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Role of Advanced Geotechnical Sensors and Analytical in Real-Time Slope Stability Monitoring

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ABSTRACT

Slope stability monitoring in real-time is essential for reducing the danger of landslides and other slope collapses. Improving real-time slope stability monitoring via the integration of sophisticated geotechnical sensors and analytical algorithms is the focus of this research. Inclinometers, piezometers, and strain gauges are some of the newer sensor technologies that can measure structure deformations, groundwater variations, and soil movement with great precision. These sensors can take readings in real time, which is crucial for finding any problems as they happen.

Keywords: Slope Stability, Bishop's Simplified Method , Minerals, Mining.

INTRODUCTION

The stability of slopes is defined as their capacity to resist and experience movement when covered with soil. Finding the sweet spot between shear stress and shear strength is what determines stability. At first, preparation variables may influence a slope that was previously stable, rendering it conditionally unstable. Extreme weather may cause a slope to become actively unstable, which can cause large-scale motions and ultimately cause the slope to collapse. An increase in shear stress, as might be generated by loading, lateral pressure, or transient pressures, can lead to mass movements. On the other hand, organic matter, weathering, and changes in pore water pressure may all reduce shear strength.
Dynamic and static stability of embankment slopes, excavated slopes, natural slopes in soil and soft rock, slopes of earth and rock-fill dams, and other forms of embankments are all part of the domain of slope stability. Engineering geologists and geotechnical engineers are usually the ones who conduct investigations, analyses (including modelling), and mitigation designs related to slope stability. In addition, geologists and engineering geologists may assess relative slope stability from on-site observations by using their understanding of earth processes and their skills in interpreting surface geomorphology.

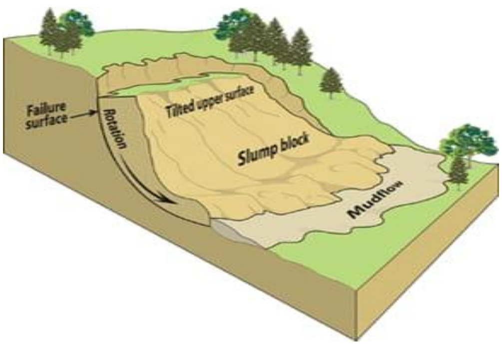


Fig.-1.1 Slope Failure (Circular Failure)

Figure 1.2 shows that cut-spherical weakness zones may form on earthen slopes. Predicting the likelihood of this event using a basic 2-dimensional circular analysis program is possible. Many landslides have only been studied after the event, which makes finding the most likely slip plane a major challenge with analysis. It should be mentioned that failures in naturally deposited mixed soils in the actual world aren't always circular, however

this simplified geometry was much simpler to analyse before computers. However, 'pure' clay may have failures that are almost round. The pore water pressure at the slip surface rises after heavy rain, decreasing the effective normal stress and lessening the restraining friction along the slip line. This causes these slides to occur.
On top of that, the soil's density has gone up because of all the extra groundwater. Another way that rainwater might force a slip forward is by filling a "shrinkage" gap at the top of the slide, which was developed during the previous dry period. On the other hand, hillside slab slides may expose the underlying bedrock by removing dirt from above. Again, this is often caused by heavy rain, but it may also be triggered by increased weight from nearby structures or the loss of toe support due to road expansion or other construction-related activities. So, reducing the destabilising stresses by the installation of drainage pathways may greatly increase stability. But even after the slide has happened, there's still a hole in the slip circle that might open up again during the next rain.

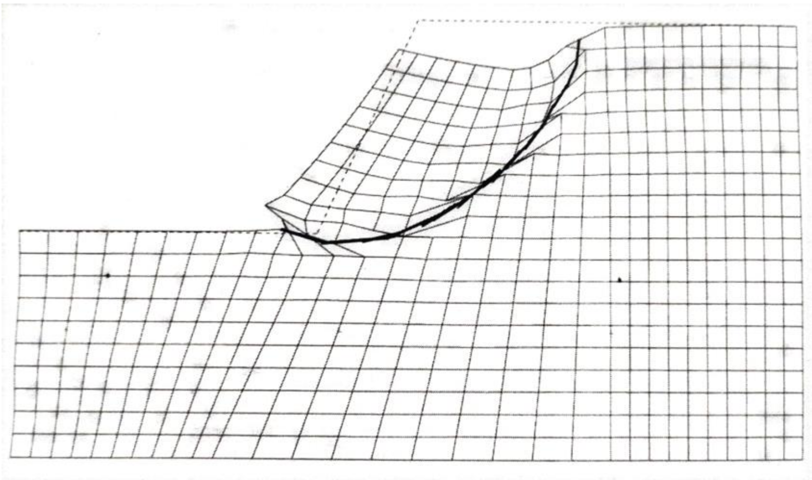


Fig.-1.2 Simple slope slip section

As the field of soil and rock mechanics has progressed, geotechnical engineers have meticulously tracked changes in slope stability studies. Depending on the situation, slopes may be either naturally occurring or man-made. As long as there have been human or natural disturbances to the delicate equilibrium of soil slopes, there will be slope stability difficulties. In addition, the need to comprehend analytical techniques, investigative instruments, and stabilisation strategies for resolving slope stability issues has grown in tandem with the rising demand for engineered cut and fill slopes on building projects. Realistic modelling and understanding are prerequisites for using slope stabilisation procedures, which include specialised building techniques.

The correct application of slope stability principles requires knowledge of hydrology, soil characteristics, and geology. An precise representation of the site's subsurface characteristics, ground behaviour, and applied loads must form the basis of any analysis. When evaluating the outcomes of studies, one must make decisions about what constitutes an acceptable level of risk or safety. Projects often have these assessments done at the outset, but they may also be done at any point in time during the planning, design, building, improvement, rehabilitation, or maintenance phases. The procedure involves a wide range of professionals, including planners, engineers, geologists, contractors, technicians, and maintenance staff.

Contributing to the safe and economical design of excavations, embankments, earth dams, landfills, and spoil heaps is the principal goal of slope stability analysis in most applications. The primary goals of a slope stability study are to ascertain the frequency, severity, and kind of possible slope issues and to identify the most important geological, material, environmental, and economic factors that will have an impact on the project. In cases when prior expertise is advantageous.

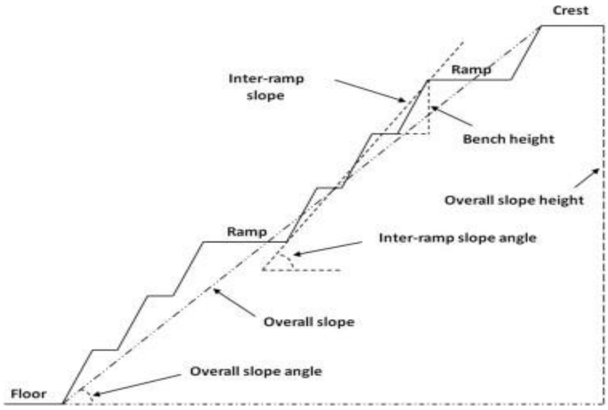


Fig.-1.3 Slope geometry

CAUSES OF SLOPE FAILURE

When a slope becomes unstable, it might eventually collapse due to the following factors:

- Gravitational forces.
- Forces due to seepage of water.
- Erosion of the surface of the slopes due to flowing water.
- The sudden lowering of water due to a slope.
- Forces due to earthquakes.

Soil shifts from high spots to low locations as a result of all these processes. It is often acknowledged that stability issues caused by flowing or leaking water are significant, although these issues are not always correctly diagnosed. True, seepage forces are generated when water seeps into a soil mass; these forces are far more powerful than most people think. If a certain amount of dirt is washed away by erosion on the slope's surface, the slope's stability with respect to mass movement may improve.

Erosion at the toe, in the form of undercutting, may either shorten the incipient failure surface or raise the slope height. Consequently, the stability is diminished. Soil loses some of its buoyancy as groundwater levels drop or when the level of free water in a reservoir drops, leading to an increase in weight.

Therefore, shearing stresses increase with increasing weight; however, these stresses may or may not be partially offset by an increase in the soil's permeability; consequently, almost no volume changes can occur other than at a slope rate, and the strength increase may be negligible despite the increased load.

FACTORS THAT INFLUENCE SLOPE STABILITY

Geological discontinuities

There is a strong correlation between the structural discontinuity in the rock that the slope is cut from and the stability of the slope. Any change in the physical or chemical properties of a bulk of soil or rock is indicated by a plane or surface that is known as a discontinuity. A bedding plane, schistosity, foliation, joint, cleavage, fracture, fissure, crack, or fault plane are all examples of discontinuities. A rock slope's potential collapse mode is dictated by this discontinuity. The stability of jointed rock slopes is greatly affected by discontinuity qualities such direction, persistence, roughness, and infilling. There could be only one discontinuity or several with very similar mechanical properties in a discontinuity set. It changes the anisotropy of a bulk of soil or rock.

Effect of Water

There are two ways to look at the impact of water on the slope. Two sources of water pressure may be identified: first, the pore water pressure generated by underground aquifers or groundwater, and second, the surface water pressure generated by precipitation infiltration as it travels downhill. The degree of precipitation in the area, the terrain, the bodies of water in the vicinity, and the geological and hydrological properties of the rock all play a role.

The weight of the slope is increased by the addition of water from precipitation and snow melt. Beyond that, there is water underneath the surface of the planet almost everywhere. This water seeps into the cracks and gaps between the rock's grains. When water seeps into cracks in rock, it may replace air in the pore space and make the soil heavier. The slope eventually gives way due to the increased effective stress.

Geotechnical Properties of Material

Shear strength, density, plasticity, permeability, moisture content, and particle size distribution are the key geotechnical parameters that influence a slope's stability. One critical component influencing slope stability is the compressive strength of rock mass. The factors that contribute to this include the strain rate, the state of drainage during shear, the effective stresses that were already operating on the soil before shear, the soil's stress history, the stress route, and any potential changes in water content and density over time. It is made up of the material's friction angle and its cohesiveness. An opposing force that acts between two surfaces is known as friction. When particles' surfaces bind, a cohesive mixture is formed. The amount of the confining pressure, the drainage conditions inside the mass, the direction and size of the applied force, and the rate of application are among the several parameters that determine it.

The relationship between the peak shear strength and the normal stress a can be represented by the Mohr-Coulomb equation$\tau = c + \sigma \tan\varphi$

where c is the cohesive strength andφ is the angle of friction.

Mining Methods

The technique used to prepare the base, the manner of stripping, the positioning, and the rehandling of dump material are all aspects of the mining procedure that contribute to the instability of the slope. Considerations of pore water pressure, engineering qualities of the dump material, possible failure surface, zonation, and dump layout are also crucial. How the deposition gradation and loading history are regulated also affects the dump's density. As a result, the dump's shear strength may be compromised. To add insult to injury, the compaction of overburden is influenced by the machinery used to drop it.

State of stress

There may be areas where the rock mass exhibits considerable in-situ stresses. As a result of the stress reduction offered by the cut, blocks may shift outward in response to high horizontal pressures operating approximately perpendicular to the cut slope. The surface of a cut slope may potentially be spalled by high horizontal forces. Ground or perpendicular to slope walls is where the accumulated stresses are located.

Geometry slope

Both the height and the angle of the slope are critical geometric elements that influence its stability. The steepness, density, and carrying capability of the slope's base determine the critical slope height. As the slope becomes steeper, the stability of the slope tends to decline. Shear tension inside the toe of the slope grows in relation to the slope height because of the increased weight. Both the material's mass and the slope angle are connected to shear stress. Its stability decreases as the slope angle rises because tangential force increases shear stress.

Erosion

From the perspective of slope stability, two facets of erosion must be taken into account. The first kind is erosion that happens on a big scale, such when a river erodes the soil at the foot of a hill. The second kind of erosion is when surface runoff or groundwater causes it to be relatively localised. The first kind occurs when erosion alters the shape of a rock mass that may otherwise collapse. Debris clearance at a possible slide's base lowers any restricting tension that could be holding the slope in place. Reducing interlocking between neighbouring rock blocks may be achieved by localised erosion of joint filler material or zones of weathered rock. When this interlocking is lost, the shear strength of the rock mass is drastically reduced. Slope failure might occur if a rock mass that was previously stable is now able to shift due to the reduced shear strength. Also, the stability of the rock slope might be affected by localised erosion, which can lead to increased permeability and ground-water flow.

TYPES OF FAILURE

- PLANE FAILURE
- WEDGE FAILURE
- CIRCULAR FAILURE
- TOPPLING FAILURE

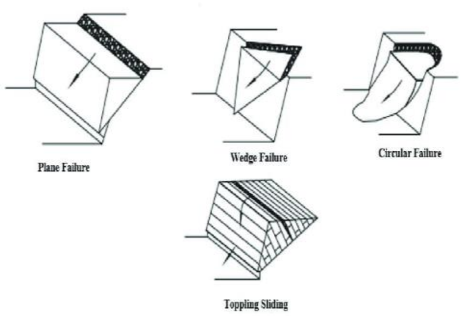


Fig.2.1- Types of failure

PLANE FAILURE

The slope fails at a specific discontinuity due to sliding in this failure type. Sliding may only take place on one plane if the following geometrical conditions are met: (1) the planes involved must be perpendicular.

The geometric circumstances necessary to induce a planar failure to happen on a real slope only very seldom, which is why they are so uncommon to see in rock slopes. We can learn a lot about the mechanics of this basic failure mode by examining the two-dimensional instance, therefore it would be unfair to exclude it. The sensitivity of the slope to variations in shear strength and ground water conditions may be better shown via plane failure than through the more complicated mechanics of a three-dimensional slope collapse. Reinforced slopes and probabilistic design are shown in this chapter, which also explains the technique of analysis for plane failure and talks about the stability of 'dip slopes' (non-day lighting sliding planes).

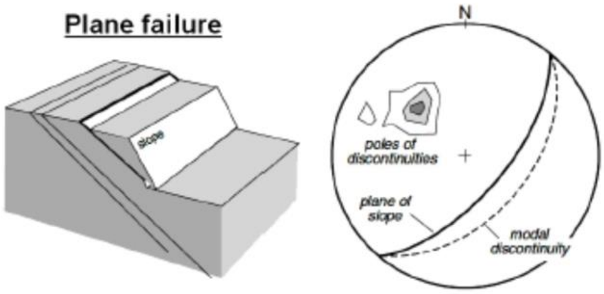


Fig.2.2- Plane failure

WEDGE FAILURE

Assuming the angle of friction is much larger than the inclination of the line of junction, the wedge of rock opposing the two discontinuities will slide down the steep face when they hit obliquely.

The subject matter revolved on the collapse of slopes caused by sliding on a flat surface that dips into an excavation and hits at a right angle to the slope face. If the failure plane's strike is within ±20◦ of the slope face's strike, then the plane failure analysis is considered valid. Slopes with discontinuities that strike at an angle to the slope face are the focus of this kind of failure, which occurs when a wedge of rock slides at the junction of two such planes. Research into wedge stability is a crucial part of rock slope engineering because wedge collapses may happen in a far broader variety of geology and geometric settings than plane failures. The geotechnical literature is rich with discussions of wedge analysis; this manual relies substantially on the writings of Goodman (1964), Wittke (1965), Londe (1965), Londe et al. (1969, 1970), and John (1970). Wedge formation by crossing planes is explained in this chapter, along with the structural geological circumstances that cause it. The chapter also provides an illustration of how to recognise wedges on the stereonet. The stereonet specifies the sliding direction, the angle of the junction, and the wedge's form. With this data, we can determine how likely it is that the wedge will slip off the cut face. Although it does not provide accurate information on their factor of safety, kinematic analysis aims to detect possibly unstable wedges.

CIRCULAR FAILURE

A single discontinuity surface, with a tendency to follow a circular route, defines failure in materials that are highly weak, such as soil slopes, or in rock masses that are particularly massive, jointed, or fragmented, like waste rock dumps.

A method for presenting slope stability charts in the event of circular collapse is used here. An easy way to quickly examine a slope's factor of safety or how it varies with changes to ground water conditions, slope angle, and material strength qualities is using these charts. These charts are only meant to be used for the investigation of circular failure in homogeneous slope materials, under the parameters that were assumed when they were derived.

These approaches may be used in situations when the slope-to-surface material qualities are not uniform, or when the slope-to-rock interface is present, or when the slope-to-surface geometry is not a simple circular arc.

Assuming the slope may be represented as a unit slice over an arbitrarily long slope, under plane-strain circumstances, this mostly deals with the stability of two-dimensional slopes. This delves into the topic of three-dimensional circular failure analysis and how the stability is affected by the slope's radius of curvature.

Fig.2.3- Circular failure

TOPPLING FAILURE

The basic mathematical requirements that control the toppling of a single block on an inclined surface, as well as the rotation of columns or blocks of rocks around some fixed base, are what cause toppling failure.

Every one of the failure scenarios that have been mentioned has to do with a rock or soil mass sliding over a natural or artificial sliding surface. Here we look at an alternative failure scenario, toppling, which is the result of rock columns or blocks being rotated around a fixed foundation. A kinematic analysis of the structural geology is performed to identify potential toppling conditions. If these conditions are found, a stability analysis specific to toppling failures is performed. This procedure is similar to that of plane and wedge failures when it comes to stability analysis.

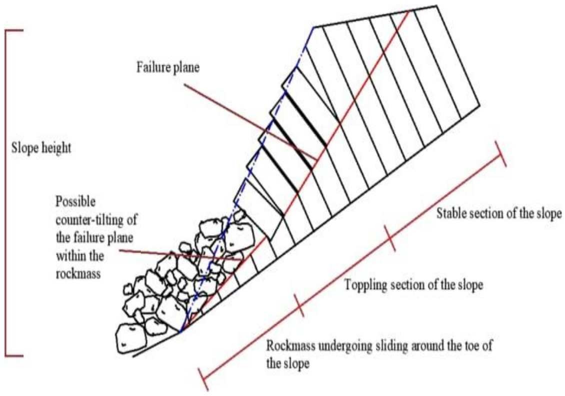


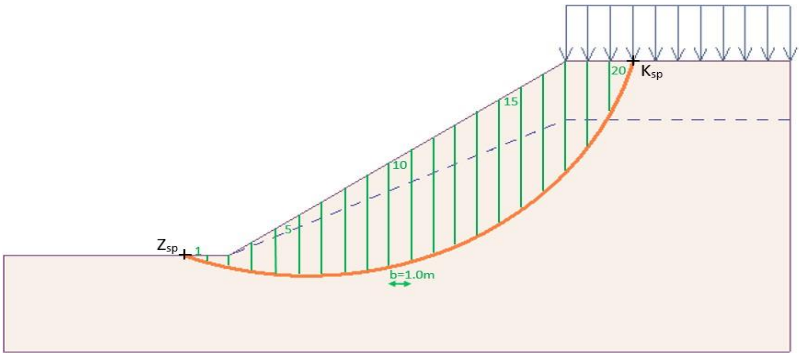
Fig-2.4: Toppling failure

ANALYSIS OF STABILITY OF THE SLOPE

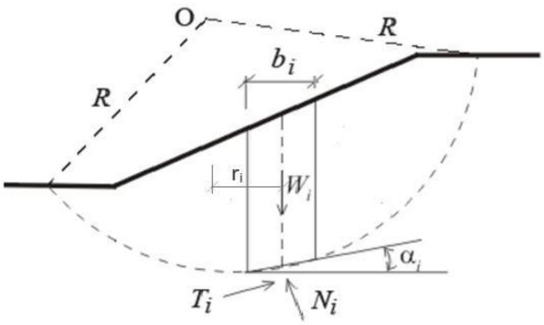
Bishop’s Simplified Method

Finding the pore pressure and determining the angle of the slip surfaces of the different blocks. The individual blocks' round slip surfaces have been replaced with lines to facilitate the hand-made computation. The angle formed by the slip surface with respect to the horizontal plane defines the slip surface's inclination.

To get the pore pressure, you need to know how high the groundwater table is. Along the axis of the block, we take into account the height of the groundwater table, hi. Water has a unit weight of □ w = 10.00 kN / m3. The influence of the pore pressure's horizontal forces, which were ignored, is not substantial. Table 2 displays the total computation. The computation for block 13 is shown here.



Slope– vertical blocks



Static scheme of the block

Determination of the area above the ground water table (the area A) and under the ground water table (the area B):

A13 = 2.100 m 2

B13 = 4.2249 m 2

Weight of the individual parts of the block: AW ,13 = A13 ·γ = 2.100·18.50 = 38.8500 kN / m

BW ,13 = B13 · γ sat = 4.2249·19.50 = 82.3856 kN / m

Weight force of the block:

W13 = AW ,13 + BW ,13 = 38.8500 + 82.3856 =121.236 kN / m

The slip surface was determined. In this case the slip surface is determined by a circle with its centre at point O = [x, z] = [13.5279 ; 18.9443] and a radius R = 15.00 m . Points Z sp and K sp indicate the beginning and end of the slip surface. The slope was divided into vertical blocks of width bi = 1.0 m . In Figure 2, a slope divided into 20 blocks is shown.

Calculation for all blocks:

Block	Area of the part		Width of The block	Weight of one part		Weight of The block	Load
	Ai [m2]	Bi [m2]	bi [m]	AW,i [kN/m]	BW,i [kN/m]	Wi [kN/m]	fi [kN/m]
1	0.0000	0.1780	1.000	0.000	3.471	3.471	0.000
2	0.0000	0.4955	1.000	0.000	9.662	9.662	0.000
3	0.1000	0.9714	1.000	1.850	18.942	20.792	0.000
4	0.3000	1.6095	1.000	5.550	31.385	36.935	0.000
5	0.5000	2.1787	1.000	9.250	42.485	51.735	0.000
6	0.7000	2.6807	1.000	12.950	52.274	65.224	0.000
7	0.9000	3.1158	1.000	16.650	60.758	77.408	0.000
8	1.1000	3.4836	1.000	20.350	67.930	88.280	0.000
9	1.3000	3.7828	1.000	24.050	73.765	97.815	0.000
10	1.5000	4.0109	1.000	27.750	78.212	105.963	0.000
11	1.7000	4.1644	1.000	31.450	81.206	112.656	0.000
12	1.9000	4.2381	1.000	35.150	82.643	117.793	0.000
13	2.1000	4.2249	1.000	38.850	82.386	121.236	0.000
14	2.3000	4.1148	1.000	42.550	80.239	122.789	0.000
15	2.5000	3.8937	1.000	46.250	75.927	122.177	0.000
16	2.7000	3.5409	1.000	49.950	69.048	118.998	0.000
17	2,.9000	3.0240	1.000	53.650	58.968	112.618	0.000
18	3.0000	2.0544	1.000	55.500	40.061	95.561	20.000
19	2.9692	0.5721	1.000	54.930	11.156	66.086	20.000
20	1.4192	0.0000	1.000	26.255	0.000	26.255	20.000

Table1 Weight and forces of the load

Finding the pore pressure and determining the angle of the slip surfaces of the different blocks. Lines have been substituted for the individual blocks' circular slip surfaces in order to streamline the hand-made computation. The angle formed by the slip surface with respect to the horizontal plane defines the slip surface's inclination.

To get the pore pressure, you need to know how high the groundwater table is. With respect to the block's axis, the groundwater table's height, h, is taken into account. The mass per unit volume of water, denoted as Y_{w}, is equal to 10kN divided by (m3). In order to calculate the horizontal forces of the pore pressure, it is necessary to establish the heights of the ground water table on the left and right sides of the block. Table 3 displays the total computation. The computation for block 13 is shown below.

* Inclination of the slip surface: alpha_{13} = 27.7192 deg

* Length of the slip surface: I_{13} = b_{11}/(cos(alpha_{11})) = 1/(cos(27.7192)) = 1.13m

* Inclination of the ground water table: a w.13 = 25.0169 deg

Height of the ground water table: h_{13} = 4.2369m

Calculation of the reduced height of the ground water table: h r, 13 =h 13 ,* cos(a w,13)^ 2 =4.2369* cos(25.0169)^ 2 =3.479m

Calculation of the pore pressure: u 13 = gamma w * h r, 13 =10.00*3.479=34.790kPa

Calculation of the horizontal forces of the pore pressure: U mL, 13 = [h L,13 * cos(a -33)]^ 2 7 n 2 = [4.2543 cos(25.0169)]^ 2 10 2 =74.312 kN/m - left side U sG - 1 \ = [h p,13 * cos(alpha infty,1)]^ 2 * gamma infty 2 = [4.1955 cos(25.0169)]^ 2 *10 2 =72.272 kN/m -right side

Calculation for all blocks:

Block	Inclination of the slip surface	Ground water table			Pore pressure
		Inclination of the ground water table	Height of the groundwater table	Reduced height of the ground Water table	
	αi [∘]	$\alpha w,i$ [∘]	hi [m]	hr,i [m]	ui [kPa]
1	-19.5956	0.0000	0.1880	0.188	1.880
2	-15.5860	0.0000	0.5048	0.505	5.050
3	-11.6525	25.0169	0.9803	0.805	8.050
4	-7.7741	25.0169	1.6180	1.329	13.290
5	-3.9314	25.0169	2.1871	1.796	17.960
6	0.1065	25.0169	2.6890	2.208	22.080
7	3.6119	25.0169	3.1242	2.565	25.650
8	7.5592	25.0169	3.4922	2.868	28.680
9	11.4351	25.0169	3.7917	3.114	31.140
10	15.3650	25.0169	4.0202	3.301	33.010
11	19.3709	25.0169	4.1744	3.428	34.280
12	23.4785	25.0169	4.2489	3.489	34.890
13	27.7192	25.0169	4.2369	3.479	34.790
14	32.1331	25.0169	4.1285	3.390	33.900
15	36.7741	25.0169	3.9099	3.211	32.110
16	41.7186	25.0169	3.5609	2.924	29.240
17	47.0841	25.0169	3.0504	2.505	25.050
18	53.0703	0.0000	2.0928	2.093	20.930
19	60.0828	0.0000	0.5872	0.587	5.870
20	69.3348	0.0000	0.0000	0.000	0.000

Table2Inclinations of the slip surfaces and pore pressures

Inclination of the slip surface:

$\alpha 13 = 27.7192$ °

Inclination of the ground water table:

$\alpha w,13 = 25.0169°$

Height of the ground water table:

h13 = 4.2369 m

Calculation of the reduced height of the ground water table:

$h_{r,13} = h_{13} \cdot \cos(\alpha_{w,13})^2 = 4.2369 \cdot \cos(25.0169)^2 = 3.479$ m

Calculation of the pore pressure:

$u_{13} = \gamma_w \cdot h_{r,13} = 10.00 \cdot 3.479 = 34.790$ kPa

Calculation of the sliding moment - Every block's mass, including any loading forces, acts on the horizontal arm that stretches from the block's axis to the centre of the slip surface, or point O.The forces' arms are determined from the slip surface's edge (Zsp = □x, z□= □8.00; 5.00□).

Calculation for all blocks:

Block	Sliding moment		Block	Sliding moment	
	$r_{a,i}$ [m]	$M_{a,i}$ [kNm/m]		$r_{a,i}$ [m]	$M_{a,i}$ [kNm/m]
1	-5.028	-17.452	11	4.972	560.126
2	-4.028	-38.919	12	5.972	703.460
3	-3.028	-62.958	13	6.972	845.257
4	-2.028	-74.904	14	7.972	978.874
5	-1.028	-53.184	15	8.972	1096.172
6	-0.028	-1.826	16	9.972	1186.648
7	0.972	75.241	17	10.972	1235.645
8	1.972	174.088	18	11.972	1383.496
9	2.972	290.706	19	12.972	1116.708
10	3.972	420.885	20	13.972	646.275

Table 3 Sliding moment

- Resultant sliding moment:

$$M_a = \sum_{I=1}^{20} M_{a,i} = 10464.338 \text{ kNm/m}$$

Calculation of the resisting moment. Because the safety factor FS is an integral part of the resistive moment calculation using Bishop's approach, the process is iterative. First iteration consideration is given to the safety factor FS = 1.5,000. The manual computation goes through five cycles. In Table 10 you can see the total. The computation for block 13 is shown here.

- Calculation of the resisting moment, FS=1.554:

$$M_{p,13}=\frac{\dfrac{21.00*1.00+(121.236+0.00-34.790*1.00)*\tan(27.00)}{\dfrac{\cos(27.7192)+\tan(27.00)*\sin(27.7192)}{1.554}}}{}-15.00=940.206\,kNm/m$$

→FS=1.554 -result of the 1th iteration

- Calculation of the resisting moment, FS=1.554:

$$M_{p,13}=\frac{21.00*1.00+(121.236+0.00-34.790*1.00)*\tan(27.00)}{\dfrac{\cos(27.7192)+\tan(27.00)*\sin(27.7192)}{1.554}} - 15.00=940.206\,kNm/m$$

→FS=1.554 -result of the 2th iteration

- Calculation of the resisting moment, FS = 1.554 :

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \tan(27.00) \cdot \sin(27.7192)} \cdot 15.00 = 940.206\ kNm/m$$

→ FS = 1.554 - result of the 4th iteration

Calculation for all blocks:

Block	1stiteration		2nditeration		3rditeration		4thiteration		5thiteration	
	Mp,i [kNm/m]	FS	Mp,i [kNm/m]	FS	Mp,i [kNm/m]	FS	Mp,i [kNm/m]	FS	Mp,i [kNm/m]	FS
1	395.044	1	393.434	1	393.198	1	393.165	1	393.165	1.5
2	401.680		400.433		400.250		400.224		400.224	
3	452.781		451.769		451.620		451.599		451.599	
4	524.644		523.886		523.775		523.759		523.759	
5	588.222		587.805		587.742		587.734		587.734	
6	644.339		644.351		644.353		644.353		644.353	
7	697.048		697.484		697.548		697.557		697.557	
8	743.745		744.700		744.841		744.861		744.861	
9	787.201		788.710		788.932		788.964		788.964	
10	827.660		829.768		830.079		830.123		830.123	
11	865.500		868.256		868.663		868.721		868.721	
12	901.264		904.725		905.236		905.309		905.309	

13	935.258	939.492	940.117	940.206	940.206
14	967.766	972.856	973.608	973.715	973.715
15	999.018	1005.073	1005.969	1006.097	1006.097
16	1029.345	1036.514	1037.576	1037.727	1037.727
17	1058.707	1067.203	1068.464	1068.643	1068.643
18	1190.155	1201.280	1202.933	1203.168	1203.168
19	1170.095	1183.162	1185.108	1185.385	1185.385
20	996.701	1010.954	1013.084	1013.387	1013.387
TOTAL	16176.173	16251.854	16263.096	16264.697	16264.697

Table4 Resisting moments and safety factors

- Resultant resisting momentin 5th iteration:

$$M_p = \sum_{I=1}^{20} M_{p,i} = 16264.697\,kNm/m$$

Verification of the Stability of Anchored Slope

Figure 4 shows a second-stage anchored slope example. There is a spacing of 2.00 m and an anchor force of 200.00 kN. The anchor head is located at Hanchor = x, z = 16.00; 9.00.

Calculation of the sliding moment. The anchor acts as a passive element, which means that active moments will be the same as in the 1ststage.

- Resultant sliding moment:

$$M_a = \sum_{I=1}^{20} M_{a,I} = 10464.338\,kNm/m$$

Resultant active force:

$$F_a = \frac{\sum_{i=1}^{20} M_{a,i}}{R} = \frac{10464.338}{15.00} = 697.623\,kN/m$$

Calculation of the resisting moment. The resistive moments are affected by the anchor force. Recalculating the resistive moments is an iterative process since the safety factor FS is a parameter in the Bishop's approach. The safety factor in the first iteration is FS=1.500. The manual computation goes through five cycles. Table 11 displays the total computation.The computation for block 13 is done as an example.

- Anchor forceat1m:

$$F'_A = \frac{F_A}{b_A} = \frac{200.00}{2.00} = 100.00 kN/m$$

- Calculation of the arm of the anchor force:

$$R_a = Z_O - Z_{anchor} = 18.944 - 9.000 = 9.944 m$$

- Resisting moment of the anchor:

$$M_{p,A} = F'_A \cdot r_A = 100.00 * 9.944 = 994.400 kNm$$

- Calculation of the resisting moment ,FS□1.500:

$$M_{p,13} = \frac{c*b_{13} + (W_{13} + f_{13} - u_{13} * b_{13}) \cdot \tan(\varphi)}{\cos(\square_{13}) + \frac{\tan(\varphi) + \sin(\alpha_{13})}{FS}} + R$$

$$M_{p,13} = \frac{21.00*1.00+(121.236+0.00-34.790*1,00)*\tan(27.00)}{\cos(27.7192)+\frac{\tan(27.00)*\sin(27.7192)}{1.500}} + 15.00 = 935.258 kNm/m$$

$FS = 1.641$ -result of the 1st iteration

- Calculation of the resisting moment,FS=1.662 :

$$M_{p,13} = \frac{21.00*1.00+(121.236+0.00-34.790*1.00)*\tan(27.00)}{\cos(27.7192)+\frac{\tan(27.00)+\sin(27.7192)}{1.662}} + 15.00 = 949.272 kNm/m$$

$FS = 1.665$ -result of the 2nd iteration

- Calculation of the resisting moment,FS=1.665 :

$M_{p,13}$

$$= \frac{21.00+1.00+(121.236+0.00-34.790-1.00)*\tan(27.00)}{\cos(27.7192)+\frac{\tan(27.00)*\sin(27.7192)}{1.665}} + 15.00 = 949.509\,kNm/m$$

$FS=1.665$ -result of the 3rd iteration

- Calculation of the resisting moment, FS=1.665 :

$$M_{p,13} = \frac{21.00*1.00+(121.236+0.00-34.790*1.00)*\tan(27.00)}{\cos(27.7192)+\frac{\tan(27.00)*\sin(27.7192)}{1.665}} * 15.00 = 949.509\,kNm/m$$

$FS=1.665$ -result of the 4th iteration

- Calculation for all blocks:

Block	1stiteration		2nditeration		3rditeration		4thiteration		5thiteration	
	Mp,i [kNm/m]	FS	Mp,i [kNm/m]	FS	Mp,i [kNm/m]	FS	Mp,i [kNm/m]	FS	Mp,i [kNm/m]	FS
1	395.044	1.641	390.429	1.662	389.817	1.665	389.731	1.665	389.731	1.665
2	401.680		398.100		397.623		397.556		397.556	
3	452.781		449.870		449.481		449.427		449.427	
4	524.644		522.461		522.169		522.128		522.128	
5	588.222		587.016		586.855		586.832		586.832	
6	644.339		644.374		644.378		644.379		644.379	
7	697.048		698.308		698.478		698.502		698.502	
8	743.745		746.511		746.885		746.937		746.937	
9	787.201		791.574		792.165		792.249		792.249	
10	827.660		833.776		834.605		834.722		834.722	
11	865.500		873.507		874.595		874.748		874.748	
12	901.264		911.332		912.703		912.896		912.896	
13	935.258		947.589		949.272		949.509		949.509	
14	967.766		982.612		984.642		984.929		984.929	
15	999.018		1016.706		1019.131		1019.474		1019.474	
16	1029.345		1050.323		1053.208		1053.616		1053.616	
17	1058.707		1083.621		1087.059		1087.545		1087.545	
18	1190.155		1222.859		1227.393		1228.034		1228.034	
19	1170.095		1208.644		1214.020		1214.781		1214.781	
20	996.701		1039.003		1044.965		1045.810		1045.810	
Anchor	994.400		994.400		994.400		994.400		994.400	
TOTAL	17170.573		17393.015		17423.844		17428.205		17428.205	

Table 5 Resisting moments and safety factors

- Resultant resisting moment in 5th iteration:

$$M_p = \sum_{i=1}^{20} M_{p,i} + M_{p,A} = 16433.805 + 994.400 = 17428.205 kNm/m$$

- Resultant passive force:

$$F_p = \frac{\sum_{i=1}^{20} M_{p,i} \square M_{p,A}}{R} = \frac{16433.805+994.400}{15.00} = 1161.880 kN/m$$

- Calculation of the safety factor in 5th iteration:

CONCLUSIONS

To guarantee the slope's stability, the following suggestions have been made based on the available analyses.

- With the exception of water seepage during wet seasons, the slope of the current benches does not show any significant signs of collapse.
- Slope angles between 36 and 48 degrees and safety factors between 1.2 and 1.5 characterise the current slope.
- With a suggested 36-degree angle of slope, the safety factor is 1.3.

RECOMMENDATION FOR SLOPE STABILITY

This study established a number of parameters related to slope stability, including bench height, angle of internal friction, material density, and cohesiveness. It is highly advised that future projects take into account the following aspects, which impact slope stability: groundwater table, grain size of dumped material, etc. of addition, you should restrict the total slope angle of the footwall of the pit to no more than 50 degrees. The following measures are necessary since the factor of safety is nearing unity at this angle and height of 420 m RL: To prevent the buildup of hydrostatic pressure in the wall, it is essential that dewatering be done prior to mining and monitoring to guarantee that the formation is sufficiently drained. Presharing and vibration monitoring are two techniques that can minimise blast damage to the final wall. Additionally, personnel should be trained on a full-time basis to control and monitor the stability of the wall using instruments like extensometers, as well as to conduct mapping inspections, keep records, and statistics. In order to assess any changes in rock types or conditions, more geotechnical studies should be conducted as the pit is depleted and new strains are revealed. As the pit continues to be dug and new strains are revealed, it will be necessary to conduct more geotechnical studies to assess the potential changes in rock types and conditions. Maintaining accurate geotechnical mapping documents how the geological structure or amount of weathering changes as the mine delves deeper. Keeping up with the data collection and mechanical property verification throughout the pit's several zones in order to compile a statistical database for future planning. It is critical to continue dewatering at the current pace such that the water table remains 15 meters below the pit bottom at the feet of the slopes. A more effective method of monitoring the slope as the mind relies on installing piezometers 35-45 meters deep at every three or four benches when these benches are at their ultimate level position. This will allow the mine to measure the water table levels behind the slope. Minimising blasting, break, and overbreak damage to benches is essential for addressing the local instability issues and preserving the ore quality. For the purpose of tracking slope displacement, two methods are suggested: borehole and borehole extensometer testing, and precise topological mapping of permanent objects.

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