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ORIGINAL PAPER

Slope failures and safety index assessment of waste rock dumps in Nigeria's major mines

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Abstract

Dump slope failure has become a recurring incident in Nigeria's major mine sites while the visible signs of instability in Nigeria's waste rock dumps are the most dangerous situation. This paper aims to present intrinsic poor safety conditions of dump slopes in Nigerian mines. Twenty-one samples were collected from three mining provinces (7 samples from each province) and were subjected to various geotechnical tests such as particle size distribution, Atterberg limits, triaxial, compaction, consolidation and permeability tests. Results obtained were analyzed using numerical simulation models. From the laboratory data, the waste dumps were proven to be cohesive materials despite their high sand content. The wastes were described by the geo-mechanical characterization of the samples as competent materials with moderate strength and low compressibility, indicating materials with intermediate engineering capabilities. However, both field observation and numerical simulation of the waste dumps revealed that high slope height and angle, as well as excessive material saturation caused by high seasonal rainfalls, could compromise the stability of the dump slopes. According to stability analysis, the most crucial failure modes would be superficial plane and polygonal failures, as well as deep circular failures on rare occasions, all of which are governed by the mines' local geology. The waste dumps' factor of safety, probability of failure and reliability index values all suggested slope instability, especially during the rainy season. To prevent future waste dump slope failures, the authors advocate recycling and reusing waste rocks as engineering materials, particularly for tailing dam structures.

Keywords Waste rock dumps · Slope failures · Structural weaknesses · Factor of safety · Probability of failure · Reliability index

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1 Introduction

1.1 Background

Slope failures refer to mass ruptures under the effect of gravity (Cruden and Varnes 1996; Calcaterra et al. 2008; Fell et al. 2008; Cruden and Couture 2010). Causative processes are weathering, disintegration of soil, discontinuities (joints, fractures and faults), increased pore water pressure in permeable stratum, liquefaction of soil due to shock from seismic activities as well as rainfall events (Wang et al. 2002; Sassa et al. 2004; Calcaterra et al. 2008; Calcaterra and Parise 2010; Cruden and Couture 2010), though Petrucci and Polemio (2009), Kainthola et al. (2011), and Del Soldato et al. (2018) capitalized that extreme weather condition is a major factor of slope failure.

Slope failures have occurred in both developed and developing countries. Landslides are responsible for the majority of all fatalities caused by natural disasters (Del Soldato et al. 2018), and dump slope failures have occurred in 70% of the world's large mines (Singh et al. 2013). Examples are dump slope failures in Canadian Rocky Mountains mines with debris run-out distances of 2 km (Dawson et al. 1998); a sliding mass of 20hm^3 of waste material occupying over 0.60 km in central Anatolia, Turkey (Kasmer et al. 2005); a slope failure in the South Field Mine in Ptolemais, Greece, which generated approximately 40 million cubic meters (hm^3) mass waste (Kavouridis and Agioutantis 2006); andopencast dump slope failures with 50 casualties in India (Gupta et al. 2015).Other historical antecedents of waste rock dump instability with their recorded fatalities are shown in Table 1.

Gaining currency in researches are slope failure and stability, safety condition, geohazard risk management, and environmental protection of mine waste dump (Casson et al. 2003; Muthreja et al. 2012; Singh et al. 2013; Del Soldato et al. 2018). This is largely driven by the monumental waste production in mining sector (Fig. 1), further exacerbated by scarcity of land for dumps, repeated cases of slope failures, angularity of slope necessitating high heaps of waste rock and other associated hazards (Fell et al. 2008; Kainthola et al. 2011; Gupta et al. 2015).Approvingly, Fell et al. (2008) and Schuster and Highland (2001) opined that social awareness, government policies and landmark regulation-cum-legislation has made its study a popular source of fascination and a very crucial issue.

Failure of these massive dumps could result in environmental, economic, social and health challenges, and at the extreme conditions could possibly lead to fatality (Fell et al. 2008; Lednicka and Kalab 2015). Hazards could range from environment damage and degradation, pollution of soil and water which destroys drinking water sources and arable lands and heavy metal poisoning (Okagbue 1992; Fell et al. 2008). Apparently, accurate prediction of slope displacement taking knowledge of the probability of failure and different challenges in mining sector is a critical need of the moment. This is because it will assist in defining sustainable and suitable disaster response strategy which will avert colossal damages (Gupta et al. 2015).

Ethical practice demands that prior to siting a waste rock dump, geology, foundation soil and waste rock particles together with the hydrogeology are evaluated (Guemache et al. 2011) to avoid dump failures (Muthreja et al. 2012). Regrettably, in Nigeria, high waste rock dumps (Fig. 1b), wherein open-pit method is practiced, are located in close proximity to the mine with information about slope instability and its effect in the environment left in complete obscurity (Agbor et al. 2014; Bamisaiye 2019), thereby making slope failure imminent (Fig. 2).

Table 1 Waste dump failure cases

Year	Event	Country	Fatality	References
1962	El Cobra tailings failure	Chile	250	Muthreja et al. (2012)
1963	Jamuna mine dump failure	India	6	Dash (2019)
1963	Jharkhand mine dump failure	India	4	Dash (2019)
1963	Kargali mine dump failure	India	8	Dash (2019)
1966	Aberfan coal waste dump failure	Wales	144	Muthreja et al. (2012)
1968	North Salanpur mine dump failure	India	6	Dash (2019)
1970	Mufulira mine tailings failure into underground workings	Zambia	89	Muthreja et al. (2012)
1972	Middle Fork Buffalo Creek (2) coal dump failure	USA	125	Muthreja et al. (2012)
1974	Bafokeng mine tailings failure	South Africa	9	Muthreja et al. (2012)
1975	Hessalong mine dump failure	India	6	Dash (2019)
1975	Pannandhro Lignite mine dump failure	India	4	Dash (2019)
1980	Jorekuri Palasthali mine dump failure	India	4	Dash (2019)
1992	Belo Horizonte waste dumpsite failure	Brazil	> 100	Lavigne et al. (2014)
1993	Istanbul waste dumpsite failure	Turkey	39	Lavigne et al. (2014)
1994	Merriespruit Harmony mine tailings failure	South Africa	17	Muthreja et al. (2012)
2000	Payatas, Manila waste dumpsite failure	Philippines	278	Lavigne et al. (2014)
2000	Kawadi opencast dump failure	India	10	Dash (2019)
2005	Leuwigajah, Bandung waste dumpsite failure	Indonesia	147	Lavigne et al. (2014)
2006	Bekasi, West Java waste dumpsite failure	Indonesia	28	
2008	Sludge, mud and mining waste failures	China	128	Muthreja et al. 2012
2008	Jayant Colliery dump failure	India	5	Muthreja et al. 2012
2009	Sasti opencast dump failure	India	2	Muthreja et al. 2012
2010	Ajka overburden mud flow	Hungary	4	Muthreja et al. 2012
2010	Bogor, West Java waste dumpsite failure	Indonesia	4	Lavigne et al. (2014)
2012	Bantargebang, Bekasi, West Java waste dumpsite failure	Indonesia	1	Lavigne et al. (2014)
2012	Tuban, East Java waste dumpsite failure	Indonesia	1	Lavigne et al. (2014)
2013	Cianjur, West Java waste dumpsite failure	Indonesia	1	Lavigne et al. (2014)
2013	Basundhara mines of Mahanadi Coalfields, Odisha	India	14	Behera et al. 2016
2016	Rajmahal opencast dump failure	India	23	Dash (2019)

Cardinal in this paper is a geotechnical investigation of waste dumps' safety under various saturation conditions in some major mines in south and central Nigeria using simulation models. Determination of the stability in terms of factor of safety (FOS), probability of failure (ρf) and reliability index (β) of the waste dump slopes occupies a premium position in this study. The rainfall pattern of waste dump areas will be evaluated because Kainthola et al. (2011) noted that rainfall is a major triggering factor in slope failure.

1.2 Geographic setting of the study areas

Three major mining districts were selected for this work. These are the Lead–Zinc mines at Enyigba, National Iron steel development mines situated at Itakpe and Tin–Columbite

Fig. 1 Typical mining sites in Nigeria **a** open cast method. **b** large waste dumps

Fig. 2 Evidences of swallow landslides

mines located in Jos. The study area stretches from southern to central Nigeria; hence the various mines have their distinct physiographic settings.

Enyigba metallogenic province encompasses of Enyigba, Ameri, Ameka and Amorie communities (Fig. 3a). The territory lies about 14 kms from Abakaliki town, the capital city of Ebonyi State, Southeastern Nigeria. The area is covered generally by an undulating landscape with the highest points, mostly pyroclastic conical hills, not exceeding 400 m a.s.l. (Fig. 3a). Vegetation and rainfall of the area are typical of a tropical rainforest belt with 8–9 months and 1750–2000 mm per annum rainfall (Omotosho and Oluwafemi 2009; Nnabo 2015). Temperature ranges between 16 and 32 °C (Aghamelu and Okagbue 2011). Enyigba is drained by the Ebonyi River and its tributaries.

Itakpe is the host of National Iron Ore Mining Company Limited and is a metallogenic town (Fig. 3b). Itakpe is characterized by gentle to high undulating topography with height varying from 250 to 450 m a.s.l. (Fig. 3b; Akpah et al. 2013). The vegetation and rainfall of the area agree with the tropical Guinea Savannah climatic type characterized by 6–7 months and 1000–1500 mm yearly rainfall (Omotosho and Oluwafemi 2009; Itodo et al. 2017). The area is drained by the River Niger and its tributaries- Pompon and Osara Rivers. Mean daily temperature is recorded 27 °C (Akpah et al. 2013).

Jos plateau is situated in North-central Nigeria. The area is broadly undulating with flat-topped hills characterized by elevation between 380 and 500 m a.s.l. (Fig. 3c). Jos climate conforms to tropical Guinea Savannah vegetation, with 7 months of annual rainfall

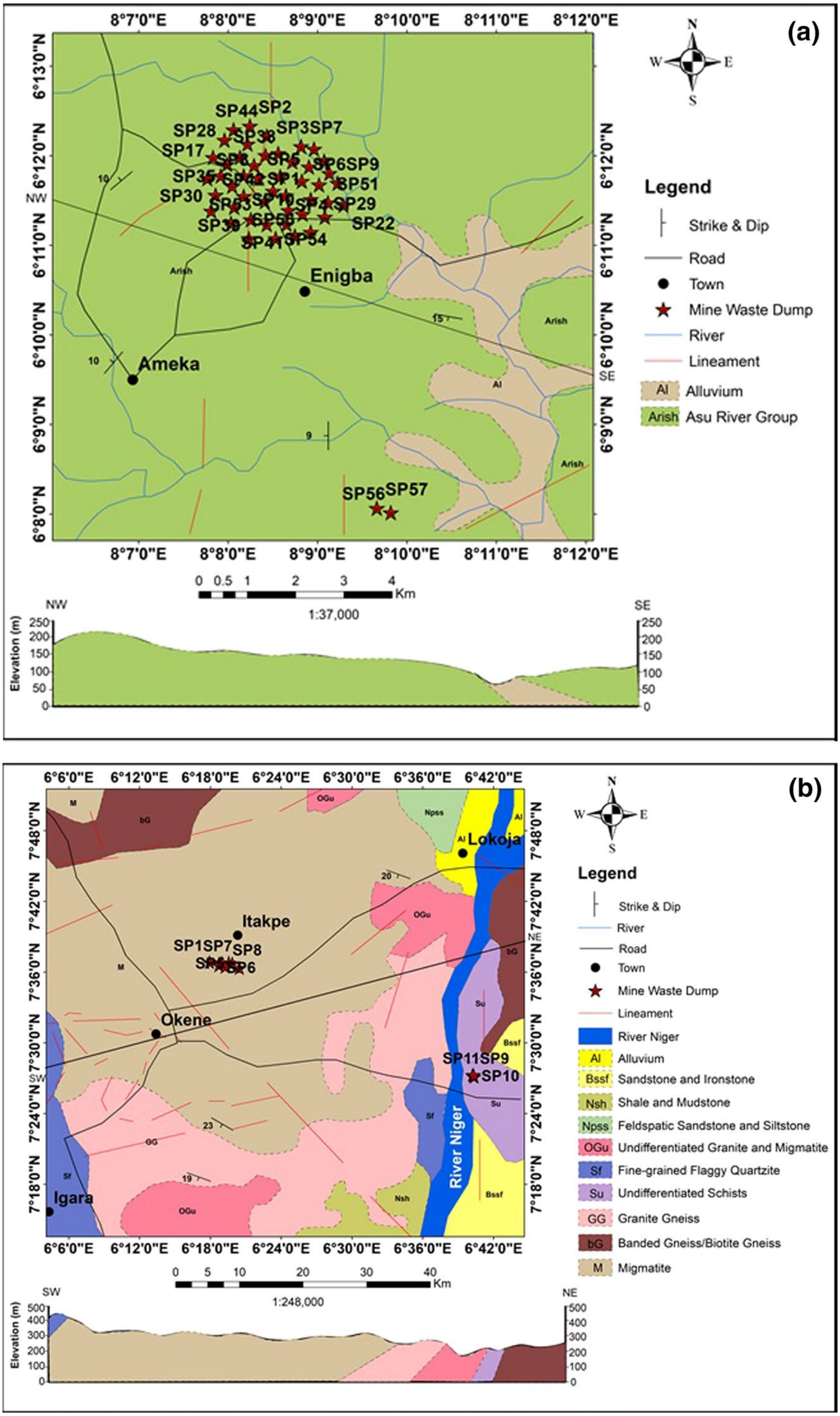

Fig. 3 Geologic maps of the studied mining regions showing several waste rock dumps' locations

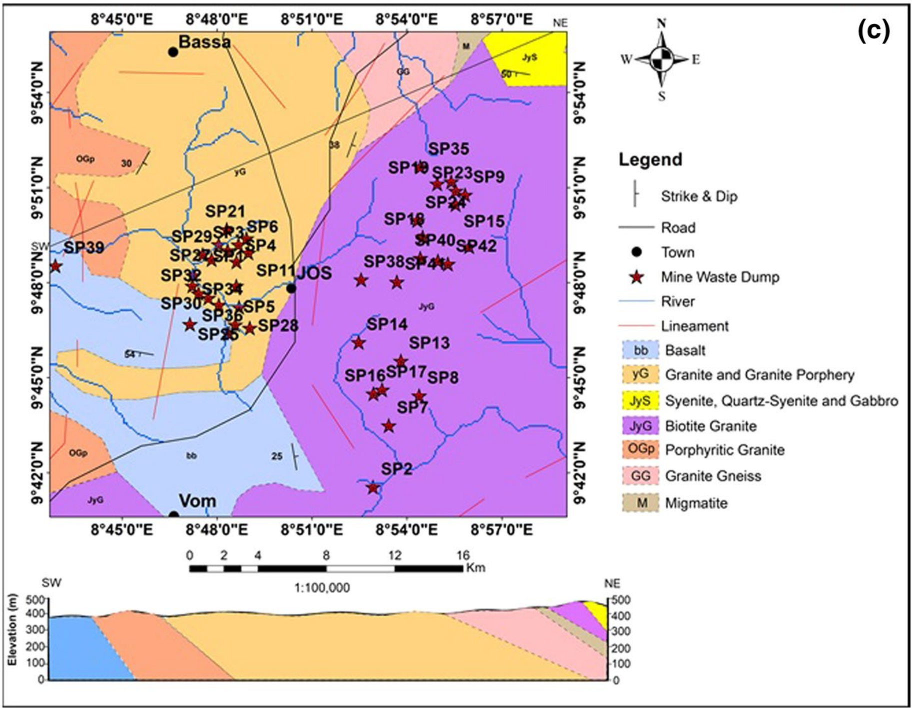

Fig. 3 (continued)

(Omotosho and Oluwafemi 2009; Ryeshak et al. 2015). The average annual rainfall lies within 1270 to 1524 mm while mean daily temperature ranges from 18 to 22 °C (Ryeshak et al. 2015). Several rivers are draining the area with some harnessed for hydropower generation (Fig. 3c).

1.3 Geological setting of the study areas

Geologically, Enyigba in Abakaliki is described as part of the Abakaliki anticline situated at the farthest south of the Cretaceous Benue Trough that forms a section of the geology of southeast Nigeria (Murat 1972). The trough became a deposition belt after its formation as a failed arm of the Rift-Rift-Rift triple junction fault system during the opening of the South Atlantic Ocean (Olade 1975). The rock type underlying the area is of Albian-Cretaceous sediments known as the Abakiliki Shale, which is part of the Asu River group (Fig. 3a; Ofoegbu and Amajor 1987; Nnabo 2015). The Asu River group, with an estimated thickness of 1.5 km consists of shale, mudstone and siltstone in alternating succession, with some lenses of poorly-bedded sandy limestone (Nnabo 2015). The shale formation is highly weathered, ferrugenized, partially metamorphosed, and to a great extent folded, fractured and faulted as a result of the Santonian tectonic events (Nwachukwu 1972a, b). The rocks were observed to be striking NE-SW with a dip angle range of between 10 and 56° in SE direction. This thick, dark gray-colored shale, which is the oldest formation in the sedimentary sequence of the basin serves as host to the lead and zinc mineralization

(Reyment 1965). In consequence, the area became object of a series of mining activities, with the waste rocks mostly composed of these shale materials as seen in Table 2.

Itakpe iron deposit is the largest of ferruginous quartzite ore bodies in Nigeria with an established reserve of over 200 million (Olade 1978). The Itakpe mine covers an area of 7770 km, mostly underlain by crystalline basement complex of compositional variability and structural complexity, with sequences of sandstone and mud-rocks of Cretaceous to Tertiary age covering about one-third of the area (Itodo et al. 2017). The area belongs to the Migmatite-Gneiss Complex of the Basement Complex of Nigeria (Fig. 3) as shown in Table 2. It has been noted that the iron ore as Precambrian metamorphosed ferruginous quartzite (iron-rich) sandstone occurred inside the Archean migmatite-gneiss-quartzite suite of the basement complex (Fig. 3b; Olade 1978). Thus, the metamorphic iron ores are often reported as banded iron formation (BIF). The BIF complex, dipping between 21 and

Table 2 Dump slope geo-reference and geometry

Mine	Sample no.	Location		Rock type	Soil lithology	Slope geometry			θ_r (°)
		Latitude	Longitude			H (m)	W (m)	θ_s (°)	
Enyigba	ENY 01	06°11′37"	008°08′22"	Shale	Clay	15	16	49	39.3–41.8
	ENY 02	06°11′23"	008°08′25"		Clay	14	16	46	
	ENY 03	06°08′01"	008°09’.46"		Silty clay	15	20	43	
	ENY 04	06°11′03"	008°08′31"		Clay	15	15	44	
	ENY 05	06°11′05"	008°08′31"		Silty clay	13	18	40	
	ENY 06	06°11′24"	008°08′25"		Clay	9	13	38	
	ENY 07	06°11′23"	008°08′25"		Clay	11	11	46	
Itakpe	ITA 01	07°36′49"	006°19′8"	Biotite-gneiss, &granite-gneiss	Clayey sand	10	17	48	33.1–38.3
	ITA 02	07°27′09"	006°40′20"		Clayey sand	11	13	50	
	ITA 03	07°36′41"	006°18′30"		Silty sand	9	13	50	
	ITA 04	07°36′35"	006°18′43"		Sandy clay	10	11	52	
	ITA 05	07°36′46"	006°18′57"		Clayey sand	8	18	46	
	ITA 06	07°27′12"	006°40′17"		Silty sand	13	11	57	
	ITA 07	07°36′43"	006°17′56"		Clayey sand	9	13	49	
Jos	JOS 01	09°48′39"	008°55′04″	Biotite-granite	Silty sand	7	10	45	34.7–40.0
	JOS 02	09°48′40"	008°48′35"		Silty sand	9	11	46	
	JOS 03	09°49′09"	008°56′00"		Silty sand	8	11	45	
	JOS 04	09°46′41"	008°48′36"		Sandy silt	6	9	39	
	JOS 05	09°47′30"	008°47′42"		Silty sand	8	9	47	
	JOS 06	09°48′54"	008°47′31"		Sandy silt	7	8	55	
	JOS 07	09°48′43"	008°47′50"		Sandy clay	7	9	45	

H: Height, W: Width, θ_s: Slope angle, θ_r: Angle of repose

85° (Fig. 3b) and conformably interlayeredwith host rocks such as migmatites, gneisses, amphibolites, schists and orthoquartzites, were occasionally intruded by granites, pegmatites and aplites (Olade 1978). The iron ore deposit which occupies a depth of 300 m implies that the region had undergone folding and metamorphism, often demonstrated by displacement of large faults and metasomatism, respectively.

Jos has a distinct geology and is part of the crystalline basement complex. The Precambrian basement rocks (migmatite-gneiss-quartzite complex) in some places are intruded by Precambrian to late Paleozoic Pan-African granite (Older Granite) (Fig. 3c; Mallo and Wazoh 2014). Other cross-cutting intrusive into the Basement rocks are the Jurassic androgenic alkali Younger Granites in association with volcanic rocks such as basalts and rhyolites (Fig. 3c; Mallo and Wazoh 2014). The volcanic rocks (older basalts and newer basalts) were formed in the early Cenozoic (Tertiary) and Quaternary, respectively (Mallo and Wazoh 2014). The basalts are weathered to produce deep clay loams (Gyang and Ashano 2009). Mining in the area is associated with the younger granites which experienced migmatization and mineralization in the Ordovician to late Jurassic age (Fig. 3c). Topography of the area is generally portrayed with the younger granite (Fig. 3c, Table 2).

2 Materials and methodology

2.1 Fieldwork and sampling

This research was carried out in three mining provinces within the months of November 2019 and February 2020.Work started with reconnaissance surveys, followed by in-depth geological field investigation using base maps of various mines. Global coordinates, elevations and physical features (geometry of the waste dumps and ground water level of the areas) were carefully measured and marked on the base maps using standard field instruments such as handy compass, global positioning system (GPS), dip meter and measuring tapes. The field mapping also entailed thorough examination and description of lithology and rock types at each location. During the field investigation, more than 40 dump slopes were studied and 7 random undisturbed samples collected for laboratory analyses at each province using a hand held auger. All the samples collected at each location were carefully packaged in black nylon bags and code-named ENY 01–07, ITA 01–07 and JOS 01–07, representing Enyigba, Itakpe and Jos, respectively.

2.2 Laboratory analyses

All representative samples from different zones were transported to the laboratory belonging to National Steel Raw Materials Exploration Agency, Kaduna within 48 h of collection. Each waste rocks' geotechnical properties such as particle size distribution (PSD), natural moisture content, bulk density, Atterberg limits, compaction, consolidation, shear strength parameters and permeability (k) were determined in accordance with ASTM (American Society for Testing and Materials) relevant standards. The particle size distribution of the materials was determined using sieve and sedimentation analyses. While the sieve analysis was performed in accordance with ASTM D422 (2007a), sedimentation was done using methods described by Kettler et al. (2001) and ASTM D422 (2007a). Samples' natural water content and bulk density were measured using procedures explained in ASTM D2216 (2005) and D2937 (2004a), respectively. The Atterberg limits and compaction tests were done according to D4318 (2010) and D1557 (2007b) specifications, respectively. While the shear strength parameters were obtained using the unconsolidated–undrained (UU) triaxial test operated according to procedures outlined in ASTM D2850 (2007c), the falling head permeability test done with methods detailed in ASTM D5084 (2003) was used to determine the material permeability. Materials' consolidation was evaluated using measures stated ASTM D2435 (2004b).

The angle of repose of the waste dumps was estimated using the fixed funnel method (Beakawi Al-Hashemi and BaghabraAl-Amoudi (2018). Three (3) representative samples from each field were tested. Approximately 450 g of each slightly pulverized sample was continuously poured through a funnel nozzle fixed 4 cm from a hard red mud base (flat surface) to form a cone, and the cone's height and diameter were measured. The angle of repose was then calculated by taking the inverse tangent (arc-tan) of the maximum height to cone radius ratio. For each waste dump material, the experiment was repeated three times, and the average value was recorded.

2.3 Data analysis and simulation

Different scenarios of the field and laboratory results were analyzed using simulation models generated with Slope/W package of the Geostudio® 2012 software suite developed by Geo-Slope International Limited. Several modeled diagrams of waste dumps' morphology and failure predictions (in terms of factor of safety) within each mine were created. Slope/W is very effective in analyzing both simple and complex slope stability using array of methods to calculate factors of safety (Yellishetty and Darlington 2010).The adopted approach of analysis in this work was the Morgenstern-Price's General Limit Equilibrium Method (GLEM) due to its accuracy in stability analysis (Assefa et al. 2016). Furthermore, it considers every interstice (normal and shear) forces and satisfies the equation of statics (moment and force equilibrium). Thus, it allows for user specified interstice function and as such provides better representation of a slope factor of safety in practice (GEO-SLOPE International Ltd. 2018).The dump materials' strength was considered to follow the Mohr–Coulomb's criterion: $\tau = c + \sigma$ tan (), where τ is the shear strength in kPa, σ is the normal stress in kPa, is the angle of internal friction in degrees (°) and c is the cohesive strength of the material in kPa. The GLEM model in Slope/W has built-in search engine that automatically calculate and display the critical slip surface and minimum factor of safety. Parameters keyed into the Slope/W package were cohesion (c), internal friction angle (), unit weights (Υ) from the dump materials' geotechnical results as well as waste dump geometry and groundwater depth measured from wells around the mines. Dimensions of the slopes imputed into the software for the stability analysis were height, width and slope angles. The cohesive strength and internal friction angle (shear strength parameters) were computed from the result of the undrained triaxial compression test performed on consolidated dump materials by plotting shear strength against shear stress values as seen in Fig. 4.

In this study, the probabilistic and reliability methods of risk assessment of slope instability were employed. Today, slope stability problems are evaluated using either deterministic or probabilistic methods (Christian et al. 1994; El-Ramly et al. 2002; Griffiths and Fenton 2004; Xue and Gavin 2007). But, to account for uncertainties in the deterministic approach of FOS determination and slope performance as a result of soil heterogeneity, the probabilistic method is becoming preferable since it takes into account the effect of uncertainties such as geological anomalies, innate spatial variability of material properties,

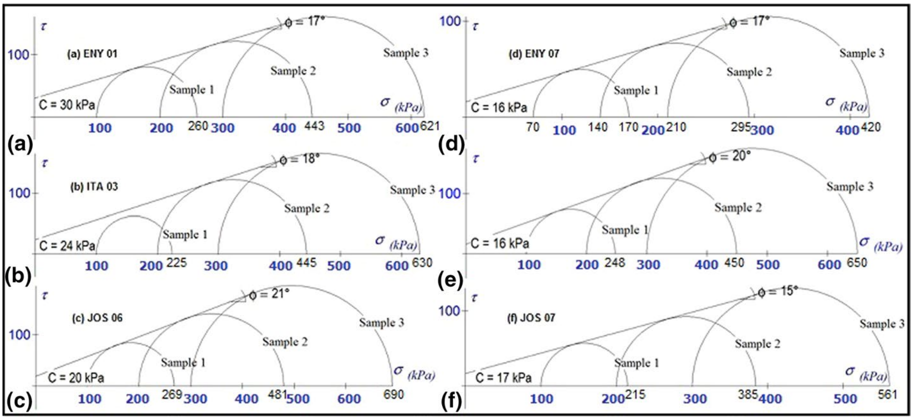

Fig. 4 Mohr failure envelop of some of the waste rocks

varying environmental situation, unforeseen mechanism of failure, generalization and estimate assumptions in geotechnical models and human errors in design and modelingon the chances of failure (Knight 2015; Assefa et al. 2016). The final results reveal the mean FOS and the probability of failure, or otherwise, the probability of unsatisfactory performance (Assefa et al. 2016). The essentials of soil spatial variability are accounted for through statistical tendencies such as mean (μ), variance ([x]), standard deviation (σx) and coefficient of variation (COV). The mean and standard deviation calculated from the author's field data sets using conventional methods were used in the Slope/W as shown in Table 3 to calculate the dump slopes' probability of failure.

One very useful tool in solving the problems of uncertainty in data inputs is the Monte Carlo Simulation Approach (MCSA) (Brooks 1998; Hanson and Beard 2012; Manafi et al. 2012). The MCSA was exploited in generating the factor of safety, probability of failure and reliability index for effective risk assessment of the studied waste dumps. The approach is one of the most reliable methods of slope risk assessment (Knight 2015). The MCSA computes the probability distribution of dependent random variables based on the probability distribution of a set of independent random variables. In this study, the c, ϕ and ϒ were considered to be random variable, and all variables were considered to be of normal

Table 3 Variability in sampled dump materials

Mine fields	Dump section	Soil parameters						Distribution
		Mean			Standard deviation			
		c (kPa)	ϕ (º)	ϒ (kN/m^3)	c (kPa)	ϕ (º)	ϒ (kN/m^3)	
Enyigba	Tailing	20.6	19.0	15.7	4.5	3.7	0.7	Normal
	Foundation	49.4	28.4	41.4	3.8	3.0	2.7	Normal
Itakpe	Tailing	21.7	21.4	19.6	2.8	2.8	1.7	Normal
	Foundation	Impenetrable (bedrock)						
Jos	Tailing	22.1	19.4	14.4	3.0	3.2	0.8	Normal
	Foundation	Impenetrable (bedrock)						

Table 4 Normal standard deviate values for levels of confidence (Abramson 2002)

ε %	D
80	1.282
90	1.645
95	1.960
99	2.576

Table 5 Number of trials required for levels of confidence (Knight 2015)

ε %	N
80	106
90	4577
95	147,579
99	275,209,520

distribution because a normal probability density function closely approximates many natural data sets as well as geotechnical engineering material properties (GEO-SLOPE International Ltd. 2018). The phreatic surface line was adjusted to a minimum of −3 m and a maximum of 3 m from the static groundwater level measured in the fields to mark material saturation (water content) variability at different seasons. An equation for the number (*N*) of trials required to achieve a high confidence level in assessment method was developed as given in Eq. 1 (GEO-SLOPE International Ltd. 2008).

$$N = \left[\frac{d^2}{4(1 - \varepsilon)^2} \right]^m \tag{1}$$

where N = number of trials, ε = desired level of confidence (in percent) expressed as a decimal, m = number of variables and d = normal standard deviation corresponding to the level of confidence.

Table 4 shows some confidence levels (ε) and their corresponding standard deviations. It is notable that the higher the number of Monte Carlo trials, the more accurate the solution of the analysis (Neal 1993; Manafi et al. 2012; Bardenet et al. 2017). However, the number of trials required can be estimated for different confidence levels using Knight (2015) suggestion shown in Table 5. In this paper, 5000 trial runs were computed for each waste dump, representing a 90% confidence level, which has been previously applied by other authors (Assefa et al. 2016). Figure 5 demonstrates graphically the methodology employed to assess the uncertainty and reliability of waste dumps' factor of safety. To calculate the probabilistic FOS of each waste dump, the mean, standard deviation and the associated probability distribution of the measured soil parameters were required in the Slope/W software. Lastly, the probability of failure (*pf*) and reliability index (*β*) were calculated for the MCSA It is worth noting that the reliability index concept is only meaningful and applicable in SLOPE/W for normal distributions (GEO-SLOPE International Ltd. 2018). The Spencer (1967) analytical method, which is also embedded in the SLOPE/W, was used to validate the results of the stability analysis in this study, and the results were compared with the results of the Morgenstern-limit Price's limit equilibrium method. The Spencer method was chosen for validation because, like the Morgenstern-Price method, it is the only method that satisfied all of the recommended conditions for reliable stability results,

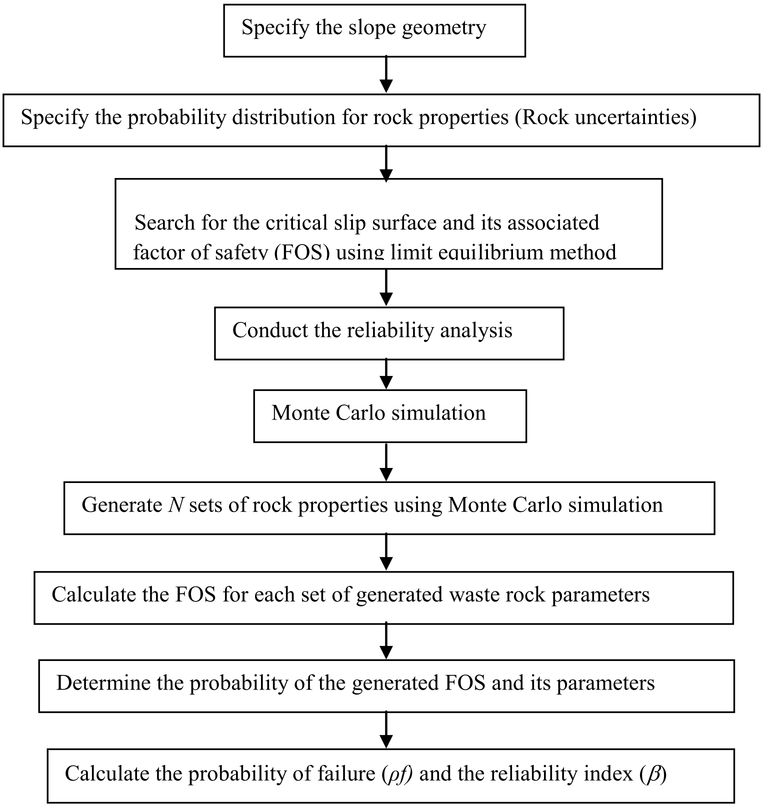

Fig. 5 Schematic representation of the Monte Carlo simulation

such as fulfilment of force and moment equilibrium, as well as the inclusion of inter-slice forces (Rocscience 2006; Geo-SLOPE International Ltd. 2018).

3 Results and discussion

3.1 Mine field observations

3.1.1 Field measurements

Thorough field observations at the three studied mines revealed several internal waste dumps with generally conical tops (Figs. 1b and 2). Some of the dump structures were very massive with steep slopes (Table 2). These slope heights and angles could have severe implications on the dumps' stability. Slope instability has been reported by many authors on steep conical top slopes, having slope angles ranging between 30 and 60° (Cortopassi et al. 2008; Kainthola et al. 2011; Behera et al. 2016). Continuous unloading of materials and removal of slope toe materials often increases slope angle, thereby initiating landslides (Fig. 2; Cortopassi et al. 2008). On this account, Enyigba dumps have a lower risk of instability than Itakpe and Jos dumps. The sliding mass (slip mass volume) and frequency of failure have also been correlated with slope angle (Igwe and Chukwu 2018). However, it was reported that slope angle does not necessarily determine landslide dimensions (length and width).

Another factor that could jeopardize the dumps' stability observed in the field is the mine morphology. The 10–85° dip angles of the foundation rocks at the mines (Fig. 3;Olade 1978) are high enough to initiate instability of dumps (Horton 1945). The Canadian Mine Waste Rock Pile Research Committee noted that dump failure could occur in field slopes with angle as low as 20° (Guemache et al. 2011; Muthreja et al. 2012). Moreover, the landscape of the regions are steep and probably with high slope gradients, having difference in height of about 120, 200 and 70 m at Enyigba, Itakpe and Jos, respectively (Fig. 3). Also, the topography of these mine fields has been largely altered, thus increasing foundation and dump inclinations. Terrains with such uneven topography are likely to experience slope instabilities (Muthreja et al. 2012).

Consequently, there has been several evidences (old scarp) and reports of shallow translational landslides on the indiscriminate rock dumps in Enyigba and Jos (Akanbi and Bulus 2017; Igwe and Chukwu 2018). Figure 2 is a true evidence of newly formed scarps from recent shallow mass movements. These slope failures may occur more in slopes at higher elevation since the dumps are lying on natural slopes whose stability could be impacted negatively by the high dip amount of the host rock. Gully erosion and cracks on the foundation soils and dump surfaces may impact negatively on the stability of the slopes. Therefore, the observed dump slope failures at the mines may have been influenced by a combination of factors such as dump geometry, topography and foundation rock inclination of the mines (Muthreja et al. 2012), coupled with waste rock properties and hydrogeology of the area (Muthreja et al. 2012; Behera et al. 2016).

3.1.2 Rock types and mineralogy

The studied waste rocks exhibited a variety of engineering characteristics because of their mineralogy. Granitic rocks are comprised of stable minerals—quartz and plagioclase that are resistant to chemical and mechanical breakdown; hence, the waste rocks from the basement (bed rocks) territories are likely to exhibit good engineering behavior. However, the presence of gneiss and schist in the basement rocks (Fig. 3 and Table 2), particularly foliated gneiss and schist limit their engineering potentials. This is because they contain minerals that are highly susceptible to chemical and mechanical weathering. Gneiss and schist being metamorphosed rocks of politic and mudrock protoliths contain distinctive minerals as orthoclase, microcline, andesine and oligoclase and biotite, hornblende and chlorite, respectively (Ekwueme 1993; Railsback 2006). Moreover, foliation (a form of rock anisotropy) in schist plays a crucial role in chemical weathering development in a rock material by permeating water into the rock profile (Marques et al. 2010), and therefore diminishing the material mechanical strength by creating weak zone for rock slippage. Similarly, the Abakiliki Shale has been reported to contain swelling clay minerals such as illite, which induce moderate to high plasticity in soils (Obiora and Umeji 2004), despite being indurated as a result of Santonian orogenic events. In the recent past, materials with such qualities have been linked to slope failure (Calcaterra and Parise 2010; Guemache et al. 2011).

3.2 Waste dump geotechnical characteristics

The geotechnical test results are presented in Tables 6 and 7. The geotechnical characteristics of the dumps can be divided into index soil properties and geo-mechanical properties. Both properties are very important to soil material behavior and structures' stability, and their results suggested huge variation in the behavior of the different waste rocks.

3.2.1 Waste rock index properties

The results of the dump materials' index properties are presented in Table 6. Data show that dumps from Enyigba, Itakpe and Jos were predominantly sandy clays, clayey sands and silty sands, respectively, thus agreeing with field observations (Table 2). The PSD curves for the different materials are shown in Fig. 6a. From the curves, Itakpe and Jos dumps may have better engineering characteristics than the Enyigba dumps due to superior grading (well graded or poorly sorted) distribution. On the other hand, the Enyigba materials possess wide range of engineering behavior as a result of their wide range of clay contents. High clay content had previous been correlated with landslide occurrence (Yellishetty and Darlington 2010). It was reported that well-graded, gravelly soils with little or no clay content have better engineering behavior than poorly graded (well sorted) soils because they are well drained and less plastic (Bell 2007; Arora 2008).Cortopassi et al. (2008) observed that dump instability mainly occur in soils with well-sorted PSD and rich in fine content. However, the observable variability in the PSD of these dump materials is mainly due to their local geology and partly influenced by the crushing and compaction mediums during extraction and dumping of the waste (Yellishetty and Darlington 2010).

The samples' natural moisture content values shown in Table 6 indicated low to medium water retention capacity of the waste rocks. These low to moderate moisture holding capacity could be suggestive of little to moderate amount of clay minerals in the soils (Yang et al. 2021). According to the results of the Atterberg (consistency) limits, Enyigba dumps materials are classified as ML or CH, whereas Itakpe is classified as CL and Jos is classified as CL or ML, using to the Unified Soil Classification System (ASTM 2006) shown in Fig. 6b. These classifications signify that Enyigba materials have a medium to high plasticity, Itakpe materials have a low plasticity, and Jos waste dumps have a low to medium plasticity. The higher NMC, LL and PI for Enyigba dumps than Itakpa and Jos could be a consequence of larger water retention capacity governed by higher clay content and clay mineral activity which could highly impact negatively on their stability (Calcaterra and Parise 2010). Clay minerals' activity gives plasticity to soils which is a very important factor in landslide occurrence (Behera et al. 2016). Therefore, low values of the Atterberg limits and medium permeability (Tables 6 and 7) of the dumps at Itakpe and Jos suggested the soils to be moderately consistent.

The unit weight (Υ) of the waste rocks was moderate (Table 6). The moderate values could be a result of low to moderate NMC which averaged 10, 9 and 8% for Enyigba, Itakpe and Jos, respectively. However the higher Υ of Itakpe waste rock could be indicative of lower void ratio and higher specific gravity of the materials that made up the dumps, and thus may impact on the shear strength of the materials and the overall stability of the slope.

Table 6 Soil index properties

Location	Sample no	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	NMC (%)	LL (%)	PL (%)	PI (%)	ϒ(KN/m^3)
Enyigba	ENY 01	17	25	23	35	11.2	35	15	20	16.25
	ENY 02	31	34	11	24	9.9	43	28	15	16.88
	ENY 03	24	16	20	40	8.7	59	34	25	15.65
	ENY 04	3	25	19	53	9.5	38	24	14	14.80
	ENY 05	21	27	15	37	12.8	60	33	27	15.30
	ENY 06	–	19	26	55	7.9	43	32	11	14.95
	ENY 07	6	45	20	29	10.8	55	34	21	16.70
Itakpe	ITA 01	14	63	11	12	9.0	25	–	–	18.34
	ITA 02	10	65	14	11	8.3	28	19	9	19.46
	ITA 03	6	63	16	15	10.6	26	–	–	17.25
	ITA 04	4	67	16	13	9.1	29	21	8	21.0
	ITA 05	3	68	17	10	8.5	24	–	–	18.69
	ITA 06	11	65	13	11	7.4	27	–	–	19.84
	ITA 07	7	71	12	8	8.5	25	–	–	22.30
Jos	JOS 01	1	44	24	31	6.5	31	16	15	13.94
	JOS 02	3	46	25	26	10.0	34	18	16	13.83
	JOS 03	1	42	32	25	9.3	33	15	18	14.46
	JOS 04	1	30	38	31	6.8	35	19	16	13.78
	JOS 05	2	40	26	32	7.4	32	18	14	14.61
	JOS 06	1	37	32	30	5.9	31	14	17	14.20
	JOS 07	5	42	23	30	8.6	33	16	16	15.94

Table 7 Soil Geotechnical properties

Sample no.	c (kPa)	ϕ (°)	MDD (g/cm^3)	OMC (%)	Υ_b (Mg/m^3)	Cv (m^2/yr)	Mv (m^2/KN)	k (cm/s)
ENY 01	30	17	1.88	13.89	1.91	0.15	0.29×10^{-4}	1.59×10^{-6}
ENY 02	18	24	2.07	13.91	1.86	1.90	0.19×10^{-4}	5.28×10^{-7}
ENY 03	20	22	2.13	13.91	1.84	0.23	0.27×10^{-4}	2.63×10^{-6}
ENY 04	21	20	2.16	13.95	2.18	0.70	0.29×10^{-4}	9.59×10^{-8}
ENY 05	20	13	2.14	13.76	1.99	0.18	0.20×10^{-4}	2.16×10^{-8}
ENY 06	19	20	1.93	13.0	2.06	0.12	0.15×10^{-4}	3.07×10^{-7}
ENY 07	16	17	2.10	13.08	1.89	0.41	0.23×10^{-4}	2.11×10^{-7}
ITA 01	23	20	1.92	10.46	1.95	0.03	0.06×10^{-4}	2.19×10^{-5}
ITA 02	21	25	1.90	11.01	1.99	0.08	0.09×10^{-4}	8.95×10^{-8}
ITA 03	22	18	1.94	12.11	2.03	0.01	0.06×10^{-4}	3.86×10^{-6}
ITA 04	22	24	1.86	10.70	1.98	0.03	0.03×10^{-4}	2.57×10^{-4}
ITA 05	25	19	1.94	10.90	1.94	0.05	0.07×10^{-4}	1.70×10^{-6}
ITA 06	23	24	1.91	10.53	2.08	0.02	0.05×10^{-4}	3.23×10^{-7}
ITA 07	16	20	1.94	10.86	1.95	0.04	0.06×10^{-4}	1.30×10^{-5}
JOS 01	21	17	1.73	12.69	1.92	0.05	0.10×10^{-4}	2.69×10^{-5}
JOS 02	23	21	1.75	13.52	1.91	0.03	0.13×10^{-4}	3.76×10^{-6}
JOS 03	26	20	1.71	13.34	1.93	0.05	0.18×10^{-4}	9.17×10^{-7}
JOS 04	24	22	1.76	13.60	1.95	0.07	0.11×10^{-4}	3.54×10^{-4}
JOS 05	22	24	1.77	11.93	1.94	0.04	0.10×10^{-4}	2.70×10^{-7}
JOS 06	20	20	1.67	13.28	1.90	0.07	0.14×10^{-4}	1.04×10^{-5}
JOS 07	17	15	1.73	13.94	1.91	0.03	0.09×10^{-4}	1.85×10^{-6}

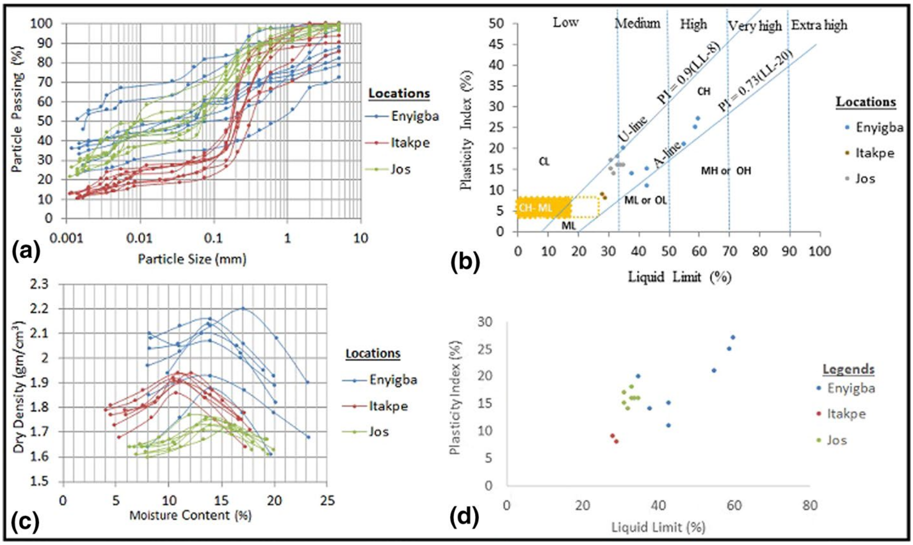

Fig. 6 Graphical representation of the waste rock properties

3.2.2 Materials' geotechnical characteristics

The waste rocks' geotechnical results are presented in Table 7. The compaction curves shown in Fig. 6c reveals the maximum compaction of the waste rocks in terms of their dry density at optimum moisture content. From the compaction results, these dump materials can be classified as competent engineering materials due to their moderate to high MDD and moderate OMC. The curves correspond to soils with low to medium plastic clays (Garg 2011), and thus are in agreement with the Atterberg limits. The soils' high clay content and cementing materials may be the cause of the significantly high MDD recorded by the samples. The same reason could be the cause of the higher OMC in Enyigba soils since other authors have noted higher OMC in fine grained soils than coarse grained soils (Bell 2007; Arora 2008). Although, Enyigba samples may achieve higher compaction, Itakpe samples are comparatively as good as the Enyigba soils, achieving a reasonably high MDD with lesser OMC. It has been noted that poor compaction leads to failure of embankments by reducing shear strength, intensifying permeability and initiating extensive consolidation which leads to differential settlement (Yellishetty and Darlington 2010).

The bulk density (Υ_b) values recorded in Table 7 lie within the range of swelling soils. Hong et al. (2012) observed that soils with Υ_b less than 2.45 Mg/m^3 experience osmotic swelling under the influence of clay minerals' activities, thus increasing the soils' natural moisture content through high water absorption. Permeability has been reported among other factors to influence on the rate of water infiltration into soils (Guemache et al. 2011). The permeability coefficient (k) of the waste rocks are presented in Table 7, and the low values of k portray soils with high fines content which is in accord with the PSD results. This low-permeability attests to the water holding ability of the dumps, and in an unconsolidated, porous waste dump, high storage of water within the dump masses are expected due to infiltration and percolation during prolonged rainfalls. As a result of the high water ingress and storage, excessive pore pressure builds up, reducing shear resistance within the unsaturated clay fraction by lowering frictional and/or cohesive strength (Cortopassi et al. 2008; Behera et al. 2016). This reduction in cohesive and internal frictional forces may result in dump slope failure and could be a strong contributing factor to most waste dump failure around the world (Yellishetty and Darlington 2010). Consequently, the low to high plastic waste dumps in Nigeria, particularly Enyigba may be prone to sliding, even under the influence of moderate rainfalls.

Consolidation results are shown in Table 7. Although Enyigba dumps recorded highest Cv and Mv, results generally indicated that Cv is low, whereas Mv is moderately high (Badmus 2010). The Mv values suggested that the soils are moderately compressible while the Cv implies low rate of compression. Therefore, the soils undergo settlement (volume change) but at a very slow rate, which may lead to failure of very high slopes depending on their cohesive strength.

Two factors mainly determine the failure of a slope: the slope geometry and the material strength as observed by Gupta and Paul (2016). Therefore, a soil strength property in terms of its cohesion and internal frictional angle is one of the important keys in ascertaining the stability of a slope. However, in many situations, the mechanical characteristics of the interface between the foundation soil and the heap material must be carefully considered. When these parameters are of poor geotechnical quality, polygonal failure surfaces can develop in part along this interface and may represent the most realistic and critical mode of failure.

The samples' shear strength parameters, cohesion (c) and internal friction angle (ϕ), are displayed in Table 7. Representative failure (Mohr circle) envelopes are shown in Fig. 4. It is worth noting that all unsaturated triaxial tests (01–06) were conducted under natural moisture conditions, with the exception of sample 07, which was tested under induced saturation to determine the strength condition of the waste rocks during the rainy season. All the recorded c and ϕ values were suggestive of low to moderate shear strength soils (Bell 2007; Arora 2008; Garg 2011). However, saturated samples were observed to record lower cohesive force than the unsaturated samples with cohesion measuring between 16 and 17 kPa (Fig. 4 d–f). This result corroborates the findings of other researchers, including Verma et al. (2017), who found that soil cohesion decreases as moisture content increases. Therefore, these waste dumps with low permeability are likely to experience shear strength reduction on moisture influx at the peak of rainfall. This is in line with work of Naeini and Akhtarpour (2018) who avowed that poorly drained soils due to low permeability have their shear strength reduced by any increase in hydrostatic pore pressure within the soils. The reduction in strength will undeniably impact on the safety factor (stability) of the dump slopes.

3.3 Waste dump stability analysis

3.3.1 Probable dump slopes' failure mechanisms

The first step in solving any slope stability problem is to identify the most likely and critical failure mechanisms, such as superficial plane failure, deep circular failure, polygonal failure (failure guided by a level of weak mechanical characteristics), and failure due to soil liquefaction. The structural and geomechanical features of the soils or rocks are responsible for the various mechanisms. All interfaces were given considerable attention in this study, especially those with minimal mechanical resistance.

The sub-soils of the investigated fields were either indurated (overconsolidated) shales, as in Enyigba, or crystalline basement rocks (bedrocks), as in Itakpe and Jos. Table 8 shows the strength qualities of the foundation rocks of the waste dumps. These might be

Table 8 Waste dumps' foundation properties

Location	c (kPa)	ϕ(º)	ϒ (kN/m^3)
Enyigba			
ENY 01	44	24	43.79
ENY 02	49	31	41.25
ENY 03	53	30	42.57
ENY 04	51	29	39.15
ENY 05	50	25	43.83
ENY 06	45	32	36.50
ENY 07	54	28	42.41
Itakpe			
	ITA 01–07	Crystalline basement complex (bedrocks)	
Jos			
	JOS 01–07	Crystalline basement complex (bedrocks)	

regarded competent foundations for the waste dumps if there are no weak zones such as beds, cracks, joints, or faults, and only superficial plain failure (shallow slides) cutting just across the waste dumps might be expected (Figs. 7 and 8a, d). Data show that if there are no structural weaknesses in the foundations, the factor of safety against deep seated slope failure is high (Fig. 7d). However, in the field, significant fines (clay and silt) content might cause catastrophic slide failure types with semi-circular arc (Figs. 7 and 8a, d). Maknoon (2016) found that the critical slip surfaces of slopes formed with cohesive materials or impacted by seepage are generally (quasi) circular in most field slope failures as well as slope simulations.

In general configuration of waste dumps, one can meet failures following polygonal surfaces. Polygonal surfaces such as tension cracks, beds, and fractures, as well as weak layers with low mechanical properties on waste dumps or foundations, can all influence failures in the present fields (Figs. 8–10 and 7e–h). These could be the triggering factors of some of the minor slope instabilities that have been reported in recent years. From the liquefaction susceptibility criteria of Seed et al. (2003), only the Itakpe waste dumps are prone to liquefaction (Fig. 6d). According to Seed et al. (2003) and Papathanassiou and Valkaniotis (2010), a soil layer is liable to liquefy if its liquid limit is less than 37% and the plasticity index is less than 12%. The Itakpe tailings' liquefaction susceptibility may be linked to their high loose sand content (Fig. 6a and Table 6). Although its average Υ_b of 1.99 Mg/m^3 is higher than the Enyigba and Jos tailings averages of 1.96 and 1.92 Mg/m^3, respectively

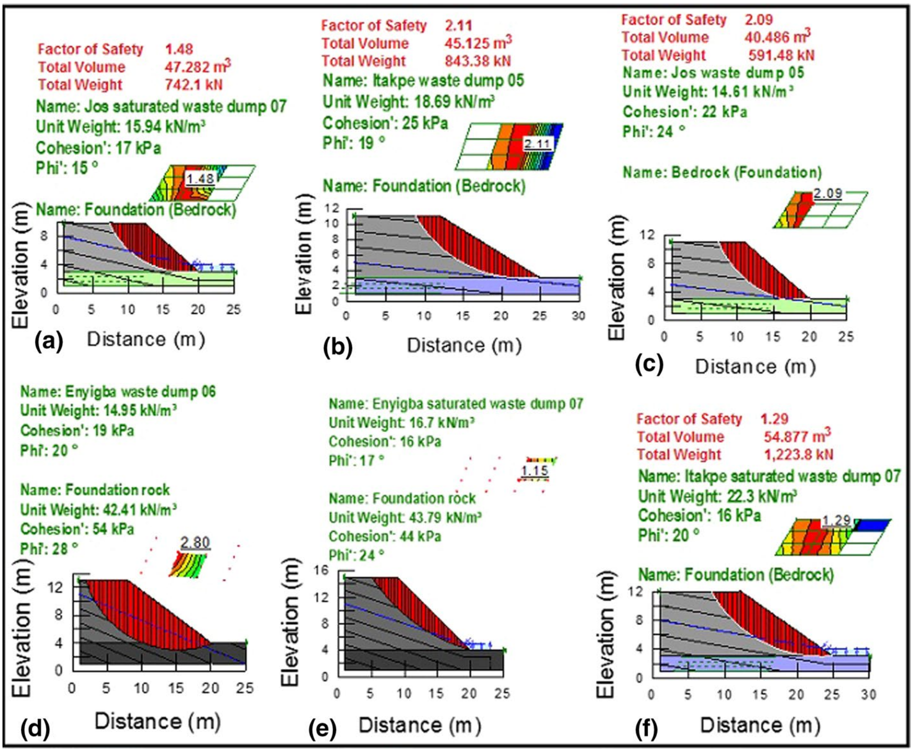

Fig. 7 Deterministic FOS analysis of some of the dumps

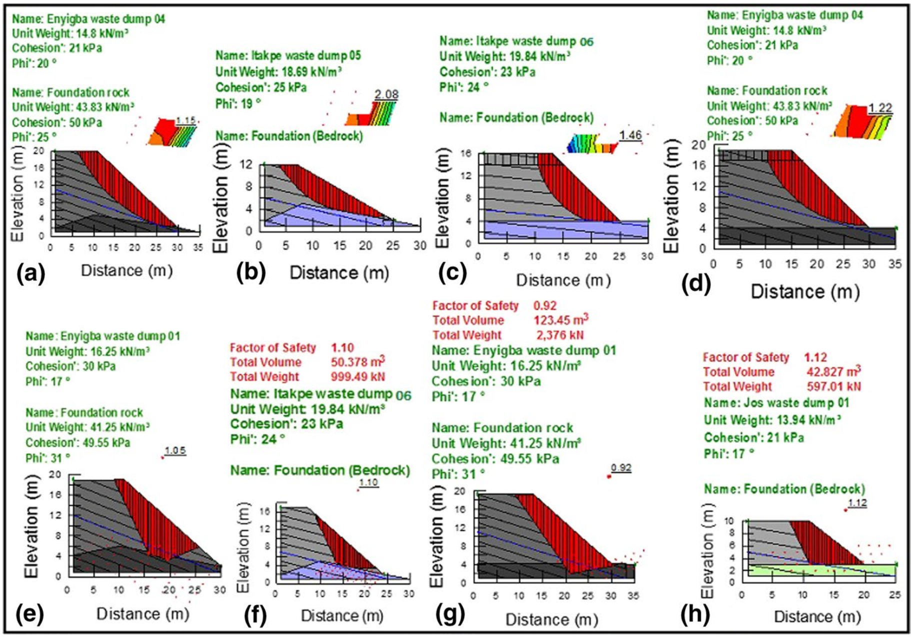

Fig. 8 Probabilistic models of some of the representative dumps

(Table 7), the slightly higher density may be undermined by high sand content and very low plasticity (Table 6).

3.3.2 Waste dumps' factor of safety

Tables 9, 10, 11 show the findings of the stability assessment of the waste dumps. According to Cheng and Lau (2014) and Ray and de Smedt (2009) in Table 12, the stability of the waste dump slopes in the studied fields ranged from unsafe to theoretically stable, based on the deterministic FOS shown in Table 9. Figures 7 and 8 show several representative models. However, a forward analysis of the samples performed to characterize a saturated condition of the slopes in a flood scenario revealed a decrease in the FOS as the water saturation of the dumps increased, signifying a decline in their stability (Fig. 7e, f, Table 9). Because of the poorer engineering properties, Enyigba dumps would likely be the most affected in that situation (Table 6 and 7).

The FOS of the dumps is likely to drop on sloppy terrain, as indicated in Fig. 8a and b, as the ground surfaces increase the total activating moment and force of the slide (Table 9). When there are parallel or inclined structural weaknesses, such as tension cracks (Fig. 8c, d) or bedding planes, fractures, joints, and faults (Fig. 8e–h), the FOS can drop to the lowest level (see Table 9). These provide polygonal sliding surfaces that pass at the level of the foundation ground-to-deposit contact. When weak zones, such as tension cracks, are filled with moisture, the situation worsens (Table 9). Findings indicate that locations with inclined weak zones are more likely to be stable than places with parallel weak zones (Table 9). This could be due to an increase in the total activating moment inside the parallel weak zones. Both scenarios, however, are likely to result in deep entrenched polygonal failures that run through the foundations (Fig. 8e–h and Fig. 9). A comparison of the FOS

Table 9 Deterministic factor of safety for different failure conditions using Morgenstern-Price approach

Mine field	Dump	Sample condition	Composite foundation		Tension cracks		Weak Zones	
			Flat	Sloppy	Without moisture	With moisture	Parallel	Inclined
Enyigba	ENY 01	Field condition (Unsaturated)	1.49	1.40	1.40	1.38	0.92	1.05
	ENY 02		1.39	1.30	1.35	1.33	0.81	0.80
	ENY 03		1.42	1.37	1.39	1.37	0.73	1.09
	ENY 04		1.25	1.15	1.22	1.21	0.66	0.76
	ENY 05		2.05	1.04	2.04	2.03	0.75	0.75
	ENY 06		2.80	1.32	2.77	2.74	0.85	0.85
	ENY 07	Modified field condition (Saturated)	1.15	0.78	1.08	1.06	0.58	0.64
	Remark		Poorly stable to very stable	Unstable to moderately stable	Critically stable to very stable	Critically stable to very stable	Unstable	Unstable to critically stable
Itakpe	ITA 01	Field condition (Unsaturated)	1.62	1.38	1.60	1.59	0.77	0.93
	ITA 02		1.50	1.40	1.45	1.43	0.83	0.88
	ITA 03		1.69	1.66	1.62	1.59	1.04	0.63
	ITA 04		1.56	1.47	1.54	1.53	0.83	1.00
	ITA 05		2.11	2.08	2.04	1.99	0.92	1.84
	ITA 06		1.48	1.32	1.46	1.46	0.76	1.10
	ITA 07	Modified field condition (Saturated)	1.29	1.15	1.26	1.24	0.96	1.20
	Remark		Fairly stable to very stable	Poorly stable to very stable	Fairly stable to stable	Fairly stable to stable	Unstable to critically stable	Unstable to very stable
Jos	JOS 01	Field condition (unsaturated)	2.13	2.10	2.00	1.59	1.12	1.11
	JOS 02		1.88	1.79	1.75	1.75	1.13	1.19
	JOS 03		2.30	1.77	2.23	2.19	1.18	1.18
	JOS 04		3.06	2.72	2.90	2.80	1.54	1.23

Table 9 (continued)

Mine field	Dump	Sample condition	Composite foundation		Tension cracks		Weak Zones	
			Flat	Sloppy	Without moisture	With moisture	Parallel	Inclined
	JOS 05		2.09	1.80	1.99	1.94	1.13	1.26
	JOS 06		2.05	1.93	1.98	1.89	1.18	1.36
	JOS 07	Modified field condition (Saturated)	1.48	1.45	1.38	1.35	0.84	0.90
	Remark		Moderately stable to very stable	Moderately stable to very stable	Moderately stable to very stable	Moderately stable to very stable	Unstable to good stability	Unstable to moderately stable

Table 10 Deterministic FOS using Spencer analytical method

Mine field	Dump	Sample condition	Composite foundation		Tension cracks		Weak Zones	
			Flat	Sloppy	Without moisture	With moisture	Parallel	Inclined
Enyigba	ENY 01	Field condition (unsaturated)	1.49	1.40	1.40	1.38	0.88	1.01
	ENY 02		1.39	1.30	1.35	1.33	0.78	0.86
	ENY 03		1.42	1.37	1.39	1.37	0.76	1.03
	ENY 04		1.26	1.16	1.22	1.21	0.66	0.69
	ENY 05		2.04	1.04	2.02	2.01	0.67	0.75
	ENY 06		2.80	1.34	2.77	2.74	0.84	0.79
	ENY 07	Modified field condition (Saturated)	1.15	0.78	1.08	1.06	0.53	0.70
	Remark		Poorly stable to very stable	Unstable to moderately stable	Critically stable to very stable	Critically stable to very stable	Unstable	Unstable to critically stable
Itakpe	ITA 01	Field condition (Unsaturated)	1.62	1.38	1.58	1.57	0.87	1.02
	ITA 02		1.50	1.41	1.45	1.43	0.89	0.94
	ITA 03		1.68	1.67	1.62	1.59	1.07	0.69
	ITA 04		1.55	1.47	1.52	1.51	0.83	1.12
	ITA 05		2.11	2.10	2.04	1.99	1.02	1.08
	ITA 06		1.48	1.33	1.44	1.44	0.81	1.10
	ITA 07	Modified field condition (Saturated)	1.29	1.22	1.26	1.24	1.05	1.25
	Remark		Fairly stable to very stable	Poorly stable to very stable	Fairly stable to stable	Fairly stable to stable	Unstable to critically stable	Unstable to very stable

Table 10 (continued)

Mine field	Dump	Sample condition	Composite foundation		Tension cracks		Weak Zones	
			Flat	Sloppy	Without moisture	With moisture	Parallel	Inclined
Jos	JOS 01	Field condition (Unsaturated)	2.13	2.10	2.00	1.72	1.13	1.19
	JOS 02		1.88	1.79	1.75	1.75	1.21	1.24
	JOS 03		2.30	1.77	2.22	2.17	1.24	1.27
	JOS 04		3.05	2.72	2.88	2.78	1.66	1.34
	JOS 05		2.09	1.80	1.99	1.94	1.18	1.26
	JOS 06		2.06	2.06	1.96	1.89	1.25	1.37
	JOS 07	Modified field condition (Saturated)	1.46	1.45	1.38	1.35	0.79	0.91
	Remark		Moderately stable to very stable	Moderately stable to very stable	Moderately stable to very stable	Moderately stable to very stable	Unstable to good stability	Unstable to moderately stable

Table 11 Results of probabilistic analysis of the various failure patterns

Mine fields	Field condition	Min. FOS	Max. FOS	Mean FOS	Stdev	*pf*	*pf* (%)	β	Remark
Enyigba	Flat foundation	0.68	1.94	1.26	0.13	0.02	2.0	1.95	Critical
	Sloppy ground	0.66	1.93	1.24	0.13	0.029	2.9	1.81	Critical
	Unsaturated tension crack	0.73	1.80	1.22	0.12	0.028	2.8	1.85	Critical
	Saturated tension crack	0.72	1.76	1.21	0.11	0.037	3.7	1.74	Critical
	Parallel weak zones	0.65	1.28	0.81	0.10	0.896	89.6	−1.28	Unstable
	Inclined weak zones	0.55	1.39	0.91	0.13	0.755	75.5	−0.65	Unstable
Itakpe	Flat foundation	0.96	1.99	1.49	0.14	0.0002	0.02	3.55	Moderately stable
	Sloppy ground	0.88	1.88	1.40	0.13	0.002	0.2	3.12	Moderately stable
	Unsaturated tension crack	0.96	1.96	1.47	0.13	0.0002	0.02	3.47	Moderately stable
	Saturated tension crack	0.95	1.95	1.46	0.13	0.0004	0.04	3.43	Moderately stable
	Parallel weak zones	0.67	1.26	0.88	0.11	0.862	36.2	−1.11	Unstable
	Inclined weak zones	0.86	1.44	1.06	0.13	0.175	17.5	0.95	Unstable
Jos	Flat foundation	1.13	3.26	2.07	0.22	0.0000	0.0000	4.38	Stable
	Sloppy ground	0.88	2.47	1.58	0.17	0.0004	0.04	3.52	Moderately stable
	Unsaturated tension crack	1.14	3.10	2.01	0.21	0.0000	0.0000	4.38	Stable
	Saturated tension crack	1.12	3.01	1.97	0.20	0.0000	0.0000	4.30	Stable
	Parallel weak zones	0.99	1.04	0.97	0.03	0.333	33.3	0.40	Unstable
	Inclined weak zones	0.72	2.24	0.96	0.46	0.481	48.1	0.42	Unstable

Table 12 Significance of factor of safety

Factor of safety	Significance	References
< 1.0	Unsafe	Cheng and Lau (2014)
1.0 – 1.2	Questionable safety	
1.3 – 1.4	Satisfactory for cuts, fills but questionable for dams	
> 1.5	Safe for dams	
< 1.0	Unstable	Ray and de Smedt (2009)
1.0 – 1.25	Quasi stable	
1.25 – 1.5	Moderately stable	
>1.5	Theoretically stable	
		Present study
0.58 – 2.80	Unsafe–Safe (Unstable–Theoretically stable)	Enyigba
0.63 – 2.11	Unsafe—Safe (Unstable—Theoretically stable)	Itakpe
0.84 – 3.06	Safe (Unstable—Theoretically stable)	Jos

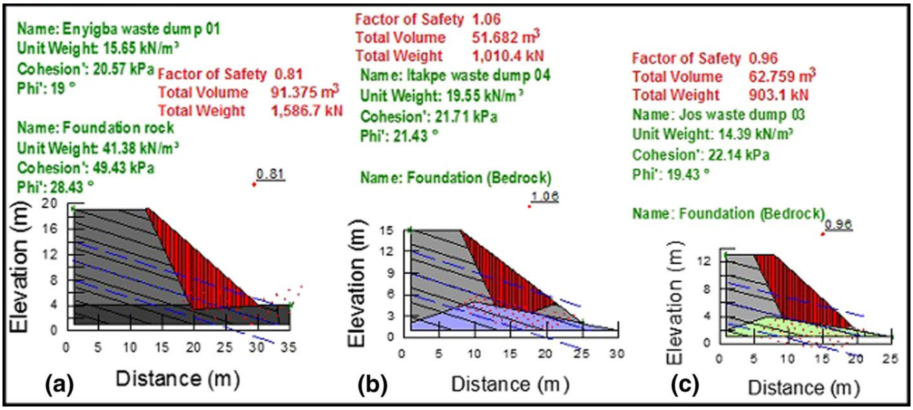

Fig. 9 Probabilistic analysis of saturated dump materials

results obtained by the Morgenstern-Price (Fig. 8 and Table 9) and Spencer's analytical methods (Fig. 10 and Table 10) revealed a 0–10% difference in values obtained by both methods for the same slope conditions, indicating good agreement between the methods (Zeidan et al. 2017).

Table 11 summarizes the findings of the probability analysis. The results revealed that, depending on the intrinsic failure triggering factors, dump slopes in Enyigba could be unstable to critically stable, based on the mean FOS. The stability of the Itakpe and Jos dumps could range from unstable to moderately stable and unstable to good stability (Table 11). Enyigba dumps, with FOS ranging from 0.81 to 1.26, are thus more prone to failure. Figure 9 depicts representative models of the most critical slip surfaces and mean FOS for dumps at the several mines analyzed. It is important to keep in mind that the most critical slip surface produced from deterministic and probabilistic assessments aren't always the same (Manafi et al. 2012). However, the probabilistic mean FOS, like the deterministic FOS, decreased as saturation increased (Table 9). The standard deviation range

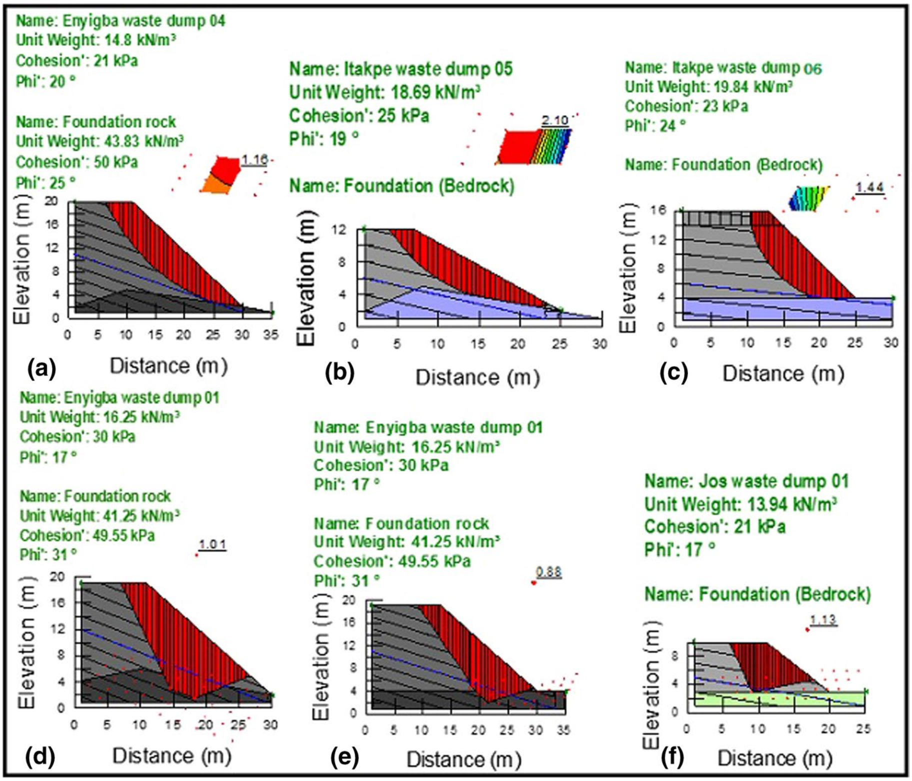

Fig. 10 Representative FOS using Spencer's approach

of 0.11–0.46 (Table 11) is regarded low, implying that the probability results are credible (Knight 2015).

Chowdhury (1978) proposed a connection between deterministic FOS and failure probability. According to the relationship, all of the waste dumps investigated have a 2–100% failure rate (Table 13). However, in today's safety assessments, 2–10 percent failure rates are considered high, and so lower percentages have been advocated by the US Army Corps of Engineers (2003). Representative probability density functions (PDEF) and cumulative

Table 13 Relationship of safety factor and probability of failure

Factor of safety	Probability of failure %	Reference
0.8	100	Chowdhury (1978)
1.0	50	
1.2	10	
1.5	2	
0.58–2.80	2–100	Present study
0.63–2.11	2–100	
0.84–3.06	2–100	

density functions (CDF) or probability distribution functions (PDIF) for 5000 Monte Carlo runs on each slope were generated (Fig. 11) from the probability models in Fig. 9. These were created so that Slope/W could calculate the probability of failure (*ρf*), percentage probability of failure (*ρf* %), and reliability index (*β*) for each slope, as shown in Fig. 10b.

Table 11 shows the *ρf, ρf % and β* data for slopes in the fields. All of the findings indicated that the dump slopes in Enyigba have a hazardous to poor level of stability performance, whereas the dump slopes in Itakpe and Jos are expected to have a hazardous to above average and hazardous to high level of stability performance, respectively (Table 14).With the exception of the slopes with weak zones, the probabilistic results are considered reliable because the difference between the Morgenstern-Price and Spencer methods is very small (0–2%) as shown in Table 15. However, the large difference (18–46%) observed in slopes with weak zones suggests that caution should be exercised when analyzing the probability of failure of such slopes, which may necessitate the use of two or more methods. Regardless, both methods demonstrated hazardous stability performance for slopes with weak zones in all three territories (Table 15). The hazardous level of stability performance indicates that slopes in the 3 studied fields are invulnerable to failure. While many of the Jos waste dumps may have mean FOS and *β* higher than the minimum 1.5 and 3.8 recommended by ANCOLD (2012) for above average stability performance (Knight 2015), the Enyigba and Itakpe dumps are projected to

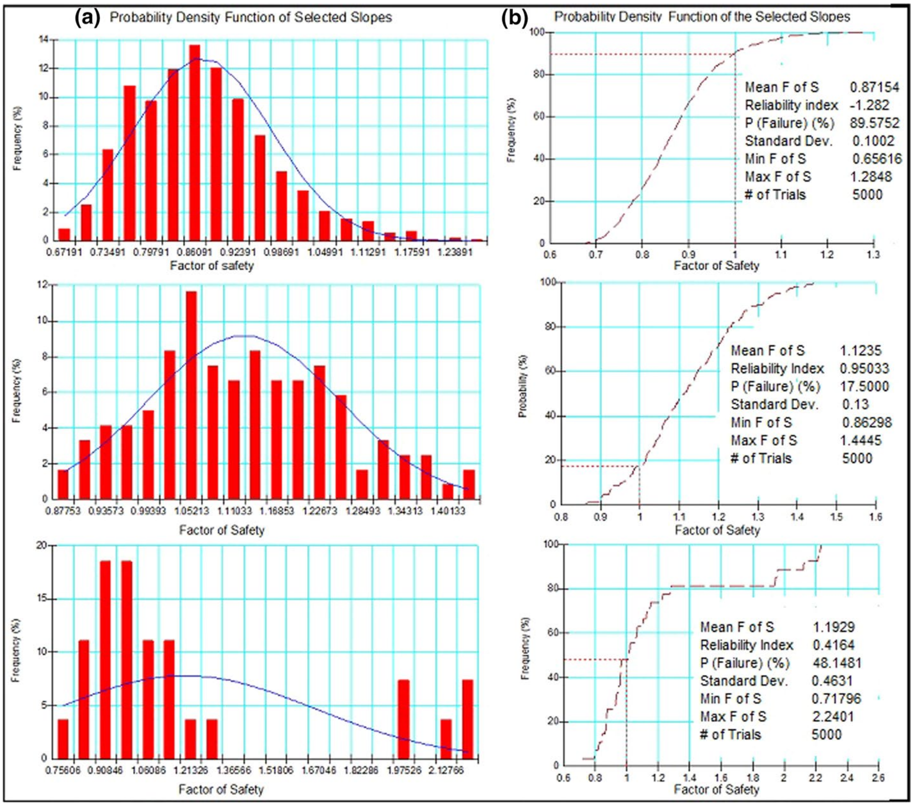

Fig. 11 Some of the PDEF for 5000 Monte Carlo trials generated for each slope

Table 14 Relation between reliability index, *β*, and probability of failure, *ρf (%)*

Reliability Index (β)	Probability of failure (*ρf*)	Probability of failure (%)	Expected performance level	Reference
1.0	0.16	15.87	Hazardous	
1.5	0.07	6.68	Unsatisfactory	
2.0	0.023	2.28	Poor	
2.5	0.006	0.62	Below Average	USACE (2003)
3.0	0.001	0.13	Above Average	
4.0	0.00003	0.003	Good	
5.0	0.0000003	0.00003	High	
				Present study
– 0.65 – 1.95	0.02 – 0.896	2.0 – 89.6	Poor—Hazardous	Enyigba
– 1.11 – 3.55	0.0002 – 0.862	0.02 – 86.2	Above average—Hazardous	Itakpe
0.42 – 4.38	0.0000 – 0.481	0.0 – 48.1	High—Hazardous	Jos

Table 15 Difference in probability of failure between methods

Location	Nature of slope	M/P	Spencer	% Difference
Enyigba	Flat foundation	2	1.96	2.0
	Sloppy ground	2.9	2.88	0.69
	Unsaturated tension cracks	2.8	2.76	1.43
	Saturated tension cracks	3.7	3.68	0.54
	Parallel weak zones	89.6	71.1	20.65
	Inclined weak zones	75.5	61.7	18.28
Itakpe	Flat foundation	0.02	0.02	0
	Sloppy ground	0.2	0.2	0
	Unsaturated tension cracks	0.02	0.02	0
	Saturated tension cracks	0.04	0.04	0
	Parallel weak zones	36.2	48.2	33.15
	Inclined weak zones	17.5	10.1	42.29
Jos	Flat foundation	0	0	0
	Sloppy ground	0.04	0.04	0
	Unsaturated tension cracks	0	0	0
	Saturated tension cracks	0	0	0
	Parallel weak zones	33.3	19.3	42.04
	Inclined weak zones	48.1	25.7	46.57

M-P connotes Morgenstern-Price

perform below average with mean FOS and lower than the acceptable values (Table 11). It is important to note that the reliability index only describes slope stability by the number of standard deviations separating the mean factor of safety from its defined failure value of 1.0 (GEO-SLOPE International Ltd. 2018), and as such, only digits have significance, rather than signs such as negative (-).In recent years, there have been reports of flooding and water logging near some of the dumps. As a result, these findings point to a very precarious situation, particularly for the Enyigba dumps, while the Jos dumps are in a less hazardous state.

According to GEO-SLOPE International Ltd. (2008), there is no direct relationship between the probability of failure and the deterministic factor of safety. According to Knight (2015) and GEO-SLOPE International Ltd. (2018), while the deterministic method of analysis suggests that slopes with higher FOS are less prone to failure than slopes with lower FOS, the probabilistic analysis method reveals that the assumption is not always the case. For example, while dump slopes on sloppy ground in Enyigba have lower FOS values than slopes threatened by moisture-filled tension cracks (Table 9), the latter have a higher failure probability (Table 11). Similar findings were made in Itakpe dumps, where slopes with inclined weak zones and those on sloppy ground had higher FOS than slopes threatened by parallel weak zones and saturated tension cracks, respectively, but the latter group had a lower failure probability (Tables 9 and 11). However, as shown in Table 16, the percentage difference between the probabilistic mean FOS and the deterministic FOS of the composite (flat foundation) is minimal (about 12%). Ozer and Bromwell (2012) reported that the maximum difference between FOS values computed by methods under LEM conditions is approximately 12%, and thus concluded that an accuracy of around ± 6% in computed FOS values is close enough for practical purposes. As a result, the deterministic FOS can be used with confidence in slope safety analysis (Knight 2015).

The assertions of Ozer and Bromwell (2012) and Knights (2015) may be applicable in the current study, where the difference between deterministic FOS and probabilistic mean

Table 16 Percentage difference between deterministic and mean probabilistic FOS

Mean FOS	Deterministic FOS	Difference in FOS	% Difference in FOS
1.26	1.49	0.23	15.44
1.29	1.39	0.1	7.19
1.33	1.42	0.09	6.34
1.17	1.25	0.08	6.4
2.17	2.05	−0.12	−5.85
2.65	2.8	0.15	5.36
1.47	1.15	−0.32	−27.83
1.58	1.62	0.04	2.47
1.4	1.5	0.1	6.67
1.68	1.69	0.01	0.59
1.49	1.56	0.07	4.49
2	2.11	0.11	5.21
1.35	1.48	0.13	8.78
1.65	1.29	−0.36	−27.91
2.27	2.13	−0.14	−6.57
1.73	1.88	0.15	7.98
2.06	2.3	0.24	10.43
2.69	3.06	0.37	12.09
1.93	2.09	0.16	7.66
2.11	2.05	−0.06	−2.93
2.09	1.48	−0.61	−41.23

FOS is less than 10% (Table 16). However, a significant difference (27–41%) was observed between deterministic FOS and probabilistic FOS in saturated samples (ENY 07, ITA 07, and JOS 07) shown in Table 9, implying that deterministic FOS may not be a true representation of stability risk analysis of saturated unnatural slopes and should not be used in confidence in safety assessment of such slopes. The large difference between the two generated FOS in saturated samples could be attributed to widespread variability in such soil properties as strength and pore-water pressure distributions. The effects of these unevenness, which is frequently caused by changing environmental conditions, as well as anomalies found in geotechnical modeling, such as insufficient soil tests, generalization and estimate assumptions, and human errors in design and modeling, may necessitate a risk analysis approach, such as the Monte-Carlo simulation-based probabilistic analysis implemented in SLOPE/W, to account for such uncertainties (Manafi et al. 2012; Knight 2015; Assefa et al. 2016).

3.3.3 Back-analysis of recent shallow slip failures

A retro-analysis of was performed to determine the causes of the recent dump slope failures at the Enyigba mine (Fig. 2). Dump "Slope 1" has tension cracks and is supported by an indurated shale foundation that is weakened by structural weakness (Fig. 12a), whereas "Slope 2" is supported by mudstone (weak foundation) with poor mechanical characteristics (Fig. 12b). These are weak zones that, when moistened, can easily provide sliding surfaces. Both slopes' stability analyses indicated that they were critically stable, with failure planes cutting through the weak zones (tension cracks and red mud). Thus, structural flaws may be the primary cause of "skin slide" or shallow slipfailures Cruden and Couture 2010) with scars of few centimeters to 1 m depth in the mining regions. The dump slopes' unweathered condition and steepness may have also influenced the shallow translational debris slides (Calcaterra and Parise 2010), and without structural defects, the studied slopes may present a higher level of safety.

3.4 Role of angle of repose on the predicted dump slope failure

The angle of repose (θ_r) is an important factor in slope stability, especially when designing man-made slopes (Beakawi Al-Hashemi and Baghabra Al-Amoudi 2018). The effect of angle of repose can be seen in slope stability problems, where the slope of earth materials becomes unstable when their slope angles (θ_s) exceed (θ_r). Table 2 shows the θ_r of the dump slopes in each region, which was found to be within the range ($15 \leq \theta_r \geq 45$) of most earth materials (Beakawi Al-Hashemi and Baghabra Al-Amoudi 2018). The results showed that waste rock dumps are prone to slope failures because θ_r (33–42°) is much lower than θ_s (38–55°) as shown in Table 2. Furthermore, the angle of repose of dump materials is generally assumed to be 37.5° (Singh et al. 2013; Dash 2019), while dump slope angles of 37–39° have been recommended (Kainthola et al. 2011; Singh et al. 2013), and should not be exceeded (Holsapple 2013). As a result, any increase in θ_s (steeper slope) of the studied dumps, whether through toe cutting as shown in Fig. 11b or the addition of more volumes of waste rocks, is likely to orchestrate catastrophic dump failures.

According to previous authors' work, the Itakpe slopes are likely to have the lowest angle of repose among the dumps (Table 2) due to higher sand content and marginally lower cohesion and moisture content. Botz et al. (2003) and Lu et al. (2015) demonstrated that angle of repose decreases with increasing particle size, whereas Lumay et al. (2012)

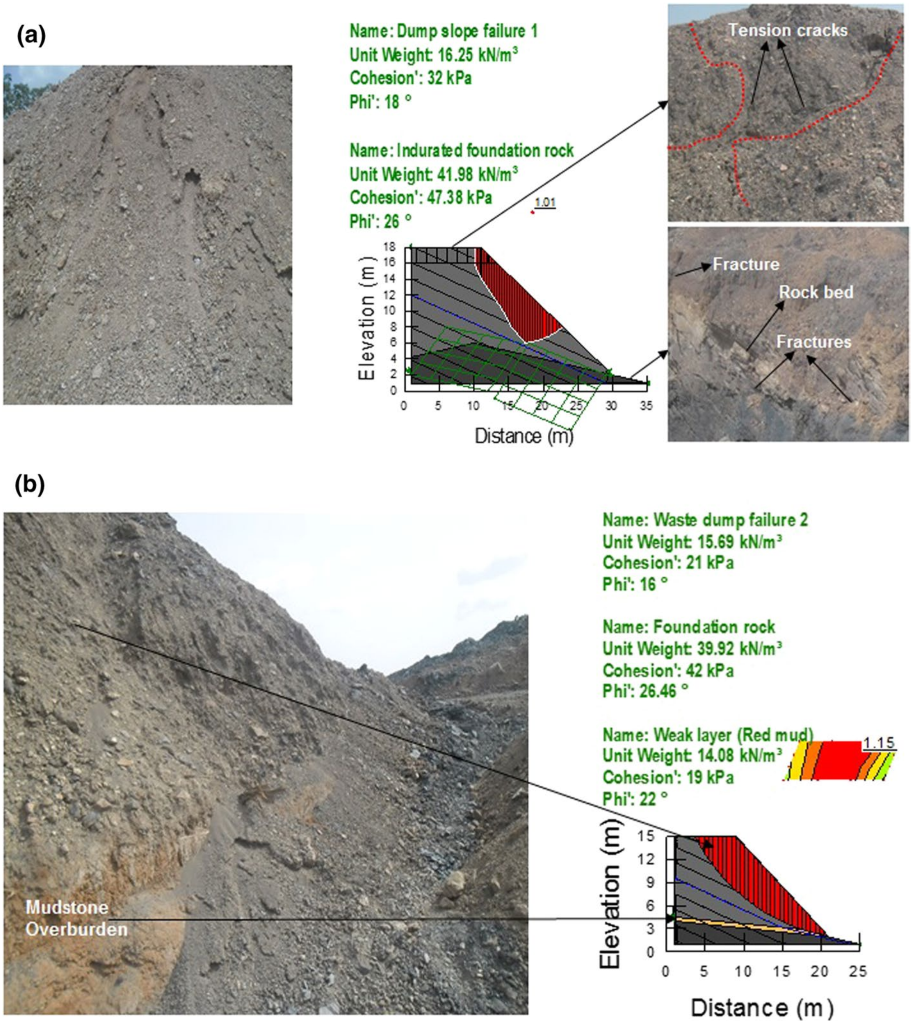

Fig. 12 Back analysis of recent shallow failures

observed that angle of repose increases with increasing cohesion. Furthermore, Zaalouk and Zabady (2009) asserted that the angle of repose commonly increases as the moisture content of the material increases. However, a more recent author reported that the angle of repose only increases after the water content of a material exceeds a critical value, which was attributed to the electrostatic attraction between water molecules and the surfaces of the material's constituent minerals (Jin et al. 2017).

3.5 Rainfall impact on the waste dumps' stability

Slope failures in West Africa are mostly triggered by rainfall (Agbor et al. 2014; Ige et al. 2016; Egboka et al. 2019). Several authors have disclosed the influence of rainfall on the stability of slopes (Cortopassi et al. 2008; Yellishetty and Darlington 2010; Behera et al. 2016). These authors observed that water infiltration and seepage during rainfalls into slope materials is one of the main triggering factors of slope instability. Rainwater infiltration triggers slope failure by reducing or eliminating matric suction, thereby weakening the slope (Rahardjo et al. 2004; Calcaterra and Parise 2010; Guemache et al. 2011). As dump material water content increases through infiltration and seepage, pore-water pressure continues to increase to the point of undermining the slope factor of safety by reducing material shear strength (Calcaterra and Parise 2010; Del Soldato et al. 2018), and consequently initiating slope material movement (landslide). Therefore, the impact of the rainfall pattern of the study areas on the stability of the waste dump cannot be overemphasized.

Landslides and slope failures in the study areas were observed to mostly occur during the rainy season (Agbor et al. 2014; Akanbi and Bulus 2017; Egboka et al. 2019). In Nigeria most researchers have not documented slope failures on waste rock dumps. However, majority of landslides on natural slopes reported in the country occurred during or shortly after torrential or prolonged rains (Ige et al. 2016; Egboka et al. 2019; Bamisaiye 2019). Landslides at Ugwueme, Iguosa, Imande Ukusu, Jos, Okemesi, Nanka, Oko, Agbaja, Eyenkorin, and Asa Dam are among many examples of rainfall-induced slope failures documented in the literature (Okagbue 1988; Agbor et al. 2014; Ige et al. 2016; Oluwafemi et al. 2017; Bamisaiye 2019; Aigbadon et al. 2021).

A glance at the rainfall data of the study areas reveals high annual rainfall pattern reminiscent of the tropics (Fig. 13). A study of the annual rainfall in the last four decades revealed that the average yearly rainfall of Enyigba, Itakpe and Jos stands at about 1850, 1210 and 1360 mm, respectively. These high values of rainfall are likely to be detrimental to the dump slopes in the fields. Moreover, evidences have shown increase in rainfall over last forty years (Fig. 13a). Although the dumps at the three mines are susceptible to failure due to high cumulative and increasing rainfall, Enyigba and Jos dumps would probably be the most predisposed to instability, particularly Enyigba as a result of its higher rainfall rate yearly (Fig. 13b). Though, Enyigba may have higher

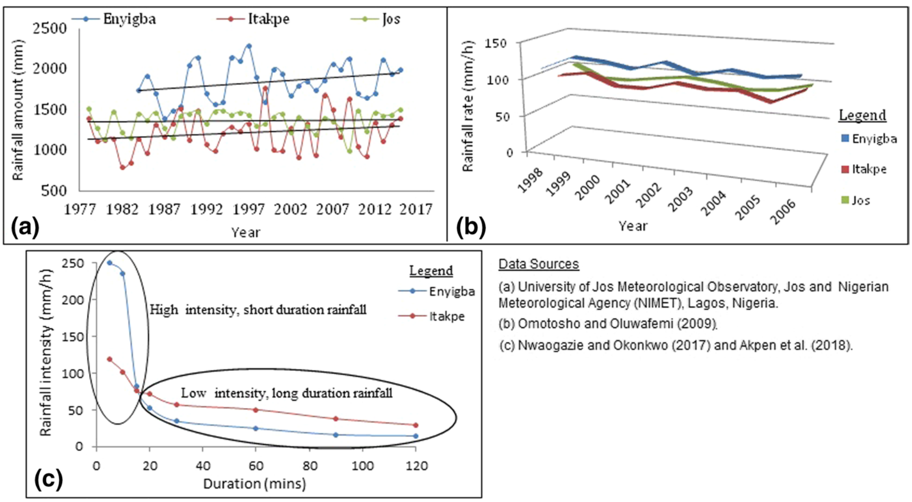

Fig. 13 Rainfall patterns of the study areas

rainfall intensity than the other studied areas, dumps in the other sites are also predisposed to slope instability due to their longer duration of rainfall (Fig. 13c).

Moreover, slope failures have been observed to occur in a wide range of rainfall conditions such as prolonged and heavy rainfalls (rainstorms), high intensity—short duration rainfall, low intensity- long duration rainfall, and cumulative (accumulated) rainfalls (Cortopassi et al. 2008; Yellishetty and Darlington 2010; Guemache et al. 2011; Tien Bui et al. 2013; Behera et al. 2016). Mild (low) rainfalls have also initiated slope failures in Nigeria. Therefore, rainfalls of high intensity or low are as effective as the others. Both can be complementary to reach rainfall thresholds peculiar for landslide initiation in these areas. Threshold (critical) rainfall is a proven minimum amount of rainfall amount required to trigger landslides in a region. As a result, it is critical to determine the study areas' landslide-triggering rainfall thresholds through a correlation analysis of daily and cumulative antecedent rainfall values with past landslide events (Tien Bui et al. 2013). Unfortunately, there are few or no records of historical landslides in Nigeria, so extensive documentation of future landslide events and their antecedent rainfalls is required. It is worth noting that determining rainfall thresholds for landslide initiation is regarded as a fundamental task in landslide hazard assessment (Tien Bui et al. 2013). Forecasting of landslide episodes by means of rainfall thresholds have been effectively employed in several developed countries such as United States, Canada, Japan, Italy and New Zealand (Tien Bui et al. 2013).

Extraordinary large contrast in groundwater level and seepage forces between the dry and rainy seasons often times have influence on slope stability (Yellishetty and Darlington 2010; Guemache et al. 2011).High rainfalls at the peak of the rainy season could result in rise in groundwater level and flooding (water-logs) in and around dumps, as had been observed in some mines by earlier workers (Okagbue 1992; Cortopassi et al. 2008; Yellishetty and Darlington 2010), which may negatively impact on their stability. These may cause movements along a weak surface which leads to liquefaction of the layer, resulting in rapid movements, long run-out distance and total liquefaction of the moving mass (Zhang et al. 2011), resulting in more sliding mass when compared to waterless (dry) slopes.

In the events of major dump failures, Enyigba dumps are likely to leave deeper scarp and larger volumes of sliding (moving) mass (Figs. 8f–h and 9). As a result of these findings, coupled with higher water content and high peaks, Enyigba sliding mass may travel a greater distance than sliding mass in Itakpe and Jos. In this study, it was clear that unsaturated dumps would have lower moving mass than saturated dumps, with simulation results presenting lower values in both total slide volume and weight in the former than the latter (Figs. 7b, c and a, f). The observation is consistent with the findings of Igwe and Chukwu (2018).

4 Conclusions

The safety of the waste rock dumps in Nigerian mines is the center piece of this work, taking in consideration of their factor of safety, probability of failure and reliability index. Evidences from field and laboratory data collected suggested that the safety of the waste dumps at the mines is threatened by instability, orchestrated by dump slopes' geometry, demonstrated by high slope height and angles. Although the geotechnical results testified that the dumps are made up of competent materials, the stability analysis through its deterministic FOS revealed that the stability of the waste dumps in the fields vary widely from unstable to stable slopes. In agreement, the mean probabilistic FOS showed that the slopes are in hazardous to high performance levels. The stability analyses indicated that the dumps in the three mining regions are susceptible to slope failure, particularly with increase in water content (saturation) during rainfalls, as portrayed by low FOS, probability of failure and reliability index. Furthermore, the slope angle of the dumps was observed to be above the angle of repose of the constituent earth materials of waste dumps, thus agreeing to the vulnerability of the dump slopes to landslides.

The tropical rainfalls of the regions could be detrimental to the stability of the dumps due to their high and increasing annual rainfalls. The extreme and erratic rainfalls may function as a triggering factor during dump slope failure events in the fields. Generally, Enyigba dumps were observed to be most prone to instability when compared to Itakpe and Jos dumps, in that order, as a result of its higher rainfall, slope height and angle as well as corresponding lower values of FOS, $\rho f\ \%\ and\ \beta$. Finally, the authors wish to recommend lower slope heights and angles and good drainage control as temporary measures to imminent slope failures in these fields. However, the best remedy in averting any foreseeable dump failure is recycling and reusing of the waste rocks as engineering materials, which must be preceded by thorough research on their geotechnical behaviors.

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Declarations

Conflict of interest The authors declare that they have no known competing interests.

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