# Failure Forecast Warning Research and In-Situ Online Monitoring of Tailings Dam Engineering

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**Abstract.** Based on the theoretical research results about the instability mechanism and online monitoring in more than ten years, as well as the problems about tailings dam instability, in-situ online monitoring and the failure forecast warning are researched deeply and systematically. In order to reveal the particularity of tailings dam structure, the complexity of deformation and the risks of dam failure, the failure mechanism of tailings dam is researched, the in-situ online monitoring systems are used on some tailings dams. The forecast warning method and risk control measures of tailings dam are presented to give the supports of theory and technology for the safety and failure prevention. A management process which is scientific, informatization, real-time, intelligent, networking and digitizing is realized. This makes a fully progress of mine safety production, scientific management, value-added efficiency, scientific innovation and technology progress.

**Keywords:** Tailings dam engineering · In-Situ online monitoring · Failure forecast warning


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## 1 Introduction

With the continuous mining of mineral resources, the number of tailings continues to increase, constantly heightening the dam, as a result that the number of tailings dam accidents is increasing. As the tailings downstream residents living and important industrial facilities on the rise, the loss caused by dam failure accidents also showed a trend of increasing. The safety problems of tailings dam has aroused the wide attention of the society.

The failure accidents of tailings dams are kinds of major hazard. The structure of the tailings dam is very complicated, so its stability is affected by many factors. First, the tailings dams which have complex structures are three-dimensional bodies at macro. They are made of different aggregates with different gradings, such as clays, tailings and rock at micro. These dams have complex structure characters obviously. Second, tailings dams are used to store tailings transported to the tailings ponds by water. The solid particles in the dams can be washed out under the seepage of water. Third, the tailings dams are under the state of high potential energy, and so on. These will lead to the hazards of tailings dam failure.

Due to many unfavorable factors influencing tailings dam, so tailings dam breaks have frequently occurred at home and abroad, such as Stave tailings dam failure in 1985 in Italy which killed nearly 300 people and caused huge losses of property, the tailings dam failure of Xinta Mining happened at 7:58 on September 8, 2008 in Xianfen county, Linfen city, Shanxi Province of China, killed 277 people, missed 4 people and injured 33 people. The direct economic losses amounted to 96.192 million yuan. On January 25, 2019, a dam-breaking accident occurred in an iron mine tailing dam in Brazil, which killed 235 people and left 35 missing.

In order to solve this serious problem, some developed countries in the world such as America, Japan have built the scene real-time data acquisition, data analyzing and security alarm monitoring and early warning system on the safe operation of the tailings monitoring [1]. U.S. Bureau of Reclamation GeoVISION Company developed the GeoVISION system. The system will analysis monitoring data by telephone, satellite communications systems and computer [2]. Italy developed a series of dam safety monitoring software. It can be used for all kinds of information storage, management, and analysis and model, which provide decision support for dam safety management [3].

The safety monitoring of tailings dam in China starts relatively late. Before 2005, the tailings dam running status can only rely on intuitive experience to judge [4]. Since 2005, China academy of safety science are systematically studying the surface displacement GPS monitoring technology and seepage monitoring technology of tailings dam, and developed the online monitoring system for the tailings dam. The systems are capable of displaying the real-time data and inquiring historical data of dam displacement, saturation line and water level. It is successfully applied in engineering practice, and achieved good results [5–10].

In this paper, we study the tailings dam failure mechanism and determine the key control as tailings monitoring indicators, developing tailings dam online monitoring system at the same time, and study the tailings dam comprehensive early warning method, in order to realize the tailings dam can monitor automatically and early warn early. It is of great significance to guarantee the safe and stable operation of the tailings.

## 2 Failure Mechanism of Tailings Dam

For the tailings dam accident statistics, since 1965, a total of 60 accidents happened at home and abroad. Seepage failure and floods account for 93.3% in the accidents [11]. Therefore, understanding dam failure mechanism caused by seepage damage and floods is particularly important.

### 2.1 Failure Mechanism of Tailings Dam Caused by the Seepage

After the tailings into production, with the progress of discharging tailings sand, at the dam upstream water pressure, the water will have to flow through the rock pores and cracks in the dam foundation, which is the seepage. The existence of seepage water will exert a force on tailings sand, the seepage pressure. With the increase of water level, further increase of pore water pressure in tailings dams, can occur tailings piping, flow of soil, causing damage to the dam and dam foundation, which might lead to the dam failure.

There are two conditions for the occurrence of seepage damage in the dam. One is the internal leakage in the dam passage. The other is that the actual dam seepage gradient is greater than the impermeability. According to the dam path, combined with the destruction caused by the seepage of dam accident, the cause of seepage failure is obtained in Fig. 1.

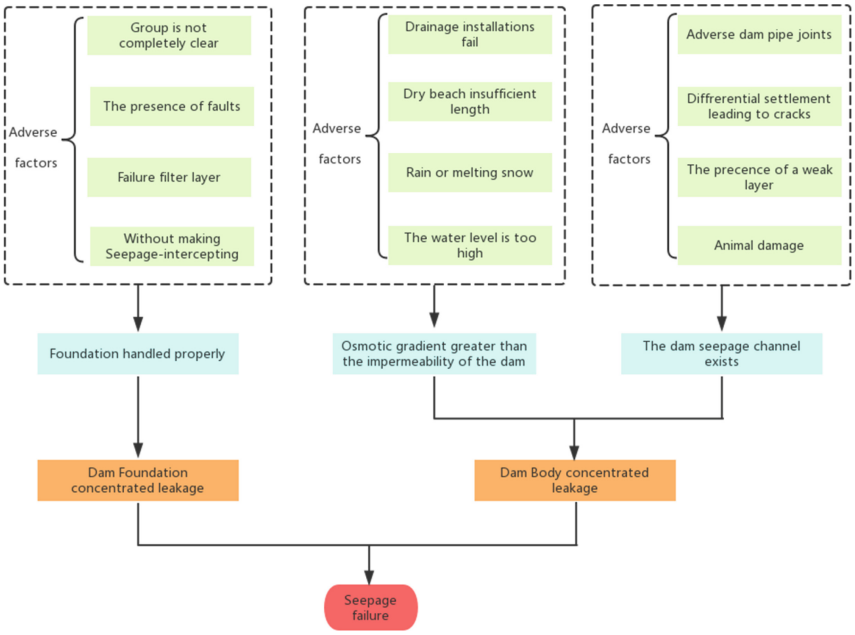


**Fig. 1.** The cause of seepage failure.

It can be seen from Fig. 1 that after the tailings dam is put into production, the exploration, design and construction have not changed. Therefore, it is necessary to prevent seepage damage from the daily production management of the controlled water level, extend the length of the dry beach, reduce the saturation line, and adhere to the uniform emission of tail ore. Quantifiable indicators are mainly water level, dry beach length and saturation line. These indicators need to be closely monitored.

## 2.2 Failure Mechanism of Dam Caused by the Tailings Overtopping

The main cause of tailings overtopping are of three types, one is inadequate flood control capacity including inadequate flood storage capacity and drainage facilities section is too small or damaged, clogged. The second is the excessive flood. (Suffered more than the standard), resulting in overtopping dam; Third, mismanagement or emergency measures. According the dam path, combined with the destruction caused by tailings overtopping of dam accident, obtained the cause of seepage failure in Fig. 2.

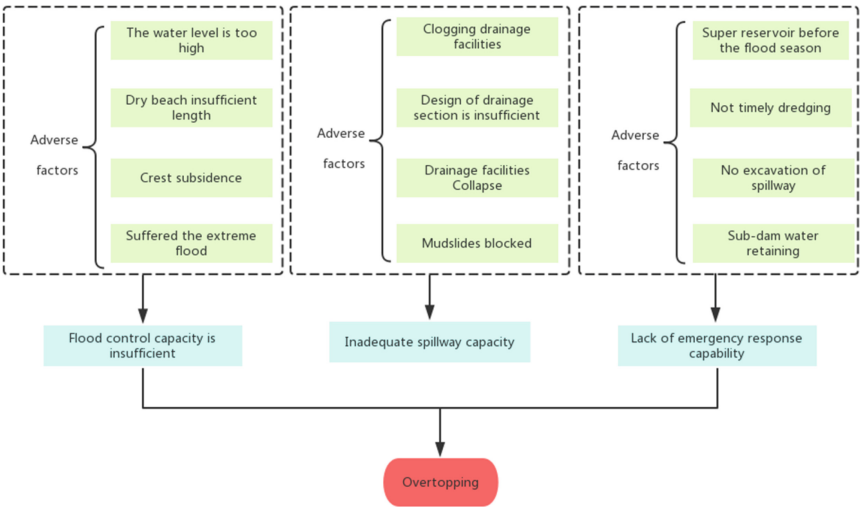


**Fig. 2.** The cause of tailings overtopping.

It can be seen from Fig. 2 that the factors causing overtopping comprise the design, construction and management of daily production and the surrounding environment. We need to do from daily production management and controlling the surrounding environment, which is lowering the water level, to extend the dry beach, on the leakage flow and real-time monitoring of atmospheric precipitation. Quantifiable indicators are mainly the water level, dry beach length, ultra-high security, drainage system leakage flow and rainfall, so these indicators must implement online monitoring, it must be strictly controlled within the safe range.

## 3 Online Monitoring of Tailings Dam Project

This paper presents a modern testing technology and equipment to achieve the security situation in the tailings dam online monitoring method. The method is based fast search algorithm using tailings line monitoring and warning system for online monitoring. System includes a control center and data collection centers and monitoring devices composed of a variety of sensors. Data collection center respectively connect to dam displacement monitoring device, seepage line monitoring device, reservoir water level monitoring devices, rainfall monitoring devices, reservoir seepage discharge monitoring device, the reservoir water quality monitoring devices and video monitoring devices. These devices collect a variety of accurate monitoring data. Using fast search algorithm for centralized monitoring data analysis and processing. On the current status of the tailings is acquired by using fast search algorithm for centralized monitoring data analysis and processing. Then determine the real-time operating conditions tailings. Tailings dam online monitoring as follows:

a. Apparent dam displacement monitoring is using the hydrostatic leveling of the tailings dam vertical surface subsidence monitoring. After the equipment arrived at the scene to use of geodetic reference method fixing reference point in stable rock and soil. After the reference point is determined using concrete mushroom pile buried 0.5 m below the surface or mounted directly on the bedrock. For internal dam horizontal displacement, using sliding-mounted inclinometer monitoring, the first use of exploration rig drilling, the aperture diameter requirements 89–110 mm, hole depth depending on the specific geological conditions, the bedrock bottom of the hole depth of not less than 2 m, bottom of the hole is not less than 2 m deep bedrock. On the hole to install inclinometer after completion of drilling.
b. Phreatic line monitoring using piezometers. Chose monitoring cross section in a typical cross section and can control the main seepage situation and is expected to appear abnormal seepage cross-sectional. Generally choose not less than three monitoring sections, and try to combine the displacement monitoring sections. Monitoring cross-section measuring points on the arrangement shall be determined by the dam structure, cross-sectional size and flow field characteristics. Monitoring points should be arranged in stacked dam crest, the initial dam upstream at its base, the leading edge of the downstream drainage body.
c. Reservoir water level gauge used for the surveillance monitor, select the measuring points in the area relatively stable water level fluctuations. Sensor requires fixed vertical installation.
d. Reservoir rainfall monitoring using rain gauge monitoring, collecting reservoir area hourly, daily, weekly rainfall. Draw historical curve diagram through the rainfall data and according to the situation of the rainfall forecast water development trends.
e. The top of beach elevation and length of dry beach monitoring laid at least three indicator in the top of beach. Combined with water level gauge readings and dry beach average slope calculated dry beach length.
f. Water flow monitoring using water level gauge and weir monitoring. In the layout at the drainage culvert outlet measuring weir and water level gauge, for real-time monitoring of water flow within the drainage culvert.

g. Water quality monitoring, according to the different treatment processes selecting different monitoring indicators. Layout different monitoring sensors monitoring water quality in the backwater area.
h. Video detection. In the top of the beach, backwater area dams, initial dam, discharge slurry pipe line set up video surveillance cameras.

The monitoring point layout of dam profile as shown in Fig. 3.

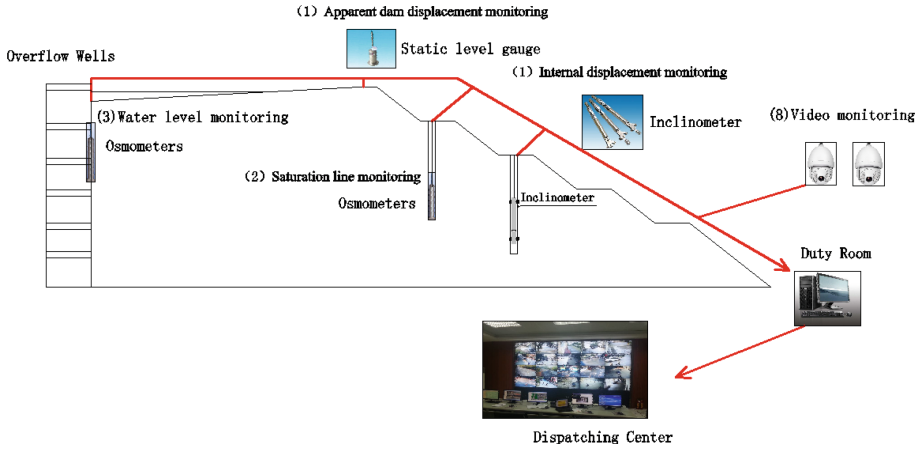


**Fig. 3.** The monitoring point layout of dam profile.

## 4 An Integrated Early Warning Method of Tailings Dam

Chinese scholars have done a lot of research in the tailings dam early warning [12–15]. It recognizes a single index cannot reflect the tailings inventory of risks and problems in the tailings dam early warning, we must establish a comprehensive evaluation system for tailings fully reflect risk and safety status. Scientific and effective integrated system determines the accuracy of early warning, therefore proposes a tailings dam comprehensive early warning method.

### 4.1 To Determine the Early Warning Alert Limits of the Indicators

a. The early warning alert limits of seepage failure

The early warning alert limits of seepage failure is critical of the accumulation of tailings seepage gradient associated with the bulk density and void ratio [16].

$$I_l = \gamma_g/\gamma_0 - (1-n) = (\Delta - 1)/(1+e) \tag{1}$$

Where $I_l$ is the critical of the accumulation of tailings seepage gradient. $\gamma_g$ is the dry weight of tailing sand. $\gamma_0$ is the severe water. $n$ is the porosity. $e$ is the void ratio. $\Delta$ is the proportion of tailing sand.

b. The early warning alert limits of saturation line depth

The early warning alert limits of saturation line is determined, should first be analyzed to determine the critical seepage saturation line, then the minimum depth with the respective rules of order are compared to determine the final control seepage line [17]. The early warning alert limits of saturation line depth as shown in Table 1.

**Table 1.** The early warning alert limits of saturation line depth.

| Dam height H(m) | $H \geq 150$ | $150 \geq H \geq 100$ | $100 \geq H \geq 60$ | $60 \geq H \geq 30$ | $H < 30$ |
|---|---|---|---|---|---|
| Saturation line minimum depth (m) | 10–8 | 8–6 | 6–4 | 4–2 | 2 |

c. The early warning alert limits of dry beach length

The early warning alert limits of dry beach length are the minimum safe tailings dam design dry beach length.

d. The early warning alert limits of reservoir water level

The early warning alert limits of reservoir water level to determine can be undertaken safely long beach method. Security dry beach length detection as shown in the Fig. 4. First of all, measure the minimum dry beach length $[L_g]$ of design flood level on the deposition beach. For measuring point a, measure the elevation of a point, the flood depth $H_t$ is

$$H_t = H_a - H_s \tag{2}$$

Where $H_a$ is the design flood water level, the minimum dry beach length corresponding sedimentary beach elevation. $H_s$ is the situation level elevation.

The flood depth $H_t$ and the actual minimum flood depth $[H_t]$ comparison, if $H_t \geq [H_t]$ accord; on the contrary, are not eligible.

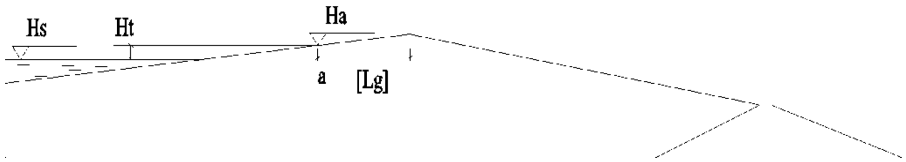


**Fig. 4.** Security dry beach length detection schematic diagram.

### 4.2 Flood Routing

The situation level data, the amount of flood storage and vent flow obtained through online monitoring system can be made flood routing by water balance method. Flood Routing should give the highest attainable reservoir water level and time of occurrence, the shortest length of dry beach key parameters, and other ultra-high security in this rain. Key parameters obtained by the flood routing are flood routing metrics. Making a direct comparison between the flood routing indicators and early warning indicators limits, if the police exceeded the limit, then warning, and giving the appropriate treatment plan, if all indicators are below the limit in police, then seepage analysis is the next step.

### 4.3 Seepage Analysis

According to data obtained Flood Routing using flow analysis method for dam seepage analysis get seepage pressure field, saturation line, and hydraulic gradient and flow rate of permeate flow analysis indicators. The seepage analysis of indicators and early warning indicators alarm limits are compared, if exceeded, early warning, and given the appropriate treatment plan, if not, then the next step stability analysis.

### 4.4 Anti-sliding Stability Analysis

According to the results of the seepage analysis, the physical and mechanical properties of the tailings in the upper and lower parts of the water level are obtained. Based on fast search algorithm for real-time analysis of tailings, the most dangerous sliding surface for tailings safety coefficient. The safety factor and design procedures contrast, if the value is less than the design rules of order, the early warning, and given the appropriate treatment plan.

### 4.5 Early Warning Method

Online monitoring data and flood routing systems analysis obtained indicators, seepage analysis indicators, safety factor compared to the value of system preset alarm value monitoring indicators and warning safety factor, if a system of monitoring indicators more than the preset alarm value, the automatic real-time early warning tailings security situation, released alert degree based on values beyond the scope of early warning, and release the appropriate treatment plan. The Fig. 5 shows the flow chart of the online monitoring system.

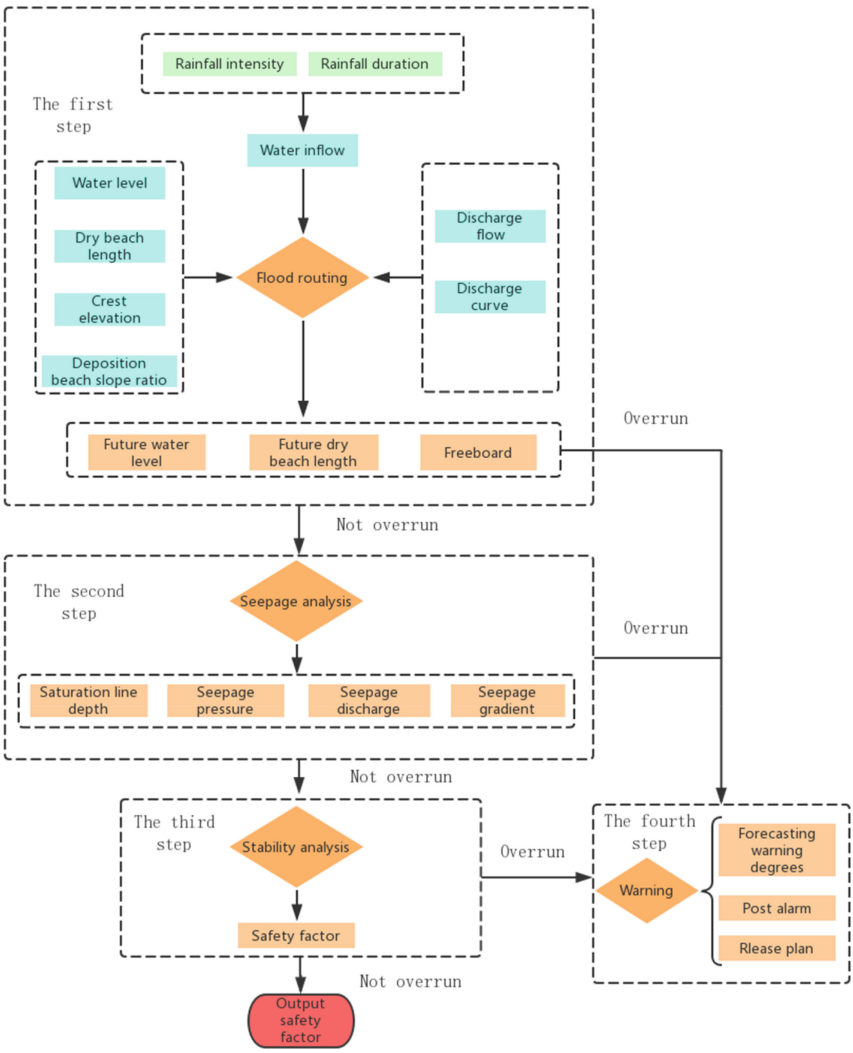


**Fig. 5.** The flow chart of the online monitoring system.

## 5 Conclusion

This paper focuses on the failure mechanism of the tailings dam, tailings dam line monitoring, an integrated early warning methods based on online monitoring of the tailings dam, the following conclusions:

a. The main cause of the tailings dam failure is overtopping and seepage failure, proposed tailings dam failure mechanisms, pointed out that the occurrence and development of dam failure is caused by the improper survey and design, construction, management, emergency improper and interrelated results in turn.

b. Proposed a tailings dam-line monitoring system based on modern technology and detection equipment, will implement the data automatic analysis, accurate evaluation of the tailings safety status and risk early warning, protect the safety of tailings dam stability and normal operation.
c. Based on tailings dam online monitoring, put forward a comprehensive early warning method, not only can realize the overrun warning single warning index, and can realize comprehensive evaluation of the safety of tailings dam, and at the same time of early warning, will release of dam failure alert as well as the corresponding warning degrees, and the most reasonable treatment plan is given.

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