Lecture 12

Geomorphic Processes (III): Movement of Materials on Slopes

KEY QUESTION:

✓ *What influences the movement of materials on slope?*

With the completion of this lecture, attached readings and tutorial, you should be able to discuss:

- how materials move on slopes through mass movement and water erosion
- the different forms of mass movements (fall, slide, flow, creep) and water erosion (splash erosion, rainwash and rillwash)
- the human and natural factors influencing movement of materials on slopes

Lecture Outline

12.1 Introduction: Movement of Materials on Slopes

- As we learnt in **Lect. 11**, different weathering processes break down rocks into regolith and soil. All these broken materials lie on slopes of the earth's surface. Since these broken materials are weak and loose, these are susceptible to the pull of gravity, running water, wind, and the movement of glaciers to move them downslope from one place to another. In this lecture, we will focus on the processes involved in the movement of materials down the slope due to the ***pull of gravity*** *(mass movement)* and due to ***water*** *(water erosion)*.
- Mass movements and water erosion are considered geomorphological processes as their actions alter slope surfaces.
- In geography, a 'slope' refers to a small strip or patch of the land surface that is inclined from the horizontal. Most slopes are covered by a layer of regolith, which transitions downward into solid, unaltered rock, known simply as bedrock (see **Fig. 1**).

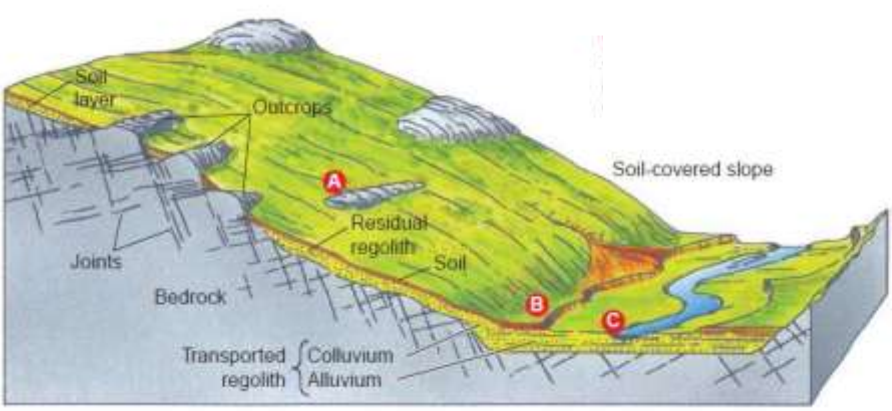


Fig. 1 Profile of a Slope

12.2 Slope Stability

- We use the term **mass movement** to refer to ***the downslope movement of materials under the influence of gravity*** (see **Fig. 2**). The rock materials move as a single unit. Mass movements take place when the driving force of gravity, which creates **shear stress**, exceeds the resisting force created by the **shear strength** of the slope materials.
  - Mass movement is <u>different</u> from erosion in that mass movement is <u>not</u> accompanied by a moving erosion agent (such as wind, water or ice) but just the influence of gravity.
  - The word "mass" in mass movement refers to the accumulation of materials of varied nature – from gigantic boulders, fragmented rock, regolith, to fine soil particles. The volume of these material that is moved can be very large, making mass movements potentially hazardous.

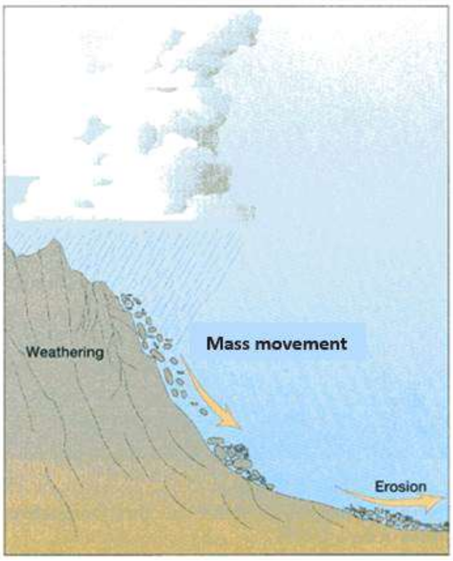


Fig. 2 Some key terms

- From **Fig. 3**, we can see that:
  - When **shear stress < shear strength** → the slope is **stable**. All weathered and loose rock materials lie at rest (i.e. no downslope movement) on a **stable** slope.
  - When **shear stress > shear strength** → the slope is **unstable**. **Mass movement** will result to bring the slope towards attaining slope stability by lowering the slope angle.
  - When shear stress = shear strength → slope is at critical threshold.

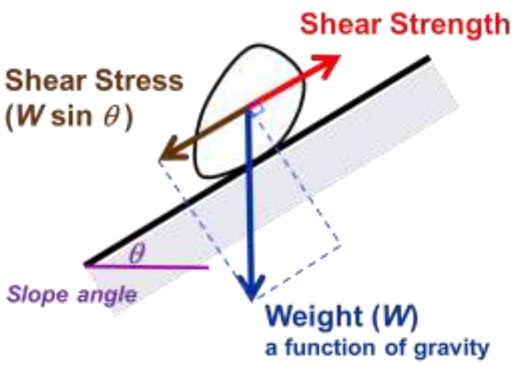


Fig. 3 Slope stability is achieved when **shear stress is *less than* shear strength**. When **shear stress *exceeds* shear strength**, **slope instability results**, giving different forms of mass movement.

- **Shear Stress**: The force that acts parallel to the slope and attempts to pull materials downslope. (*aka* **downslope force**)
  - The primary driver is the pull of **gravity**, which the weight of the weathered material is a function of.
  - The magnitude of shear stress varies with the ***gradient*** or ***steepness*** (θ) of the slope. The steeper the slope, the greater the tendency for gravity to pull materials down the slope.
  - The **steepest angle at which materials on a slope remain stable** is called the ***angle of repose*** (see **Fig. 4** and **Section 12.8.1.4(a)**). Beyond this angle, gravitational force will move materials downslope.
  - Shear stress can be increased by a range of factors (see **Section 12.8.1.5**) including violent shaking caused by earthquakes, volcanic eruptions and manmade explosions.

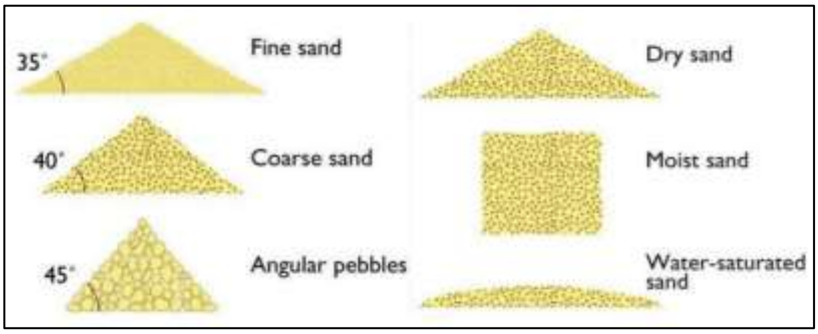


Fig. 4 Angle of repose

- **Shear strength**: The forces that cause soil material to stay in place on a slope contribute to shear strength. It is the underlying **resisting force** that acts against shear stress. (*aka* **upslope force**)
  - Shear strength is dependent on the friction and resistance forces between particles such sands and gravels, and cohesive forces (cementing) between silt and clay particles. These

particles are all found within the "mass" that is potentially or eventually "moved" (hence the term, "mass movement").

- Shear strength is also dependent on root cohesion (capacity of plant roots to bind soil together).

12.3 Classification of Mass Movements

- Mass movement show great variety of scale, rate, material and resulting landforms. Many different classifications have been proposed using these criteria, but one of the more frequently cited ones is by Carson and Kirby (1972) as shown below.
- Carson and Kirby acknowledged the presence or absence of water as an important role in triggering and determining the type of mass movement. Hence, they used:
  - **the amount of moisture present,** and
  - **the speed of movement**

as characteristics to distinguish between the various types (see **Fig. 5**).

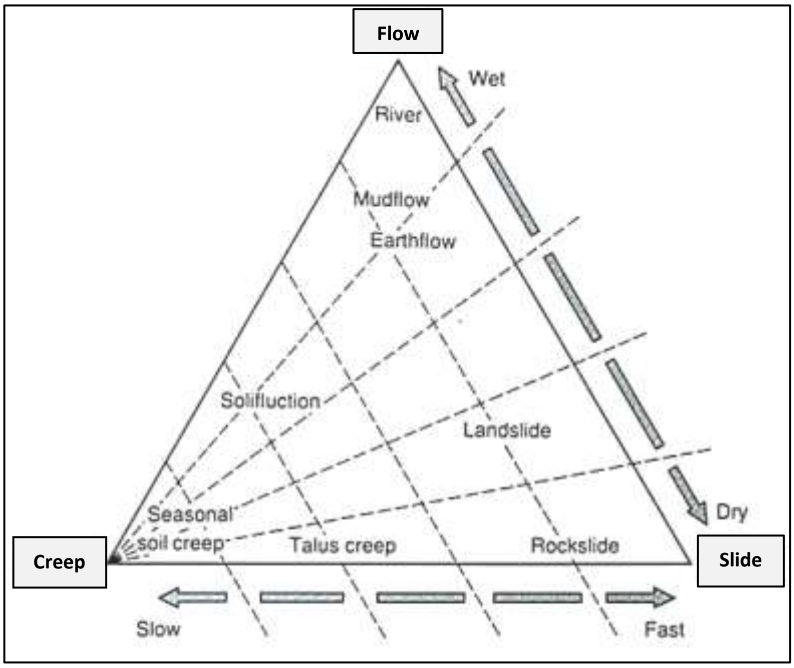


Fig. 5 Carson and Kirby's classification of mass movement processes

- Carson and Kirkby recognised three main types of mass movement; **fall** (see **Section 12.4**), **slide** (see **Section 12.5**), **flow** (see **Section 12.6**) and **creep** (see **Section 12.7**).
- As **Fig. 5** shows, there are many different (sub-)types of mass movements. In our syllabus, we will focus on the main types, i.e., fall, slide, flow and creep.
- The notes will outline the characteristics of each mass movement *as if* they were discrete movements, **although in nature the various types often overlap**.

12.4 Fall

- **Fig. 5** does not include fall, but if it were to, the placement of "fall" would be somewhere close to *slide* (see **Section 12.5**) because it has the **fastest** rate of movement and is also the **driest**.
- Falls are generated on the **steepest slopes** (angles greater than 40°), allowing a mass of material (e.g. pieces of rock) to break off and fall through the air. The detached fragments fall and bounce, accumulating at the base of the slope (talus) (see **Fig. 6** & **8**).
- Falls will occur when the weathering processes acting on a cliff face have done enough damage to allow a block of rock to become detached and fall under gravity.
- Most falls involve individual fragments which may disintegrate on impact, but occasional major slope collapses take place.
- Potential conditions for fall exist when the rock is **well-jointed** and weakened over time by **weathering** processes such as freeze-thaw action. The presence of joints and faults offers lines of weaknesses along which further weathering could occur, leading to **reduced shear strength** and eventual detachment of blocks (see **Fig. 6**).

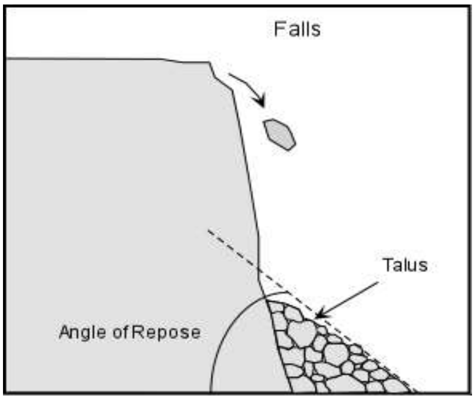


Fig. 6 Fall

- Falls also occur in seismically active mountains where **earthquakes** trigger rock falls along well-jointed cliffs.
    - Example: Falls commonly occur in the Himalayas and Andes due to earthquakes. The potential for falls in these high mountains is also higher because present glaciers used to extend further down the valley during glacial periods. The retreat of glaciers in the warmer Holocene removed ice masses from the lower valleys, resulting in pressure release and the development of new joints in rocks.
    - Example: The 6.0 magnitude earthquake in 2015 triggered dangerous falls on Mount Kinabalu, Malaysia when a jointed rock pillar collapsed due to the increased shear stress.
- Another trigger action for starting a fall usually involves a well-jointed rock cliff being **undercut by a river or the sea waves** (see **Fig. 7**). The removal of subjacent support (that is, support from below) increases shear stress in the overhang and often triggers overhang to fall (see **Section 12.8.1.3b**).

Fig. 7 Fall along the Jurassic Coast, UK

- The presence of **very low water content** at a cliff face reduces the effect of capillary attraction and thus the rocks are not held together by surface tension. This reduces shear strength. The lower the water content, the less cohesive the rock fragments will be and results in fall.
- Falls are one of the most common types of mass movement in the **arid tropics** (see **Fig. 8**) due to the low water content present and joints created in rocks by physical weathering.
  - Example: In the 2008 Mokattam Mountain incident in Cairo, Egypt, falls occurred due to the exposed lines of weaknesses in the rocks and steep slope angle of about 70°. At least 8 boulders, each around 70 tonnes in weight, fell from the mountain.

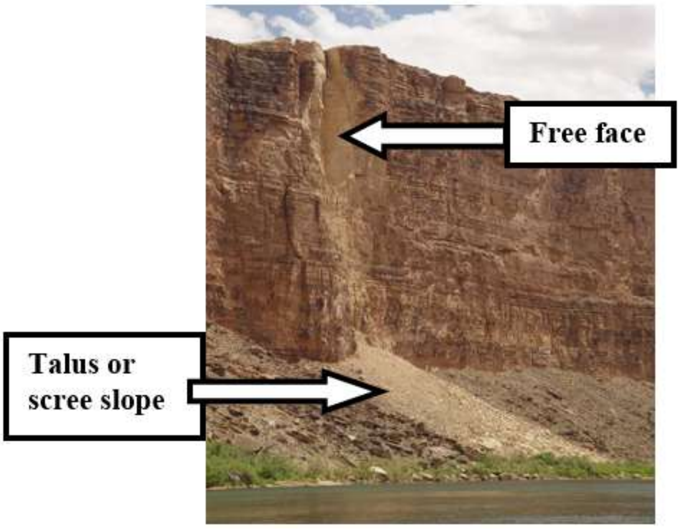


Fig. 8 Talus slope

- Falls are common as well in the **humid tropics** where there are jointed sedimentary rock cliffs, such as in karst landforms (see **Lect. 13**).
  - Example: In Malaysia, several incidents of falls have been recorded along well-jointed limestone cliffs (chemical weathering is promoted by the warm and wet climate). For example, in 1973, a limestone rock slab approximately 33m in length and weighing 23,000 tonnes collapsed off the entire cliff face of Gunung Cheroh.

12.5 Slide

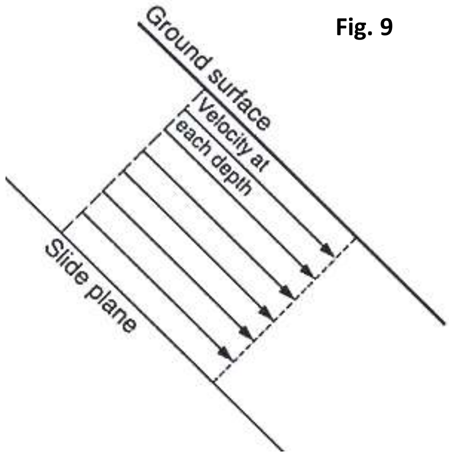


Fig. 9

- Although many types of mass movements are included in the general term "landslide", the more restrictive use of the term refers only to mass movements where there is a **distinct zone of weakness** that separates the slide material from **more stable** underlying material.
- Thus, slides are characterised by a **discrete slide plane** (see **Fig. 9)** over which the entire **coherent** 'slab' of material moves downhill at the **same velocity** at each depth from the surface.
    - Definition: **Slide plane** is a plane within the slope along which failure occurs.
- In slide, the weathered materials that move downslope are **dry or unsaturated**. For slide water is ***not essential***. However, if there is water in the slide plane, it *might help* in lubricating the points of contact between the weathered material and the slide plane.
- Slide plane can be straight or curved concave. Steep slopes with lines of weaknesses like joints, bedding and foliation planes, and fault lines, dipping steeply downslope forms straight slide plane (see **Figs. 10** and **11**). However, slide plane becomes curved concave when weathered materials on the slope have distinct layers or weak zones, such as layers of clay, silt, or sand, that have different strengths or stiffness.
- Also, as seen in **Fig. 9**, **velocity is essentially uniform** throughout the sliding mass.

Straight slide plane

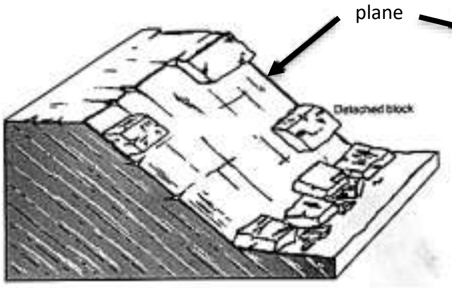


Fig. 10


Fig. 11

    - Slides are among the **fastest** (speed ranging from 1mm/day to 1m/sec) and most destructive mass movements.
- Slides occur in **both** the arid and humid tropics.
    - Slides occur in the **arid tropics** as little/no water is required. For example, slides are common at the Coyote Mountain in California, where blocks of rocks fail and slide along foliation planes in well-foliated gneiss.
    - Within the **humid tropics**, slides are common in karst landscapes, especially where lines of weaknesses like joints and bedding planes dip steeply downslope. For example, two massive slides occurred at the steep limestone cliffs of the Yudong Escarpment in Guizhou Province, China on 18 February and 16 April 2013. Both slides saw an unstable block sliding across shear planes that were pre-existing vertical joints cutting through thick limestone (see **Figs.**

12 and **13**). Besides the presence of joints that reduce shear strength, active underground mining by undercutting the base of the slope further steepened the cliff, increasing shear stress to cause mass movement.

Fig. 12

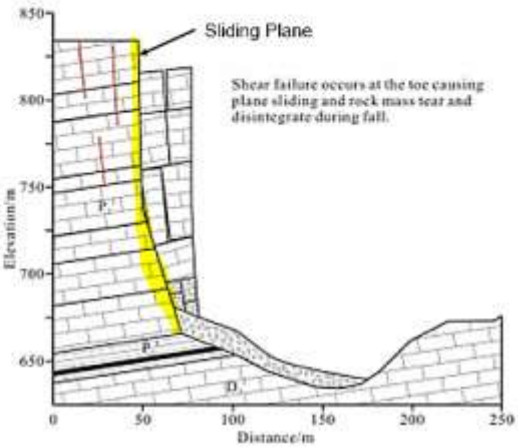


Fig. 13

- Where the **slide plane is curved concave**, as the movement occurs, a **crescent-shaped scarp** is created at the **head** of the sliding materials (see **Fig. 14**).
  - The top of the displaced block is usually tilted backwards to form a **back-tilted slope**.
  - Sediments that were at the lower end of the slope are pushed outwards, often forming a lobe protruding into a valley at the base of the slope known as **toe**.

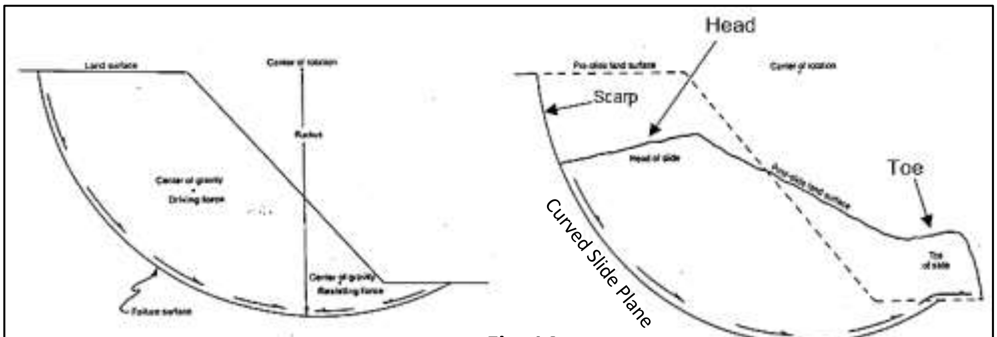


Fig. 14

12.6 Flow

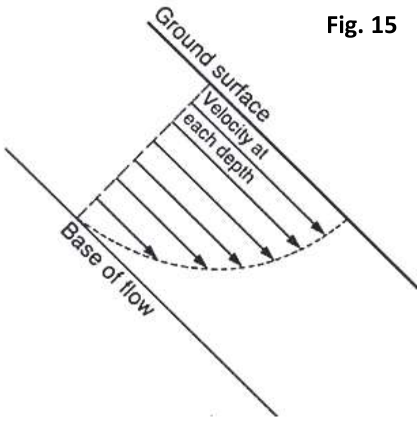


Fig. 15

- As seen in **Fig. 5**, flows are indicated by the **high presence of moisture** and **high speed** of the downslope moving mass.
- Unlike slides, flows **do not** occur along sharply defined slide planes. They move downslope over any surface. Also, unlike slides where the entire 'slab' of material move coherently downslope, in flows the entire mass is **deformed internally** and the moving mass behaves like a viscous liquid.
- In a flow, maximum velocity will be at or just below the surface (see **Fig. 15**) and the rate of flow will diminish sharply with depth to zero at the junction between the regolith and the solid rock. This is because of increased friction towards the base of the weathered layer, where rock fragments are normally larger, often more angular and less mobile than overlying fine materials.
- Flows occur characteristically on **steep slopes** (over 10°). They are **more rapid** and have been known to reach speeds of up to 100 km/h! <u>Note</u> that *flows can take place even over gentle slopes*.
- Usually occur during or right after **heavy rainfall**.
  - When there is an **absence of vegetation** to hold the soil in place, **fine-textured sediments** such as clay, fine sand and silt become saturated and flow downhill **over the impermeable sub soil** because the excess water has reduced shear strength.
  - As water and saturated soil run down the slope, it forms a thin mud which continues to flow until it becomes so thick it must stop.

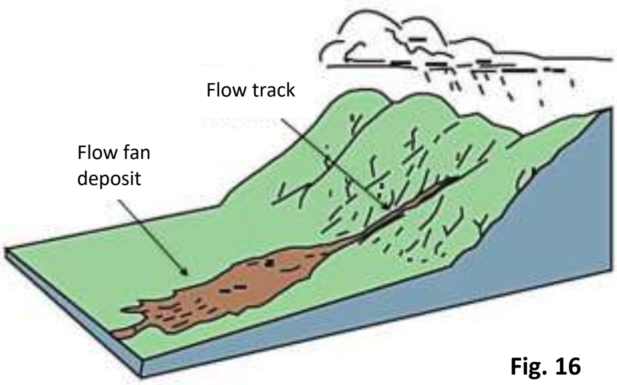


Fig. 16

- Flows move along the surface of slope and **follow established channels**, before producing **sediment fans** at the base of slopes (see **Fig. 16**).
- Flows mainly occur in the **humid tropics**, especially on **deforested slopes** during heavy rainfall. They are also common in areas with **thin soil overlying impermeable rocks**.
  - <u>Example</u>: The 2001 Limbe Flows on the volcanic cones of Mount Cameroon were triggered by intensive rainfall which preceded the event for two days and human intervention in the form of deforestation and agriculture on the steep volcanic slopes. The flows were generated on impermeable surfaces of basalt and compacted clayey volcanic tuff (which is a type of volcanic rock).
- Flows may also occur in the arid tropics during violent local storms. They occur most often in **semiarid and arid environments** with **sparse vegetation**.
  - <u>Example</u>: In March 2015, an extreme precipitation event (which contained the desert's last seven years' worth of water) generated damaging flows in the Atacama Desert, Chile, where there is sparse vegetation due to the extremely arid conditions. Oversaturation and the lack of vegetation both led to significantly reduced shear strength.

- Example: The Ilo region in the desert coast of Peru experienced flows triggered by very strong El Nino (see **Cluster 2 Lect. 4**) events in 1982-83 and 1997-98. The El Nino events brought heavy rainfall, which saturated unconsolidated debris and reduced shear strength by increasing pore water pressure, resulting in the loss of cohesion and internal friction between particles due to reduced capillary attraction.

- Volcanic eruptions can cause huge flows known as **lahars** when volcanic ash and pyroclastic materials mix with water from the melting of snow and ice, draining of crater lakes and/or heavy rainfall.
  - Example: Nevado Del Ruiz is the highest active volcano in Colombia and it is covered in 25km^2 of snow and ice. On 13 November 1985, an explosive eruption from the summit crater covered the summit in deposits of ash and pyroclastic materials. The hot ash and pyroclastic materials quickly mixed with the heavy rain that begun earlier in the day as well as melted snow and ice on the summit, resulting in a series of lahars that killed nearly 25,000 people.
- Compared to other mass movements, flows are **potentially more dangerous** to humans because of the rapid movement, larger quantity of materials involved, and the fact that these flows often discharge abruptly into areas of low relief and gentle slopes, which are likely to be favoured for human settlement and intensive agriculture.
- When water saturates regolith and soil on a slope, the material may break away, leaving a **scarp** on the slope and forming a **tongue-shaped** or tear-drop shaped mass that flows downslope. These flows often form **distinctive bulging lobes** when they arrive on a valley floor (see **Fig. 17**).
- As **Fig. 18** suggests, it is also common for flows to be confined to a channel "of some sort" and lose their velocity quickly when they reach a flat surface.

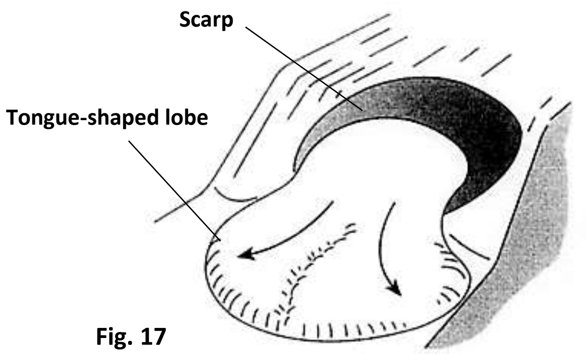


Fig. 17

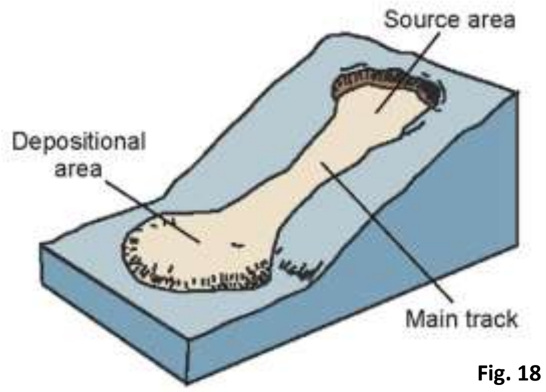


Fig. 18

- Shocks such as **earthquakes** could also liquify soil and trigger flows.
- Flows most often form on slopes in **humid areas** during times of heavy precipitation or snowmelt.
  - Example: In 1995, flow occurred in La Conchita, Southern California, where regolith is thick and weakly cemented. The flow occurred in March, near the end of a rainy season in which seasonal rainfall was about twice the normal amount. The mass movement events thus formed because of rising groundwater levels in response to deep infiltration of antecedent seasonal rainfall, which saturates and reduces shear strength of the overlying mass.

12.7 Creep

- In the bottom left corner of **Fig. 5 (page 4)** is **creep**. Not only are these **slower** than the slides and flows, but they tend to be on a **smaller scale** and are far less catastrophic.

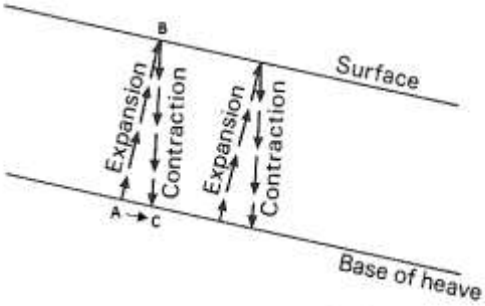


Fig. 19

- Creep is the result of the **expansion and contraction of soil** (see **Fig. 19**), combined with the influence of gravity. This expansion-contraction sequence can be due to **differential heating, freeze-thaw and wetting-drying** of the soil near the surface.
  - When the soil increases in volume, the only direction in which it can expand is perpendicular to the ground surface (see **Fig. 19**, **A** to **B**).
  - When it contracts, gravitational force tends to cause a vertical downward movement (see **Fig. 19**, **B** to **C**).
  - As a result, each cycle of expansion and contraction produces a net downward movement (see **Fig. 19**, **A** to **C**). In other words, weathered materials **creep** slowly down a slope.

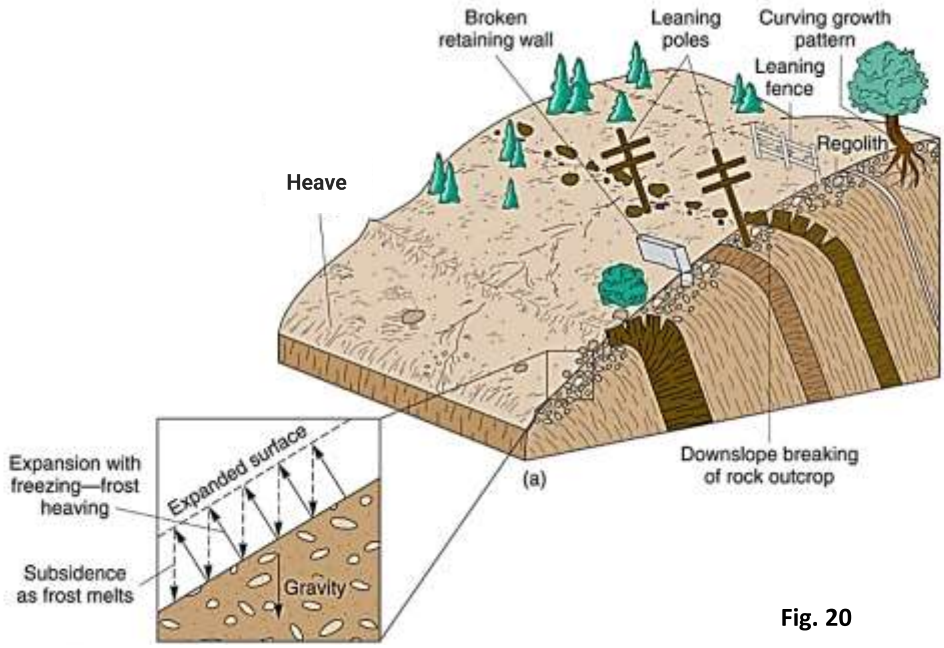


Fig. 20

- Creep is the slowest and least perceptible form of mass movement. It consists of a very gradual downslope movement of regolith which is barely noticeable and can be recognised only by indirect evidence (see **Fig. 20**).
- The main factor influencing the movement is **gravity.** Generally, the **entire** slope is involved.
- Creep occurs all over the world on sloping land. Although most notable on steep, lightly vegetated slopes, it also occurs on gentle slopes that have dense vegetation cover.

- Causes of creep in the tropics include:
  - **Differential heating and cooling of soils:** When the soil particles heated in the day, these expands at right angles to the original ground surface, lifting particles up perpendicularly. When the soil particles cool and contract at night, gravitational force results in a vertical downward movement of particles. The net result is the downward movement of soil particles along the slope called creep (see again, **Fig. 19**). Differential heating is most effective in the arid tropics, where the diurnal temperature range is large.
  - **Wetting and drying of soils:** Wet soil particles expand and dry soil particles contract, thus causing downward movement of soil particles (see **Fig. 19**). Diurnal and seasonal wetting-drying is most common in the humid tropics.
  - **Diurnal and seasonal freeze-thaw cycles:** Freezing of water in saturated soil leads to the formation of ice in the pore spaces between soil particles. As the ice increases in volume, it lifts up soil particles perpendicularly to the surface. When the ice melts, the particles will then drop downslope under the influence of gravity (see **Fig. 20**). Freeze-thaw occurs on slopes of high altitudes in the tropics, where temperatures fluctuate above and below 0^oC.
- Usually, creep is a very slow process, but its rate of movement is faster under certain circumstances (see **Section 12.8** on factors affecting slope stability).
  - **Slope angle**: Creep operates faster on steep slopes than on gentle slopes.
  - **Vegetation**: Deep-rooted and dense vegetation inhibits creep as roots bind the soil.
  - **Moisture content**: Creep is generally faster on water-saturated slopes than on dry ones.
- Because of the above reasons, the rate of creep does vary across different climatic regions.
  - Humid tropics: 3-6 mm/year
  - Arid tropics, with cold winters: <10 mm/year
- Many other agents contribute to creep:
  - Burrowing and trampling by animals may disturb soil particles.
  - As plants grow, they also tend to displace soil particles down slope.
  - Even the shaking of earthquake or thunder produces disturbances that stimulate creep.
- Evidence of creep (see **Fig. 21** for an overview):
  - Trees with unusual, curved growth near the base of trunks.
  - Leaning telephone poles and fences.
  - Broken retaining walls which fail due to the tremendous force and weight exerted by the creeping sediment.
  - Accumulation of soil behind walls or other manmade structures.
  - **Terracettes** (see **Fig. 21**): small, quasi-parallel, staircase-like stepped landforms generally less than 1m in tread.

Fig. 21

12.8 Factors that Influence Mass Movements

- The causes of mass movement are usually related to instabilities in slopes caused by natural and human factors. As **Section 12.2** suggests, natural and human factors lead to slope instability through:
  - **Increasing** shear **stress**
  - **Decreasing** shear **strength**
- In evaluating the factors the influence mass movements, it would be relevant to consider:
  - the extent of influence of one factor over another
    - the extent to which a factor triggers mass movements, as opposed to being the fundamental mechanism through which mass movement occurs
    - the extent to which a factor could prevent the occurrence of mass movements
  - the spatial extent of a factor's influence
  - the temporal extent of a factor's influence
  - the categories of mass movements a factor has influence over
- The above list is not exhaustive and any discussion must be well-supported by examples, that could include an in-depth analysis of the processes involved and/or specific mass movement episodes.

12.8.1 Natural Factors

12.8.1.1 Gravity

- Gravity is the **controlling factor** for mass movement.
- The natural and human factors that follow **trigger** mass movement.

12.8.1.2 Climate – the Availability of Water

- The importance of climate can be discussed in terms of the availability of water, as well as how the availability of water may change due to contemporary climate change (see **Cluster 3**).
- Water can <u>trigger mass movement</u> by increasing shear stress and decreasing shear strength, <u>but</u> it can also help to <u>prevent mass movement</u> by increasing shear strength of soil particles of the slope.

(a) Slope saturation by water is a primary trigger for mass movement. Saturation can occur because of intense rainfall, snowmelt, rise in ground water level, etc.

- The presence of water will affect the behaviour of unconsolidated sediments through the phenomenon of **capillary attraction**. Capillary attraction is *the attraction that results from surface tension between water and particles in the sediments – a force that tends to hold wet sediments together as cohesive mass, thus increasing shear strength* (see **Fig. 22a**).
- However, if the mass becomes **over**-saturated with water, shear strength decreases as the mass will lose cohesiveness and begin to flow like a fluid (see **Fig. 22b**). This is because water gets between the grains and eliminates grain-to-grain frictional contact by increasing the **pore water pressure** and allowing sediments to slide over one another.

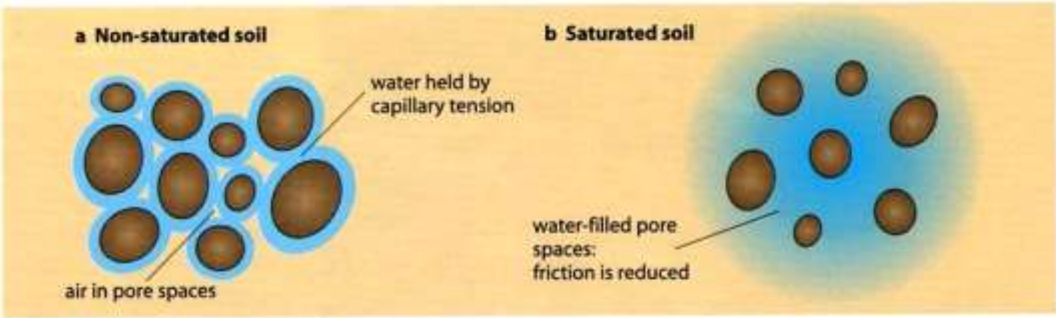


Fig. 22

(b) **Increase in the volume of water increases the weight** of a potentially mobile mass as the pore spaces are filled with water, thus *increasing the shear stress*.

(c) Water also **lubricates the slide plane** at the base of a regolith and/or rock mass (e.g. bedding planes and fault lines; see **Section 12.5** on slides), *reducing friction and shear strength*.

(d) **Excessive and/or prolonged rainfall** is a common reason for high availability of moisture. Wet seasons in the humid tropics and even the occasional convective storms in the arid tropics therefore often lead to slope failure because of *reduced shear strength* ***and*** *increased shear stress* (see examples in **page 10** & **11**).

12.8.1.3 Vegetation

- Forest cover maintains slope stability both by absorbing and intercepting rain, reducing the retention of moisture in soil. The ability of vegetation to use up soil moisture also helps to ensure that over-saturation is less likely, thus **lowering shear stress**, **increasing shear strength** and reducing chance of mass movement. By securing soil and other vegetation to the bedrock with tree roots, **shear strength is increased**.
- The removal of vegetation therefore threatens slope stability. Yet, it can be doubtful whether vegetation can prevent or even slow down any large-scale movement as even a dense vegetation cover may offer little resistance to movement on a steep slope or oversaturated slope (see **Section 12.8.1.3(b)**). Also, mass movement are frequent in the humid tropics, which are areas with dense vegetation – this means that the protective role of vegetation may also become negligible in times of excessive moisture.

12.8.1.4 Slope Characteristics

(a) Steepness of Slope

- Steepness of slope plays a very important role in triggering mass movement (see **Box 1**). The **steeper the slope, the more vulnerable** it is to mass movement (see **Fig. 3**, when θ increases, shear stress increases, raising the likelihood for slope instability).
- The steepest angle at which a slope or material on the slope remains stable is called the ***angle of repose*** (**Fig. 23**).

Fig. 23

- In **Fig. 24A**, when the slope angle = angle of repose, the slope is stable. In **Fig. 24B**, when the slope angle is smaller than the ***angle of repose***, the slope is also stable. However, when the slope angle increases and exceeds the angle of repose as in **Fig. 24C**, shear stress is more than shear strength resulting in slope instability thereby leading to mass movement.

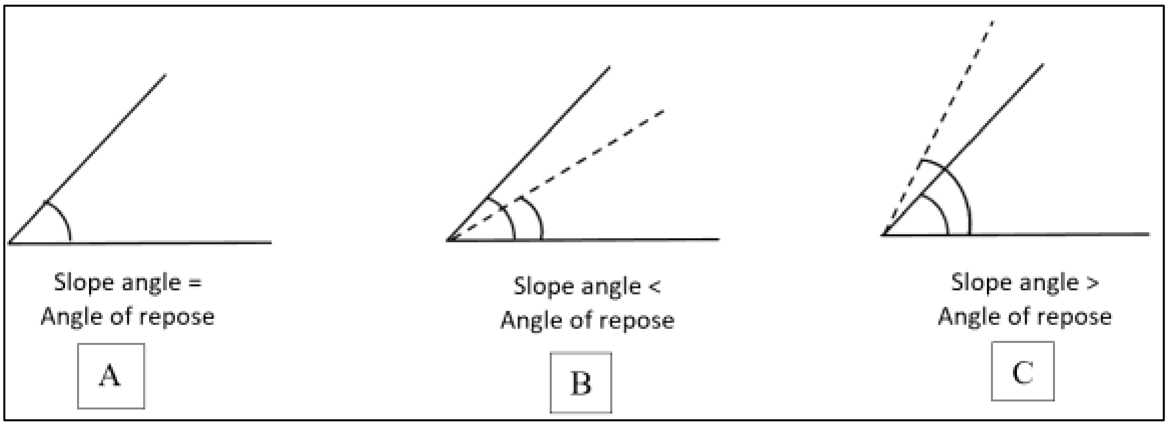


Fig. 24 Relationship between slope angle and angle of repose

- Depending on the size and shape of the particles, the angle varies from 25° to 45°. Larger, more angular particles maintain the steepest slopes (**Fig. 25**). If the angle is increased, it will increase the shear stress and to attain stability the rock debris will adjust the angle of repose by moving downslope.
- However, angle of repose also changes with the amount of water present in the mass. For example, slopes of moist sand have higher angle of repose than slopes of dry sand. This means moist sand has higher slope stability than dry sand. Conversely, water-saturated sandy slope has very low angle of repose and this results in slope instability (**Fig. 25**).

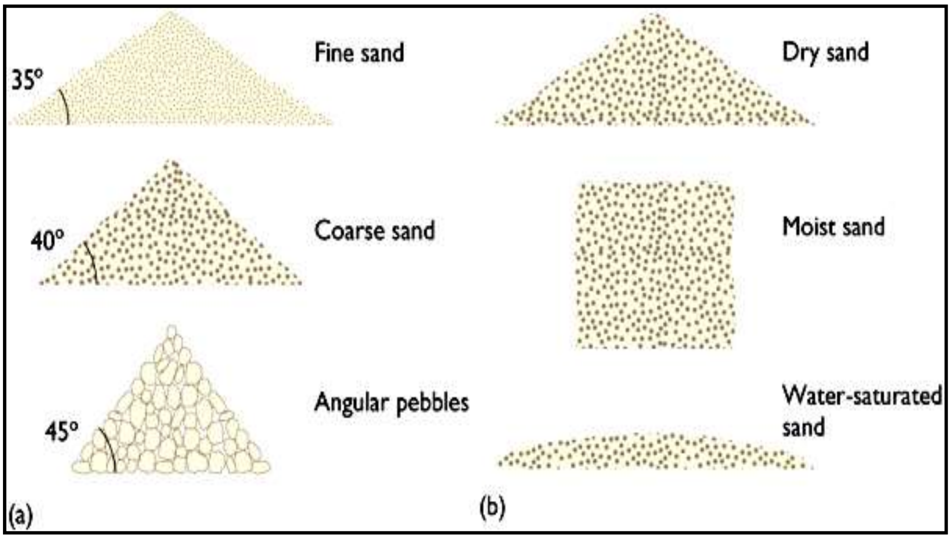


Fig. 25

  - Example: In the 2008 Mokattam Mountain incident in Cairo, Egypt, falls (see **Section 12.4**) occurred due to the steep slope angle of about 70° and exposed lines of weaknesses in the rocks. At least eight boulders, each around 70 tonnes in weight, fell from the mountain.

- In some cases, mass movements are triggered as a result of **undercutting of the base of the slope** by a river (see **Fig. 26**), especially during a flood (or even through human activities, see **Section 12.8.2**). This undercutting causes removal of the base of the slope thus causing slope angle exceed angle of repose which causes shear stress exceed shear strength and thus causes mass movement.

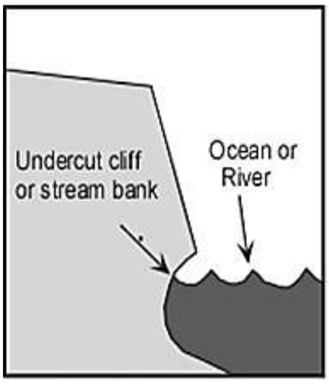


Fig. 26

(b) Geology

- The **dip of rocks**, or the presence of inclined faults and bedding planes, will influence the likelihood of slide.
  - Sedimentary rocks with *upslope dipping strata* tend to maintain their steepness and have stable slopes as individual stratum, even when loosened by weathering, remains in situ.
  - However, where dip is *downslope*, detached masses of rock can readily slide over bedding planes (see **Fig. 27**).

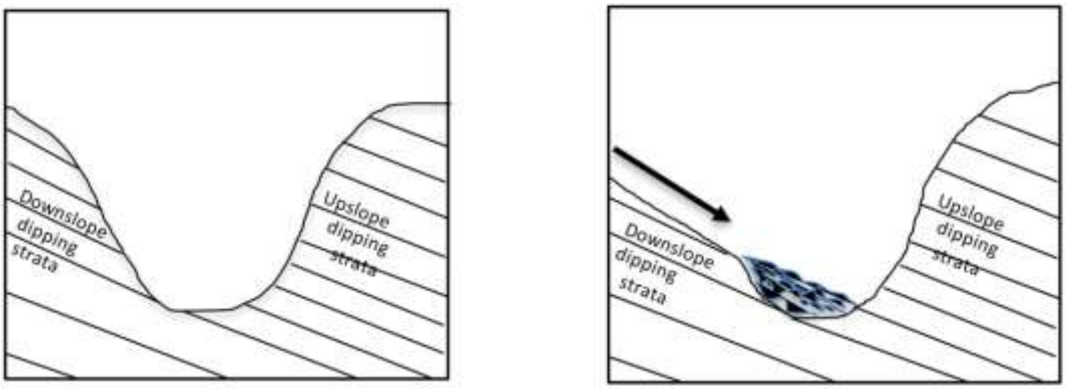


Fig. 27

(c) Underlying Rock Type

- Generally **hard rocks** like granite will be more ready to support steep slopes than **weakly cemented** sandstones.
  - However, shear strength of such hard rocks will be greatly reduced if it possesses joints and fractures into which water can percolate.
  - In addition, slopes in granite with many lines of weaknesses may undergo rapid and effective **weathering**, as in warm and humid climates, resulting in a thick regolith (see **Section 12.8.1.3 (e)**) of little shear strength, thus making the slope vulnerable to mass movement.

(d) Characteristics of Regolith

- **Degree of consolidation.** Slopes that are composed of loose and unconsolidated materials have reduced shear strength and are much more prone to collapse, especially on steep slopes.
- **Thickness.** The **thicker** the regolith, the likelihood of instability is more as there is d**ownward force acting on a larger mass of soil material is greater** than the downward force on a smaller mass.
- **Composition. Clay-rich** regolith is prone to mass movement as it can absorb and retain water, which adds both to its weight (increasing shear stress) and to mobility (decreasing shear strength). Conversely, **sand-rich** regolith is less prone to mass movement as it is well drained and allows water to pass through thus remaining less wet. Composition therefore affects level of saturation.

12.8.1.5 Tectonic Forces

(a) Earthquakes

- One of the factors that can trigger mass movement is earthquakes. Mass movements occur during earthquakes as a result of two separate but interconnected processes:
  - **seismic shaking** (which **increases shear stress**); and
  - **pore water pressure generation** (which **decreases shear strength**) (see *soil liquefaction*)
- **Soil liquefaction** refers to the loss of shear strength that causes otherwise solid soil to behave temporarily as a viscous liquid.
- When earthquake shocks occur in water-saturated unconsolidated soils, water-filled pore spaces collapse. This increases pore water pressure between individual soil grain, leading the grains to lose contact with one another and move freely in the watery matrix. *(Recall: O-level Plate Tectonics)*
  - Example: On 13 January 2001, a massive 7.6-magnitude earthquake hit the Central American state of El Salvador, triggering a massive flow (see **Section 12.6**) at Los Colinas. Other contributory causes to the mass movement event include: **(i)** heavy rains prior to the event that had made the soils heavy and saturated (see **Section 12.8.1.2**), **(ii)** a very steep hillslope (see **Section 12.8.1.3(a)**) and **(iii)** developers cutting down trees and cutting into the base of the hillslope (see **Section 12.8.2**).

(b) Volcanic Activity

- Some of the largest and most destructive mass movements known have been associated with volcanoes. These can occur either in association with the eruption of the volcano itself, or as a result of the movement of the very weak deposits that are formed as a consequence of volcanic activity.
- Volcanic eruptions may trigger earthquakes and violent ground shaking, **increasing shear stress**.
- Hot lava and pyroclastic material erupted may melt snow rapidly or may get saturated by torrential rainfall, thus forming a mobile mass of wet unconsolidated debris known as **lahar** that moves down the steep slope of a volcano. Lahar is a type of *flow* (see **Section 12.6**). Excess addition of water reduces shear strength and thus makes the slope unstable causing mass movement.

- Example: After the explosive eruptions of La Soufrière volcano in April 2021, the island of St. Vincent experienced at least 25 rainfall-triggered lahar events over the following year. These lahars caused significant impacts and losses, affecting infrastructure and livelihoods.
- Nevado Del Ruiz is the highest active volcano in Colombia and it is covered in 25km^2 of snow and ice (see **Fig. 28**). On 13 November 1985, an explosive eruption from the summit crater covered the summit in deposits of ash and pyroclastic materials. The hot ash and pyroclastic materials quickly mixed with the heavy rain that begun earlier in the day as well as melted snow and ice on the summit, resulting in a series of lahars that killed nearly 25,000 people.

Fig. 28 The November 13, 1985 eruption took place during night. Although Armero was 74 kms (46 miles) from the crater of Nevado del Ruiz, it took the lahar only two and a half hours to reach the village.

12.8.2 Human Factors

- **Deforestation** due to human activities such as **logging, cattle ranching,** and **mining** reduces vegetation that may serve to shelter the slope, intercept rainfall and provide a network of roots to hold slope material in place (see **Section 12.8.1.4**).
- Construction activities **add extra weight on the head of a slope** with new buildings and more structures (e.g. septic tanks, swimming pools and irrigation), increasing shear stress (see **Fig. 29**).
- **Alteration of slope angle** (see **Fig. 30**) through the construction of roads and settlements at the base or mid slope, or quarrying at the base of a slope, may lead to slope angle exceeding angle of repose, thus increasing shear stress and resulting in mass movement.

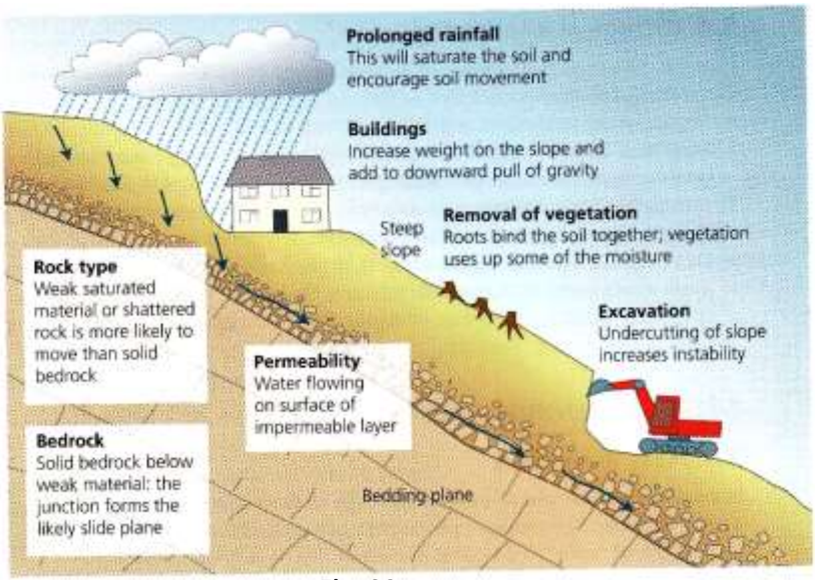


Fig. 29

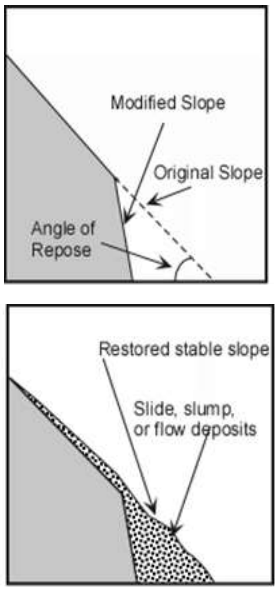


Fig. 30

- The **construction of roads** in mountainous terrain not only undercuts slopes, but the vibration caused by heavy traffic can also increase shear stress and destabilise slopes.
  - Example: The increasing number of roads and settlements built along the foot of slopes in the Himalayas has further increased the frequency of mass movement events. Mass movements are common in the Himalayas due to the high intensity of monsoon rainfall and the presence of many fault lines that could act as slide planes. On 12 Sept 1995 near Kulu in Himachal Pradesh, India, a slide occurred, killing 65 people. Heavy rain between 3 and 6 Sept had caused the river to exceed bankfull discharge, flooding *a roadway that had been cut into the foot of the slope and undercutting the unconsolidated foot of the slope*. Without the road, the slope would be less vulnerable to undercutting by the fast flowing and turbulent river.
- **Construction of dams** across a river valley, where water is stored behind the dam to form a reservoir, can lead to mass movement along the valley sides. Such mass movements are caused by the saturation of the adjacent rock material. Adjacent areas get saturated with water which increases pore water pressure and weakens the material at the base of the slope causing mass movement.
  - Example: The Three Gorges Dam in China has created a giant 1000 km^2 reservoir, which undercuts and saturates materials at the banks of the reservoir. Furthermore, the huge reservoir influences the local climate, making cloudbursts and heavy rainfall more likely. The Three Gorges region has already become prone to mass movement, with over 5000 danger points identified. In 2012, China's Ministry of Land Resources admitted that there had been 70% more mass movements in the area than predicted.
- Humans can also **adopt slope stabilisation measures** to increase the shear strength of slopes and thereby prevent mass movements. This can be done pre-emptively or in response to mass movements (see **Box 1 and 2**).

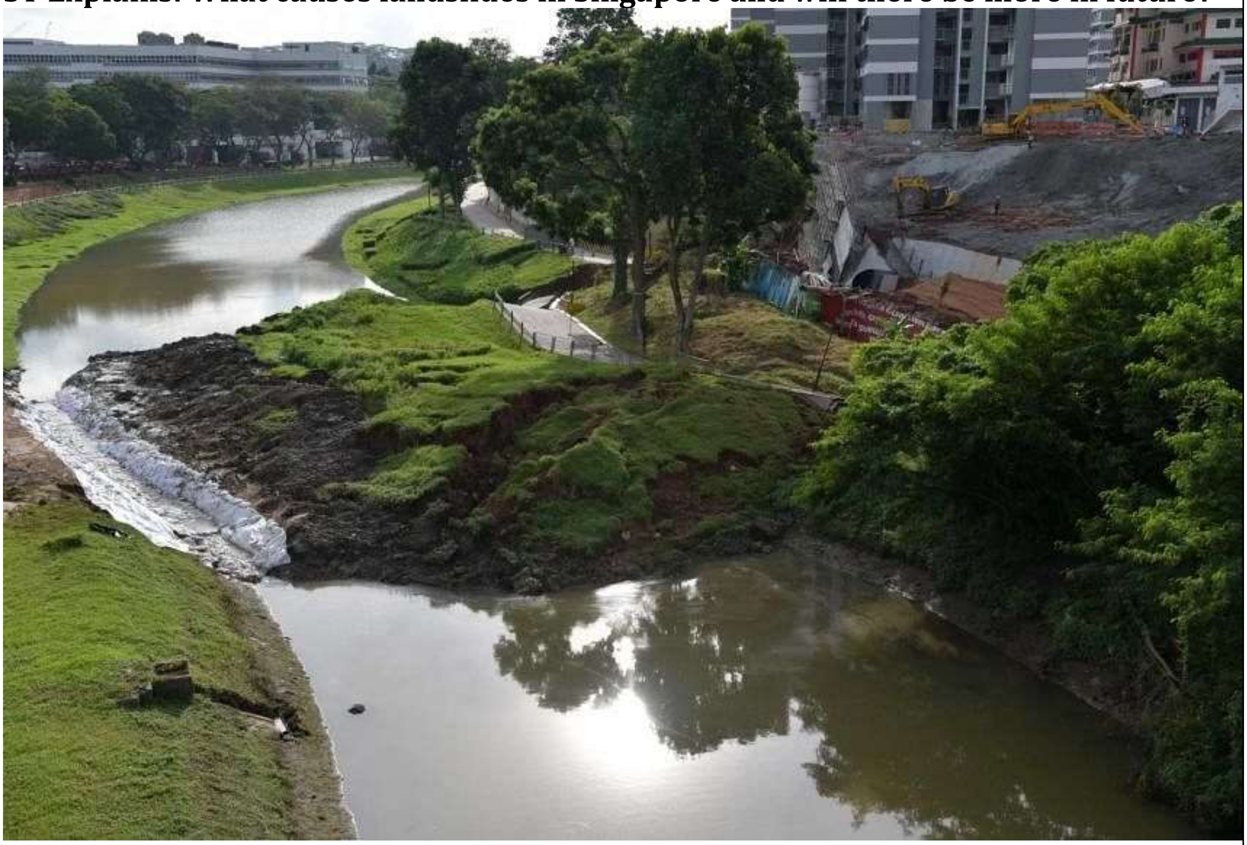
Box 1: Factors Affecting Mass Movements in Singapore

Landslide Near the Clementi NorthArc on 2 Sep 2022

A landslide near the Clementi NorthArc construction site in Clementi Avenue 6 on 2 Sep 2022 caused damage to the Ulu Pandan Park Connector and soil displacement into the Ulu Pandan Canal.

The before and after of the Ulu Pandan Canal. PHOTOS: SCREENGRAB FROM GOOGLE MAPS, SIM ANN/FACEBOOK

ST Explains: What causes landslides in Singapore and will there be more in future?



A landslide at the Housing Board's Clementi NorthArc Build-To-Order site last Friday is being investigated. PHOTO: ST FILE

Ang Qing
PUBLISHED
SEP 8, 2022, 12:00 PM SGT

SINGAPORE - The factors that contributed to a landslide at the Housing Board's Clementi NorthArc Build-To-Order (BTO) site last Friday are still being investigated.
Engineering experts tell The Straits Times that such incidents in Singapore are commonly caused by heavy rain, adding that with more frequent bouts of intense rainfall projected, more landslides may occur.
Here, they explain how landslides happen and whether parts of Singapore are more prone to these incidents.

Q: What causes landslides in Singapore?

A: Landslides occur when the sliding force of a slope, which comes from the weight of its soil and load imposed on the slope, exceeds the internal strength of the soil in the slope that resists these forces.
Professor of Civil and Environmental Engineering Harianto Rahardjo from Nanyang Technological University said various factors can contribute to landslides.
One example is additional weights placed at the top of a slope or heavy rain infiltrating the soil, said Prof Rahardjo, who helms the university's research on unsaturated soil mechanics.
As Singapore is located next to the equator, where rainfall is abundant, frequent and intense downpours are the most common causes of landslides here, said Associate Professor Darren Chian from the National University of Singapore's Department of Civil and Environmental Engineering.
With Singapore's relatively flat topography, he said, landslides are smaller in scale, less damaging and generally less common here than in other countries in the region.
Prof Rahardjo said rain-induced landslides occur when large amounts of water infiltrate the slope's soil and reduce its ability to resist sliding forces.
In 2019, engineers from Surbana Jurong Consultants studied the relationship between rainfall and 430 reported landslides here.
They found that there is a risk of landslides when daily rainfall in Singapore exceeds 189mm.
The engineers also found that rainfall of 100 hours or longer, with an average intensity of 5mm an hour, can trigger landslides in Singapore.
In January 2021, heavy rain caused landslides in Outram and along Loyang Avenue, with the national water agency PUB reporting that 184.4mm of rainfall had fallen in Changi from midnight to noon on the day of the incident.

Q: Are parts of Singapore more prone to landslides?

A: No specific part of Singapore is more prone to landslides, said Prof Chian and Prof Rahardjo.
In addition to the variable nature of ground conditions across Singapore, there is the practice of topping up land in an area with soil from elsewhere.
This adds to the diversity of the type of soil found near the ground surface, said Prof Chian.
Landslides occasionally occur at slopes that have been altered for the construction of buildings when heavy rain causes water to accumulate beyond the slope's drainage system capacity, said Dr Teo Tee Hui.
Dr Teo, who is from the Singapore University of Technology and Design, has done work on predicting landslides in other countries.
But this is rare in Singapore as there are typically precautions in place, he added, noting that the Clementi landslide was unexpected.
In June, ST reported that the Building and Construction Authority, which oversees buildings and construction sites, has not recorded any incidents of a slope giving way in the last five years.
"Slopes altered for construction or natural slopes are usually checked and reinforced to prevent landslides in most cases," said Dr Teo.

Q: Will the frequency of landslides increase in future?

A: "With greater intensity and frequent rainfall, occurrences of landslides are expected to rise," said Prof Chian.
This is because water has more time to gather and seep into the ground, leading to rapid reduction in shear strength of the soil that is supporting the slope against sliding, he added.
A slope made of moist soil is kept stable by capillary suction between the soil particles, or negative pore water pressure, which contributes significantly to the shear strength of the soil.
When too much water infiltrates a slope, this decreases capillary suction, decreasing the shear strength of the soil.
This, in turn, increases chances of the slope giving way.
The number of landslides across the island spiked last year as a result of intense rainfall during Singapore's second-wettest year since 1980.
The National Parks Board told ST in June this year that cases of a slope giving way in spaces managed by the statutory board jumped from one in 2020 to 20 last year - the highest in five years.
It noted that the increase could have been due to the abnormally high rainfall in 2021, which was nearly 70 per cent more than in the previous year.

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- https://www.straitstimes.com/singapore/part-of-clementi-park-connector-closed-after-landslide
- https://www.straitstimes.com/singapore/st-explains-what-causes-landslides-in-singapore-and-will-there-be-more-in-future

Box 2: Recovery, construction efforts after Clementi landslide 'may take a few months': Desmond Lee

CNA
04 Sep 2022 11:24PM

SINGAPORE: The recovery and construction efforts to repair the damage caused by the recent landslide in Clementi "may take a few months", said National Development Minister Desmond Lee said on Sunday (Sep 4).

This includes removing the dislodged soil in Sungei Ulu Pandan, reinstating the damaged part of the Ulu Pandan Park connector and reconstructing the slope and retaining walls within the site, he said in a Facebook post.

The landslide occurred at a construction site for the Clementi North Arc Build-to-Order (BTO) flats on Friday morning, causing "soil displacement" into the canal and damage to the park connector. A passer-by sustained minor injuries.

Mr Lee said he visited the area with Senior Minister of State for National Development Sim Ann on Sunday afternoon.

The Housing and Development Board (HDB), National Parks Board (NParks) and national water agency PUB have been "working round the clock" over the weekend to carry out "immediate repair and slope stabilisation recovery works", Mr Lee said.

"HDB and the contractors have applied a thin layer of concrete to help stabilise the slope ... (and) created a channel to allow water flow through the canal to mitigate any flood risks upstream," he added.

Mr Lee said more permanent measures to stabilise the slope are being carried out, followed by the "main recovery and construction efforts, which may take a few months".

Engineers from the Building and Construction Authority (BCA) and HDB, together with the project's Qualified Person - either an architect or engineer - have inspected surrounding buildings and structures and they remain structurally sound, said Mr Lee.

He added that BCA, HDB and the Ministry of Manpower are investigating the "slope failure".

"In the meantime, safety remains our priority. We will continue to check the instrument readings deployed within and around the site, to closely monitor structural safety throughout the entire recovery process," he said.

12.9 Water Erosion

Erosion is the removal of weathered rock materials from its original site on the Earth's crust **and** the transportation of the eroded material by natural agencies such as water or wind from the point of removal.

- Often occurs **after** weathering of rock.

Erosion involves the following processes:

- **Detachment**
  - Loosening of materials at the surface as a precursor to the actual movement.
  - It occurs as a result of energy applied to the sediment particle.
- **Entrainment**
  - Initial movement of the sediment at the surface and may under certain circumstances be continuous with the detachment process.
  - Controlled by the energy of the natural erosion agent.
- **Transport**
  - Actual movement of a sediment particle and may be by direct movement through the air or through rolling/sliding along the surface, by saltation or by suspension.

Deposition of particles will follow erosion:

- This is when the process of erosion stops, and transported particles fall out and settle on a surface.

- In our syllabus, we are specifically focusing on water as an agent of erosion. The three processes are splash erosion, rainwash and rillwash.

12.9.1 Splash Erosion

- In the arid tropics, **raindrops fall directly on the surface** due to lack of vegetation. The direct force of falling drops on bare soil causes 'splashing' in which soil particles are lifted and then dropped into new position.
- This process is termed **splash erosion**. The raindrop splash effect is a result of the energy of falling raindrops causing detachment (or loosening) of sediments and down-slope movement of detached sediments (see **Fig. 31**).

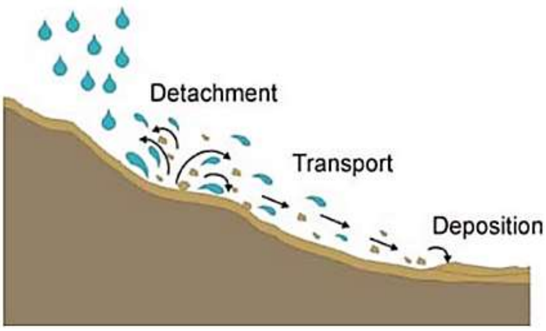

Fig. 31 Splash erosion

12.9.2 Rainwash

- Usually splash erosion (see **Section 12.9.1**) detaches and displaces sediments. However, at times it turns soil surface impermeable (see **Fig. 32**). This occurs because the natural soil openings become sealed by particles detached by raindrop splash.

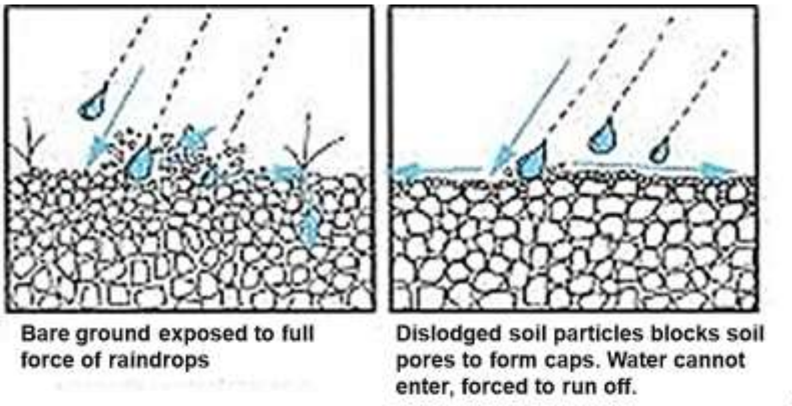

Fig. 32 Raindrop impact compacts soil surface, lowering infiltration capacity, generating IEF under high intensity rain

- When soil surface gets sealed by raindrop impact, infiltration capacity is reduced, generating more infiltration excess overland flow (IEF). This then spreads over the land surface and flows as a sheet of water removing the soil as a uniform thin layer by a process termed as **rainwash** (see **Fig. 33**).

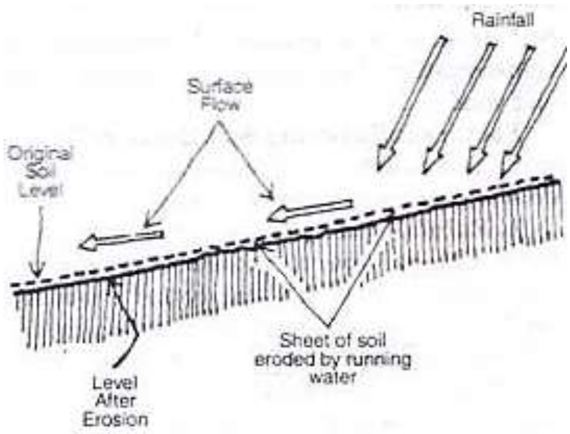

Fig. 33 Rainwash; notice the dashed lines that represent the original soil level.

- Among the erosive processes by water in the arid tropics, rainwash is the **main erosive force**. Yet, rainwash is less noticeable compared to other erosive processes, as it does not leave obvious cuts in the soil surface as with rillwash (see **Section 12.9.3**).
- Soil particle size and the erosive capacity of the flowing water influence the amount of detached sediment transported in rainwash. Sediment transport is greater with smaller sediment size and greater erosive capacity.
- The velocity of rainwash is reduced by vegetation cover as vegetation may serve as a barrier. In the arid tropics, however, vegetation is scarce, hence the velocity of rainwash is high. The sediment carrying-capacity of rainwash is therefore also high, increasing sedimentation.

12.9.3 Rillwash

- During a rainwash (see **Section 12.9.2**), the overland flow may concentrate into grooves and very small channels (or microchannels) in the surface. Within these flow paths, the ability of water flow to erode and transport sediments increases substantially to create *rills* (see **Figs. 34** and **35**). This process is referred to as **rillwash**.

- Factors that promote rillwash and formation of rills:
    - **Slope angle**: Persistent rills require slopes steeper than 2 to 3°. As slope angle increases, so does the probability of rill formation, not only because of the increase in concentrated overland flow erosivity but also because of a decrease in topsoil shear strength.
    - **Sediment size**: Erodibility is at a maximum in soils with small mean particle size.
    - **Vegetation**: Rilling is a potent form of erosion on hillslopes with little vegetation, generally contributing from 50 to 90% of total sediment removal.

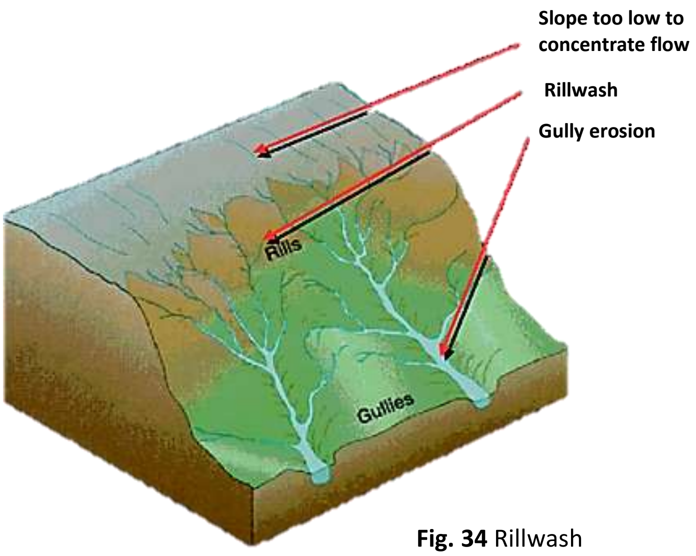

Fig. 34 Rillwash

Fig. 35 Rills in Death Valley, California. In almost all deserts, even in the most arid locations, the effects of erosion and deposition by running water are prominent in the landscape.

12.10 Factors Affecting Water Erosion

12.10.1 Natural Factors

a) Rainfall and runoff

- The greater the intensity and duration of a rainstorm, the higher the erosion potential. The impact of raindrops on the soil surface can break down soil aggregates and disperse the aggregate material. Lighter aggregate materials such as very fine sand, silt, clay and organic matter are easily removed by the raindrop splash and runoff water; greater raindrop energy or runoff amounts are required to move larger sand and gravel particles.
- Soil movement by rainfall (raindrop splash) is usually greatest and most noticeable during short-duration, high-intensity thunderstorms. Although the erosion caused by long-lasting and less-intense storms is not usually as spectacular or noticeable as that produced during thunderstorms, the amount of soil loss can be significant, especially when compounded over time.
- Surface water runoff occurs whenever there is excess water on a slope that cannot be absorbed into the soil or is trapped on the surface. Reduced infiltration due to antecedent soil moisture, crusting or freezing increases the runoff.

b) Slope Gradient and Length

- The steeper and longer the slope of a field, the higher the risk for erosion. Soil erosion by water increases as the slope length increases due to the greater accumulation of runoff. Consolidation of small fields into larger ones often results in longer slope lengths with increased erosion potential, due to increased velocity of water, which permits a greater degree of scouring (carrying capacity for sediment).

c) Soil Characteristics

- Generally, soils with faster infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion. Sand, sandy loam and loam-textured soils tend to be less erodible than silt, very fine sand and certain clay-textured soils.
- Past erosion also influences a soil's erodibility. Many exposed subsurface soils on eroded sites tend to be more erodible than the original soils were because of their poorer structure and lower organic matter.

d) Vegetation

- The potential for soil erosion increases if the soil has no or very little vegetative cover. Vegetative cover protects the soil from raindrop impact and splash, tends to slow down the movement of runoff water and allows excess surface water to infiltrate.
- The erosion-reducing effectiveness of vegetation depends on the type, extent and quantity of cover. Vegetation that completely cover the soil and intercept all falling raindrops at and close to the surface are the most efficient in controlling soil erosion (for example forests, permanent grasses).

12.10.2 Human Factors

Human factors typically alter one of the natural factors, resulting in **either** the worsening of soil erosion **or** the reduction of soil erosion.

Worsening of soil erosion:

- Runoff from agricultural land is greatest during spring months when the soils are typically saturated, snow is melting, and vegetative cover is minimal.
- Tillage and other practices performed up and down field slopes creates pathways for surface water runoff and can accelerate the soil erosion process.

Reducing soil erosion:

- The potential for soil erosion by water is affected by tillage operations, depending on the depth, direction and timing of ploughing, the type of tillage equipment and the number of passes. Generally, the less the disturbance of vegetation or residue cover at or near the surface, the more effective the tillage practice in reducing water erosion. Minimum till or no-till practices are effective in reducing soil erosion by water.
- Cross-slope cultivation and contour farming techniques discourage the concentration of surface water runoff and limit soil movement.
- Tillage and cropping practices that reduce soil organic matter levels, cause poor soil structure, or result in soil compaction, contribute to increases in soil erodibility. As an example, compacted subsurface soil layers can decrease infiltration and increase runoff. The formation of a soil crust, which tends to "seal" the surface, also decreases infiltration. On some sites, a soil crust might decrease the amount of soil loss from raindrop impact and splash. However, a corresponding increase in the amount of runoff water can contribute to more serious erosion problems.
- The effectiveness of any protective cover also depends on how much protection is available at various periods during the year, relative to the amount of erosive rainfall that falls during these periods. Crops that provide a full protective cover for a major portion of the year (for example alfalfa or winter cover crops) can reduce erosion much more than can crops that leave the soil bare for a longer period of time (for example row crops), particularly during periods of highly erosive rainfall such as spring and summer. Crop management systems that favour contour farming and strip-cropping techniques can further reduce the amount of erosion.
- Contour farming is the practice of using the contours of the land (see **Fig. 36**). The method involves tilling or planting across a slope and building small ridges at right angles to the land's natural slope. The ridges themselves will also have a slope, albeit a shallow one, to control the speed of the water. The shallow ridges slow down water runoff by creating a new pathway for it to travel. In turn, slower water means less soil erodes as it moves.

Fig. 36 Contour Farming of Grape Vines

- Strip cropping is a method of farming used when a slope is too steep or too long, or otherwise, when one does not have an alternative method of preventing soil erosion. It alternates strips of closely sown crops such as hay, wheat, or other small grains with strips of row crops, such as corn, soybeans, cotton, or sugar beets. Strip cropping helps to stop soil erosion by creating natural dams for water, helping to preserve the strength of the soil. Certain layers of plants will absorb minerals and water from the soil more effectively than others. When water reaches the weaker soil that lacks the minerals needed to make it stronger, it normally washes it away. When strips of soil are strong enough to slow down water from moving through them, the weaker soil can't wash away like it normally would. Because of this, farmland stays fertile much longer.

12.11 Conclusion

- Mass movements and water erosion are crucial geomorphic processes that significantly shape the Earth's surface. Mass movement plays a fundamental role in redistributing materials downslope, contributing to the formation of various landforms. This process is essential in sculpting landforms and influencing the development of slopes and hillsides. On the other hand, water erosion, driven by processes such as rivers, streams, and rainfall, is a potent force that shapes valleys, riverbanks, and coastal areas. It not only transports weathered materials or eroded sediment but also plays a key role in carving intricate landforms over time. Both mass movements and water erosion are interconnected, often working in tandem to modify and mould the Earth's topography.
- Mass movements and water erosion contribute to the development of both karst and fluvial landforms. Mass movements are particularly significant in the collapse processes that shape karst landforms (see **Lect. 13**). In addition, both mass movement and water erosion can modify the sediment load of rivers, thereby affecting the formation of fluvial landforms, as well as the occurrence of floods.
- Understanding these geomorphic processes is vital for managing landforms, mitigating natural hazards, and preserving ecosystems. In conclusion, the importance of mass movement and water erosion lies in their transformative abilities to shape and reshape the Earth's surface, influencing geological features and impacting the environment in profound ways.