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Liquefaction, landslide and slope stability analyses of soils: A case study of soils from part of Kwara, Kogi and Anambra states of Nigeria

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ABSTRACT

Landslide is one of the most ravaging natural disaster in the world and recent occurrences in Nigeria require urgent need for landslide risk assessment. A total of nine samples representing three major landslide prone areas in Nigeria were studied, with a view of determining their liquefaction and sliding potential. Geotechnical analysis was used to investigate the liquefaction potential while the slope conditions were deduced using SLOPE/W. The results of geotechnical analysis revealed that the soils contain 6-34 % clay and 72-90 % sand. Based on the unified soil classification system, the soil samples were classified as well graded with group symbols of SW, SM and CL. The plot of plasticity index against liquid limit shows that the soil samples from Anambra and Kogi are potentially liquefiable. The liquefaction screening criteria also revealed that Anambra and Kogi are potentially susceptible to liquefaction, whereas samples from Kwara are not susceptible to liquefaction. Samples from Kogi and Anambra have lower values of MDD and OMC, ranging between 1.64-1.80 g/cm^3 and 8.0-12.3 % respectively. These values showed that the samples are granular material with soil having anticipated embankments performance, subgrade and base material as poor-fair, fair-good and good-poor, respectively. The direct shear strength test on the soil samples indicated that the cohesion and angle of internal friction varies between 40-80 kPa and 24-35º. The Coefficient of permeability vary between 8.71×10^{-5} and 1.18×10^{-3}. The factor of safety (FOS) values for soils from Anambra, Kogi and Kwara are 1.452, 1.946 and 2.488, respectively. These values indicate stability but care must be taken as the condition at the site shows that the slope is in its state of impending failure. The FOS for dry slope was higher when compared to the FOS values from wet slope. This was due to the effect of pore water pressure on the soil as it reduced the

33   shear strength of the soil. A reduced value of FOS was observed in the model under loading

34   conditions, which indicate that loading is also a contributing factor to the slope failure. It is

35   recommended that proper and efficient drainage system should be employed in these areas to

36   reduce the influence of pore water pressure in the soil.

37   *Keywords*: Liquefaction, landslide, slope stability, geotechnical analyses, Nigeria

38

39   1. **INTRODUCTION**

40   The effect of natural disaster in the world cannot be over-emphasized, as a number of failures

41   of embankments, natural slopes, earth structures and foundations have been attributed to the

42   liquefaction of sands, landslides and slope instability. According to the report documented by

43   National Research Council (1985), case studies of landslides or flow failures due to

44   liquefaction are the 1937 Zeeland coast of Holland slides involving 7 million cubic meters of

45   alluvial sands, and the 1944 Mississippi River slide near Baton Rouge containing about 4

46   million cubic meters of fine sands. Just to mention a few cases, failure of hydraulic fill dams

47   such as the Calaveras Dam (California) in 1918, Fort Peck Dam (Montana) in 1938, and Lower

48   San Fernando Dam (California) in 1971, were triggered by the liquefaction of sands. Landslides

49   are a major hazard in Africa where resources worth several millions of dollars are lost annually

50   during seasons of heavy and light rains. In West Africa, landslides are caused primarily by

51   rainfall. Depending on meteorological and geomorphologic conditions, individual rainfall

52   events can trigger small or large slope failures.

53   One of the most recent natural disasters threatening Nigeria is landslide. In Nigeria, landslide

54   has done a serious destruction to physical structure and resulted in the loss of lives and

55   properties. For instance, the December 2005 landslides in Umuchiani community of Anambra

56   state has led to the inhabitation of about 250 families, while over 20 communities in Awgu and

57   Oji-River Local Government Areas of Enugu State were thrown into serious difficulties by

58   landslides cutting off a portion of the Awgu-Achi-Oji River Federal road in October

59   2011. According to the report documented by State Emergency Management Agency (SEMA),

60   the landslide that occurred in Oko Community of Anambra State has rendered more than 150

61   people homeless. In addition, they reported that 15 buildings were destroyed, but no life was

62   lost. In 2013, no fewer than nine persons were buried alive, while many others sustained

63   injuries in the landslide that occurred at Edim Otop community of Calabar metropolis (Figure

64   1). The landslide occurred after heavy rainfall which lasted for more than five hours. Landslides

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and Earth System
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Discussions

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65 induced by high-intensity or prolonged rainfalls constitute a major risk factor in Nigeria

66 especially because they have generally been poorly defined in the past. The landslides have the

67 potential to damage human settlements, industrial development, cattle ranch, forestry and

68 agricultural activities. Landslide is mass movement on slope involving rock fall, debris flow,

69 topples, and sliding (Varnes et al., 1984). Landslide occurs as result of the presence of saturated

70 clay materials on the impermeable layer on steep slopes. Landslide that occurred on a slope is

71 influenced by gravity. The internal and external causes of landslide is presented in Table 1. The

72 presence of soil moisture also increases the pore water pressure and lessens the material

73 stability. A change in pore water pressure is regarded as the main triggering factor to land

74 sliding (Ngecu and Mathu, 1999 and Knapen et al., 2006). If an external load is applied to a

75 soil mass on a slope in the form of additional water or overburden, the pore water pressure will

76 build up such that mass and water will be expelled at weak points (Alexander, 1993).

77 Slope instability is the condition which gives rise to slope movements (Alexander, 1993). In

78 every slope, there are forces (stresses) that tend to instigate or cause movement (shear stress),

79 and opposing forces which tend to resist movement (shear strength), (Bromhead, 1984;

80 Alexander, 1993). Sliding occurs when shear stress is greater than shear strength. In normal

81 circumstances, the shear stress is balanced by shear strength and a state of equilibrium is

82 maintained (Alexander, 1993). However, this equilibrium can be disturbed by stress increments

83 or weakening of frictional force. The failure of slope material depends partly on the strength of

84 frictional force between the sliding mass and the bedrock (Crozier, 1984; Alexander, 1993; and

85 Matsushi et al., 2006). Slope stability analysis can be performed using either total or effective

86 stress. Total stress analysis is applicable to embankments and multistage loading problems

87 where the short term condition is critical, while effective stress analysis should be used for

88 excavation problems where the long-term condition is critical (Duncan, 1996). The search for

89 the preparatory factors and cause(s) of an individual landslide or an attempt to designate the

90 state of instability is prompted to find an efficient way of responding to the problem by legal

91 necessity, or simply by a desire for knowledge (Crozier, 1984). The danger of slope instability

92 can never be over emphasized in its destructive property. To understand and evaluate

93 liquefaction potential of soils and degree of slope stability, as well as causes of landslide in the

94 area, three localities (Anambra, Kogi and Kwara state, Figure 3) that differ in geology and land

95 use were studied. While slope failure and landslides are common and frequent in the

96 mountainous parts of Anambra and Kogi state because of their unique geology, long-time

97 residents report that the recent landslides at Oko, in Anambra state (Figure 1) is the first major

Natural Hazards
and Earth System
Sciences
Discussions

98   slope failures despite the much higher elevation and steepness of slopes in the area. These

99   differences in scale and frequency were the major motivating factors for the research.

2. GEOLOGICAL BACKGROUND

101 Nigeria is a part of Africa that forms the continental crust and lies in the Pan-African mobile

102 belt that has been affected by Pan- African events during the ages of orogenic, epeiorogenetic,

103 tectonic and metamorphic cycles (Rahaman, 1976). The geology of Nigeria can be subdivided

104 into the Precambrian Basement Complex and Cretaceous to Tertiary sedimentary basins. The

105 Nigerian Basement Complex forms part of the Pan-African mobile belt and lies between the

106 West African and Congo Cratons (Figure 3) and to the south of Tuareg Shield (Black, 1980).

107 It consists of gneiss migmatite complex, schist belt and granitoids (older granites) of the

108 Archean, Paleoproterozoic and Neoproterozoic (Annor, 1998). The Nigerian basement

109 (Fig.2.1) was affected by the 600 Ma Pan-African orogeny and it occupies the reactivated

110 region which resulted from plate collision between the passive continental margin of the West

111 African craton and the active Pharusian continental margin (Burke and Dewey, 1972; Dada,

112 2006). About 50% of the total landmass of Nigeria is covered by sedimentary basins. These

113 basins are Bida Basin, Benue Trough, Chad Basin, Anambra Basin, Dahomey Basin and Niger

114 Delta Basin. The basins generally develop over the Precambrian basement and dominated by

115 clastic deposit and in places, ironstone and organic coal-bearing sediments (Nguimbous-

116 Kouoh, 2012). The study area falls in both the Basement Complex and sedimentary areas. The

117 areas under sedimentary part of Nigeria are Oko in Anambra State and Agbaja in Kogi State,

118 while those in the Basement Complex are Eyenkorin and Asa Dam in Ilorin, Kwara State.

119 **2.1 Location of the study area**

120 **2.1.1 Oko, Anambra State**

121 Oko is situated in Orumba North Local Government Area (LGA) of Anambra state. It is

122 geographically situated between 6º02'37.34" N and 7º 04'54.32" E and has humid climatic

123 condition. The average annual rainfall in Oko is about 2,000 mm. Most rainfall occurs in well-

124 defined rainy seasons of six to seven months (April to October) and is typically concentrated

125 in high intensity storms   and often causes flooding and erosion leading to the formation of

126 gullies. Oko is a rain forest area and is characterized by vast undulating landscape and of

127 alluvial plain. Greater part of its vegetation is made up of forest (tropical vegetation).

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2.1.2 Agbaja, Kogi State

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131 Agbaja is the locality of a large iron ore deposit in Kogi State, central Nigeria. It is located on

132 a plateau about 300 km south of the capital Abuja, and more importantly about 70 km from the

133 heavy duty railway to the sea at Itakpe which is about 70 km to the south. It is geographically

134 situated between 7°56'53.33" N and 6°39'38.40" E. The land rises from about 300 m along the

135 Niger Benue confluence, to the heights of about 500 m above sea level in the uplands. Agbaja

136 Plateau, which ranges from 335-366 m above sea level, is one of the predominant landforms in

137 the state. The state is drained by the Niger and Benue rivers and their tributaries.

2.1.3 Asa Dam and Eyenkorin, Kwara State

138

139 The sample localities are located in Ilorin metropolis which is a Basement Complex terrain that

140 has undergone deep weathering. The Nigeria Basement Complex is a group of igneous and

141 metamorphic rocks of Precambrian age (Kogbe, 1975). It is largely undifferentiated and

142 constitutes about 50 % of the bedrock in Nigeria. Large outcrops of granite and gneisses with

143 cross-cutting pegmatites are common (Alao, 1983). The general trend of the outcrops in the

144 area is SW-NE with a west dip.

3. MATERIALS AND METHODS

145

3.1 Site visit and Data collection

146

147 Oko area in Anambra State, Agbaja Hill in Lokoja, Kogi State as well as Asa Dam and

148 Eyenkorin (Ilorin metropolis) in Kwara State of Nigeria were visited for soil sampling and to

149 evaluate existing conditions of slopes situated in the site. The weathered surface was removed

150 and the outcrop was horizontally dug inward in order to obtain fresh samples. The effective

151 soil sampling depth was determined using a screw soil auger, a surveying tape, depths of recent

152 landslides and slope remodelling. However, areas where landslides had occurred, the

153 samples were collected from the sides of scar. In special cases, selection of sample locations

154 were based on indications of slope instability, mainly soil creeping and cracking. Coordinates

155 of the sampling pits (sites) and photographs were taken during field visits to provide additional

156 records. The collected fresh soil samples were transported to the Mechanical Engineering

157 Department soil laboratory, University of Ilorin, Nigeria for geotechnical tests in order to

158 access the probable mechanical behaviour. The investigated shear strength parameters of the

159 soil samples were later used in slope stability evaluation.

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3.2 Geotechnical analysis

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163 Preliminary geotechnical classification and identification tests such as moisture content, bulk

164 density, specific gravity, grain size distribution, hydraulic conductivity, particle density, bulk

165 density, liquid limit, plastic limit, and plasticity index, compaction and shear strength tests were

166 carried out on the soil samples based on the British Standard (BSI 1377:1990). Each

167 geotechnical test was performed twice on the same soil sample under the same condition in

168 order to determine the reliability of the geotechnical test results. The result of the Atterberg

169 consistency limits were plotted after Seed et al. (1983; 2003) in order to deduce whether the

170 soils are susceptible to liquefaction. The boundaries in the gradation curves for soils susceptible

171 to liquefaction, as proposed by Tsuchida (1970) were also used to determine whether the soils

172 are susceptible to liquefaction.

3.2.1 Grain Size Analysis

173

174 Mechanical and hydrometer methods were used to determine the grain size distributions. The

175 mechanical method (wet sieving) was employed in the analysis of particles that are greater than

176 0.075 mm in diameter. A calibrated (ASTM 152H) hydrometer was used to analyse the finer

177 grains (d < 0.075 mm) in the laboratory.

3.2.1.1 Procedures for mechanical method (wet sieving)

178

179 The soil particles were gently separated from each other. The sieve set (stack of sieves) were

180 arranged in descending order from the top with a retainer beneath it. 100 g of each soil sample

181 was weighed and poured into the sieve stack. The soil filled sieve stack was placed on the

182 mechanical sieve shaker for about 10 minutes. The sieve stack was later separated and the soil

183 fraction retained by the mesh of each sieve was retrieved. The soil fraction retained by each

184 sieve was weighed and the statistical data of the grain size analysis was computed.

3.2.1.2 Procedures for hydrometer method

185

186 The sieved clay and silt from the sieve washing was collected in a container and allowed to

187 settle. The supernatant water was decanted and the mud residue was dried in the drying oven

188 for about 24 hours. 500 g of the dried mud was soaked in distilled water for 24 hours and mixed

189 properly in a stirrer with a dispersive agent (hexametaphosphate) added to avoid flocculation

190 of the grains. The suspension was poured into 1 litre measuring cylinder and mixed before the

191 soil grains were allowed to settle in the suspension. The hydrometer was later inserted into the

192 water in the measuring cylinder and its reading was recorded periodically. As the settling

193 proceeds, the hydrometer sinks deeper into the solution. The temperature at each hydrometer

194 reading was recorded and then a statistical data sheet was produced showing the results of the

195 analysis. The clay and silt percentage in the samples were then calculated from the graph

196 obtained by plotting percentage passing against the grain diameters.

197 **3.2.2 Atterberg limits determination**

198 To determine the liquid limit of the soil samples, the fraction of the soil that passed through the

199 425μm sieve was weighed (230 g) on a weighing balance and carefully mixed with clean water

200 in order to form a thick homogeneous paste. A groove was cut through the paste (soil sample)

201 that was placed inside the Casangrade's apparatus cup and the numbers of blows were counted

202 and recorded until the groove in the soil closes. The moisture contents were determined and

203 the moisture contents were plotted against the numbers of blows in order to determine the liquid

204 limit. To determine the plastic limit, soil sample was also taken from the soil sample that passes

205 through the 425μm sieve and weighed on the balance. Then it was thoroughly mixed with water

206 using the hand until it becomes homogenous and plastic enough to form ellipsoidal-circular

207 shape (i.e. ball). The ball-shaped soil was rolled in a rolling device until the thread cracks or

208 crumbles at about 4 mm diameter. The crumbled sample (4 mm) was then air-dried thus the

209 moisture contents were determined.

210 **3.2.3 Procedures for compaction test**

211 3 kg of soil sample was weighed and poured into the mixing pan. 120 cm³ (4 %) of water was

212 measured, added and mixed with the soil in the mixing pan using a hand trowel. The cylinder

213 mould was placed on a base plate, then a representative specimen of the soil was put into the

214 mould and compacted with 25 evenly distributed blows of the rammer. This represents the first

215 layer. After the compaction, the volume of soil in the mould reduced, more soil specimen was

216 added into the mould and compacted with another 25 evenly distributed blows. The extension

217 collar was fixed unto the mould. This is mainly for the last layer and removed after the last

218 layer was made and aided to achieve a smooth level surface. The mould was filled with more

219 of the soil specimen and compacted to make the third layer. This is for standard Proctor, and

220 five layers of the soil specimen with 55 evenly distributed blows of the rammer makes the

221 modified Proctor. The mould with the soil was weighed and the soil was sampled at the top

222 and bottom of the mould for water content and the dry density determination. The mould was

223 emptied into the mixing pan and another 120 cm³ (4%) of water was added to the soil and

224 mixed. The same procedure was repeated for all the samples. The dry densities were plotted

225 against water contents for the standard Proctor and modified Proctor in order to determine the

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and Earth System
Sciences

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EGU

Discussions

226   maximum dry densities (MDD) and optimum moisture contents (OMC) of the soil samples in

227   each situation.

3.2.4 Shear strength determination

229   Two 3 kg of both soil samples (standard and modified Proctor for each soil sample) were

230   weighed and mixed with the corresponding optimum moisture content. The soil samples were

231   then compacted as described in the above procedure. A square sampler was then gently used

232   to collect a representative sample. Each collected sample was placed in a shear box and a load

233   was placed on it both in horizontal and vertical positions and the deformation dial gauges were

234   set at zero. A set of normal loads of 5 kg, 10 kg, 15 kg and 20 kg were applied one after the

235   other in successive tests. The readings on the load dial units were recorded, and the procedure

236   was repeated for the standard Proctor and modified Proctor for other samples. The shear

237   strength results were presented as stress-strain curves and the shear stress was plotted against

238   the normal stress, thus the angle of cohesion and angle of internal friction were determined.

3.3 Method of slices using SLOPE/W software

240   The slope model was analysed using SLOPE/W and SEEP/W software with the aim of giving

241   the state of the slopes with their factor of safety using Limit Equilibrium Method (LEM).The

242   software computes the factor of safety (FOS) for various shear surfaces (SS), for example

243   circular and non-circular. However, only the circular SS was automatically searched. The

244   method of slices was considered in relation to its application to SLOPE/W and traditional

245   methods of analysis. According to Abramson et al. (2002) slices method is widely used by

246   much computer software because it can accommodate geometry of complex slope, different

247   soil conditions and influence of external boundary loads. Conventionally, the weight of soil

248   lying at a particular point should influence the stress acting normal to that point on sliding

249   surface. Theoretically, the basic principle of slices method is the potential slide mass, which is

250   subdivided into several vertical slices and the equilibrium of individual slice can be evaluated

251   in terms of forces and moments. This would allow easy estimation of the allowable safety factor

252   of a slide mass. In this study, two soil layers obtained from shear strength test, with different

253   strength parameters were used for slope stability analyses. This same shear strength parameters

254   were used in both dry and wet conditions. Similarly, two unit weight of soils, one above the

255   groundwater table (GWT) and the other below the GWT were also considered. The complete

256   set of input parameters used in the study are shown in Table 9. The three different conditions

257   considered for slope stability analyses are dry slope, wet slope and dry slope with external

258   loads. The analysed load conditions were defined as:

Natural Hazards
and Earth System
Sciences
Discussions

259 • Case 1: Completely dry slope, i.e. no GWT inside the model,

260 • Case 2: Completely saturated slope, i.e. GWT on the surface (hydrostatic pore pressure),

261 • Case 3: Dry slope with external forces, i.e. q = 40 and 50 kPa.

262 The stability of the dry slope was first analysed in SLOPE/W. The minimum factor of

263 safety (FOS), critical slip surfaces (CSS) were searched by entry and exit option as well as

264 groundwater table (GWT) level shown in the model using limit equilibrium (LM) principle.

265 The CSS was searched from thousands of possible SS by defining the input of 15

266 slices, 1500 iterations, 15 increments for entry, 10 increments for exit and 5 increments for

267 radius. In addition to the limit equilibrium methods (LEM), the Bishop's and Janbu's simplified

268 methods as well as the Spencer and Morgenstern-Price (M-P) factors of safety were used for

269 rotational and irregular surface failure mechanisms.

4. RESULTS AND DISCUSSION

4.1 Grain size distribution and soil classification

272 The results of grain size analysis is shown in Figure 4 and Table 2. The grain size distribution

273 curves show that the soil samples consist of all fractions ranging from gravely to clayey. The

274 clay content is found between 2-34 % in all the soil samples. The soil sample from Asa Dam

275 road in Ilorin, which is plastic in nature has the highest clay content of about 34 %. Soil samples

276 from Lokoja and Anambra states have very low fine content ranging from 2-12 % and are not

277 plastic in nature. The sand fraction dominated the samples (constituted about 70-80 % of the

278 samples) especially those gotten from Lokoja and Anambra states. Similarly, the grading

279 coefficient (Cu = D60/D10) varies from 5-275, except for the sample from Asa Dam 1 with Cu

280 of 2000. Based on the Unified Soil Classification System (ASTM D2487-90, 1992), all the soil

281 samples are classified as well graded with group symbols SW, SM and CL (Figures 4 and 5;

282 Table 2).

4.2 Atterberg limit

284 The summary of results obtained from moisture content, liquid limit, plastic limit and plasticity

285 index analyses are presented in Figure 6 and Table 3. The plasticity charts (Figure 7) was used

286 to classify the samples and most of the samples are above A-line (Figure 8). Eyenkorin 1, 2

287 and Asa Dam 1, 2 are in the region with symbol CL, thus they are classified as inorganic clays

288 of medium compressibility. Anambra 1, 2 and Lokoja 1, 2 and 3 falls in the CL-ML region and

289 thus they are classified as cohesionless and inorganic silts of low compressibility.

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4.3 Compaction test

The compaction test at standard state condition yielded maximum dry densities (MDD) of 1.84g/cm³ and 1.88g/cm³ for Eyenkorin 1 and 2, respectively (Figure 9). The optimum moisture content (OMC) for Eyenkorin (in Kwara state) 1 and 2 are 14.0 % and 13 %, respectively. Samples from Lokoja (Kogi state) and Oko (Anambra state) have lower values of MDD and OMC, ranging between 1.64-1.80 g/cm³ and 8.0-12.3 %, respectively. These values when compared to Table 4 show that the samples can be described as granular material with soil having anticipated embankments performance as poor to fair, value as subgrade material as fair to good and value as a base course as good to poor (Table 5).

4.4 Shear strength and permeability

The summary of shear strength and permeability results, as well as their interpretations are tabulated in Tables 6 and 7. The direct shear strength test the soil samples show that the cohesion and angle of internal friction varies between 40-80 kPa and 24-35º. The Coefficient of permeability of the soil samples vary between 8.71×10^{-5} and 1.18×10^{-3}.

4.5 Liquefaction susceptibility

The results of liquefaction studies after Seed et al. (1983; 2003) are depicted in Figures 10 and 11. Liquefaction involves the temporary loss of internal cohesion of material, such that it behaves as a viscous fluid rather than as a soil (Alexander, 1993). Soils containing a high percentage of sand and silt will deform more quickly than those containing high percentage of clay. Due to their cohesive strength, clays adjust more slowly to increase pore-water pressure than unconsolidated soils. The plot of plasticity index against Liquid limit after Seed et al. (2003) shows that the soil samples from Anambra and Lokoja are potentially liquefiable. The liquefaction screening criteria after Andrews and Martin (2000) also shows that Oko (Anambra), Eyenkorin (Kwara) and Lokoja (Kogi) are potentially susceptible to liquefaction, whereas samples from Asa Dam 1 - 2 (Kwara) are not susceptible to liquefaction (Figure 11).

Boundaries in the gradation curves for soils were used to determine liquefaction susceptibility of the soil samples (Tsuchida, 1970). Boundary most susceptible to liquefaction is in the sand region, with about 60-80 % of sand, whereas boundary for potentially liquefiable soil is in the region of 20-40 % sand (Tsuchida, 1970). Soils with a higher percentage of gravels tend to mobilize higher strength during shearing, and to dissipate excess pore pressures more rapidly than sands. However, there are case histories indicating that liquefaction has occurred in loose gravelly soils (Seed, 1968; Ishihara, 1985; Andrus et al., 1991) during severe ground shaking

Natural Hazards
and Earth System
Sciences
Open Access
Discussions
EGU

323 or when the gravel layer is confined by an impervious layer. Based on Tsuchida (1970)

324 classification, it can be deduced that soil samples from Anambra 1and Lokoja 1-3 have % of

325 sand ranging from 72-96 %, thus they are liquefiable in nature (Figure 12; Table 8). Anambra

326 2 has 63 % of sand which is potentially liquefiable, based on the classification proposed by

327 Tsuchiba (1970). Some of the soil samples fall outside Tsuchida's boundaries and Walker and

328 Steward (1989) documented that non-plastic and low plasticity silts, despite having their grain

329 size distribution curves outside of Tsuchida's boundaries for soils susceptible to liquefaction,

330 have a potential for liquefaction similar to that of sands. In addition, they further stated that

331 increased plasticity will reduce the level of pore pressure response in silts. This reduction,

332 however, is not significant enough to resist liquefaction for soils with plasticity indices of ≤ 5.

4.6 Landslide and slope stability

334 Slope angles, slope length play important roles in the stability of slopes. The slope angle is

335 regarded as the major topographic factor in determining stability. The physical characteristics

336 of the terrain influencing slope instability were measured. The characteristics recorded

337 included slope length, angles, and altitude. The slope angles can be classified as steep angle as

338 they are close to $60\text{-}70^o$ in the study areas. Though the embankment slopes in Asa Dam area

339 and Eyenkorin area have values in the range of $30\text{-}35^o$ and are classified as moderate angles.

340 The factor of safety (FOS) gotten from SLOPE/W software were used to classify the slopes

341 into safe, state of impending failure and failed slopes. Several authors have proposed different

342 values for slope classification. The general and acceptable value for stable slope is 1.5, whereas

343 a value less than 1 is always classified as unsafe. The analysed samples have values ranging

344 from 1.366 - 2.488 (Figure 13-19; Table 10). The value of 1.366 is from the Oko area in

345 Anambra state where landslide occurred. The maximum value of 2.488 was obtained at Asa

346 Dam, which is an embankment slope and it depicts stable slope. The FOS for dry slope was

347 higher when compared to the FOS values from wet slope (Figure 13). This was due to the effect

348 of pore water pressure on the soil as it reduced the shear strength of the soil. Figure 14 shows

349 the critical slip surface (CSS) and factor of safety (FOS) for non-optimised wet slope. The slip

350 surface was at the top of the slope (Figure 13a) whereas in Figure 13b, it shows the CSS passing

351 through ground water table (GWT), thus making the slip surface size bigger and occupies all

352 of the entry point. Since suction effect has not been considered in the analysis, the located

353 GWT has serious effect on the FOS. Figure 14 shows an increased in the geometry, and the

354 CSS and FOS was affected drastically. The reduction in FOS from 2.51 to 1.45 (Figure 13) is

355 an indication of the effect of pore water pressure and gravity on the failed site. Limit

Natural Hazards
and Earth System
Sciences
Discussions

356 equilibrium methods computed the values of FOS slightly lower than 1.5 which depict

357 instability. The pore pressure at the toe causes reduction in the effective normal stresses, and

358 hence the shear strength.

359 Two of the primary assumptions of Bishop's simplified method ignores interslice shear forces

360 and satisfies only moment equilibrium. However, not considering shear forces in the General

361 Limit Equilibrium (GLE) terminology mean that lambda (λ) is zero. As a result, the Bishop's

362 Simplified factor of safety falls on the moment curve in Figure 17 where lambda is zero.

363 Janbu's Simplified method also ignores interslice shear forces and only satisfies force

364 equilibrium. The Janbu's Simplified factor of safety consequently falls on the force curve in

365 Figure 17 where λ is zero. The Spencer and Morgenstern-Price (M-P) factors of safety are

366 determined at the point where the two curves cross. At this point the factor of safety satisfies

367 both moment and force equilibrium. Whether the crossover point is the Spencer or M-P factor

368 of safety depends on the interslice force function. Spencer only considered a constant X/E ratio

369 for all slices, which in the GLE formulation corresponds to a constant (horizontal) interslice

370 force function.

371

5. CONCLUSION

373 Liquefaction was suspected as the main cause of the landslide that occurred in Oko area of

374 Anambra State. The results from gradation curve which gave over 80% sand for the samples

375 from Lokoja and Anambra suggested that liquefaction is possible in the area if necessary

376 vibration is generated either from blasting or trucks/vehicular movement. In addition, from the

377 satellite image, the terrain is rugged in nature and the slope is steep which can facilitate

378 landslide by gravity. The results from the Atterberg limits show mixed values and therefore

379 making it difficult to use the values in the liquefaction interpretation. The liquefaction effects

380 on the soils has been proven to be one of the strong factors in the failure of these sites especially

381 the site at Oko area in Anambra State. With necessary vibration, liquefaction in those sites

382 could be a serious issues because of the composition of the grains (70-90%) sand and low

383 plasticity. The FOS values for Anambra 1-2, Lokoja 1-3, Eyenkorin 1-2 and Asa Dam 1-2 are

384 1.452, 1.946, 2.196 and 2.488, respectively. These values indicate stability but care must be

385 taken as the condition at the site shows that the slope is in its state of impending failure.

386 Optimisation effects was also tried and the results shown that loads on these slope might

387 contribute to the failure of the slopes.

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Natural Hazards
and Earth System
Sciences
Discussions

AUTHOR CONTRIBUTION

Dr Omoniyi Ige supervised the field work and writing of the manuscript. Tolulope Oyeleke and Temitope Oloniniyi carried out the fieldwork. Christopher Baiyegunhi carried out data processing and writing of the manuscript, while Luzuko Sigabi was involved in data processing and correction of manuscript.

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CONFLICT OF INTERESTS

The authors declared that there are no conflicts of interest concerning the publication of this research work.

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and Earth System
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512   Table 1: Causes of landslides (After McCall, 1992).

External Causes	Internal Causes
1. Geometrical change • Height • Gradient • Slope length	1. Progressive Failure (internal response to unloading) • Expansion and swelling • Fissuring • Straining, softening • Stress concentration
2. Loading • Natural • Man-induced	2. Weathering • Physical property changes • Chemical changes
3. Unloading • Natural • Man-induced	3. Seepage erosion • Removal of cements • Removal of fine particles
4. Vibrations • Single • Multiple/Continuous	4. Water regime change • Saturation • Rise in water table • Excess pressures • Draw down

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515   Table 2: Summary of the grain size analysis and soil classification.

Sample ID	S.G	% clay	% silt	% fine	% sand	% gravel	Cu	Cc	Group symbol
Lokoja 1	2.53	2	2	4	96	0	5	1.19	SW
Lokoja 2	2.78	8	10	18	80	2	12	0.0005	SM
Lokoja 3	2.56	12	8	20	72	2	389	81	SM
Anambra 1	2.58	6	5	11	83	6	86	38	SM
Anambra 2	2.47	12	18	30	63	7	267	6	SM
Eyenkorin 1	2.67	18	35	55	31	16	220	7	CL
Eyenkorin 2	2.68	22	39	61	31	8	33	0.42	CL
Asa Dam 1	2.65	32	18	50	30	20	2000	0.035	CL
Asa Dam 2	2.65	34	26	60	36	4	275	0.074	CL

516   Key: SW and SM = Poorly Graded Sand, CL= Well Graded Sandy silt.

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518   Table 3: Plasticity values of the soil samples.

Sample ID	Depth (m)	Moisture content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
Lokoja 1	8.6	1.6	23.0	15.0	8.0
Lokoja 2	12.5	0.8	28.0	24.0	4.0
Lokoja 3	17.0	9.8	27.0	18.0	9.0
Anambra 1	10.2	0.8	21.0	16.5	4.5
Anambra 2	12.0	0.8	23.0	19.45	3.55
Eyenkorin 1	2.3	1.3	41.0	21.3	19.7
Eyenkorin 2	3.0	1.8	44.5	15.5	29.0
Asa Dam 1	2.5	2.5	40.0	17.5	22.5
Asa Dam 2	3.4	3.3	43.0	22.5	19.5

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520   Table 4: Compaction characteristics and ratings of unified soil classification classes for soil
521   construction (ASTM, 1557-91).

Visual Description	Maximum Dry-Weight Range (g/cm^3)	Optimum Moisture Range (%)	Anticipated Embankment Performance	Value as Subgrade material	Value as Base Course
Granular material	2.00-2.27	7-15	Good to excellent	Excellent	Good
Granular material with soil	1.76-2.16	9-18	Fair to excellent	Good	Fair to poor
Fine sand and sand	1.76-1.84	9-15	Fair to good	Good to fair	Poor
Sandy silts and silts	1.52-2.08	10-20	Poor to good	Fair to poor	Not suitable
Elastic silts and clays	1.36-1.60	20-35	unsatisfactory	Poor	Not suitable
Silty-clay	1.52-1.92	10-30	Poor to good	Fair to poor	Not suitable
Elastic silty clay	1.36-1.60	20-35	unsatisfactory	Poor to very poor	Not suitable
Clay	90-115	15-30	Poor to fair	Very poor	Not suitable

Natural Hazards
and Earth System
Sciences
Discussions

522   Table 5: Compaction characteristics and ratings of the soil samples based on the unified soil

523   classification classes for soil construction (ASTM, 1557-91).

Sample ID	MDD (g/cm^3)	OMC (%)	Anticipated Embankment Performance	Value as Subgrade material	Value as Base Course
Lokoja 1	1.73	8.5	Poor	Fair	Good
Lokoja 2	1.80	8.0	Fair	Good	Poor
Lokoja 3	1.76	12.3	Fair	Good	Poor
Anambra 1	1.76	10.1	Fair	Good	Poor
Anambra 2	1.64	8.8	Poor	Good	Fair
Eyenkorin 1	1.84	14.0	Fair	Good	Fair
Eyenkorin 2	1.88	13.0	Fair	Good	Fair
Asa Dam 1	1.85	13.4	Fair	Good	Fair
Asa Dam 2	1.87	12.2	Fair	Good	Fair

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526   Table 6: The summary of the shear strength parameters and interpretation.

Sample ID	Cohesion, c (kPa)	Angle of internal friction, φ	Interpretation
Lokoja 1	48	28.5^0	Loose sand: rounded grains
Lokoja 2	70	29^0	Loose sand: rounded grains
Lokoja 3	65	24^0	Loose sand: rounded grains
Anambra 1	50	29^0	Loose sand: rounded grains
Anambra 2	55	28^0	Loose sand: rounded grains
Eyenkorin 1	60	23^0	Loose sand: rounded grains
Eyenkorin 2	80	26^0	Loose sand: rounded grains
Asa Dam 1	40	35^0	Medium sand: rounded grains
Asa Dam 2	60	32^0	Medium sand: rounded grains

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531   Table 7: Coefficient of permeability for the samples and their interpretations.

Sample ID	K (mm/sec)	K (cm/sec)	Interpretation	Drainage condition
Lokoja 1	1.18×10^{-3}	1.18×10^{-4}	Clean sand and gravel mixtures	Good
Lokoja 2	9.77×10^{-4}	9.77×10^{-5}	Very fine sand	Poor
Lokoja 3	3.61×10^{-4}	3.61×10^{-5}	Very fine sand	Poor
Anambra 1	8.71×10^{-4}	8.71×10^{-5}	Very fine sand	Poor
Anambra 2	7.80×10^{-4}	7.80×10^{-5}	Very fine sand	Poor
Eyenkorin 1	1.18×10^{-3}	1.18×10^{-3}	Clean sand and gravel mixtures	Good
Eyenkorin 2	1.18×10^{-3}	1.18×10^{-3}	Clean sand and gravel mixtures	Good
Asa Dam 1	1.18×10^{-3}	1.18×10^{-3}	Clean sand and gravel mixtures	Good
Asa Dam 2	1.18×10^{-3}	1.18×10^{-3}	Clean sand and gravel mixtures	Good

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535   Table 8: Grain size distribution summary showing the % of the grain fractions.

Sample ID	Specific gravity	% clay	% silt	% fines	% sand	% gravel	Classification after Tsuchiba (1970)
Lokoja 1	2.53	2	2	4	96	0	Liquefiable
Lokoja 2	2.78	8	10	18	80	2	Liquefiable
Lokoja 3	2.56	12	8	20	72	2	Liquefiable
Anambra 1	2.58	6	5	11	83	6	Liquefiable
Anambra 2	2.47	12	18	30	63	7	Potentially liquefiable
Eyenkorin 1	2.67	18	35	55	31	16	Potentially liquefiable
Eyenkorin 2	2.68	22	39	61	31	8	Potentially liquefiable
Asa Dam 1	2.65	32	18	50	30	20	Potentially liquefiable
Asa Dam 2	2.65	34	26	60	36	4	Potentially liquefiable

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542 Table 9: Input parameters used in SLOPE/W analyses.

Location	Soil layer	C (kPa)	Phi (°)	γ (kN/m^3)
Oko1 (Anambra state)	Upper	50	29	16.30
Oko 2 (Anambra state)	Lower	55	28	15.70
Lokoja 1 (Kogi state)	Upper	48	28.5	16.40
Lokoja 2 (Kogi state)	Middle	70	29	17.10
Lokoja 3 (Kogi state)	Lower	65	24	15.50
Eyenkorin 1 (Kwara state)	Upper	70	26	14.21
Eyenkorin 2 (Kwara state)	Lower	90	27	14.70
Asa Dam 1 (Kwara state)	Upper	40	35	14.70
Asa Dam 2 (Kwara state)	Lower	60	32	15.48

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547 Table 10: Summary of the factor of safety (FOS) for the soil samples.

	O.D		B.M		J.M		M.P		FOS
	M	F	M	F	M	F	M	F	M
Anambra 1 and 2	1.366		1.396	-	-	1.434	1.452	1.462	1.452
Lokoja 1 and 2	1.885		1.951	-	-	1.883	1.946	1.950	1.946
Eyenkorin 1 and 2	2.430		2.489	-	-	2.462	2.488	2.485	2.196
Asa Dam 1 and 2	2.118		2.200	-	-	2.112	2.196	2.201	2.488

548 M = Moment, F= Force, O.D = Ordinary method, B.M = Bishop method, J.M = Janbu method,

549 M.P = Morgestein price.

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Sciences
Discussions

562   Table 11: Summary of the reviewed literatures on slope stability and landslide.

Authors	Locality	Methodology	Research Interest	Findings
Okogbue, 1992	Nanka, Anambra State	Geotechnical studies	Causes of 1988 Nanka landslide	Over consolidation of very highly plastic mudstone layer
Ashiru et al., 2014	Nasarawa Northeastern Nigeria	3 LEMs: Stability chart, SLOPE/W and traditional methods	Stability of slopes on Black Cotton Soils	Dry- stable Wet- unstable
Ako et al., 2014	Nkomon District Benue State	Interview, Field observation and Laboratory studies	Causes of Nov. 13th, 2010 landslide in Azenge Mountain in Imande Ukusu, Benue State	Highly fractured gneisses, granite and basaltic rocks and 2 grains type. Also, other causes are geological, morphological and human factors contributed
Ogbonnaya, 2015	Southeastern Nigeria	Geotechnical studies	Differentiation between landslides from sedimentary and metamorphic terrain	Sedimentary terrain- shallow volume movement, material slumps and short run out Metamorphic terrain- complex translational and rotational landslide
This study	Oko in Anambra state, Lokoja in Kogi state, and Asa dam and Eyenkorin both in Kwara state, Nigeria	Field observation, geotechnical studies and SLOPE/W	Evaluating liquefaction potential, causes of landslide and degree of slope stability	Soil samples from Anambra and Kogi are potentially liquefiable, whereas those from Kwara are not susceptible to liquefaction. The factor of safety (FOS) values shows that the slope is in its state of impending failure. Liquefaction is inferred as the main cause of the landslide in the areas.

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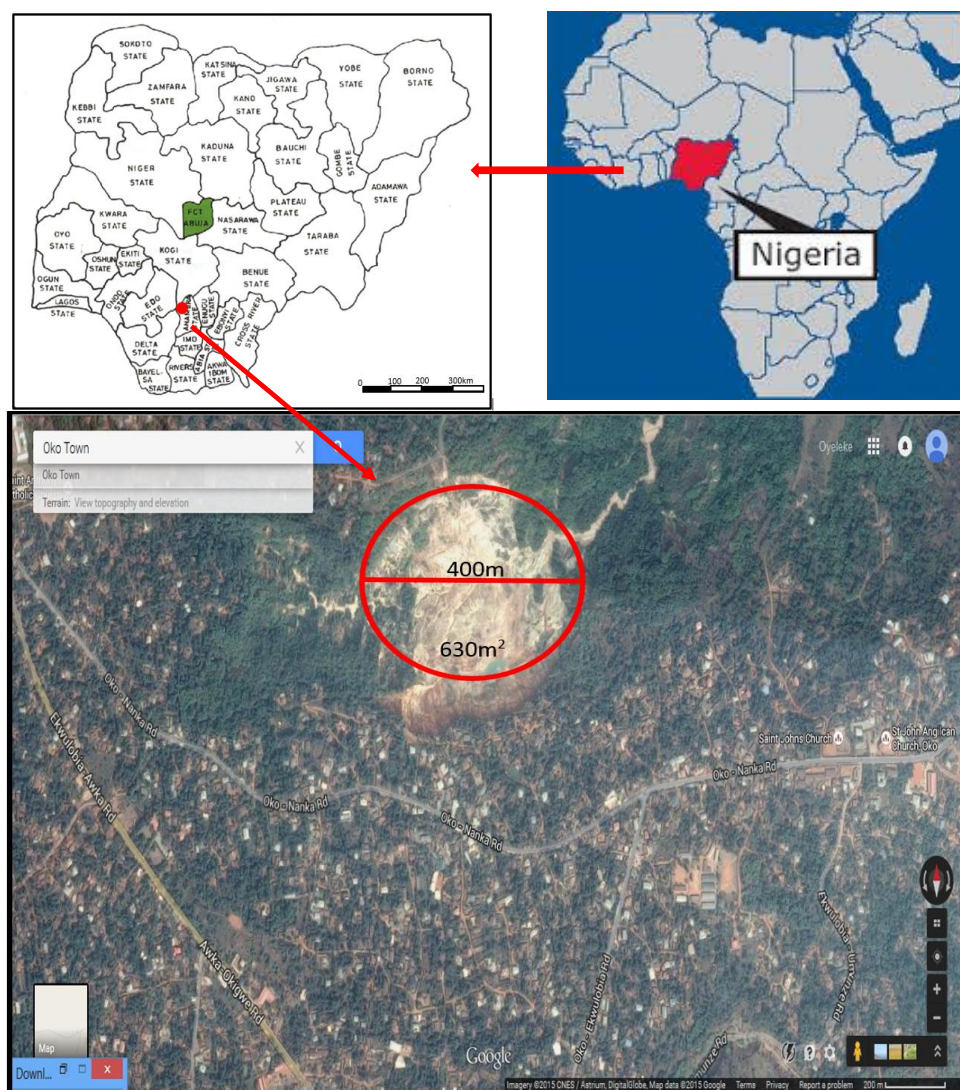
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565 Figure 1: Satellite image of Oko area in Anambra State showing the landslide region (Red
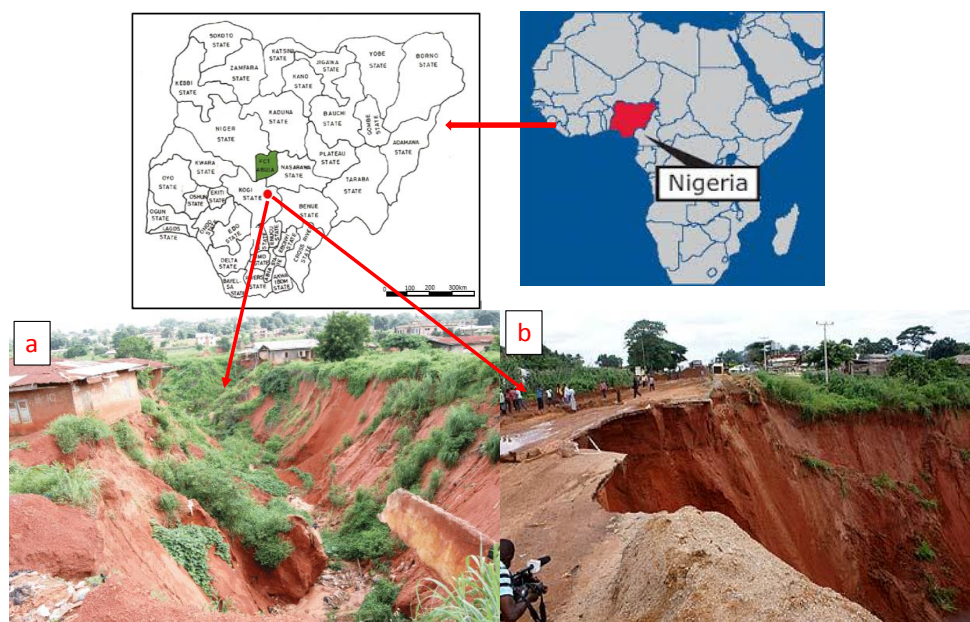
566 circle: Landslide affected area).

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and Earth System
Sciences
Discussions

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Figure 2: Structural failure in Lokoja (Kogi State) due to slope failure.

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Sciences
Discussions
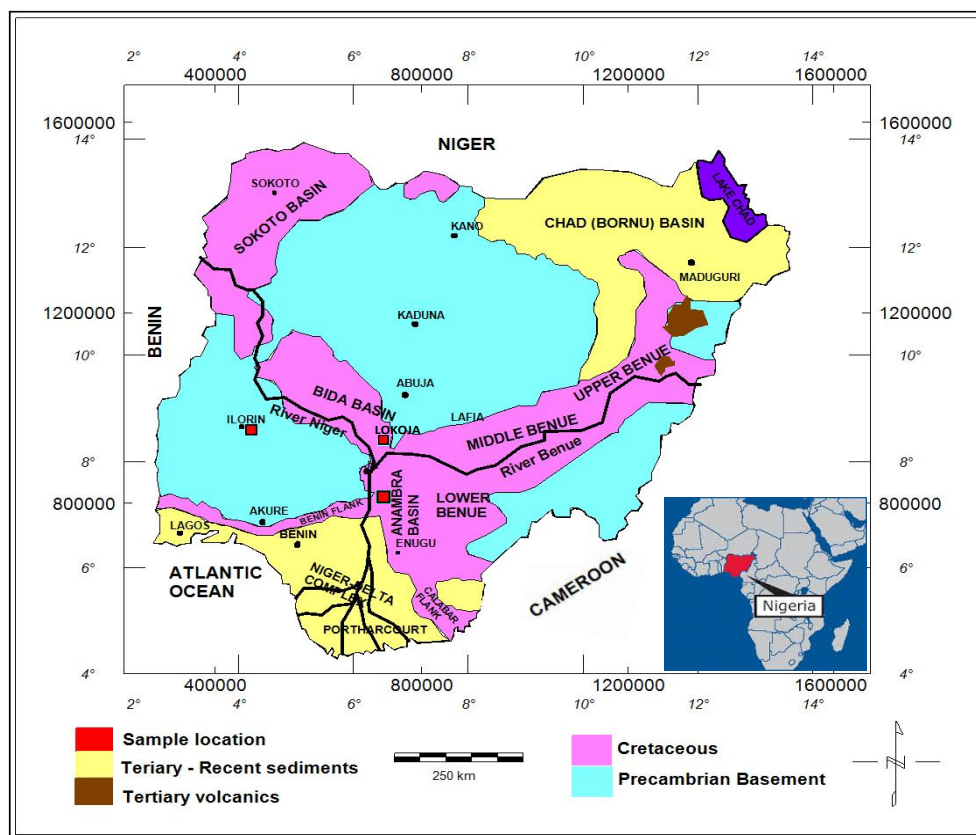
Figure 3: Geological map of Nigeria showing the major geological components and sampling location (After Obaje, 2009).

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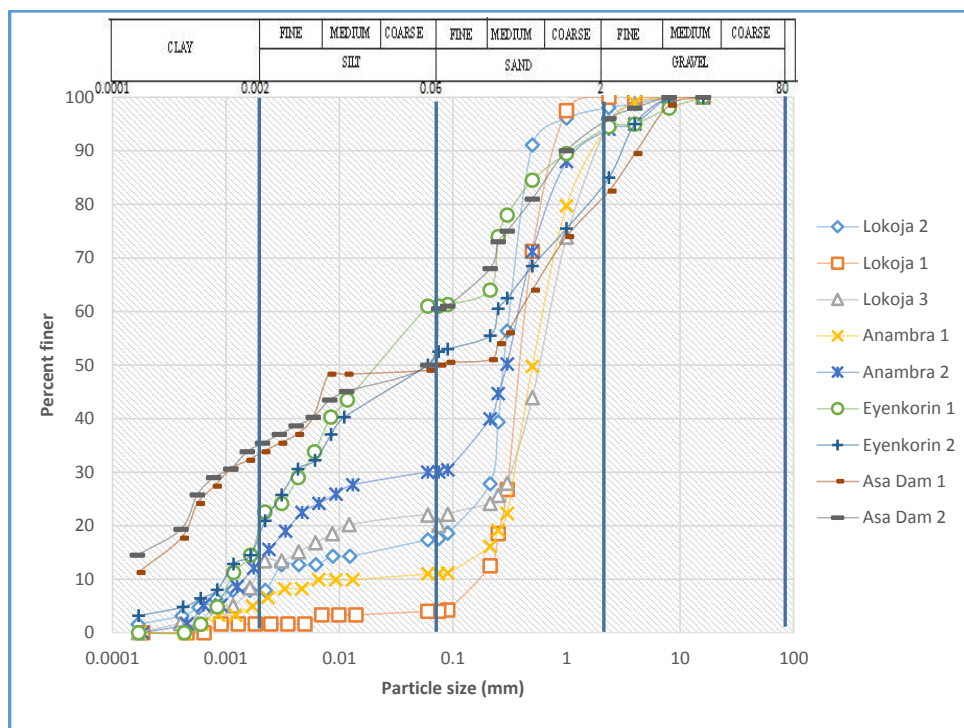
591   Figure 4: Grain size distribution curves for the soil samples.

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Sciences

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Major division		Group symbol	Criteria
$F_{200} < 50$	Gravels	GW	$F_{200} < 5$; $C_u \geq 4$; $1 \leq C_z \leq 3$
		GP	$F_{200} < 5$; Not meeting the GW criteria of C_u and C_z
	$\dfrac{R_4}{R_{200}} > 0.5$	GM	$F_{200} > 12$; $PI < 4$ or plots *below* A-line (Fig. 4.2)
		GC	$F_{200} > 12$; $PI > 7$ and plots *on or above* A-line (Fig. 4.2)
		GM-GC	$F_{200} > 12$; PI plots in the hatched area (Fig. 4.2)
		GW-GM	$5 \leq F_{200} \leq 12$; satisfies C_u and C_z criteria of GW and meets the PI criteria for GM
		GW-GC	$5 \leq F_{200} \leq 12$; satisfies C_u and C_z criteria of GW and meets the PI criteria for GC
		GP-GM	$5 \leq F_{200} \leq 12$; does not satisfy C_u and C_z criteria of GW and meets the PI criteria for GM
		GP-GC	$5 \leq F_{200} \leq 12$; does not satisfy C_u and C_z criteria of GW and meets the PI criteria for GC
	Sands	SW	$F_{200} < 5$; $C_u \geq 6$; $1 \leq C_z \leq 3$
		SP	$F_{200} < 5$; Not meeting the SW criteria of C_u and C_z
	$\dfrac{R_4}{R_{200}} \leq 0.5$	SM	$F_{200} > 12$; $PI < 4$ or plots *below* A-line (Fig. 4.2)
		SC	$F_{200} > 12$; $PI > 7$ and plots *on or above* A-line (Fig. 4.2)
		SM-SC	$F_{200} > 12$; PI plots in the hatched area (Fig. 4.2)
		SW-SM	$5 \leq F_{200} \leq 12$; satisfies C_u and C_z criteria of SW and meets the PI criteria for SM
		SW-SC	$5 \leq F_{200} \leq 12$; satisfies C_u and C_z criteria of SW and meets the PI criteria for SC
		SP-SM	$5 \leq F_{200} \leq 12$; does not satisfy C_u and C_z criteria of SW and meets the PI criteria for SM
		SP-SC	$5 \leq F_{200} \leq 12$; does not satisfy C_u and C_z criteria of SW and meets the PI criteria for SC
$F_{200} \geq 50$	Silts and Clays $LL < 50$	ML	$PI < 4$ or plots *below* A-line (Fig. 4.2)
		CL	$PI > 7$ and plots *on or above* A-line (Fig. 4.2)
		CL-ML	PI plots in the hatched area (Fig. 4.2)
		OL	$\dfrac{LL_{(oven\ dried)}}{LL_{(not\ dried)}} < 0.75$; PI plots in the OL area in Fig. 4.2
	Silts and Clays $LL \geq 50$	MH	PI plots *below* A-line (Fig. 4.2)
		CH	PI plots *on or above* A-line (Fig. 4.2)
		OH	$\dfrac{LL_{(oven\ dried)}}{LL_{(not\ dried)}} < 0.75$; PI plots in the OH area in Fig. 4.2
	Highly organic matter	Pt	Peat

Note: C_u = uniformity coefficient = $\dfrac{D_{60}}{D_{10}}$; C_z = coefficient of gradation = $\dfrac{D_{30}^2}{D_{60} \times D_{10}}$

LL = liquid limit on minus 40 sieve fraction

PI = plasticity index on minus 40 sieve fraction

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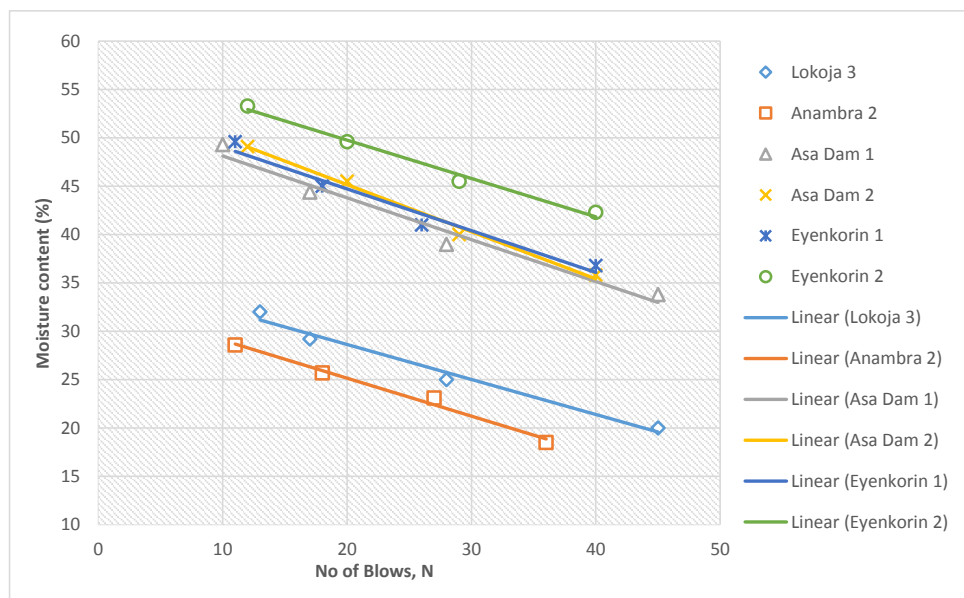598   Figure 5: Unified Classification System (Based on materials passing 75mm sieve) (Based on

599   ASTM-2487).

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604   Figure 6: Plot of Moisture Content against No of blows, N for the soil samples.
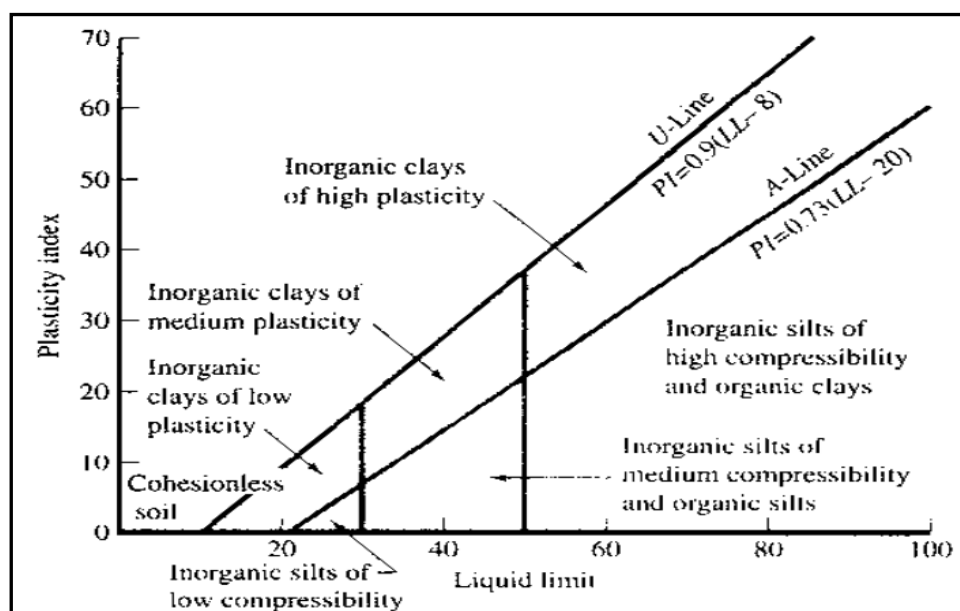
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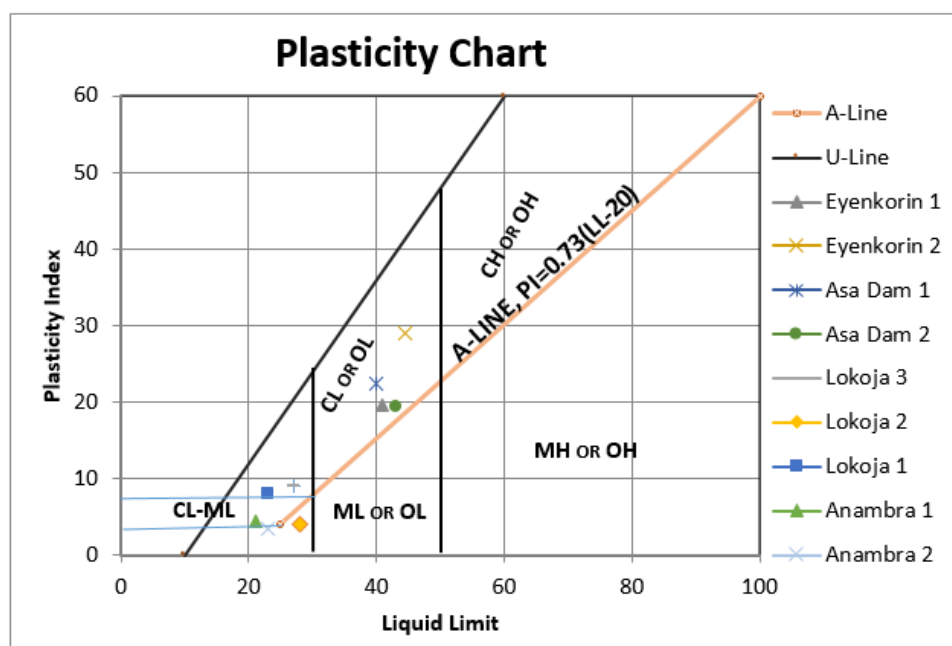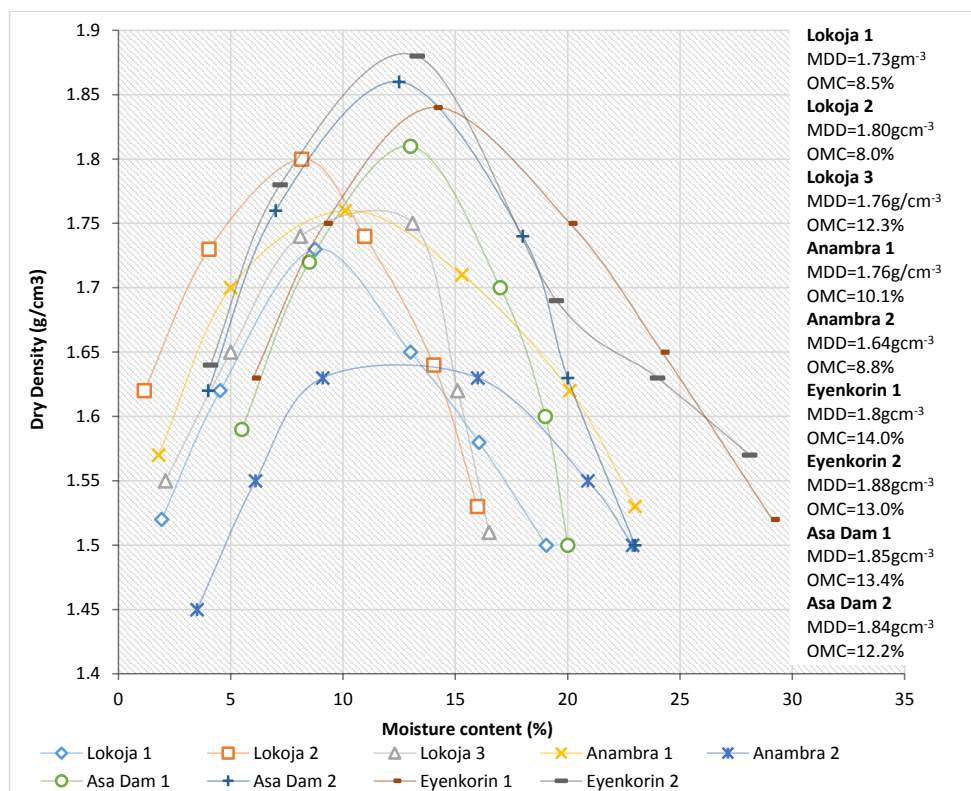Figure 7: Standard plot of plasticity index against liquid limit (AASHTO SOIL classification system).

Figure 8: Plasticity chart plot for fine grained soil and fine fraction in coarse grained soil.

Natural Hazards
and Earth System
Sciences

Discussions

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619   Figure 9: Compaction curves showing MDD and OMC of the soil samples.

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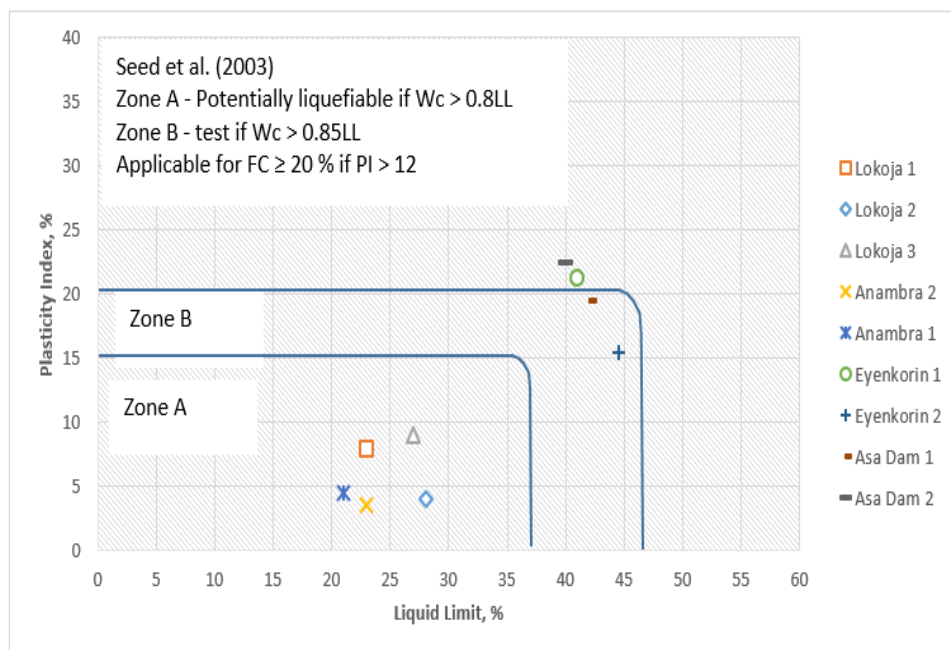
Figure 10: Plasticity chart showing the recommendations by Seed et al. (2003) regarding the
assessment of "liquefiable" soil types and the Atterberg Limits of fine-grained soils.

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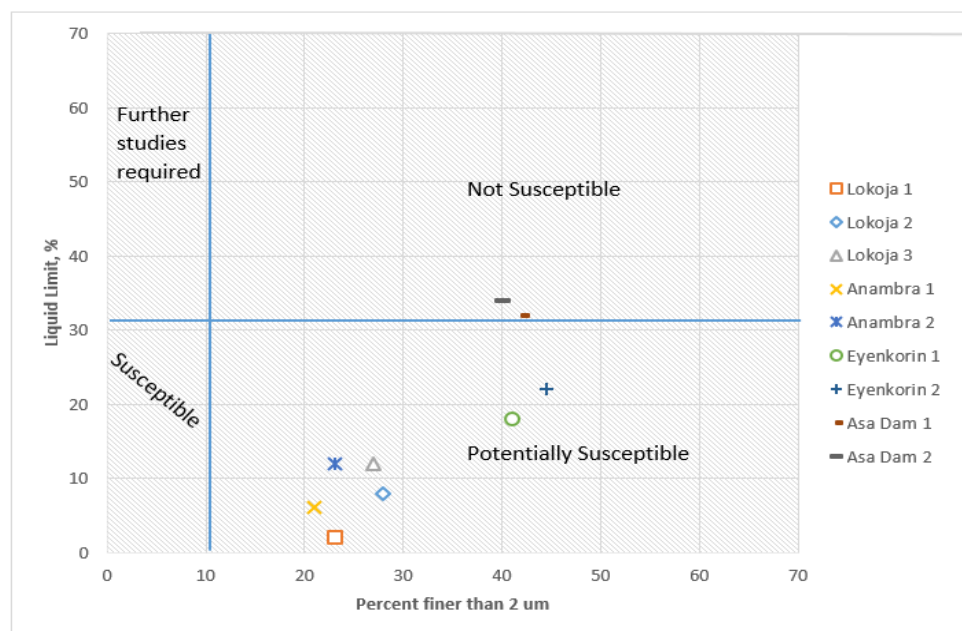
631   Figure 11: Liquefaction screening criteria after Andrews and Martin (2000).

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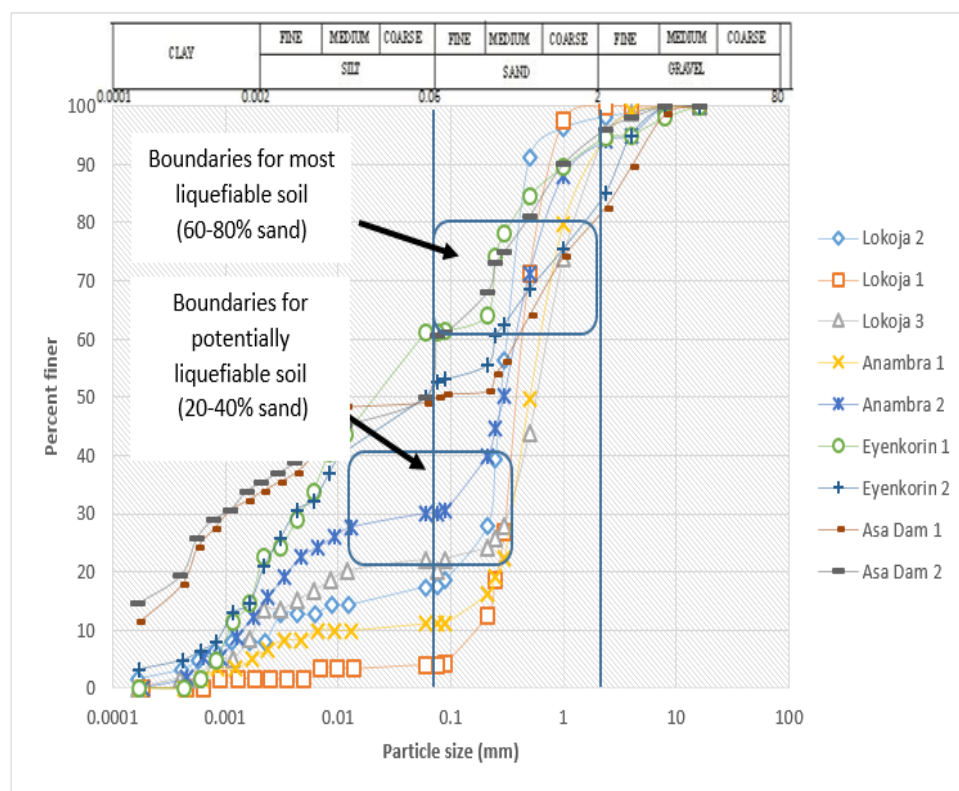
Figure 12: Boundaries in the gradation curves for soils susceptible to liquefaction (After
Tsuchida, 1970).

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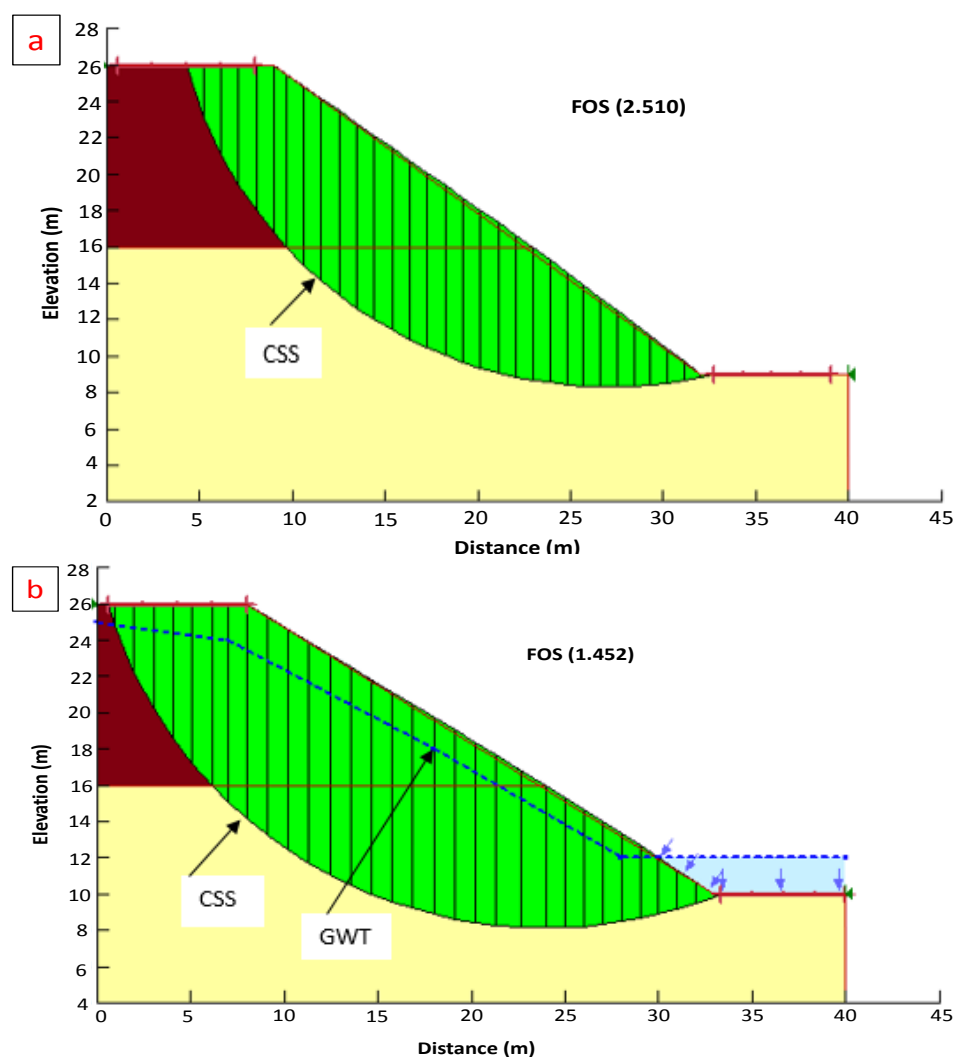
641   Figure 13: Non-optimised (a) dry and (b) wet slopes for Oko 1 and 2 (Anambra state).

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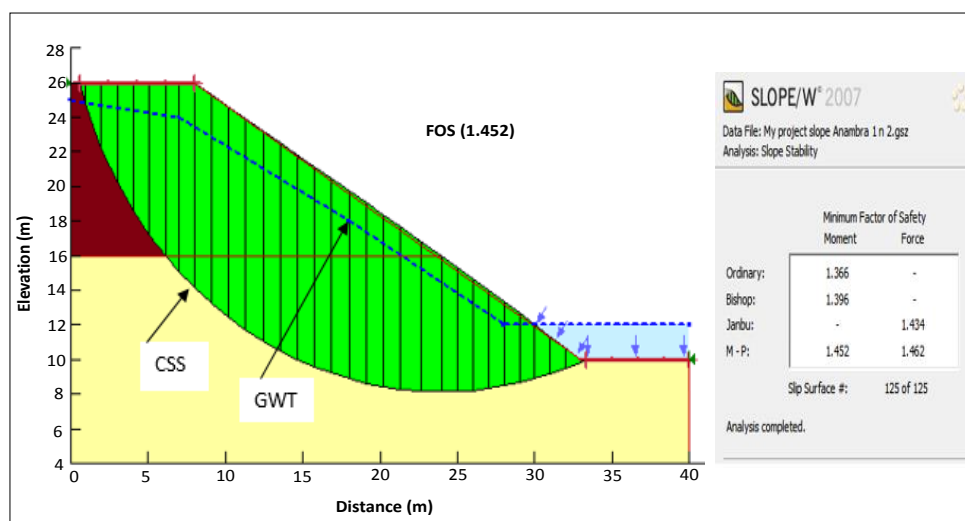
Figure 14: Non-optimised wet slope and factor of safety for Oko 1 and 2 (Anambra state).
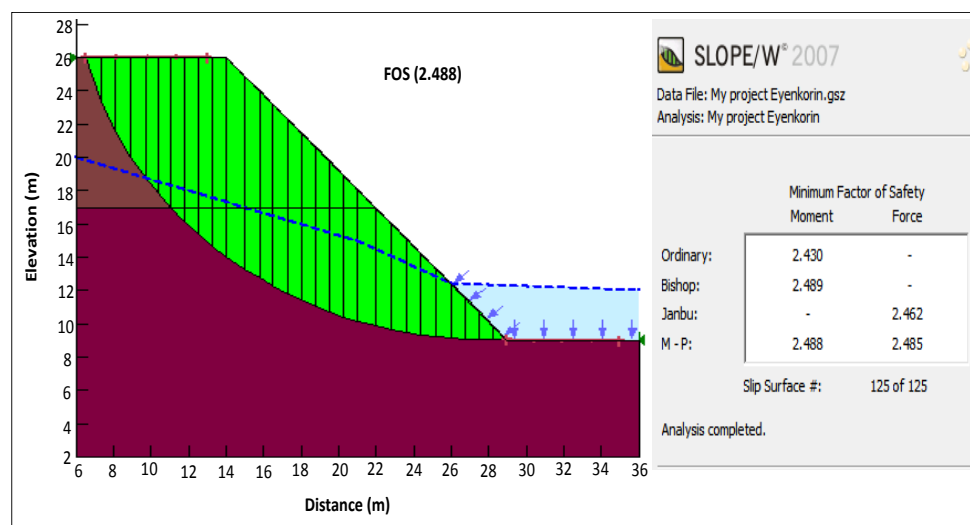
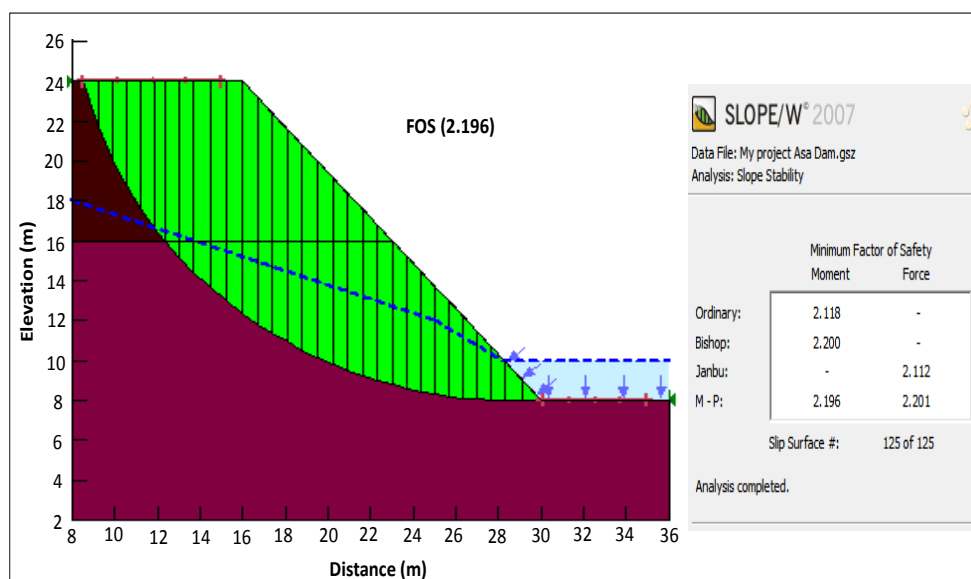Figure 15: Non-optimised wet slope model and factor of safety for Eyenkorin 1 and 2 (Kwara).

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652   Figure 16: Non-optimised wet slope model and factor of safety for Asa Dam 1 and 2 (Kwara).
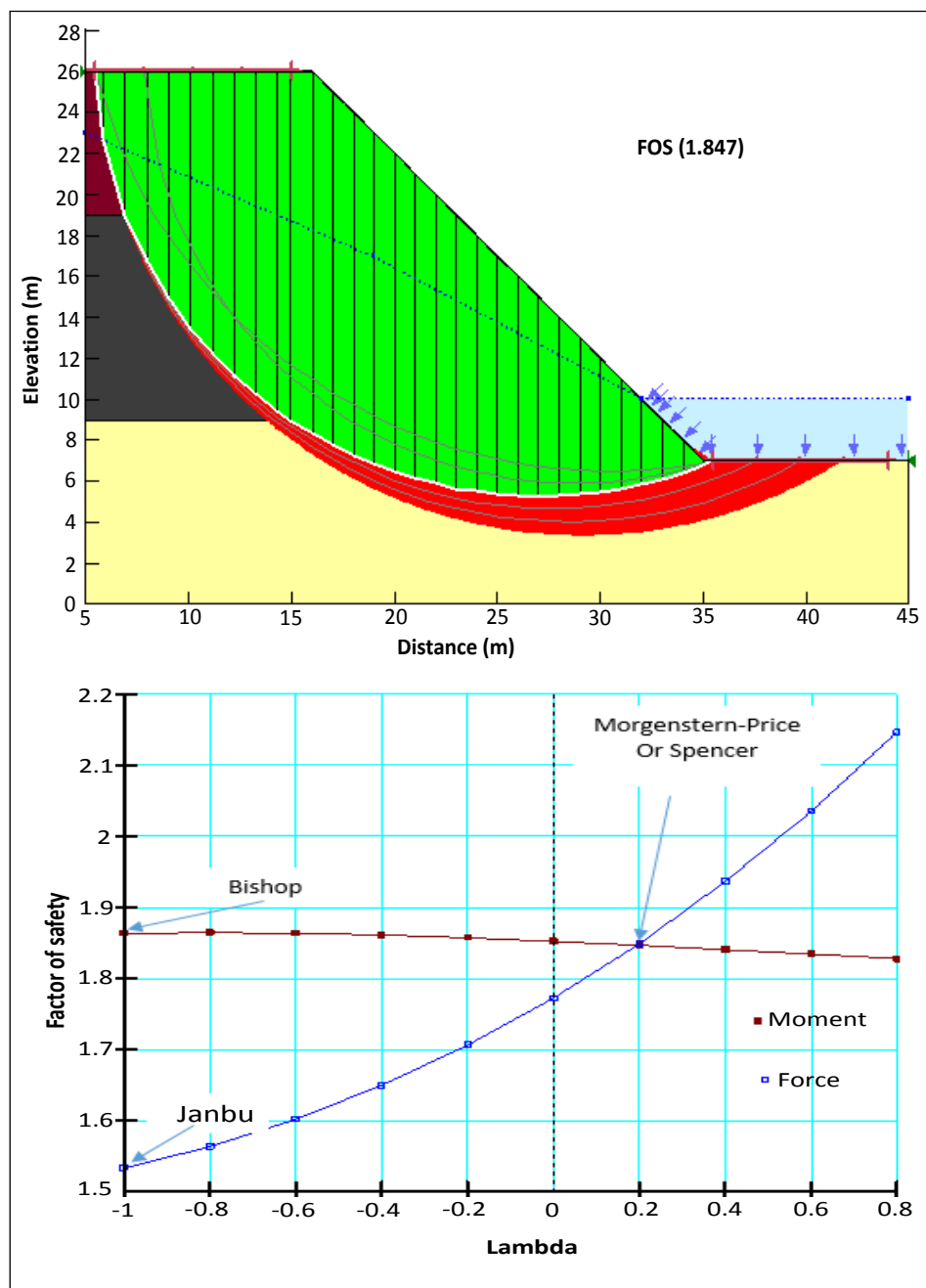
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Figure 17: Critical slip surfaces and factor of safety from limit equilibrium analysis using

SLOPE/W for 3 soil layers in Agbaja Hill, Lokoja (Kogi state), and plot of factor of safety
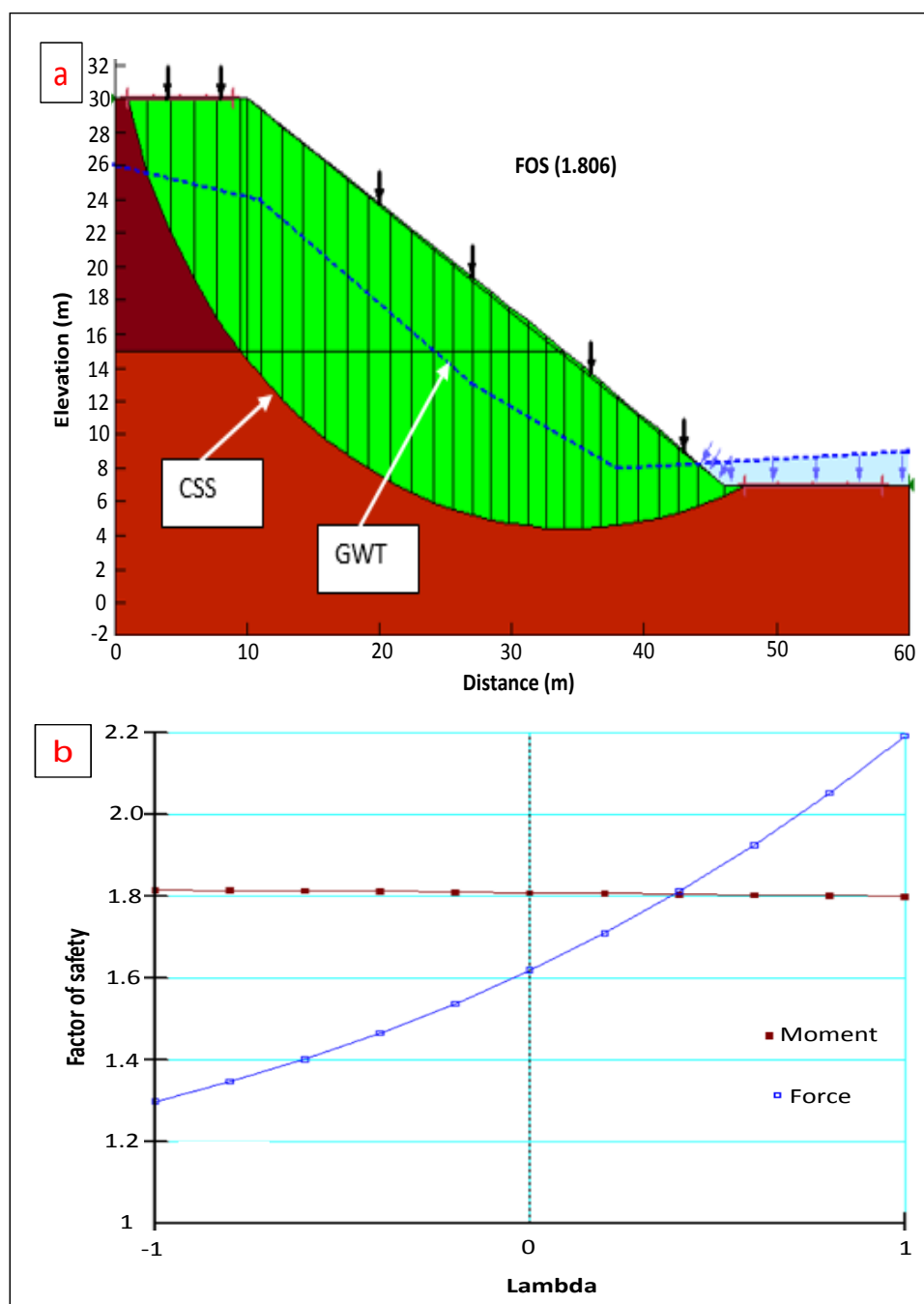
versus lambda, λ (non-optimized).

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Figure 18: Showing (a) Optimised slope with point load of 40kPa, (b) Plot of FOS versus

lambda, λ (optimised) with external loads of 40 kPa.

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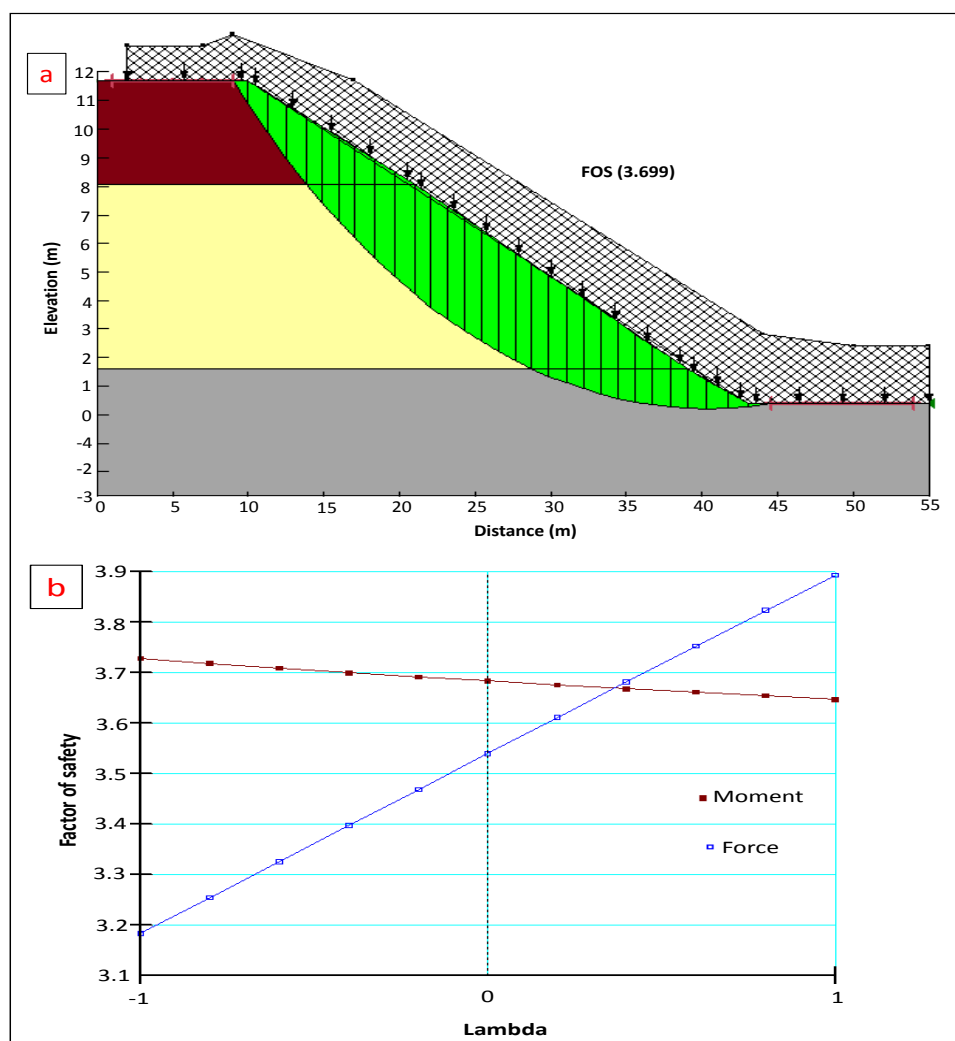
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665 Figure 19: Showing (a) Optimised slope with reinforcement load of 50 kPa, (b) Plot of FOS

666 versus lambda, λ (optimised) with reinforcement load of 50 kPa.

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