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Research Article

The relationship between morphometric parameters of alluvial fans' upland catchment basin and soil resistance properties

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Abstract

Morphometric properties of alluvial fans' upland catchment basin e.g. the area, length of the main flow channel, and slope can affect particles' features like roundedness, surface texture, and shear resistance i.e. grains' angle of internal friction and cohesion. To carry out the current study, first 21 alluvial fans were selected through examining satellite images and conducting field observations. The selected alluvial fans were similar in terms of lithological features and different with regard to their morphology. Samples were obtained from the top, middle, and bottom of alluvial fans. The results showed that, through geomorphological processes, alluvial fans' area and length of the main flow channel increases and their slopes declines from the top to the bottom. These features make grains at the bottom more rounded and less rough. The highest degree of roundedness and smoothness were observed in particles in the largest area, the longest main flow channel, and the lowest average slope of catchment basin. Depending on the morphometric parameters of the catchment basin, the angle of internal friction ranged from 44.3° at the top to at the bottom of alluvial fans. Indeed, the highest angle of friction was detected in alluvial fans with the smallest catchment basin area, shortest main flow channel, and highest slope. Thus, the rise in catchment basins' area and length of the main channel flow and the reduction in their slope will lead to smaller angle of internal friction.

Keywords: Alluvial fans, Morphometric, Geomorphological, Geotechnic, Soil.

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Introduction

Alluvial fans constitute one of the main geomorphologic environments in humans' lives. Given that they are widely scattered across the earth and provide suitable conditions for human life, alluvial fans are of great importance for human activities as well as urban and rural settlements. From an economic perspective, alluvial fans play a significant role in providing sedimentary materials (e.g., sand) used in road and building construction. They are also important reservoirs of underground water (Bahrami et al, 2015). Various factors influence the properties of soil and materials accumulated in alluvial fans. One of these factors is the rock type of catchment basin feeding alluvial fans (Ritter et al, 2001). Moreover, the geomorphological properties of the catchment basin, such as area, slope, length of the main flow channel, and geomorphological processes, can impact soil properties like grain size, roundness, and surface texture (Bahrami et al, 2018). An alluvial fans' morphology depends on morphometric properties of its catchment basin (Moscariello, 2017). The area of the catchment basin of an alluvial fan affects the volume of the sediment produced and transported in a flow (Tucker and Hacock, 2010; Blair, 2003; Snyder et al, 2003). As the area of the drainage basin goes up, so does the volume of transported degraded materials (Harvey, 2002; Ferrill et al, 1996). Thus, larger catchment basins give shape to larger alluvial fans and produce more sediment (Tomczyk, 2021). The area of alluvial fans' catchment basin also influences the intensity of incoming flood flows (Bahrami et al, 2018) in that larger area of catchment basin results in longer and larger volume of flows in alluvial fan flooding (Talling, 2000; Synder et al, 2003; Tucker and Hacock, 2010). In fact, large flow volumes are capable of constructing big alluvial fans (Blair, 2003). Changes in grain morphology depend on the transport distance, grain type, surface roughness, and grain size (Bahrami et al, 2018). Alluvial fans whose catchment basins have longer and larger main flow channels have a smaller average slope in comparison with those that possess smaller catchments (Seif and Mokarram, 2013; Valkanou et al, 2013). The diameter of sedimentary grains often is smaller in larger catchment basins since the grains are likely to travel distances further away from the apex of alluvial fans, which also have more gentle slopes (Blair and Macpherson, 2009). If the grains travel longer distances, they will undergo more abrasion (Bahrami et al, 2018). During the abrasion process, the grains first lose their corners and edges, followed by becoming smoother (Blair, 2003). Transport distance, degree of abrasion, degree of roundness, and surface texture are influenced by the area of upland catchment basin. Therefore, larger alluvial fans have larger amounts of round grains with smooth surface texture (Bahrami et al, 2018). Sediments transported by glaciers and debris environments or under the influence of gravity are generally angular and have a rough texture. When grains are transported by wind or water, they are more likely to have a smooth and round texture (Bridge and Demicco, 2008). Grains' type also affects their roundness. Calcareous and soft grains become rounder than silica and hard ones even in shorter distances (Blatt et al, 1980). On average, small alluvial fans with small catchment basins possess steeper slopes than bigger basins and their grains are typically bigger since they are transported over shorter distances (Lustig, 1965; Tomczyk, 2021). As the slope goes up and the area of alluvial fans declines, soil will have more angular corners with irregular shapes and hard texture. Higher porosity and angularity in soil increase its interlocking property in comparison with round grains. In fact, angularity and roughness influence shear strength (Barton, 1993; Santamarina and Cho, 2004). The interlock between angular grains enhances their cohesion and angle of internal friction (Sukumaran and Ashmawy, 2001). For example, angular sand grains have higher friction angle compared to round grains (Terzaghi, 1967; Santamarina and Cho, 2004). Thus, shear strength rises with increase in grain angularity (Mirghasemi et al, 2002). Bigger grains are less cohesive. Moreover, bigger grain size increases soil resistance, which is due to shear strength caused by friction. In grains with smaller size, the angle of internal friction goes down, leading to lower shear strength (Santamarina and Cho, 2004). Nonetheless, cohesiveness of smaller grains increases their shear strength (Zhao et al, 2014). Soil cohesiveness is also influenced by soil moisture because raising moisture results in lower resistance in clay soils (Mitarai and Nori, 2006). Moist clay has low resistance since it does not contain big grains, which reduces internal friction. As such, higher moisture drops cohesiveness. If the soil is dried in the air, it becomes more cohesive and, therefore, its resistance goes up (Fookes, 2007). From a quantitative perspective, there is no published comprehensive study examining the association between soils' geomorphological processes and geotechnical properties. The existing studies have narrowly concentrated on the relationship between soils' geomorphological parameters and physical properties as well as the association between soils' physical and geotechnical properties. Consequently, little is known about the correlation between soils' geomorphological and geotechnical features. To address this gap, the current study sought to explore the relationship between geomorphological parameters and geotechnical properties of soils accumulated in alluvial fans. The primary aim of this study is to analyze the relationships between the morphometric characteristics of upland catchment basins and the geotechnical properties of soil. Specifically, the research focuses on examining how the basin area, channel flow length, and basin slope influence soil cohesion and internal friction angle. The findings will be helpful in macro discussions of urban management, industrial towns, and development plans. They can also contribute to locating the best options for development plans.

Materials and Methods

Study area

Dane-Khoskh anticline is located in the western side of Kermanshah Province between Sarpol-e Zahab and Gilan-e Gharb, and is part of folded Zagros (Bahrami, 2013; Bahrami et al, 2018). The highest part of this anticline with a height of 1352 m is located in its central part, while the lowest point, which is 600 m high, is in its northwestern part. Direh plain and Qaleh Shahin plain are respectively located in its southwestern and northeastern sides. The anticline stretches from the northwest to the southeast. Moving from the center to the northwest of the anticline, one can observe slight changes in the western side. The width of the anticline in the southeastern, central, and northwestern parts respectively are 6400 m, 5000 m, and 1300 m. It is advancing in both northwestern and southeastern sides. In the western side of the anticline, the layers' slope is steeper in the southwestern part than the northeastern one. In general, layer slope steepness goes up from the northwest to the southeast as one approaches the center of the anticline, which is its highest spot. In the central part of the anticline, there is a slight depression and deviation of flow channels parallel to the anticline axis. This is attributed to the operation of a reverse fault in the southwestern slope. The entire anticline is made of Asmari limestone formation. The occurrence of earthquakes, narrow valleys on the edge of the anticline, and changes in the direction of drainage networks, which are some geological and geotechnical evidence of the study region, show that the studied anticline is still rising and is tectonically active (Bahrami, 2013; Bahrami, 2019). The area climatically features a relatively dry to Mediterranean climate, characterized by mild winters and warm summers. The average rainfall at the nearest rain gauge station to the study area (Sarpol-e Zahab Station) during the statistical period (2000–1989) is 468 millimeters. Figure 1 showes the location of the study area. Figure 2 shows the location the the samples were obtained in the edge of Daneh-Khoshk anticline.

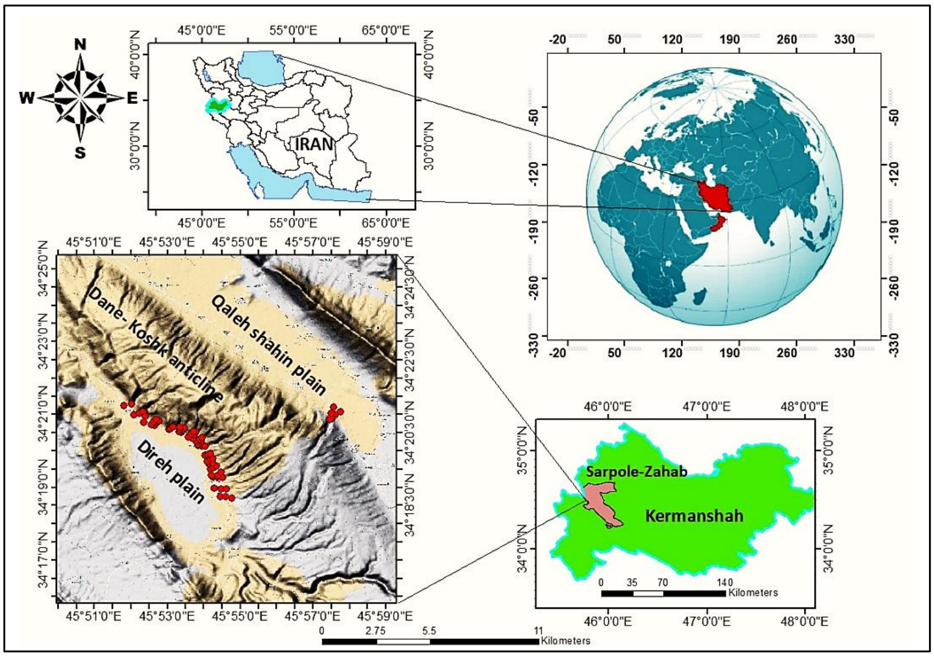


Fig. 1: Location of the study area

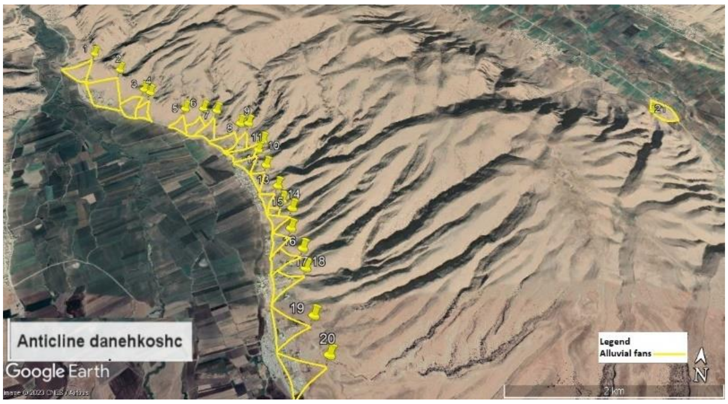


Fig. 2: Alluvial fans' location on the edge of Daneh-Khoshk anticline and the spots were the samples were obtained

Study Material

In addition to the study of paper and scientific references and field-based works, experimental-inductive method was used for data collection and analysis. The results were obtained based on laboratory principles. In order to examine the relationship between the area, slope, and length of the main flow channel of upland catchment basin of alluvial fans with shear resistance properties (e.g., cohesion and angle of internal friction), 21 alluvial fans located in Direh Rural District in Gilan-e Gharb County in western Iran were selected. Given that discrepancies in rock type can influence soil properties, care was taken to select alluvial fans with similar sediment types. To this end, first geological maps, satellite images, and field observation of Sarpol-e Zahab and Gilan-e Gharb were carried out. As a result, the southern slope of Dane-Khoskh anticline was selected as the best area. The upland catchment basin of all alluvial fans in this region are made of thick Asmari formation. Upon selecting the alluvial fans and drawing their maps, their upland basins and flow networks were identified. Then, the area, length of the main flow channel, and slope of the upland catchments were gauged. Sampling was conducted systematically from three point. This was followed by collecting samples from the top, middle, and bottom of the alluvial fans. Samples were obtained from five different spots of each of these three parts which about 10 meter apart. The samples were subsequently mixed and the average sample was gleaned through dividing the mixture into four parts. Following this procedure will make it more likely to have a sample with utmost similarity to the soil composition of the study area. Figure 3 Field of sample collection from the study area. The samples were then taken to the laboratory to conduct lithological, sedimentological, and geotechnical tests. The samples were promptly transferred to the Part Strength Testing Laboratory for grain size analysis and subsequently sent to the Kavosh Pey Sharan Laboratory for direct shear testing. Sediment particle size analysis was conducted on the samples following ASTM-D421. To examine geotechnical properties of alluvial fans' sediments, soil resistance parameters (including cohesion and angle of internal friction) were assessed via running direct shear test in line with ASTM-D3080. In this study, 21 alluvial fans located on the margins of the Daneh Khoshk anticline were selected. Three samples were collected from the upstream, midstream, and downstream sections of each fan. In total, 63 collected samples underwent direct shear testing. In order to minimize the impact of density and moisture on soil resistance parameters, the tested samples had the same degree of moisture (i.e. percent 18) and the same weight per unit volume (i.e. 1.6 g/cm^3). Figure 4 Image of the laboratir environment. SPSS, Excel, and GIS software programs were exploited to analyze the data. For the analysis of relationships between variables, Microsoft Excel was used for univariate analysis, including basic statistical calculations and trend examination. Additionally, SPSS was employed for multivariate analysis, encompassing correlation tests, regression analysis, and statistical significance evaluation. These methods enabled a more precise examination of the relationships between the studied variables and provided a quantitative assessment of the results. In this study, the points related to the study area were first extracted using Google Earth. Then, these points were saved using the Export to KML/KMZ feature and imported into the ArcMap environment within the GIS software. After importing the data, the points were processed, geographic positions were corrected, and appropriate layers for spatial analysis were created. In the next step, the points were mosaicked to ensure seamless and analyzable data within the GIS environment. Explore the associations between geomorphological parameters and physical properties as well as the relationships between physical and geotechnical properties of soil. At the end, the findings were conflation to shed light on the correlation between soil resistance parameters and morphometric properties of upland catchment basins in alluvial fans.

Fig. 3: Field of sample collection from the study area

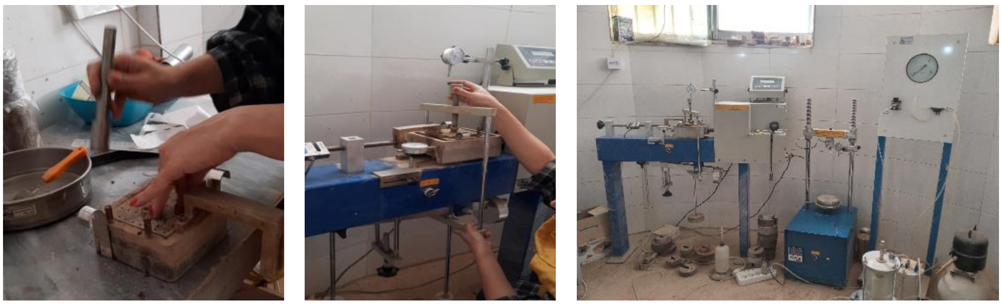


Fig. 4: Image of the laboratir environment

Results and Discussion

The present study sought to examine the relationship between morphometric parameters of upland catchment basin and soil resistance properties of alluvial fans. As such, the study intended to explore physical properties of the grains including shape, surface texture, sedimentation of sediment particles in alluvial fans. Samples were obtained from the top, middle, and bottom of 21 alluvial fans on the edge of Dane-Khoshk anticline. In total, 63 direct shear tests in line with ASTM-D3080 were carried out to estimate the angle of internal friction.

The relationship between grain roundness and area, slope, and length of main flow channel in the upland catchment basin of alluvial fans

Grains' roundness refers to the degree of curvature of the corners or edges. In various geological environments, grain roundness depends on geomorphological processes. Alluvial fans comprise one of geological landforms whose roundness is a function of geomorphological processes. The degree of roundness in different parts of alluvial fans depends on the morphometric properties of their catchment basin. It is influenced by the duration of grain transfer flow as well as the area, slope and length of the main flow channel in the upland catchment basins. Figure 5 illustrates the degree of roundness in the samples obtained from the 21 alluvial fans in light of their catchment basin area.

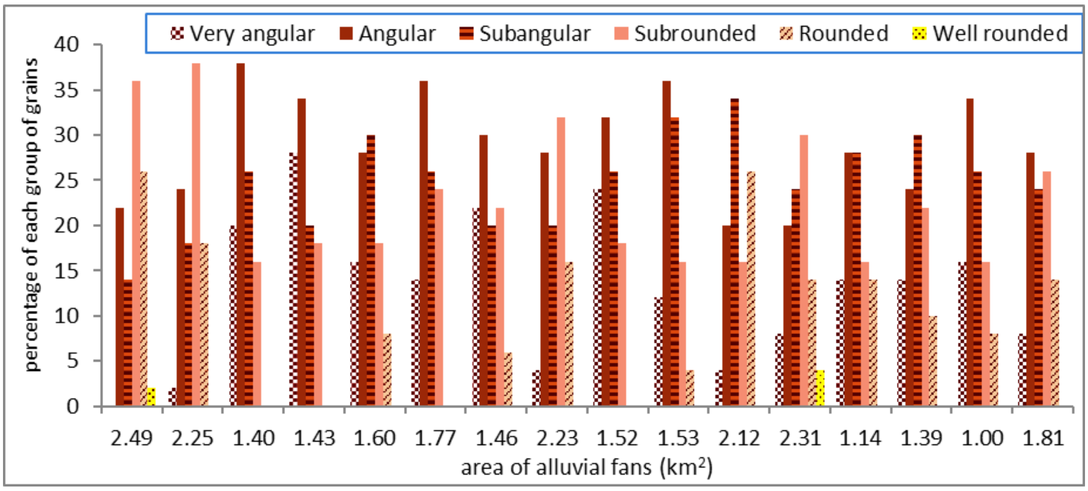


Fig. 5: The relationship between the area of upland catchment basin of alluvial fans and grain roundness for grain sizes ranging from 4.75 mm to 25 mm

Various criteria have been proposed to classify grains in terms of the degree of their roundness. Nonetheless, it is highly difficult and time consuming to estimate grain roundness from a statistical perspective. Thus, Powers' (1953) categorization, which is in turn inspired by Pettijohn (1949), was used to visually check the degree of grain roundness. Accordingly, grains are divided into six groups based on their roundness – namely very angular, angular, subangular, subrounded, rounded, and well rounded. Figures 6, 7, and 8 and Table 1 present the results for the degree of roundness of the samples collected from the 21 alluvial fans in light of the area of their upland catchment basins. Based on Figure 6, the area of catchment basin influences the flow intensity and energy. Higher area of upland catchment basin results in higher sediment particle abrasion. Therefore, grains obtained from alluvial fans with bigger catchment basins are more rounded. Figure 5 shows that, given the direct association between area and length of the main flow channel, grains in bigger basins will travel longer distances over low slope surfaces in the main flow channels to arrive in the exit point. As a result, the rise in the length of the main flow channel leads to more rounding. Considering the slopes of catchment basins in Figure 8, it is argued that sediment particles in steep slopes, which are generally located at the top of alluvial fans with smaller area and shorter length of main channel flow, are less influenced by geomorphological processes, rendering them more angular.

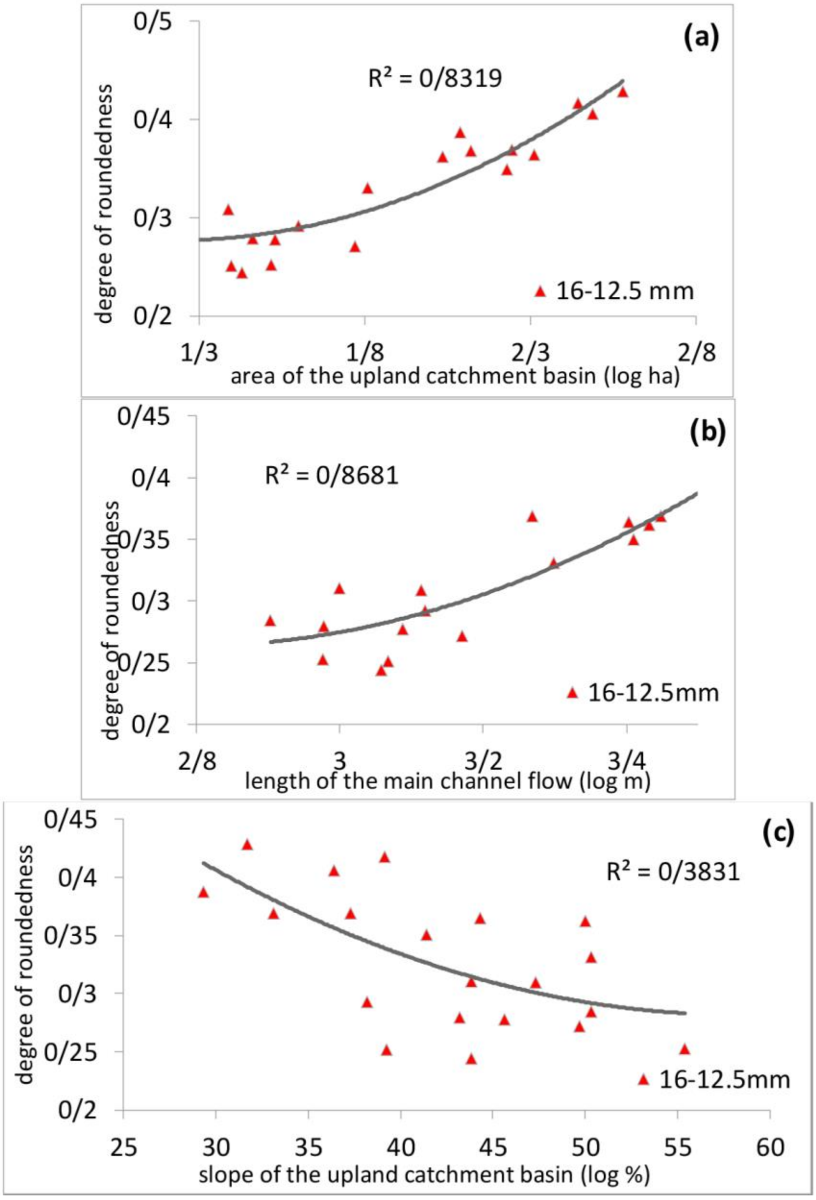


Fig. 6: a: The relationship between the area of upland catchment basin and degree of roundness in grains ranging from 12.5 to 16 mm in size; b: The relationship between the length of the main flow channel in the upland catchment basin and degree of roundness in grains ranging from 12.5 to 16 mm in size; c: The relationship between the slope of the upland catchment basin and degree of roundness in grains ranging from 12.5 to 16 mm in size

Based on Figure 6 (a), there is a significant direct correlation between the area of catchment basin and the degree of sediment particle roundedness (R^2 = 83). In other words, percent 83 of the variation in sediment particle roundness is explained by the area of upland catchment basin, while percent 17 of the variation is accounted for by other factors. Table 1 also shows that the correlation coefficient is equal to percent 86, meaning that percent 85 of the variation in sediment particle roundness is directly influenced by the area of upland catchment basin. Therefore, as the area of catchment basin goes up, so does the degree of sediment particle roundness, which in turn decreases soil resistance. According to Figure 6 (b), there is a significant direct correlation between the length of the main flow channel and the degree of sediment particle roundedness in alluvial fans. The R square is equal to percent 86, indicating that percent 86 of the overall variance in soil roundnce is explained by the length of the main flow channel. The correlation coefficient of percent 91 shows that percent 91 of the variance in sediment particle roundness is accounted for by the length of the main flow channel. Figure 6 (c) further demonstrates a significant inverse association between the slope of upland catchment basin and sediment particle roundedness in alluvial fans. The R square is percent 38 and the correlation coefficient is equal to percent 60, which are smaller than the indices obtained for the area and length of the main flow channel. In other words, there is a statistically meaningful inverse association between the degree of roundness and the slope of catchment basin. More precisely, as the slope of upland catchment basin goes up, the degree of sediment particle roundness declines. The inverse relationship between slope and grain roundness was observed in the study, indicating that steeper slopes result in less rounded grains. This phenomenon can be attributed to the role of gravity on steep slopes, where particles experience shorter transport distances and increased kinetic energy. Consequently, grains have fewer opportunities for abrasion and smoothing during transportation. Steeper slopes also enhance particle fragmentation and angularity due to the higher impact forces, further contributing to reduced roundness.

The relationship between surface texture with the area, slope, and length of the main flow channel in the upland catchment basin of alluvial fans

Surface texture is used to describe the roughness and complications at the grain surface. Sediment particles vary in terms of the degree of roughness in their surface. Surface texture is influenced by the geological environment of the place sediment particle are accumulated as well as grain mineralogy and lithology. In alluvial fans, surface texture causes changes in sediment particles' shape through geomorphological processes like erosion, weathering, and sedimentation. There is no quantitative method to assess sediment particle s' surface texture. In the current study, the collected grains were divided into six categories depending on their roughness, i.e. very rough, rough, subrough, subsmooth, smooth, and very smooth. Figure 7 demonstrates the degree of roughness in the samples collected from the 21 alluvial fans in light of the area of upland catchment basin.

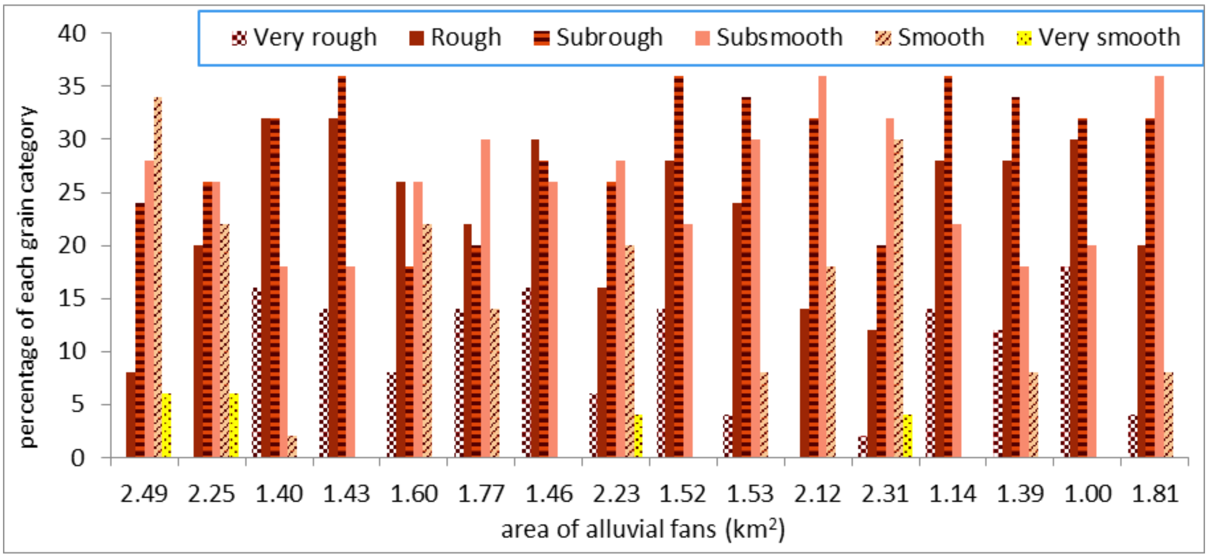


Fig. 7: The relationship between the area of alluvial fans' upland catchment basin and surface texture in grains ranging from 4.25 to 25 mm in size.

Surface texture for the samples obtained from the 21 alluvial fans are displayed in Figures a, b, and c as well as Table 1 in light of the area, length of the main flow channel, and slope of the catchment basin. The results show that, in alluvial fans with bigger areas and longer main flow channels of the catchment basin, the grains travel longer distances and, therefore, have smoother surface texture. At the bottom of alluvial fans, the slope declines and the area goes up. In such a situation, the surface texture is mainly impacted by geomorphological processes like weathering. In fact, besides rounding the sediment particles, weathering creates porous and weathered surfaces along grains' edge. After leaving the mountains and steep slopes, the grains settle over larger areas. Due to their cohesive nature, clay grains stick on weathered and porous surfaces, facilitating the soil sedimentation process through creating rough surface texture. As a result, with the rise of the area and the length of the main flow channel and the decline of catchment basin's slope, surface texture becomes less smooth and the percentage of grains with rough surface texture goes up.

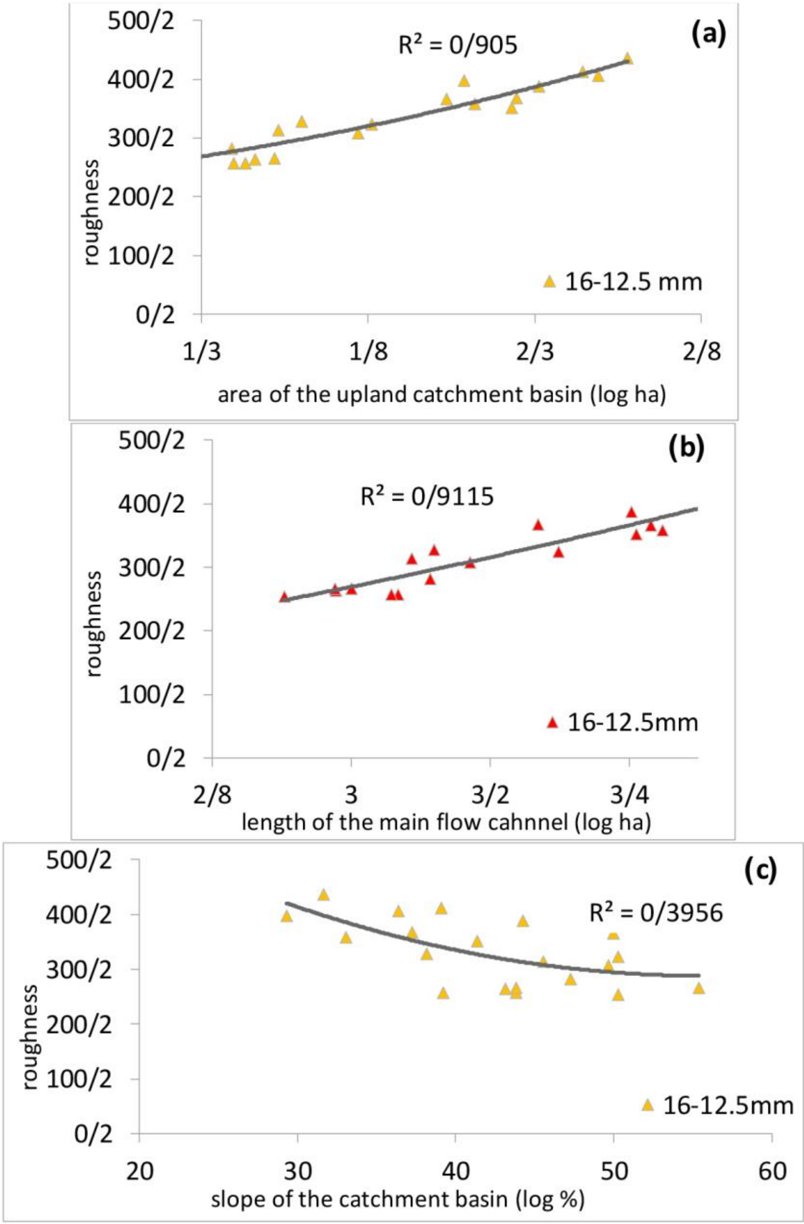


Fig. 8: a: The relationship between the area of upland catchment basin and surface texture of grains ranging from 12.5-16 mm in size; b: The relationship between the length of the main flow channel and surface texture of grains ranging from 12.5-16 mm in size; c: The relationship between the slope of upland catchment basin and surface texture of grains ranging from 12.5-16 mm in size.

According to Figure 8 (a), R^2 = 90, which means that percent 90 of the variation in grain surface texture is explained by the area of alluvial fans' upland catchment basin. Moreover, R = 89, indicating that percent 89 of the variance in grain roughness is accounted for by the direct impact of the area of catchment basin. The high correlation coefficient between the two parameters shows that, as the catchment basin area rises, grain surface texture becomes smoother. Following Figure 8 (b), R^2 = 91, demonstrating that percent 91 of the variance in grain surface structure is attributed to the length of the main flow channel. Also, the correlation coefficient is equal to percent 95, indicating the strong association between the two variables. Thus, longer main flow channels will likely yield smoother surface texture. Moreover, the results show that percent 95 of the variance in grain roughness is directly influenced by the length of the main flow channel. Figure 8 (c) indicates that R^2 and R respectively are percent 39 and percent -60. These indices demonstrate that the slope of the catchment basin has a weaker association with surface texture in comparison to the area and length of the main flow channel. Thus, there is no strong relationship between grain surface texture and the slope of catchment basin. Moreover, given that the correlation coefficient of the relationship between surface texture and slope has yielded a negative value, the rise in the slope of the catchment basin reduces the smoothness of surface texture. Sedimentological properties, such as grain roundness and surface texture, play a significant role in influencing soil resistance characteristics. Grain roundness affects the contact points between particles, which directly impacts the shear strength and compaction behavior of the soil. Well-rounded particles generally exhibit lower shear strength due to reduced interlocking.between grains, while angular particles enhance frictional resistance and stability. Similarly, the surface texture of particles contributes to internal friction, with rougher textures increasing particle interlocking and overall soil resistance. Figure 9 demonstrates grains' shape.

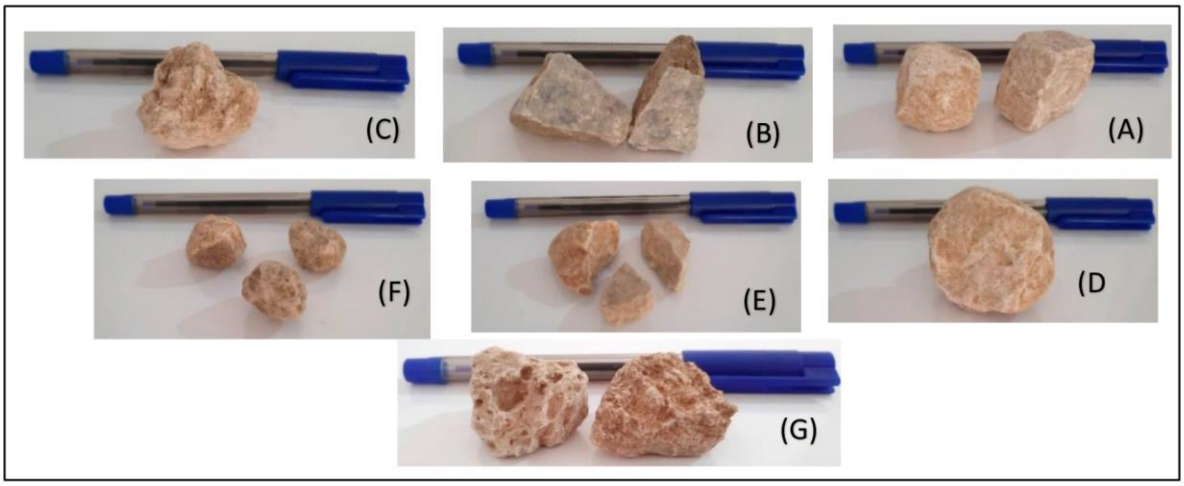


Fig. 9: A: elimination of angular edge and grain roundness; B: calcium carbonate cementation in grain surface; C: clay grains' sedimentation; D: smooth surface texture; E: angular grains; F: rounded grains; G: rough and porous surface texture.

As previously mentioned, the numbers used to assess surface texture and roundness in the grain samples were not modeled after any prior study; rather, they were originally utilized in the current research to quantify the collected data. Since the present study aimed to explore the impact of morphometric properties of alluvial fans' catchment basins on grain roundness and surface texture, both univariate and multivariate analyses were carried out. SPSS and Excel were used to estimate the statistical indices like the ANOVA (P-value, Sig), coefficient of determination (R^2), and correlation coefficient (R). Besides, to check the independence of error in multivariate relationships, Durbin-Watson statistic was exploited to gauge the associations. The results are presented in Table 1.

Table 1: The results of univariate and multivariate analyses to examine the relationships between morphometric properties of alluvial fans' upland catchment basins and the degree of grain roundedness and surface texture.

Parameter type	**Grain size 12.5-16 mm**				**Parameter type**	**Grain size 12.5-16 mm**			
Roundedness	**R square**	**R**	**Sig**	**Durbin-Watson**	**Surface texture**	**R square**	**R**	**Sig**	**Durbin-Watson**
Relationship the catchment basin area and roundness	0.746	0.863	9.27	-	Relationship the catchment basin area and surface texture	0.895	0.899	2.84	-

Relationship the length channel catchment basin area and roundness	0.841	0.917	1.28	-	Relationship the length channel catchment basin area and surface texture	0.910	0.954	7.1	-
Relationship the catchment basin slope and roundness	0.363	-0.603	0.004	-	Relationship the catchment basin slope and surface texture	0.367	-0.606	0.004	-
Relationship the area and length channel of the catchment basin with roundness	0.840	0.916	0	1.696	Relationship the area and length channel of the catchment basin with surface texture	0.932	0.966	0	2.350
Relationship the area, length, and slope channel of the catchment basin with roundness	0.844	0.918	0	1.507	Relationship the area, length, and slope channel of the catchment basin with surface texture	0.935	0.967	0	2.351

Based on the results of univariate analysis, the highest values for coefficient of determination, correlation coefficient and significance level were recorded for the area and length of the main flow channel of catchment basin. The corresponding values for the catchment basin slope were notably lower. Thus, there is a significant direct correlation between the area and length of the main flow channel of catchment basin with grain roundness and surface texture in alluvial fans. This indicates the goodness of fit of the relationships between independent and dependent variables.

Moreover, regarding the results of multivariate analysis, the area and length of the main flow channel registered high values in coefficient of determination and correlation coefficient while studying their associations with grain roundness and surface texture. The highest correlation coefficients and coefficient of determination (Sig = 0) were observed for the multivariate relationships between the area, length of the main flow channel, and slope of the catchment basin with grain roundness and surface texture.

Independence of errors is one of the assumptions of regression. The errors are the difference between obtained values and predicted values in the regression equation. One cannot run regression if the errors correlate with each other.

The Durbin-Watson statistic is used to explore the independence of errors. Output values ranging from 1.5 to 3 are indicative of error independence. Based on the results of bivariate and trivariate analysis presented in Table 1, the Durbin-Watson statistic supports the independence of errors. Thus, it is possible to run multivariate analysis. With respect to the morphometric properties of alluvial fans, using the area and length of the main flow channel as independent variables can offer a good model for explaining variations in grain roundness and surface texture.

In contrast, using the slope of alluvial fans as the sole independent variable cannot properly account for variations in grain roundness and surface texture, indicating that the proposed model is not a reliable one. This could be attributed to the inverse association between the slope and area of alluvial fans' catchment basin.

The relationship between morphometric properties of alluvial fans and angle of internal friction at the top, middle, and bottom of alluvial fans

The degree of the angle of internal friction differs in various parts of alluvial fans. It ranges from 44.3° at the top to 25.6° at the bottom of alluvial fans, and is influenced by morphometric properties including the area, length of the main flow channel, and slope of upland catchment basin. Figures 10-15 present the results in this regard for the studied alluvial fans in Dane-Khoshk anticline. The results suggest that the rise in the area and length of the main flow channel of alluvial fans' catchment basin leads lower degrees of the angle of internal friction. Also, the findings demonstrate that the increase in the slope of alluvial fans' catchment basin results in higher degrees of the angle of internal friction. The correlation coefficient for the association between these two variables, however, is lower than the ones obtained for the area and length of the main flow channel.

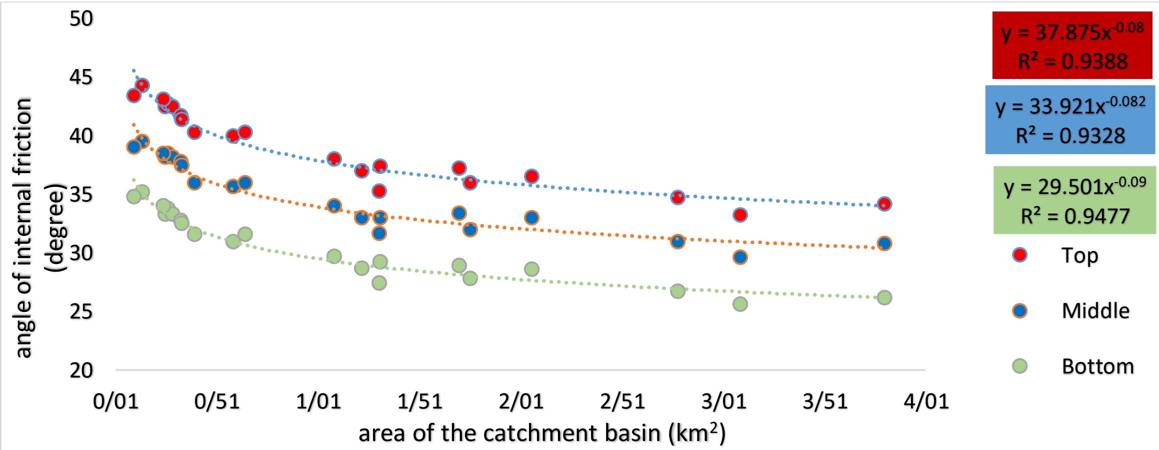


Fig. 10: The regression relationship between the area and the angle of internal friction at the top, middle, and bottom of alluvial fans.

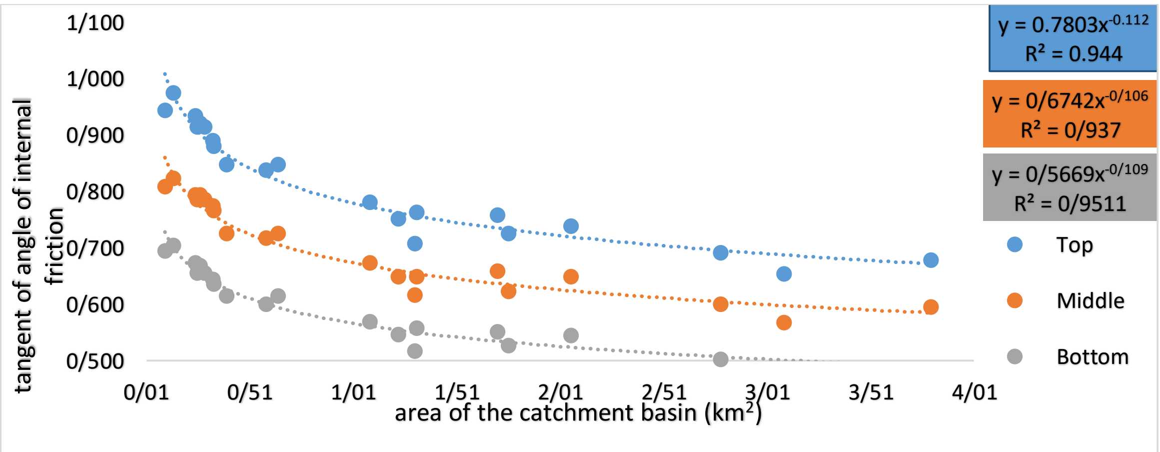


Fig. 11: The regression relationship between the area and internal friction tangent at the top, middle, and bottom of alluvial fans.

In the Mohr-Coulomb model, the tangent of angle of internal friction is used to determine soil's shear strength. Thus, in the figures above, the relationships between the area of catchment basin with the angle of internal friction and the tangent of angle of internal friction were explored. The increase of the area of upland catchment basin raises the angle of internal friction in alluvial fans. At the top of alluvial fans, sediments travel shorter distances. They are therefore bigger in size, angular, and rough. Thus, these grains have higher degrees of angle of internal friction. As one moves down the alluvial fans, sediment particles are scattered over larger areas. Because these sediment particles travel longer distances, they are more rounded, smaller in size, and smoother in terms of surface texture. As a result, the degree of the angle of internal friction is smaller at the bottom of alluvial fans. Additionally, the presence of cohesive clay grains at the bottom of alluvial fans enhances soil's uniaxial compressive strength. Given that R^2s range from percent 93 to 95, it is inferred that percent 95 of the variation in the grains' angle of internal friction is accounted for by the area of the upland catchment basin, with the rest of the variation (percent 5) being attributed to other factors. The results of univariate analysis (Table 2) indicate that the correlation coefficient is percent -90. Thus, there is a significant inverse relationship between these two parameters. In other words, larger catchment basin areas will yield lower degrees of angle of internal friction in grains. The association between soil's angle of internal friction and the slope of catchment basin was also explored, with the results being illustrated in Figures 12 and 13.

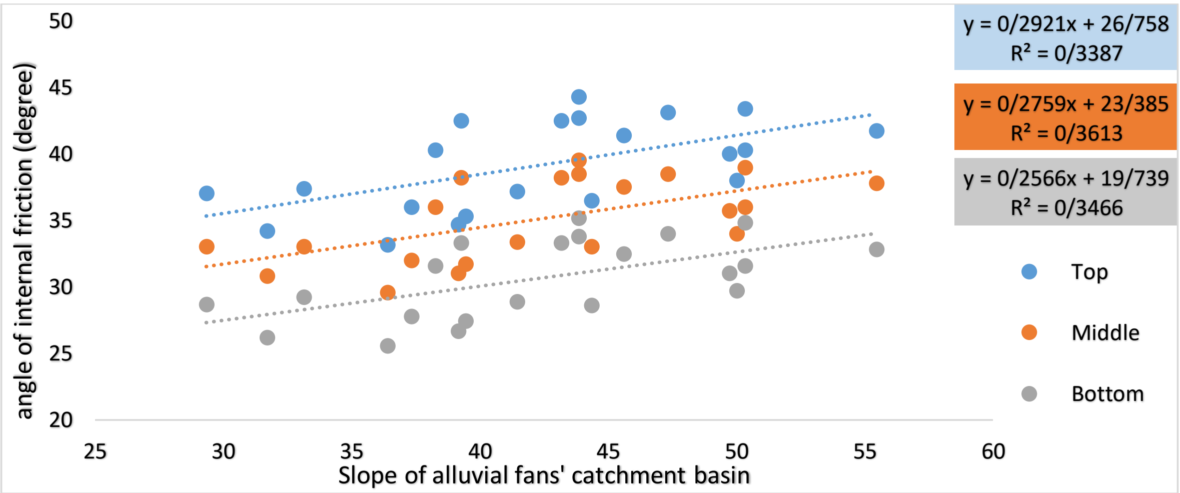


Fig. 12: The regression relationship between catchment basin's slope and angle of internal friction at the top, middle, and bottom of alluvial fans.

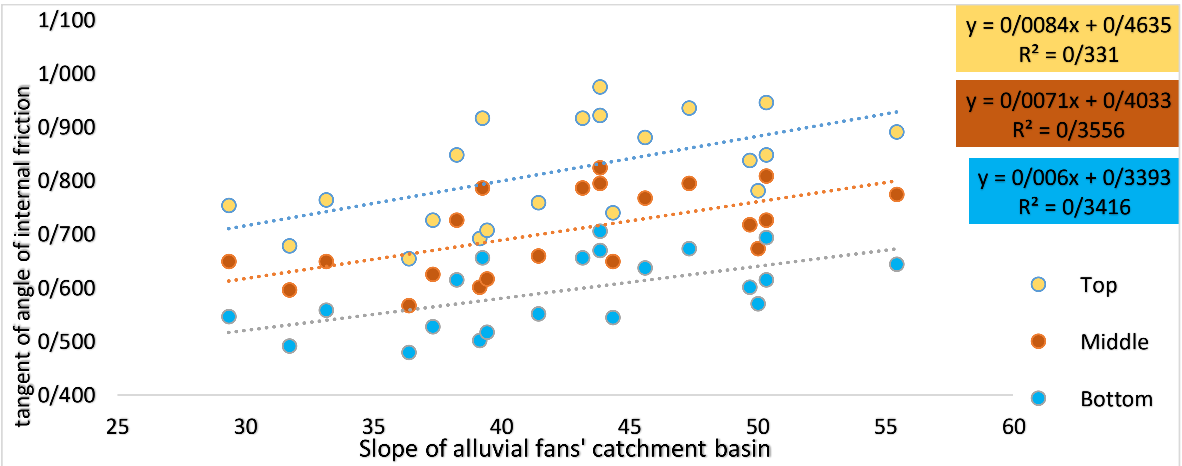


Fig. 13: The regression relationship between catchment basin's slope and the tangent of angle of internal friction at the top, middle, and bottom of alluvial fans.

Figures 12 and 13 show that the rise in the slope of upland catchment basin results in the higher degree of angle of internal friction. Slope is negatively associated with the area and length of the main flow channel. Thus, at the top of alluvial fans, sediment particles are transported in shorter distances due to the smaller area and steeper slope. There are therefore less influenced by erosion and weathering, and more affected by gravity and transportation. As such, the sediment particles in steep slopes at the top of alluvial fans are more angular and possess rougher surface texture, hence the higher degree of their angle of internal friction. As one moves down the alluvial fans, the slope declines. Thus, the grains become more rounded with smoother surface texture, hence the decline in the degree of their angle of internal friction. The R^2 values range from percent 33 to 36, indicating that only around percent 33 of the entire variation in the angle of internal friction can be attributed to the slope of catchment basin. Moreover, R values are positive and vary from percent 58 to 60, demonstrating that steeper slopes in catchment basins are more likely to produce grains with higher degrees of the angle of internal friction. The low correlation coefficient and the fact that the points are not clustered around the regression line may be attributed to the discrepancy in the area of alluvial fans' catchment basins, which is inversely associated with the slope. We also examined the correlation between the angle of internal friction and the length of the main flow channel, with the results being illustrated in Figures 14 and 15. Figures 14 and 15 indicate that longer main flow channels produce grains with higher degrees of the angle of internal friction. This could be explained in light of the impact of transportation on grain shape. Given the direct association between the length of the main flow channel and the area of catchment basin, larger areas boost the process of grain abrasion. Therefore, at the bottom of alluvial fans, the settled grains are mainly rounded and possess smooth surface structure, hence their lower degree of their angle of internal friction.

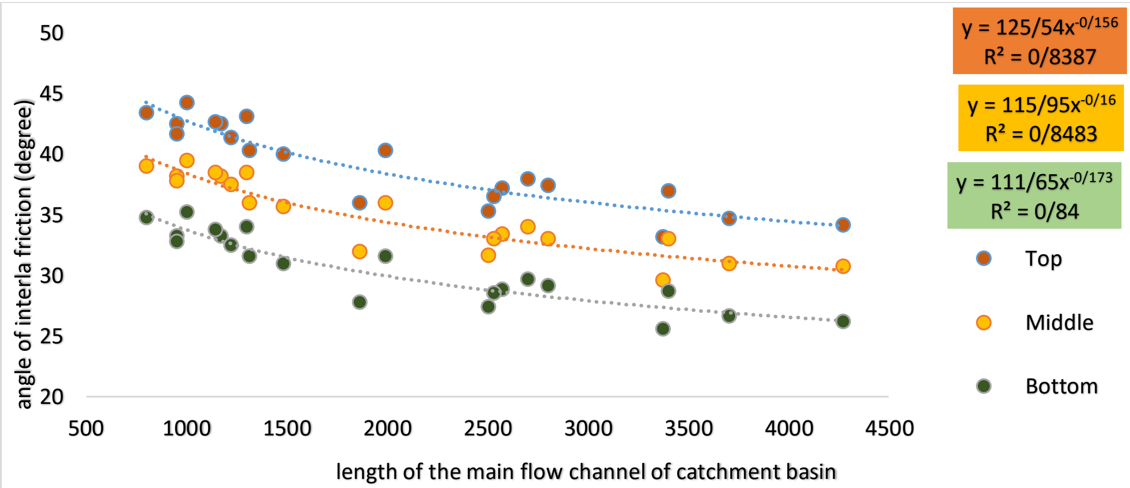


Fig. 14: The regression relationship between the length of the main flow channel and grains' angle of internal friction at the top, middle, and bottom of the alluvial fans.

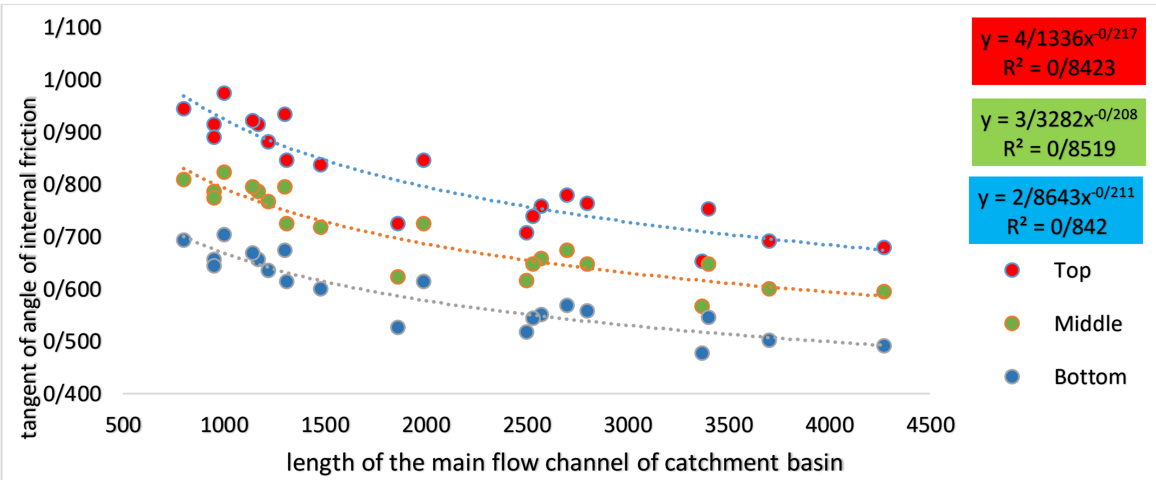


Fig. 15: The regression relationship between the main flow channel and tangent of the angle of internal friction at the top, middle, and bottom of alluvial fans.

According to Figures 14 and 15, R^2 ranges from percent 84 to 85. Thus, percent 85 of the variation in the angle of internal friction is accounted for by the length of the main flow channel. Moreover, R varies from percent -89 to -90, indicating that there is a significant inverse association between the angle of internal friction and the length of the main flow channel. In other words, the rise in the length of the main flow channel results in smaller angle of internal friction in the grains obtained from the alluvial fans. Based on the displayed figures, the correlations between the angle of internal friction and morphometric properties of alluvial fans' catchment basin can be separately demonstrated. To further go to the details, the correlations and regressions between morphometric properties of catchment basin and the angle of internal friction were calculated for the top, middle, and bottom of the alluvial fans. Table 2 gives information about the R^2 values and the significance level of multivariate analyses.

Table 2: The results of analyzing the relationship between morphometric properties of alluvial fans and grains' angle of internal friction.

Parameter type	R square	R	P-value	Parameter type	R square	R	P-value
Relationship area and angle of internal friction at the top	0.79	-0.90	1.27	Relationship area and tangent of angle of internal friction at the top	0.77	-0.89	2.88
Relationship area and angle of internal friction in the middle	0.77	-0.90	2.78	Relationship area and tangent of angle of internal friction in the middle	0.76	-0.89	4.68
Relationship area and angle of internal friction at the bottom	0.79	-0.90	1.43	Relationship area and tangent of angle of internal friction at the bottom	0.77	-0.900	2.56
Relationship slope and angle of internal friction at the top	0.31	0.58	0.01	Relationship slope and tangent of angle of internal friction at the top	0.33	0.57	0.006
Relationship slope and angle of internal friction in the middle	0.33	0.60	7.34	Relationship slope and tangent of angle of internal friction in the middle	0.32	0.59	0.008
Relationship slope and angle of internal friction at the bottom	0.33	0.58	0.00	Relationship slope and tangent of angle of internal friction at the bottom	0.31	0.584	0.010
Relationship the length channel and angle of internal friction at the top	0.79	-0.89	1.26	Relationship the length channel and tangent of angle of internal friction at the top	0.78	-0.89	1.89
Relationship the length channel and angle of internal friction in the middle	0.80	-0.90	1.01	Relationship the length channel and tangent of angle of internal friction in the middle	0.79	-0.89	1.31
Relationship the length channel and angle of internal friction at the bottom	0.79	-0.89	1.48	Relationship the length channel and tangent of angle of internal friction at the bottom	0.78	-0.89	2.00

The results of univariate analysis in Table 2 show that although the impact of slope is significant, it cannot be regarded as the sole parameter to analyze the relationships between catchment basins' morphometric properties and grains' resistance properties in various parts of alluvial fans. Conversely, the area and length of the main flow channel can function as independent variables to explain variations in the angle of internal friction of the grains obtained from the alluvial fans. The regression model for the relationship between the area of catchment basin and angle of internal friction as well as the regression model for the relationship between the length of the main flow channel and angle of internal friction are good models indicating the fitness of the models explicating the association between independent and dependent variables. Consequently, these two parameters can properly explain variations in the soil's angle of internal friction in alluvial fans. To further examine the associations between the soil's angle of internal friction and morphometric parameters of alluvial fans' catchment basin using SPSS, significance values, R^2, and R were explored. Also, with the aim of assessing error independence in multivariate relationships, the Durbin-Watson statistic was utilized. This test examines multiple relationships and multiple regressions. Table 3 provides a detailed presentation of the results of multivariate analyses.

Table 3: The results of multivariate analyses for examining the relationships between morphometric properties of alluvial fans' catchment basin and soil's angle of internal friction.

Parameter type	R square	R	Sig	Durbin-Watson	Parameter type	R square	R	Sig	Durbin-Watson
Relationship area and length channel with angle of internal friction at the top	0.86	0.927	0	1.983	Relationship area and length channel with the tangent of angle of internal friction at the top	0.846	0.925	0	1.973
Relationship area and length channel with angle of internal friction in the middle	0.854	0.924	0	2.001	Relationship area and length channel with the tangent of angle of internal friction in the middle	0.847	0.92	0	2.014
Relationship area and length channel with angle of internal friction at the bottom	0.857	0.926	0	1.836	Relationship area and length channel with the tangent of angle of internal friction at the bottom	0.847	0.92	0	1.831
Relationship area, length channel, and slope with angle of internal friction at the top	0.861	0.928	0	1.999	Relationship area, length channel, and slope with the tangent of angle of internal friction at the top	0.847	0.92	0	1.989
Relationship area, length channel, and slope with angle of internal friction in the middle	0.856	0.925	0	2.023	Relationship area, length channel, and slope with the tangent of angle of internal friction in the middle	0.848	0.921	0	2.036
Relationship area, length channel, and slope with angle of internal friction at the bottom	0.858	0.926	0	1.867	Relationship area, length channel, and slope with the tangent of angle of internal friction at the bottom	0.847	0.921	0	1.858

The results of bivariate analyses for the relationships between the two independent variables namely the area and length of the main flow channel and the angle of internal friction at the top, middle, and bottom of alluvial fans show that the correlation coefficient is suitable and the coefficient of determination (Sig = 0) indicate a significant inverse relationship between catchment basins' area and length of the main flow channel with grains' angle of internal friction. Thus, the bivariate regression model in which catchment basins' area and length of main flow channel are independent variables can properly predict variations in the angle of internal friction. Also, examining the errors obtained through the Durbin-Watson statistic in the bivariate analyses shows the independence of errors; therefore, it is possible to use the bivariate regression model with linear relationships. On the other hand, the results of trivariate analyses show that the correlation coefficient and coefficient of determination for the relationships between the three independent variables namely the area, length of the main flow channel, and slope of catchment basin with the angel of internal friction are statistically significant (Sig = 0) while the error percentage is at its lowest. The Durbin-Watson statistic supports the independence of errors. Thus, it is possible to use the multivariate regression model with linear relationships.

Comparing differences in the angle of internal friction at the top and bottom of alluvial fans in light of catchment basins' morphometric properties

Figures 16-21 present the results of comparing the maximum and minimum difference in the angle of internal friction in the soils obtained from the top and bottom of alluvial fans based on the area, slope, and length of the main flow channel of catchment basin. The results are compared in Table 4. Table 5 also provides information about the correlations and regressions between morphometric properties of upland catchment basin and soils' angle of internal friction at the top and bottom of alluvial fans.

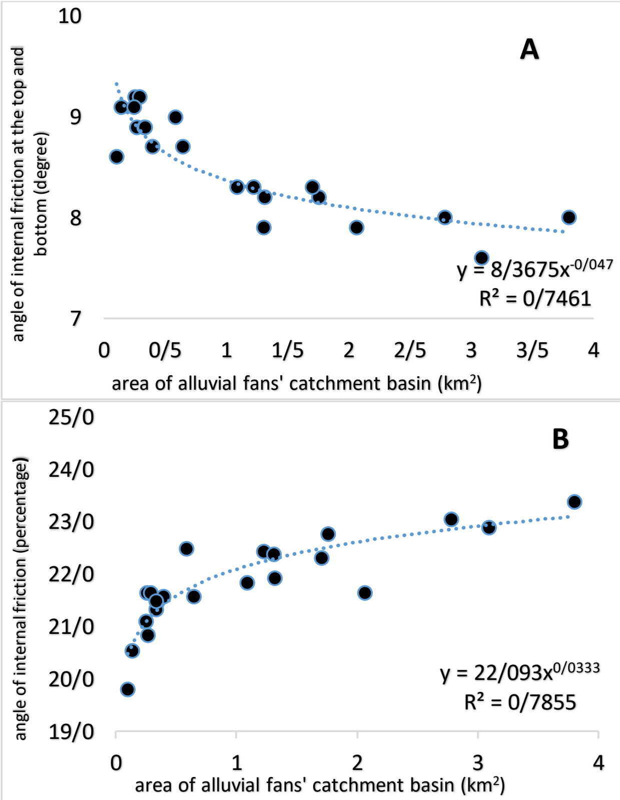
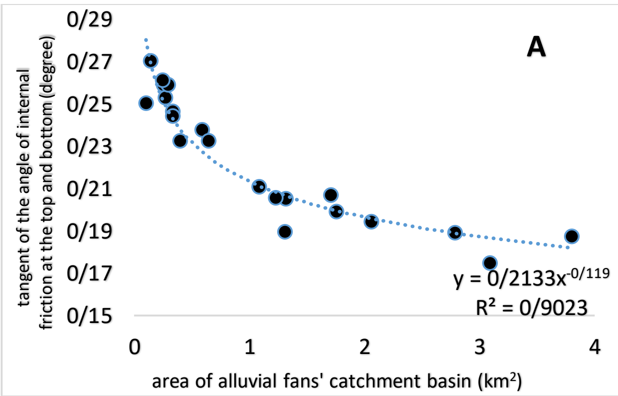


Fig. 16: A: The difference between soils' angle of internal friction at the top and bottom of alluvial fans in light of the area of catchment basin; B: The percentage of the difference between grains' angle of internal friction at the top and bottom of alluvial fans in light of the area of catchment basin.



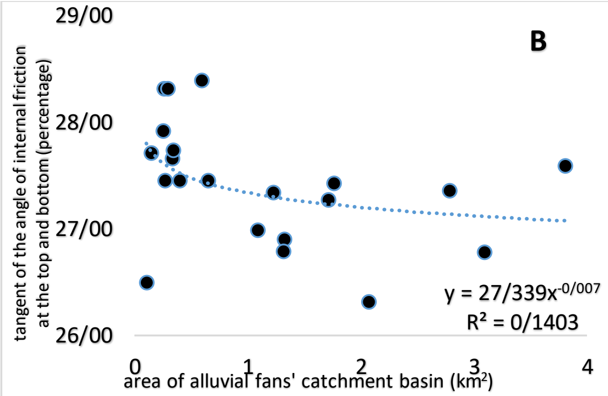


Fig. 17: A: The difference between the tangent of soils' angle of internal friction at the top and bottom of alluvial fans in light of the area of catchment basin; B: The percentage of the difference between the tangent of soils' angle of internal friction at the top and bottom of alluvial fans in light of the area of catchment basin

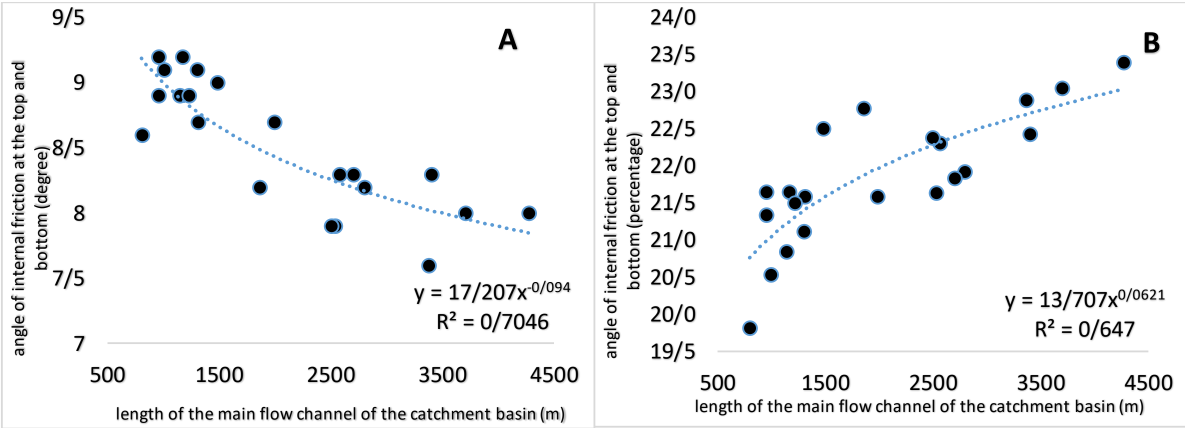


Fig. 18: A: The difference between soils' angle of internal friction at the top and bottom of alluvial fans in light of the length of catchment basin's main flow channel; B: The percentage of the difference between soils' angle of internal friction at the top and bottom of alluvial fans in light of the length of catchment basin's main flow channel.

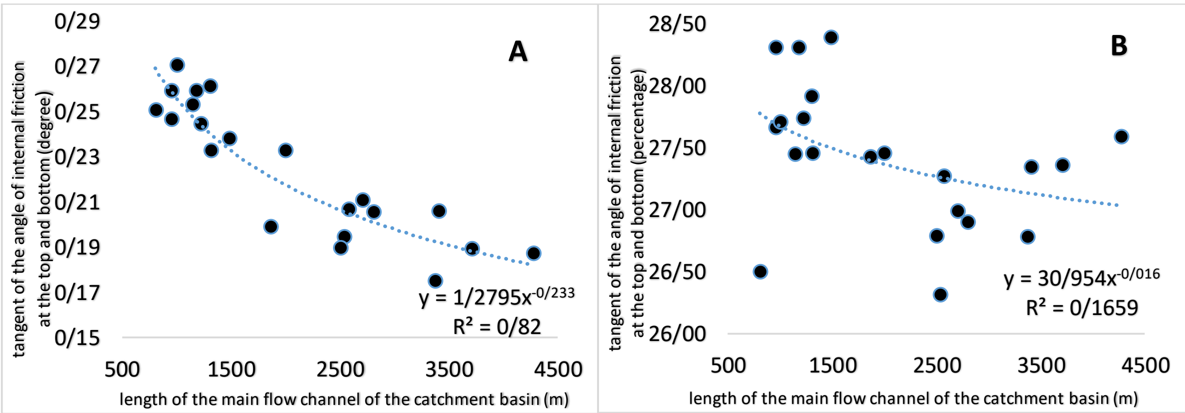


Fig. 19: A: The difference between the tangent of soils' angle of internal friction at the top and bottom of alluvial fans in light of the length of catchment basin's main flow channel; B: The percentage of the difference between the tangent of soils' angle of internal friction at the top and bottom of alluvial fans in light of the length of catchment basin's main flow channel.

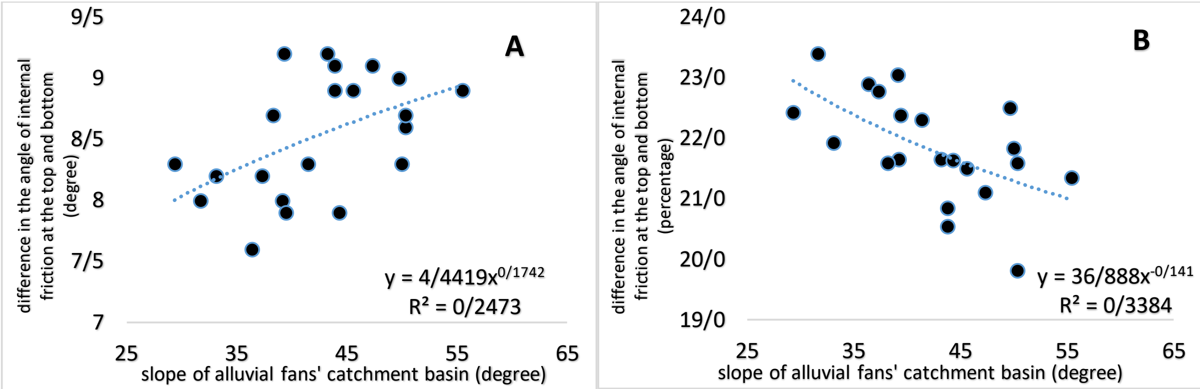


Fig. 20: A: The difference between soils' angle of internal friction at the top and bottom of alluvial fans in light of the slope of alluvial fans' catchment basin; B: The percentage of the difference between soils' angle of internal friction at the top and bottom of alluvial fans in light of the slope of alluvial fans' catchment basin.

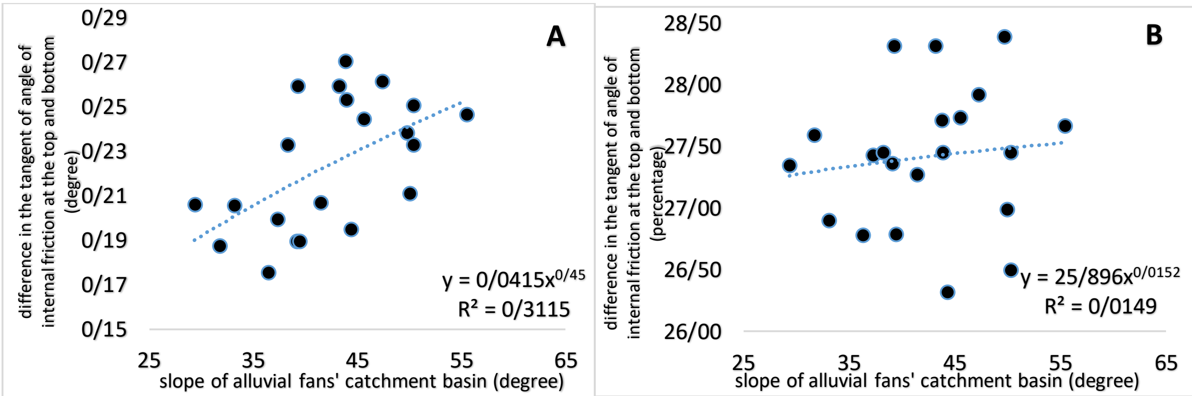


Fig. 21: A: The difference between the tangent of soils' angle of internal friction at the top and bottom of alluvial fans in light of the slope of alluvial fans' catchment basin; B: The percentage of the difference between the tangent of soils' angle of internal friction at the top and bottom of alluvial fans in light of the slope of alluvial fans' catchment basin.

Table 4: The results of comparing the figures indicating the difference between the angle of internal friction at the top and bottom of alluvial fans in light of the morphometric properties of catchment basin

Parameter type	**Difference in grains' angle of internal friction at the top and bottom**		**Percentage of the difference in grains' angle of internal friction at the top and bottom**		**Difference in the tangent of grains' angle of internal friction at the top and bottom**		**Percentage of the difference in the tangent of grains' angle of internal friction at the top and bottom**	
Range of changes in the angle of internal friction	7.6	9.2	19.8	23.4	0.19	0.26	26.50	**28.39**
Catchment basin's area	3.09 Km^2	0.289 km^2	0.101 Km^2	3.802 Km^2	2.062 2.783 3.802 1.309 Km^2	0.255 0.289 0.246 Km^2	0.101 Km^2	**0.588 Km^2**
Length of the main flow channel of catchment basin	3370 m	950/ 1170 m	800 m	4270 m	3370 m	1000 m	2530 m	**1480 m**
Catchment basin's slope	36.17°	43.17°	50.33°	31.7°	31.7° 39.14° 39.43° 44.33°	39.25° 43.17° 47.31°	50.33°	**49.7°**

Table 5: Comparing the difference in the angle of internal friction at the top and bottom of alluvial fans in light of the area, slope, and length of the main flow channel of catchment basin

Parameter type	R square	R	Sig	Parameter type	R square	R	Sig
Relationship the difference in the angle of internal friction at the top and bottom of alluvial fans with the area of catchment basin	0.717	-0.84	1.27	Relationship the tangent of the difference in the angle of internal friction at the top and bottom of alluvial fans with the area of catchment basin	0.74	-0.88	1.03
Relationship the percentage of the difference in the angle of internal friction at the top and bottom of alluvial fans with the area of catchment basin	0.621	0.80	3.68	Relationship the tangent percentage of the difference in the angle of internal friction at the top and bottom of alluvial fans with the area of catchment basin	0.09	-0.37	0.18
Relationship the difference in the angle of internal friction at the top and bottom of alluvial fans with the slope of catchment basin	0.211	0.49	0.04	Relationship the tangent of the difference in the angle of internal friction at the top and bottom of alluvial fans with the slope of catchment basin	0.26	0.54	0.01
Relationship the percentage of the difference in the angle of internal friction at the top and bottom of alluvial fans with the slope of catchment basin	0.311	-0.58	0.01	Relationship the tangent percentage of the difference in the angle of internal friction at the top and bottom of alluvial fans with the slope of catchment basin	0.005	0.12	0.75
Relationship the difference in the angle of internal friction at the top and bottom of alluvial fans with length the catchment basin's channel	0.667	-0.83	1.09	Relationship the tangent of the difference in the angle of internal friction at the top and bottom of alluvial fans with length the catchment basin's channel	0.76	-0.88	4.93
Relationship the percentage of the difference in the angle of internal friction at the top and bottom of alluvial fans with length catchment basin's channel	0.594	0.78	6.85	Relationship the tangent percentage of the difference in the angle of internal friction at the top and bottom of alluvial fans with length catchment basin's channel	0.11	-0.39	0.13

According to the obtained results, the strongest correlation was recorded for the relationship between the difference in the angle of internal friction at the top and bottom of alluvial fans with the two independent variables of catchment basins' area and length of main flow channel. More precisely, the rise in the catchment basins' area and length of main flow channel results in smaller difference in the angle of internal friction of grains collected from the top and bottom of the alluvial fans. The same results were obtained for the difference in the tangent of angle of internal friction. On the contrary, the percentage of the differences regarding the role of area and length of the main channel showed the opposite. At the same time, comparing the difference in the angle of internal friction at the top and bottom of alluvial fans in light of the catchment basins' slope revealed the weakest significant correlation. Additionally, since the points widely scattered around the regression line and the correlation coefficient was very small, the tangent percentage obtained with respect to the role of the catchment basin's slope did not indicate a significant association.

Conclusion

As geomorphologic landforms, alluvial fans cause changes in soil's geotechnical properties through the morphometric properties of catchment basin and geomorphological processes like weathering, abrasion, and sedimentation. Concentrating on both geomorphological and geotechnical features, the current study examined resistance parameters in different parts of alluvial fans. Given the innovative nature of this research, which integrates geomorphology and geotechnics, there have been limited studies in this area so far. As a result, a direct comparison and comprehensive analysis of findings with previous studies are not entirely feasible. However, the results of this study can serve as a foundation for future research and contribute significantly to the advancement of knowledge in this field.

With respect to sediment particle s' shape, the findings indicate that:

1. The rise in the area and length of the main flow channel in alluvial fans' upland catchment basin will yield more rounded grains with smoother surface texture.

2. As the slope of alluvial fans' catchment basin goes up, grains are less influenced by geomorphological processes and more affected by gravity. Hence, they are less rounded and rougher.

The results obtained from the direct shear test indicate the internal friction angle:

3. As the area of alluvial fans' catchment basin increases from the top to the bottom, grains travel longer distances and undergo more abrasion. Thus, their angle of internal friction reduces. On the other hand, given the direct relationship between the area and length of the main flow channel in the catchment basin, in all parts of alluvial fans, as the area of catchment basin increases, the angle of internal friction declines.

4. When the slope of the catchment basin rises, the angle of internal friction goes up, and the correlation coefficient is small. However, given the inverse association between slope and the area/length of the main flow channel, the rise in the area and length of the main flow channel and the reduction in the slope of catchment basin at the bottom of alluvial fans leads to smaller angle of internal friction.

5. In general, at the top of alluvial fans, geomorphological processes have a slight impact on grains' shape. Thus, in this part of alluvial fans, grains are more angular, irregular, and coarse, and have a rough surface texture. Hence, their angle of internal friction is bigger.

The obtained results show that, based on the univariate analyses, the area of the upland catchment basin and length of the main flow channel can be used as independent variables. In contrast, slope cannot be used as the sole independent variable to analyze morphometric relationships of upland catchment basin and soil resistance properties in alluvial fans. The results of bivariate analyses also indicated that the regression model can properly predict the impact of area and length of the main flow channel in the catchment basin on the angle of internal friction. The results of trivariate analyses further demonstrated that the combination of the area, length of the main flow channel, and slope of upland catchment basin will yield the highest correlation coefficient, correlation of determination, and significance level, and lowest error.

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