ORIGINAL ARTICLE

Slope stability analysis of mine waste dumps at a mine site in Southeastern Nigeria

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Abstract

This paper presents results on the stability of slopes of the mine tailing dumps at Enyigba, Southeastern Nigeria. The geotechnical parameters of the slopes were investigated, and stability analysis was carried out with GeoStudio® 2012 developed by Geoslope International Limited. The slope materials were composed of gravel (1.42–30.13%), sand (15.94–33.34%), silt (9.75–26.87%) and clay (32.1–56.25%). The materials have LL, PL and PI ranging from 24 to 49%, 24 to 35% and 9 to 26% respectively, signifying low to medium plastic materials. These results agree with the soil low permeability ($10^{-4} - 10^{-8}$ cm/s) recorded. The MDD and OMC of the material ranged from 1.86 to 2.22 g/cm^3 and 13.45 to 17.05%, while cohesion and internal friction angle were recorded to be 13–34 kN/m^2 and 8–37° respectively; implying moderately durable materials capable of slip and shear failures. XRD confirmed the presence of swelling mineral (illite) in soil material, hinting at clay plasticity on absorption of moisture, which is one of the factors influencing all forms of mass wasting. The slopes' computed factor of safety ranged from 0.8 to 1.33, suggesting critical to poor slope stability when exposed to landslide triggering agents. Hence, slope stabilization is required on the mine tailing dumps at Enyigba to prevent major landslide occurrence.

Keywords Mine tailing dumps · Enyigba · Slope stability · Factor of safety · Landslide · Stabilization

Introduction

Background

Mining is a process used for the production of economic minerals. In Nigeria, open cast mining is the commonest method of mining for the extraction of ore minerals. Opencast mining includes rupturing of the upper layer of rocks with blasting, drilling to excavate the valuable mineral (Gupta and Paul 2016) beneath the earth. During this process, massive amounts of wastes or tailings are generated. These waste materials are dumped in a place for future use or disposal, or dumped permanently (Das 2011). The storage could be internal (within the mine site) or external (outside the mine). Waste dumps usually possess steep angled slopes because the wastes have been deposited over from the top of the dump in an incessant and progressive manner (Bahadur and Sudeep 2013) and are continually moving downslope due to gravity.

The study area (Enyigba and Ameri Mines) has Pb-Zn mineral deposits that are locally mined by the old open-pit mining method, and mine tailings are indiscriminately dumped internally within the areas (Fig. 1) in close proximity to the mines. The tailings are composed of ore and gangue minerals which when weathered release those composing heavy metals into the soil (Ezeh and Anike 2009). The tailing dump-sites are scattered within the localities, which cover an area of approximately 80 km^2 and are strategically located at about 14 km from Abakaliki (capital city of Ebonyi State, Nigeria) along the Abakaliki—Afikpo expressway (Igwe et al. 2012a, b). The surface topography has been greatly distorted, and there is severe environmental degradation.

As land available for mining activities has been a great problem for mining industries, the knowledge and study of dump design is highly needed to store dump wastes within a limited space (Kumar 2013). In any open cast mine, the management of the wastes generated during mining is vital, as it contributes greatly to the mine's successful operation. Inappropriate management of the overburden (OB) dump can result in stability issues which in turn may affect the safety and the overall production of the mine (Poulsen et al. 2014). Blight and Amponash (2004) noted that abandoned waste

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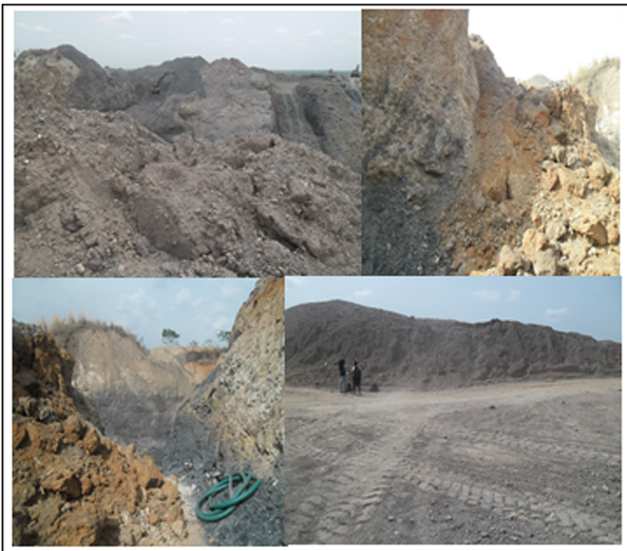[1] Department of Geology, University of Nigeria, Nsukka, Nigeria

Fig. 1 Indiscriminate dumping in the mines

heaps that do not receive proper treatment and maintenance can often experience partial losses of slope and surface erosion.

Slope movements could be disastrous, and it needs not be very massive to be destructive. Disastrous landslides have occurred in several places in the world sometimes claiming lives and properties, for instance: the Shenzhen catastrophic flow, killing at least 165 people with many collapsed buildings in China, which took place on 20 December 2015 (Gao et al. 2017); in April 2013, a massive slope failure occurred at the open pit of the Bingham Canyon mine in Utah, USA. Failure of internal dumps is a complex problem; in addition to environmental considerations, it directly affects the mine safety (Kainthola et al. 2011), deprivation of production, and additional cost for recovery, mine abandonment or premature closure and potentially loss of life in the study area. As a result, analysis of stability of operation or abandoned tailings is important. Hence, this paper is aimed at applying different geotechnical parameters to evaluate the waste dump safety using stability analysis, so as to suggest an economical, consistent and safe disposal of the mine wastes, and also provide possible remedial measures for slope failures.

Comprehending the factors that contribute to slope instability provide important information for safe mining operations. Due to the continuous increase in dump heights, there is a possible threat to their stability and related problems (Gupta and Paul 2016). Shear strength of mine tailings has a major role to play in analysing the stability of tailings. A good understanding of the shearing behaviour of soil for stability design involves a combination of laboratory-scale diagnostic testing and engineering judgment (Bradfield et al. 2013). Shear strength involves

evaluating the cohesion and frictional angle of the slope material.

Slope stability is mainly evaluated using the slope geometry and the strength of the materials. However, geometrical properties of the slope are significant factors that affect its stability. Some of the key features of slope design parameters that affect the geometric properties are the height of the slope, slope angle, the width of the slope and the total area of failure surface. Slope stability is thus dependent on height such that as the slope height increases the stability decreases. More so, the stability of mine tailings depends upon several other factors: compaction rate, specific gravity of the slope material and degree of saturation.

Study area description

The study area is located in Abakaliki local government area of Ebonyi state. It lies within longitudes $006°$ $05′$ N and $006°15′$ N and $008°$ $05′$ E and $008°10′$ E (Fig. 2). It falls under the lower Benue Trough. Figure 3 shows the geologic map of the study area. According to King (1950), Farrington (1952), Nwachukwu (1972), Murat (1972) and Cratchly and Jones (1965), the Benue Trough originated as a failed arm at the time of the opening of the South Atlantic Ocean during the separation of the African plate and the South American plate. The area is part of the "Abakaliki anticlinorium" and it is underlain by the Abakaliki shales of the Asu River Group of the Albian-cretaceous sediments.

The Asu River Group consists of an alternating sequence of shales, mudstone and siltstone with some occurrence of sandstone and limestone lenses in some places and attains an estimated thickness of 1500 m (Agumanu 1989; Farrington 1952). Kogbe (1989) stated that the sediments consist of poorly-bedded sandy limestone. Much weathering and ferruginization have greatly transformed the black shales to a bleached pale grey shale with mottles of red, yellow, pink and blue (Orajaka 1965; Ukpong and Olade 1979). The lithostratigraphic succession of the area include: Albian-Cenomanian-Turonian-Conaician-Santonian-Campanian-Maastrichtian. The rocks are extensively fractured, folded and faulted particularly following the series of tectonic episodes acted on them from Albian times (Benkhelil 1986). The fractures in the area serve as reservoirs for lead-zinc mineralization in the area. The highly indurated shales were interpreted by Obiora and Charan (2011) to have undergone low grade metamorphism, which is the reason for its usage as construction material. The areas studied generally consist of brown clay to reddish brown shales underlain by black shale, which formed part of the components of the dumps.

The vegetation is part of the rainforest savannah region of south-eastern Nigeria (Blench 2004), and it is characterized by grasses and large trees of various sizes. The topography of the area is generally undulating with elevation not

**Fig. 2** Location, accessibility and drainage map of the study area
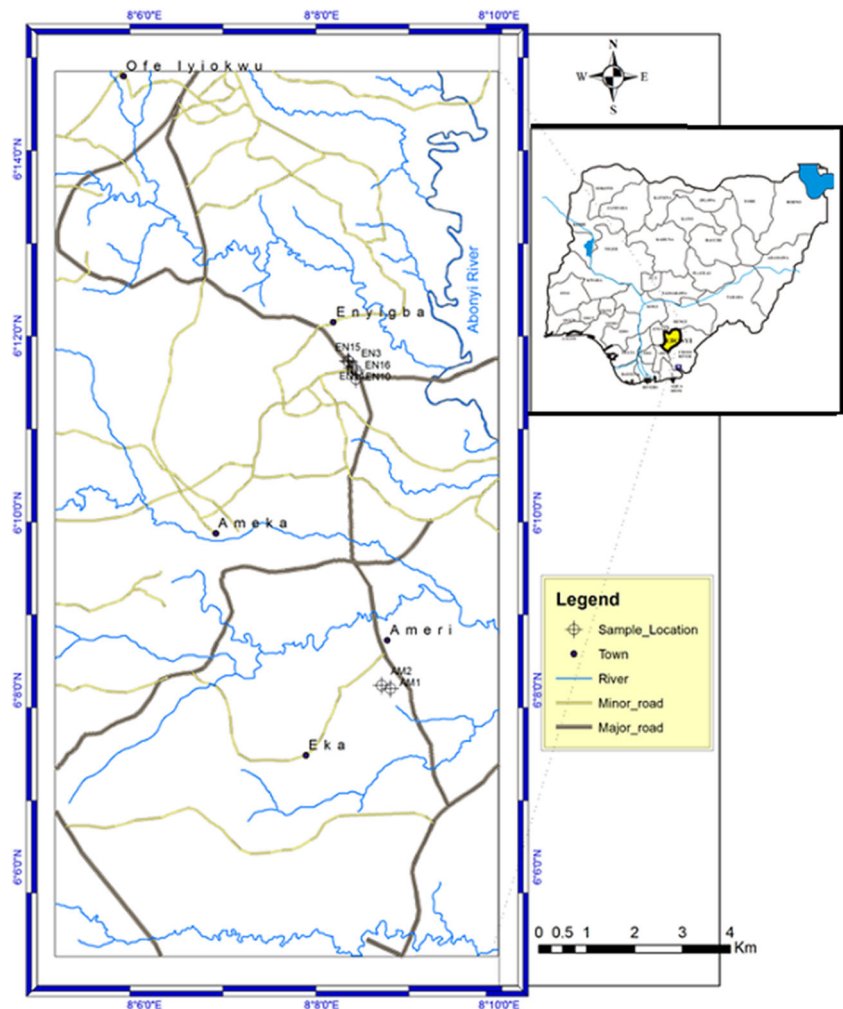
more than 400 m above-sea-level (Fig. 4). The rocks in the area are striking NE-SW with dip amount ranging from 10 to 56° in the SE direction (Fig. 3). However, the areas with high elevation are more vulnerable to failure than the regions with lower elevation. This is because the tailing slopes are supported by natural slopes whose stability could be compromised due to high dip amounts. The surface topography of Enyigba has been greatly altered as shown in Fig. 1. The area is underlain predominantly by shale, which could be responsible for its low erodability. It is characterized by a humid tropical climate. The mean annual temperature stands at 28 °C (Nweke 2015). It experiences rainy and dry seasons in a year (8 months of rainfall and 4 months of dryness). The area is drained by a major river known as the Ebonyi River and its tributaries (Iyiudene and Iyiokwu). Both tributaries are perennial and usually overflow their banks at the peak of the rainy season. The major river and its tributaries form a network of narrow, meandering and feeder streams depicting a dendritic pattern of drainage controlled by the geology of the area (Igwe et al. 2012a, b) as seen in Fig. 2.

Methodology

Fieldwork

Field investigations involving reconnaissance survey and detailed geologic field mapping were carried out to carefully study the observable features on the mine tailings of the Enyigba district, generate the slope geometry and coordinates of the area and to collect samples for geotechnical analysis. This was done in May 2017 (at the beginning of the rainy season). The authors wish to state clearly that all Human and Animal Rights were preserved throughout the course of the field work. A total number of 50 slopes were studied and seven disturbed samples were collected from abandoned and new mine tailings at Enyigba and Ameri mines as representative samples from different locations of the mine site. The samples are labeled AM 1 (OT), AM 2 (NT), EN 3 (OT), EN10 (OT), EN14 (NT), EN15 (OT) and EN16 (OT) respectively for the seven samples (Fig. 3). The OT and NT attached to the labels signify old tailings and new tailings respectively.

Fig. 3 Geologic map of the area


(a)

(b)
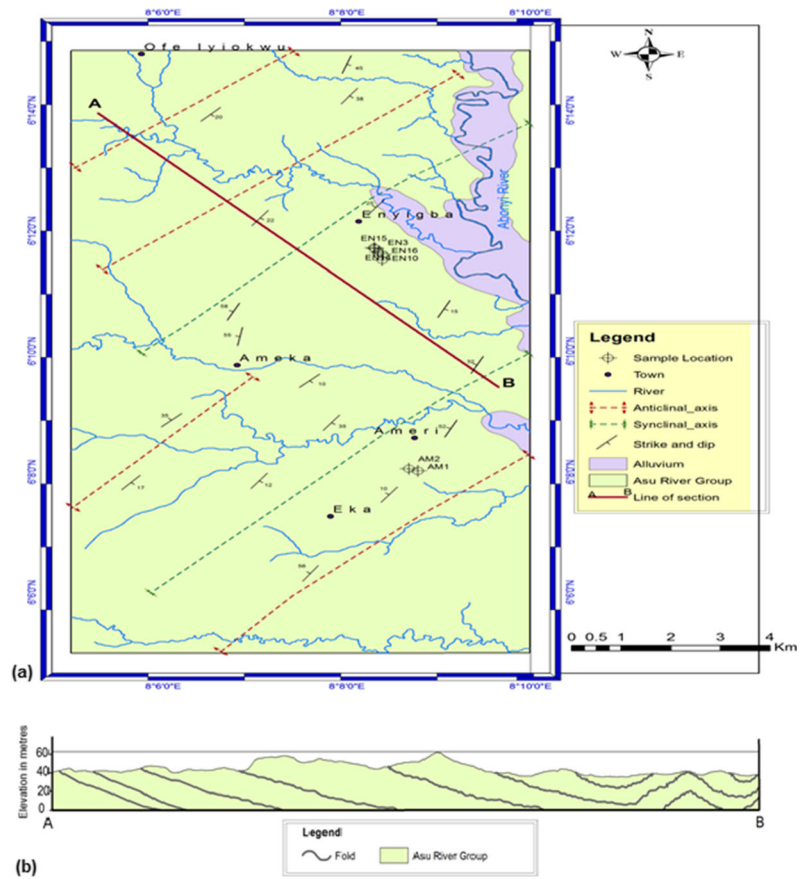
Laboratory analysis

The samples collected from the site were analysed in the laboratory to reveal properties, such as natural moisture content, permeability, Atterberg limits, grain size distribution, specific gravity, compaction and shear strength of the materials. X-ray diffraction test was also carried out at the Nigerian Geological survey agency, Kaduna, to reveal the component minerals of the tailings.

The samples were oven dried and the laboratory tests were carried out according to the relevant ASTM standard of soil testing. The particle size distribution was done in accordance with ASTM D421 (1994) using sieve analysis for coarse materials, while the fine (percentage passing 0.075 mm sieve) fractions were passed through sedimentation analysis as outlined by Kettler et al. (2001) and the ASTM D422 (2007) standard test method for hydrometer analysis for soil. The natural moisture content was done in accordance with

Fig. 4 3D topographic model of the area
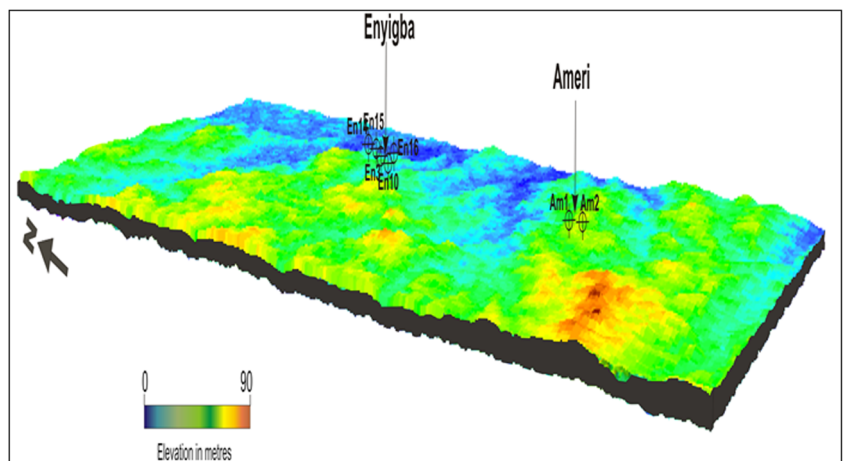
ASTM D4959, whereas the shear strength was tested in a triaxial device according to ASTM D4767. The triaxial device was used to obtain shear strength parameters. Samples were first prepared at in situ density and moisture content and were further saturated to test for shear strength of material at different moisture conditions. The Atterberg limits were performed according to ASTM D4318. Compaction characteristics were measured in accordance with ASTM D698 using standard effort (600 kN-m/m^3). The permeability was determined by the falling head permeability test according to ASTM D5084, while specific gravity was done in accordance with ASTM D854.

Coordinates of the study area were used to develop a digital elevation model of the area (Fig. 4). The Slope/W Geostudio® 2012 software developed by Geo-Slope International Limited was used to produce modeled diagrams of slope morphology and failure prediction (in terms of factor of safety) of the slopes. The analysis type used was the Morgenstern-Price limit equilibrium method. Parameters from the geotechnical tests conducted on the slope lithologies were entered into the Geostudio software, and the parameters keyed in included the dry unit weight, saturated unit weight, cohesion, internal friction angle and the slope geometry (mainly the slope height and slope angles).

Results

The samples presented a wide range of variability in their geotechnical characteristics. The particle size distribution result revealed that the content of gravel, sand, silt and clay in the Enyigba tailing dump units are 1.42–30.13%, 15.94–33.34%, 9.75–26.87% and 32.1–56.25% respectively (Table 1). The tailing materials were uniformly graded (Fig. 5). The results showed that there is a high percentage of clay and a low to medium percentage of sand and gravel. The permeability (k) of the samples ranges between 1.49×10^{-4} cm/s and 9.04×10^{-8} cm/s. The low k values imply that the soils are fine grained, which agrees with the particle size distribution result, and suggests the water holding ability of the soil.

The natural moisture content (NMC) measured was observed to be between 3 and 13%, signifying low to medium water content in the soil. The Atterberg limits indicate that liquid limit (LL) ranges from 24 to 49%, plastic limit (PL) ranges between 24 and 35% and plasticity index (PI) ranges from 9 to 26% (Table 2). These consistency limit values suggested that the soils possess low to high plasticity, which agrees with the soils' low to moderate moisture content. Compaction result showed maximum dry density (MDD) ranges between 1.86 and 2.22 g/cm^3, while optimum moisture content (OMC) ranges from 13.45 to 17.05% (Table 3). The result revealed intermediate OMC values and medium to high MDD. Cohesion and friction angle of the tailings ranges from

Table 1 Particle size distribution

Location	Am1	Am2	En3	En10	En14	En15	En16
Gravel (%)	12.72	30.13	12.98	1.95	11.32	1.42	22.65
Sand (%)	30.84	26.82	15.94	18.18	33.34	20.45	28.6
Silt (%)	14.89	9.75	19.83	26.87	16.84	21.88	16.66
Clay %	41.55	33.29	51.24	53	38.5	56.25	32.1

13 to 34 kN/m^2 and 8 to 37° respectively. Samples specific gravity (Gs) falls within 2.58 and 2.70. The minerals present in soil are quartz (39–49%), illite (38–58%), magnetite (2–3%), anatase (2%) and millosevichite (8%) according to the XRD result.

Discussion of result

Field description

Evidence of sliding surfaces and minor landslides were seen on the tailings (Fig. 6). Field observations showed that the landslides were more evident on the old tailings compared to the new ones and consist of mainly translational slides. Mud cracks were seen on the natural ground which is evidence of very fine clay materials in the area.

Most slopes were observed to be concave in curvature (Fig. 6), and from the field measurements, slope angles of the individual slopes ranged from 30 to 60°. The steep concave nature of the slopes and the inherent weakness (erosion) as observed at the two mine sites have important implications on the slope stability. Most landslide events have normally been reported to occur on concave slopes ranging between 36 and 58 slope angles (Mugagga 2011; Mugagga et al. 2011). A spatial correlation between landslide occurrence and topographical concavity has been noted by Mugagga (2011). Igwe (2015a) also reported that positive correlation exists between frequency of landslide and slope angle and noted that landslides occur more on slopes with angles greater than 30° but less than 40°. Thus, slope geometry could be one of the causes of the sliding surfaces as shown in Fig. 6, since it presents moderate to high slope angles.

Grain size analysis

Results obtained from this test are presented in Table 1. The particle size distribution revealed that the slope material comprises gravel ranging from 1.42 to 30.13%, sand ranging between 15.94 and 33.34%, silt ranging from 9.75 to 26.87% and clay ranging from 32.1 to 56.25%. This implies that clay dominates the slope materials. The high amounts of clay in the slope material at the mine sites also have strong implications

Fig. 5 Particle size distribution curve
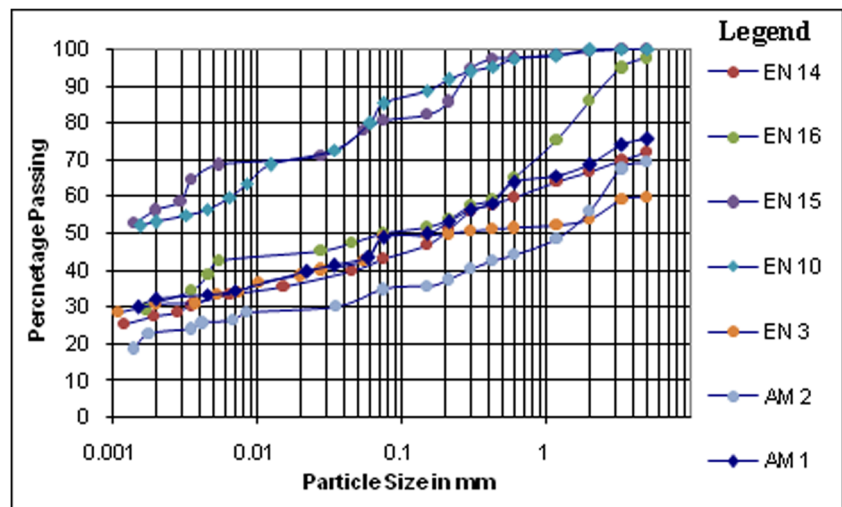
for landslide occurrence. Several works, such as Knapen et al. (2006), Yang et al. (2007), Kitutu et al. (2009) and Wati et al. (2010), have reported that high clay content contributes largely to landslide occurrence depending on the amount and type of clay minerals present. The high clay content of the tailings dump (average of 44%) could have implications on the shrink-swell properties of the soil. Mugagga et al. (2011) noted that materials with clay content exceeding 20% will exhibit expansion depending on the type and amount of clay minerals present. Ten percent (10%) clay content has often been used as an indicator of the expansion potential of materials (Baynes 2008), and thus 44% average clay content of the samples could imply medium to high expansive potential.

Moisture content and consistency limits

The result of Atterberg limits and moisture content tests are shown in Table 2. The materials' natural moisture content ranges from 3 to 13%. This NMC may be suggestive of a low to medium moisture holding ability of the tailings,

especially at the time of this work which coincides with the beginning of the rainy season. The soil liquid limit (LL) ranges from 24 to 59% and the PL ranges from 24 to 35%, while PI ranges between 9 and 26%. Thus, the soils can be classified as ML or CH according to the Unified Soil Classification System (USCS) (Fig. 7). It is observed that AM 2 and EN 14, which represent the new tailings, have the lowest values of liquid limit, with LL = 24 and 36% respectively, whereas the old tailings have higher values with LL = 42–59%. This could be the outcome of higher water content in the old tailings as a result of water infiltration over a longer period of time. Much emphasis has been made by many authors on the role of LL in characterizing problematic soils (Msilimba and Holmes 2005; Fauziah et al. 2006; Baynes 2008). The high LL coupled with high clay content at the site could qualify the soils as problematic soils that are susceptible to landslides. The LL for all the sites is quite above the threshold of 25%, indicating medium expansion potential of the soils (Mugagga et al. 2011).

Sowers and Sower (1970) established that soils with a high PI tend to be clay, those with a lower PI are likely to be silt and those with a PI of 0 (non-plastic) tend to have little or no silt or clay. This is in line with the non-plastic nature of AM 2. The average PI value of tailing dump materials is 17%. The average values of plasticity index and liquid limit for most of the samples could be an indication of low to moderate swelling potential of the clay, such that the soils exhibit medium expansion potential (Mugagga et al. 2011). Igwe et al. 2013 also noted that materials with high clay content hinder water movement; thereby, increasing pore water pressure in the material. A positive correlation has been observed to exist between high plasticity and fine-grained inorganic clay and silts

Table 2 Soil index properties

Location	Sample No	Description	NMC	LL	PL	PI	Υ (KN/m³)
Ameri	Am1	Old tailing	13	52	33	19	16.45
Ameri	AM2	New tailing	7	24	NP	NP	15.80
Enyigba	EN3	Old tailing	8	43	34	9	14.93
Enyigba	EN10	Old tailing	3	59	35	24	16.59
Enyigba	EN14	New tailing	4	36	24	12	15.41
Enygba	EN15	Old tailing	4	59	33	26	15.38
Enyigba	EN16	Old tailing	3	42	28	14	15.82

Table 3 Geotechnical properties of the soil

Sample No	C (kPa)	Φ (^{0})	MDD (g/cm^2)	OMC (%)	Gs	Υ_b(mg/m^3)	k(cm/s)
AM1	32	14	2.22	17.05	2.60	2.04	5.35×10^{-7}
AM2	13	37	1.86	13.79	2.67	1.96	1.49×10^{-4}
EN3	15	20	2.06	13.79	2.58	1.79	1.33×10^{-6}
EN10	34	10	2.18	14.02	2.70	2.21	3.16×10^{-7}
EN14	18	22	2.12	13.65	2.62	1.84	2.66×10^{-4}
EN15	27	8	1.92	13.92	2.63	1.86	9.04×10^{-8}
EN16	18	18	2.12	13.45	2.61	1.91	1.32×10^{-6}

(Isik and Keskin 2008). This swelling ability could signify the presence of swelling clay minerals. Due to the reduction of shear resistance, sliding has been found to be prevalent in plastic inorganic soils during rainfall events (Dai et al. 2002). Therefore, these plastic inorganic clays could be susceptible to sliding even under moderate rainfall events.

Permeability and bulk density

Infiltration capacity of soil depends on the permeability, degree of saturation, vegetation and amount and duration of rainfall (Todd 1980). The permeability coefficient (k) showed results ranging from 1.49×10^{-4} to 9.04×10^{-8} cm/s (Table 3). The low permeability of the tailings could cause excess pore pressure build up during the rainy seasons due to high water levels. This in turn reduces the strength of materials and may result in dump failure.

Fig. 6 Conical hills of the dump at the mine site

Very fine-grained clayey materials have been observed to possess small pores that usually release water due to their high water retention capacity; thus, rendering such clay susceptible to landslides (Yang et al. 2007; Jadda et al. 2009; Wati et al. 2010; Mugagga et al. 2011). The vulnerability of these clay soils are also aggravated by their low permeability (Wati et al. 2010). According to Glade (2002), Knapen et al. (2006) and Mugagga et al. (2011), deep rotational landslides on concave slopes can be attributed to the concentration of runoff and subsurface water, which reduces slope shear resistance.

The bulk density (γ_b) of the slope samples ranges between 1.79 and 2.21 Mg/m^3 (Table 3), which falls within the range of swelling clays. Seedman (1986) and Hong et al. (2012) noted that osmotic swelling occurs in clays with bulk density less than 2.45 Mg/m^3. This is because very high activity of smectite minerals in clays enhances high water absorption ability, and thus increases the natural moisture content of the soil.

Compaction

Figure 8 shows maximum dry density curves for the samples. It explains the maximum compaction of the soil at optimum water content and dry density. The compaction result showed that the soil optimum moisture content (OMC) ranges between 13.45 and 17.05%, while the maximum dry density (MDD) ranges from 1.86 to 2.22 g/cm^3 (Table 3). The curves represent that of low to medium plastic clays, which agrees with the consistency limits. At high water content, energy has little effect on the compacted density of a clay soil because the water is incompressible and takes the applied force without densifying the soil. Invariably, moderate OMC and moderate to high MDD suggest an intermediate to high density material.

Specific gravity

The results of the tested samples are presented in Table 1. The values range from 2.58 to 2.70 (Table 3). Tuncer and Lohnes (1977) noted that the specific gravity of sandy soil, which is mostly made of quartz, may be estimated to be about 2.65, whereas for clayey and silty soils, it might vary from 2.60 to 2.90. Thus, the average specific gravity value of 2.63 confirmed the high clay content of the materials.

Fig. 7 Soil plasticity chart of the samples
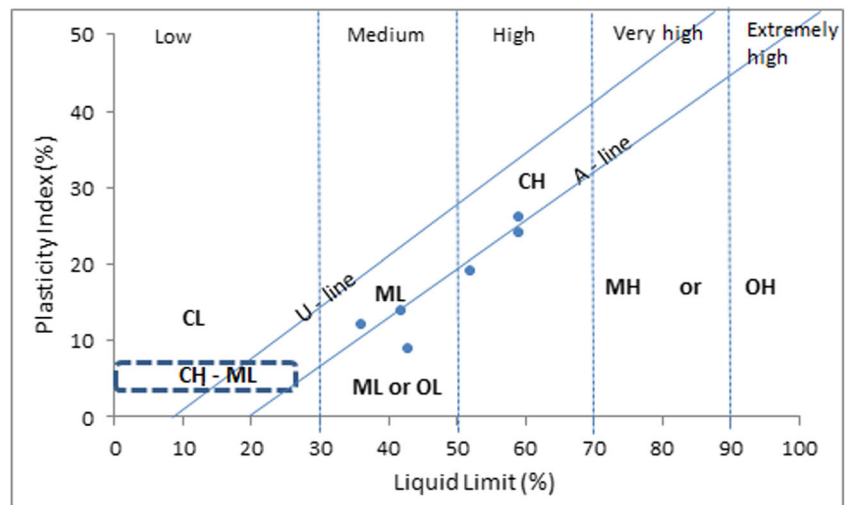
Shear strength

This is one of the key tests in establishing the stability of a slope material as it indicates cohesion and angle of internal friction of the material. Gupta and Paul (2016) clearly stated that slope stability is ultimately determined by two factors; the slope geometry and the strength of the materials on it. The range of the angle of internal friction and cohesion are 8–37° and 13–34 kN/m^2 respectively (Table 3). These results implied low-moderate values of cohesion and low values of internal friction angle for AM1, EN3, EN10, EN 15 and EN 16 (Table 3). Some of the samples' failure envelopes are shown in Fig. 9.

It was observed that AM 2 is the least cohesive and has the highest angle of internal friction. This confirms the cohesionless nature (low clay content and plasticity) of the material. The low shear strength of AM 2 could be a result of the presence of expansive minerals. Blyth and de Feritas (1984) postulated that the strength of any rock or soil where permeability prevents the draining of water in the voids would be reduced by any increase in hydrostatic pore pressure that develops within them as observed in Fig. 9. Water-infiltration weakens slopes and induces failure by reducing suction and strength (Crosta and Frattini 2008; Igwe and Fukuoka 2014;
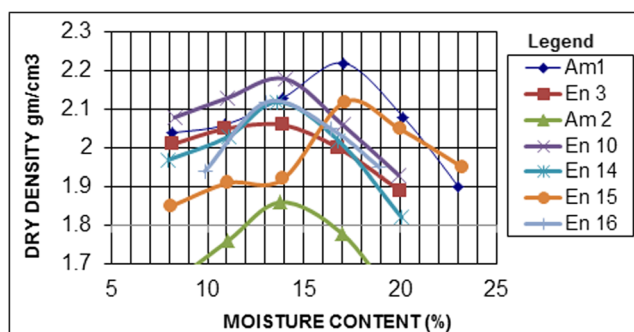
Igwe 2014). The strength reduction is experienced when the shear forces on a slope become greater than the mobilized resisting forces; thereby, causing a considerable drop in the slope factor of safety (Igwe 2015b). Steep slopes are mostly affected owing to the increasing shear stress against reducing shear strength (Yang et al. 2007; Wati et al. 2010; Mugagga et al. 2011). Behera et al. (2016) observed that a decrease in shear strength may trigger landslide in the dump slope along weak planes.

Soil minerals

The XRD result showing the minerals present in soil is given in Fig. 10. The presence of illite indicates plasticity of the soil due to its swelling ability. There is evidence of the shrink-swell ability of the soils in the form of voids or desiccation cracks within the site (Fig. 11). The presence of clay minerals could give more plasticity to the soil, which is one of the most important causes of slope failure (Behera et al. 2016). Previous authors (Kitutu et al. 2009; Ohlmacher 2000; Yalcin 2007) have observed the role of dominant plastic clay minerals in landslide occurrence owing to their low shear strength and high swelling potential.

A comparison made between the old and new dumps revealed differences in the number and percentage of minerals. The old dumps have a lower number of minerals (3) but higher percentage of illite (58%) than the new dumps with five minerals and 38% illite (Fig. 10). This could be the effect of leaching and weathering respectively. The effects of the leaching and weathering could negatively impact the strength of the slope materials; thus, subjecting the slope to instability.

Rainfall pattern of the area

The stability of slopes could be compromised by the influence of external and internal factors. Looking at the rainfall data of
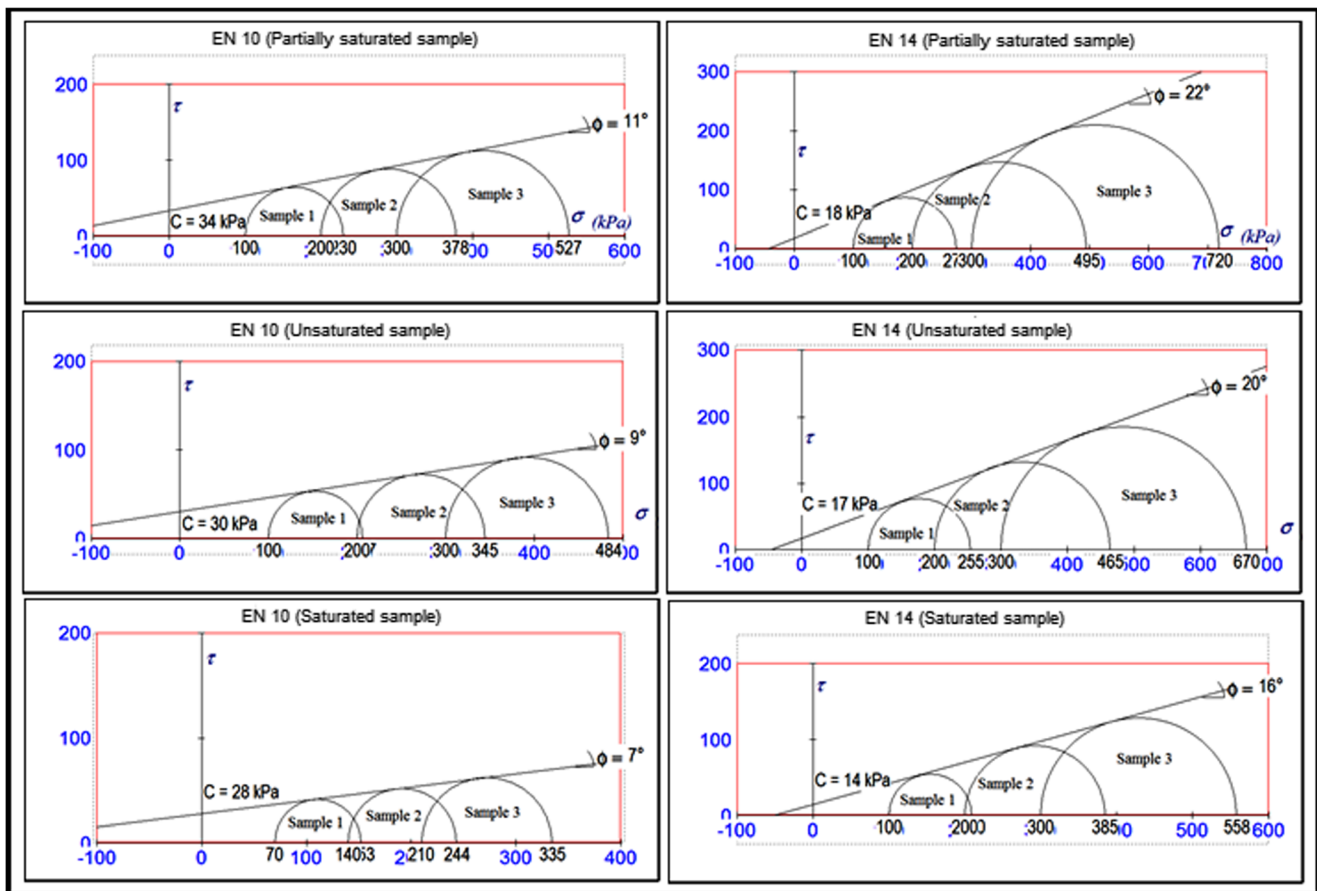

Fig. 8 Compaction curves of the samples

Fig. 9 Failure envelop showing strength parameters

the area (Fig. 12), it is evident that the study area has very high cumulative annual rainfall that could be as high as 1200 mm and sometimes up to 2500 mm. This high rainfall pattern could be detrimental to the stability of the tailing dump slopes. High rainfall may result in high infiltration and seepage through the dump slope, and thus increase pore pressure within the tailing dumps which thereby undermines the shear strength of the materials (Verma et al. 2013). The decrease in shear strength could initiate movement in the tailing dump slope along weak planes (Behera et al. 2016). As the erratic increase in rainfall continues, there will be a need to make adequate preparations for stabilization works in order to prevent the occurrence of landslides.

Stability analysis of the dumps

The integration of experimental and stability studies have assisted extensively in the analyses of slopes subjected to rainfall infiltration (Griffiths and Marquez 2007; Igwe et al. 2012a, b; Sarkar et al. 2012; Ma et al. 2013; Singh et al. 2013; Alemdag et al. 2014; Kalatehjari et al. 2014; Igwe 2015b). Slope stability analysis has been carried out on the tailing dump slopes, using the limit equilibrium method (LEM), which presently is the most common stability approach in

the field of slope stability analysis (Cheng and Lau 2014). The analysis type adopted was the Morgenstern-Price limit equilibrium method.

Stability analyses of several slopes of the Enyigba mine dumps were evaluated, and their factor of safety (FS) computed. Figures 13 and 14 are the stability analysis of slopes EN10 and EN14, and the computed FS were 1.27 and 1.33, suggesting fairly stable slopes (Figs. 13a and 14a). The FS of the other slopes analysed ranges from 1.00 to 1.30, implying critically to fairly stable slopes (Table 4). These factors of safety were recorded at the onset of the rainy season. At this time of the year, the slope materials could be partially saturated, with little water in the dumps. A back analysis performed on the samples to represent the unsaturated state of the slopes in the dry season showed FS of 1.10 and 1.29 (Figs. 13e and 14e), which is a reduction in the stability of the slopes. The higher FS recorded at the start of the rainy season could be as a result of the shear strength mobilized by the tailings due to suction.

However, many authors have reported a significant drop in FS with increasing saturation (Onda et al. 2004; Rahardjo et al. 2005; Igwe 2015b). There is evidence of flooding (waterlogs) at the sites from previous rainy seasons (Fig. 11), and considering the possible influence of tailing saturation by groundwater rise and flooding within and around the old
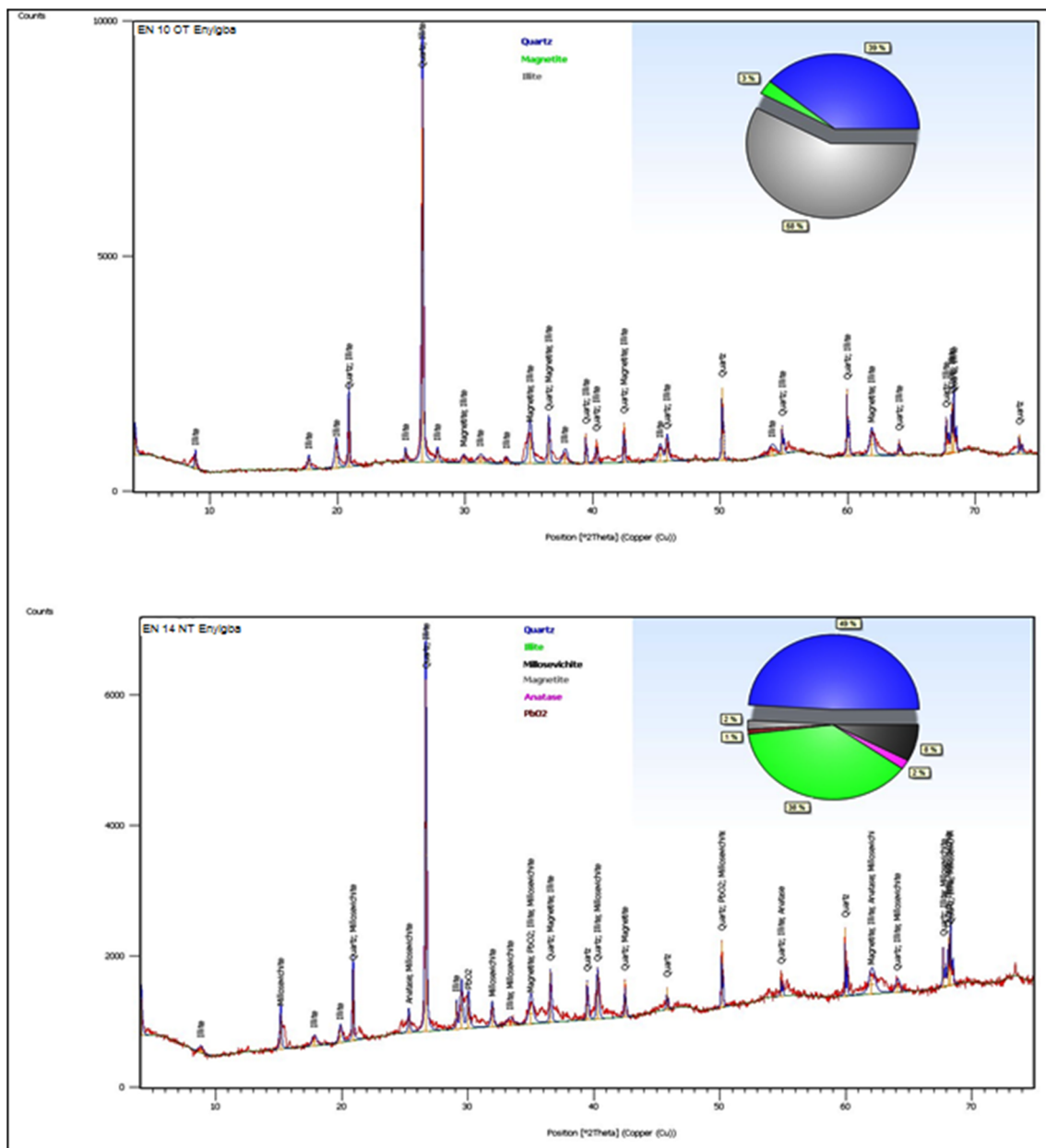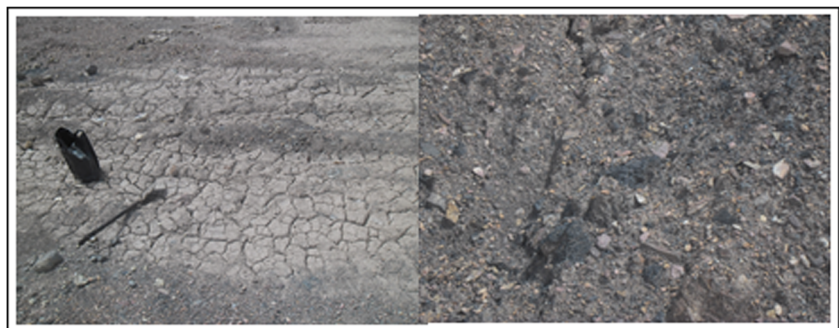
Fig. 10 XRD showing the mineral components of the samples

tailing slope, our analysis, revealed a further reduction in FS to 0.99 (Fig. 13f); thus, declining from fairly stable to critically stable. This fall in FS was also observed on the new mine tailing slope, where the FS dropped to 0.94 (Fig. 14f).

Fig. 11 Evidence of smectite minerals, soil plasticity and flooding
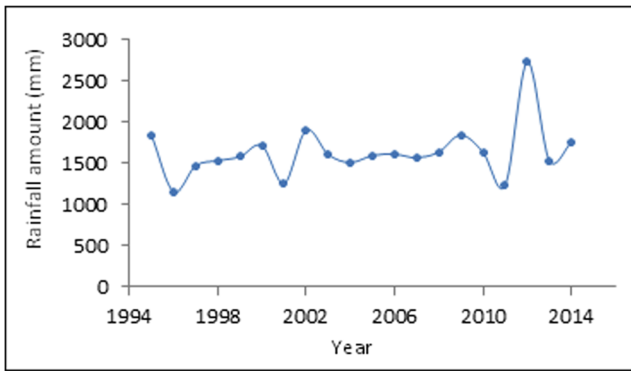
Fig. 12 Rainfall data of the study area

Therefore, saturation of the tailings could be detrimental to the dump slopes' stability, and thus should be avoided by using appropriate drainage control methods. The drop in FS may remain continuous as water content increases to a level where suction is replaced by saturation in the slopes before failure is initiated at FS < 1. At FS < 1, the activating forces are greater than resisting forces; thereby, triggering a mass wasting process, such as landslide or mudflow.

It is important to note that water in and around the slopes could increase the volume of the sliding materials. The sliding masses increased from 156 m^3 to 292 m^3 and 99 m^3 to 176 m^3 as water content increased within the slopes at the old and new tailing dumps as seen in Figs. 13 and 14. These increases in

sliding mass agree with the findings of other authors such as Maduka et al. 2016, who also noted that slope failures with these magnitudes of sliding masses could be described as intermediate to high landslide. The new mine dumps would likely undergo shallower landslides with slip surfaces ranging between 11 and 14 m when compared to the depth of 12–17 m of the old mine dumps (Figs. 14 and 13 respectively). These values and other disparities in failure parameters as seen in Figs. 13 and 14 could be as a result of differences in their level of compaction and cohesion. The friability of the new tailing dumps could be the reason for the shallow landslides observed in Fig. 6.

Several trial slip surfaces were analysed on the modeled slopes (Fig. 13c and 14c) to produce a safety map for each. A safety map reflects a zone of potential failure in which the factors of safety of the trial slip surfaces are similar. Although the FS for the trial slip surfaces range from 1.27 to 1.75 for the old tailing dump and 1.33 to 1.44 for the new dump, the safety zone ranges between FS = 1.27–1.32 and 1.33–1.38 for the old and new tailing dumps respectively. The safe zones are the area covered by the red band (Figs. 13d and 14d), and all the factors of safety within the region indicated a fairly good stability. It is important, however, to state that even slopes with FS >1 are conditionally stable (Mugagga et al. 2011). This could be the appropriate description of allegedly stable slopes because slope failure often occurs as a result of localized
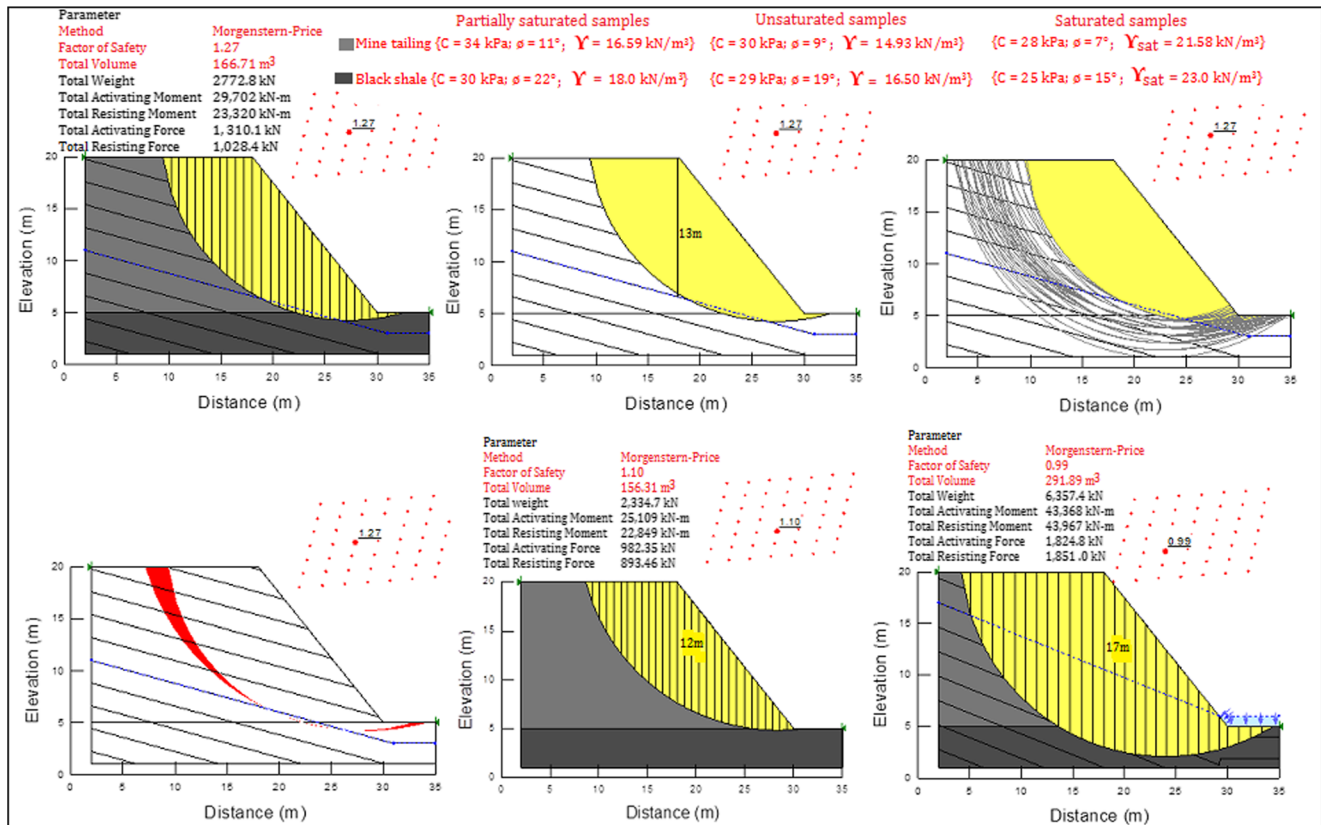

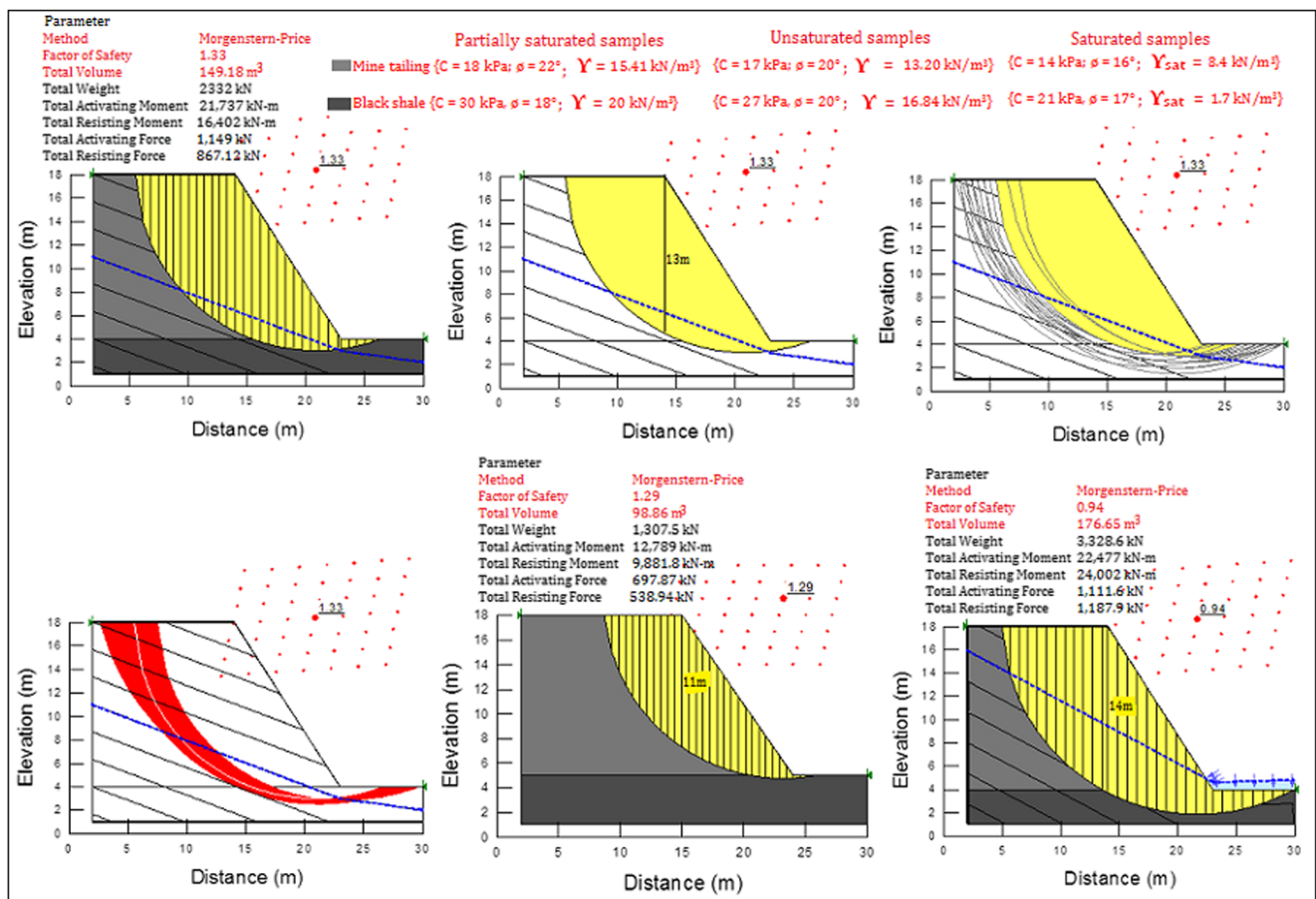
Fig. 13 Slope stability model of an old mine tailing

Fig. 14 New mine tailing slope stability model

deformation in a thin zone of intense shearing. Consequently, this thin intense shearing force may not be duly represented by the overall stress–strain measurement (Gonghui et al. 2010), owing to the influence of several physical and anthropogenic factors (Mugagga et al. 2011).

Moreover, in this era of erratic rainfall regimes, which is the principal trigger of slope instability (such as landslide and mudflows), coupled with the inherent weaknesses of the slope materials (low shear strength, low permeability and high clay content and OMC) and other visible triggers of landslides, such as erosion and discontinuities (tension cracks), it would be impossible to rule out the occurrence of a massive landslide, capable of undermining the safety of lives and properties

within the mine sites. Therefore, stabilization of the slope is needful, particularly on slopes in proximity to the mining pits (Fig. 15), though only shallow landslides are evident on the

Table 4 Stability analysis result

Location	Slope description	Fs	Remark
Ameri	Old dump	1.30	Fairly stable
Ameri	New dump	1.00	Critically stable
Enyigba	Old dump	1.30	Fairly stable
Enyigba	Old dump	1.15	Poorly stable
Enyigba	Old dump	1.24	Fairly stable

Fig. 15 The dangerous closeness of the tailings to the mines

site at present (Fig. 6). However, some shallow landslides at the site could be as a result of cyclic loading and vibrations on the slope from heavy vehicles and machines and blasting (Igwe 2015a).

The stability of the slopes can be improved by water removal (dewatering) from the slope. However, this method of slope stabilization is expensive, time consuming and a tedious practice. Maduka et al. (2016) suggested the benching method (reduction on slope angles and slope heights) as a reliable, efficient and less expensive way of increasing the stability of slopes.

Conclusions

The physical properties of the Enyigba mine slope material have been characterized in this study, and their implications on the slope stability elucidated. Steep slopes, slope curvature, high clay contents as well as high water content and poor shear strength of the Enyigba tailing dumps have been pointed out as some of the factors that would negate the stability of the slopes, coupled with the recent rise in annual rainfall in southeastern Nigeria.

The slope materials at the Enyigba mine site have been characterized generally to be dark grey shale. The soil particle distribution, moisture content, permeability, compaction and shear strength indicated low to medium plastic soil, with low to medium water holding ability. These physical attributes could be as a result of soil mineralogy. The presence of illite minerals further in samples explains the reason for the soil weakness at the time of analysis. Soils with the above attributes have been observed to exhibit low strength either as foundation or slope materials and capable of causing engineering failures at sites. This agrees with the measured shear strength parameters (cohesion and internal friction angle), computed to be 13–34 kN/m^2 and 8–37° respectively, signifying low to medium strength soil materials, capable of shear failure at engineering and mining sites.

The result of the stability analysis hints at the possibility of landslide occurrences on the tailing dump slopes within the Enyigba mine sites. The studied mine tailing slopes were inferred to be critically to poorly stable, with the computed factor of safety ranging from 1.00 to 1.30, suggesting possible failure of the slope. Therefore, there is a need for slope stabilization on the mine tailing dumps at Enyigba and Ameri.

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