systems introduced in the literature for solving such decision problems.

This paper proposes a decision support system (DSS) for solving two above-mentioned problems. It is necessary to systemically study all relevant factors in substage-zoning filling design and planning the construction visage of each stage, and reflecting the filling process with scientific analysis and advanced simulation technology. In this study, the main factors which are relevant to substage-zoning filling design problem are analyzed in terms of the theory of system analysis [38]. Based on these analyses, an optimization model for dam filling was built. Based upon this, we develop a decision support system for the substage-zoning filling design of rock-fill dams. Some principles outlined by Zhang et al. are applied to the system to make it more resilient [10–15]. The purpose for this system is to help *China Gezhouba Group Corporation* (CGGC) manage the construction of a large-scale rock-fill dam. *China Gezhouba Group Corporation* (CGGC) is one of the largest hydropower corporations in China and has completed many large hydropower projects including the Three Gorges Dam that is the largest in the world. During the construction of the Three Gorge Dam, the process control system, statistical analysis system, project cost management and quality

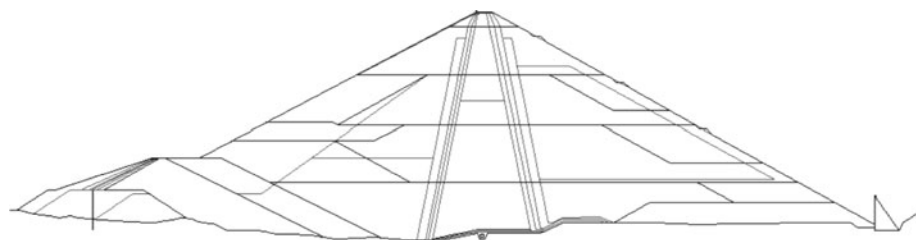
control system and the comprehensive supervision system for concrete production, transportation and molding are been successfully used. The world class Gezhouba Project was completed in 1988 with great success which set an example of high quality and efficiency at minimal cost [39, 40]. More than 20 local area networks and thousands of terminals have been built at CGGC after developing information technology for several decades. An MIS (Management Information System) that integrates production, operation and management has been developed by CGGC, in cooperation with Beihang University [40]. The implementation of the DSS introduced in this paper involves a national key project in Yunnan Province, China, which is a basic infrastructure project for the projects of “West-to-East Power Transmission” and “Power Transmission from Yunan Province to other Provinces”.

## 2 The algorithm

Stage construction is well adapted by the rock-fill dam with an upstream diaphragm. The dam can be constructed without interfering with the reservoir because the rock is dumped behind the impervious diaphragm. To make the dam water-tight, the impervious face upward is continued. The stage construction is also applied in coffer damming which is the first of the dam serves. Before the construction of a large-scale rock-fill dam, the entire filling period is divided into a number of time slots in accordance to the overall project planning. Figure 1 is a diagram of a core rock-fill dam's partition of the phases. Although a model can be established according to the current set of phases based on geographical constraints and the number of phases needed for division [41], the model is applicable only to high core rock-fill dams. In order to extend it to a wide range of rock-fill dam types, and to meet the needs of specific projects, it is desirable to use the traditional method of staging the initial zoning program based on the phases of the adjustment line, and the design will need to integrate the traditional optimization methods with simulation experiments to meet the needs of the real settings and improve the effectiveness and efficiency.

On the basis of substage-zoning filling design based upon the traditional approach for all phases, adjustment for

**Fig. 1** A stage-zoning diagram of a rock-fill dam



the line which formed the schedule of the construction can be broken down into: horizontal movement, vertical movement and the adjustment of the angle of the line.

As Fig. 2 shows, when the line is moved up (from the dotted line to the solid line) the 2nd, 3rd, 4th layers are added to the Y period accordingly, the 2nd, 3rd, 4th layers are to be removed from the X period. As Fig. 3 shows, when it moves to the right from the dotted line to the solid line, the X period's quantities will be influenced by the distance which the line is moved. The new quantity of the X period is the original quantities minus the quantities of the sum of the relevant layers multiplied the ratio of the movement to the original length of relevant layers and the length of the line moved, and the corresponding value added to the Y period will increase, as the following equations show:

$$V_X = V_X - \frac{L}{W} \times \sum_{i=1}^4 V_i \tag{1}$$

$$V_Y = V_Y + \frac{L}{W} \times \sum_{i=1}^4 V_i \tag{2}$$

$V_X, V_Y$  represent the filling volume of the X period and the Y period,  $V_i$  is filling volume of the  $i$ th layer,  $W$  is the length of the relevant layers,  $L$  is the length of the line moved. As Fig. 4 shows, the X period's filling volume will base on the distance the Y period moves and length of relevant layers minus the ratio of the corresponding value. Y period will increase its corresponding value as the following equations show:

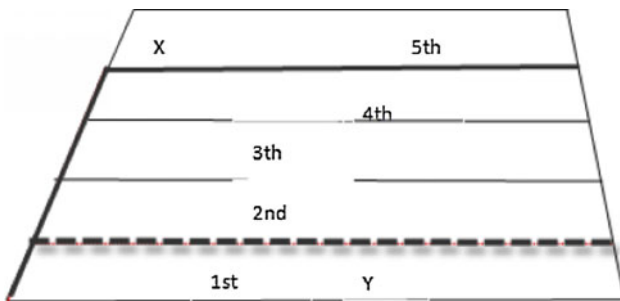


Fig. 2 Vertical movement of the line

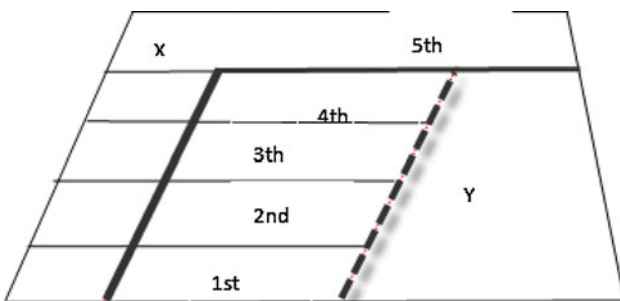


Fig. 3 Horizontal movement of the line

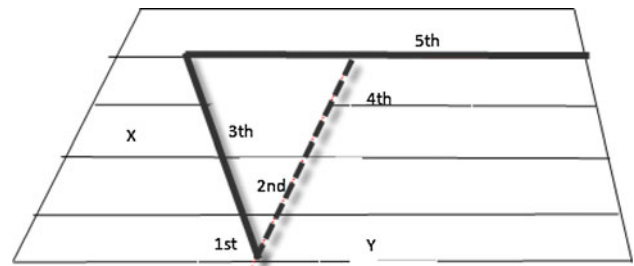


Fig. 4 Adjustment of the angle of inclination

$$V_X = V_X - \frac{1}{2} \times L \times \sum_{i=1}^4 (H_i \times a_i) \tag{3}$$

$$V_Y = V_Y + \frac{1}{2} \times L \times \sum_{i=1}^4 (H_i \times a_i) \tag{4}$$

$V_X, V_Y$  represent the filling volume of the X period and the Y period,  $a_i$  is the length of dam axis,  $L$  is the length of the line move.

### 3 Systems analysis

The premise of a reasonable solution to the problem in substage-zoning design is to make a comprehensive analysis about how to optimize the phased zoning based on the factors' properties and their relationships. Due to the fact that many factors influence such optimization problems, factors could be simplified which do not affect the system state significantly or those that have relatively smaller influence based on systematic analysis, emphasizing on the focal point of the construction system in the modeling process and proposing some hypothesis about the non-key part of the construction, as well as simplifying the constraints existing in the systems [42].

It is known that filling construction system's main factors can affect the system's three subsystems. Corresponding to the three subsystems of filling construction, there are three main limits during the construction period: material flow equilibrium or material planning, capacity of the haul roads, form of construction work on the dam face. As described by Zhang and Xia [1], in a high embankment dam engineering project, the following engineering project elements are related to material flow equilibrium.

Excavation project refers to dam foundation, dam abutment, power station and diversion engineering that should be excavated to meet engineering construction demand. The excavated materials can be used as earth and rock needed by the construction of embankment dam.

Filling project refers to all the items to be filled such as dam, upstream and downstream cofferdam during the engineering construction.

Transferring yard refers to excavated material storing place which is used to temporarily store materials because of the inconsistency of time between excavation project and filling project or purpose of material reserve. Materials with different physical properties should be stored separately. Therefore, transferring yard is not only a place providing materials but also one for storing materials. In the case of rock-fill dams, the factors included in the material flow equilibrium are the same as high embankment dam engineering project, especially in the construction of high of high core rock-fill dams.

Moreover, the quarry site is a very important factor. The basis of rock quality is a critical factor. The fragmented rock must be sound, hard and clean. It is reasonable to separate the quarry and the haul roads from other works such as the spillway, power station construction or intake when the location is not dictated by rock quality. If the reserves of the material are sufficient and the capacity of the quarry sites is big enough, the material planning can adjust according to the main work. Environmental factors such as noise, vibration from explosives and dust should be considered.

The process of the construction work on the dam face can be divided into three steps [42–44]:

*Step 1* The rock-fill should be dumped. The main body of fill is placed by dumping from clamshell cranes, cableways or from ramps on the abutments. The initial part of the fill can form a mound or bank. More fill is dumped from the top of this mound. The rock can fall down the sloping surface during the dumping. The pieces become tightly wedged together under the influence of the combined effect of sliding, tumbling and impact.

*Step 2* Heavy rubber tired rollers and heavy vibrating rollers are used to rolled rock-fill if the rock is soft or breaks readily into pieces. It should be placed in layers and then rolled. The number of the passes required for compaction is between four and eight.

*Step 3* The fill should be reshaped. Side slope of the angle of repose is determined by the dumped rock-fill. More horizontal berms can form a flatter slop if it is designed.

Construction work on the dam face is related to the arrangement of the construction machinery, rainfall, the space limit and so on. The relationship between the factors is too complex to estimate the influence of each factor separately. To represent the constraints on the form of construction work on the dam face, a concept, named as accessible intension, is suggested as an important optimization factor by synthetically considering the influences of operation mode, size of filling section and construction machinery [41]. There is a concept named construction

intension which is the result of planning of the construction work. It is often determined just to be on the safe side. Obviously, the accessible intension must be smaller or equal to construction intension.

Project schedule is influenced by the haul roads which restrict the transport capacity of materials. The required speed of construction is a critical factor to design and build haul roads, and this involves the size of the haulage units. The width of roads should be at least 13 m for two way traffic. The gradients must be such as to give minimum cost for the vehicles involved. The general layout of haul roads and ramps can be greatly facilitated with scale models [3]. When calculating transport capacity of materials of the period  $t$ , the engineers can choose roads according to the pavement performance, road hierarchy, width of the road. Then the intension of the transport of all dam sections on various elevation allowable areas can be fixed.

#### 4 Modeling

In construction work, the rational and balanced allocation of resources must be achieved. Based on this, an optimization model for dam filling is built which aims at reducing the disequilibrium degree of filling intensity. The objective function is as follows:

$$\min Z = \frac{P_{\max}}{\sum_{j=1}^n p_{ij}(\bar{x})/n} \tag{5}$$

$P_{ij}(x)$  describes the intensity of the  $j$  zone in the stage  $i$ . The  $n$  denotes the number of the constructing zones of the whole project at the same time.  $P_{\max}$  is the mixture intensity in the stage  $i$ . The constraints that must be met include the capability of the transport system, construction organization method, the accessible intensity and the progress of the construction. The details are as follows.

##### 4.1 Accessible intensity

The accessible intension should not be exceeded as,

$$\begin{cases} p_{i1}(\bar{x}) \leq p_{ci1}(\bar{x}) \\ p_{i2}(\bar{x}) \leq p_{ci2}(\bar{x}) \\ p_{i3}(\bar{x}) \leq p_{ci3}(\bar{x}) \end{cases} \tag{6}$$

For obtaining the accessible intensity,

$$\begin{cases} P_0 = \frac{60}{tp} \times tm \\ P = V/(t_1 + t_2) \\ P = s \times p_0 \\ t_1 = \frac{V}{p_0 \times s} \\ t_2 = \frac{n \times l \times b}{v_0 \times b_0 \times m} \end{cases} \tag{7}$$

The meanings of notations in the above formulas are:  $tp$  (minute) and  $tm$  (cubic meter) describe the required time of unloading by dump trucks and the volume that can be loaded each time respectively.  $P_o$  is the intensity of unloading.  $V$  means the volume of the unloading.  $s$  is the number of the unloading point.  $l$  and  $b$  is the length and width of the construction area,  $v_o$  is the mean velocity of the vibratory vibrating roller,  $b_o$  is the width of the vibrating roller wheel,  $m$  is the number of the vibratory rollers,  $n$  describes the number of times of vibrating roller compaction. We assume that the vibrating roller is operated along the dam axis.

#### 4.2 The constraints of the transport system of the dam

The formula below indicates that in a specific district, the actual productivity generated by all the machineries in the  $i$  stage and  $j$  zone should not exceed the planned intensity of the transport system of the district.

$$p_{ij}(\bar{x}) \leq P_{rj} \quad (8)$$

$P_{rj}$  is the plan intensity of the transport system in the zone  $j$ .

#### 4.3 The control constraints in progress

$$\sum_{j=1}^i \frac{V_j}{P_j(\bar{x})} \leq T_i \quad (9)$$

$T_i$  is the longest time spent that the dam is filled to the  $i$  stage.  $V_j$  and  $P_j(x)$  represent the volume and the intensity of the  $j$  stage respectively.

## 5 Solution

The objective function of the model is not derivable or continuous and there are some complex multivariate non-linear relationships in the constraints. Therefore, traditional mathematical programming methods such as the penalty function method cannot help to reach a good result. Particle swarm optimization (PSO) is a stochastic algorithm for problem solving. PSO is simple to code and has a low computational cost. It is a kind of swarm intelligence. The particle swarm optimization algorithm was first described in 1995 by Kennedy and Eberhart [45]. The particle swarm simulates kind of social optimization [45, 46]. In problem-solving process, it is possible to evaluate a proposed solution in the form of a fitness function. A communication structure or social network can be defined, and neighbors for each individual to interact with are assigned. Then a population of individuals defined as random guesses for the problem solutions is initialized. These individuals are candidate solutions. They are also known as the particles.

The swarm is typically modeled by particles in multidimensional space that have a position and a velocity. These particles fly through hyperspace and have two essential reasoning capabilities: the memory of their own best position and knowledge of the global or their neighborhood's best.

Ever since the inception of PSO in 1995, a significant number of modifications have been made to the basic algorithm for realizing performance improvements [47]. We use modified inertia weight PSO to solve this problem which has been tested and verified [48]. We take (5) as the fitness function of the PSO. The particle position and velocity update equations in the modified inertia weight PSO are given by:

$$v_i^{d+1} = \omega v_{id}^k + c_1 r_1 (P_i^d - X_i^d) + c_2 r_2 (P_g^d - X_i^d) \quad (10)$$

$$X_i^{d+1} = X_i^d + v_i^d \quad (11)$$

Where,  $c_1$  and  $c_2$  are constants that tell how much the particle directs toward good positions. Usually we set their value to 2.  $v_i^d$  is the velocity of the particle  $i$ .  $X_i^d$  is the position of the particle  $i$ .  $r_1$  and  $r_2$  are two random vectors with each component generally a uniform random number between 0 and 1.  $\omega$  is an inertial constant. Good values are usually slightly less than 1.  $P_i^d$  represents the best position of the particle in its history trail.  $P_g^d$  represents the best particle location in the entire swarm.

Solutions generated by the algorithm may be infeasible because the constraints may be violated [49]. Several methods are used to handle the constraint of optimization problem such as specific crossover operator and penalty method. We analyze the cases of constraint violation, and then find a simple method to repair the infeasible offspring solutions. When (6) or (9) are violated, the change of the position of the particle must be cancelled. When (8) is violated, we repair the position of the particle to make sure the constraints are met.

### 5.1 System implementation

There are two kinds of decision support systems in current engineering design. One is a distributed decision support system in a networking environment; the other is stand alone system. It is the same in the hydraulic engineering. We develop a hydraulic engineering construction management decision support system based on an optimization model and an algorithm with Visual Studio 2005. A sample screen of the system is shown in Fig. 5. Users can input the data about the dam, such as the construction schedule, placement of access roads to dam site and materials used in the project. The system can create alternative solutions by using the model and the algorithm. Users can also print

**Fig. 5** Hydraulic engineering construction management decision support system



reports about the intensity of each zone, the progress of the project, and the equipment utilization ratio.

5.2 Application

The system has been applied to a water conservancy and hydropower project in Yunan Province, China. This project is consisted of a rock-fill dam, a water escape, a flood-discharge tunnel, a diversion construction and a generating system. The width of the dam crest is 18 m. The crest elevation is 821.5 m and the maximum of the height of dam is 261.5 m. The total time of construction is 49.5 months without the construction of the cofferdam. The dam can be divided into 10 stages or 92 zones. The average intensity on filling construction is  $62.58 \times 104 \text{ m}^3$  per month. The intensity of each stage is shown in Table 1.

**Table 1** Intensity of stages

Stage	Upstream	Core	Downstream	Sum
1	28.83	0	0	28.83
2	21.06	0	13.37	34.43
3	11.69	14.18	12.01	37.88
4	51.19	0	11.9	62.98
5	16.35	23.99	38.10	78.44
6	32.71	0	49.37	82.08
7	25.46	22.64	31.85	79.95
8	42.16	0	37.35	79.51
9	27.51	20.20	27.65	75.36
10	5.564	9.196	5.62	20.38

Typical convergence conditions include reaching a certain number of iterations, reaching a certain fitness value, and so on. We set the number of iterations to 500

6 Conclusion

A rock-fill dam project typically involves millions of cubic meter of earth and stone. A variety of substage-zoning filling design can be adopted by dam filling. Its construction cost is not only affected by machinery grouping and traffic layout but also by the dispatching of materials. Therefore, substage-zoning filling design is a key factor affecting the construction progress of rock-fill dam, and an important avenue for saving resource and reducing construction cost. In order to solve the existing problems concerning construction plan and control of rock-fill dam engineering and meet the requirements of high quality, high speed and low cost, this paper conducted a study on the substage-zoning filling design in accordance to the features and specific requirements of rock-fill dam so that the engineers can select an optimum construction scheme and work out a reasonable construction plan. This paper provides guidance to water conservancy projects in the following aspects: shorten construction period, saving resource and improving economic efficiency in the rock-fill dam engineering. Combined with the simulation technology, a hydraulic engineering construction management decision support system is developed in this study. A DSS based on an optimization model is built through analyzing the main factors that can influence the construction of rock-fill dams. The implementation result demonstrates the applicability of the system to various types of rock-fill dams and shows that the system can provide decision support for substage-zoning filling design of rock-fill dams.

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