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Slope Stability Assessment in and around Taiz City, Yemen, Using Landslide Possibility Index (LPI)

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ABSTRACT

Every nation strives hard to achieve economic development for which adequate infrastructure is required to accomplish the desired goals. In mountainous terrain, road and highway networks play an important role for transportation, public conveyance and other socio-economic activities. Infrastructure development in hilly areas warrants excavations for the construction or road widening purpose undermining the stability of the slopes. The unplanned excavations of Tertiary rock slopes for construction and/or widening purposes before the political unrest in and around Taiz city have caused the instability of the slopes and thus threatened the very purpose of achieving the economic development. In the present work, evaluation of the stability of 12 rock slopes along road cuts and natural outcrops in and around Taiz city was carried out, employing the Landslide Possibility Index (LPI) system. The results showed that the possibility of failures and the degree of hazard in one rock slope location (No.25) is 'Moderate', while in the eight rock slope locations (Nos. 15, 16, 17, 20, 22, 23, 24 and 26) are 'High'. The possibility of failure in the slope location Nos. 18 and 19 are 'Very High' while in the location No. 21 is 'Low'. The areas of 'Moderate Hazard' are represented by granite and jointed rhyolite /dacite rocks while the slopes of 'High Hazard' are represented by different lithologies. The remedial measures for 12 slope locations are suggested based on the degree of possibility of failure and field observations. The intensive field studies indicate that the various causal factors in addition to rainfall have a bearing on causing the instability along the rock slopes of the study area.

Keywords: Taiz city in Yemen, Slope stability, Possibility of failure, Landslide Possibility Index

INTRODUCTION

Rock slope failure along roads, highways, railways and in urban and industrial areas is one of the geologic hazards that will destroy engineering projects such as dams, buildings, roads and railroads [1]. In urban areas such as Taiz city, rapid development of buildings and other infrastructure facilities have caused unfavourable changes in the configuration of Tertiary rock slopes causing instability to the building foundations and development of cracks on their walls, in addition to damages of roads and the local traffic and to obstruct the traffic for several hours. Foundation problems triggered the collapse of the buildings and landslides [2]. These incidences made impacts on the socio-economy and brought undesirable changes in the lives of the citizens. For these reasons, the slope stability evaluation of rocks is vital for the assessment and designing safety measures for excavated slopes, and/or the equilibrium conditions of a natural slope.

There are different geomechanical classification systems proposed by many researchers for the evaluation of the rock slope stability such as rock mass rating (RMR, Bieniawski [3-4]), rock mass strength (RMS, Selby[5- 6], Moon and Selby [7], slope mass rating (SMR, Romana[8], slope rock mass rating (SRMR, Robertson [9], modified mining rock mass rating (MRMR, Haines and Terbrugge [10], natural slope methodology (NSM, Shuk [11], Chinese slope mass rating (CSMR, Chen [12]), modified rock mass rating (M-RMR, Ünal [13], Rock slope Deterioration Assessment (RDA, Nicholson and Hencher [14], Nicholson *et al*[15], Nicholson [16-18]), slope stability probability classification (SSPC, Hack [19], Hack *et al* [20]), modified slope stability probability classification (SSPC, Lindsay *et al* [21]), Volcanic Rock Face Safety Rating (VRFSR, Singh and Connolly [22], continuous rock mass rating (Sen and Sadagah [23], Tomás *et al* [24]), Slope stability rating system (SSR, Taheri and Tani [25-26]) and the alternative rock mass classification system proposed by Pantelidis [27], Fuzzy Slope Mass Rating (FSMR, Daftari-besheli *et al* [28]), New Slope Mass Rating (NSMR, Singh *et al* [29]).

These rock mass classification systems are based on the assessment of rock mass in the field and determination of selected mechanical properties in the laboratory. Due to the increasing cost of site investigations and geotechnical work, other methods were adopted for the evaluation of slope stability against landslide hazards including the determination of Geological Strength Index (GSI, introduced by Hoek [30], and modified by Hoek *et al* [31], Hoek and Brown [32], Marinos and Hoek [33], Marinos [34]) and Landslide Possibility Index (LPI) system suggested by Bejerman [35]). These two systems/indices are basically based on simple field observations of the rock mass.

In the present work, twelve slope locations along road cuts and natural outcrops in and around Taiz city have been studied to evaluate their stability, employing the Landslide Possibility Index (LPI) system [35]. This system is adopted because of its simplicity, effectiveness and to infer the actual field conditions.

STUDY AREA

Taiz city is located in the middle of the Central Highlands of Yemen, in the watershed area of upper Wadi Rasyan, mainly at the foot hill and slope regions of Sabir mountain and bound by the latitudes, 13° 31' 49’ and 13° 44' 29’ N, and longitudes, 43° 54' 17’ and 44° 09' 04’ E (Fig. 1).Topographically, the study area is well represented by mountains, isolated hills, steep slopes, undulating eroded lands with major Wadis, and plains and loess covered plateau (Al-Janad Plateau) with levels ranging from about 800 m to 3000 m above mean sea level. These features make the rock slopes in Taiz city and its surrounding areas vulnerable for landslide hazards that threaten the lives and properties of the people living in the area. Hydrologically, the annual rainfall in the investigated area is bimodal, the first season extends from April to June with peak in May and the second season is from August to October with peak in September. During the month July, there is less rainfall while the dry months begin in mid-October and end in mid-March. Rainfall record obtained from three rain gauge stations (Ussayfra/79-03, NWRA/ 98-04 and Taiz airport/76-79 & 83-89) located in and around Taiz city reveal that the average annual rainfall in the study area is about 520 mm. During the rainfall periods, the meteoric water flows from high lands over steep slopes into natural flow channels which are in most cases are connected together forming the Wadis. Several intermittent Wadis pass through the city of Taiz and/or in its vicinity. The principal Wadis are, Wadi Al- Hawban, Wadi Al-Lasab, Wadi Hasanat, Wadi Salah, Wadi Kalabah, Wadi Al-Qadhi, Wadi Al-Madam and Wadi Mouasal. Water discharged through these Wadis form the major tributaries of Wadi Rasyan and join Red Sea [36].

GEOLOGICAL SETTING

The major geological units and their distributions in the investigated area are shown in the geological map (Fig.2). The Tertiary bimodal volcanic materials are represented by alternating sequences of volcanic lava flows and volcaniclastic deposits of variable composition ranging from the mafic to the silicic types. These sequences of volcanic lava flows and volcaniclastic deposits were erupted in five phases [37-39] and in a repeated manner. From bottom to top, the sequence is made up of the following (Fig.2):

1) Tertiary lower mafic sequence phase (Tb1, Eocene): Tb1 is represented by dark grey (in fresh surface) to chocolate brown or dark reddish brown (on outer weathered/altered surface) jointed/ massive basaltic lava flows which are associated with basaltic volcaniclastic materials. Often the jointed basaltic lava flows are interbedded /alternated with basaltic volcaniclastic materials. They are affected by different types of discontinuities most of them are irregular and columnar joints of thermal origin in addition to other discontinuities. The rock blocks formed by these joints vary in their sizes and shapes such as columnar, polyhedral, tabular, prismatic and rhombohedral blocks. It forms scarps and highly dissected mountain relief.

2) Tertiary lower silicic sequence phase (Tr1, Eocene -Oligocene): It forms plateaus and rarely small hills. Petrologically Tr1 is represented by jointed rhyolites /dacites, ignimbrites, rhyolitic tuffs, lapillistones volcaniclastic breccias, and random pumice and obsidian [40]. The higher amounts of volcaniclastic rocks in Tr1 sequence indicate that initially volcanism of silicic volcanic rocks was more explosive [39]. This sequence shows vertically change in lithology and colonnade columnar jointing features.

3) Tertiary middle mafic sequence phase (Tb2, Oligocene-Miocene): Tb2 is represented by the basaltic lava flows and volcaniclastic deposits extruded primarily through the feeders’ like- dykes. Volcaniclastic deposits are classified into tuff-breccias, lapilli-tuffs, agglomerates and lapillistones based on their particles sizes [40]. In the study area, the rocks and deposits of Tb2 have a greatest areal extent relative to all other units with a thickness reaching up to 100 m, and covering an area of 39.61 % of total area. These lava flows have different physical characteristics (colour, heterogeneity, discontinuity, thickness, horizontal attitude, weathering/alteration, intercalation and repetition with depth) in both vertical and horizontal directions implying variation in eruption type, mode of transport,

distance travelled from the vent, temperature of the deposits, particle size, water content and paleorelief of older Tr1 sequence [40].

4) Tertiary upper silicic sequence phase (Tr2, Oligocene-Miocene): The outcrops of Tr2 sequence are limited in extent and are restricted to E-W trending Sabir fault system. They constitute isolated domal mountains and plugs of different sizes and shapes. It covers an area of 41.47 sq.km of the total area (10. 6%).Tr2 is represented by fine-grained, porphyritic, yellow to gray, white, red, green and pink jointed/massive rhyolites/dacites and/or varicolored volcaniclastics of rhyolitic composition. Pitchstone is also observed in different locations as lava flows or as irregular bodies intercalated with volcaniclastic materials. Al-Qadhi *et al* [40] classified the volcaniclastic materials of the study area into rhyolitic tuffs, rhyolitic lapilli-tuffs and rhyolitic lapillistones based on the particle sizes. The most characteristic feature of Tr2 is its occurrence as alternating sequence of more than one lava flow with lateral and vertical variations even in the same location, for the same reasons as mentioned in Tb2.Tertiary Sabir granitic pluton, emplaced as laccolithic body inside the older stratified Tertiary Yemen volcanic rocks forms the dominant morphological feature named Sabir Mountain, overlooking the city of Taiz in the southern part of the study area (Fig.2). It is characterized by high lands, steep slopes and deep valleys. Physical weathering of varying intensities has produced different sizes of granitic blocks and boulders along the slope sides. Granite shows white to greyish white colour, massive, medium to coarse-grained grading up to granite porphyry and contains almost < 5 % of dark coloured minerals. They belong to the alkaline or peralkaline suite of A-type granites [41]. These are produced by fractional crystallization in the basic magmas [42, 43]. All the rock units are faulted and sheared to varying degrees, and they have been subjected to different levels of weathering/ alteration and erosion.

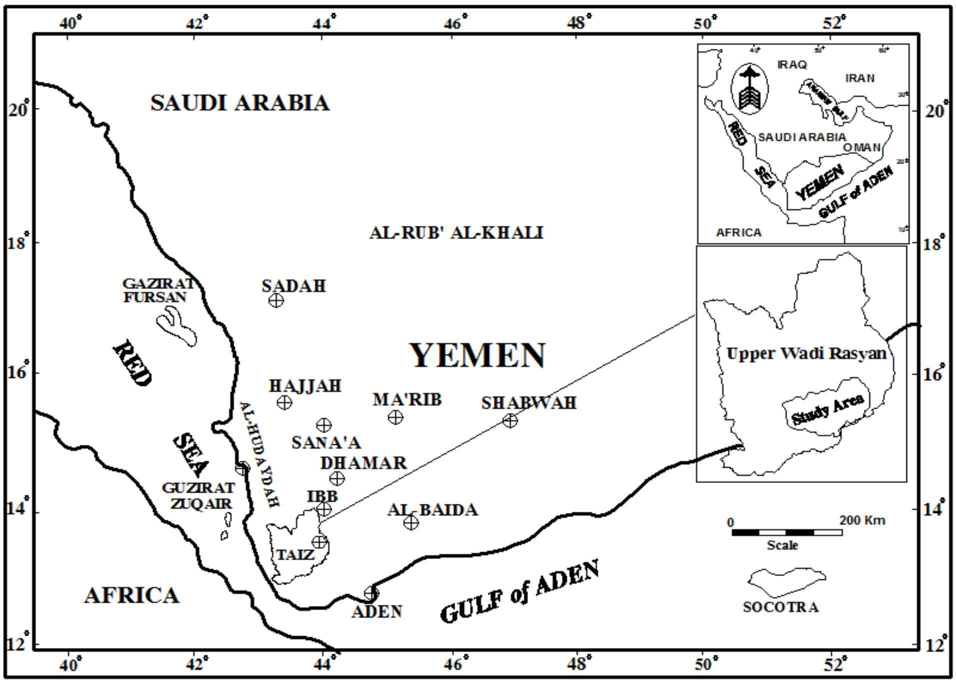


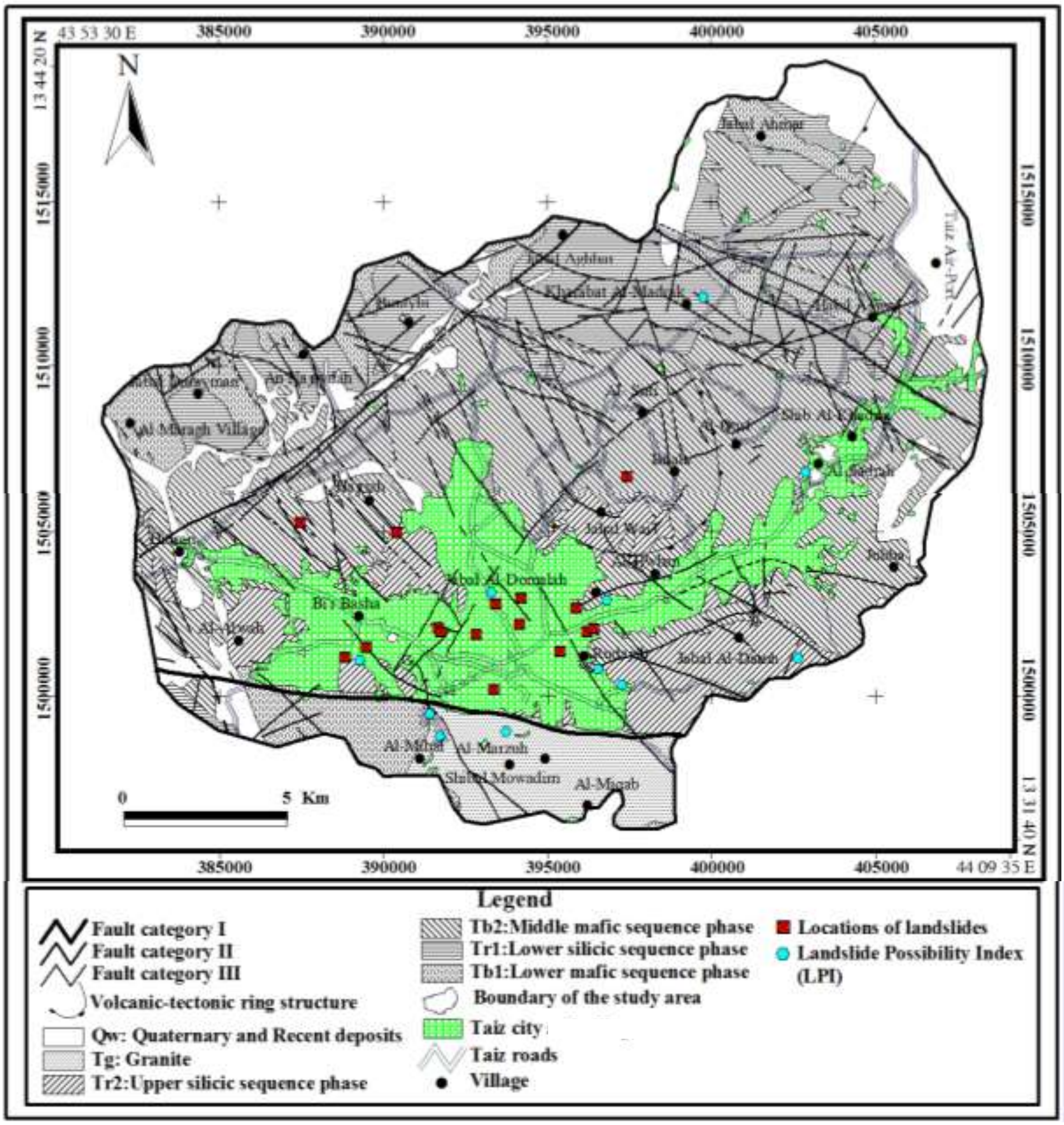
Fig.1 Location map of the study area

LANDSLIDES IN AND AROUND TAIZ CITY

From the recent landslides and collapsing of houses and other facilities in the study area, it is inferred that this phenomenon may become more hazardous in the future, especially where the rapid development of civic amenities and other infrastructure facilities are causing unfavorable changes in the configuration of Tertiary rock slopes. Taiz city is densely populated and three recently laid important highways viz., Taiz-Sana'a, Taiz –Hodeidah and Taiz-Aden in addition to the internal road networks run through the mountains, hills and plains composed of diversified Tertiary rock materials such as basalt, rhyolite/dacite, volcaniclastics and granite.As a result of the newly laid roads which involved the rock cuts along the slopes, the slopes have become unsTable -posing danger to the vehicular traffic as well as the other properties such as the houses built on or near the slopes. The study area has witnessed landslides and consequent damages especially during the rainfall periods.A number of buildings have been damaged by catastrophic landslides, such as Jabal Amid Al-Habil, Jabal Al-Mahjoor Kalabah, Jabal Al-Abiad Wadi Al-Qadhi, Jabal Al-Kahirah Castle etc.

The locations of all recorded landslides are shown on the geological map (Fig.2) of the study area. In-depth studies carried out by the present investigators brought to light the following factors for most of the incidences of landslides in the study area:

a) 'Poor' to 'Fair' quality of the rock mass of the slope which is composed of jointed acid/basic lava flows alternated/intercalated with varicolored volcaniclastic of basaltic/rhyolitic composition.
b) Presence of weak volcaniclastic layers with poor geotechnical properties such as low density, high porosity, low strength, low capacity, high plasticity, etc., at the bottom parts of the slopes [2].
c) Overhanging of the upper jointed lava flows (basalt/rhyolite) which often have discontinuities with unfavourable orientation.
d) Poor drainage conditions of slope
e) The area has semiarid climatic conditions (about 520 mm/yr).



METHODS AND MATERIALS

The rock masses of the slopes investigated comprise of Tertiary bimodal volcanic materials and their associated intrusive bodies. Site investigations were carried out on exposures along road cuts and on the natural rock outcrops at 110 locations, 12 of them representing various lithological and geotechnical conditions in and around Taiz city (Table -1 and Fig. 2) were selected as rock slope stations. The stability of the investigated slopes was evaluated using the LPI. The LPI system involves the study of ten main characteristic features encompassing geological, structural, hydrological and geomorphological conditions of the given area.

Table --1 Location and Lithologies of the Investigated Slope Stations in the Study Area

Slope St. No.	Location of slope St. (UTM)		Lithology
	X	Y	
28	402904	1506821	Volcaniclastic rocks
35	396829	1502984	Volcaniclastic rocks
38	390417	1505056	Co-Rhyolite
54b	402635	1501211	Co. rhyolite
78	393755	1498977	Granite
87	391429	1499513	Granite
88	391739	1498833	Granite
104	399781	1512145	J. rhyolite
105	393299	1503211	J. basalt
109	389291	1501146	Co. rhyolite
110	396549	1500899	Co. rhyolite/dacite
100	397281	1500393	J. rhyolite

J: Jointed; Co.: Columnar.

Table --2 Landslide Possibility Index (LPI) Calculation (after Bejerman [35])

NUMBER SLOPE ☐☐☐ PAGE ☐☐☐

KILOMETER ☐☐☐☐☐ DATE ☐☐☐☐☐☐

1. SLOPE ESTIMATE HEIGHT (m)		2. SLOPE ESTIMATE ANGLE		3. GRADE OF ESTIMATE FRACTURE	
1 ---------- 8	1	< 15°	0	Sound	0
9 ---------- 15	2	15° ------ 30°	1	moderately fractured	1
16 ---------- 25	3	30° ------ 45°	2	highly fractured	2
26 ---------- 35	4	45° ------ 60°	3	completely fractured	3
> ---------- 35	5	> 60°	4		

4. GRADE OF ESTIMATE WEATHERING		5. GRADIENT OF ESTIMATE THE DISCONTINUITIES		6. SPACING OF ESTIMATE THE DISCONTINUITIES	
Fresh	0	< 15°	0	> 3 m	0
slightly weathered	1	15° ------ 30°	1	1 --------- 3 m	1
moderately weathered	2	30° ------ 45°	2	0.3 ------- 1 m	2
highly weathered	3	45° ------ 60°	3	0.05 --- 0.3 m	3
completely weathered	4	> 60°	4	< 0.05 m	4
residual soil	5				

7. ORIENTATION OF THE ESTIMATE DISCONTINUITIES		8. VEGETATION ESTIMATE COVER	
favorable	0	void (< 20%)	0
unfavorable	4	scarce (20 - 60%)	1
		abundant (> 60%)	2

9. WATER INFILTRATION ESTIMATE		10. PREVIOUS LANDSLIDES ESTIMATE	
inexistent	0	Not registered	0
scarce	1	registered (small volume)	1
abundant:		registered (high volume)	2
permanent	2		
seasonal	3		

1 + 2 + 3 + 4 ± 5 + 6 + 7 + 8 + 9 + 10 = ☐☐

I (small) (0 – 5)	III (low) (11 – 15)	V (high) (21 – 25)
II (very low) (6 – 10)	IV (moderate) (16 – 20)	VI (very high) (> 25)

The LPI value is obtained by adding the estimations of attributes 1 to 10. If the orientation of the discontinuities is favorable, subtract the estimation of gradient.

OBSERVATIONS:

The parameters are:

1.Slope height	6.Spacing of the discontinuities
2.Slope angle	7.Orientation of the discontinuities
3.Grade of fracture of the rock mass	8.Vegetation cover
4.Grade of weathering of the rock mass	9.Water infiltration
5.Gradient of the discontinuities	10.Previous landslides

Each feature has a range of values (Table --2). The value of each feature is estimated and quantified in the field as per the procedure prescribed by Bejerman [35]. Estimated values of 10 parameters are added to determine the Landslide Possibility Index (LPI) value for the slope as shown in the following equation:

$$\text{LPI}= \sum_{i=1}^{10}(\textbf{estimated value s}) = \mathbf{1 + 2 + 3 + 4 \pm 5 + 6 + 7 + 8 + 9 + 10}.$$

If the orientation of the discontinuities is favorable, the estimated value of the discontinuity gradient is subtracted from the total LPI for the purpose of correcting the LPI value. The degree of the hazard of the slope is determined based on the LPI value i.e., the sum of ten estimations (Table -2). Accordingly, the possibilities of failures of slopes were classified into six categories as listed in the Table -3 [35]. These are: I (small) (when LPI=2-5), II (very low) (when LPI=6-10), III (low) (when LPI= 11-15), IV (moderate) (when LPI 16-20), V (high) (when LPI=21-25) and VI (very high) (when LPI >25). Also, based on the defined LPI category for each rock slope, the landslide hazard of the rock slope can be evaluated. Three hazard categories were considered by Bejerman [45] as shown in the Table-4.

RESULTS AND DISCUSSION

LPI values of the investigated slopes are provided in Table -5. The degree of hazard and failure possibility for all the investigated slope locations in different lithologies is shown in Figure 3. The computed values of LPI at slope locations 18 and 19 are 27 and 26.5 respectively indicating that the possibility of failure along these slopes is 'Very High'and the degree of hazard is'High'. These slopes are characterized by steep gradient, intensively fractured and weathered rocks, and unfavourable orientation of discontinuities. Figure 3 is example for Very high hazard slopes. The suggested remedial measures for the stability of these slopes are provided in Table -5.

The LPI values for the rock slopes at location Nos.15, 16,17,20, 22, 23, 24 and 26 are 24, 21, 21, 22.5, 23, 23, 22 and 22.5 respectively that indicate the possibility of failure and the degree of hazard along these slopes are 'High' (Table -5). From the landslide inventory and field observations, maximum numbers of incidences of landslides have been recorded along these slopes. The average heights and dips of these slopes range from 2.3 m to 14.5m and from 56 to more than 90° (overhanging) respectively. Almost all these slopes (except slopes of granite) are divisible into two parts, upper and lower parts. The upper parts of these slopes consist of brown to yellowish brown coloured, slight to highly weathered jointed rhyolite/dacite or light reddish brown coloured, pyroclastic textured, slightly weathered, moderately weak huge blocks of volcanic lapilli-tuff of various dimensions. The lower parts are formed from moderate to highly weathered, unconsolidated to semi-consolidated volcaniclastic deposits or volcanic ash (volcanic soil) with different thickness. The upper jointed rhyolite/dacite or lapilli-tuff rock masses are cut by three or four main joint sets in addition to randomly oriented joints. The average spacing of these main joint sets range from 0.04m to 3m. Figure 5 depicts an example for high hazard slopes.

Table -3 Failure Category for Each LPI Category (after Bejerman [35])

LPI Category	Failure Possibility	LPI
(I)	Small	(0-5)
(II)	Very Low	(6-10)
(III)	Low	(11-15)
(IV)	Moderate	(16-20)
(V)	High and	(21-25)
(VI)	Very High	(>25)

Table -4 Landslide Hazard Categories, according to LPI categories (after Bejerman [45])

LPI Category	Hazard Category
I- II (1-10)	Low
III-IV (11-20)	Moderate
V-VI >21	High

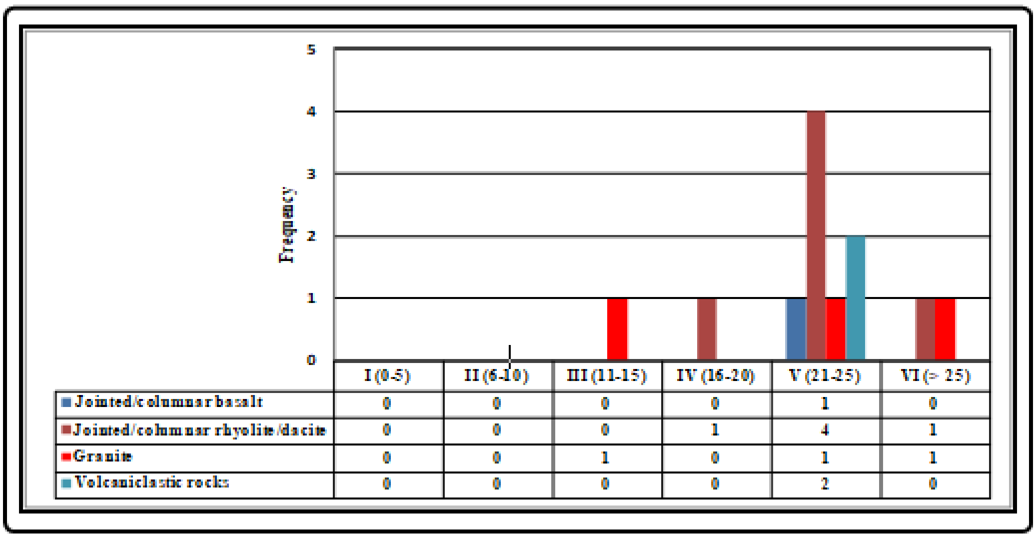


Fig. 3 LPI values and slope categories (after Al-Qadhi [46])

Table -5 Computed LPI values for the investigated rock slopes (12 locations) in and around Taiz city, Yemen (after Al-Qadhi, 2017)
M: Moderate, H: High, V.H: Very High, L: Low[1]: Volcaniclastic rocks, [2]: Jointed/columnar rhyolite/dacite rocks, [3]:Granite rocks, [4]:Jointed/ columnar basalt rocks, [5]: Big boulders and cobbles of rhyolitic rocks, *: Suggested remedial measures based on Failure possibility (Romana,1985) and field observations

No.	Characteristic features of the slope	Rock slope stations (locations)											
		28[1] (15)	35[1] (16)	38[2] (17)	54b[2] (18)	78[3] (19)	87[3] (20)	88[3] (21)	100[5] (22)	104[2] (23)	105[4] (24)	109[2] (25)	110[2] (26)
1	Slope Height	1	2	1	4	5	1	2	2	1	1	1	1
2	Slope angle	4	4	4	4	4	4	4	3	4	4	4	4
3	Grade of fracture of the rock mass	2	0	1	1.5	1	1	1	1	1	1.5	1	2
4	Grade of weathering of the rock mass	2.5	1	0	2.5	1.5	2.5	0	2.5	2.5	1.5	0.5	1.5
5	Gradient of the discontinuities	+ 4	+ 4	+ 4	+ 4	+ 4	+ 3	-3	+ 4	+ 4	+ 4	+ 3.5	+ 4
6	Spacing of the discontinuities	2.5	1	1	2	2	2	2	1.5	2	2	2	2
7	Orientation of the discontinuities	4	4	4	4	4	4	4	4	4	4	4	4
8	Vegetation cover	0	0	1	0	1	0	0	0	0	0	0	0
9	Water infiltration	3	3	3	3	3	3	3	3	3	3	3	3
10	Previous landslides	1	2	2	2	1	2	2	2	1.5	1	1	1
Landslide Possibility Index (LPI)		24	21	21	27	26.5	22.5	15	23	23	22	20	22.5
LPI category		V	V	V	VI	VI	V	III	V	V	V	IV	V
Failure possibility		H	H	H	V.H	V.H	H	L	H	H	H	M	H
Hazard category		H	H	H	H	H	H	M	H	H	H	M	H
Suggested remedial measures*		(b)	(c)	(c)	(b)	(g)	(b)	(f)	(a)	(a)	(a)	(d)	(e)
(a):	Removing all unstable or potentially unstable rock blocks from upper part of the slope (head) and erection of gravity retaining wall along with drainage holes at slope toe												
(b):	Scaling and trimming of the upper portion of slope and erection of gravity retaining wall along with drainage holes at slope toe.												
(c):	Removing all unstable or potentially unstable rock blocks from upper part of the slope (head) and plant roots												
(d):	Scaling and trimming of the upper portions of the slope												
(e):	Erection of gravity retaining wall along with drainage holes at slope toe and use the surface drainage methods												
(f):	Removing all unstable or potentially unstable rock blocks from upper part of the slope (head) and construction of toe ditches.												
(g):	Removing all unstable or potentially unstable rock blocks from some parts of the slope and stabilization of the other parts by routing with cement. In cast the unstable steep slope is inaccessible, the avoiding the construction of housings at slope toe is preferable.												

LPI value for slope location no. 25 is 20 implying the possibility of failure and the degree of hazard of this slope belong to the class'Moderate' (Table -5), while at slope location no. 21, the possibility of failure and the degree of hazard are 'Moderate to Low'. The LPI values for jointed/columnar rhyolite/ dacite slopes vary from 20 to 27 while for the granitic slopes are from 15 to 26.5 indicating that these slopes have 'High to Very High' and 'Low to Very High' failure possibilities respectively (Table -5). Remedial measures required to thwart the incidences of slope failures and landslides for all the investigated slopes are provided in Table -5. These remedial measures have been suggested based on the possibility of failure [8] and field observations.

Fig. 4 Jointed rhyolite slope at location No. 18.

Fig. 5 Weathered granite slope at location No. 20

CAUSATIVE FACTORS FOR SLOPE INSTABILITY IN THE STUDY AREA

Based on the field investigations at 110 field survey stations representing different geo-engineering conditions, it was found that various factors play significant roles in causing the instability of the slopes and are triggered by rainfall events.

The principal factors are:

- In most of the investigated areas it was found that the Tertiary volcanic materials occur as alternate/intercalated sequences of jointed lava flows (basalt/rhyolite/ dacite) and varicoloured weakly welded volcaniclastic materials (ignimbrites, tuffs, volcaniclastic breccias, volcaniclastic agglomerates, volcanic ashes /soils) of basaltic/rhyolitic composition.
- The upper hard jointed lava flows are underlain by weakly welded volcaniclastic materials. Density of the upper jointed volcanic rocks is high and the rocks are characterized by open discontinuities especially vertical joints which easily induce instability as the discontinuities act as the passage for the movement of the infiltrated water into the lower layer especially during rainfall periods [2].
- The lower volcaniclastic deposits which show discontinuities at places, are characterized by low strengths, low densities, high porosities, high plasticities, medium to very high in degree of expansiveness (in case of soil) [2].
- In some locations, the Tertiary volcanic lava flows are overhanging due to the undercutting of the lower weakly welded volcaniclastic materials owing to weathering and anthropogenic activities. Further, the stability of the rocks is affected by different types of joints (discontinuity) which have various orientations inducing toppling, fall and planer failures, especially on the upper parts of the slopes such as near the AL-Thawrah hospital and Al-Sha'ab palace.
- The main triggering factor that cause slope instability and increasing the probability of landslides in the study area is rainfall. Tremors along fault lines may probably have contributed for the instability on a minor scale.
- Human activities through the excavation of the toe portion of the slope for the construction purposes, laying the new roads, loading the upper slope or crest, etc., have contributed for the stability of the slope
- Moderate to highly weathered irregular unstable -slope faces especially in the granitic rocks have caused landslides in the present study area.

CONCLUSION

In the present research work the Landslide Possibility Index (LPI) system was used for the evaluation of the degree of failure possibility and hazard at 12 rock slope locations. The obtained results of LPI values indicate that there are two locations (18 and 19) have 'Very High' possibility to landslides and 'High' landslide hazard degrees (LPI >25, VI-class). The slope of this region is made up of jointed rhyolitic rocks and weathered granitic rocks. While eight locations Nos. (15, 16, 17, 20, 22, 23, 24 and 26) have 'High' possibility to landslides and also 'High' landslide hazard degrees (LPI= 21-25, V-class). The slope at location No. 25 of columnar rhyolite has LPI value is 20 which indicates' Moderate' possibility to landslide and also 'Moderate' hazard rating (Table -5). Only one location (no.21) has 'Low' possibility to landslides and 'Moderate' landslide hazard degree (LPI= 11-15, III-class) and is formed from granitic rocks. The required remedial measures for all the cases are provided in Table -5. These remedial measures have been suggested based on the failure possibility and field observations.

Based on this study, the factors that play a significant role in controlling the conditions of slope instability in the study area can be grouped under two main categories namely -

I. Causal factors group: these include, 1) Geological factors (type of rock and mode of its emplacement, strength of intact rock, strength along surface of discontinuities, presence of weakly welded volcaniclastic materials and discontinuities with unfavourable orientation), 2) Morphological factors (slope forms and the processes that shape them) and 3) Hydrological factors (movement, distribution, drainage and infiltration)

II. Triggering factors group: these include, 1) Rainfall, 2) Weathering especially of granitic rocks and weakly welded volcaniclastic materials,3) Human activities (excavation of the toe region of the slope for construction purposes, road building, loading of the upper slope or crest, etc), 4) Undercutting (weathering/human activities), or 5) A combination of all the above listed factors.

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