Reuse of red mud in construction of tailing dam

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Abstract. Red mud, a by-product of the alumina industry, is disposed through construction of clay lined dams or dykes. Into these constructions, red mud is pumped and allowed to dry naturally. This red mud when disposed is slurry with a solid concentration of 10\%, high ionic strength and pH in the range of 10-13. It should be noted that it is toxic in nature at this stage because of the harmful chemical composition present in it. Hence utilization of it in various applications results in decrease of its environmental impact. In the present study, red mud has been used in the construction of a tailing dam. Its stability has been evaluated considering various cases such as end of construction, steady seepage, rapid draw down and seismic conditions. The data from this evaluation has been compared with borrowed soil to assess the compatibility of red mud. The comparison has shown that there is little difference between usage of either borrowed soil or red mud as tailing dam material. However, red mud gives better factor of safety compared to the borrowed soil considered in this study.

Key words: Red mud, tailing dam, stability

1. Introduction
Red mud, a by-product of the alumina industry, is a global environmental problem. It is the left over product in the Bayer’s process of alumina production. After Bauxite digestion with sodium hydroxide at elevated temperature and pressure, the remaining insoluble product is red mud. This red mud when disposed is slurry with a solid concentration of 10\%, high ionic strength and pH in the range of 10-13. The iron compounds present in this product confer the red colour to it and hence it is called as red mud.

The major problem with red mud is its toxic nature. A chemical analysis on red mud reveals its constituents - silica, aluminium, iron, calcium, titanium. There are also an array of minor ones, namely – sodium, nickel, chromium, potassium, zinc, vanadium, manganese, barium, copper, lead, etc [1] Due to the above harmful chemical composition present in red mud, its disposal and storage are the major difficulties to be overcome by the industries dealing with it. Due to substantial increase in annual alumina production, generation of red mud has also increased. An effective solution to deal with this problem is to reuse it in various fields.

In the studies conducted by [2], it was found that the traditional disposal methods usually involved construction of clay-line dams or dykes. In such constructions, the slurry of red mud is pumped and left to dry naturally. There has been a significant variation in the design and construction of such structures with time [3]. Additionally, it was found that the disposal practices were dependent on the immediate surroundings. Though conventional approach of disposal was simple and economical, the
likely effect on the groundwater and the subsequent problems in relation to surface rehabilitation forced changes [4]. This resulted in the construction of doubly sealed impoundments integrating a polymeric membrane with clay lining. Drainage networks incorporated in the lining material has also seen widespread use. These drained disposal systems reduce the threat of the residue and also increases the storage capacity as a result of better residue consolidation.

Red mud’s geotechnical properties and its subsequent reusability as soil have been reported by various researchers. Despite its high pH value (11-13), it was observed that clay size particles (> 50%) constituted a major portion of red mud [5]. It was found to have low plasticity in nature and possess higher specific gravity [6]. The undrained shear strength of the red mud has also been observed to very high compared to that of the uncemented clay and internal friction angle was found to be about 38° to 42° [7]. The compression index and coefficient of consolidation properties were noticed to be similar to that of silty-clay soils [8].

Technologically and economically efficient utilization of red mud is possible [9] and such use in various applications results in decrease of environmental hazards. In order to decrease the land decomposition by the toxic material, an impounding is created by constructing earthen (tailing) dams. Thus the imminent red mud can be disposed on the previous cover of the red mud. According to need and further analysis, the height of the embankment can be increased in stages.

The utilization of red mud in building red mud ponds benefits us in two ways:
- More space for the upcoming waste can be created and thus the storage problem will be reduced.
- It also reduces the usage of borrowed soil and also soil within economical haulage distances can be utilized. Thus it is both safe and economical.

A tailing dam is an embankment dam utilized to store toxic by-products of mining operations. The term “tailing” refers to the remaining industrial effluent after the processing of ore. The effluent will be liquid, solid or slurry of fine particles depending on the type of ore and the type of extraction of the product. Unlike other types of dams, the containment in a tailing dam is permanent. The present paper addresses the tailing dam construction for alumina industry in which red mud as an industrial effluent will be discussed.

Tailing dykes are similar in design to water storage dams. As the tailing slurry is diluted and has around 10% concentration of solids, the dam is designed as if it holds water. If the tailings are highly acidic/alkaline and toxic like ‘red mud”, it needs to be contained within the dyke system. While it is important to reduce seepage in water retention dams, it is a critical requirement in tailings dykes to prevent ground water contamination.

The height of tailings dam is raised whenever needed unlike water storage dams. After the construction of base dam, as more and more tailings and water mixture needs to be added, the height is increased gradually. There are three types of dam raises depending on the position of the new crest relative to the previous crest of the dam. A downstream tailing dam refers to the progressive raising of the embankment that will position the crest and fill further downstream. An upstream design has embankments of trapezoidal shape which are constructed one above the other in a manner such that the toe of one is on the crest of another. A centerlined tailings dam has embankment dams constructed directly on top of another in which the upstream side is supported by slurry and the downstream side by fill. The method of dam raise to be adopted will depend on the climate, topography, type of tailings and construction cost.

The objective of this research is to study the utilization of red mud in the construction of tailing dams. This results in a safe and effective disposal of red mud. Factor of safety for various cases like ‘end of construction’, ‘steady state seepage’, ‘seismic condition’ and ‘rapid draw down condition’ are evaluated. The obtained results are compared with normal soil to assess the compatibility of red mud.

2.Methodology
Experimental investigations have been conducted on the red mud samples procured from the National Aluminium Company Ltd, Damanjodi of Koraput district, Odisha. The following experiments have been conducted:
Atterberg’s limit test (IS 2720-5 1985), (IS 2720-6 1972)
Grain size distribution (IS 2720-4, 1985)
Compaction test (IS 2720-7, 1980)
Direct shear test (IS 2720-13, 1986)
Specific gravity (IS 2720-3-1, 1980) and pH (IS: 2720 -26, 1987)
Falling head test (IS 2720-17, 1986)

The required index and engineering properties have been obtained from these experiments and the detailed report has been illustrated in Table 1. It has been observed that red mud is of high alkaline nature with a pH of 11.34. The presence of minerals such as iron has contributed to the increased specific gravity (3.06). The grain size distribution in figure 1 shows that the red mud has mostly fine grained particles. It is observed to exhibit low plasticity characteristics and as per IS soil classification system it is classified as CL. Though, the graph evidently doesn’t show the clay size particles, it has been observed from the experimental studies by [10] using Laser diffraction analyzer technique that 20% of clay size particles are present in the red mud sample of Damanjodi of Koraput district Odisha. The results from direct shear test has shown that red mud has low cohesion with higher angle of internal friction and such kind of behavior has been observed to be exhibited by red mud extracted from Bayer’s process. This high friction is due to the presence of angular and sub-angular particles and the presence of heavy minerals [11, 12].

Table 1. Red mud geotechnical properties

| Description of the test      | Result |
|------------------------------|--------|
| Liquid limit (%)             | 28.9   |
| Plastic limit (%)            | 18.73  |
| Shrinkage limit (%)          | 15.77  |
| Plasticity index             | 10.17  |
| Specific gravity             | 3.06   |
| pH                           | 11.34  |
| Dry density (g/cc)           | 1.89   |
| OMC (%)                      | 20.5   |
| Cohesion (kPa)               | 10     |
| Friction                     | 32°    |
| Permeability (m/s)           | 5 × 10^9 |
Of the three methods of the construction of tailing dam (upstream, downstream and centre line method), downstream method has been chosen in the present study due to the following reasons:

- Downstream method gives better factor of safety compared to other methods under seismic forces.
- A huge quantity of red mud can be used for further rising of dam in subsequent stages.
- The storage capacity of red mud pond increases in downstream method in comparison with other methods [13].

The analysis procedure of tailing dam is similar to that of the embankment dam. Stability analysis of both upstream and downstream is carried out with and without seismic forces. Upstream slope is critical at the end of construction stage. Downstream slope is critical at the end of construction and long term steady seepage condition.

The slope stability analysis of tailing dam is analyzed using slide software. It is based on the limit equilibrium approach. Different conditions were evaluated for the embankment such as ‘steady seepage’, ‘end of construction’ and ‘rapid draw down’. The stability of tailing dam has been analysed using red mud. To check the effectiveness of red mud as construction material, the same analysis has been performed using borrowed earth material available at a nearby site. Different input parameters for red mud, foundation and borrowed soil have been given in Table 2.

In the first phase, the height of the dam has been provided as 8m with a slope of 1V: 2H on both upstream and downstream methods. As subsequent phases have to be developed within the same construction, the foundation height has been raised to 10 m.

Figure 2 shows the initial stage of embankment constructed using red mud. Note that y-axis of the figure shows the height of the tailing dam and the corresponding length has been represented in x-axis. The same convention has been followed in all the figures. The periphery of the structure has been...
covered with borrowed soil. This is because as red mud is dispersive in nature, it is more susceptible to erosion [14]. The following analysis has been done to evaluate the stability of the embankment on both upstream and downstream.

- End of construction stage without seismic analysis
- End of construction stage with seismic analysis
- Steady seepage condition without seismic analysis
- Steady seepage condition considering seismic condition
- Rapid draw down condition

### Table 2. Properties of borrowed soil and red mud for the tailing dam design

| Soil type      | Cohesion (kPa) | Friction angle | Unit weight (kN/m³) | Permeability (m/s) |
|----------------|----------------|----------------|---------------------|-------------------|
| Red mud        | 10             | 32             | 22.8                | 5.00e-9           |
| Borrowed soil  | 30             | 20             | 20.2                | 5.00e-8           |
| Foundation     | 30             | 20             | 19                  | 5.00e-8           |

The evaluated factor of safety (FS) for the above conditions has been tabulated (Table 3). It has been observed from table 3 that the first phase of embankment is safe and hence second phase of the construction has been done (Figure 3).

The raised height of the next layer is 10m with respect to the crest of the previous one. An upstream (u/s) slope of 1V:2H and downstream (d/s) slope of 1V:2.5H has been provided. Stability analysis has been done for all the 5 cases discussed above on both borrowed soil and red mud and the FS values have been tabulated in Table 3. As reasonable FS values have been obtained in the second phase, the third phase is constructed by raising the height a further 10 m with respect to the previous crest position as shown in Figure 4. Comparison is done by taking both borrowed soil and red mud as embankment materials.
2.1 End of construction stage
Figures 5 to 8 show the detailed analysis for the empty reservoir at the end of construction for phase 3. The FS values and its corresponding critical circular failure surface have been obtained. For the borrowed soil, a minimum factor of safety of 1.645 (Figure 4), 1.809 (Figure 5), has been obtained in upstream and downstream side respectively. For red mud, a factor of safety of 1.85 (Figure 6), 1.979 (Figure 7, Figure 8) has been obtained in upstream and downstream side respectively.

In order to compute the forces caused by earthquake, horizontal and vertical seismic coefficients are used. These forces are in turn added to the overall equilibrium computation for the individual slices composing the failure surface. Here anticipating severe earthquake condition, horizontal coefficient of 0.1 in the positive direction of failure and 0.06 in the vertical direction has been given in the analysis [15]. The failure surface gives global minimum factor of safety of 1.405 in the upstream side (Figure 9) and 1.469 in the downstream side (Figure 10) for red mud as tailing dam material.

2.2 Steady seepage condition
As seepage forces add to the gravity forces in inducing instability, steady seepage under full reservoir condition is important for the downstream slope. Figure 11 shows the analysis on downstream slope considering full reservoir condition under steady seepage state. The critical failure surface with detailed analysis such as radius of slip surface, driving and resisting moment, and factor of safety has been depicted in the figure briefly. A factor of safety of 1.435 has been obtained. While considering seismic forces under similar conditions, the FS has been observed to reduce to 1.042 (Figure 12)

2.3 Rapid draw down condition:
The rapid draw down condition is not significant for tailing dam design as sudden drop down of pressure on the upstream side in the case of tailings is rarely observed. However for the completion of analysis, the results of the same have been presented for the upstream side of the slope. This condition has been observed to be critical for the analysis (Figure 13) and a factor of safety of 1.165 has been obtained.
**Figure 4.** Phase 3 model: Red mud as an embankment material

**Figure 5.** Phase 3 Borrowed soil as an embankment material: End of construction stage; upstream

**Figure 6.** Phase 3 Borrowed soil as an embankment material: End of construction stage; downstream
Figure 7. Phase 3: Red mud as an embankment material: End of construction stage; upstream

Figure 8. Phase 3: Red mud as an embankment material: End of construction stage; downstream
Figure 9. Phase 3: Red mud as tailing dam material: End of construction stage; Seismic condition: u/s

Figure 10. Phase 3: Red mud as tailing dam material: End of construction stage; Seismic condition: d/s
Figure 11. Phase 3: Red mud as tailing dam material: Steady seepage condition; d/s

Figure 12. Phase 3: Red mud as tailing dam material: Steady seepage condition considering seismic force; d/s
Figure 13. Phase 3: Red mud as tailing dam material: Rapid draw down condition: u/s

The results of factor of safety obtained from the analysis considering different conditions for both upstream and downstream are tabulated below (Table 3).

Table 3. Factor of safety results of tailing dam design with different phase

| condition               | Phase 1  | Phase 2 | Phase 3  | Phase 3  | Phase 3 |
|-------------------------|----------|---------|----------|----------|---------|
|                         | u/s slope| u/s slope| d/s slope| d/s slope| d/s slope|
| End of construction     |          |         |          |          |         |
| Borrowed Soil           | 2.453    | 1.889   | 1.645    | 1.835    |         |
| Red mud                 | 2.251    | 1.949   | 1.809    | 1.979    |         |
| With seismic            |          |         |          |          |         |
| Borrowed Soil           | 1.934    | 1.454   | 1.267    | 1.374    |         |
| Red mud                 | 1.8      | 1.515   | 1.405    | 1.469    |         |
| Seepage condition       |          |         |          |          |         |
| Borrowed Soil           | 2.845    | 2.234   | 2.042    | 1.435    |         |
| Red mud                 | 2.456    | 2.299   | 2.094    | 1.452    |         |
| Seepage with seismic    |          |         |          |          |         |
| Borrowed Soil           | 2.042    | 1.581   | 1.412    | 1.042    |         |
| Red mud                 | 1.834    | 1.604   | 1.175    | 1.06     |         |
From the table, it is obvious that the obtained FS for the red mud as well as for borrowed soil are within the limits up to phase 2 construction. The general guidelines suggest the minimum values of FS as 1.3, 1.5 and 1.3 for the End of construction stage, steady seepage condition and sudden draw down condition respectively for the tailing dam design without seismic force. Considering seismic force the minimum FS may be 1.1 [16]. The values of FS for phase 1 and phase 2 dam constructions are observed to fall within these limits. Therefore, the dam height has been further raised to a height of 10 m and the stability of phase 3 has been evaluated.

Using red mud as a construction material for phase 3, FS of 1.809 for u/s and 1.979 for d/s has been obtained at the end of construction stage. For borrowed soil, the corresponding FS values are obtained as 1.645, 1.835 respectively. As these values fall below 1.5, this stage is considered safe. Considering seismic forces, the above values has been observed to decrease further to 1.405 (u/s) and 1.465 (d/s) for red mud and 1.267 (u/s), 1.374 (d/s) for borrowed soil. As these values are greater than 1.1, it is found to be satisfactory.

For the seepage condition, d/s of the dam is found to be critical. The FS has been observed to reduce from 2.094 for the u/s slope to 1.452 for the d/s slope for red mud. Similar trend has been observed in case of borrowed soil. Considering seismic forces, the FS has been found to be more critical for d/s slope which is obtained as 1.042. As these values are found to be less than 1.5 (seepage condition) and 1.1 (seepage with seismic condition), further rise of dam would be unsafe. The stability of the dam has also been evaluated for the rapid draw down condition. Under this condition, it has been observed that FS has been found to be 1.245 on d/s and 1.164 on u/s which is less than 1.3. Thus it is found to be critical and the results show that further rising of dam is not feasible under these conditions.

From the analysis it has been observed that a critical stage has been obtained in the third phase of analysis. Further rising of the dam is not possible as it is unsafe.

3. Conclusions
In the present study ‘design of tailing embankment using red mud has been analysed. Experimental investigations have been done in the laboratory to determine the physical properties of red mud. Using these results stability analysis of the dam based on limit equilibrium approach has been done using slide software. Based on the above observations, the following conclusion have been be made.

- Red mud is a fine grained soil with high alkalinity. The specific gravity of red mud is observed to be high due to the presence of rich iron minerals in it.
- Unlike fine grained soil it has high internal angle of friction, but permeability is observed to be low similar to that of fine grained soil.
- The FS has been observed to be critical in the third phase i.e. when the height of dam reached to a height of 28 m. So, using red mud as a construction material the dam height can be safely raised to a height of 18 m.
- The comparison shows there is very little difference between borrowed soil and red mud when used as tailing dam materials. Therefore, red mud is observed to be highly feasible to be used as construction material for tailing dam design.

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