Crocker Formation	Massive Sandstone (Facies B)	100 – 1,000	Light grey to cream colour, medium to course - grained and some time pebbly. It is highly folded, faulted, jointed, fractured occasionally cavernous, surfically oxidized and exhibits spheriodal weathering.	Importance to groundwater.	Good site for heavy structures with careful investigation. Stable from mass movement and provide some modification like closing of continuous structure.	Quarzarenite and Sublitharenite (Immature)	, Q R U J D Q L F 6 W U X F W X U H V 3 U H ± G H S R V L W L R Q D O 1. Climbing Ripple 2. Ripple Marks 3. Tool Marks 4. Scour Marks 6 \ Q ± G H S R V L W L R Q D O 1. Bedding 2. Lamination 3. Graded bedding 4. Cross bedding 5. Convolute lamination 3 R V W ± G H S R V L W L R Q D O 1. Slump structures 2. Soft sediment fault 3. Lutite clasts 4. Load structures 5. Ball and pillow structures 6. Water escapes structures 2 U J D Q L F 6 W U X F W X U H V 3 O D Q W U H P D L Q V 7 U D F H I R V V L O 3 U H ± G H S R V L W L R Q D O W U D F H V 1. *Paleodictyon minimum* Cosmorhaphe sinuosa 3 R V W ± G H S R V L W L R Q D O W U D F H V 1. Post – depositional burrow type 1 2. Post – depositional burrow type 2 3. Post – depositional burrow type 3 4. Post – depositional burrow type 4 5. Post – depositional burrow type 5	1. Bathysiphon spp 2. Glomospira sp 3. Cyclammina cancellata (Brady) 4. Haplophragmoideswalteri (Grzybowski) 5. Trochamminoides sp.	Grain flow deposits	Upper fan to Middle fan
	Thick bedded Sandstone (Facies C)	10 – 50 (Sandstone) 1 – 15 (Shale)	It is a sequence of interlayering of permeable sandstone with impermeable shale. The permeability of this unit is quite variable.	Groundwater in this unit tends to be under semi-confined to confined system. Little importance to groundwater provides some water but not enough for groundwater development.	Dangerous site for heavy structures and high potential for mass movement.	Moderately well sorted to moderately sorted (Mature and Immature)			High density, high velocity turbidity currents (Proximal turbidites)	Outer fan localized in channels and in the prograding depositional lobes.
	Thin bedded Sandstone (Facies D/E)	3 – 5 (Sandstone) 5 – 10 (Shale)							Waning or low velocity turbidity currents (Distal turbidites)	Middle to outer fan and particularly basin plain
	Slumped (Facies F)	-	This unit is composed of two types of shale red and grey. It is a sequence of alteration of shale with siltstone of very fine.	It has no significant to groundwater development due to its impermeable characteristic.	Very dangerous site for heavy structures and the main causes of mass movement.	-			Turbidite and debris flow sedimentation	Shelf to lower slope and partly in the channels of inner fan, middle fan and basin plain
	Red / Grey Shale (Facies G)	1 – 2 (Siltstone) 10 – 50 (Mudstone)				-			Debris flow	Plain basin, middle fan and slope region

4. SLOPE STABILITY ASSESSMENT

In this study, a total of 28 selected critical slope failures were studied and classified into two main groups: rock slope and soil slope (Figure 2). Failures in soil slopes (including embankments) are 18 (64 %) (Figure 3) whereas 10 of all failures (36 %) of rock slope (Figure 4). Soil slope failures normally involved large volumes of failed material as compared much rock slopes, where the failures are mostly small. Of the 18 failures in soil slopes, 6 (33 %) are embankment failures making them 21 % of all types of failure.

Results of a detailed analysis of soil slope stability are presented in Table 2. Considering cut slopes, all the major lithologies are involved showing that this type of failure is mostly controlled by lithology. The failure volume scale involved generally small to large in size possibly endangering road users. In term of weathering grades, the materials that underwent failure were in the ranges from grade IV to VI (Figures 5 to 8). Intense water runoff and emitted water seepage is the main factor causing failure with the depth of weathering influencing the volume of material that fails. It appears that grade IV to grade V materials actually failed with the overlying grade VI material sliding or slumping down together with this material during failure. Physical and mechanical properties of 72 soil samples indicated that the failure materials mainly consist of poorly graded to well graded materials of sandy clay and clayey silt soils, which characterized by low to intermediate plasticity content (9 % to 28 %), containing of inactive to normal clay (0.34 to 1.45), very high to medium degree of swelling (5.63 to 13.85), variable low to high water content (4 % to 25 %), specific gravity ranges from 2.57 to 2.80, low permeability (9.66 X 10^{-3} to 3.32 X 10^{-3} cm/s), friction angle (ϕ) ranges from 7.70° to 29.50° and cohesion (C) ranges from 3.20 KPa to 17.27 KPa. Soil slopes stability analysis indicates that the factor of safety value as unsafe (0.76 to 0.94). The presence of ground water, slope angle, removal of vegetation cover, lack of proper drainage system, artificial changing, climatological setting, geological characteristics and material characteristics are additional factors contributing to the failures.

Table 3 shows the results of a detailed analysis of rock slope failures. Although rock slope failures contributed only 36 % (10 failures) of the total failures, they involved large volume of weathered and brecciated rocks (Figures 9 & 10). The main factor contributing to rock slope failures was the orientation and intensity of discontinuity planes. That is why rock slope failures occur most frequently along the highway on slate, phyllites, meta-sediment and sedimentary rocks, which were highly brecciated and fractured. Generally the failed material underwent only moderately to completely weathering (grade III to V). The rock properties characterization for 10 rock samples indicated that point load strength index ranges from 0.35 MPa to 0.52 MPa (moderately week). Kinematics slope analyses indicates that the variable potential of circular, planar, wedges and toppling failures modes as well as the combination of more than one mode of aforementioned failure. Rock slopes stability analysis indicates that the factor of safety value as unsafe (0.52 to 0.96). Other factors contributing to rock slope failure are the presence of groundwater, climatological setting, joints filling material, high degree of rock fracturing due to shearing, steep of slope angle, high intensive of faulting and folding activities and locating at the fault zones area.

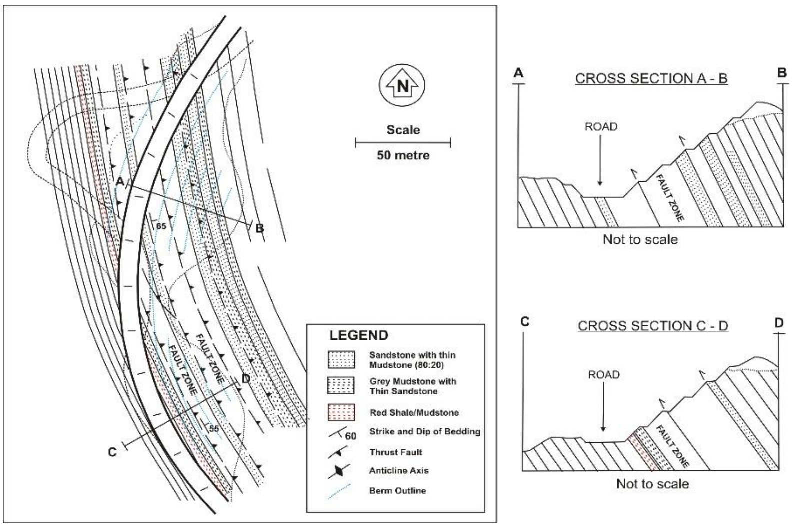

Figure 3: Sketch of slope failure showing the failure movement are starting from the hill side to the road and/or village sides through the development of water runoff (Location: KM 134 (S8)) [24]

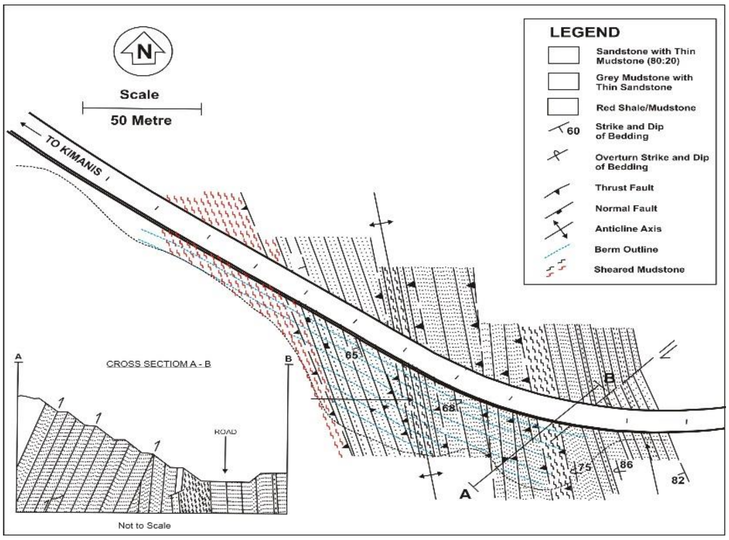

Figure 4: Sketch of slope failure showing the movement pattern is to collapse at the head, fall rapidly within narrow tracks, finally dispersing across the accumulation talus deposits (Location: KM 156 (R8)) [24]

Table 2: Analysis results of soil slope failures

Type of failure	**Shallow slide (T1 –a)**					**Deep slide (T1 – b)**			
Location (km)	KM 110	KM 113	KM 117	KM 120	KM 122	KM 129	KM 130	KM 134	KM 138
Slope	S1	S2	S3	S4	S5	S6	S7	S8	S9
	Crocker Formation	Trusmadi Formation	Trusmadi Formation	Trusmadi Formation	Trusmadi Formation	Trusmadi Formation	Trusmadi Formation	Crocker Formation	Trusmadi Formation
Lithology	Interbedded Sandstone & Shale	Sub-Phyllite	Slate	Sub-Phyllite	Slate	Sub-Phyllite	Sub-Phyllite	Interbedded Sandstone & Shale	Slate
Weathering grade	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI
Volume (1)	Large	Medium	Large	Large	Small	Large	Medium	Large	Medium
Sand (%)	63 – 65	20 – 23	48 – 51	45 – 48	21 – 24	46 – 50	44 – 45	59 – 61	22 – 24
Silt (%)	5 – 12	52 – 55	18 – 22	13 – 16	54 – 58	18 – 20	16 – 19	6 – 10	13 – 14
Clay (%)	32 – 36	20 – 22	26 – 30	38 – 40	20 – 22	30 – 33	32 – 35	30 – 33	76 – 78
Liquid limit (%)	28 – 31	28 – 32	31 – 33	31 – 33	31 – 34	35 – 37	39 – 41	26 – 30	37 – 39
Plastic limit (%)	15 – 18	13 – 15	14 – 16	16 – 19	12 – 14	22 – 25	16 – 19	10 – 14	21 – 23
Plasticity index (%)	12 – 16	15 – 19	17 – 19	15 – 17	19 – 22	13 – 15	20 – 23	12 – 18	15 – 18
Liquidity index (%)	- 0.68 to – 0.60	- 0.35 to - 0.30	0.18 to 0.20	- 0.11 to - 0.09	0.14 to 0.18	- 1.08 to - 1.05	- 0.33 to - 0.25	- 0.02 to - 0.01	- 0.88 to - 0.85
Clay activity	0.47 – 0.50	0.98 – 0.99	0.38 – 0.47	0.41 – 0.45	0.53 – 0.55	0.35 – 0.40	1.00 – 1.11	0.87 – 0.91	0.38 – 0.39
Shrinkage limit (%)	7.51 – 7.95	8.68 – 8.89	8.22 – 10.54	7.28 – 7.55	8.84 – 9.98	6.10 – 7.33	9.16 – 9.86	8.53 – 9.12	5.63 – 6.66
Moisture content (%)	4 – 8	5 – 8	14 – 17	11 – 14	22 – 25	8 – 10	6 – 10	13 – 15	4 – 8
Specific gravity	2.57 – 2.58	2.60 – 2.62	2.65 – 2.68	2.60 – 2.62	2.60 – 2.62	2.64 – 2.65	2.61 – 2.64	2.61 – 2.63	2.66 – 2.68
Permeability (cm/s) (X 10^{-3})	7.83	3.32	8.47	6.39	5.66	7.61	5.60	5.41	8.78
Cohesion, C (kN/m^2)	9.82	5.13	8.53	9.50	7.76	10.36	17.27	11.43	10.40
Friction angle (^{o})	29.50	7.70	20.45	25.50	27.70	18.50	23.70	11.29	24.50
Factor of Safety	0.78	0.65	0.92	0.78	0.88	0.95	0.56	0.85	0.98
Main factors causing failures	SA, W, V, GWL, M, C, G, OBV, DS, EC and AC								

Table 2: (*Cont'd*) Analysis results of soil slope failures

Type of failure	**Multiple Slump (T2-b)**			**Complex failure (Slide Flow) (T5 – a)**			**Complex failure (Slump flow) (T5 – b)**		
Location (km)	KM 140	KM 142	KM 145	KM 147	KM 152	KM 155	KM 158	KM 162	KM 165
Slope	S10	S11	S12	S13	S14	S15	S16	S17	S18
	Trusmadi Formation	Trusmadi Formation	Trusmadi Formation	Trusmadi Formation	Crocker Formation	Trusmadi Formation	Crocker Formation	Trusmadi Formation	Trusmadi Formation
Lithology	Sub-Phyllite	Slate	Slate	Sub-Phyllite	Interbedded Sandstone & Shale	Slate	Shale	Sub-Phyllite	Slate
Weathering grade	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI	IV to VI
Volume (1)	Small	Large	Medium	Large	Large	Medium	Large	Medium	Large
Sand (%)	36 – 39	46 – 47	31 – 33	48 – 51	54 – 58	39 – 42	68 – 70	30 – 33	22 – 26
Silt (%)	22 – 26	10 – 13	9 – 13	7 – 11	21 – 23	18 – 20	12 – 16	6 – 10	10 – 13
Clay (%)	38 – 40	36 – 38	55 – 58	38 – 42	20 – 22	40 – 43	18 – 22	59 – 61	62 – 63
Liquid limit (%)	41 – 44	46 – 49	25 – 29	29 – 32	31 – 33	41 – 43	28 – 30	26 – 30	33 – 38
Plastic limit (%)	22 – 24	19 – 21	15 – 18	13 – 17	13 – 16	23 – 25	16 – 20	10 – 14	16 – 19
Plasticity index (%)	17 – 19	27 – 28	14 – 16	18 – 21	18 – 20	18 – 20	9 – 12	12 – 18	17 – 20
Liquidity index (%)	- 0.85 to - 0.83	- 0.41 to - 0.38	0.09 to 0.15	- 0.26 to - 0.22	- 0.88 to - 0.85	- 0.84 to - 0.78	- 0.62 to - 0.58	- 0.05 to - 0.03	- 0.18 to - 0.14
Clay activity	1.43 – 1.45	0.69 – 0.77	0.42 – 0.47	0.62 – 0.68	0.38 – 0.39	0.43 – 0.49	0.48 – 0.50	0.98 – 1.00	0.46 – 0.52
Shrinkage limit (%)	8.45 – 9.26	12.68 – 13.85	7.98 – 8.33	7.98 – 8.12	5.63 – 6.66	7.98 – 8.65	5.63 – 6.53	8.45 – 8.50	6.34 – 677
Moisture content (%)	7 – 11	6 – 10	10 – 14	9 – 12	4 – 8	9 – 12	7 – 12	20 – 22	12 – 14
Specific gravity	2.62 – 2.69	2.58 – 2.60	2.74 – 2.80	2.60 – 2.62	2.66 – 2.68	2.64 – 2.68	2.72 – 2.77	2.65 – 2.68	2.68 – 2.72
Permeability (cm/s) (X 10^{-3})	5.58	4.62	7.40	7.81	8.78	4.33	9.66	8.54	7.98
Cohesion, C (kN/m^2)	15.47	11.43	3.20	10.40	10.40	12.80	9.62	7.20	12.54
Friction angle (^{o})	22.30	11.29	21.00	24.50	24.50	21.50	21.20	26.30	9.30
Factor of Safety	0.63	0.79	0.91	0.87	0.98	0.58	0.89	0.87	0.89
Main factors causing failures	SA, W, V, GWL, M, C, G, OBV, DS, EC and AC								

Note: (1) Volume: small (10 – 50 m^3), Medium (50 – 500 m^3) and Large (> 500 m^3) and (2) Discontinuity (D), Slope angle (SA), Weathering (W), Vegetation (V), Groundwater level (GWL), Material characteristics (M), Climatological setting (C), Geological characteristics (G), Over burden or vibration (OBV), Drainage system (DS), Embankment construction (EC) and Artificial changing (AC)

Apart from that, fieldwork observation indicates that too many cut and filled slopes was designed does not take into account input or geological interest. For example most of the slopes were designed too steep, lack of monitoring on proper drainage system or slope physical state and also we can found most of the slope cutting surface activities is parallel following to the strike direction of the sandstone bedding orientation. The trend of strike and dip of the sandstone bedding orientation along the highway can be observed in different patterns such low angle dip (030-100/10-20); medium angle dip (220-280/30-50) and high angle dip (320-345/60-70). The slope surface orientation was observed is ranging from 210-330 (dip-direction) and 35-80 (dip) values. Hence, the main factors of slope failures occurrences along the highway are sourced from the relationship between the factors of dip-direction slope cutting surfaces with the strike direction of the sandstone bedding orientation. That is why there were some slopes in the study area were found in the variable potential of falls, slides and topples mode types as well as the combination of more than one mode of aforementioned in the form of the slope failures complex due to this design negligence described to the above aided by the discontinuities nature complex very often encountered at study area.

The way groundwater flows; its pressure and gradient at any point within a slope depend on the local geology. Water plays a very important role in landslide study. Water can influence the strength of slope forming material by chemical and solution, increase in pore water pressures and subsequent decrease in shear strength, reduction of apparent cohesion due to capillary forces (soil suction) upon saturation and softening of stiff fissured clays, shale and sandstone [4,6,7,14,15]. All slope forming materials are subject to initial stresses as a result of gravitational loading, tectonic setting activity, weathering, erosion and other processes [25,26]. Stresses produced by these processes are embodied in the materials themselves, remaining there after the stimulus that generated them has been removed (residual stresses). Stress relief many structural features and stress release activity is an important feature in many rock formations [27-30]. High lateral stresses have played a crucial role in initiating in over consolidated of the slope materials.

5. CONCLUSIONS

In light of available information, the following conclusions may be drawn from the present study:

a. A total of 28 selected critical slope failures were studied and classified into two main groups: rock slope and soil slope. Failures in soil slopes (including embankments) are 18 (64 %) whereas 10 of all failures (36 %) of rock slope.
b. Physical and mechanical properties of 72 soil samples indicated that the failure materials mainly consist of poorly graded to well graded materials of sandy clay and clayey silt soils, which characterized by low to intermediate plasticity content, containing of inactive to normal clay, very high to medium degree of swelling, variable low to high water content, specific gravity ranges from 2.57 to 2.80, low permeability, friction angle (ϕ) ranges from 7.70° to 29.50° and cohesion (C) ranges from 3.20 KPa to 17.27 KPa.
c. The rock properties of 10 rock samples indicated that the point load strength index and the uniaxial compressive strength range classified as moderately week. Kinematics slope analyses indicates that the variable potential of circular, planar, wedges and toppling failures modes as well as the combination of more than one mode of aforementioned failure.
d. Rock and soil slopes stability analysis indicates that the factor of safety value as unsafe (0.52 to 0.98).
e. The main factors causing slope failure occurrences in the study area are natural (geology, meteorology, topography and drainage system) and human factors (lack of proper planning, human activities and community's attitude).

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