Geomechanics and Engineering, *Vol. 19, No. 5 (2019) 383-392*
DOI: https://doi.org/10.12989/gae.2019.19.5.383

An alternative upstream method for the Zhelamuqing tailings impoundment construction of a Copper Mine in China

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(Received August 11, 2017, Revised November 13, 2019, Accepted November 14, 2019)

Abstract. How to safely and economically dispose mining tailings is a challenge to mine operators. This paper presents an alternative upstream method for tailings dam construction, termed as the template construction method (TCM), which has been successfully implemented at Zhelamuqing tailings impoundment since 2004. By the beginning of 2015, the tailings dam wall had reached 95 m in height for the 46 upstream raises, with the total height of the dam including the starter dyke being 128 m. The proposed TCM is relatively simple and cost-effective and provides a good way for constructing rapidly raising tailings dam based on this case.

Keywords: tailings; waste disposal; template construction method (TCM); environmental engineering

1. Introduction

With the development of new mining and mineral processing technologies, increasing volumes of tailings have been produced as mining waste that requires tailings disposal. This has become a major challenge for the mining industry (Komurlu and Kesimal 2015, Adiansyah *et al.* 2017). In China, tighter legislation and regulations on tailings disposal were proposed to force mine operators to better manage and control the vast quantity of highly visible wastes (Yin *et al.* 2004).

Up to now, the most common way to store both tailings and mine water is the conventional impoundment storage method. There are four basic methods of constructing a hydraulic-fill impoundment, named, the downstream, the upstream, the centerline, and the point or line discharge methods (Blight 2010). Among these four methods, the upstream method, which requires the lowest initial cost and lesser dam fill volumes, has been widely used for the construction of tailings dams in mining engineering. Currently, China has more than approximately 12,000 tailings impoundments and nearly 95% of them use the upstream construction method (Zhang *et al.* 2015). The tailings dams are built higher as more tailings are produced and need to be stored. Thus tailings impoundments are some of the largest of man-made structures and they are also one of the most technically challenging elements in geotechnical practice (Davies 2002, Shamsai *et al.* 2007, Ozcan *et al.* 2013). Therefore, the need for consideration and careful tailings management in the mining industry is obvious (Adiansyah *et al.* 2015, Ishihara *et al.* 2015).

Table 1 Main failures of tailings dams in China

Name of dam	Type of tailings	Method of construction	Year of failure	Consequences due to failure
Huogudu, Yunnan Tin Group Co., Yunnan	Tin	Upstream	1962	171 killed
Niujiaolong, Shizhuyuan Non-ferrous Metals Co., Hunan	Copper	Upstream	1985	49 killed
Longjiaoshan, Daye Iron Ore mine, Hubei	Iron	Upstream	1994	31 killed
Dachang, Nandan Tin mine, Guangxi	Tin	Upstream	2000	28 killed
Zhenan Gold mine, Shanxi	Gold	Upstream	2006	17 killed
Xiangfen tailings pond, Shanxi province	Iron	Upstream	2008	277 killed

Over the last 30 years there have been two to five major tailings impoundment failures per year, which is 10 times higher than that for water retention dams (Rico *et al.* 2008). In China, there have been some failures of tailings dams. These failures had significant adverse socioeconomic consequences, resulting in the loss of lives, property, and irreversible pollution in the downstream areas (Wei *et al.* 2013). Table 1 summarizes the main failures of tailings dams happed in China. Therefore, much more attention should be paid to design, construction, and operation of tailings dams in mining practice.

The Upstream dams were initially designed in an empirical manner by mine operators, and were generally raised against some sort of regional slopes, or in a valley, and water pools against the starter dam. The rate of raising the dam should be suitably slow to make sure that there is a sufficient degree of dissipation of excess pore pressures in

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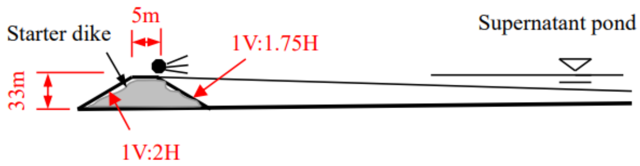
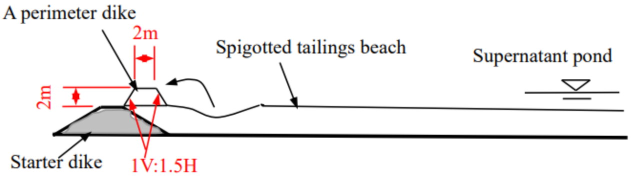
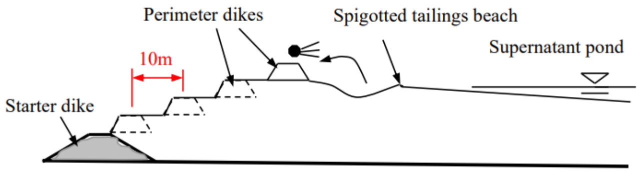
ISSN: 2005-307X (Print), 2092-6219 (Online)



(a) The pipe spigots are used to discharge tailings into a tailings pond from a starter dike crest



(b) A perimeter dike is constructed with coarse sand excavated by hand from a tailings beach



(c) The upstream method tailings dam is raised progressively along with tailings discharge

Fig. 1 Schematic of the conventional upstream construction method of tailings dam

the outer shell and in the slimes. Normally, the rate of dam rise suggested by Vick (1990) should be significantly lower than 4.6 to 9.2 m/yr. to allow the excess pore pressure to be dissipated.

However, this suggested rise rate, obviously, cannot meet the mine production targets in China. In this case study, the maximum rise rate of the Zhelamuqing tailings dam at the Shifengshan Copper Mine is considered up to 23m per year, which is far higher than the suggested rate. Research by Vick (1990) showed that if the construction rate of an upstream dam is more than 15 meters per year, it will have negative effects on the stability of the upstream dam; as the tailings particles need time to consolidate to their highest permeability. If the particles do not consolidate sufficiently, it will produce excess pore pressure within the deposit that leads to the decrease of dam stability.

How to safely and economically dispose mining tailings is a challenge to mine operators. In this research, based on the conventional upstream method, a template construction method (TCM) is proposed, which provides an alternative way for construction of a rapidly raised tailings dam. This method has been successfully implemented in constructing the Zhelamuqing tailings impoundment for the Shifengshan Copper Mine.

In this paper, the conventaional upstream construction method is introduced in section 2. The Shifengshan copper mine and its tailings disposal system is described in section 3. The proposed template construction method and its application are presented in section 4. Meanwhile, base on the subsurface exploration, in-situ tests and laboratory tests, the stability of tailings dam was analyzed.

2. Conventional upstream construction method in China

The tailings impoundment operation involves two main procedures that need to be done frequently. One is to pump tailings as slurry into the surface tailings storage facility using pipelines and discharge sub-aerially, which is relatively easy. The other is to periodically construct many perimeter embankments at the edge of the tailings storage facility to contain tailings and water and prevent tailings slurry from overflow. Generally, the perimeter dikes are added on a yearly basis. For economic reasons, most of perimeter dikes are constructed using sandy material directly excavated from the tailings beach.

The upstream method for tailings dam construction is illustrated schematically in Fig. 1, which includes three steps as follows:

Step 1: A starter dike is usually required and it is often constructed of local borrow materials or mine waste rock (Fig. 1(a)).

Step 2: Before the height of the tailings approaches the top of the starter dam, an upstream raise is constructed using excavated sandy material from the tailings beach or local borrow material to increase the storage capacity of the impoundment (Fig. 1(b)).

Step 3: As the tailings dam is raises sequentially, a number of subsequent perimeter embankments are constructed one by one on top of the consolidated and desiccated tailings beaches (Fig. 1(c)).

In step 2, there are two excavation methods available, by machine and by hand-dug. For large tailings impoundments, bulldozers and loaders are often used to construct the perimeter dikes. However, for small tailings impoundments, workers usually use shovels to dig sandy material from the tailings beach to construct the perimeter dikes, which is inefficient.

The most important requirement in using the upstream construction method is that the tailings beach must form a solid foundation to support the next dike. Also, in order to provide a stable foundation for the next dike and a good working platform, there is restriction on the use of the

Fig. 2 Location of Shifengshan copper mine

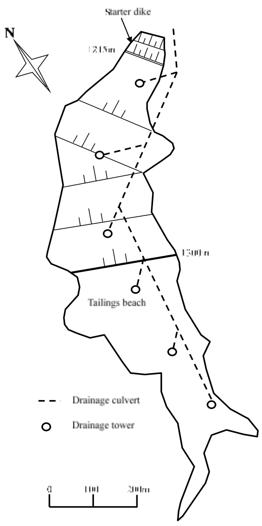


Fig. 3 The plan of the first phase of the Zhelamuqing tailings impoundment designed in 2000

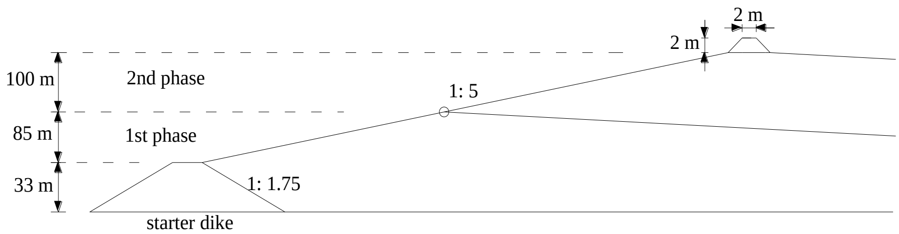


Fig. 4 Construction of the Zhelamuqing tailings impoundment

upstream construction method. In general, at least 40-60% of the tailings slurry should consist of sand size particles for this method to be successful.

3. Shifengshan copper mine and its tailings disposal system

3.1 Shifengshan copper mine

The Shifengshan copper mine is located in the central area of Yunnan province, China (Fig. 2). The Shifengshan copper mineralization zone was a part of the Yimen copper mineralization zone which is a porphyry copper deposit discovered by the Kunming geological exploration team in 1953. The mine was built in 1958 and started operating in 1960. An underground mining method, consisting of adits with blind vertical shafts, has been used. A sublevel caving method was selected. So far, it has been mined for over 50 years. With the depletion of ore resources, the mine was in a period of declining output. It is predicted that mining operations will cease in ten years. The capacity of mineral processing at the mine is 800,000-900,000 tonnes per annum.

3.2 Tailings disposal system in the field

Since the early 1990s, according to the Chinese national environmental protection legislations and regulations (TB10501-1990), the tailings disposal facilities of all mines must be commissioned at the same time as mine operations.

Based on the investigation of site topography and

Table 2 Storage capacity per year and dam wall height during tailings pond operation

Time (year)	Total storage capacities (10^4 m^3)	The dam crest elevation (m)	Raise height (m)
1	80.84	1238.0	23.0
2	161.68	1255.0	17.0
3	242.51	1272.0	17.0
4	323.50	1284.5	12.5
5	404.19	1295.0	10.5
6	485.03	1305.0	10.0
7	568.86	1314.0	9.0
8	646.70	1322.5	8.5
9	727.54	1330.5	8.0
10	808.38	1338.5	8.0
11	889.21	1346.0	7.5
12	970.05	1353.5	7.5
13	1050.84	1361.0	7.5
14	1131.73	1368.5	7.5
15	1212.56	1375.5	7.0
16	1293.40	1381.5	6.0
17	1374.24	1387.5	6.0
18	1455.08	1392.5	5.0
19	1535.91	1397.5	5.0
20	1549.17	1400.0	2.5

*The top of starter dike is at elevation of 1215.00 m

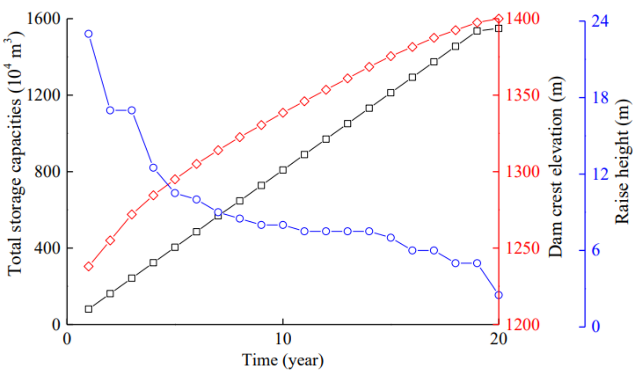


Fig. 5 Total storage capacities, dam crest elevation and raise height during tailings pond operation

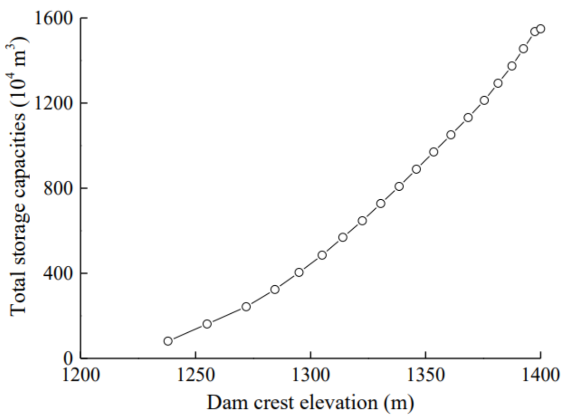


Fig. 6 Total storage capacities versus dam crest elevation

environment around the copper mine, a mountain valley named Zhelamuqing, was selected as the tailings disposal area. The project cost is 5.4 million dollars and was commissioned in January 2001. A cross valley tailings impoundment was built for which the conventional upstream method was used for the construction of the tailings dam raises as shown in Fig. 3. The tailings slurry was discharged into the pond through multiple spigots. The starter dike, constructed with locally available rockfill material, is 33 m in height. The crest width is 5 m with an upstream slope of 1V:1.75H and a downstream slope of 1V:2H.

Based on the need of the mine production, the construction of the Zhelamuqing tailings impoundment was completed in two phases (Fig. 4). The tailings dam wall heights of the first and second phases were designed to be 85 m and 100 m, respectively. The total height of the dam including the starter dike will be 118 m in the first phase and 218 m in the second phase. The wall of the tailings dam will be built at a 1V: 5H slope. The tailings dam consists of many subsequent perimeter dikes (bunds). Each perimeter dike, 2 m in height and 2 m in crest width, was constructed with coarse sands excavated by hand from the tailings beach.

Six reinforced concrete drainage towers and one reinforced concrete culvert (1.5 m in diameter) were constructed along the bottom of the dam to discharge the pond flood (Fig. 2). Due to the topography between the processing plant and the tailings impoundment site, pumping and piping were used to transport the tailings slurry to the tailings impoundment. The design capacities of the first phase and the second phase of the Zhelamuqing tailings impoundment were 4,445,300 m^3 and 15,491,700 m^3 for wet tailings, respectively. The total design life is 20 years. The tailings dam was raised at an average rate of 9.25 m per year, as shown in Fig. 5 and Table 2, which is the fastest construction rate in China. Fig. 6 shows the increasing trend of total storage capacities with the dam crest elevation.

3.3 Serious problems during the Tailings Storage Facility (TSF) operation

It was found that there are two serious problems that needed to be solved during the operation of the Zhelamuqing tailings impoundment as follows:

(1) In order to meet the mine production targets, the construction rate of subsequent tailings dams for the first five years was very fast, as shown in Table 2. The dam wall was raised 23 m in the first year, which is far more than the normal rise rate about of 4 m to 6 m per year.

(2) Due to the site topography limitation and the relatively steep slopes on both sides of the mountain valley at the tailings pond site, the axis of the dam was relatively short, about 260m at the longest, therefore, it could not be divided into three subarea. In practice, for perimeter dike construction and dam slope stability, the beach along the dam axis direction is divided into three subareas namely the discharging tailings area, the drying area and the perimeter embankment construction area.

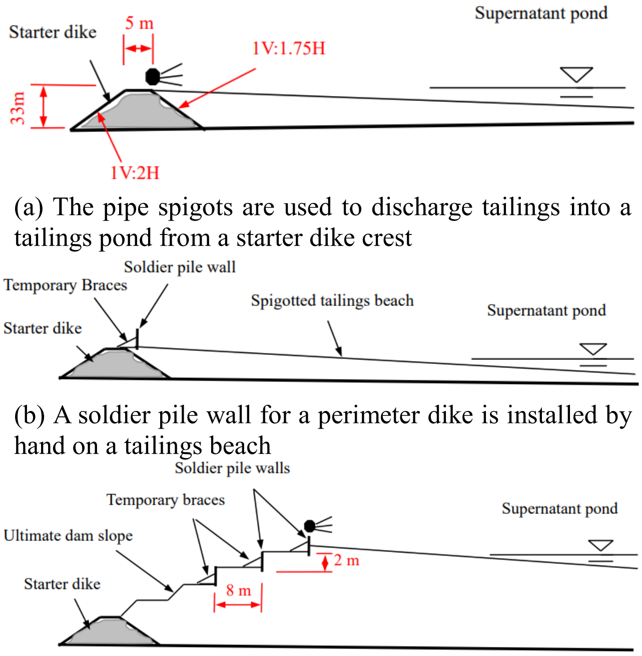
During the design stage, these two problems were not

Fig. 7 Tailings dam constructed using the TCM at the Zhelamuqing tailings impoundment

appropriately considered in the original design. The tailings dam was still constructed based on the original design. Using the conventional upstream method, each perimeter embankment was initially constructed using coarse sands excavated by hand from the tailings beach. During the process of perimeter embankment construction, however, it was hard for workers building embankments by hand to meet the mine production target. For example, the tailings dam was raised 23 m in the first year, which means 11.5 perimeter embankments were built by hand. Such a workload was too much for workers to complete in a short time. Additionally, the dam axis was too short to be divided into three subareas on the tailings beach, which resulted in difficulty in beach construction and excavation.

Therefore, tailings slurry from the mill was either stopped or was illegally discharged to the nearby river while embankments were constructed. This caused significant economic losses and had serious negative impacts on the surrounding environment.

In order to solve this adverse situation, site technicians tried to increase the height of the perimeter embankment from 2 m to 4 m, but this effort did not effectively resolve the problem. This way not only increased the labor intensity of workers, but also increased the time of embankment construction.



(a) The pipe spigots are used to discharge tailings into a tailings pond from a starter dike crest

(b) A soldier pile wall for a perimeter dike is installed by hand on a tailings beach

(c) The TCM tailings dam is raised progressively along with tailings discharge

Fig. 8 Schematic of the template construction method of tailings dam

4. A template construction method (TCM) and its application

Within the frame work of the conventional upstream construction method, a new upstream method of constructing tailings dam, namely a template construction method (TCM) (as shown in Fig. 7), was proposed to solve these problems. Comparing two construction methods, the TCM only uses wooden plates to temporally build each perimeter wall for raising the tailings dam, does not need to directly build each perimeter embankment using excavated sandy material from the tailings beach.

4.1 Template construction method (TCM)

As stated above, the proposed TCM was based on the conventional upstream method. The stages of the TCM for tailings dam construction are illustrated in Fig. 8, as follows:

Step 1: A starter dike (Fig. 8(a)) is constructed using excavated borrow materials, based on structural and drainage requirements, as well as the processing mills start-up needs. In order to keep the phreatic surface as low as possible in the tailings dam, the construction materials consist of rock blocks, so the wall has high permeability.

Step 2: The tailings slurry is discharged peripherally from dam crest to fill the pond and to create a tailings beach with a lean slope towards the supernatant pond.

Step 3: When the tailings beach rises to half of the design height, a row of soldier piles with braces at regular intervals are installed on the tailings beach in the direction

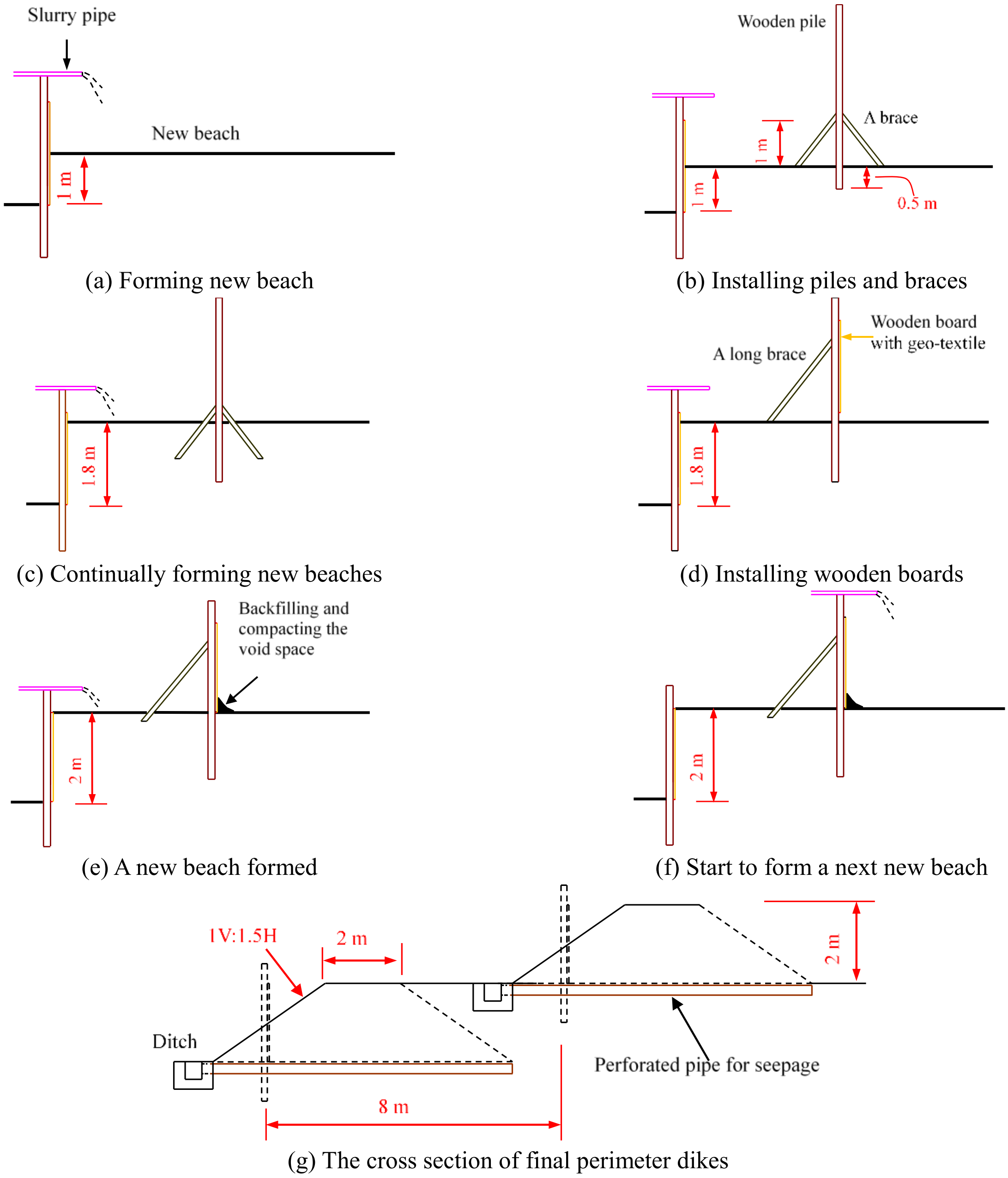


Fig. 9 The construction process of a soldier pile wall

Table 3 Tests results of physical and mechanical properties of tailings samples

Parameters	Silt and clay
Unity weight γ (kN/m^3)	19.8-20.6
Specific gravity Gs	2.82-2.83
Void ratio e	0.64-0.68
Water content w (%)	15-18
Plasticity index PI (%)	5-8
Cohesion c' (kPa)	16.1-23.6
Angle of friction ϕ' (°)	18.2-21.6
Coefficient of permeability (cm/s)	3.42×10^{-4}- 5.61×10^{-5}

of the dam axis. After the tailings beach nearly reaches its design height, horizontal timber boards are installed as laggings and braces. Geotextiles, as filter-liner, are also installed on the timber boards. At that time, a soldier pile wall is formed to increase the storage capacity. The tailings slurry is continually discharged until the beach reaches the design height. And then those discharge pipes are moved and installed on the top of the soldier pile wall so that they can discharge to form the next tailings beach (Fig. 8(b)).

Table 4 Chemical characteristics of water from the pond (unit: mg/L)

CL^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}	Ca^{2+}	Mg^{2+}	$K^+ + Na^+$	pH
106.4	104.8	164.8	30	56.1	14.6	122.1	8.34

Step 4: After 3 to 4 stages as the dam rises, the first soldier pile wall constructed can be dismantled and removed, and the materials, such as timber piles and

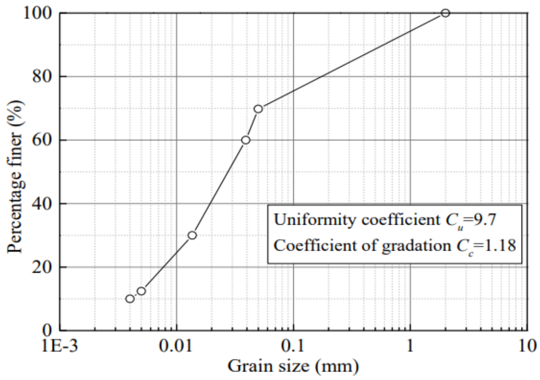


Fig. 10 Particle size distribution of the tailings

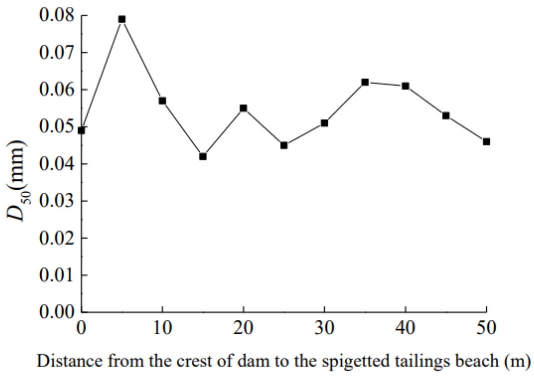


Fig. 11 Tailings particle-size distribution curve on the spigotted tailings beach (Note: D_{50} = mean diameter of soil particle)

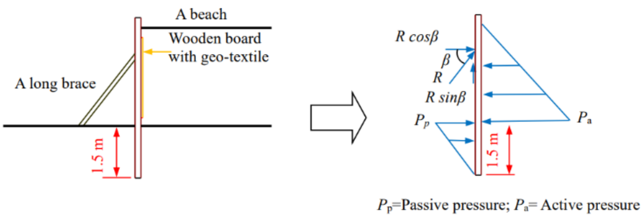


Fig. 12 A force and lateral earth pressure diagram on the solider pile walls

wooden boards, can be reused for the next soldier pile wall. Also, this part of the uncovered dam slope face is flattened in accordance with the design slope to form the ultimate dam slope (Fig. 8(c)). A soldier pile wall is a temporary structure and its construction is straightforward.

4.2 Application of TCM in the Shifengshan copper mine

As stated above, Shifengshan Copper Mine encountered serious problems in using its new TSF (tailings storage facility). In order to continue using this new TSF and also to avoid large economic losses, the innovative TCM has been adopted.

At the Zhelamuqing tailings impoundment, the construction of a soldier pile wall involves three main stages, as follows:

(1) Constructing a row of soldier piles at regular intervals (typically 1.0 m to 1.5 m) along a tailings beach. As shown on Fig 9(a) and 9(b), when the tailings beach rises 1 m (the design height of perimeter dike is 2 m), a row of piles are installed on the beach. The pile bottom should penetrate 0.5 m below the ground surface and two braces should be fixed to the left and right sides of the pile to provide the stability.

(2) Installing horizontal timber sheeting (lagging). When the tailings beach rises 1.8 m, the former two braces are firstly removed, and then a long brace is installed for each pile, horizontal timber sheeting is fixed on the front of the piles, and geo-textiles are spread and installed on the sheeting as shown in Fig 9(c) and 9(d).

(3) Backfilling the void space on the lagging toes and compacting prevents slurry flowing out (Fig. 9(e)).

After finishing the above three stages, there is a need to move the slurry pipes on top of the soldier pile wall to continue discharge to build a new beach (Fig.9f). Fig. 9g shows the cross section of final perimeter dikes and the location of the soldier pile walls as the TCM was implemented in the Zhelamuqing tailings impoundment.

4.3 Geotechnical investigations of the existing tailings dam

To ensure the success of the new method implementation, geotechnical investigations of the site were first implemented by a local geotechnical company, which included subsurface geological exploration, in-situ tests (standard penetration test, cone penetration test and elastic wave test), and laboratory tests, to obtain the subsurface profiles of the existing tailings dam and the mechanical properties of the tailings. The tailings particle composition was shown in Fig. 10. The tailings particle size distribution characteristics along the beach were shown in Fig. 11.

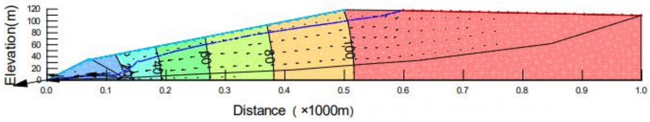
The main properties of the tailings are summarized in Table 3. The depth of the phreatic surface below the dam crest was more than 10 m. The chemical characteristics of water from the pond were tabled in Table 4. The cohesion and angle of friction were derived by consolidated undrained tests.

4.4 Lateral earth pressure on the soldier pile walls

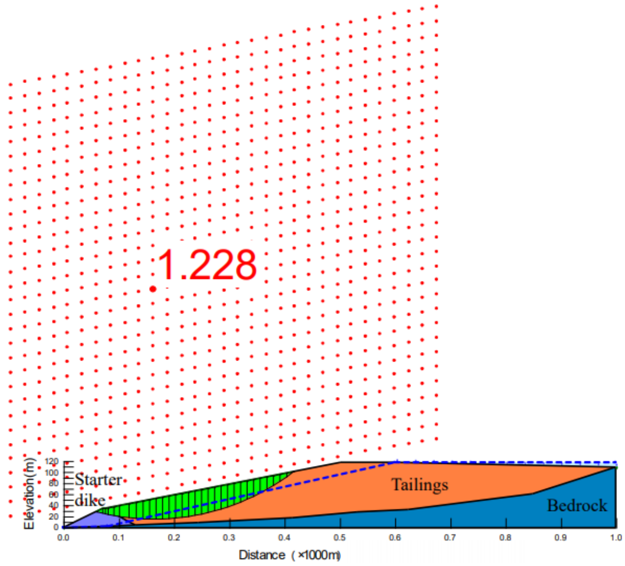
Lateral earth pressures are the primary driving factor in the design of retaining walls. Based on the results of the geotechnical investigations, the calculation of lateral earth pressure on the soldier pile walls were carried out. A force model of lateral earth pressure on the solider pile walls was constructed as in Fig. 12. In which the solider pile wall was simplified as a simple beam, and Rankine' theory of earth pressure was using to calculate both of the active pressure and the passive pressure on the solider pile walls. On the basis of these calculation results, the design of the solider pile walls was completed. In practice, the structures were also adjusted according to the actual condition during implementing.

4.5 Stability analysis of the tailings dam during phase one

On the basis of the results of the geotechnical



(a) The seepage through the tailings dam by using SEEP/W



(b) Stability analysis results for tailings dam under special condition under special condition

Fig. 13 Stability analysis results for 118 m high tailings dam

Table 5 Factors of safety calculated for the tailings dam in comparison with the criteria required by Chinese Standards

Work conditions	Normal	Flood	Flood and earthquake
Required by Chinese code*	1.3	1.2	1.15
118 m dam height (first phase)	2.32	2.16	1.23

*Code for design of tailings facilities (GB 50863-2013) (in Chinese)

Table 6 Cost of two construction methods in 2004

Item	Units	Traditional upstream method	TCM
Labor cost	Yuan/ m∗	475.2	160.3
Cost of materials	Yuan/ m	424.7	538.9
Total	Yuan/ m	899.9	699.2

∗Yuan/ m means the unit cost of perimeter dike construction in Chinese dollars per meter length

investigations, preliminary analyses were carried out by using Geo-Studio software to evaluate the stability of the 118 m high tailings dam in the first phase. The seepage analyses by using SEEP/W (GEO-SLOPE International Ltd. 2011) were first implemented to assess the seepage through the tailings dam. The soil parameters are listed in Table 3. The results of numerical simulation of seepage are as shown in Fig. 13(a).

Then Bishop's simplified method (Bishop 1955) was used to analyze the stability of tailings dam under different conditions imposed in Chinese code for design of tailings facilities (GB50863-2013). For the Bishop's simplified method, the factor of safety (FOS) is written as,

$$FOS = \frac{\sum_{i=1}^{i=n}[c'b_i + (W_i - u_i b_i)\tan\phi']\frac{1}{m_i}}{\sum_{i=1}^{i=n} W_i \sin\alpha_i} \tag{1}$$

$$m_i = \cos\alpha_i + \frac{\tan\phi' \sin\alpha_i}{FOS} \tag{2}$$

where n is the number of vertical slices; b_i is the width of the ith slice; α_i is the angle of the ith slice bottom with the horizontal; W_i is the weight of the slice; c' and ϕ' are, respectively, the cohesion and the angle of friction that develop along the potential failure surface; u_i is the average pore water pressure at the bottom of the ith slice. Note that term FOS is present on both sides of Eq. (1). Hence, a method of successive approximations must be adopted to find the value of FOS.

To conform to the national technical code, seismic load and pore pressures were taken into account in calculating the safety factor of the tailings dam. An earthquake peak ground acceleration of 0.2 g was used, based on the location of the mine, which is classified as earthquake zone VIII. The slope stability was carried out using analysis Geo-studio Slope/W software to determine the minimum factor of safety (Fig. 13(b)). The stability analysis results are tabulated in Table 5. The results show that the tailings dam at phase one (118 m high) is stable.

4.6 Effect of application of TCM in the Shifengshan copper mine

The TCM has been successfully used for Zhelamuqing tailings impoundment since 2004, and the tailings dam wall reached 95 m in height with 46 subsequent perimeter dikes in March 2015, as shown in Fig. 14. The total height of the dam was 128 m. The first phase construction of the Zhelamuqing tailings impoundment has finished, and now it has entered the second phase. A satellite image of the current situation of the tailings pond was shown in Fig. 14d. It demonstrated that the Zhelamuqing tailings impoundment has been operated well. Compared to the conventional upstream method, the TCM is relatively easy and fast to construct, and cost-effective. The major advantages of the TCM are:

(1) The TCM is relatively simple. The key to the TCM is to construct a soldier pile wall on the tailings beach. The construction of soldier pile walls is relatively simple and does not require very advanced construction techniques.

(2) Soldier pile walls can be built in a short time, which can satisfy the need for rapidly raising the tailings dam.

(3) The TCM is also inexpensive and cost-effective. The construction of a perimeter dike using the conventional upstream method costs about 75,000 dollars and the cost of the TCM for the same perimeter dike construction is about 55,000 dollars. After using the TCM for the Zhelamuqing tailings impoundment, the mining company has saved nearly 100,000 dollars each year since 2004. Detailed comparison between two method costs is shown in Table 6.

(a) The tailing dam slope face through TCM

(b) Discharging slurry though the top of a solder pile wall

(c) Final tailings dam slope face

(d) Satellite image of the current status of the Zhelamuqing tailings pond (from Google map on Mar., 2015)

Fig. 14 View of Zhelamuqing tailings impoundment

5. Conclusions

Based on the conventional upstream method, a template construction method (TCM) has been proposed to provide an alternative way to construct a raising tailings dam. The proposed TCM has been successfully implemented at the Zhelamuqing tailings impoundment for the Shifengshan copper mine since 2004. And its advantages as stated above is relatively easy and fast to construct, and cost-effective. However, as it is a new construction method, some improvements would be worth considering in the future. For example, steel formworks and steel piles, which are easy to install, could be used to replace the timber pile and wood board for constructing the temporary perimeter wall on the beach. At the same time, the constructability of the wall can be greatly improved. With respect to the safety of the tailings dam, a stability assessment for the tailings dam should be carried out in detail and lateral earth pressures should be also considered carefully in the design of the soldier pile wall.

Acknowledgments

The authors are very grateful to Dr. Jiayi Shen and Mr. John Craig for their useful comments. This research has been funded by the National Natural Science Foundation of China (No. 11372363) and the Ganpo (Jiangxi Province) 555 Elites Prize.

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