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Negligence of geological Investigations site leading to slope failure incidents: a case study from Saih Al Ahmar in Bidbid, Northern Oman

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ABSTRACT: This paper describes and analyzes a recent slope failure alongside Saih Al Ahmar water storage tank in Bidbid, and identifies the natural and induced causes of the landslide. Our analysis demonstrates that the landslide in Bidbid was the result of several combined factors: slope-forming materials, distribution of geological discontinuities and disturbance by human activities. Moreover, field observations, satellite imagery and geology of the study area indicate that the major factors which caused the landslide are the steep slope excavation along the developed tensional faults, the material in the slide ranging from talus deposits to interlayered peridotite and gabbro, cutting perpendicular to slope talus and removal of the toe of the slope. The slope failure and other stability concerns in the subsurface threatening the structural integrity of water storage infrastructure would not have arisen if the geology of the area had been carefully taken into account before the excavation phase. Landslide hazard assessment in the water tank area and its surrounding is necessary to manage the landslide risk. Proper measures should also be adopted to mitigate the impact and to avoid further failure in the slope already on the verge of movement by rainfall.

Keywords: Landslide; Slope failure; Incidents; Geological conditions; Oman.

إهمال التحريات الموقعية الجيولوجية يؤدي الى حوادث انهيار للمنحدرات: دراسة حالة من السيح الأحمر في بدبد، شمال عمان

طلال الحوسني و صبحي نصر

الملخص: يصف هذا البحث ويحلل انهيار منحدر بجانب خزان مياه سيح الأحمر في بدبد، ويحدد الأسباب الطبيعية والمستحدثة التي نتج عنها الانهيار الأرضي. وتظهر التحاليل أن الانهيار في بدبد هو نتيجة لعدة عوامل مجتمعة تشمل: المواد المكونة للمنحدر، وتوزيع الانقطاعات الجيولوجية كالفوالق والكسور، والاضطراب الناجم عن الأنشطة البشرية. كما تشير الملاحظات الميدانية وصور الأقمار الاصطناعية والجيولوجيا لمنطقة الدراسة إلى أن العوامل الرئيسية التي تسببت في الانهيار هي الحفر والقطع الحاد في المنحدر على طول صدوع الشد الموجودة في صخور المنحدر، وطبيعة المواد المكونة للمنحدر من رواسب التعرية إلى طبقات البريدوتيت والجابرو المتداخلة، والقطع المتعامد على اتجاه ميلان المنحدر، وإزالة أسفل المنحدر. لم يكن انهيار المنحدر ومخاوف الاستقرار الأخرى في باطن الأرض التي تهدد السلامة الهيكلية للبنية التحتية لتخزين المياه قد ظهرت لو تم التحري الموقعي بشكل صحيح في جيولوجيا المنطقة قبل التخطيط لحفر المنحدر. كما أن تقييم مخاطر الانهيارات الأرضية في منطقة خزان المياه ومحيطها ضروري الأن لإدارة مخاطر الانهيارات الأرضية. وينبغي اتخاذ تدابير مناسبة للتخفيف من الأثر ولتجنب المزيد من الانهيار في المنحدر الذي هو بالفعل على وشك الحركة التي يمكن تجديدها بفعل هطول الأمطار.

الكلمات المفتاحية: انزلاقات أرضية، انهيار المنحدر، حوادث، ظروف جيولوجية، عُمان.

1. Introduction

Landslides are the movement of a mass of rock and sediments down a slope due to the force of gravity [1]. Recognition of landslides and other slope instability processes requires knowledge of the local geologic, geomorphic and hydrologic conditions, the intensity, duration and frequency of rainfall, seismicity, change in land use practices and human activity [2-4]. Geologic conditions greatly influence the occurrence of landslides and help identify areas prone to potential slope failure. Since different rock types respond differently to the shearing stresses that act upon them, a high possibility of failure exists in steep sediments overlying bedrock because the loose material transmits water more readily to the underlying impermeable bedrock, increasing the pore water pressure and weakening the shear strength, and thus leading to slope failure [4-7]. Therefore, a survey of the geology plays a significant role in the assessment of landslide hazards. In some construction projects, including road cuts in mountains, minor landslides of limited effect are common and inevitable [8-10]. All efforts, in such cases, should be exerted to minimize the adverse impact of such landslides. If major landslides are anticipated, then a drastic change in the design of the project or its location should be considered [11-13]. For landslides of limited extent, protection and stabilization measures should be thoroughly assessed technically and economically. Many disasters are related to geotechnical failure [14]. For both risk management and the development of a scientific approach, research on slope failure is important to learn how to prevent these disasters [14]. There might also be unforeseen landslide triggering mechanisms, a lack of scientific knowledge, a lack of local data, a lack of qualified personnel or even a lack of willingness at the designing and planning stage motivated by time and money saving and increasing profits that could lead to potential sliding risks [10,11,14].

Hazards resulting from the mass movement of material on mountain slopes are the most significant threats in the mountain ranges of Oman, whether the slopes are natural or man-made, as a direct result of human exploitation [15-17]. Many roads have been constructed across and along the Oman Mountains. These roads traverse through topographically challenging terrain and in many cases required significant rock cuts and alteration of slopes. Many of these rock cuts were constructed using blasting techniques and/or mechanical excavation, resulting in highly unstable slopes that are highly irregular and contain numerous weak zones [16,17]. The stability of fractured rocks is governed by their rock-mass properties. The engineering behavior of these masses is controlled not only by their lithological types, but also by their discontinuity characteristics, such as joints, faults, and shear zones.

An active landslide and collapse of rocks were observed along a newly constructed area of the Saih Al Ahmar water storage tank in Bidbid within the Samail ophiolite. The collapse resulted in the downward movement of rocks of a formerly intact rock mass towards, and into, the base of the cutting. The collapse occurred over a plane of cutting of around 200 m long. The rock cutting had been excavated via a series of benches and steps with very limited stabilization measures comprised of shotcrete. The landslide started as a thin crescent shape fracture in October 2019 and ground displacement gradually continued to increase. The fracture occurred just after the completion of a rock cut made for the water tank.

This paper reports a human-induced landslide at the site of the water storage tank in Bidbid and aims to identify the natural and induced factors that triggered the slope failure. The aim is also to assess and identify the local geologic, geomorphic and hydrologic conditions that, in addition to the removal of the toe of the slope and disturbance by human activities, have caused this recent landslide. This understanding will improve our prevention and mitigation measures and reduce slope failure incidents in Oman.

2. Geology and Tectonic Setting

The geological setting of the Oman Mountains is dominated by the convergence of the Arabian and Iranian plates which has resulted in the formation of the Zagros fold-thrust belt which defines the NE margin of the Arabian Gulf and the continued closing of the Sea of Oman. This closure resulted in the ophiolites of the Oman Mountains being obducted onto the Arabian plate. The obduction occurred in the Cretaceous, beginning approximately 100 million years ago. Tectonic events that post-date the emplacement of the ophiolites relate to the continued closing of the Sea of Oman and the collision of the Arabian and Iranian plates, a process which is continuing today [19, 20]. The fracturing that would be expected to form within the ophiolites would relate to these two tectonic events and to the subsequent exhumation of the rocks from depth to the surface (Figure 1). The earliest fractures would relate to the emplacement, which was associated with a thrusting stress regime. The maximum principal compression was oriented NE – SW and where the vertical stress was the lowest principal stress. This would result in SW directed thrusts, and sub-horizontal extensional fractures. As the thrusts stacked up on the continental plate, the vertical stress would have increased and may have become the intermediate principal stress. This would have changed the thrust regime to a wrench fault regime, which would result in vertical faults and vertical extensional fractures. Subsequent plate motion linked to the on-going collision between the Arabian and Iranian plates may have produced new fractures or caused motion along pre-existing fractures [19]. Finally, the fractured rock mass was exhumed to the surface, a process that was likely to lead to further fracturing and motion on existing fractures. The pattern of fractures observed in the rocks of the region is compatible with the tectonic history outlined above.

The Samail ophiolite area is characterized by rugged rolling and mountainous topography reflecting the complexity of the different geologic and tectonic elements including Cretaceous ophiolite obduction, Tertiary extension, and rejuvenated uplift and erosion, which was initiated at the end of the Oligocene and continues to the present.

Most mountainous areas of the Samail ophiolite, which consists of Gabbro, basalt and peridotite are characterized by steep slopes, of between 50° to 80° [19]. The landscape of the region is the combined effect of tectonic uplift of the Samail Ophiolite, drainage erosion, and the strengths of the different rock units. The existence of old primary faults in these areas leads to the descent of rocky masses and plays an important role in the instability and deformation of the rocks. Steep slope gradients associated with abundant cracks, gaps and fissures in the Ophiolite sequence promote slope failure.

The landslide area lies around GPS UTM 40Q: 614650 m E, 2596623 m N (Figure 2). The Saih Al Ahmar water tank area in Bidbid traverses a geologically complex part of the Samail Ophiolite, where the topography of the ophiolitic rock sequence is characterized by steep slopes of 50-60°. The area is dissected by seasonal watercourses of wadis following the major fractures and forming the drainage pattern in the area.

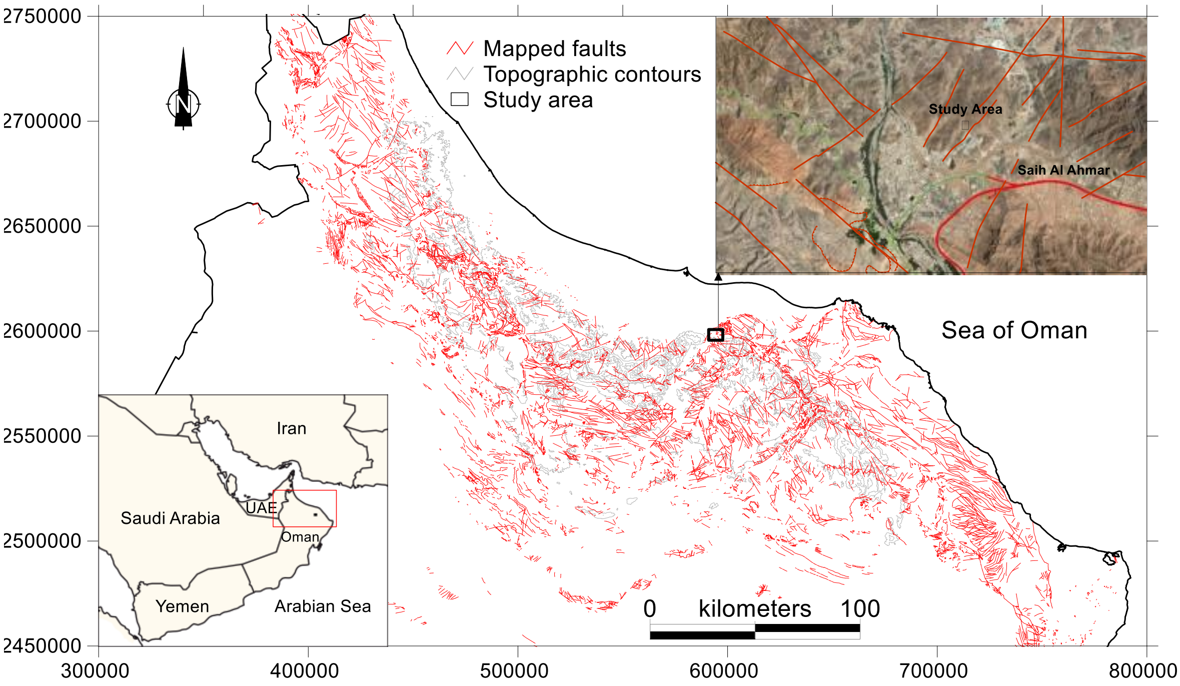

Figure 1. Structural map after Kusky *et al*. (2005) showing the Tertiary-Quaternary faulting in the Northern Oman Hajar Mountains [20].

Figure 2. Landsat Google image (20 Mar 2021) showing the water tank and slope failure above it.

Plutonic igneous rocks of ultramafic composition, mainly harzburgite, wehrlite and dunite, are the most common varieties of peridotite encountered along the length of the high cuts of the water tank area. Peridotite encountered at the natural ground surface, in general, has been subjected to extensive alteration that completely masks its original texture with a brown weathered surface and minor cavities in the highly fractured zone. Serpentinites are found along the sheared peridotite. The serpentinites are grey khaki to black and consist of dark grey to green antigorite with irregular lenses of a bright green chrysotile and complex net-veined white magnesite. Massive laminated and layered medium to coarse-grained gabbro overlies the ultramafic rocks in many areas. Colluvial deposits cover the hillsides of the natural slopes. The colluvium is derived from downslope movement of mechanically weathered bedrock, with thicknesses in the range of 2 to 10 m. The deposits are poorly sorted angular boulders, cobbles and pebbles embedded in a fine-grained matrix.

The geologic study for the area indicates that the geomorphic appearance of the area accommodating the water tank was shaped by prominent regional fractures (faults and joints). The presence of faults and joints is a common feature in the region and, on a larger scale, in the Sultanate of Oman, as observed from the structural map of the Sultanate of Oman (Figure 1). The geological map (Figure 3) shows the presence of a major fault parallel to the cut slopes around the water tank. The major faults strike dominantly in two directions, NE-SW and NW-SE, which are superimposed on the older fold-thrust belt structures. At the cut slope area, the excavation works cut through weak materials of a fault zone with highly altered materials coating the fractures along the fault zone.

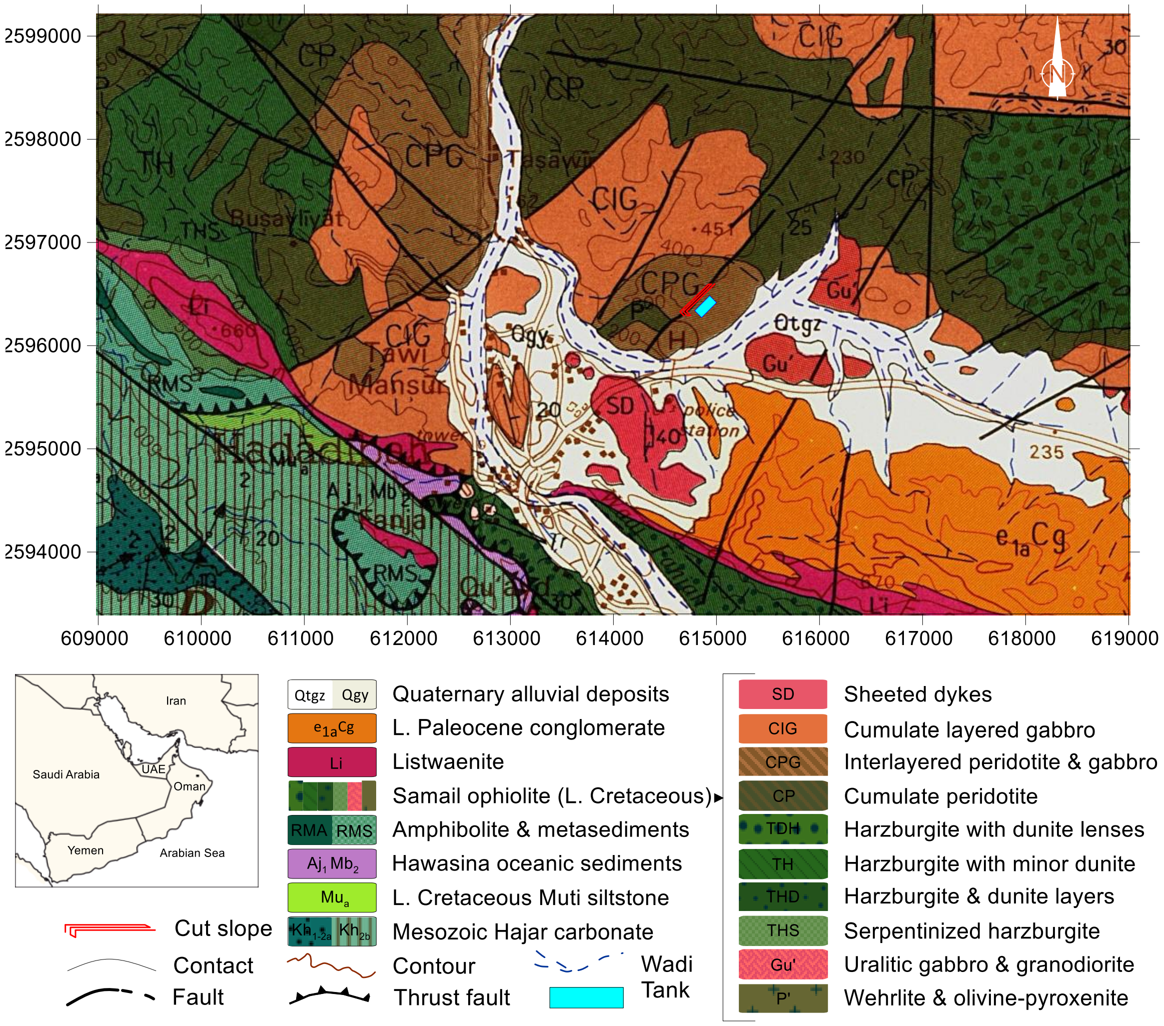

Figure 3. Geological map after Villey *et al.* (1986) to show the location of the slope failure and the geology of Saih Al Ahmar (Bidbid, Northern Oman) [19].

3. Methodology

Some factors triggering the landslide might be determined from aerial photography or satellite imagery, but they must still be assessed from the ground through field observations and measurements. This work involved compilation of existing maps, interpretation of Google historical imagery, and field work. Much of the bedrock geology is shown on the geological map of Fanja, 1:100,000 [19], which also details the surficial geology and structures. Additional data on the material involved in the landslide and direction of movement was collected during field visits to the landslide site. Google historical imagery helps to determine the timing of the landslide and its evolution since October 2019. Representative samples have been collected from the slide area and were prepared to determine uniaxial compressive strength (UCS), according to the American Society for Testing and Materials (ASTM C170), as well as for a rebound hardness test using a Schmidt Impact Hammer.

4. Results

4.1 Field Observations and Measurements

Based on the geologic mapping on the excavated slopes, the corresponding rock masses are classified into two main groups (Figure 4): - Group 1) Slightly weathered and highly fractured, highly jointed, moderately strong to strong gabbro and plagiogranite, and Group 2) Highly weathered and fractured, very weak to weak peridotite rocks (harzburgite, dunite and wehrlite). The rock strength (UCS) is 100 to 140 MPa for group 1 and 35 to 80 MPa for group 2 (Figure 5 and Table 1). The Schmidt Rebound Hardness test found values varying between 47 to 60 for rocks of group 1, and 14 to 35 for rocks of group 2. The low values of the UCS and Schmidt rebound hardness of group 2 rocks indicate poor surface conditions (Figure 5). The compressive strength values of rocks from group 1 (Gabbro) is relatively high, but these rocks are highly fractured and highly jointed in the field.

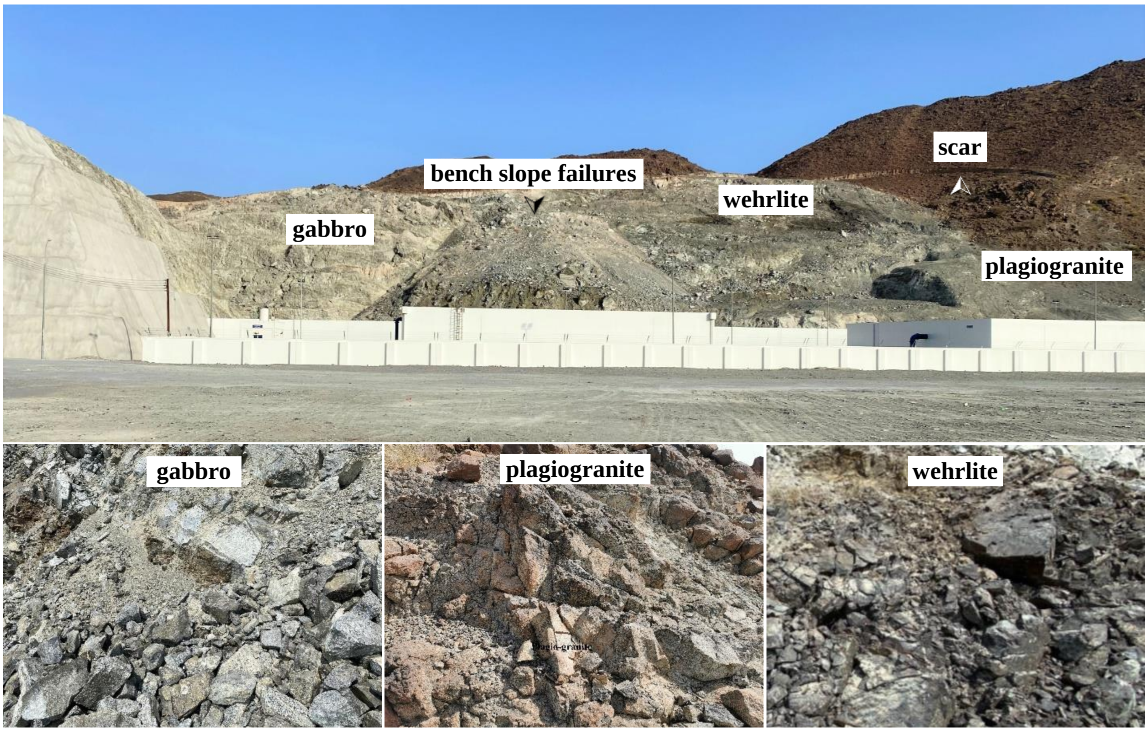

Figure 4. The excavated slopes are made of weak peridotite rocks (harzburgite, dunite and wehrlite) and strong gabbro and plagiogranite.

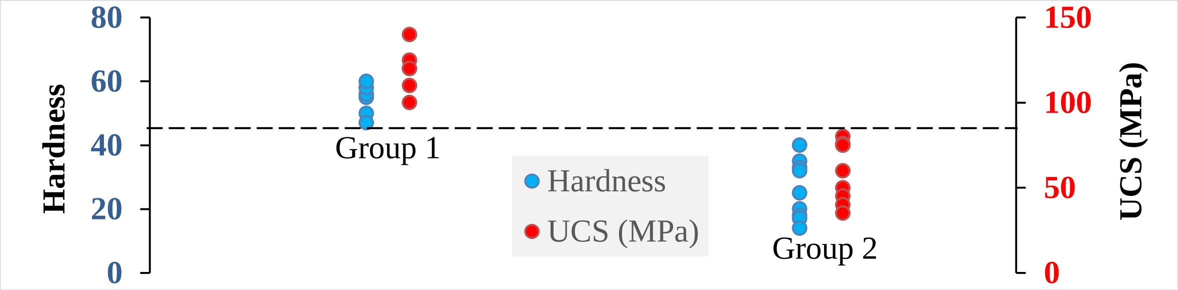

Figure 5. High values of the uniaxial compressive strength (UCS) and Schmidt rebound hardness for rocks of group 1 (gabbro) compared to that of group 2 (peridotite).

Table 1. Schmidt hammer rebound hardness and uniaxial compressive strength (UCS) of the collected slope-forming rocks.

Sample	Group	Rock type	Hardness	UCS (MPa)
F1	1	Plagiogranite	50	110
F2	1	Fine-grained gabbro	55	120
F3	1	Moderate-grained gabbro	56	125
F4	1	Layered fine-grained gabbro	58	120
F5	1	Layered course-grained gabbro	47	100
F6	1	Pegmatitic gabbro	60	140
F7	2	Harzburgite	40	80
F8	2	Harzburgite	35	76
F9	2	Harzburgite	33	75
F10	2	Harzburgite	32	75
F11	2	Dunite	25	60
F12	2	Dunite	20	50
F13	2	Wehrlite	18	45
F14	2	Wehrlite	17	40
F15	2	Wehrlite	14	35

The collapsed cut slope occurs at an elevation of 71 m above tank level, and the equivalent slope angle is 50 to 70º for the excavated slopes. The height of the mountain is 388 m above sea level. The major orientation of the failure surface is undulated with strike orientation ranges between 330º and 355º and between 020º and 040º dipping very steeply towards the south and southwest. This landslide is rotational as the surface of rupture is curved concavely upward (Figure 6).

The landslide area is characterized by northwest-trending mountain ranges and NW and NE wadis (valleys) bounded by many NE, EW and NW faults (Figure 3). Viewing the failed slope from above (Figure 6), there is evidence of significant displacement at the back scarp with both loss of level and forward displacement on the scale of meters on the low side of the scarp. Tension cracks or dilated rock joints showing similar trends to the line of the back-scarp are located at levels higher than the back-scarp. A fault zone passing into the failed slope can be observed on the collapsed area and is apparently expressed as a series of tension cracks running across the failed area. There are blocks of rock mass that have rotated outwards from the slope within the vicinity of the tension cracks. A central portion of the failed area where the bench and berms have failed has been replaced with a slope of rock scree and disintegrated rock mass. At its maximum extent, the rock scree nearly extends to the face of the rock cutting. The amount of displacement on the back-scarp varies, ranging from around 0.2 to 3 m. The overall impression from the surveys is that a large-scale deep-seated failure surface or zone had formed within the hillside. The major orientations of induced fractures are N-NW and N-NE and they extend clearly across the area and within the slope above the water tank.

4.2 Satellite Imagery

Available Google satellite images are dated October 2016 to September 2021. These satellite images show that construction started sometime between September and October 2016, as no construction can be observed in August 2016. In the imagery before October 2019, the cut slope had been advanced down to around the base level of the water tank area, through the full vertical depth of excavation (Figure 7). Deep and long cracks can be observed in the area above the cutting after October 2019. It should be noted that the ground falls significantly in elevation after that date.

Google satellite images show that slope failure started between 28 and 31 October 2019 as a result of major slope excavation and removal of the toe support for constructing the water tank area (Figure 8). Upon approaching the failed section, the cut benches and berm lines show a convergence, resulting from the forward displacement of the failed slope. For this region, the sense of slip movement is estimated as south to southeast. In comparing the imagery pre- and post-failure, it is found that certain key characteristic features on the berms as detected on the 2019-2021 imagery had displaced downslope by distances of 0.2 to 3 m. The images of 2021(Figures 7 and 8) show more clearly the surface of the tension cracks and many features that trend in the same fashion as fractures and joint set, indicating that there are likely to be many planes of weakness parallel to the fault zone running through the failed slope. There are also other surface cracks that are trending nearly perpendicular to the slope.

5. Discussion

Despite the rapid advances in technology, the instances of slope failure have increased rather than decreased [12-14]. This increase can be attributed to unscientific excavation techniques and inappropriate application of stability analysis methods [1,12,14]. In jointed rocky slopes, the complexity of structure and uncertainty in determining relevant parameters can make stability analysis more challenging [1-5]. In a proper investigation, naturally occurring events are known to exist, anticipated, and properly incorporated in the design. As a result, the potential consequences of these events are mitigated and the failure does not occur. The study area has a richly varied relief, geologic structure and lithology, which have contributed to the recent landslide. The potential for land sliding depends on the steepness of slopes, rock types, geologic structure, drainage pattern and modification of slopes for the construction or other human activities. The landslide alongside the water tank in Bidbid is the result of several factors combined:

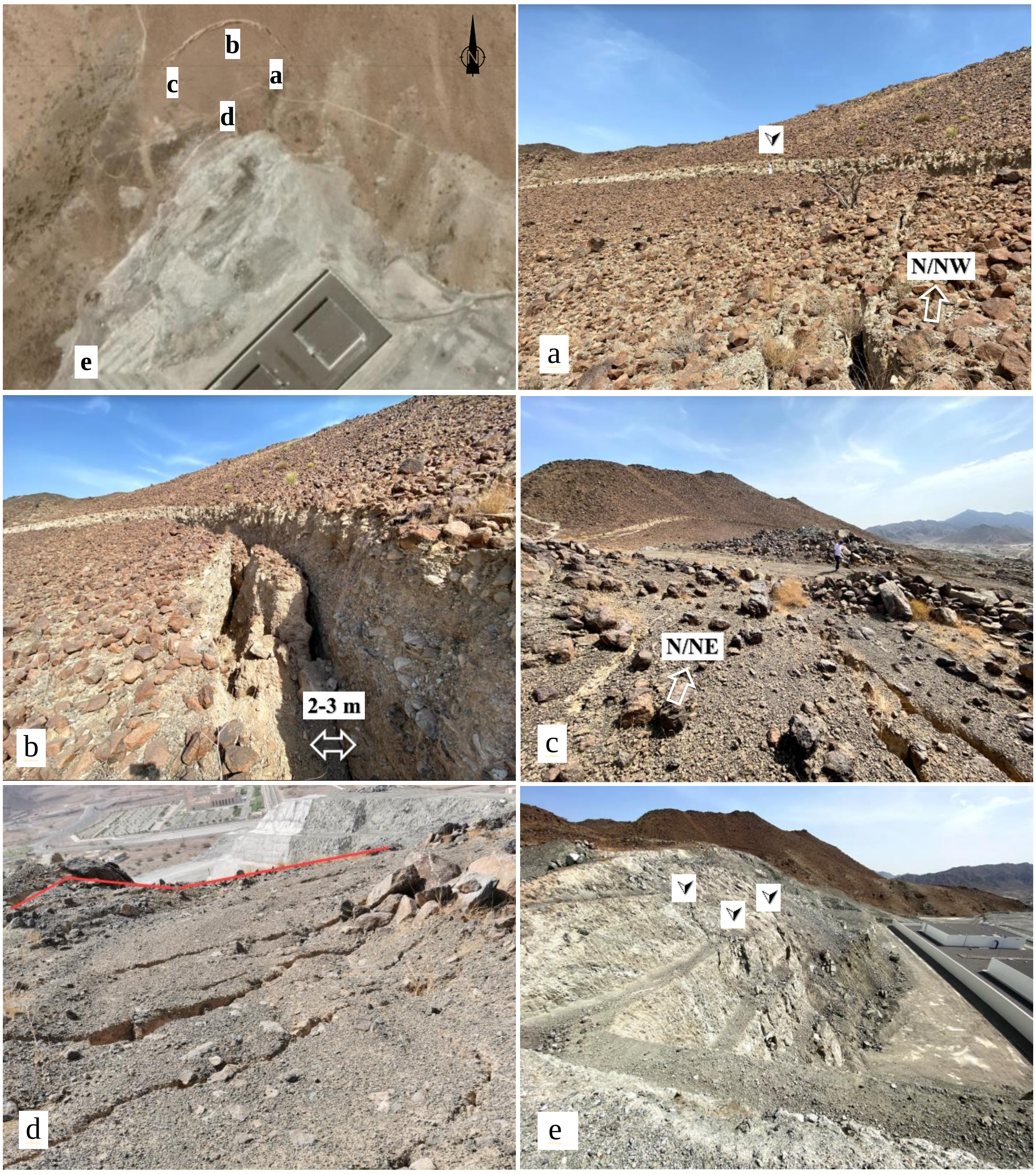

Figure 6. The surface of rupture is curved concavely upward (a), the vertical displacement is 1.8m in the center decreasing towards the sides (b), while the horizontal displacement is up to 3m (b) and the major orientations of induced fractures are 330° to 355° (N/NW) and 020° to 040° (N/NE) (a and c). The fractures extend clearly with the slope above the tank area (d and e).

5.1 Lithology

The area traverses a sequence of highly deformed gabbro underlain by highly weathered and serpentinized peridotites (dunite, wehrlite and Harzburgite) of the Samail ophiolite (Figure 4). The movement was facilitated by the varying shear strengths of different rock masses in contact with each other, mainly along the contacts between the harzburgite, wehrlite, plagiogranite and the gabbro. The Gabbro rests on the soft peridotite that becomes highly plastic when serpentinized. This plasticity increases the possibility of slippage, which is multiplied by the gravitation forces along the steeply dipping planes and contact zones between different lithologies, which do not bond well. Serpentinized peridotite rocks are present along the fracture surface of the rock formation and may have acted as a lubricant and greatly enhanced the slope slide. The weak harzburgite and wehrlite within the slope would have exacerbated the slope failure toward the water tank area. The gabbro has a varied deformation, which causes a very poor induration, causing it to crumble under the slightest pressure.

Figure 7. Collapse of benches initiating large fractures parallel to the main slide area.

5.2 Structures

The rocks are heavily deformed with a large amount of fracturing, and the litho-structural complexity is a consequence of the northeast-southwest trending structures resulting from episodes of compressional and extensional deformations in different ages. The direction of dip of the fault surface is 050^o (N50E), effectively close to the overall sense of movement of the slipped rock mass. The main faults cutting the site are trending NE-SW. Their dips are steep and this may have been caused by continued compression or by back rotation as overlapping thrusts developed. The occurrence of high numbers of tensional fractures perpendicular to the dipping plane has decreased the stability of rocks, and played a role in the occurrence of the landslide. In the landslide area, the occurrence of faults and joints is the other major element that led to the slope failure where the stress balance was altered. Movements also occur along minor fault planes. The gabbroic rocks have numerous vertical cracks and joints, which run for several meters and dissect the gabbro mass, causing fragility in the slope. These rocks show many zones of movement along areas of structural weakness. The breakdown of supporting rocks at the base will cause the succeeding gabbroic rocks to collapse more.

5.3 Slope

The slope is one of the most important major controlling factors influencing the landslide zone. The potential for landslide damage to a construction ranges from low in downslope areas to very high in upslope areas. An increase of slope gradient intensifies the risk of landslides in any region. Down slope geological discontinuities separating rocks of different competence, as well as planar discontinuities orientated parallel to the slope, act as potential failure planes. The failure of a rock is often related to the instability of the slope, which is definitely higher in extensively jointed and faulted areas. The slope of the gabbroic rock mass dips at an angle of 25 to 50 degrees towards the south-southeast, while the cut slopes dip at an angle of 58 to 78 degrees creating a steep slope towards the water tank. The slopes were thus exposed to sudden and cumulative downfalls while the demolition of their bottom portion which was removed while the construction of the water tank was taking place. The entire slope was subjected to downwards movement, which suggests that the slide might have happened on the hidden blind shear zone preserved beneath the gabbroic cover. It is possible that the site of the landslide may represent the location of paleo-shear zones. There is no doubt that the intensive slope cutting and the removal of supporting base rocks have triggered the landslide.

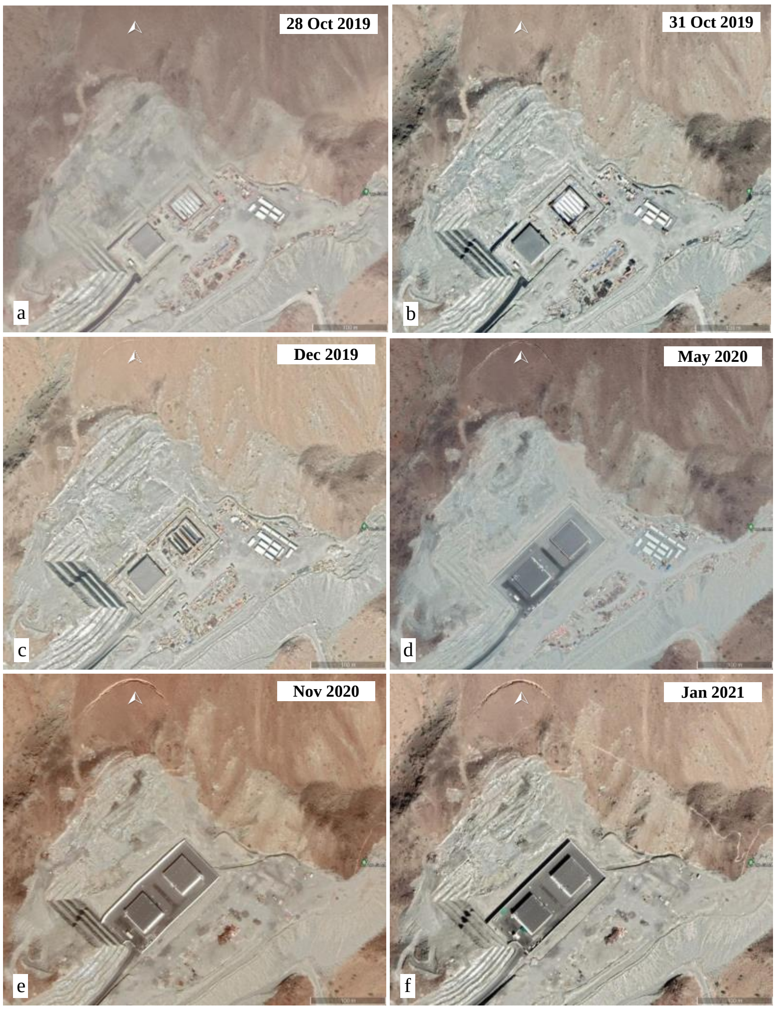

Figure 8. Satellite images (a-f) show that slope failure started between 28 and 31 October 2019 (a and b) as a result of major slope excavation and removal of the toe support in order to construct the tank.

5.4 Human Activities

Human-induced landslides are often seen in road cuts and construction along hillsides. Modern mountain cuts are generally designed with slide prevention in mind, but there are too often unexpected conditions, such as unexpected weak rock layers or undetected fractures that lead to the failure of what was thought to be a stable slope. Construction activities on the lower parts of slopes can trigger slides that move down onto construction areas. The removal of support at the toe and the addition of material at the top are among the human activities which reduce the strength of the slope materials and trigger landslides. Field investigations and observation indicate that there are many unstable blocks that are located at the different levels along the construction area and, by any triggering actions such as excavation of base rock and changing the relief, these unstable blocks will come down. Excavation of base support rock will be sufficient to cause sliding. Unplanned excavations or aggressive excavation methods render excavation faces vulnerable to landslide hazards. The potential for landslides along the water tank area will be concentrated in areas where several aspects of the geology converge to make landslide movement more likely. Excavation appears to be one of the triggering mechanisms and, consequently, causal of the landslide in the area and the reactivation of hidden blind shear zones.

The design process should include preliminary design, design development, design verification during construction, and design checks in relation to any change of method of excavation. If a complete design process had taken place, the vulnerability of the slope to poor rock conditions and a fault encountered earlier in the excavation may have been identified by the engineers. If so, they would have needed to consider suitable design changes in order to improve the slope stability.

The slope failure is approximately 140m long and 120m wide and the failure spread from east to west with the greatest displacement being evident in the middle. The failure mechanism changed from translational with dilation in the east to a toppling like movement at the crest to the west. The most likely sequence of events was compression failure in the plane of the slope leading to bulging of the lower slope, followed by translation, dilation and rotation of blocks on the upper slope. Failure of the lower slope would then have led to destabilization of the upper slopes as progressive failure. A key factor in the failure was avoidable damage to the rock at the toe of the slope caused by uncontrolled excavation. In order to avoid the risk of failures and of debris encroaching on to the water tank with any degree of certainty, extensive rock support and protection would be required and/or very flat slopes adopted. Because the terrain is generally very steep, a small reduction in the slope angle would lead to large changes in excavated volume; and therefore lead to a large increase in construction cost, which might have been the motivation to avoid cutting the slope with steep angles. It is essential therefore that considerable care is taken by the engineers in the assessment of stability. Considerable effort is required to identify and to justify these measures, especially where the method of execution bears a direct impact on the stability of the slopes and the safety of the water storage infrastructure.

6. Conclusion

The landslide alongside the water storage tank in Saih Al Ahmar, Bidbid, was the result of several combined factors, mainly lithological, structural and due to human activities. The landslide area is characterized by moderately-to-highly deformed, fractured slope materials, the presence of moderately-to-highly plastic interlayered serpentinized peridotite and highly deformed gabbro, the presence of major fractures parallel to the slope, and has been influenced by human activities and slope excavation. The slope failure has been determined by natural shear zones within the rock mass, which seem to have been neglected in the site investigation and during the construction phase. No stabilization or protection measures for the slopes have been considered as of this date. Further sliding of the slope is a major concern, jeopardizing the structural integrity of water storage infrastructure. Thus assessment of the landslide hazard is required to avoid further failure in the slope, which is already on the verge of movement that could be revived by rainfall.

7. Recommendation about Mitigation Measures

In the future it is of high importance to observe and record any unusual features that may affect the cut slopes in the project area. Such features may be detected at an early stage by field inspection, periodic survey measurements or by the examination of aerial photographs taken at different periods of time. The most common method for reducing the risk of sliding in the area is changing the geometry of slopes by gently flattening, unloading and benching. The stability of rock slopes should be analyzed at different local scales, as each scale will require different remediation methods. When possible, slope stability can be improved by supporting the foot of a slope using retaining structures, removing unstable and potentially unstable slope materials, breaking up the slope into flat benches and fracture grouting. These methods can improve the slope stability and substantial benefits can be obtained at a relatively low cost.

Conflict of interest

The authors declare no conflict of interest.

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