Geosciences

AIMS Geosciences, 12(2): 570–586.
DOI: 10.3934/geosci.2026022
Received: 05 June 2025
Revised: 22 October 2025
Accepted: 04 January 2026
Published: 08 June 2026

https://www.aimspress.com/journal/geosciences

Mini review

Colluvial sediments: lithofacies, depositional processes and contribution to geotechnics

Saeed Khodabaksh*

Geology Dept., Bu-Ali Sina University, Hamedan, Iran

* **Correspondence:** Email: skhodabakhsh@yahoo.com.

Abstract: Colluvial deposits are heterogeneous and unconsolidated clastic sediments accumulated at the base of hills or mountain slopes. In recent years, these sediments have received attention in environmental and geological research, as they record valuable data about paleo-tectonic activities, paleoclimate, and weathering conditions in subaerial slopes. This chapter reviews and discusses concepts of colluvial deposits in geosciences and describes lithofacies, depositional processes, models, and practical implications. A combination of field observations, laboratory work, and geotechnical investigations allows for a better understanding of slope processes responsible for colluvial accumulation. These deposits accumulate in various climatic conditions, being transported and deposited mainly by gravity (i.e., mass wasting and mass flow). The main lithofacies are rock falls and debris-flow deposits. Subordinate facies include calcrete/paleosol horizons and water-flow deposits (slope wash). While mass wasting occurs in tectonically unstable periods, soil horizons may develop during periods of tectonic quiescence.

Keywords: depositional processes; lithofacies; slope models; subaerial slope; clastic sediments; slope stability

1. Introduction

Colluvial deposit (or colluvium) is a general name for sediments formed by the accumulation of a loose and unconsolidated mixture of coarse and fine debris at the base of hills or mountains (Table 1, Figure 1). Colluvial debris is primarily produced by subaerial weathering of exposed rocks at the surface; it may subsequently be remobilized downslope by various processes [1,2]. Based on sediment origin, a colluvial deposit can be considered as a transported regolith, which is defined as a layer of unconsolidated debris that rests on bedrock [3] (Table 2). Three main operational key characteristics for colluvial deposits are as follows:

(1) They occur mainly along hillslopes, mountain fronts, or other topographic escarpments.
(2) Texturally, they are heterogeneous, immature, and coarse-grained clastic sediments.
(3) Gravity is their dominant sediment transport process.

It is important to distinguish between colluvium and alluvium. The word "colluvium" is taken from the Latin: co-, with, and alluvium [4]. Colluvium is transported and deposited mainly by gravity [2]. Flowing water has little contribution to colluvial sedimentation. In contrast, alluvium (or alluvial deposit) comprises sediment solely transported and deposited by flowing water (weather channelized or un-channelized; Figure 2). Relative sediment transport in colluvium is much lower than in alluvium.

Table 1. Selected definitions of colluvium.

Definition	Reference
1) Colluvium (synonyms: colluvial deposit, colluvial soil, talus)	
* "Slope debris, moved downslopes mainly by gravity".	[2]
* "Sediment eroded from and transported along hillslopes by water, gravity, or human action and usually forms a wedge-shaped sediment body at the foot slope".	[5]
* Loose, heterogeneous, and incoherent mass of soil material or rock fragments, or both, deposited by rain wash, sheetwash, or slow, continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.	[6]
* "A general term for clastic slope-waste sediments, typically coarse-grained and immature, deposited in the lower part and foot zone of a mountain slope or other topographic escarpment and brought there mainly by sediment-gravity processes.	[7]
* Clastic slope material, mainly coarse-grained and immature, deposited in the lower part and foot of a mountain slope, transported chiefly by sediment-gravity processes.	[8]
* Sediment and organic matter delivered by mass wasting from adjacent hillslopes, which are usually immobile except during rare hydrologic events.	[9]
* "Mobilized hillslope sediment".	[10]
2) Talus cone (synonym: colluvial/debris/scree cone, colluvial fan)	
*Cone-shaped debris formed by the accumulation of rockfalls at the cliff base. It has a slope angle of about 35 degrees.	[11]
3) Colluvial apron (synonyms: colluvial/talus/scree sheet, talus mantle, boulder/slope apron)	
* Steep coalescent fans formed at the foot of mountain fronts.	[12]
* Accumulated debris that are more or less evenly distributed along a cliff face.	[13]

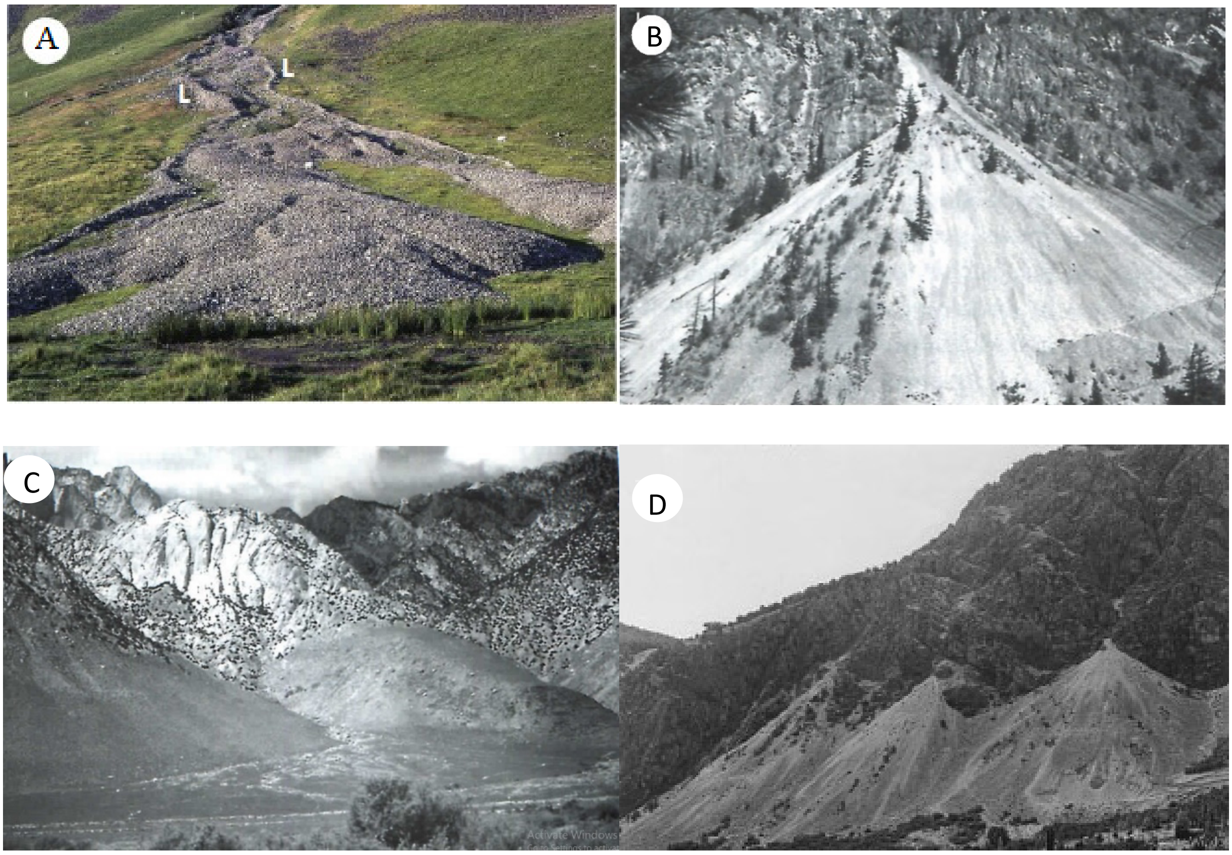


Figure 1. Field photographs of slope materials: A) debris cone [14] (L = levee), B) talus cone [15], C) colluvial mantle [15], D) colluvial apron formed by coalescent colluvial cones [12].

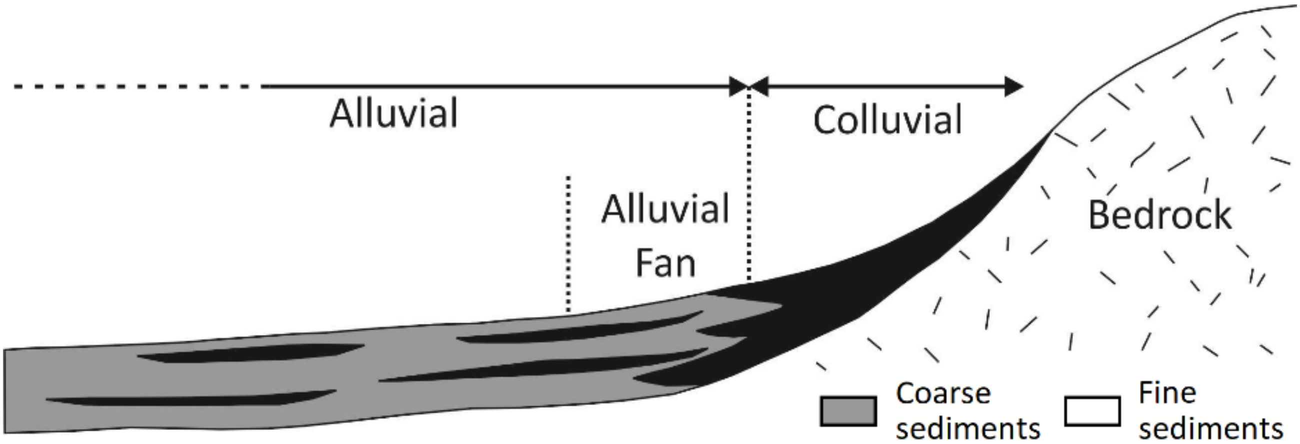


Figure 2. Domain of colluvial and alluvial processes at the base of the slope [16,17] (modified).

Table 2. Regolith types (including colluvial deposit) [3].

Type	Example
(1) In situ	
(1-1) Residual deposits	Laterite, soil
(1-2) Cumulose deposits	Peat
(2) Transported	
(2-1) Colluvial deposits	Talus
(2-2) Alluvial deposits	River deposit
(2-3) Eolian deposits	Sand dune, loess
(2-4) Glacial deposits	Morain, till

Particular attention should be paid to colluvial deposits, because a significant portion of human activities takes place in slope areas, most of which are covered by colluvial deposits (Figure 3). They are the parent material for most of Earth's alluvium and soils [6,17]. In addition, colluvial sediments are subjected to slope instabilities [18]. They record data about human impacts on slope landscapes [19], paleo-tectonic uplift, climate, and weathering conditions in subaerial slopes [18] and seismic hazards [20].

Human activities may alter the natural slope equilibrium. Large amounts of coarse materials are released to slope areas by human activities such as cultivation, construction, deforestation, and mining (see [19,21] for reviews). These disturbances may increase slope instability and disasters or cause other geo-environmental problems (see [17] for a review). Some examples of environmental consequences of human impacts on colluvial sediments in slope areas are enhanced slope and soil erosion, increased sediment accumulation on slopes, enhanced sediment load of rivers, closure of springs, diversion of river channels, and road and building damage. In this chapter, some sedimentological aspects of colluvial deposits are discussed.

Figure 3. Anthropogenic colluvium (C) produced by surface mining (north flank of Shahrud River, northern Iran). Waste dumping may increase slope instabilities or cause other geoenvironmental problems.

2. Depositional processes

Deposition of colluvium takes place at the base of the slope, where the angle of the surface reduces, and remobilized materials accumulate. Although some colluvial sediments are accumulated via a point source (e.g., talus cone, Figure 1b), most of them are not fed by a distinct drainage system but receive their sediment from various upslope processes [10]. This type of colluvium has drape-form geometry (Table 1, Figure 1c and d). Detrital materials in subaerial slopes are primarily produced by in situ weathering of exposed bedrocks. The weathered debris subsequently remobilizes and accumulates downslope, forming colluvial deposits.

Slope processes responsible for colluvial deposition can be classified into two main groups: (1) mass movements and flows (i.e., debris flow) and (2) slope wash [3]. Mass movements in slopes include rockfalls, soil creep, earth flow, and landslides (Tables 3 and 4). These processes are often associated with coarse-grained deposits [19]. A small part of slope sediments may be transported by overland flows (as rain wash or channeled ephemeral streams [7]). Rain wash is formed by shallow surface water flows and mostly transports fine-grained colluvial deposits [19], while eolian processes may deliver fine-grained sediments to colluvial profiles [22].

After stabilization of sediments, colluvial deposits may be subjected to secondary (or modifying) processes. The most prominent secondary processes are soil and calcrete development, which is associated with case hardening of colluvial sediments [23]. Other secondary processes include surficial reworking (by running water, wind, bioturbation, and groundwater) and neotectonics [15,18].

Debris flows and rock falls are two main gravity-driven processes on subaerial slopes [15,24] (Figure 4). Rockfalls are also known as scree or grain flow, which occur in steep slopes (up to 36° [11] or 25°–35° [15]). Initiation of subaerial debris flows requires slopes of 15°–20° [25]. After primary initiation, the flow may continue moving on gentler slopes. The behavior of debris flows is intermediate between landslide and flood flows. Incorporation of water with the initial landslide or colluvium may also cause the development of debris flows [24,26]. This conversion happens when sediment concentration in the flow reaches 70%–90% (by volume, [27]).

Table 3. Main characteristics of colluvial deposits.

Character	Example	Reference
(1) Sediment transport processes		
(1-1) Mass wasting	Creep, landslide, rockfall/rock Avalanche	[2,19]
(1-2) Sediment-gravity flow	Debris flow and grain flow	
(1-3) Overland flow	rain or sheetwash	
(2) Landforms		[12,28,29]
(2-1) Erosional	Slump, rill, gully	
(2-2) Transportational	Slide, fall	
(2-3) Depositional	Talus or debris cone	
(3) Sediment texture	Fine to coarse (soil or calcrete horizons may zxist)	[6,23]
(4) Sediment geometry	Sheet-fan-like and conical	[29]

Table 4. Selected classifications of sedimentary processes in subaerial slopes.

Classification	Reference
(1) Rock-gravity processes (i.e., rockfall), (2) sediment-gravity processes (i.e., debris flow), (3) fluid-gravity processes (i.e., sheet flood)	[15]
(1) Avalanches (rockfall, debris flow, snow flow), (2) water flow	[8]
(1) Snow/ice, (2) gravity, (3) flowing water, (4) flowing air, (5) man	[9]
(1) Valley-glacier system, (2) coarse debris system, (3) fine debris system, (4) geochemical system	[30]
(1) Mass wasting (avalanche, rockfall, debris flow, creep), (2) sheetwash, ephemeral water flow	[6,19]

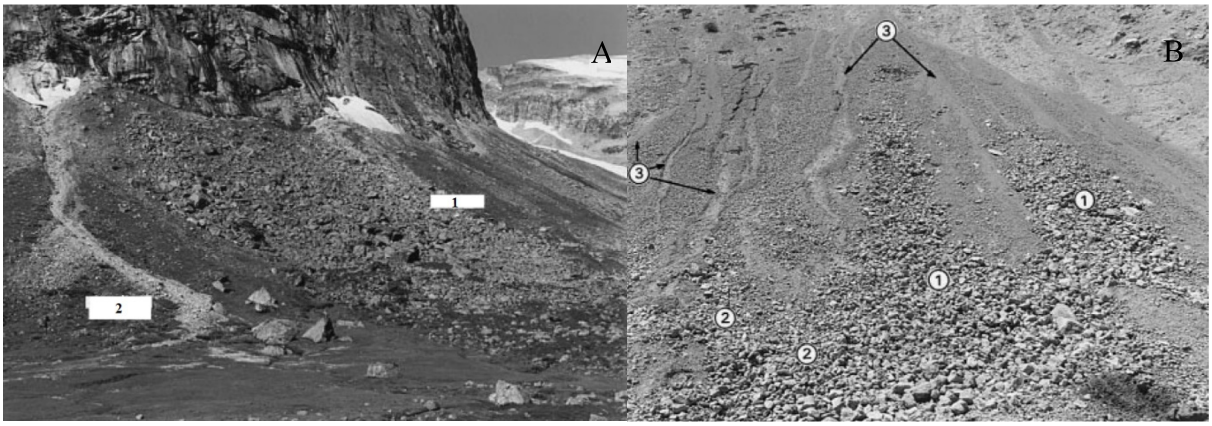


Figure 4. Colluvial processes [8,12]. (1) rockfall avalanche, (2) debris flow, (3) mud flow. Note the upslope-fining trend in gravel tongues in Figure B.

Subaerial debris flows are slurries of water, sediment, and organic debris, moving rapidly downslope [9]. They are viscous fluids that transport a mixture of various-sized clasts as a result of gravity. They are capable of transporting large clasts in a buoyant condition. Their character is more similar to a plastic mass than a fluid [31]. In arid regions, subaerial debris flows may be generated as a result of rapid rainfall. Debris flows are erosive at their head, where abundant coarse materials are transported by the flow. They are either channelized (confined) or unchannelized (unconfined or sheet flow). Channelized debris flow with a relatively low gradient, moving as a rigid plug. In steeper channels, debris flows propagate as surging waves [26], which form on the free surface of the flow. Unconfined debris flows may also propagate in this manner.

The sedimentation of colluvium is influenced by periodic stability and instability [7,24]. Mass wasting occurs in unstable periods, when frequent upslope erosion enhances remobilization of slope deposits. On the other hand, slope instability depends on tectonic uplift, climate-controlled weathering, slope form (relief, [18]), and sediment texture. Non-cohesive debris tends to adapt a relatively constant slope after failure and remains stable for a period. The slope angle for this type of material is controlled by the angle of repose. Slopes covered by cohesive debris are more stable than those of non-cohesive material (because of cohesion; [11]). During stable periods, soil horizons may develop in colluvial deposits [24,32].

The most important controlling factors on colluvial development are climatic conditions and tectonic activities. This explains why colluvial deposits are widely used as geo-archives for paleoclimate and tectonic activities in continental environments [33]. Climate plays a dominant role in water discharge, weathering conditions, sediment yield, and vegetation cover. Colluvial sediments may accumulate in various climates. Most colluvial sediments are mainly situated in arid and semi-arid regions. However, they may also form in temperate and cold climates. Much data about paleoclimates on continents is actually taken from soil horizons in the colluvial profiles (see [18,34]). Among climatic controlling factors, rainfall is the most significant [35]. High-intensity precipitation in humid climates increases major slope failures in the sourcing basin [29] and enhances soil development and surface runoff. Therefore, colluvial sediments in this condition contain thicker soil horizons and a higher proportion of alluvial facies.

In cold climates, slope sediments primarily originate as glacial tills in upper elevations of mountainous regions [36]. Subsequently, they may be remobilized and accumulated at foot slopes as colluvial deposits. Furthermore, colluvial sediments in glaciated regions are also associated with glaciofluvial processes, which occur at or within the ice front. They are deposited during summer meltwater discharges at the glacier front [10]. In arid conditions (as well as cold climates), scarce vegetation cover enhances colluvial and soil erosion [29]. Periodic changes in vegetation cover in semi-arid regions cause colluvial sediments to alternate with lenses of coarse and fine sediments [37]. This rhythmic depositional style is an indication of the periodic occurrence of rock falls and debris flows.

From a tectonic point of view, colluvial sediments typically form along normal faults at mountain range fronts [29]. In this condition, periodic fault movements cause subsidence at the range front or uplift in the source area. These events trigger deposition of coarse colluvium at the slope base [10]. In tectonically active regions, colluvial sediments contain several colluvial units (see [20,34,38]) separated by soil horizons (see [33]). While colluvial units are formed during active periods, soil horizons form during periods of tectonic quiescence. Therefore, by stratigraphic analysis of colluvial sediments, we can distinguish phases of tectonic activity in order to evaluate recurrence intervals of fault activation [33].

3. Slope development

Slope is an inclined surface of the Earth's crust. It may be covered by rock mass, soil, or sediment. Subaerial slopes are areas of active erosional, transportational, and depositional processes. The concept of erosion-transport-accumulation (ETA) in subaerial slopes was elaborated for management purposes [28]. In this system, the main mechanism of sediment transport and accumulation on the slope is gravitation (Table 3). The subaerial slope profile is classified into 9 units [37] (Figure 5). In this model, the slope angle progressively decreases downward. In the nine-unit model, units 4–6 are known as the upper, mid, and lower slope, respectively. The lower slope (also known as the foot slope or colluvial foot slope) is a gently inclined surface at the base of the slope. The surface profile is generally concave, which is a transition between the mid-slope and the toe slope. The toe slope (or alluvial toe slope) is the outermost, gently inclined surface at the base of the slope. The classification by Warburton [17] for high-mountain environments can also be applied to subaerial slopes. He recognized five major terrain zones in high-mountain environments: (1) glacial, (2) free rock faces and debris slopes (= upper slope), (3) degraded middle slopes and ancient valley floors, (4) lower slopes, and (5) valley floors.

Generally, the upper slope is an erosional zone with high angles [29]. It has a rock face covered mainly with rockfall and talus scree [31], which covers the erosional surface. The mid-slope is considered the transportational zone. In this zone, sediment transport takes place via mass movements (e.g., slide, slump, creep). Eroded materials are carried across the upper- and mid-slope to the foot slope (or lower slope), which is an area of predominant accumulation [24]. Sediment cover at this zone is thicker than that of the upper- and mid-slopes and mainly consists of debris flow deposits.

Slope development takes place through different processes, which cause it to reach an equilibrium form. Three general models for slope development are the slope decline, parallel retreat, and slope replacement (Figures 6–9). The concept of slope decline was first proposed by W.M. Davis. This theory describes slope evolution due to a combination of erosion, tectonic forces, and climate-controlled weathering. Slope decline results from gradual denudation of the slope by gravitational processes and surface runoff, which causes a progressive decrease in the slope angle [24,39] (Figure 7). The decline rate is highest at the mid-slope. At the slope foot (or lower slope), the decline rate is slower, and a basal convexity is created. The lower slope receives all the debris removed from the upper and mid-slopes [11].

Slope retreat occurs mainly under the action of two processes: weathering and removal of debris from the base and surface of the slope. This condition causes parallel retreat (or backward regrading) of the cliff/slope face [39] (Figure 8). Progressive retreat gradually reduces the slope angle. Removal of debris occurs by sliding, rolling, or falling of clasts. During slope retreat, other processes, such as wind action and wash processes, enhance the declination of the slope angle [24] (Figure 10).

Some slopes may have a linear surface and rectangular corners (Figure 6a). However, in many semi-arid areas, the slope profile has a concavo-convex form, which consists of the following parts (from top to bottom): (1) convex crest, (2) steep cliff (free face), (3) debris slope, and (4) slope toe (pediment, Figure 8a). The concavo-convex slopes evolve through a process of retreat. In this type of slope, loss of materials takes place from the free face (or upper slope) and mid-slope. Consequently, the slope toe gradually extends downward as the slope face and debris retreat [11]. It is noteworthy that parallel retreat may also occur due to basal undercutting of a valley side-slope by a stream. In the parallel-retreat model, it is assumed that the basal debris accumulated at the slope is gradually transported or eroded by surface runoff or gravitational processes. In the absence of active basal erosion, slope replacement takes place (Figure 9). This process occurs in coarse debris and leads to the development of a scree slope. Three phases of slope replacement exist: (1) first, there is the formation of initial talus cones at the slope base. Then, (2) as talus cones grow, they overlap each other and a scree slope forms. At the same time, the cliff retreats, and the scree slope becomes straight. Finally, (3) the straight scree covers the whole slope, and the slope angle reduces [39].

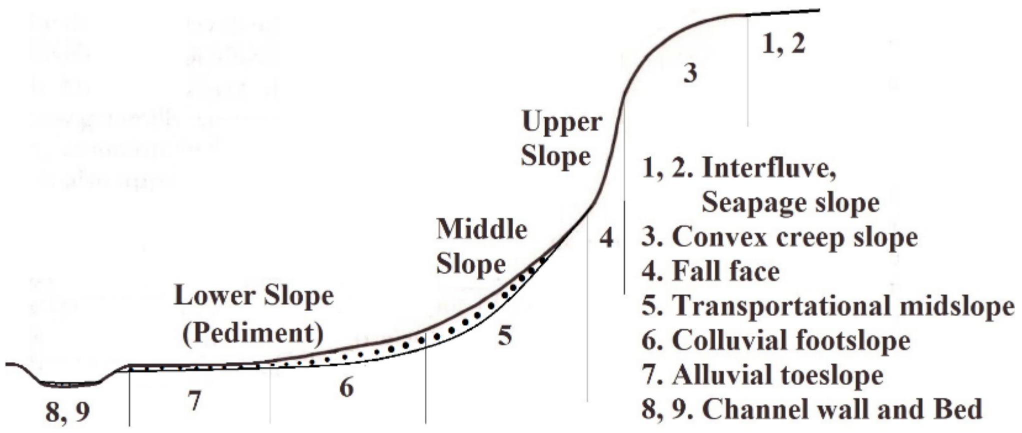


Figure 5. The nine-unit model for subaerial concavo-convex slopes (based on [37,40]).

Figure 6. A) Schematic model for colluvial wedge development at the slope foot after upslope failure. B) Schematic steps of slope retreat [24].

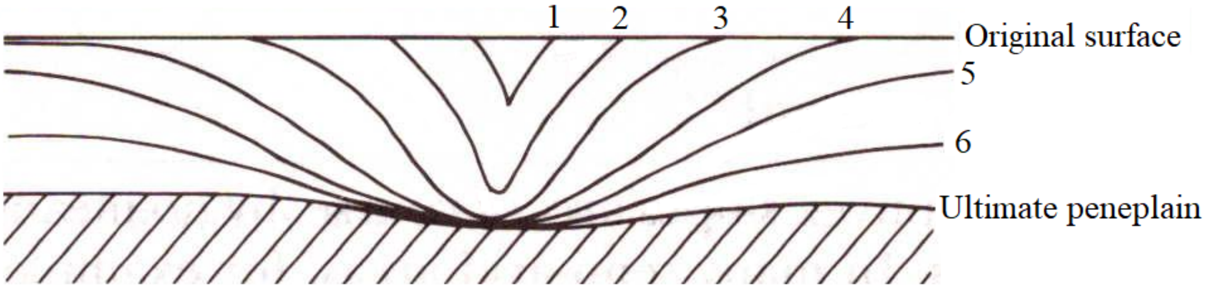


Figure 7. Concept of slope decline [39] (modified). Numbers are sequences of slope denudation.

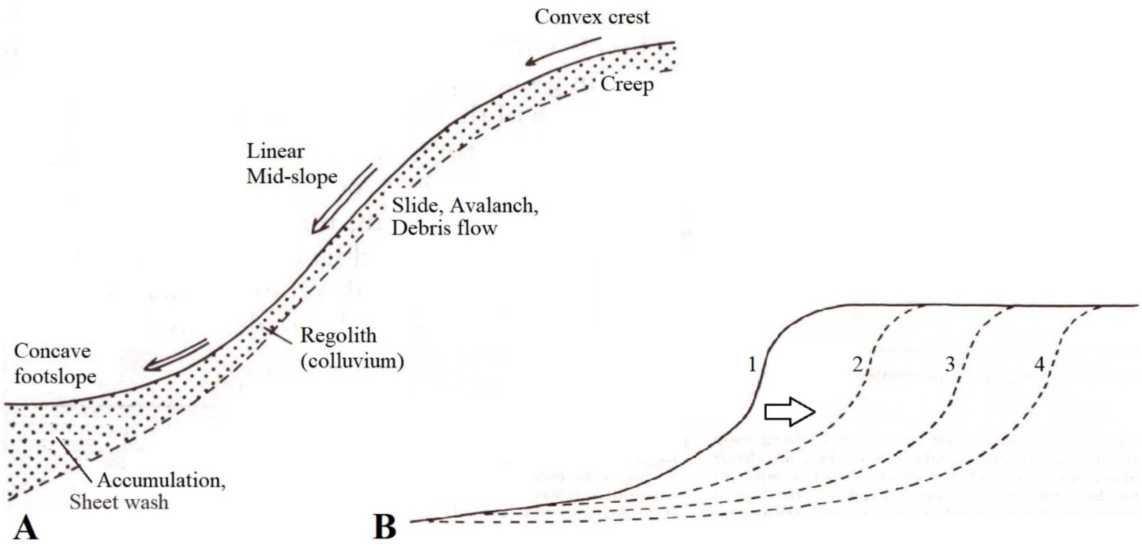
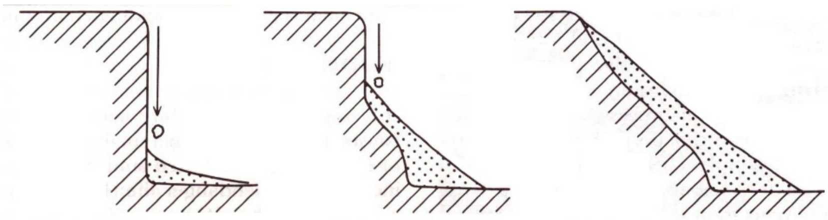


Figure 8. (A) Schematic profile of a concavo-convex subaerial slope. (B) Lines of slope parallel retreat [39].



1. High cliff, small concave scree forms at the slope base

2. Cliff retreats, scree extends upward, scree surface becomes straight

3. Straight scree covers whole slope

Figure 9. Schematic model for slope replacement [39] assuming that there is no removal of scree from the base.

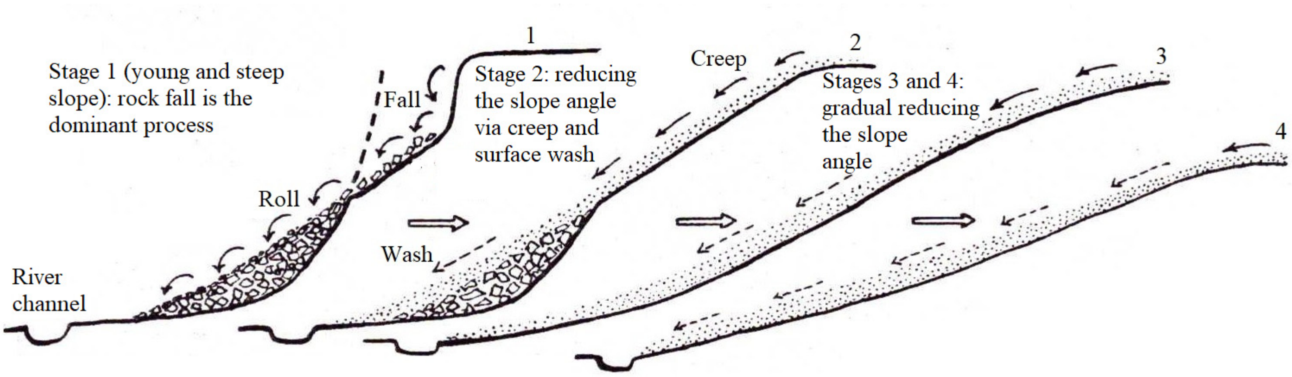


Figure 10. Schematic model of slope evolution of a talus slope. Weathering produces a veneer of fine-grained debris over rock falls. The slope development is followed by wash processes, which gradually reduce the slope angle [24].

4. Colluvial lithofacies

Three types of materials cover the drainage network in a slope environment: colluvial, alluvial, and bedrock [9]. While the uppermost part of the network is mainly covered by bedrock, the lower part is covered by colluvial and alluvial sediments. Colluvial sediments mainly accumulate as a blanket of detrital sediments with almost uniform thickness. They may be cone-shaped when fed by a distinct feeder channel [31]. Transition of colluvial to alluvial facies is associated with a distinct change in depositional processes (Table 5, Figure 2).

Colluvial facies can be classified based on sediment-grain size or depositional mechanisms. Considering sediment-grain size, colluvial facies are differentiated as fine, coarse, or a mixture of both [6,11,19]. Based on sediment texture and depositional mechanism, colluvial sediments mainly consist of two facies types: matrix-supported gravel (cohesive debris-flow deposit) and openwork gravel (rock-fall deposit or avalanche; Figures 11 and 12). Both facies are poorly or unsorted and non-stratified. However, alternation of fine- and coarse-grained beds may form bedded colluvial deposits [19]. Rock-fall deposits consist of relatively uniform-sized clasts. Subordinate facies include calcrete/paleosol horizons and water-flow deposits. Soil horizons are formed by rock weathering and accumulation of colluvium, associated with biological activity [24]. They are also known as K-horizons. In this regard, K-cycles are discontinuous soil horizons in slope profiles. The modern horizon is K_1, and older horizons are K_2, K_3, K_n [24]. The total soil profile depth in colluvial sediments thickens in the downslope direction [32]. A minor portion of the colluvial profile consists of water-flow deposits (also called surface wash or wash facies [20]). Surface wash may form rills with small fans at the foot slope [32].

The most prominent character of rockfall is upslope fining of grain size [8]. Most debris flow on slopes are cohesive. Their deposits consist of a series of overlapping lobes and associated channels, which form a complex facies pattern. They have no internal organization of particles and poor sorting and may have some graded bedding and imbrication. They may show a crude stratification where successive flows accumulated. They have almost uniform thickness throughout their extent [31].

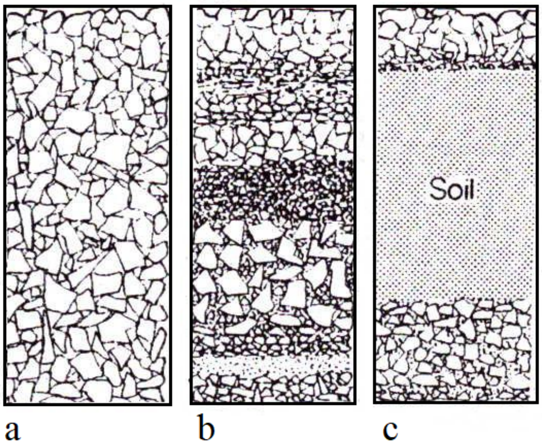


Figure 11. Schematic profile of coarse colluvial lithofacies: a) open-work gravel (non-stratified), b) stratified gravel alternating with fine debris, and c) coarse debris with paleosol horizon [24].

Figure 12. Field photograph of colluvial lithofacies: a) open-work gravel alternating with fine debris, b–c) open-work gravel (rock fall deposit). For bedded gravel, see Figure 11b.

Table 5. Comparison of colluvial- and alluvial-fan characteristics [8,15,16,29].

Characteristics	Colluvial fan	Alluvial fan
Catchment	Mini-drainage system on slopes	Large catchments; intermontane valley or canyon
Location of apex	High on the slope	At the base of the slope
Slope angle	Various reported ranges: 30–45° at the apex, 15–20° at the toe; 15–56°; 20–35°	10–15° at the apex, 1–5° at the toe
Size	Radius: <0.5–1.5 km, length: a few tenths to hundreds of meters long	Radius: <10 to >100 km
Sediment texture	Gravel dominated, small sand bodies, very immature without bedding and traction-flow structure	Immature to mature gravel and/or sand
Grain-size trend	Upslope fining	Downslope fining
Depositional processes	Gravitational processes (rock fall, debris flow, landslide, grain flow, and snow flow), minor water flow	Water flow and debris flow
Morphometric parameters	No relationship between drainage basin area and fan area	Relationship between drainage basin area and fan area

5. Contribution to geotechnics

Colluvial sediments occur on slope areas. As such, they are potentially unstable and subject to failure, which may cause damage or destruction. Slope stability refers to the slope materials (colluvial sediment, in this case) resisting downslope movement. Instability in slopes depends on the ratio of driving forces (e.g., shear force) to the resisting force (e.g., shear strength). Shear force is primarily related to slope angle. The shear strength of the slope material depends on various factors, which may trigger mass wasting. The most common trigger mechanisms for mass wasting are an increase in water content (e.g., heavy rain) or earthquakes. Water content is a crucial factor in slope stability [41]. It reduces shear strength and increases pore pressure and weight. For example, in 1972, the Po-Shan road landslide (Hong Kong), which killed 67 people, occurred after a heavy rainfall. It is noteworthy that the steep slope and cut face (as a result of new construction at the middle of the slope) enhanced the slope failure [2] (Figure 13). Large slope failures, if incorporated and diluted by water, may develop into debris flows.

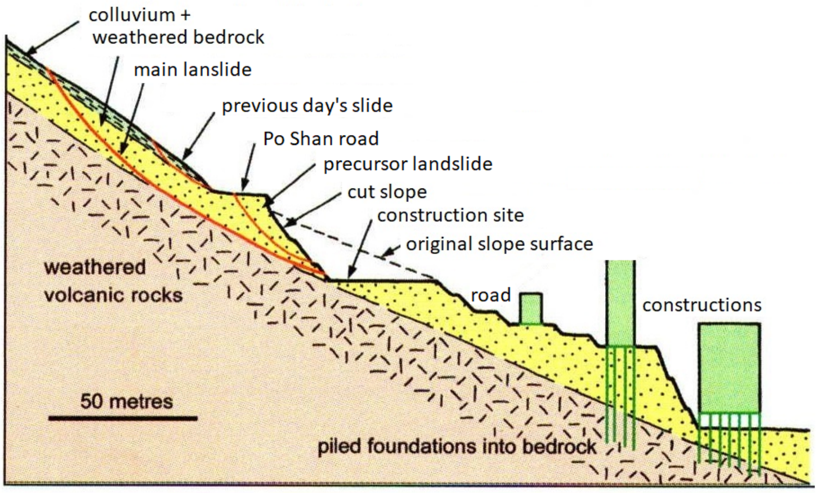


Figure 13. Po Shan road landslide, 1972, Hong Kong [2]. It occurred in a 15-m thick colluvium and completely weathered volcanic rocks on a slope dipping 36°. The location of two minor slides, which took place before the main slide, are also shown.

Understanding the factors that control slope stability is vital to preventing slope failures. The most important factors influencing slope stability are as follows:

(1) Slope material properties: Bedrock lithology and characteristics of colluvial sediments covering the slope (e.g., texture, clay content and cohesion, sedimentary structures, especially bedding planes and joints, cementation, and case hardening and thickness).

(2) Water content and degree of saturation (e.g., rainfall, groundwater table).

(3) Slope angle and geometry (shape).

(4) External forces: Tectonic activity, erosion, climate and weathering conditions, and human activities.

Bedrock lithology controls the formation processes of colluvial sediments and slope-failure type. For example, fine colluvial sediments are produced on bedrocks such as shale, slate, and schist, whereas bedrocks such as granite and quartzite produce coarse colluvium, which generates rockfalls. Fine colluvial sediments are susceptible to failures such as landslides; they also promote debris-flow generation. On the other hand, slope angle also controls the type of slope failure. For instance, debris flows generate on gentle slopes, whereas rockfalls occur on relatively steeper slopes (see section 2 of this chapter).

Various methods are used to evaluate slope stability. For example, the limit equilibrium method analyzes the forces acting on a given slope to evaluate the factor of safety (FS). In a more advanced method, the finite element analysis, the stress and strain distribution in the given slope are modeled to predict potential failure (see [42] for a review).

6. Conclusions

This chapter is dedicated to reviewing basic concepts of colluvial sediments for geoscience researchers. As colluvial sediments accumulate on subaerial slopes, this chapter puts a strong emphasis on depositional processes responsible for colluvial deposition on slopes. Both primary and secondary processes are discussed. The primary processes include mass wasting (i.e., rockfall, landslide), mass flows (i.e., debris flow), and alluvial processes (slope wash). The most important secondary processes are soil formation and surficial reworking. Colluvial sediments occur in various climates. They accumulate mainly along tectonically active areas (e.g., mountain range fronts). Therefore, colluvial sediments provide valuable data for the reconstruction of paleoclimate and tectonic activities in continental environments.

The heterogeneity in bedrock lithology, climate, and tectonic conditions in different regions makes it challenging to compare slope processes. This indicates a need for further studies to understand depositional mechanisms responsible for colluvial accumulation in different geological and climatic settings. The concepts discussed in this chapter can be used as a basis for engineering and environmental projects in slope areas.

Use of AI tools declaration

The author declares he has not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

The author would like to thank the editorial team of AIMS Geosciences for precise edition of this chapter.

Conflict of interest

The author declares that he has no conflict of interest related to this publication.

References

1. Flint RF, Skinner BJ (1974) Physical geology, J. Wiley.
2. Waltman T (2009) Foundations of engineering geology, Spon Press.
3. Miller BA, Juilleret J (2020) The colluvium and alluvium problem: Historical review and current state of definitions. *Earth-Sci Rev* 209: 103316. https://doi.org/10.1016/j.earscirev.2020.103316
4. Miller BA, Juilleret J (2015) What is colluvium, Iowa State University, Department of Agronomy.
5. Allen JRL (2013) Luminescence, Colluvial Sediments, In: Encyclopedia of scientific dating methods, Springer.
6. Zádorová T, Penížek V (2018) Formation, morphology and classification of colluvial soils: a review. *Eur J Soil Sci* 69: 577–591. https://doi.org/10.1111/ejss.12673
7. Nemec W (2013) Colluvium - the ugly duckling of clastic sedimentology, *6th Latin-American Congress of Sedimentology,* São Paulo, Brazil.
8. Blikra LH, Nemec W (1998) Postglacial colluvium in western Norway: depositional processes, facies and palaeoclimatic record. *Sedimentology* 45: 909–959. https://doi.org/10.1046/j.1365-3091.1998.00200.x
9. Bisson PA, Montgomery DR, Buffington JM (2006) Valley Segments, Stream Reaches, and Channel Units, In: Hauer, F.R., Lamberti, G. Author, Methods in stream ecology (Ch. 2), 3 Eds.
10. Leeder M (2011) Sedimentology and sedimentary Basins: From Turbulence to Tectonics. Blackwell Publishing.
11. Strahler AN, Strahler AH (1983) Modern physical geography, Wiley.
12. Nemec W, Kazanci N (1999) Quaternary colluvium in west-central Anatolia: sedimentary facies and palaeoclimatic significance. *Sedimentology* 46: 139–170. https://doi.org/10.1046/j.1365-3091.1999.00210.x
13. Selby MJ (1994) Hillslope sediment transport and deposition, In: Pye K, Sediment transport and depositional processes, Ch. 3 (61-83), Ed., Blackwell Scientific Publ.
14. Harvey A (2018) Alluvial fans. In: Reference Module in Earth Systems and Environmental Sciences. https://doi.org/10.1016/B978-0-12-409548-9.11066-8
15. Blair TC, McPherson JG (2009) Processes and Forms of Alluvial Fans, In: Parsons AJ, Abrahams AD, Geomorphology of Desert Environments *(Ch. 14)*, 2 Eds., Springer. https://doi.org/ 1007/978-1-4020-5719-9-14
16. Corner G (2006) Alluvial fans and fan deltas, Course Lectures (Geo-3112, Lecture 5), Dep. Geology, University of Tromso.
17. Warburton J (2007) Mountain environments, In: Perry Ch, Taylor K, Authors, Environmental Sedimentology (Ch. 2), 2 Eds., Blackwell Publ.
18. Botha GA, Temme AJAM, Singh RG (2016) Colluvial deposits and slope instability, In: Knight J, Grab SW, Authors, Quaternary Environmental Change in Southern Africa Physical and Human Dimensions (Ch. 9), 2 Eds., Cambridge University Press. https://doi.org/10.1017/CBO9781107295483.009

19. Kaiser K, Tolksdorf FJ, de Boer AM, et al. (2021) Colluvial sediments originating from past land-use activities in the Erzgebirge Mountains, Central Europe: occurrence, properties, and historic environmental implications. *Archaeol Anthropol Sci* 13: 220. https://doi.org/10.1007/s12520-021-01469-z
20. Gray HJ, DuRoss CB, Nicovich SR, et al. (2022) A geomorphic-process-based cellular automata model of colluvial wedge morphology and stratigraphy, *Earth Surf Dynam* 10: 329–348. https://doi.org/10.5194/esurf-10-329-2022
21. Henkner J, Ahlrichs JJ, Downey S, et al. (2017) Archaeopedology and chronostratigraphy of colluvial deposits as a proxy for regional land use history (Baar, southwest Germany), *Catena* 155: 93–113. https://doi.org/10.1306/74D7223E-2B21-11D7-8648000102C1865D
22. Persico LP, McFadden LD, McAuliffe JR, et al. (2021) Climate and Vegetation Change, Hillslope Soil Erosion, and the Complex Nature of Late Quaternary Environmental Transitions, Eastern Mojave Desert, *USA, Geol. Soc. America.* https://doi.org/10.1130/G49270.1
23. Lattman LH, Simonberg EM (1971) Case-hardening of carbonate alluvium and colluvium, Spring mountains, Nevada. *J Sediment Res* 41: 274–281. https://doi.org/10.1306/74D7223E-2B21-11D7-8648000102C1865D
24. Selby MJ (1993) Hillslope materials and processes, Oxford University Press.
25. Morino C, Conway SJ, Balme MR, et al. (2018) Debris-flow release processes investigated through the analysis of multi-temporal LiDAR datasets in north-western Iceland. *Earth Surf Process Landform* 44: 144–159. https://doi.org/10.1002/esp.4488
26. Webb RH, Melis TS, Griffiths PG, et al. (1999) Lava falls rapid in the Grand-Canyon effects of the Holocene debris flows on Colorado River. *U.S. Geol. Survey,* Prof. Paper 1591. https://doi.org/10.3133/pp1591
27. Pierson TC, Scott KM (1985) Downstream dilution of a lahar: transition from flow to hyper-concentrated streamflow. *Water Resour Res* 21: 1511–1524. https://doi.org/10.1029/WR021i010p01511
28. Engelen GB, Venneker GW (1988) ETA (Erosion Transport Accumulation) systems, their classification, mapping and management, Sediment Budgets, Proceedings of the Porto Alegre Symposium.
29. Bowman D (2017) Principles of Alluvial Fan Morphology, Springer. https://doi.org/10.1007/978-94-024-1558-2
30. Winter MG (2020) Debris flows, In: Eggers MJ, Author, Diversity in the Science and practice of engineering geology, (Ed.), Geological Soc. London, Spec. Publ., 29, 163–185. https://doi.org/10.1144/egsp29.5
31. Davis RA (1983) Depositional systems, a genetic approach to sedimentary geology, Printice-Hall.
32. Pye K (1994) Sediment transport and depositional processes, Blackwell Scientific Publ.
33. Amit R, Harrison JBJ, Enzel Y (1995) Use of soils and colluvial deposits in analyzing tectonic events – the southern Arava Rift, Israel. *Geomorphology* 12: 91–107. https://doi.org/10.1016/0169-555X(94)00081-2
34. Vanneste K, Verbeeck K, Camelbeeck T, et al. (2001) Surface-rupturing history of the Bree fault scarp, Roer Valley graben: Evidence for six events since the late Pleistocene. *J Seismol* 5: 329–359. https://doi.org/10.1023/A:1011419408419

35. Leopold M, Völkel J (2007) Colluvium: Definition, differentiation, and possible suitability for reconstructing Holocene climate data. *Quat Int* 162: 133–140. https://doi.org/10.1016/j.quaint.2006.10.030
36. Völkel J, Leopold M, Mahr A, et al. (2002) Concerning cold climate slope deposits in Central European Highlands and their terminology. *Petermanns geographische Mitteilungen* 146: 50–67.
37. Conacher AJ, Dalrymple JB (1977) The nine-unit land surface model: an approach to pedogeomorphic research. Geoderma I8, no. 1/2, special issue. Amsterdam: Elsevier.
38. Wiwegwin W, Sugiyama Y, Hisada K, et al. (2012) Re-evaluation of the activity of the Thoen Fault in the Lampang Basin, northern Thailand, based on geomorphology and geochronology. *Earth Planets Sp* 63: 975–990. https://doi.org/10.5047/eps.2011.06.018
39. Briggs D, Smithson P, Ball T (1989) *Fundamentals of physical geography*, Copp Clark Pitman Ltd.
40. Knight J (2021) Stratigraphy and palaeoenvironmental interpretation of late Quaternary colluvial slope deposits in in southern Africa. *S Afr J Geology* 124: 915–926. https://doi.org/10.25131/sajg.124.0031
41. Earle S, Panchuk K (2019) Physical geology, Press Books Dictionary.
42. Ullah S, Ullah Khan M, Rehman G (2020) A brief review of the slope stability analysis methods. *Geol Behav* 4: 73–77. https://doi.org/10.26480/gbr.02.2020.73.77