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Construction of a Dry Ash Dam with Soilbags and Slope Stability Analysis

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Abstract: In thermal power plants, it is necessary to build ash dams to store fly ash, which is the by-product after the combustion of coals. To solve the problem of lacking rockfill materials in Africa, a new technology of constructing ash dams using solibags filled with local sands is proposed and the method of analyzing its slope stability is suggested. The design of the ash dam using soilbags in Lamb Thermal Power Plant of Kenya is introduced in detail. The slope stability of the soilbags-constructed ash dam was analyzed by adopting the suggested method. The results show that the soilbags filled with ash or sands have high compressive strength, and the primary dam constructed with soilbags can effectively retain the backfill ash and the stacking dam reinforced with soilbags can stand stable even with the slope of 1:1.5.

1. Introduction

With the increasing construction quantity and scale of the thermal power plants, the emissions of fly ash are also increasing. As the main industrial waste of the thermal power plants, the fly ash can bring about a serious pollution to the environment if it was discharged directly without appropriate treatment, such as producing dust, polluting the atmosphere and silting the river. Besides, the toxic chemicals in the fly ash is harmful to humans and living creatures [1], [2]. However, it was shown by researchers [3], [4] that, the comprehensive utilization of fly ash has a very broad prospect. Due to its advantages such as large quantity, light weight, high strength and good permeability [5], the fly ash can be used as a basic material [6] when preparing building materials including bricks, blocks, cement and concrete, etc. Moreover, it can not only be made into fertilizers and soil amendments [7] but also be used for waste water treatment and flue gas desulfurization [8], [9]. Nevertheless, the quantity of fly ash in utilization is still far less than the total quantity discharged by thermal power plant, so it is necessary to solve the storage problems of the remaining large amount of fly ash.

At present, the most world-widely used storage method is to construct an ash dam. And ash dam is an important part of the thermal power plant [10]. It is composed of the primary dam and the stacking dam. In engineering, the key method of constructing ash dams is by installments. Figure1 shows the schematic diagram of a conventional ash dam and the construction stages. Firstly, the initial dam is built with soils and stones. After the ash bank behind of the initial dam is compacted by fly ash, the fill dam will be built layer by layer until reaching the designed dam height. Meanwhile, the local soils and stones will be used to build the slope of the fill dam. According to the “Design Specification of the Dry Ash-storage Field of the Thermal Power Plant (DL/T5488-2014)” of the People's Republic of China, there should be enough construction materials near the ash field. The initial dam is usually the rockfill dam
or the masonry dam, using rockfill materials with compressive strength greater than 30MPa, weathering coefficient greater than 0.75 and rock softening coefficient greater than 0.8. The slope of the fill dam is built with soils and stones with weak permeability. The height of each layer of the fill dam should be 5–10 meters, and the gradient of the slope should be 1:3–1:4. However, for the thermal power plants where the traffic conditions are poor and the local materials are not suitable for dam construction, such as the Kenyan Ram Thermal Power Plant in Africa, the cost of purchasing and transporting dam construction materials is very high, which results in a high investment by using the traditional materials such as rockfills to construct the ash dams. Therefore, a new method to construct the ash dam by using the soilbags is proposed in this paper to make full use of local construction materials and reduce the dam construction costs.

Figure 1. Schematic view of Conventional Ash dam construction Scheme

Recently, Matsuoka and Liu studied the strengthening mechanism and engineering characteristics of the soilbags [11]-[14]. They found that soilbags had a high bearing capacity, good integrity, high ability in resisting deformation, make use of local materials and low construction cost. What’s more, it had enough durability if the soilbags were buried in the soil or protected by the concrete pavement from the sunlight. Owning to these advantage, soilbags have been widely used in many geotechnical engineering, such as road foundation [15], slope protection [16] and dam reinforcement [17]. In this paper, the soilbags filled with local sands are firstly stacked on the slopes of the ash dam, which not only solve the problems that there is not enough rockfill materials to construct the ash dam but also take full advantage of the local materials.

Therefore, in this paper, based on the principle of soilbags technology, a construction method of the ash dam located in the Kenyan Ram Thermal Power Plant in Africa using soilbags filled with local sands is proposed for the first time. Furthermore, the slope stability of the ash dam is studied by using the limit equilibrium method.

2. Reinforcement Principle of Soilbags

As a kind of geotextile fabric, soilbags are filled with soil or soil-like materials. For a long time soilbags are widely used to raise embankments during floods and to construct temporary structures after disasters as well as other temporary projects. They are seldom applied in the permanent buildings such as the slope reinforcement, which is mainly because of the lack of understanding of the characteristics of soilbags and the incomplete appearance of woven bags under the long-term irradiation of ultraviolet light. Recently, Matsuoka and Liu [18] found that soilbags had a very high compressive strength through experimental tests and theoretical analysis. The bearing capacity of a soilbag with size of 40 cm×40 cm×10 cm (length × width × height) is more than 20 tons, which is equivalent to 1/5 ~ 1/10 of the concrete block strength.
Figure 2 is a schematic illustration of the reinforcement mechanism of soilbags. The overall strength of soilbags is closely related to the friction strength between soil particles in the soilbags, which is developed due to the interparticle normal contact force \( N \). Under the upper vertical pressure, the compression deformation of the soil causes the extension of the bag perimeter, which leads to the tensile force \( T \) along the bag. The tensile force \( T \) along the bag enhances the contacts between the soil particles inside the bag, resulting in an increase in the normal contact forces \( N \) and the frictional forces \( F \) between the soil particles \( (F=\mu N) \), where \( \mu \) is the friction coefficient. Therefore, the overall strength of soilbags is improved.

![Figure 2](image_url)

**Figure 2.** Schematic view of reinforcement mechanism of soilbags

Figure 3(a) shows a two-dimensional soilbag subjected to the principal stresses \( \sigma_{yy} \) and \( \sigma_{yy} \). The material inside the soilbag is assumed to be frictional and granular. At constant volume condition, under the actions of \( \sigma_{yy} \) and \( \sigma_{yy} \), the total perimeter of the bag usually increases because the soilbag becomes flatter, as shown in Figure 4. Subsequently, the bag becomes flat and a tensile force \( T \) is developed high tensile forces. The tensile force \( T \) produces an additional stress on the particles inside of the bag with components \( \sigma_{yy} = \frac{2T}{B} \) and \( \sigma_{yy} = \frac{2T}{H} \), in which \( B \) and \( H \) are the width and height of the soilbag, respectively. As illustrated in Figure 3(b), the stresses acting on the particles are thus the combination of the external stresses and the stress caused by the tensile force \( T \). At failure, the major principal stress \( \sigma_{yy} \) can be calculated by:

\[
\sigma_{yy} + \frac{2T}{B} = K_p \left( \sigma_{yy} + \frac{2T}{H} \right)
\]

Therefore

\[
\sigma_{yy} = \sigma_{yy} K_p + \frac{2T}{B} \left( \frac{B}{H} K_p - I \right)
\]

in which \( K_p = \frac{(1+\sin \phi)}{(1-\sin \phi)} \) is the lateral earth pressure ratio at passive state. For cohesive-frictional materials, the following relationship exists between the major and minor principal stresses at failure:

\[
\sigma_{yy} = \sigma_{yy} K_p + 2c \sqrt{K_p}
\]

Where the apparent cohesion \( c \) is thereby expressed as \([11]\):

\[
c = \frac{2T}{B \sqrt{K_p}} \left( \frac{B}{H} K_p - I \right)
\]
3. Design of an Ash Dam with Soilbags

3.1. Geological Condition of the Project

The Lamb Thermal Power Plant is located in the north side of a Navy Terminal, which is in the northwest area of Manda Island, Kenya, with total installed capacity of 1080MW. Through geological prospecting, the region of the Thermal Power Plant is covered by Quaternary tectonics within depth of 50 meters, and the lithology is dominated by sand and clay. Sand I is mainly distributed in the depth of 0 ~ 15 meters, forming the bearing stratum of the foundation of the structure. The basic physical and mechanical parameters of sand I are: unit weight $\gamma = 17.2\text{kN} / \text{m}^3$, cohesive strength $C = 3.2\text{kPa}$, internal friction angle $\varphi = 35.4^\circ$, and elastic modulus $E_0 = 18.2\text{MPa}$. The clay and sand II, which are distributed in the depth of 12 ~ 30 meters and 30~ 50 meters respectively, constitute the substratum of the structure foundation. The basic properties of clay are $\gamma = 18.5\text{kN} / \text{m}^3$, $C = 60.3\text{kPa}$, $\varphi = 12.6^\circ$ and compression
modulus \( E_s = 9.75 \text{MPa} \) while the properties of sand II are \( \gamma = 21.1 \text{kN/m}^3, C = 5.1 \text{kPa}, \varphi = 42.3 ^\circ \) and \( E_0 = 25.6 \text{MPa} \).

According to geological data, there are not appropriate dam construction materials on the site of the power plant. Therefore, the solibags are used in this project and are filled with local materials to pile on the slope of the dam.

### 3.2. Properties of Soilbags

The soilbags used in the project are woven polypropylene (PP) bags filled with local sand. The size of the soilbag is 120 cm long, 60 cm wide and 30 cm high. The mechanical properties of the soilbags are as follows: the unit mass is 150 g/m²; the radial and latitudinal tensile loads are greater than or equal to 30 kN/m and 25 kN/m, respectively; the radial and latitudinal elongations are both less than or equal to 25%.

As the Lamb Thermal Power Plant is located near the equator where ultraviolet rays are strong, the durability of soilbags is particularly important to the long-term behavior of the ash dam. Therefore, the accelerated aging tests were carried out on the soilbags mixing with 1% UV resistant materials. The test equipment was the Type-Ci5000 artificial weathering test chamber made by the ATLAS company of United States. The light source is the water-cooled xenon arc lamp (5kW ~ 14kW) with irradiance \( 0.5W/m^2 \cdot \text{mm} \). The temperature of the blackboard is \( (65 \pm 3) ^\circ \text{C} \) and the relative humidity is \( (65 \pm 5) \% \). When conducting the tests, the soilbags with 1% UV resistant materials were put in the test chamber and were exposure under the ultraviolet rays of the xenon arc lamp for 1200h. The tests would be ended until the retention rate was no more than 50%. The retention rates of tensile strength and elongation were recorded at the time of 0h, 300h, 600h, 900h and 1200h, respectively.

Table 1 shows the results of accelerated aging tests. The test results showed that after explosion under the ultraviolet ray of the xenon arc lamp for 1200h, the retention rate of tensile strength of tested PP bags was 94% while the retention rate of elongation was 84%. The aging performance index of PP bags mixing with 1% UV resistant material was higher than the required value in the “Technical standard for applications of geosynthetics (GB/T17690-1999)” of the People's Republic of China. Therefore, the PP bags mixing with 1% UV resistant materials were used in this project.

Table 1. Results of accelerated aging tests

| Irradiation time of Xenon arc lamp | 0h   | 300h  | 600h  | 900h  | 1200h |
|-----------------------------------|------|-------|-------|-------|-------|
| Retention rate of tensile strength, % | 100  | 106   | 96    | 94    | 94    |
| Retention rate of elongation, %    | 100  | 99    | 91    | 82    | 84    |

The physical and mechanical properties of fly ash of the Lamb Thermal Power Plant in Kenya were analyzed by laboratory tests, as shown in Table 2. According to equation (3), the maximum additional cohesion of solibags filled with ash and sand under the ultimate load was 165 kPa and 181 kPa, respectively. According to the laboratory friction tests, the friction angle of the interface between soilbags and ash slopes was 16 degrees [11]. Because of the embedding function between two layers of the soilbags, the bottom horizontal friction coefficient of the soilbag slopes is as large as 0.7.

Table 2. Properties of the ash

| Properties | Natural content \( w \) ( % ) | Natural unit weight \( \gamma \) ( kN/m³ ) | Dry unit weight \( \gamma_d \) ( kN/m³ ) | Cohesion \( c \) (kPa) | Internal friction angle \( \varphi(\circ) \) |
|------------|-------------------------------|------------------------------------------|------------------------------------------|------------------------|------------------------------------------|
| Ash        | 16.1                          | 10.4                                     | 10.5                                     | 4.3                    | 31.6                                     |
3.3. Design Scheme
Due to the lack of water in Kenya, choosing the way of dam construction with dry ash can achieve the objective of water saving. Moreover, compared with the wet ash dam, the investment of dry ash dam is lower, especially in the plain area. Figure 5 shows the dam body cross-section drawing of dry ash dam using soilbags. The initial dam of dry ash dam is piled up by sand to the final height of 3m. The initial dam is made up of soilbags filled with local sand, and the slope ratios are 1:1. Meanwhile, the crest was equipped with concrete pavement. The fill dam is constructed by using upstream method. The slope of the fill dam is piled up by two rows of soilbags filled with sand, with slope ratio 1:1.5. There are three layers of the fill dam. The height of each layer is 10m and the total height of the dam is 33m. Meanwhile, 8m berm in width is located in the slope per 10m height.

![Figure 5. The cross-section of the ash dam built with soilbags](image)

The dam body is quadrilateral distribution and the dam area is about $5.97 \times 10^5$ m$^2$. The total reservoir capacity is about $1.5 \times 10^7$ m$^3$. The ash dam is constructed by layer buried method. The soilbags are packed and transported by large machines. The dry ash in the ash field and the soilbags in the slopes are finally compacted by using the vibrating rollers.

The soilbags filled with sand, which are placed in a certain arrangement on the ash slopes, can not only restrict the deformation of the ash behind the soilbags effectively, but also increase the stability of the ash dam slope. The main reasons are as follows: 1) Reinforcement effect. Because of the compaction effect in the process of construction, the compression deformation of the soil causes the extension along the bag perimeter and the tensile strength in the soilbags, which is equivalent to the effect of an additional cohesion and leads to the improvement of the overall strength of the soilbags. For the assembly of soilbags, because of the embedding and friction effect between two layers of soilbags, the overall strength is further improved, which is equivalent to a reinforced body; 2) Pressing slope effect.

4. Slope Stability Analysis of the Stacking Dam
The soilbags filled with sand have high compression strength, which is similar to the rock. When the soilbags are stacked on the slope of the ash dam, it is equivalent to a loading pressing on the ash slope. Therefore, the soilbags can be considered as a pressing slope load when calculating the slope stability of the ash dam with soilbags. Due to the high compression strength of a single soilbag, the individual bag is hardly to be damaged. However, for the combination of soilbags, the interlayers between soilbags are weak surfaces and are easy to slide. Moreover, when calculating the stability of the ash dam slope piled up by soilbags, sliding failure will not occur in the contact surface between the pressing slope of soilbags and the ash behind it, that is to consider the soilbags and the ash slope as a whole when analyzing the slope stability of the ash dam. The sliding surface of the slope with soilbags is shown in
Figure 6. The sliding surface of slope with soilbags

Figure 7 shows the diagram of the forces on the slope of the ash dam with soilbags. According to the force equilibrium conditions on the pressing slope of soilbags, the sliding resistance force $T_i$ and the vertical stress $N_i$ on the bottom of the pressing slope can be calculated by

$$T_i = P_i \sin(\theta - \phi_i) \quad \text{and} \quad N_i = W_i - P_i \cos(\theta - \phi_i) \quad (5)$$

where $W_i$ is the gravity load of the pressing slope piled up by soilbags, $P_i$ is the force of the pressing slope applied on the ash dam slope, $\theta$ is the slope angle, and $\phi_i$ is the interlayer friction angle between the pressing slope of soilbags and the ash dam slope.

Assuming that $F_S$ is the factor of safety of the slope, $\mu$ is the friction coefficient between different interlayers of soilbags in the pressing slope, the relationship between $F_S$ and $\mu$ can be obtained by

$$T_i = \frac{\mu \cdot N_i}{F_S} \quad (6)$$

According to the equation (5) and equation (6), the force of the pressing slope applied on the ash dam slope $P_i$ can be calculated by

$$P_i = \frac{\mu \cdot W_i}{F_s \cdot \sin(\theta - \phi_i) + \mu \cdot \cos(\theta - \phi_i)} \quad (7)$$

In this paper, it is assumed that $P_i$ is uniformly distributed on the ash slope, so the magnitude of the uniform load $p$ can be calculated by $p = P_i \cdot \sin(\theta/H)$, where $H$ is the height of the pressing slope of soilbags.

As shown in Figure 7, the ash slope behind the pressing slope of soilbags is discretized into slices and the simplified Bishop method is used to determine the factor of safety $F_S$. According to the definition of factor of safety and the Mohr-Coulomb criterion, for slice $i$, the following equation can be obtained

$$T_i = \frac{1}{F_S} F_S \cdot \left( c_{\text{total}} \right) \cdot l_i \cdot N_i \cdot \tan \left( \phi_{\text{total}} \right) \quad (8)$$

Where $c_{\text{total}}, \phi_{\text{total}}$ are shear strength indexes of the ash, $T_{\bar{F}_i}$ is the shear force of slice $i$, $l_i$ is the bottom length of slice $i$, $l_i = \Delta x_i / \cos \phi_i$.

The simplified Bishop [19] method satisfies vertical force equilibrium for each slice and overall moment equilibrium about the center of the circular trial surface. Since horizontal forces are not considered at each slice, the interslice shear forces are assumed to be zero. For each slice, it can be obtained that
\[ W_i + p\Delta x \frac{\cos(\theta - \phi)}{\cos \theta} + \Delta Z_i - T_i \sin \alpha_i - N_i \cos \alpha_i = 0 \tag{9} \]

\[ \sum W_i R \sin \alpha_i - P_i y - \sum T_i R = 0 \tag{10} \]

If the same factor of safety is assumed for all the slices, the safety factor \( F_s \) of the sliding surface can be calculated by combining equations. \((8-10)\)

\[ F_s = \sum \frac{1}{m_i} \left( c_i \Delta \alpha + (W_i + p\Delta x \frac{\cos(\theta - \phi)}{\cos \theta}) \tan(\phi_{int}) \right) \left( W_i R \sin \alpha_i - \frac{P_i y}{R} \right)^{\frac{1}{n}} \tag{11} \]

in which \( m_i = \cos \alpha_i + \frac{\tan(\phi_{int})}{F_s} \sin \alpha_i \). The cohesion \( c_i \) and internal friction angle \( \phi_{int} \) are related to the normal stress on the bottom of slice \( i \), \( \sigma_i = N_i / l_i \). Since the \( m_i \) and \( P_i \) in the right term of equation (11) are functions of the factor of safety, equation (11) can be solved by iterative method.

![Diagram of the forces on the slope of the ash dam with soilbags](image)

**Figure 7.** Diagram of the forces on the slope of the ash dam with soilbags

According to the calculation equations, the slope stability analysis of the ash dam with soilbags shown in Figure 2 is carried out. The results of calculation show that the slope factor of safety with soilbag is 1.441 while the slope factor of safety of the ash slope without soilbags is 1.113, with an increase of 29.4%. Therefore, the method of construction of an ash dam with soilbags was effective.

5. Conclusion

In this paper, a new technology to construct an ash dam with soilbags filled with local sands is proposed and the method of analyzing the slope stability of the ash dam with soilbags is suggested. The design of the ash dam with soilbags in Ram Thermal Power Plant of Kenya is introduced in detail. By using the suggested method, the slope stability of the soilbags-constructed ash dam is analyzed. The conclusions are summarized as follows:

1. The soilbags filled with ash or sands have a high compressive strength. The durability of the PP bags mixing with 1% UV can be guaranteed near the equator in Kenya based on the results of the accelerated aging tests.

2. The ash dam built with soilbags is composed of the primary dam and the stacking dam. The soilbags are used to build the primary dam and reinforce the slope of the stacking dam.
(3) The primary dam constructed with soilbags can effectively retain the backfill ash and the stacking dam reinforced with soilbags can stand stable even with the slope of 1:1.5.

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