Applied Seismology for Engineers

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Week – 11 Lecture - 01

Lecture – 27

Hello everyone, myself Dr. Abhishek. In earlier lectures, we have discussed plate tectonics, continental drift theory, and the phenomena associated with these, how they are responsible for the movement of the plates and subsequently, because of the increase in the stresses along the plate boundaries, and the same phenomena will apply to within the plates, there will be the development of earthquakes. When these earthquakes happen, there will be different kinds of waves generated at the focus or the source of the earthquake, and these will travel from the focus in all directions away. When these interact with the material, that is the crustal medium along the propagation path or through different soils, there will be phenomena of amplification and de-amplification which will happen in different frequencies of waves. In today's lecture, I am going to give you an overview of one important phenomenon, which is primarily important as far as safety, casualties, loss of infrastructure, connectivity, and many more such information, that are relevant in order to ensure what will be the damage scenario primarily during an earthquake, is landslide. As we know, a significant portion of our country is prone to landslide occurrence every year, whether it is the rainy season or during major to great earthquakes, there will be information on landslide occurrence in different parts of the country. If you talk about the northeastern part or other parts like the Western Ghats and other parts of the country, which are particularly in hilly terrain, often we hear the news that during such a particular earthquake or during prolonged rainfall, a piece of land has been slid and triggered a lot of landslides, blockage of roads, sometimes toppling of vehicles, and in the worst scenario, it can even lead to casualties.

So, in today's lecture we will be talking about different induced effects. That means whenever earthquake-generated waves interact with the system, whether it is a layered surface on level ground, whether it is saturated ground subjected to loading because of the passage of waves, or whenever the sloping ground is there, though it looks stable in its static condition or in routine, but because of prolonged rainfall or because of additional loading which is generated because of the waves during an earthquake, these can destabilize that particular slope and finally, it will lead to a landslide. So, in today's topic, that is lecture 27, we will be discussing an overview of what a landslide is and how one can classify the landslide.

Please understand, the topic of this particular lecture is not to help in understanding how to quantify the landslide hazard because that is again a vast topic and that is not the syllabus of this particular course. But I will be giving you an overview of what a landslide is and how, because different materials are there, depending upon the material which is involved, you can classify the landslide. The next time whenever you see any particular slide, depending upon what geometry is available, what physical properties are available, and what material is involved in that particular kind of failure, you will be able to understand what kind of landslide has occurred on a particular site. Sometimes, it can be one material that has undergone failure; sometimes, it will be more than one material that has undergone failure.

So here we can see an introduction to landslides. Generally, we use landslide as the downward movement of material that exists on a slope, primarily the rocks. If you go to hilly terrain, there are no soils available on the surface; you will have rocks. At times, you will be having weathered rocks, even soils also, or a combination of rocks and soils. Even at some locations, you will often encounter organic materials getting deposited over a period of time, and there are hillocks, mounds, and even big hills. So, what if the material that the hill is composed of undergoes failure subjected to downward movement? That is called a landslide.

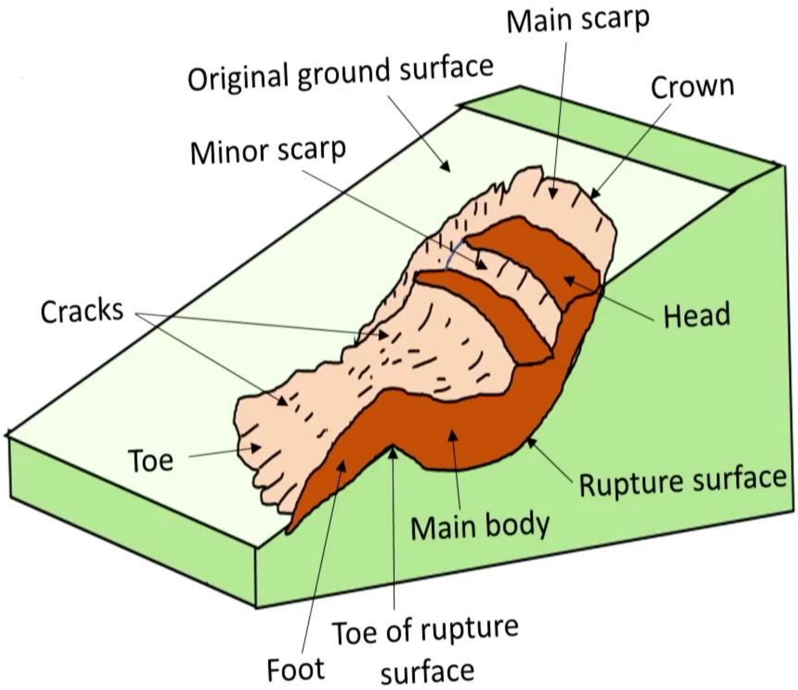


Fig.1 illustration showing different components of a landslide (modified after Varnes, 1978)

In the photo which is given on the right-hand side, you can see here, it's not simply the slide that has happened along a particular slope, but depending upon the geometry, and depending upon the characteristics of the failure, there are different components, as you can see over here. So, the top portion that is given over here, is the crown. That is the topmost portion, after which, if you come down further, there will be failure you will experience along the slope. Then there will be a main scarp, that is the failure or the slippage which has happened in a significant portion just after the crown. After that, as you move towards the toe, there will be significant signatures of failure along the surface of the slope. So, you have a crown, then you have a main scarp. The main scarp means the main projection which is an indication of some kind of failure that has happened along the slope. Then you will come across minor scars. Relatively, in comparison to the main scarp, there will be deformation, but those deformations will be relatively smaller, and there can be more than one kind of minor scarp. Then you can see subsequently, the failure of the material along the slope, which will also lead to the development of cracks along the slope. Depending upon the nature in which the material has undergone failure, you can have longitudinal cracks also, and you can have signatures of material undergoing rotation or toppling. That will also happen along the great surface. So, what it indicates is there was a slope that, in its initial condition, was quite levelled, just like you can see on this particular side, the slope is quite stable, but you have another significant portion of the slope that has undergone failure.

So, you start with the crown, which is the topmost portion, then a significant portion along which the material has undergone downward movement, which is called the main scarp. Then you have the original ground surface with respect to which you are actually measuring how much displacement along the slope or in the vertical direction has happened along the scarp. Then significantly, you will have more than one minor scarp. Then there will be the development of cracks along the fault length along the slope. Then there will be the toe. So, just like our feet, there will be a toe along which the material, which is undergoing failure from the crown and along the failure surface, has started gathering. Now, again, you can see over here, that the entire material which has undergone failure has actually started showing some kind of rotation or some kind of slip or some kind of movement along this surface. For that reason, this particular surface is called the rupture surface. That means the material which was undergoing failure has actually taken this particular surface. It's not in one dimension; you can see it's moving along the slope and also parallel to the slope. So, if you are seeing on the screen, it's along the line of sight. So, it's actually a plane; that's why it is called the surface. So, the rupture surface is actually the surface along which the material in three dimensions has actually moved, and this is the actual material or the body of the material that has undergone failure.

Again, you will see, that often some material that has undergone failure will start failure from the surface, and then once it reaches the toe or just before the toe, the material reaches its natural slope or initial slope. This can happen over here, and this can happen slightly downward also, and accordingly, one can classify whether it was a slope failure, toe failure, surface failure, or base failure. So, depending upon what is the position of the failure surface with respect to the toe, the lens can be classified. Then again, you can see the feet which is visible over here, which is the end portion just before the toe. So, this is the typical nomenclature of different parts of a failure that has happened to the slope indicated by the landslide. Whenever we are discussing this correct material, whenever we are discussing the material available on the main scarp, material available on the minor scarp, there will be soil, there will be rock, there will be organic material, and there will be combinations of different kinds of material. Not every time will you have homogeneous material. You can have a different combination of materials because if you consider the slope, whether it is a man-made slope, whether it is a natural slope, also taken into account, what are the weathering and depositional agencies which have been dominating in this particular region where this particular slope is available, that will also help in understanding whether the material along the height of this particular slope will be relatively homogeneous or there will be varieties of material which you will find across different sections of this particular failed slope.

So, depending upon the process involved, the formation of this particular slope will define what the characteristics of the slope will be. Subsequently, if the process is very slow, there are more chances that the material deposited in this particular slope will be relatively stiffer in comparison to the material exposed to a lot of weathering and deposited in a relatively small span of time. So, that is going to give you some indication about whether it is a natural slope, whether it is a man-made slope, whether the material at the slope is homogeneous, whether the material at the slope is heterogeneous, the material is single type, meaning throughout it is soil, or it is rock, or it is organic material, or it is a combination of organic material and soil, organic material and rock, or soil and rock. Thirdly, whether the material is relatively stiff in its in-situ conditions or the material is relatively weak such that it is almost at the brink of failure, or the slope is almost waiting for any triggering mechanism and suddenly the material will undergo failure by downward movement of the material. So, we have discussed about typical parts of the slope or landslide: that is, crown, then main scarp, then head, then the main body of this failure, then foot, then toe, and then the surface of the failure. Surface of the failure, as I mentioned over here also, depending upon where the surface of the failure is interacting with the original ground surface, you can categorize whether it is a toe failure, whether it is a surface failure, or whether it is a base failure.

So, this is a brief overview about what a landslide is: that is, downward movement of the material along a particular slope. There can be a number of triggering mechanisms. As I mentioned, it can be primarily because of rainfall. If the rainfall is continuous, or the resultant occurrence of rainfall has created some weaker planes along the particular slope, then there are more chances the slope will undergo failure. Secondly, there is a lot of disturbance. Vegetation has been cut off from the particular slope such that the vegetation or the roots of the plants were keeping or holding the slope back in its position. That can also lead to failure. Thirdly, because of earthquake-induced loading, there will be vibration, which will trigger additional load on the material which was on the brink of failure, or the material otherwise was in stable condition, but because of this additional disturbing force, the material has undergone failure. So, the importance of different kinds of restoring forces and different kinds of disturbing forces can be observed when you study slope stability. There, it will be very clear what the possible components are that lead to the failure of the slope and what the components are that lead to restoring the slope against any kind of failure. So, landslides are classified into different types, primarily depending upon the type of movement and the type of material involved. As I mentioned earlier also, not every time will you find a slope having the same signature: that the material was there in its in-situ condition and then the material started failing, or depending upon the movement. Sometimes you will see the material is simply falling from the slope. Sometimes, the material is flowing like a slurry. At times, you will see the material is undergoing some kind of rotation. The material will undergo topple. The material will undergo lateral spread. So, in each of these phenomena, the outcome is failure, but how this particular failure has occurred from its initial position of the slope to the final failed slope, that will define what type of landslide has happened at a particular site. Then, depending upon the material involved, you can say it is rock failure, soil failure, or a combination of those. So, depending upon the type of movement, you can classify the landslide again. Depending upon the material involved, you can classify the landslide.

So, the material involved in landslides is primarily soils and rocks, because if you are talking about hilly terrain, you may experience intact rock, you may experience weathered rock, you may find some weaker planes along which there is a possibility that the rock will undergo movement. Then, there may be some cracks along which precipitation, or because of freezing of the material, there will be additional loading which is getting generated. And the same in terms of soil: because of prolonged rainfall, because of precipitation, because of problematic material where the soil comes in contact with the problematic material, it may weaken the soil, or it may cause some kind of localized channel along which possible movement in the soil is possible. Finally, as this particular phenomenon progresses, it will lead to failure in a particular slope that will be witnessed in the form of landslides. Often, we will see failure when you are moving along particular roads. Sometimes you will see some boulders starting to move from the top of the particular slope, falling on the road, sometimes falling on the vehicle, sometimes moving further down, primarily when we are traveling along hilly terrains. So, that is one kind of failure which is very prominent in the case of landslides, particularly in rocky terrain.

So, soil is often described as earth, which is composed of sand-sized particles and other finer particles. Whenever we are discussing debris, we are indicating some kind of coarser material, which is not sand-sized but coarser than sand-sized. So, whenever we are talking about earth, we are mainly referring to finer material. When we are talking about debris, we are referring to bigger material. And, of course, there is movement of the boulders also, which at times you can witness rolling down primarily along the slopes. Depending upon the type of movement occurring during a particular landslide or slope failure, you can call it primarily into four types, which are shown on the screen: first one is, falls. Again, depending upon whether it is the falling of the material directly from the top, you can call it a rock fall. If the material is undergoing toppling while detaching from its parent material, you can call it a topple. So, both rock fall and topple are categories of landslides. Then you can have spreads. As the name suggests, the material along the slope will experience lateral spreads. As the material goes down, it is also spreading in a lateral direction. So, often you will see there was a slope which has undergone failure, and at the toe of the particular slope, you will see the material is all spread along the length perpendicular to the failure surface. That will come under lateral spreads. The third one is slide. As the name suggests, and as we have seen in the previous figure also, slide means the material was there in equilibrium, but because of some reasons, now the failure has happened and the material has undergone some kind of sliding. So, the material was there, and then it has undergone sliding. When we say sliding, generally there will be a failure surface along which the sliding has happened. So, you can call it as a rotational landslide or a translational landslide. The last one is flows, as the name suggests. So, here, unlike spread, where the material is undergoing failure in terms of lateral spreading on its own, in case of flows, the material will be mixed with respect to water, and then in terms of slurry, the material mostly will be flowing. So, you can call it an earthen flow. The material will be actually undergoing failure, and continuous movement of the material along the flow will be happening. Then, debris flow is also possible. And then, as I mentioned, at times, water will be mixed with the material, and it will be flowing just like a slurry. If the parent material or the debris are of volcanic origin and have been deposited subsequently, if such material is undergoing failure, you can call it lahars. So, that is also one category of flow-type landslides.

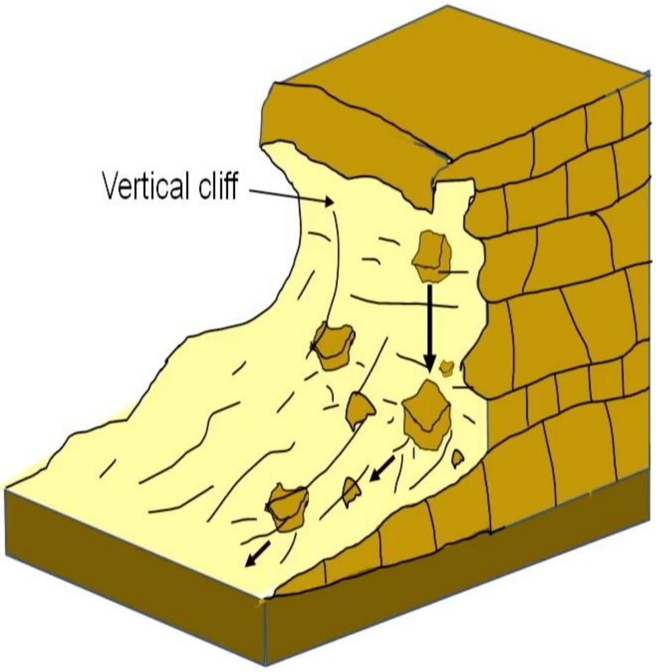


Fig. 2 Schematic of a rockfall (modified from Cruden and Varnes,1996)

So, the first one that we were discussing about fall, you can see over here. One slope is there. Looking at the slope, we can understand the slope is quite steep; it is almost vertical. And the material which was there at the top, almost in the hanging portion, in case of fall, has actually been detached from its parent material and started vertical movement. This vertical movement most of the time will not be happening along the surface because the hanging portion of the material will be slightly outside with respect to the original slope or the vertical ground. As a result, when the material is undergoing detachment, the material will simply drop from its parent position to some portion of the slope, but it will not certainly undergo movement with continuous contact with the slope. So, a fall starts with the detachment of the soil or rock, or both, from a steep slope along the surface on which little to no shear displacement occurs. No shear displacement means the material, because there is a slight lag between the material undergoing failure and the steep slope, so you can say almost there is no shear displacement available on the slope surface between the slope and the material involved in case of falls. In case of rock falls, there will be abrupt downward movement of rock or soil, or both. Primarily, you can see these in steep slopes or vertical cliffs. So, if you see vertical cliffs and some material was there at the top of that particular cliff, by virtue of failure, the material is actually detached from its parent medium and then suddenly drops and then started moving further. Now, that drop can depend upon whether the entire cliff is almost vertical, or some portion of the slope is vertical. That will define whether the drop will be within the slope or outside the slope. That will be the characteristic of rock fall.

So, detaching of the material described by falling, and then subsequently, when the material is falling on the slope, it will further go down because, after all, it is dropping on a particular slope. So, by the mechanism of dropping and further, in order to reach equilibrium, the material will further undergo bouncing, rolling, and then it will reach more or less a stable ground surface. Generally, it is triggered whenever you will see, because of a vertical cliff or steep slope, you will often encounter it whenever there is some kind of cut made along the road slopes or along the slopes for the construction of roads, undercutting of the slope. So, you cut a slope and leave them in very steep positions. So, certainly, the material which is there hanging on the top will undergo rock fall. Similarly, you can see this, the one just I mentioned. It is related to human activities. At times, there will be very fast movement of the streams or rivers adjacent to the ground, as a result of which there will be subsequent weathering. There will be subsequent cutting of the material, leaving the actual slope in a very stable or almost vertical position. In these cases also, you can often encounter rock falls. Similarly, because of differential weathering, whether it is sometimes because of freezing, sometimes because of thawing, also, if it is happening differentially, what will happen as a result? Because of these differential weathering agencies or the rates at which these processes are happening, there will be localized formation of the channels along which weaker planes will be generated and subsequently, by virtue of its position and overcoming load, these will undergo failure.

Human activities, as I mentioned earlier, many a time while constructing roads in hilly terrains, we often cut some portion of the slopes, make it almost horizontal, and then lay roads. But the remaining portion of the slope, which many a time is not continuous, you have actually cut some part of the slope which was very close to the original toe, and then after that, it is left almost in a vertical position or very steep slope. There also, you can see some kind of rock falls witnessed. Third part was if there is intense vibration, it can happen because of earthquake loading conditions, and subsequently, if some kind of construction activity, explosion, happens in and around that particular slope, then that can also trigger additional loading and subsequently lead to failure by means of almost no to little shear displacement, which is the primary characteristic of rock fall. So, rock fall, as I mentioned, was one kind of failure that comes under the category of fall.

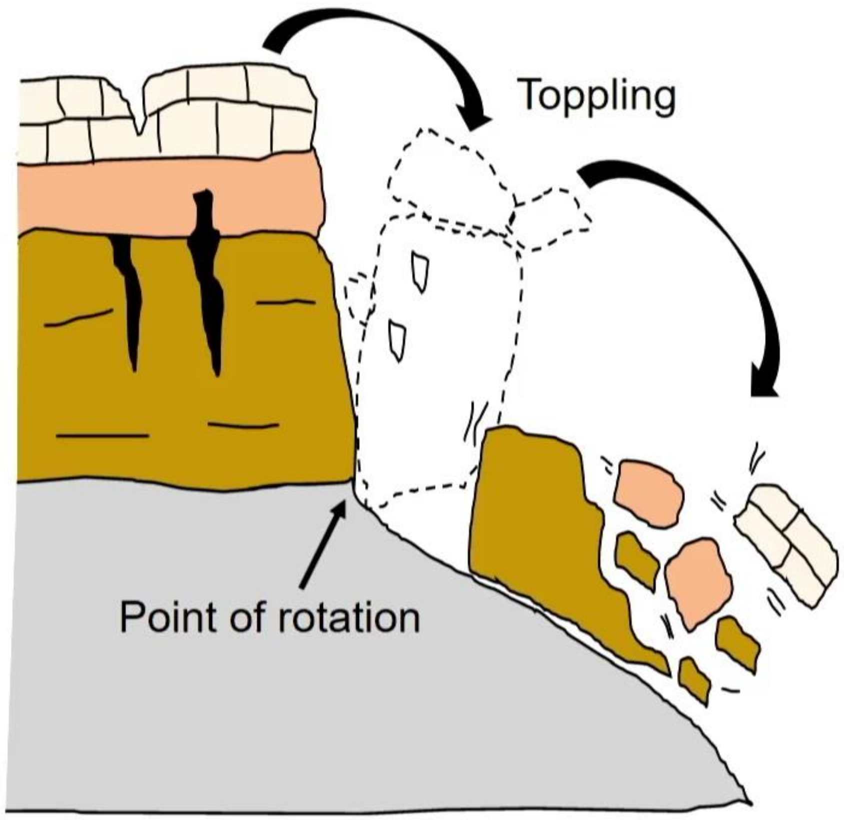


Fig. 3 Schematic of a topple (modified from Cruden and Varnes,1996)

The second one was topple. Now, you can see in this particular figure, it is different from rock fall because there, the material was simply dropping from a particular height and was undergoing bouncing and rolling and reaching the surface. In this particular one, you can see the material remains. Firstly, it is not related to a very steep slope, but you will see the material has undergone forward movement. So, you see the material was located somewhere over here. Primarily, one example is given over here also because of columnar joints in the rocks, which is a possible indication of weaker planes. If some kind of additional forces, because of freezing of water along this particular plane, has happened, or because of earthquake loading also, which is actually generating some kind of destabilizing forces, what will happen? The material will detach from its original position. So, this particular material, which has actually undergone toppling, which was actually located attached to the original ground, that particular material has now undergone failure, and this particular failure is not abrupt. This particular material is not in forms of no to little shearing, but you can clearly see the material, in the name of failure, is actually undergoing rotation. So, this material is undergoing rotation along this particular point of rotation, which usually will be located below the center of gravity of the displaced mass. Only then the material can undergo rotation. So, you see, subsequently, the material will undergo rotation and depending upon whether it is intact rock mass or boulder, the same thing will keep on toppling and then will reach the bottom. Or if it is composed of fragments of other materials, during the course of rotation and downward movement, these materials will further disintegrate into individual components and then subsequently will undergo failure as it moves from its parent position to downward movement. So, this is again toppling. The characteristics of toppling, though it comes under falls, it is significantly different from rock fall. So, if you go to a particular site and you see if downward movement directly is there, you can call it a rock fall. If the material is undergoing some kind of rotation, toppling, you can call it as undergoing toppling, provided the material is undergoing rotation along the point of rotation.

So, this can occur again in both rock mass as well as in the earth material prevalent in columnar jointed volcanic terrains also. It is common where there are very steep banks and adjacent to that, some rock, some river is flowing. Then, suddenly we see a large chunk of material is falling from its parent position and dropping down. So, again, that is also an example of topple, which is a kind of failure of the slope. So, here we are talking in terms of the slope, which are adjacent to the riverbanks. Generally, it is triggered by the gravity exerted by the material located up slopes from displacing mass. So, you will see the material actually, in its position, in its initial position, was almost subjected to some kind of external loading condition because of earthquake loading, because of prolonged rainfall. But certainly, there was some weaker position portion along which the material was actually possible to undergo failure, which has actually happened during topple. Same way, if there is water or ice available in these particular locations, these will also induce loading within the cracks, as a result of which it will try to widen the cracks. As it widens the crack, that means it is destabilizing the adjacent landmass. This means the landmass undergoes destabilization. Certainly, if it is already on the side of the slope, it will be ready to undergo any kind of failure. Then, subsequently, it will undergo failure for downward movement. Vibrations: again, the material was in an intact position, though it was adjacent to the slope but was not undergoing failure. But because of vibration, it induced additional loading, and subsequently, the material has been detached from its parent material and undergone failure by toppling.

Underground excavations or undercutting: many times, you will see that the material was quite intact, but by virtue of excavation, the material, in its initial position when the excavation was not done, was quite stable because it was getting its restoring force generated again at this particular levelled surface. But once you remove this particular slope, the material will again be in a more destabilized position, and subsequently, because of undercutting or excavation, the material will undergo failure. Excavation can also be considered if the slope was quite level and gentle, but because of excavation, you remove a significant portion of the slope, leaving the balance portion or the other portion in a quite unstable position. So certainly, that particular material, which is now left adjacent to the slope, is actually ready to undergo failure once it gets the favourable condition, which is primarily the external loading or the pressure generated in the cracks that will lead to failure. Then, erosion: many times, as I mentioned, erosion, which is created by the stream flowing adjacent to the slope, will also cause some kind of loading to the material, and subsequently, the chunk of material will undergo failure. Differential weathering agencies and their rates will also lead to the development of cracks along the slope or within the material located along the slopes, and subsequently, these will cause weaker sections through which the material can undergo failure.

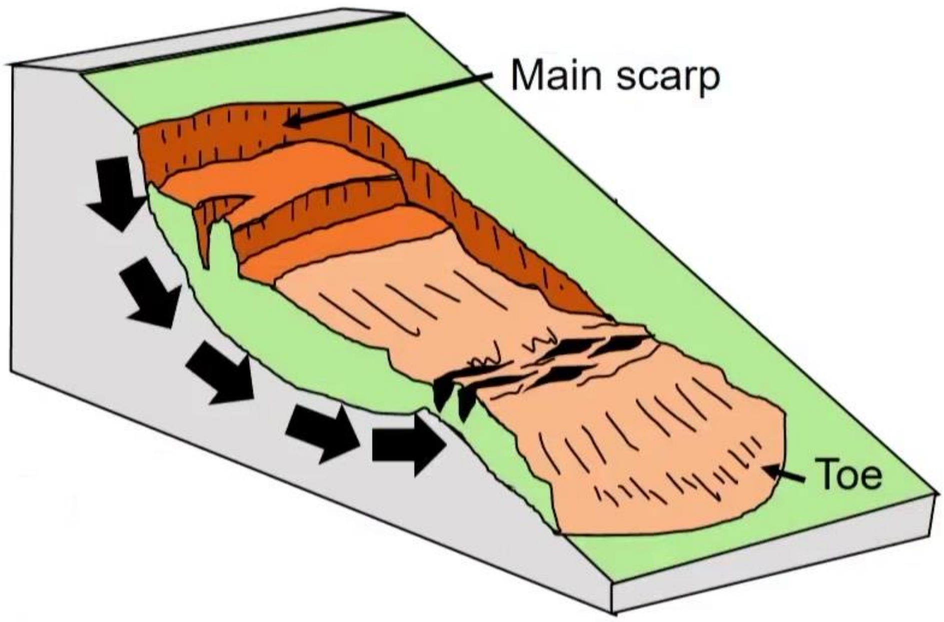


Fig. 4 illustration of a rotational landslide (modified from Cruden and Varnes,1996)

Slides: now, you see over here, irrespective of the failure, the nature of the mechanism of failure, which is shown in this particular slide, or the nature in which the material (that is, the rock and the soil) has undergone failure, is significantly different in the case of slides. There will be downward movement of the slope or rock mass along the rupture surface. So far, whether it was rockfall or toppling, there was no mention of a rupture surface or the surface along which the material is undergoing movement or the slope is undergoing failure. So, the rupture surface means the surface along which the material is undergoing failure. The initial position was this particular landmass, which was quite stable; the slope was quite stable, quite levelled. But by means of some triggering mechanism, now, this entire portion of this material, starting from the crown to its toe, has undergone failure. Again, you can see over here, there is some section through which the failure surface will reach the slope, depending upon which you will say it is toe failure surface, failure at the base, but here you can see when the material is undergoing failure, the material is actually undergoing some kind of lateral movement or downward movement along the slope.

Depending upon the material involved, you can have rock, you can have soil, you can have organic material. You can see over here, when the material was undergoing lateral movement, there was development of cracks in the lateral direction. Subsequently, over here, you can see in addition to lateral movement, there is lateral movement also. So, one was cracks along the longitudinal direction, then you can see some cracks developed along the lateral direction because of variable rates at which the movement of the material along the slope is happening. As a result of which, you can see there will also be development of lateral cracks along the failed surface or along the rupture surface. So, the downward movement of the slope of a soil or rock mass occurs along the surface of the rock or the surface of rupture or relatively thinner zones. You can see over here again, these are sections indicating intense shearing happening all along the rupture surface. So, this was the rupture surface along which intense shearing is happening. The shearing, so far, was not available whether you talk in terms of rockfall or whether you talk in terms of toppling, but in this particular case, the field condition of the failure is an example of pure shear. The material is undergoing pure shear, or there is development of rupture surfaces through which the material is undergoing slight movement and going downward. Depending upon the material involved, you can have longitudinal cracks, and subsequently, as you go deeper, because you see over here, when the rupture surface is over, you will see the rate at which the material is undergoing lateral movement along the slope will significantly change. As a result, there will be development of lateral cracks, or there will be deposition of material all along this particular surface. So, this is an example of slides, which are a type of landslide.

If you talk about rotational landslides, the characteristics are a landslide in which the surface of rupture is curved upwards. So, you can see over here, though it is undergoing rotation, you can see this particular surface appears to be the surface of a spoon shape. There is downward movement, and the surface of failure is actually coming onto some other section of the failed slope. The slide movement is rotational; you can see it is undergoing rotation, and that's why it is called rotational failure. The surface of rotation or the slide movement of rotation is parallel to the contour of the slope. This is the contour of the slope, and the rotation is also happening parallel to the slope. This is generally prevalent in homogeneous soil because, if it is heterogeneous soil, depending upon whether the relatively stiff soil is there at the top or at the bottom, that certainly will ensure that there are more chances the material will undergo lateral spread or some kind of detachment rather than continuous failure, which is happening along this particular surface of failure.

So, it is prevalent in homogeneous soil, especially when the slope angle ranges from 20 degrees to 40 degrees. This is the slope angle you measure with respect to the ground level, the ground surface. So, this angle, I am assuming it as delta. Depending upon the value, it generally ranges between 20 and 40 degrees, and it is in the case of homogeneous soil. That's why you see the continuous material—the entire material is continuously undergoing failure. So, there is no indication that some material is undergoing rotation, some undergoing toppling, or some undergoing lateral spread. It is continuously sliding, and the material is undergoing intense pure shearing along the failure surface. Again, the rate of movement may vary from as low as 0.3 meters within 5 years to 1.5 meters per month. So, this is the rate at which the movement along this particular slope is possible, starting from 0.3 meters (which is very slow movement—0.3 meters in a time span of 5 years) to almost 1.5 meters in just one month. So, that will tell you that one and a half months back nothing was there, and suddenly, because of excessive movement along the slope, the material has undergone failure that triggered a landslide.

Generally, these are triggered by intense or sustained rainfall. Whether the intensity of rainfall is more or, even though the intensity is less, it is prolonged rainfall. So, rainfall is continuous for maybe 10 hours, 15 hours, or 2 days. Prolonged rainfall, as a result of which, when the water is falling on the surface, it will actually form weaker planes along the surface of this slope, through which there will be channels through which the water is continuously moving. These weaker planes will also make it easier for the slopes or the material available on the slope to start moving. Because now, the material which was below and above these particular channels are actually separated by the channels created by water, as a result of which there will be ease in terms of the movement of material along the slope. So, that is one triggering factor whenever it comes to rotational landslides.

Same way, if there is snow deposited along the slope, but for some reason the rate at which the snow melted was very fast, that will also be very similar to prolonged rainfall or high-intensity rainfall. So, again, these will also create local channels through which water will pass under the slope, and these will create weaker channels through which this will actually break the linkage or cause some kind of ease between the two materials located above and below these channels. Subsequently, that will pose two failures. So, one is prolonged rainfall or intensive rainfall, or quick melting of the snow, then rise and drop in the groundwater table. A drop in the groundwater table many times causes cracks that will subsequently trigger the generation of weaker planes. Similarly, a rise in the groundwater table will suddenly cause some material to become completely saturated, while other material will be partially saturated or dry. This can also cause favorable conditions in terms of failure, typically occurring during flooding and reservoir filling in terms of dams. Then, earthquake-induced loading conditions: though the slope was stable, consisting of homogeneous material, if you analyze it under static conditions, the restoring forces were dominating over the disturbing forces. However, because of the additional component of disturbing force, that is, earthquake-induced loading, you will get more disturbance. As a result, the slope, which was stable before the earthquake loading condition, has now undergone failure.

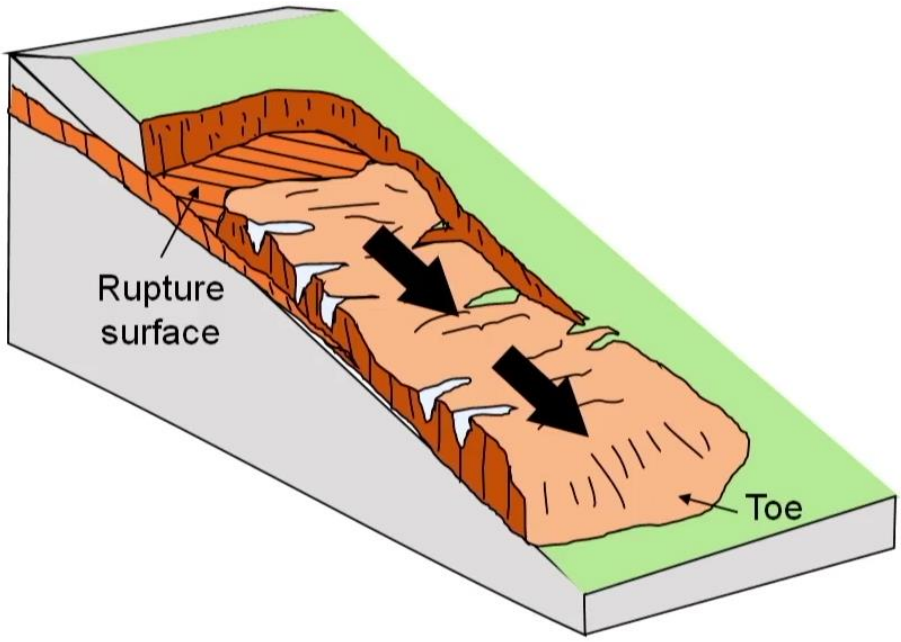


Fig. 5 Schematic of translational landslide (modified from Cruden and Varnes,1996)

Next is translational failure. You can see here, in comparison to rotational failure, where the material was undergoing rotation and failure. The slope was undergoing rotational failure, and there was the creation of a rupture surface through which the material was undergoing failure. In the case of translational failure, you see there is no rotation; the rupture surface is still there, but because there is no rotation, the material is simply sliding. As a result, there is no curved rupture surface; the rupture surface is almost parallel to the slope. In this particular case, the mass moves downward and outward along a relatively planar surface. So, in comparison to rotational failure, where the entire material was undergoing failure, indicating that the slope has undergone failure and the material on the slope, or along this particular surface, underwent downward movement. In this case, the material simply came out and started moving laterally and downward on a planar surface. Again, this planar surface is also called the rupture surface because, along this particular surface, the material has been detached from its parent material. This generally occurs in the presence of geological discontinuities such as faults, joints, or bedding planes, because these are weaker planes through which there is more ease for the material to undergo movement. So, as shown here, the material has started detaching from its parent material and moving laterally. There is no rotational component here; the material is simply moving along the planar surface. When these kinds of discontinuities are present between the rocks and the slope, the material along these discontinuities will find ease, and the material above this discontinuity will start moving along this particular planar surface. The most common types of landslides, occurring in any environment or condition, are translational landslides. The rate of movement can vary from 1.5 meters per month. So, you see, translational failures are much quicker compared to rotational failures, ranging from 1.5 meters per month to 1.5 meters per day. This is the rate at which translational failure can be triggered in actual site conditions.

The triggering factors include intense or sustained rainfall. As I mentioned, either the rainfall duration is very high, though the intensity is very low, it can trigger a landslide, or the intensity of rainfall is very high, though the duration is not significantly long. Both can help in the creation of weaker channels through which the material can later undergo failure. If the rainfall is very intense, even during the rainfall, it can undergo failure. Similarly, the rise in the groundwater table within the slide due to prolonged or intense rainfall, snowmelt, or flooding can also cause some separation between the materials by virtue of different water contents present there. Human-related settlements or disturbances, such as undercutting, where the slope is cut without considering the moisture content, the material's susceptibility to failure, etc., can also trigger landslides. The last one is earthquake-induced loading conditions. As I mentioned in the beginning, landslides are one of the various types of induced hazards or phenomena that can be triggered or associated with earthquake-induced loading. That is the reason why landslides have been introduced here. So, every time you discuss rock falls, translational landslides, or rotational failures, there will always be some component or triggering factor of earthquakes, which can also induce these kinds of failures.

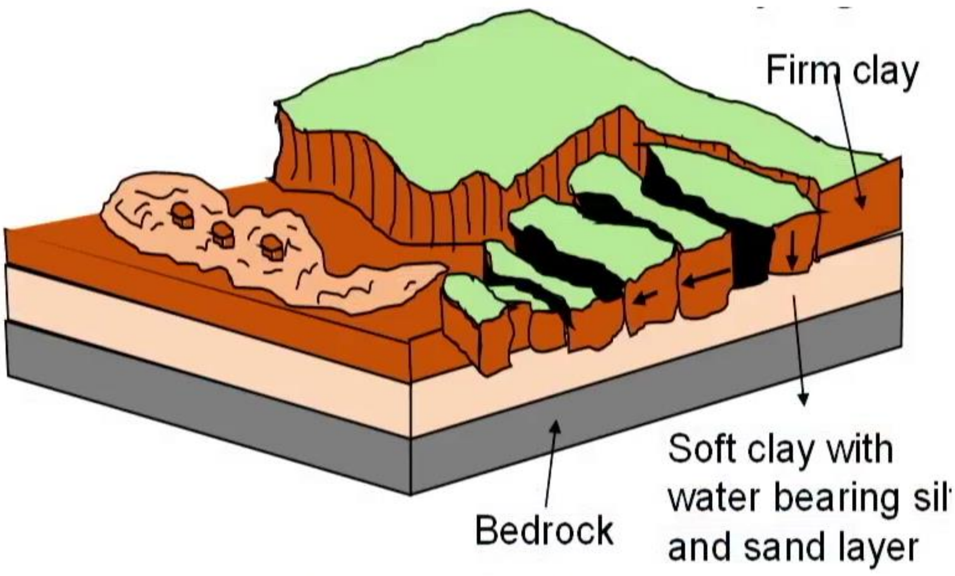


Fig. 6 Schematic of a lateral spread (modified from Cruden and Varnes,1996)

Next is spread. As the name suggests, the material spreads along the direction of failure. It will not undergo any kind of rotation, but the material will remain intact and spread to a larger area. So, generally, the characteristics include the extension of cohesive soils or rocks, accompanied by general subsidence of the fractured mass of cohesive material into softer material beneath. As you have seen here, there is relatively softer material, and this is relatively cohesive and stiffer material. Because of the significant contrast in the stiffness of the material, there will be the development of a plane through which the material can undergo failure. Any movement in the weaker material will not follow the same pattern in the stiffer material, but there will be some kind of relative movement, as indicated here in terms of spread. Lateral spread generally occurs on a very gentle slope. So, the slope is not very steep, yet it happens because the material above and below has significant contrast in terms of stiffness. It occurs on very gentle slopes or essentially along flat terrain when the stronger upper layer of rock or soil undergoes extension. It undergoes extension because the material below is relatively soft and is experiencing some kind of movement. This movement can happen because of liquefaction, subsidence, or any other triggering factor. But because of the movement happening in the softer material, the stronger material undergoes some extension or movement with respect to its parent material. Because it is relatively stiffer, the material moves in its stiff form, forming cracks, but it simply spreads. There is no slippage, no movement along the planar surface, and no rotational failure as was seen in the previous case. This is generally accompanied by ground subsidence in the weaker material. So, whenever the weaker material undergoes ground subsidence, whether due to static loading conditions, dynamic loading conditions, or significant changes in the water table, it will trigger some kind of extension or cracking in the relatively stiffer material located above the softer material.

The triggering factors in this particular case include liquefaction induced by earthquakes, natural or anthropogenic overloading of the ground above the unstable slope, saturation of the underlying weaker layer due to precipitation or snowmelt. Many times, because most of these hilly terrains are located at higher altitudes, landslides often occur during snow formation. So, whenever there is fast snowmelt, it can cause weaker channels, which will lead to the formation of failure surfaces along these weaker channels, ultimately causing slope failure. The next is saturation of the underlying weaker layer due to precipitation and snowmelt. Precipitation, again due to prolonged rainfall, can create saturated weaker layers in the softer material. As a result of this weaker layer, the material above it, which is relatively stiff, will undergo some extension or spread. The last one is plastic deformation of unstable material at depth. Since it is undergoing plastic deformation, the material above this weaker layer will also show some kind of movement. Though it is not plastic movement, you can see that the material has been detached in small fragments and has started moving, or lateral spread has occurred in the relatively stiffer material.

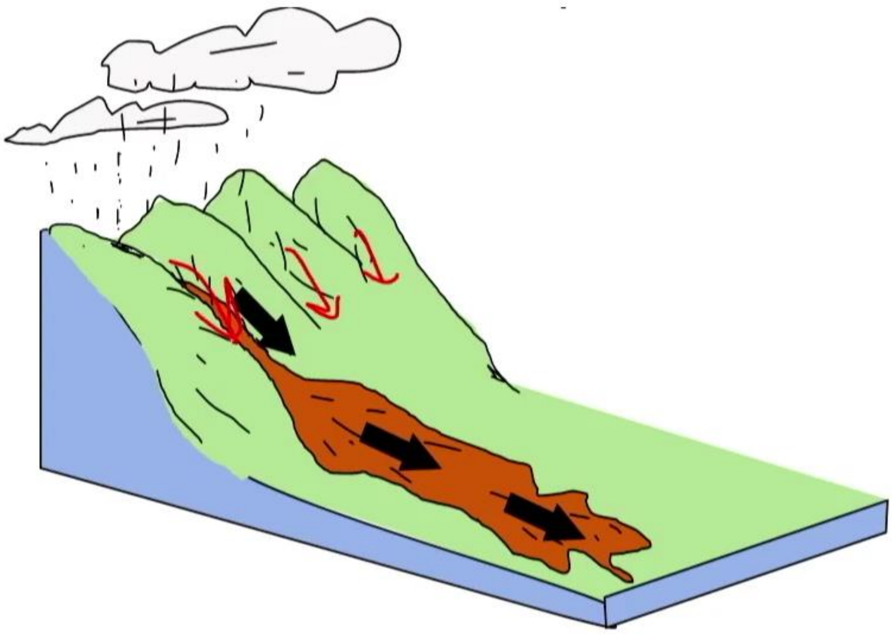
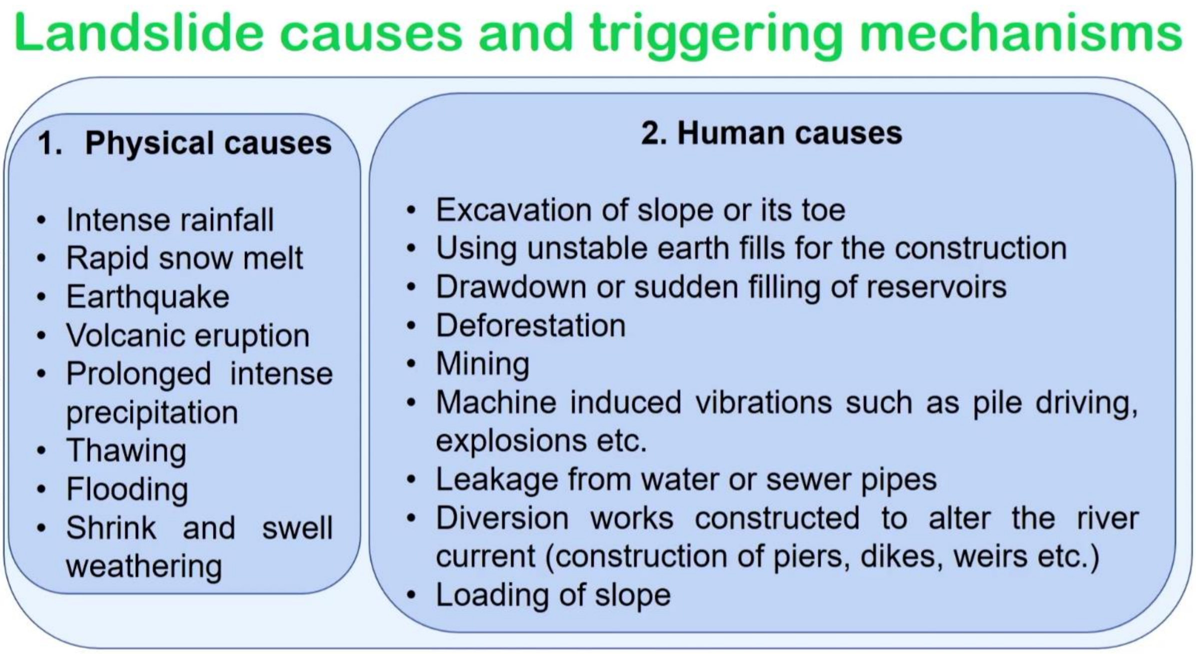


Fig. 7 illustration showing a typical debris flow (modified from Cruden and Varnes,1996)

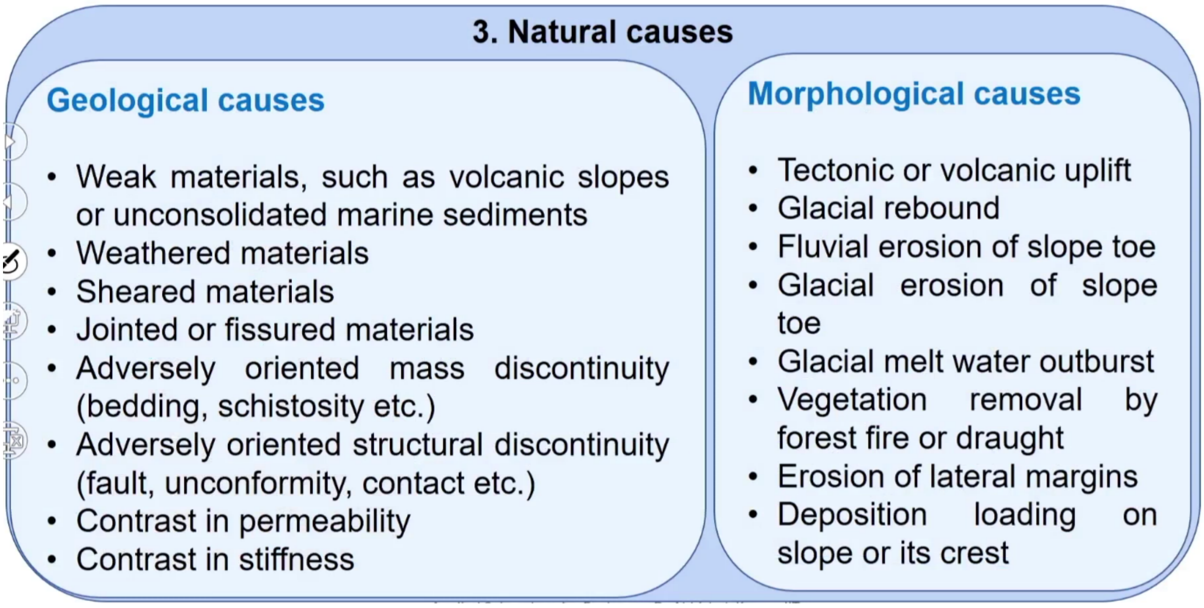
The next one is flows. So, initially, we discuss about fall, where you are having rock fall—the material is simply dropping. Then, we were having toppling. So, material, after getting detached, undergoes some kind of rotation, and along the point of rotation, which is located beneath the center of gravity of the displaced material, the material undergoes rotation and subsequently may remain intact, or it may be broken into smaller fragments. Then, we have slides, where the material undergoes failure along the failure surfaces. Then, we had spread, so the material, though it is undergoing failure, there is no movement or development of shearing within the stiffer material, but it is simply disintegrated into small fragments and then started moving downward over a relatively softer material. The last one is flows, as the name suggests, the material in this particular case will start flowing. So, there will be continuous movement of the material along the particular flow, along the particular surface, and unlike the case of spread, which is even possible in case of gentle slopes, here the slopes are relatively steeper. So, flows are special, especially continuous movement of material, in which the surface of shear are short-lived or closely spaced. So, you can see over here there are surfaces through which the material, when it is subjected to debris flows, mud flows, the material, along with the water, has actually been mixed together and then started continuous movement in terms of the flow, which we see in water. So, material, along with water in terms of slurry, has combined and then started forming and then started moving along the surface. So, this is the parent material after getting mixed with respect to the water, which was primarily because of snowmelt or prolonged rainfall. It mixed with water, and this entire slurry has started moving downward along the slope. That particular kind of failure in landslide is called as flow. So, the rate of movement of displacing material is a resemblance of viscous material. So, the soil mixed with water, and it is flowing just like viscous liquid flows; it is flowing downward from the slope.

Again, it can be debris flow or mud flow, depending upon the material which is in contact with the water and started flowing. So, rapid mass movement in which loose soils, rocks, and occasionally organic material also combined with water to form a slurry, then flows downslope—that is the typical characteristic of flow landslide at high water content. These slides may evolve in terms of debris flows. So, if the water table is very high, even debris with water starts flowing. The typical movement which one can witness is 35 kilometers per hour. That is the movement of the slurry with respect to its parent medium, which has been triggered during a particular landslide. Again, these are triggered by intense surface flow because water should be present there in order to get mixed and form the slurry. So, this is intense surface flow induced by heavy rainfall or snowmelt. So, it can be because of rainfall, it can be because of snowmelt, but certainly, in this particular case, there will not be any earthquake loading condition alone triggering, because you have to have some kind of water present, which can be because of snowmelt or it can be because of prolonged rainfall, which is actually bringing the material, getting mixed with it, and then bringing it downward.



So, landslide causes and triggering mechanisms—what are the difficult causes you can see which can actually trigger a landslide? Physical causes: intense rainfall—if the rainfall is intense, there will be formation of weaker planes, through which possibly the failure may trigger. Rapid snowmelt—again, because of rapid snowmelt, the water is also getting flowing along the material, that will also cause weaker planes. Earthquakes, they are going to induce additional loading conditions in the slope, destabilizing the slope, and finally, you will have a landslide. Volcanic eruptions—again, these can also lead to movement of the material, or because of the vibration generated over there, you can have some kind of movement triggering phenomena. Prolonged intense precipitation—rainfall is there, intense or any kind of other intense phenomena, which is responsible for triggering of weaker planes. Thawing, flooding, shrink and swelling, weathering, which can again be responsible for detaching the same material or different material, but from its parent position and leading to or triggering some kind of movement, whether it is undergoing rotation, whether it is undergoing fall, whether it is going movement along the planar surface, whether it is formation of the crack and subsequently separating. But each of these are the physical phenomena, the physical causes, which can trigger a landslide.

Human causes: excavation on the slope or its toe—that can destabilize the particular slope. Using unstable earth material for the construction. So, using unstable material for the construction, these will undergo failure and then lead to landslides. Drawdown or certain filling of reservoir, because if you are going to do these activities very quickly, that will also lead to failure or formation of weaker planes, through which the material undergoes failure. Deforestation, as we know, because of the roots, it will hold the ground in its position, but because of deforestation, these roots will not remain in their position, so the material will not be able to withstand in its parent position and will subsequently undergo failure. Mining activities also create a lot of disturbance, as a result of which the material will undergo failure. It is relatively the cementation, aging effect, which otherwise would have provided material with a lot of resistance to movement; now it will be lost. Machine-induced vibrations, such as pile driving, explosions, leakage from water and sewage pipelines—because that will also cause continuous passage of water through the material itself, causing weaker planes. Now, loading of the slopes: you put some surcharge, you start constructing on the slope or the road of the slope—that will cause additional load on the slope and subsequently will undergo failure.



Geological causes: weaker materials, such as volcanic, slopes of unconsolidated marine deposits, weathered material, sheared material—these are the possible materials which are relatively weaker, and that is why they have undergone failure. Jointed or fissured material—because it is jointed or fissured material, there are more chances, when it is subjected to any favorable condition, these will undergo failure. And then, subsequently, contrast in permeability. If there is contrast in permeability, you will certainly have weaker channels through which the material will start undergoing failure. Slowly, initially there will be movement of the soil, and subsequently there will be creation of the channels through which the entire material above will start sliding. Morphological causes: tectonic and volcanic uplift, because these are going to create some vibrations, even change in the topography of the medium, glacial rebounds, fluvial erosion, we have discussed in previous slides also. Because of the river, there is a lot of weathering and triggering mechanisms, so that will also cause some kind of landslides. Glacial melt, water outburst—because of melting of the glacier, somewhere near the downstream of that particular glacier, you will have accumulation of water in terms of a glacial lake. At times, these lakes will also undergo outbursts, triggering slope failure or landslides. Erosion of lateral margins, deposition loading on the slope or its crush—that is very, very prominently visible in many instances, whenever the slope undergoes failure.

Effects and consequences of landslides

▪ **Effects on built environment**

- Damage to residential dwellings as landslides destabilize or destroy foundations, walls, surrounding property, and above-ground and underground utilities.
- Damage to trunk sewer, water, or electrical lines and common-use roads.
- Cut and fill failures along roadways and railways, as well as collapse of roads from underlying weak and slide-prone soils and fill.
- Road or rail blockage by dirt, debris, and (or) rocks
- Temporary or long-term closing of crucial routes for commerce, tourism, and emergency activities.
- Rockfalls may injure or kill motorists and pedestrians and damage structures.

So, effects and consequences: effects on the built environment, you can see damage to residential buildings, dwellings, because the ground undergoes failure, destabilization. So, that can also cause some kind of destabilization to the foundation and underground utilities also. Damage to sewer, water, electrical cable lines—because you never know on which particular side of the slope there is relative motion. So, there can be breakage in the electric and water pipelines if they are located along the slope. If it is downward, then, by virtue of the material which is coming from the slope and getting deposited on the level surface, that can even cause damage to these pipelines and electrical lines, even though they are not located along the slope. Cut and fill material, which is generally used in road and railway construction, as well as collapse which can happen along the roads, because whatever material you are using is relatively weak and prone to failure. And subsequently, rock fall may injure or kill motorized pedestrians and even trigger some kind of damage to the structures.

- **Effects on natural environment**

- **Submarine landslide:-** Downslope mass movement of geologic materials from shallower to deeper regions of the ocean.
- Major effects to the depth of shorelines, ultimately affecting boat dockings and navigation.
- Can trigger deadly tsunamis.
- Destructive to aquatic life, such as fish and kelp.
- Rapid deposition of sediments in water bodies often changes the water quality around vulnerable shorelines.
- Formation of landslide dams which are short- lived, the failure of which can affect the areas downstream of it.

So, submarine landslides—again, if these kinds of landslides are happening beneath the ground surface, so downward movement of geological material from shallower to deeper regions of the oceans, if these slides are happening within the ocean, a major effect to the depth of the shorelines, ultimately affecting the boat dockings and navigation. When these things are happening suddenly, we will see there is significant increase or decrease in the depth of the water column, which otherwise was used for docking of the boats and ships, and can trigger deadly tsunamis also, because the material which has undergone failure and falling inside the water bodies is actually going to disturb the equilibrium of the water column, and that can also trigger, at times, tsunamis or similar phenomena. Then, destruction to aquatic life, such as fish and kelp formation of landslide dams, which are short-lived, the failure of which can affect the area downstream. So, these are typical effects which can be witnessed, whether it is on the ground, or it is in offshore regions which are happening, or even onshore regions, offshore regions also, which are happening, primarily because of the failure of the slope and how the failed material is interacting with the environment around it.

So, this is the overall objective, as I mentioned in the beginning, is to introduce the intended user of this particular lecture to get accustomed to the term landslide, what are the different landslides, what are the materials involved, and what are the mainly triggering factors related to the landslide occurrence. Thank you, everyone. We'll continue with other topics in the next lecture. Thank you.