Geotechnical Investigations of Coal Mine Waste Dump Material

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Abstract
Mining is an essential activity for obtaining the raw materials required for infrastructure and energy needs. During the extraction of coal, a significant amount of overburden (OB) material is generated. Managing the overburden produced by mining activities demands a substantial land for disposal which can be quite challenging in limited spaces. Consequently, it becomes imperative to design safe coal mine OB dumps, optimizing the use of available ground space. The challenge of ensuring the stability of overburden dumps is directly linked to the geotechnical properties of these materials.

Therefore, it is crucial to characterize the properties of the dump material accurately to assess its engineering properties reliably. The focus of this study is to outline the various testing procedures necessary for the proper characterization of dump materials to ensure the stability of the dumps. Additionally, the study provides an analysis of laboratory test data and presents typical results from a case study.

Keywords: Dump material, Geotechnical properties, Opencast mining, Overburden dump.

Introduction

Coal is the only major natural resource significantly contributing to the electricity production. In India, the major source of electricity production is achieved from thermal power plants, accounting for approximately 75% of the total power generation[18]. Opencast mining offers greater production and productivity compared to underground mining method[3]. Large opencast mining operations in India have not only resulted in a substantial increase in the production of overburden waste materials but have also required the transportation of massive quantities of loose materials from coal mining sites to designated storage areas in the form of internal or external dumps[13]. Due to the space constraints within the lease hold area and increasing of seam depth, the height of the overburden dumps is increasing.

The increased heights of the dumps are properly maintained to avoid the dump instability issues which may affect production and safety of the mine. Recent years have witnessed an increased rate of dump slope failures, resulting in significant loss of life, property and equipment. To prevent such failures, it is better to establish a well-designed and structurally safe dump slope. Achieving a safe and efficient dump slope design necessitates a thorough examination of the geotechnical properties of the dump material. A review focused on the stability challenges of coal mine overburden dumps, especially in opencast mining, considering the impact of old underground workings on dump slopes[7]. Many researchers have studied on dump stability analysis considering different geotechnical tests. Table 1 shows the list of geotechnical tests that were considered for the stability analysis of the dump. Among them, Grain size analysis, Proctor compaction test and Direct shear test were mostly considered for the analysis.

The nature of dump material is quite diverse. The shape, size, formation, physical, chemical and mechanical qualities etc. differ from area to area. As a result, it is important to define them thoroughly in order to create a safe and optimal dump slope design. So, in this research study, focus is made on some of the most essential and basic standard tests for evaluating the geo-mechanical characteristics of dump material. These tests provide information regarding the cohesion, angle of friction, optimal moisture content, maximum dry density, grain size grading and other characteristics of dump material.

Table 1
Geotechnical tests considered for dump stability analysis by different researchers (Source: Authors)

Researchers	Sieve analysis	Proctor compaction	Triaxial test	Direct shear test	Atterberg limits	Hydraulic conductivity
Koner et al[13,14]	✓	✓	-	✓	-	✓
Karan et al[12]	✓	✓	-	-	-	-
Sahoo et al[26]	✓	✓	-	✓	-	-
Gupta et al[6]	✓	✓	✓	✓	-	-
Bishwal et al[2]	-	✓	-	✓	✓	-
Nayak et al[19]	✓	✓	-	✓	✓	-
Gautam et al[5]	✓	✓	-	✓	✓	-
Kumar et al[15]	-	✓	-	✓	-	-
Verma et al[28,29]	✓	-	-	✓	-	-

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From table 1, it is clear that Grain size analysis, Proctor compaction test and Direct shear test are required tests for determining the stability of the dumps. Table 2 displays the geotechnical parameter results obtained from Proctor compaction and direct shear tests conducted by various researchers for coal dump. These results serve as input data for the numerical modelling of the dump slopes. Table 2 compiles geotechnical parameters from diverse studies, offering a comprehensive dataset for numerical modelling of dump slopes. The density ranges from 17 to 23.8 kN/m^3, cohesion spans 0 to 117.6 kPa and friction angle values vary between 10° to 51°.

Case Study

A study was conducted to examine the geotechnical characteristics of samples taken from a dump in an opencast mine situated in southern India.

Collection of Dump Samples: Total 7 samples were collected for the study from the opencast coalmine mine. Overburden samples were collected from various locations across the dumps. These samples were carefully sealed in airtight polythene bags and transported to the laboratory for the experiments detailed in figure 1.

Geo-Technical Assessment of Dump Material: A number of standard tests have been conducted to assess the geo-technical properties on granular dump material.

Grain size analysis test: It is done to assess the different particle size distribution in the granular material where the amount of gravel, sand, silt and clay present in granular material is determined. The various particle sizes play an important role in determining the permeability, void ratio, shear strength and other essential characteristics of granular materials.

Table 2
Input data of the parameters used by different researchers for dump stability analysis (Source: Authors)

S.N.	Researchers	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)
1	Harish et al[7,8]	15.9	90	22
2	Verma et al[28,29]	17.70–18.10	42– 47	26–29
3	Maiti et al[17]	21.41	50	20
4	Layek et al[16]	17.94	50	25.55
5	Sekhar et al[27]	17.00–20.00	60	25
6	Rajak et al[24]	17.72	19.5	32.2
7	Rajak et al[25]	17.75–18.50	24.46–35.56	24.10–31.10
8	Koner et al[13,14]	15.17–18.45	0–117.6	17.7–51.1
9	Behera et al[1]	18.35–20.39	36	22
10	Dewangan et al[4]	20.28	–	29–37
11	Koner et al[13,14]	17.90–23.80	13.97–26.89	22.25–38.56
12	Rahul et al[21]	–	10–70	10–45
13	Poulsen et al[20]	20.70	27–48	25–34
14	Verma et al[28]	13.18–19.45	14–30	13–25
15	Verma et al[28,29]	17.33–19.37	91	24.4
16	Rai et al[22,23]	18.35	14	39

Figure 1: Dumps samples collected from an opencast mine

The formation of stable and optimal overburden dumps completely depends upon the geo-mechanical properties of the material. Grain size analysis experiment is performed in two different forms: dry and wet. Dry analysis is performed when the sample containing particles larger than 0.075 mm and when the sample contains fine grains smaller than 0.075 mm, wet analysis is opted. Figure 2 illustrates the arrangement of the sieve analysis test apparatus.

Sieve analysis test was performed to overburden dump sample for the grain size distribution analysis as per IS:2720 part 4[10]. Approximately 400 grams of the sample were dried for 24 hours in an oven. Subsequently, the dried sample was taken for sieve analysis. The sieves were arranged in decreasing order of the sizes and a pan placed beneath the finest sieve. The entire assembly was securely covered and placed on a sieve shaker. The soil retained on each sieve was weighed and the mass was recorded. Depending on the specific analytical requirements, additional sieves could be incorporated between the existing ones.

Based on the sieve analysis of the dump samples, distribution of the grain size for the collected dump soil was determined by plotting the sieve sizes on the X-axis (abscissa) and the percentage of weight passing on the Y-axis (ordinate).

Standard proctor compaction test: It determines optimum moisture content (OMC) and its corresponding maximum dry density (MDD) of dump material is a critical step in conducting a meaningful dump stability analysis using numerical modelling. To accomplish this, the standard proctor compaction test was performed, aiming to ascertain MDD and OMC for a given set of samples following the standard Proctor method (IS:2720)[11]. This test serves to establish the OMC to be added to the dump material, thereby achieving the highest compaction level. Maximum compaction, in turn, results in the highest dry density, ensuring that the deformation and strength characteristics of the dump material reach their optimum values. The testing apparatus comprises of a cylindrical mould, collar, base plate and rammer, as illustrated in figure 3.

Figure 2: Sieve Analysis Test apparatus

Figure 3: Proctor compaction test apparatus

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The procedure initiated with the weighing of the empty mould, followed by attaching the mould to the base plate and affixing the collar to the mould. Next, a thin coat of grease was smoothly spread across the inner surfaces of both the mould and collar. The sample was then divided into three equal parts. Initially, one part of the soil was placed into the mould and compacted using 25 evenly distributed blows with the standard rammer. This process was repeated for the second and third parts of the sample, ensuring that the top of each compacted layer was gently disturbed with a spatula to maintain uniformity and to prevent stratification. Subsequently, the mould containing the compacted soil was separated from the base plate and the weight of the compacted soil along with the mould was recorded. This procedure was iterated by gradually introducing water into the sample and repeating the experiment for density measurement until optimization was achieved.

Geo-Mechanical Strength Tests: Geo-mechanical strength tests are used to understand the mechanical properties of materials like soil and rock. These tests are necessary in mining and civil engineering to analyse materials behaviour under different conditions. Direct shear test is one of the significant methods for determining shear strength, particularly for soil and dump samples.

The direct shear test: As outlined in IS 2720, part 13[9], it is performed to ascertain the shear parameters of soil specimens. Shear strength, particularly concerning dump soil, characterizes its utmost resistance against shear displacement induced by external shear forces. This resistance arises from a combination of factors including surface frictional resistance along sliding planes, interlocking among individual rock grains and cohesion within the sliding surface of the soil.

This is simple and easiest test, when compared to the triaxial test. It contains a square shear box that splits into upper and lower halves, with the fixed lower half and the upper half is subjected to horizontal shear forces. The application of this horizontal force continues until the sample shears completely. Figure 4 shows the shear box and direct shear test apparatus. The test comprises of two fundamental stages. First, a nominal load is applied to the specimen, followed by application of a shear stress to make the sample fail.

Initially, the sample is kept in an oven and is dried for 24 hours. An appropriate quantity of water is added to achieve its OMC and the sample was thoroughly mixed. The shear box was subsequently filled with a representative sample. After that, the shear box was properly placed in the direct shear apparatus. Shear stress was applied and continually increased while maintaining a constant normal load until failure occurred. A minimum of three tests were conducted under increasing normal stress and a graph was plotted correlating shear strength with normal stress to determine the cohesive strength and the angle of internal friction.

Results and Discussion

Grain size analysis data of the mine dump sample is tabulated in table 3 showing the classification of dump materials based on their particle sizes. It shows that 0.8-3.25% of the sample is composed of silt (grain size >0.002mm but <0.075mm). The presence of sand particle (>0.075mm but less than 4.75mm) is 89.95-95.05% whereas the presence of gravel (particles size >4.75mm but less than 20mm) is about 1.75-4.85%. No clay content was found in the sample studied. From table 3, it is clearly indicating that sample 1 is having the highest gravel and sand percentage and sample 3 is having highest silt content while the lowest percentage of gravel, sand and silt was observed in samples 3, 4 and 8 respectively in the dump material.

Based on the sieve analysis of the dump samples, the grain size distribution of the collected dump soil is determined by plotting the sieve sizes on the X-axis and the percentage of weight passing on the Y-axis. The results of the analysis are shown in figure 5. Proctor compaction test results of the dump sample obtained are given in table 4. Based on the experimental results, a graph is plotted between the percentage of water content and dry density as shown in figure 6.

Figure 4: Direct shear test apparatus

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Table 3
Classification of dump material with respect to particle sizes

Sample No.	Percentage weight of dump sample retained as per the particle size distribution			
	Gravel (>4.75 mm)	Sand (0.075 - 4.75 mm)	Silt (0.002 - 0.075 mm)	Clay (<0.002 mm)
1	4.85	91.5	3.25	-NA-
2	2.3	92.85	2.55	
3	1.75	95.05	2.65	
4	2.35	89.95	2.7	
5	3.4	91.65	2.45	
6	2	91.35	2.65	
7	3.05	92.9	0.8	

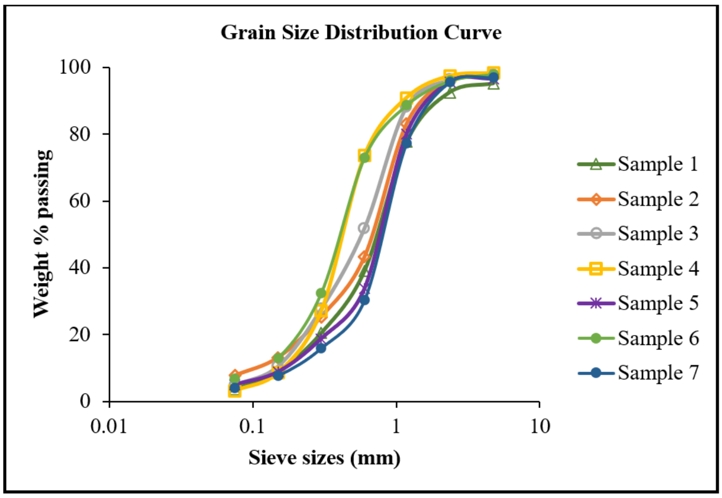

Figure 5: Grain size distribution curve

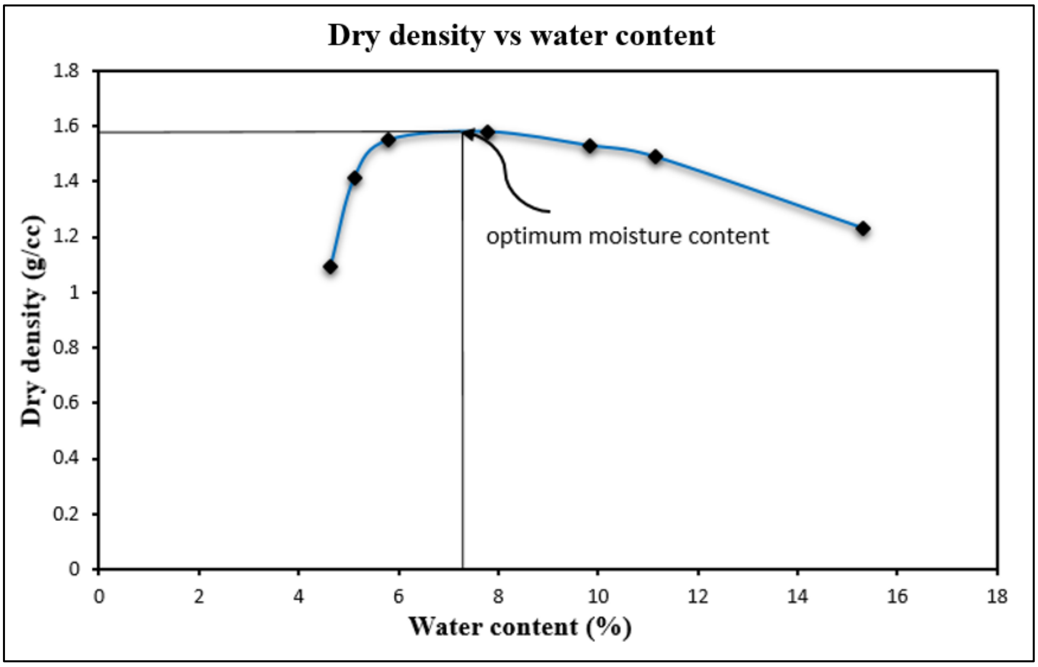

Figure 6: Dry density vs water content of the dump sample

From table 4, it is observed that sample 1 has relatively lowest water content (4.65%) and a corresponding low dry density (1.09 g/cc). Sample 7 has the highest water content (15.32%), but the dry density is lower (1.23 g/cc). This indicates that the soil is beyond the OMC and further water addition is causing a reduction in dry density. Samples 2 to 6 show a general trend of increasing water content and dry density up to a certain point, suggesting that they are approaching or are at the OMC. Going beyond the OMC can result in decreased stability and strength of the compacted soil. Cohesion and friction angle are determined from the direct shear tests conducted on the dump samples, by plotting a Mohr's circle failure envelope as shown in figure 7.

The values of normal and shear stresses of the dump samples with the friction angle and cohesion values are summarized in table 5. Each sample is tested at three different normal stresses and for each normal stress, its respective shear stress is calculated. Table 5 clearly explains that samples 4 and 5 exhibit higher shear strengths (both cohesion and friction angle) at different normal stresses compared to other samples. Sample 7 generally has lower shear strengths compared to other samples, especially in terms of cohesion. Samples 1, 2, 3 and 6 show varying trends in shear strength parameters with increasing normal stress.

Conclusion

The geotechnical investigation of coal mine dump material holds paramount importance in ensuring the safety, efficiency and environmental sustainability of mining related projects such as for the overburden dump slope stability. In the present study, the geotechnical investigation of dump material is carried out to obtain the physico-mechanical characteristics of dump samples which serve as inputs for numerical modelling of overburden dump slope stability. From the investigation of dump samples, it was found that average dry density of the sample is 1.58 g/cc, indicating the mass of the dump soil per unit volume without moisture. The moisture content, representing the percentage of water in the dump soil, was measured at 7.78%.

Table 4
Dry density and water content

Sample No.	Water Content (%)	Dry Density, (g/cc)
1	4.65	1.09
2	5.12	1.41
3	5.81	1.55
4	7.78	1.58
5	9.83	1.53
6	11.14	1.49
7	15.32	1.23

Table 5
Friction angle and cohesion of the OB dump samples

Sample no.	Normal stress (kN/m^2)	Shear stress (kN/m^2)	Cohesion (kN/m^2)	Friction Angle (°)
1	49	61.05	41.9	23.07
	98	87.3		
	147	102.8		
2	49	59.2	33.54	26.53
	98	80.23		
	147	108.2		
3	49	63.4	45.98	21.09
	98	86.75		
	147	101.2		
4	49	71.02	51	23.11
	98	94.8		
	147	112.86		
5	49	69	44.9	25.3
	98	89.78		
	147	115.46		
6	49	61.2	40.48	23.6
	98	84.76		
	147	104.06		
7	49	70.01	52.65	20.7
	98	92.29		
	147	107.18		
Average			44.35	20.48

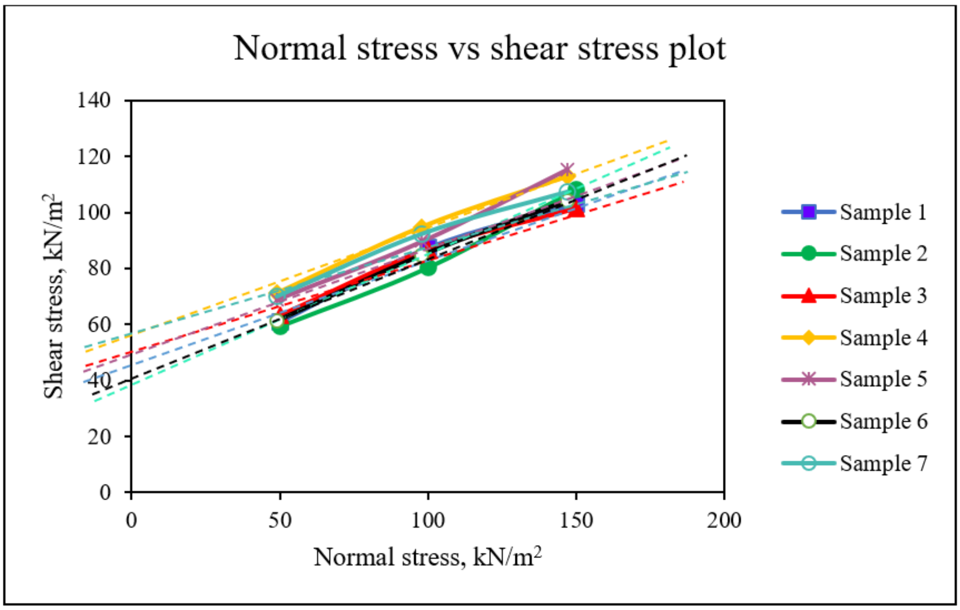

Figure 7: Mohr-Coulomb failure envelope for the tested samples

The cohesion of the soil, a measure of its internal strength, is determined to be 44.35 kN/m². Additionally, the friction angle, which characterizes the resistance of the soil particles to sliding against each other, was determined to be 20.48 degrees. These values collectively provide insights into the physico-mechanical characteristics of the soil sample, essential for understanding its behaviour in overburden dump slopes and various other engineering applications.

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