Landslide stability analysis using the sliding block method

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ABSTRACT: The authors of this paper dealt with a stability analysis related problem of a landslide located in the Central part of Peru. This landslide was divided into South and North sectors. There is a special interest in the North landslide since it directly affects a driving channel located at the toe of the slope. The movement was classified as translational and the calculation methodology applied was the sliding block. Upper and intermediate cuts were carried out on the slope. After having completed both works, the real configuration of the failure surface was highlighted and for this reason, new stability analyses following the new direction of the movement were performed.

1 INTRODUCTION

During 2010 and 2014, SRK had an active participation in analyzing the sliding of a slope located in the Central zone of Peru. The first visits to the landslide area were carried out at the end of 2010, where this landslide was characterized as a problem of external geodynamics on steep slopes.

In May 2011, the material that makes up the landslide was characterized as a granular material corresponding to an old slip in the zone and the trigger factor of the movement of the ground mass was the water. The sliding was divided into two sectors South and North (see Figure 1); the sliding volume was 370.000 m^3 in the northern sector which implies a potential danger to the channel of a hydroelectric plant located in the lower part.

In July 2011, SRK presented the first results of monitoring carried out in the northern slope sector. In May 2012 was concluded that the failure surface is at level or slightly above the base of the channel located in the lower part of the slope. As a result, one of the recommendations of this report was to unload the upper part of the sliding slope in order to reduce the stress on the driving channel.

In August 2012, SRK designed the upper cut of the slope, which was carried out between September 2012 and February 2013. In April of this year, SRK presented the design of the intermediate cut in the slope. This work was carried out between May and October 2013, where the limits of the South and North landslide were exposed (see Figure 14).

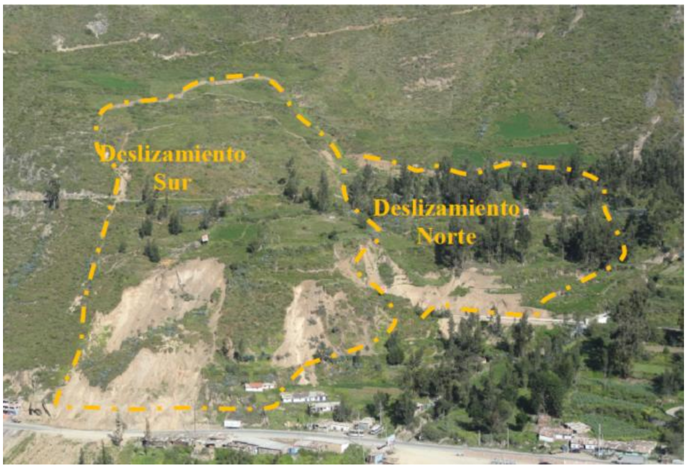

Figure 1. South and North landslides, year 2011

2 GEOLOGICAL ASPECTS

The landslides took place on soil of colluvial origin and andesite rock; the water table was located in the failure plane. The rock and the soil present different geological and geotechnical conditions in both sectors that make up the landslide. In the larger sector, the rock is yellowish brown which is highly altered by transformation of minerals in clay and oxidation. Plus, the rock is moderately weathered with a high fracturing. A layer of burdensome soil with little or no matrix covers it superficially. The failure plane is in rock.

In the smaller sector, the body of the landslide is formed by a predominantly clay sandy and clay gravel, the andesite rock is slightly weathered, and the failure plane is located on the ground, very close to the ground-rock contact.

3 GEOTECHNICAL CHARACTERIZATION

The material that forms the North landslide has been characterized by twelve (12) trial pits of up to 5.20 m depth and three (3) trenches located in the toe of the slope. The results are contained in Table 1 and Figure 2.

Table 1. USCS Classification Tests

Trial pits	G	A.	F	LL	LP	IP	SUCS
C-01/M-2	52.8	31.3	15.9	30	22	8	GC
C-01/M-2	55.1	28.3	16.6	33	21	12	GC
C-01/MI	67.9	21.2	10.9	28	15	13	GP-GC
C-02/MI	16.1	62.2	21.7	26	19	7	SC
C-03/M-1	53.5	34.7	11.8	30	18	12	GP-GC
C-03/M-1	51.1	39.2	9.7	29	20	9	GP-GC
C-03/MI	71.2	19.4	9.4	27	17	10	GP-GC
C-04	73.1	21.9	5.0	36	24	12	GP-GC
C-04	17.4	59.6	23.0	27	18	9	SC
C-05	50.4	29.3	20.3	33	21	12	GC
C-05	36.1	46.0	17.9	33	21	12	SC
C-05	33.1	30.4	36.5	29	19	10	GC
C-06	49.7	35.2	15.1	29	19	10	GC
C-06	44.2	41.9	13.9	32	21	11	GC
C-07	73.8	22.0	4.2	30	22	8	GW
C-07	58.8	32.4	8.8	25	18	7	GP-GC
C-08	38.3	45.8	15.9	25	17	8	SC
C-08	63.5	30.0	6.5	28	16	12	GP-GC
C-09	83.4	13.9	2.7	34	18	16	GW
C-09	24.6	47.6	27.8	27	14	13	SC
C-10	33.4	40.9	25.7	27	18	9	SC
C-11	24.5	48.3	27.2	32	20	12	SC
C-11	61.3	30.5	8.2	25	16	9	GP-GC
C-12	34.5	41.3	24.2	34	21	13	SC
C-12	26.6	46.4	27.0	29	18	11	SC
T-1	33.5	42.5	24.0	31	20	11	SC
T-1	40.8	43.0	16.2	31	17	14	SC
T-2	71.3	24.1	4.6	27	20	7	GW
T-3	42.7	35.0	22.3	27	18	9	GC
T-3	36.2	49.2	14.6	29	18	11	SC
MI	43.9	30.1	26.0	32	17	15	GC

Note
G: (%) Percentage of gravel (n° 4 < ϕ < 3)
A: (%) Percentage of sand (n° 200 < ϕ < N° 4)
F: (%) Percentage of fines (ϕ < n° 200)
LL: (%) liquid limit
LP: (%) plastic limit
IP: (%) plasticity index
*: Classification According to ASTM D-2487

According to the results obtained in Table 1, the material that makes up the slip has a variable particle size among clayey gravels (GC) and clayey sands (SC). The percentage of gravel ranges from 16 to 83%; for sands, from 14 to 47% and for fine materials, from 3 to 37%.

The compactness of the material and its respective humidity were evaluated by means of natural density tests and the method of the calibrated sand and cone (ASTM-D1556), which were carried out in each excavated trial pits. The results obtained are described in Table 2.

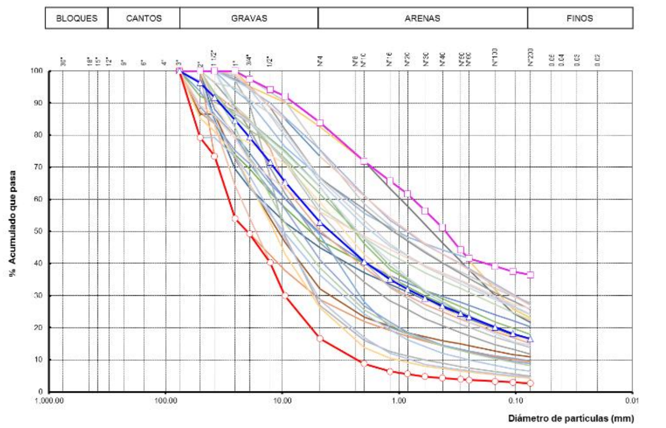

Figure 2. Size Analysis – Granular Material

Table 2. On-site density testing

Trial pit	Humidity (%)	Dry Density < 3/4 (gr/cm^3)	Global dry Density (gr/cm^3)
C-1	7.4	1.66	1.70
C-2	7.4	1.60	1.65
C-3	10.0	1.45	1.50
C-4	8.1	1.60	1.60
C-5	6.8	1.53	1.65
C-6	8.2	1.65	1.70
C-7	5.8	1.55	1.70
C-8	7.8	1.71	1.80
C-9	7.7	1.70	1.80
C-10	7.2	1.76	1.81
C-11	9.8	1.65	1.70
C-12	8.1	1.50	1.60
T-1	6.4	1.56	1.70
T-2	6.3	1.55	1.75
T-3	7.3	1.60	1.70

A total of five (5) CU triaxial test and eight (8) shear direct tests were carried out in order to evaluate the resistance properties of the sliding soil. The results indicate that the material has a friction angle that varies between 15 and 39 degrees with no cohesion in drained conditions, while the angle of friction varies between 10 and 14 degrees with no cohesion in undrained conditions.

4 SLIP CLASSIFICATION

According to Jaime Suarez [3], the displacement in soils can be rotational, translational and combined. This differentiation is important because it can define the type of analysis to be performed and the stabilization measure to be recommended.

An important ratio to differentiate the types of slip is the quotient between the thickness (D) and the length of the failure surface (L). A movement is considered as rotational if the value of D/L is greater than 0.15 and less than 0.33[2]. If the D/L ratio is less than 0.10, the movement is translational [3]. Figure 3 and Figure 4 show that the movement in the slope is translational.

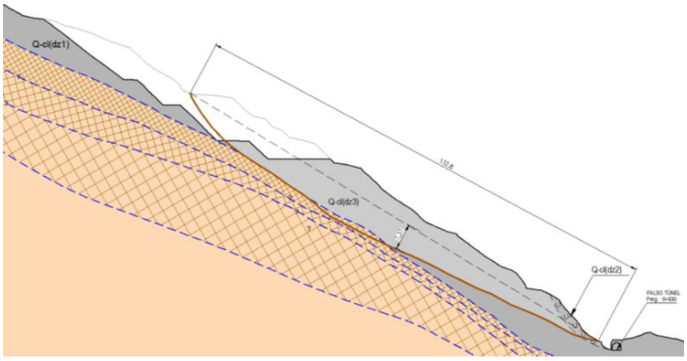

Figure 3. D/L Ratio = 0.06 geological section 4-4.

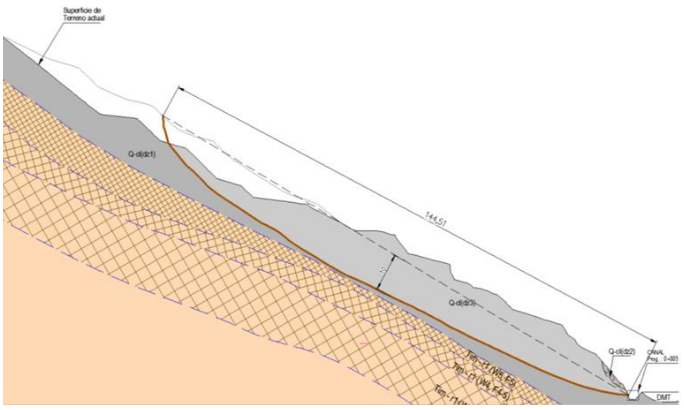

Figure 4. D/L Ratio = 0.07 geological Section 8-8.

5 CALCULATION METHODOLOGY

Knowing that the movement of the hillside is translational, the calculation method implemented in the DIN 4084 [1] German standard was used for the stability analysis. This methodology considers a failure mechanism composed by straight landslide lines, that is, it considers a sliding block involving all the movable mass and is considered as an exact method within the calculations of stability by equilibrium limit. Unlike the calculation methods by slices, such methodology avoids the assumptions related to the internal forces between slices and is better for landslides that have a translational failure mechanism. In this type of analysis the surfaces can be composed by a single line or by several lines, forming single, double or triple wedges [3].

6 SLIDE BLOCK DEFINITION

The geological section 8-8 was taken as a reference, the results of the monitoring and the inclinometer measurements carried out in the landslide allowed to identify the failure surface. Figure 5 shows the sliding block that was analyzed; the internal and external forces described correspond to the following description:

- W1, W2 and W3: weights of each sliding block
- Q1, Q2 and Q3: External friction forces acting on external failure surfaces (1, 2 and 3)
- Q21 and Q23: Internal Friction forces acting on the internal failure surfaces.

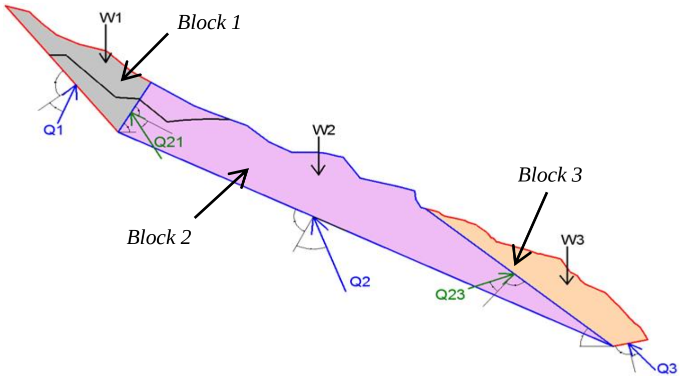

Figure 5. Sliding block

For the analysis, the friction angle and specific weight of the granular material were considered as 30° and 18 kN/m^3, respectively.

7 SLIDE BLOCK DEFINITION

7.1 *Inclinations of the failure surfaces*

The sliding block presents two internal failure surfaces (on which the forces Q21 and Q23 act) and three external (where the Q1, Q2 and Q3 forces act). The movement is produced along surface 2, where Q2 force acts.
The inclinations of the internal failure surfaces are known and equal to 45 + ϕ/2 and 45-ϕ/2, where ϕ is the friction angle of the material that predominates in the landslide. The inclinations of the external surfaces are known from the identification of the failure surface based on inclinometers records and boreholes. This work adopted a value of 60° of inclination for the surface where Q21 acts and an inclination of 40° for the surface where Q23 acts, see Figure 5.

7.2 *Inclinations of the acting forces*

The forces Q1, Q2, Q3, Q21 and Q23 (see Figure 5) have an inclination related to the normal surface.
The inclinations of the forces Q1, Q3, Q21 and Q23 are known and equal to the friction angle of the material in the landslide (ϕ=30°). This is value is related to a factor of safety (FoS) of 1.0. If the FoS is 1.5, the inclination will be 21° basically because the strength of granular soils depends only on the friction angle and therefore, the following definition of factor of safety was adopted:

$$\tan\varphi'_D = \frac{\tan\varphi'}{FS} \qquad \varphi'_D = a\tan\left(\frac{\tan\varphi'}{FoS}\right)$$

The inclination of the force Q2, which represents the friction angle of the contact between surface 2 and the landslide, is unknown and to determine such value a back analysis must be performed considering FoS = 1.0 on the other surfaces. Therefore, it must be taken into account the areas and weights described in Table 3.

Table 3. Block area – Initial condition

Block	Area (m^2)	γ (KN/m^3)	Weight (KN/m) (area x γ)
1	250,10	18	4.502
2	1,120.53	18	20.170
3	304,17	18	5.475

8 BACK ANALYSIS

In order to perform this procedure according to German standard DIN4084 it is necessary carry out a static analysis of the sliding block (Figure 5) taking into account that the resulting force must be equal to zero. In this analysis, it should be noted that the orientations of all forces are known, except for the orientation of the force Q2 which must be calculated. Therefore, the analysis is statically determined.
In Figure 6, it is possible to observe the back analysis where the red line (N) represents the normal straight to the surface 2 of the sliding block.

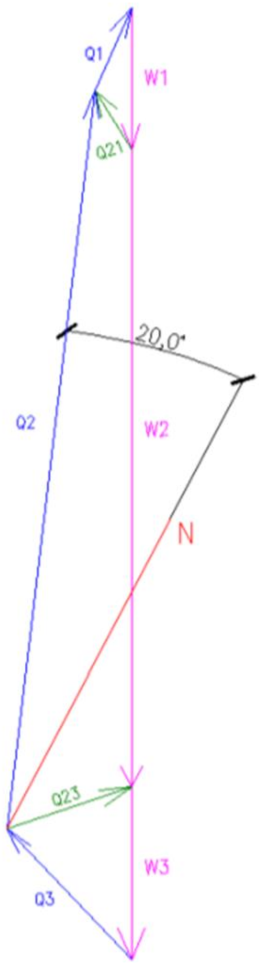

Figure 6. Back analysis – Force equilibrium

The angle of friction calculated in the back analysis is 20°, this value represents the resistance to which it is available to achieve the equilibrium of the system considering a FoS=1.0 in all surfaces. However, considering a FoS=1.5, a friction angle of 13.64 ° should be used in the design of the stabilization.

9 ANALYSIS WITH THE UPPER CUT IN THE SLOPE

9.1 *Static and Pseudo-static analysis in dry conditions*

The back analysis was carried out in the initial conditions, however, after the upper cut in February 2013, the weights 1 and 2 of the sliding block were modified (see Figure 5), which leads to a new stability analysis. This analysis will be completed considering a FoS=1.0 on all failure surfaces (internal and external).

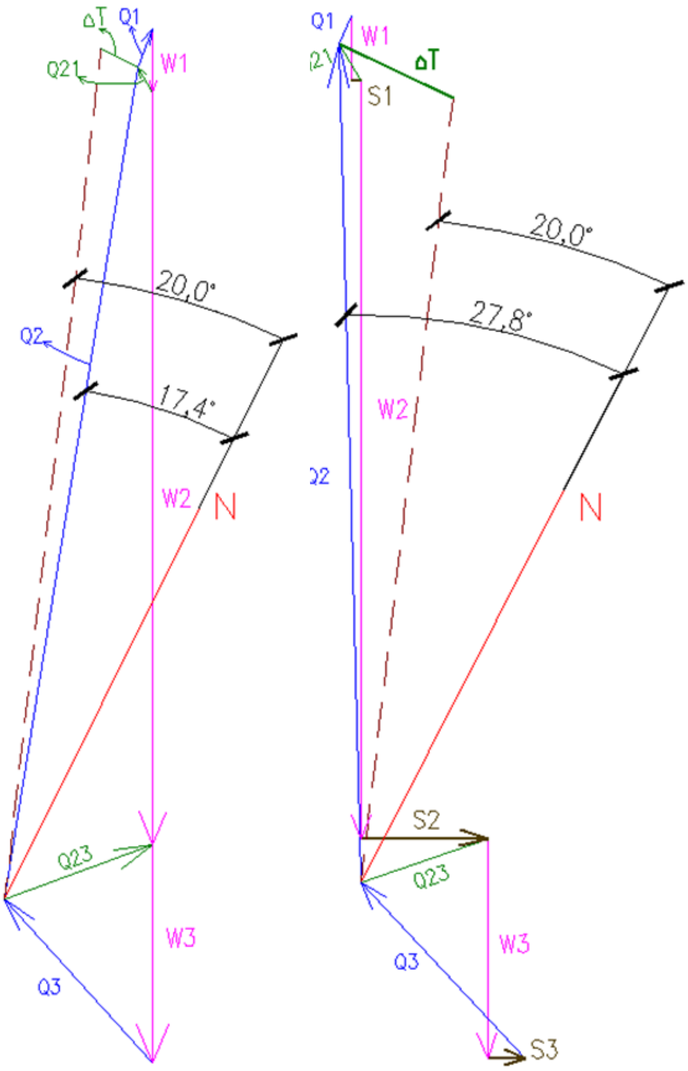

Figure 7. Static analysis (left) and pseudo-static a = 0.16 g (right) after the upper cut has been performed.

Table 4 shows the areas and forces considered in the analysis described in Figure 7. It should be noted that the areas of blocks 1 and 2 have decreased due to the upper cut performed (see Figure 5).
With regard to the results obtained it should be indicated that for the static analysis the friction angle required for the equilibrium is 17.4°. In addition, knowing that the available friction angle of the material in the failure area is 20° (see Figure 6) and applying the equation described in section 7.2, a FoS=1.16 is obtained on surface 2 after the upper cut has been made.

Table 4. Block's area – Upper cut

Block	Area (m^2)	γ (KN/m^3)	Weight (KN/m)	Earthquake force (KN/m) (Weight x 0.16)
1	89.70	18.0	1.615	259
2	1,050.84	18.0	18.915	3.026
3	304,17	18.0	5.475	876

For the pseudo-static analysis, a horizontal force that follows the direction of the movement has been considered; this force is proportional to the weight of each block. In this type of analysis, all failure surfaces (external and internal) have FoS=1.0. Figure 7 shows that a friction angle of 27.8° is required to achieve equilibrium. However, only a 20° friction angle is available, which represents a FoS=0.69 on surface 2. Therefore, it is concluded that in a pseudo-static analysis the system is not in equilibrium and to achieve such condition the application of a force (ΔT) parallel to surface 2 is necessary to balance the system.

9.2 *Static analysis considering filtering forces*

The German standard [3] mentions that the stability analyses involving water can be carried out in two ways: considering effective stress and filtering forces or considering total stress and pore pressure. In this project, the first option was used and as a result, the effective weight was calculated with the following expression:

$$Effective\ Weight = \gamma_t \times A_{above\ WT} + \gamma'_b\ A_{under\ WT}$$

Where:

$$\gamma'_b = \gamma_t - \gamma_w$$

Where γ_w and γ_t, unit weight of water and wet soil respectively.

The filtering forces are calculated with the following expression:

$$Filtering\ Forces = \gamma_w \times A_{under\ WT} \times sin(\alpha)$$

Where α is the inclination of the external failure surface (see Figure 5).

The analysis has considered the saturation of 2 m of soil located at the bottom of the sliding block (see Figure 8). Likewise, the upper water level will be parallel to the external failure surfaces, except for Block 3, where the water surface was considered horizontal, therefore the infiltration force is equal to zero because α=0°.
The weights and filtering forces considered in the analysis can be seen in Table 5.

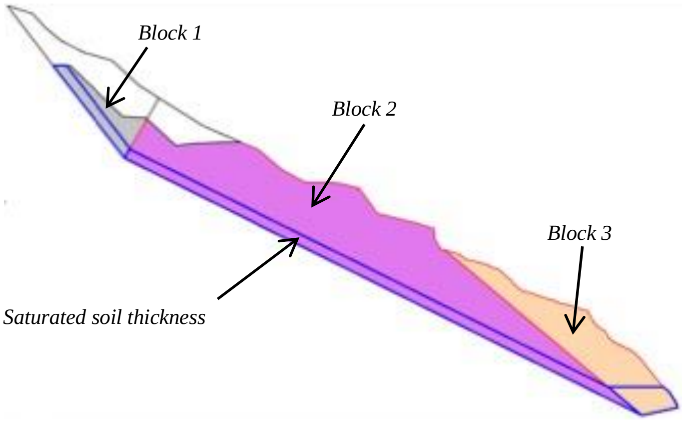

Figure 8. Sliding block and saturated soil

Table 5. Upper cut with water table

Block	Area (m^2)	Effective weight without WT (KN/m)	Effective weight with WT (KN/m)	Filtering forces (KN/m)
1	89.70	1.615	1.181	190
2	1,050.84	18.915	16.736	955
3	304,17	5.475	5.266	0

The values indicated in the last two columns of Table 5 were used in the calculation of stability considering filtering forces and effective weights. The forces corresponding to each block were raised, thus forming the polygon of forces shown in Figure 9. It should be indicated that the inclinations of the external and internal forces consider FoS=1.0 on all failure surfaces.

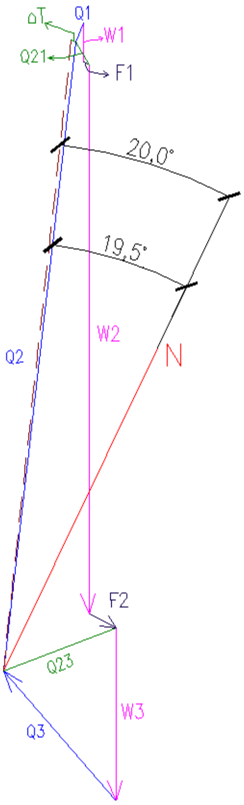

Figure 9. Static analysis considering filtering forces

The analysis performed, considering filtering forces, indicates that an angle of 19.5° is required to balance the system. Having a friction angle of 20° (back analysis) the FoS is 1.03, this represents an imminent movement under the conditions analyzed.

Previous analyses correspond to the condition of the hillside after the upper cut has been performed and have considered a FoS=1.0 on all failure surfaces (external and internal). However, this factor of safety does not represent the design criterion required by the Ministry of Energy and Mines (MEM), except for the pseudo-static analysis that should be assessed for a FoS=1.0.

9.3 *Static analysis in dry conditions, with filtering forces and a FoS = 1.50*

Figure 10 shows static stability analysis in dry conditions with filtering forces considering a FoS=1.50 on all failure surfaces (external and internal). Consequently, the inclination of the Q1, Q3, Q21 and Q23 forces is 21°, while the inclination of the friction force located on the Surface 2 is 13.64 ° for a FoS=1.50. Note that the Force Q2 is now the resulting between the friction force (ϕ=13.6°) and the force ΔT which is parallel to surface 2.

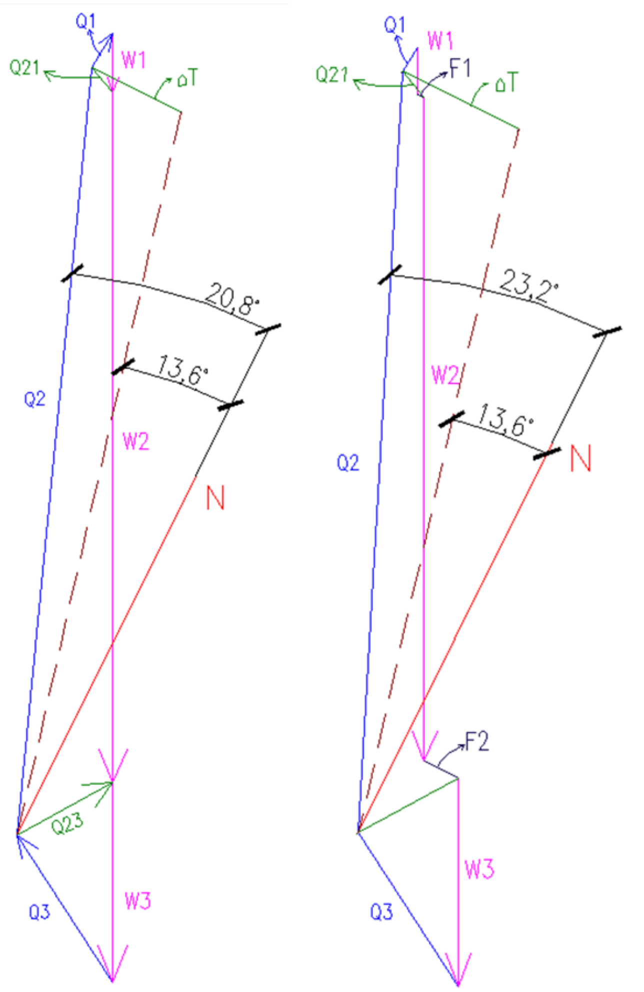

Figure 10. Static analysis in dry conditions, with filtering forces and a FoS = 1.50

The calculation described in Figure 10 has been carried out using the data shown in Table 5. In addition, it should be noted that the angle of friction required to achieve the equilibrium taking FoS=1.50 into account is 20.8° in dry conditions and 23.2° considering filtering forces. Note that the force ΔT, needed to balance the system, is greater in the case where it is considered to be filtering forces.

9.4 *Summary of results*

The results obtained in Figures 7, 9 and 10 are summarized in Table 6.

Table 6. Analysis Summary - Upper cut

Analysis	ϕ° Resistant	ϕ° Required	FoS *	Δ T (KN/m)	Ref.
1	20	17.4	1.16	+1022	Fig. 7
2	20	19.5	1.03	+155	Fig. 9
3	20	27.8	0.69	-3038	Fig. 7
4	13.64	20.8	0.64	-2723	Fig. 10
5	13.64	23.2	0.57	-3247	Fig. 10

1: Static, dry and with FoS = 1.0 on all surfaces
2: Static, with water and with FoS = 1.0 on all surfaces
3: Pseudo-static, dry and with FoS = 1.0 on all surfaces
4: Static, dry and with FoS = 1.5 on all surfaces
5: Static, with water and with FoS = 1.5 on all surfaces

The following conclusions are established from Table 6:

- The stability of the system is expressed by the value of FoS* which is calculated with the equation of paragraph 7.2 taking into account the angle of friction required for the equilibrium and the angle of friction that is available according to the factor of safety adopted.
- A value of FoS* greater than or equal to 1 indicates that the system is stable for the factor of safety adopted on external and internal failure surfaces. On the contrary, if FoS* is less than 1, it indicates that the system itself is not stable and requires an additional force ΔT to balance the system.
- The value of ΔT is positive when is associated with a FoS* greater than or equal to 1. In this case, the value of ΔT is negative represents a condition of instability (FoS*<1.0).
- Analyses 3 and 5 are of special interest for design purposes, because both apply the factor of safety required by the MEM (FoS=1.50 in static conditions and FoS = 1.0 under pseudo-statics conditions).
- In the case analyzed, the design is governed by the static analysis with filtering forces for a FoS = 1.50 as it requires a greater force ΔT (-3247 kN/m) to balance the system, in comparison to the force ΔT (-3038 kN/m) required in the pseudo-static analysis for a FoS = 1.0.
- The best way to reduce the value of the force ΔT (for economic purposes) is to decrease the weight

of the blocks and as a consequence, another cut in the slope must be conducted.

10 SLOPE STABILIZATION

The stabilization of the slope will be carried out on the geometry proposed in Figure 11. This consists of 4 berms: The first one is located on the lower part and has a variable width, the second one has a width of 7.0 m, the third one has a width of 6.0 m and the last one, has a width of 5.0 m. All slopes have a tilt of 1V:1.5H and a height of 10.0 m.
It should be noted that the geometry proposed in Figure 11 considers a filling at the toe of the slope, which gives greater weight to block 3 and contributes to the overall stability of the landslide. This filling has a maximum height of 10.0 m and a slope of 1V: 1.5H.

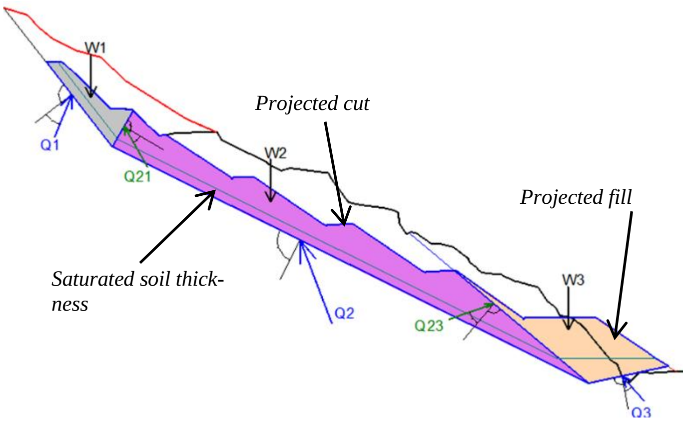

Figure 11. Sliding Block – slope stabilization

The data used in the calculation described in Figure 12 are shown in Tables 7 and 8. It should be noted that the area of block 3 has been reduced by 15%.

Table 7. Data for hillside Stabilization (1)

Block	Area after upper cut (m^2)	Area Projected (m^2)	γ (KN/m^3)
1	89.70	89.70	18
2	1,050.84	676,63	18
3	304,17	257,12	18

Table 8. Data for landslide Stabilization (2)

Block	Effective weight without WT (KN/m)	Effective weight with WT (KN/m)	Filtering forces (KN/m)	Earth-quake forces (KN/m)
1	1.615	1.181	190	259
2	12.161	9.982	969	1.946
3	4.628	3.851	0	741

The test results are described in Table 9.

Table 9. Analysis-Stabilization Summary

Analysis	ϕ° Resistant	ϕ° Required	FoS *	Δ T (KN/m)	Ref.
1	13.64	24.8	0.52	-2421	Fig. 12
2	20	26	0.75	-1571	Fig. 12

1: Static, with water and with FoS = 1.5 on all surfaces
2: Pseudo static, dry and with FoS = 1.0 on all surfaces

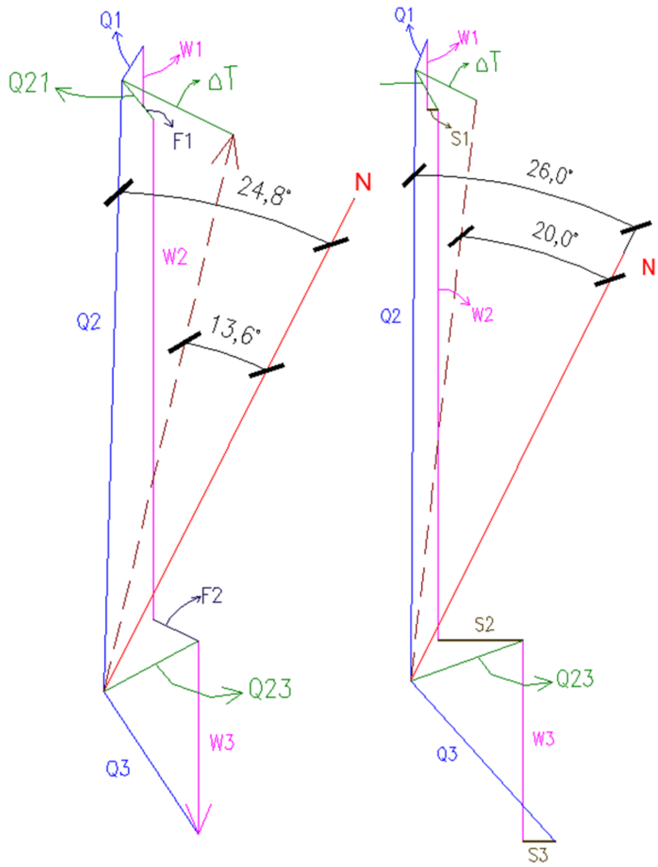

Figure 12. Static analysis with filtering forces (left) and pseudo-static analysis (right).

The following conclusions can be drawn from the results obtained in Table 9:

- The type of analysis that governs the design is the static with filtering forces, because the force ΔT required to achieve the equilibrium of the system is greater than the pseudo-static analysis.
- The magnitude of the force ΔT, considering FoS=1.50 in all failure surfaces is 2.421 kN/m. This force is less than the ΔT indicated in Table 6 (3.247 KN/m), this verifies the advantage of the cut and fill projected.
- The structural fill located in the toe of the slope contributes to the local stability in the vicinity of the canal. In addition, it represents an important component within the overall stability of the system because in its absence, the force ΔT required to reach the equilibrium will be greater than 2.421 kN/m.
- The stability of the slope is guaranteed by the execution of 3 following components:
  - The intermediate cut of the slope.
  - The construction of the structural fill.

- The placement of structural elements which should supply the force Δ T necessary for the equilibrium of the system (micropiles).

11 CURRENT CONDITION OF THE SLOPE

Figures 13 and 14 show the condition of the slope, after having performed the upper and intermediate cut respectively. The works were completed in October 2013.

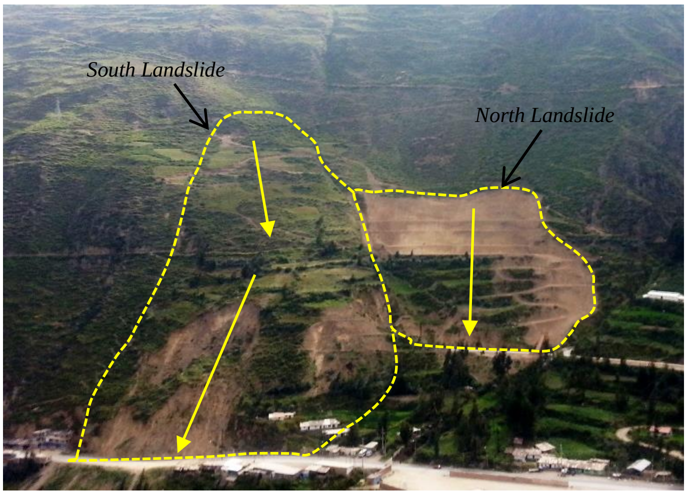

Figure 13. Upper cut – February 2013

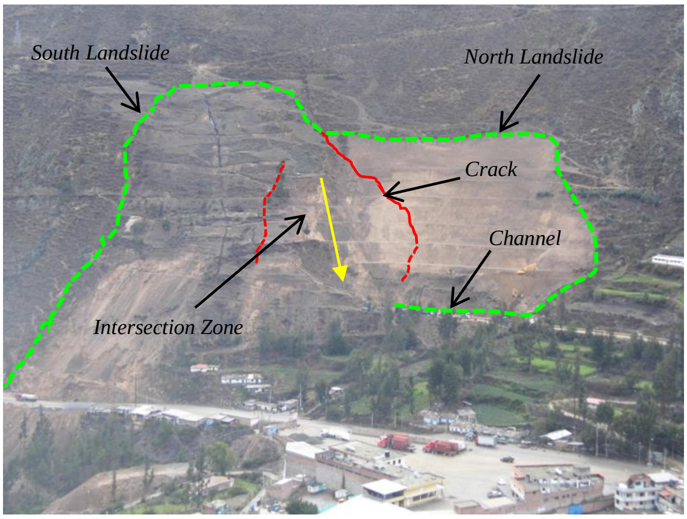

Figure 14. Intermediate cut – December 2013

As a result of the cuts carried out in the slope, the current configuration of the landslide was revealed. A wedge was formed between the South and North landslides (see Figure 14). The direction of the movement in the wedge is different from the direction of the movement in the North Landslide as indicated in Figure 13 and as a consequence, a new stability analysis was carried out considering this finding. The sliding block considered in the new analysis is described in Figure 15 and it was obtained from the recorded measurements in the field.

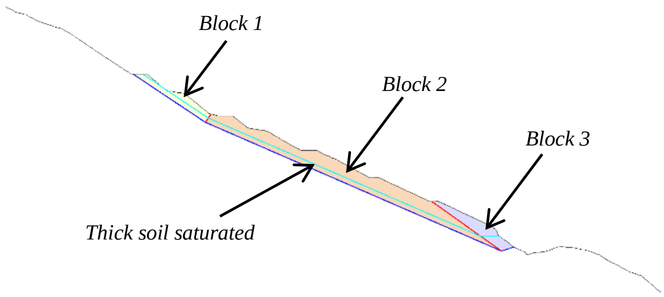

Figure 15. Sliding Block – new direction of movement

The data considered in the new stability calculation are described in Tables 10 and 11 and the results obtained are shown in Table 12.

Table 10. Data for new calculation (1)

Block	Area (m^2)	γ (kN/m^3)
1	98.05	18
2	800,20	18
3	119,04	18

Table 11. Data for new calculation (2)

Block	Effective weight without WT (kN/m)	Effective weight with WT (kN/m)	Filtering forces (kN/m)	Earth-quake forces (kN/m)
1	1.765	1.160	372	282
2	11.199	9.003	997	1.792
3	2.143	1.825	0	343

Table 12. Analysis Summary – New calculation

Analysis	ϕ° Resistant	ϕ° Required	FoS*	Δ T (KN/m)
1	20	20.0	1.00	0.00
2	20	26.1	0.74	-1.210
3	20	30.5	0.62	-2.425
4	13.64	23.3	0.56	-2.136
5	13.64	29.1	0.44	-2.930

1: Static, dry and with FoS = 1.0 on all surfaces
2: Static, with water and with FoS = 1.0 on all surfaces
3: Pseudo static, dry and with FoS = 1.0 on all surfaces
4: Static, dry and with FoS = 1.5 on all surfaces
5: Static, with water and with FoS = 1.5 on all surfaces

From the results obtained in Table 12, the following conclusions are established:

- After having made the upper and intermediate cuts in the area corresponding to the intersection zone, a cross-section of this sector is in equilibrium in dry conditions (FoS*=1.0). If filtering forces are considered, the section is not in equilibrium and requires a force ΔT that should balance the system. This analysis justifies the movement of intersection zone at the end of 2013 with the direction shown in Figure 14.

- The force ΔT required for the equilibrium is greater for the sliding wedge (2.930 kN/m) than for the North Landslide (2.421 kN/m).

As a preliminary measure to control stability in the intersection zone, a 5 m-high filling material have to be located at the toe of the sliding block described in Figure 15. This analysis considered a FoS = 1.1 on all failure surfaces. The results obtained are contained in Table 13.

Table 13. Analysis with 5 m-high filling

Analysis	ϕ° Resistant	ϕ° Required	FoS*	Δ T (KN/m)
1	18.31	18.31	1.00	0.00

1: Static, dry and FoS = 1.1 on all surfaces

The filling was built during 2014 and can be observed in Figure 16.

Figure 16. Filling at the toe of the landslide – April 2016.

Figure 17 shows the current state of the landslide, it should be indicated that the works performed to date correspond to the upper and intermediate cut and the construction of the filling at the toe of the intersection zone.

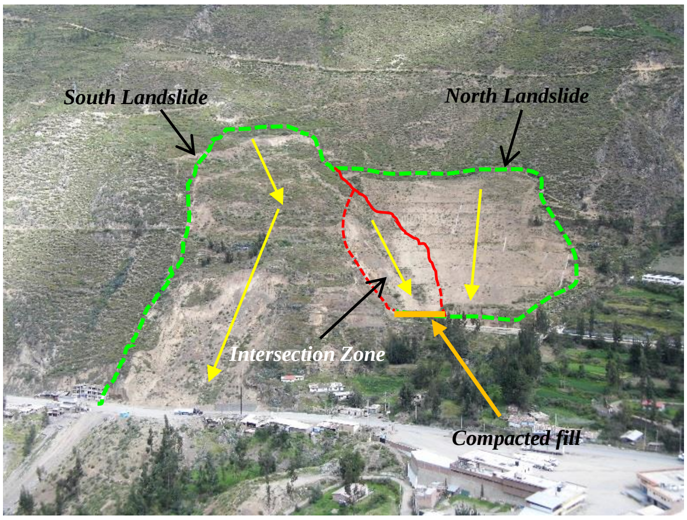

Figure 17. Current landslide – April 2016.

12 CONCLUSIONS

The landslide presented in this work has been divided into two sectors: South and North. The reason for the analysis of the North landslide is that it affects the driving channel located at the toe of the slide. Stability analyses have been carried out by applying the sliding block methodology described in detail in the German standard DIN-4084.

Based on historical information and monitoring performed, the movement was categorized as translational. Therefore, the calculation methodology used is according to the type of movement established and the remediation measures for the North Sector of the landslide were recommended.

Finally, the sliding block method is considered an exact method within stability calculations and is better suited to slides that have translational failures.

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