The Role of Depressurization in Stabilizing a Large Pit Slope in Northern Peru

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Abstract

Minera Yanacocha is one of the world’s largest gold mines; located between 3,000 and 4,000 mASL in the Andes of northern Peru. The La Quinua orebody is a unique debris flow deposit located on the steep western slopes of the Yanacocha project area. Mining of La Quinua has been ongoing since 2001, with over 700 million tons mined to date. The debris flow is up to 300 m thick, consisting of a variably-cemented layered gravel sequence, and including well-developed ferricrete intervals. The project has been successfully dewatered using a field of up to 20 wells producing a total of 250-300 l/s. Significant movement of the East high wall in the Phase 2C sector was noted in early 2010. Following a detailed investigation program, a series of new remediation wells was installed from the lower slope to reduce pore pressures by up to 1,500 KPa within and immediately below the identified failure surface. This paper describes the results of the investigation program, pore pressure modeling, well installations and monitoring carried out during 2010 to assist stabilization of the slope.

1 General site setting

The Minera Yanacocha operations consist of multiple mining areas located within a district encompassing about 18 km east-west and about 14 km north-south. There are currently six pits being actively mined, of which La Quinua is the largest. Figure 1 shows the general site setting of Yanacocha and the location of the La Quinua mining area in the southwestern part of the site.

Mean annual precipitation at the site varies locally with topography and aspect, but is generally between about 1,450 mm. Table 1 shows the mean monthly precipitation at the site. Most of the precipitation occurs as rain during the pronounced wet season between October and May. The pre-mining groundwater table across most of the site is relatively shallow because of the high seasonal precipitation and the compartmentalized nature of the district-hydrogeology. All of the major pits mined at Yanacocha to date have extended a considerable distance below the pre-mining groundwater table and have each required the operation of a substantial dewatering program.

In addition to providing seasonal recharge to the site-wide groundwater system, the intense rainfall events that occur during the pronounced wet season need to be managed in terms of their effect on slope stability. Rainfall events of greater than 20 mm/hr occur commonly during the wet season. There are three major issues in this regard, as follows:

- Surface water diversions are required outside the pits to prevent run-on to the slopes below
- The weaker materials in the pit slopes themselves need protection to prevent erosion and back-cutting.
• The surface water needs to be shed from the slopes as quickly as possible to minimize the extent to which seasonal recharge sustains the pore water pressures in the underlying slope materials.

Figure 1. Layout of Minera Yanacocha operations, showing the total site and La Quinua.

Table 1. Mean monthly precipitation (mm) at Yanacocha.

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<th>Month</th>
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</tr>
<tr>
<td>November</td>
<td>145.5</td>
</tr>
<tr>
<td>December</td>
<td>206.4</td>
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**Total** 1,439.5
The La Quinua orebody is hosted in strongly cemented silty-sands and gravels, termed the Upper Sequence Gravels (USG) and the Lower Sequence Gravels (LSG). The sequence shows strong geologic layering and exhibits a number of prominent ferricrete layers. The USG and LSG are typically separated by a ~50 m thick horizon where the ferricrete layers have coalesced. It is thought that the deposit was laid down mostly as a debris flow eroded from the steep slopes above. The combined USG/LSG sequence is typically up to 300 m thick in the central part of the mining area.

Figure 2 shows that the La Quinua pit is comprised of a number of mining phases. Mining occurred initially during 2001 in La Quinua Central (Phase I) with the excavation a broad pit and development of the La Quinua East high wall. Mining of the gravel sequence in Phase I has extended progressively down-slope. The El Tapado pit occurs immediately west of La Quinua and exploits reserves in a massive silica bedrock orebody that was originally buried beneath the gravel sequence.

![Figure 2. Map of La Quinua, showing the Central 2C mining areas.](image)
The Phase 2C pit area was recently mined between 2007 and 2010 as a southern extension of the La Quinua Central (Phase I) orebody. This paper discusses the East high wall of the LQ2C mining area.

Figure 3 shows a schematic long section through the La Quinua orebody illustrating the geometry of the USG/LSG sequence. The eastern boundary of the deposit area is controlled by the prominent north-south trending La Quinua fault. The fault zone dips steeply to the west and has played a major part of the design and performance of the La Quinua high wall. The footwall of the fault consists of a sequence of altered volcanic rocks (mostly silica alunite, propylitic, and clay-altered volcanics). The LSG sequence occurs on the hanging wall side of the fault.

Figure 3. Schematic long section through La Quinua showing geology and pre-mining groundwater conditions.

2 Hydrogeology

Figure 4 shows the pre-mining groundwater levels at in the La Quinua area. There was a well developed pre-mining groundwater gradient to the west (down-slope) reflecting the recharge from the area of higher ground to the east of the La Quinua fault area, and the discharge to the quabredas in the lower western part of the project area, to the west of El Tapado. The pre-mining groundwater through-flow at the site was estimated to be about 150 l/s. Initial groundwater levels varied from about 3,750 masl in the area of the east high wall to about 3,500 masl in the lower parts of the site, immediately to the east of El Tapado.
The gravel sequence shows strong layering with a marked variation in hydraulic parameters between layers. The more permeable layers, often associated with the ferricrete deposits, typically show permeability values within the range $10^{-4}$ to $10^{-5}$ m/s. The intervening layers, containing more fine grained materials typically show permeability values below $10^{-7}$ m/s. As such, it was possible to install production dewatering wells within the deposit area. Individual well yields for the LSG dewatering wells were initially within the range 20-35 l/s, progressively decreasing with time to less than 10 l/s as the groundwater table was gradually lowered and the overall saturated thickness of the gravel sequence was reduced by dewatering. The large number of mineral exploration holes drilled through the deposit area helped cross connected the permeable layers within the gravel sequence and create good vertical drainage of the orebody.

Pre-mining groundwater levels within the LQ2C area were typically within the range 3,680-3,720 masl. Groundwater levels within LQ2C area showed a subdued response to dewatering the Phase I part of the orebody, but were generally isolated from dewatering activities in the Phase I area, most likely because of offsets to the permeable gravel horizons because of displacement caused by structures.

![Pre-mining groundwater level map of La Quinua](image)

**Figure 4.** Pre-mining groundwater level map of La Quinua.

### 3 Dewatering of Phase I

The overall plan for dewatering the La Quinua orebody was as follows:

#### 3.1 Upgradient interceptor wells

Upgradient bedrock wells were installed within permeable bedrock material on the upgradient (footwall) side of the La Quinua fault zone. The wells targeted permeable fracture zones within silica alunite material on the footwall side of the fault. There purpose was to intercept groundwater recharge from upgradient that would otherwise flow through the deposit area.
The combined initial yield of the upgradient bedrock interceptor wells was about 130 l/s. The number of wells on line varied from 6 initially to 3 latterly. The combined yield remained relatively stable over time. The final combined production rate from the interceptor wells as about 90-110 l/s.

The goal was to use the upgradient interceptor wells to minimize the amount of pumping from within the orebody, and therefore minimize the required number of in-pit wells.

### 3.2 In-pit dewatering wells

Dewatering wells were installed within the USG/LSG orebody to progressively lower the groundwater table in the mining area ahead of the advancing pit floor.

The combined yield of the in-pit dewatering wells has varied between 55 and 110 l/s. The number of wells on line has typically varied from 5 to 12, depending on the mining sequence.

Even though the mining operation adopted a successful practice of mining around in pit wells, it was necessary to implement an on-going program of well replacement due to a combination of: 1) reducing yields caused by reducing saturated thickness of the LSG sequence, and 2) residual damage caused by blasting and mining.

### 3.3 Implementation

The actual implementation of the dewatering system for La Quinua was consistent with the design, and the required dewatering targets were successfully achieved ahead of mining. The dewatering system progressively created about 230 m of total drawdown, lowering the groundwater levels from 3,750 masl initially to about 3,520 masl at the end of mining. Figure 5 shows the La Quinua pit at its maximum extent.

![Figure 5](image_url) Photograph showing the completed La Quinua Central pit (looking west).
Although the dewatering system was installed according to design, it became increasingly difficult to create drawdown during the final phases of mining. Pilot-hole drilling beneath the LSG orebody had revealed the presence of permeable silica alunite material below the base of the deposit area. It was therefore necessary to add two supplemental components to the dewatering program, as mining progressed. These were:

- The installation of a series of angled gravity drain holes along the toe of the La Quinua high wall to reduce the bedrock pressures in the silica alunite behind the toe of the wall. The spacing of the drains was approximately 50-100 m. The drains were drilled by reverse circulation methods to about 150 m depth. They were drilled at 5 ¼-inch diameter and were completed with 2-inch diameter UPVC slotted liner pipe. The drain holes flowed at a combined rate of between 20 and 40 l/s.

- The installation of an additional in-pit bedrock well to depressurize the silica alunite below the base of the deposit. This well was also artesian (flowing at the collar) and was pumped at a rate of about 40-45 l/s through the final phases of the mine life.

With these additional measures, the original mine plan was successfully completed, including the mining of three additional benches below the base of the original pit.

4 Dewatering of the Phase 2C area

The Phase 2C LSG orebody was hydraulically isolated from the main part of the La Quinua mining area (the Phase I area). A supplementary in pit dewatering well field was therefore planned to lower the water levels in the 2C deposit area ahead of mining. During the initial studies, it was noted that water levels in piezometers in the 2C area dropped in response to pumping from the upgradient bedrock interceptor system installed for the main Phase I area. Therefore, the dewatering plan for 2C also included the maintenance of the Phase I upgradient interceptor wells.

A total of 6 in-pit dewatering wells were installed to lower the water levels in the Phase 2C area. The location of the wells is shown in Figure 6. The initial 2C LSG dewatering wells are shown in black on the figure. The combined yield of the system typically ranged between about 50 and 120 l/s, as shown in Figure 7. The figure shows the in-pit dewatering wells were successful in lowering the piezometric levels within the deposit area.

Figure 6. Map of Phase 2C showing original dewatering wells and piezometers.
Figure 7. Hydrographs showing total pumping rate with time, and pumping water levels (prior to installing the 5 remediation wells on the step out).

5 East high wall

The height of the east high wall was progressively increased during the course of mining of the LQ2C pit. The final height of the wall was about 350 m (see Figure 8). The material exposed in the slope was predominantly USG and LSG material. The La Quinua fault zone and the bedrock contact were present a short distance behind the active slope, as shown in Figure 9 (2C Zone 1) and Figure 10 (2C Zone 2). During early 2010, cracking water observed around the crest of the slope, and acceleration was observed in prisms within the Zone 1 area. The initial movement in the prisms was up to about 7 mm/day. As a result, a geotechnical and hydrogeological investigation program for the wall was initiated. The program included:

- The installation of additional prisms in key areas of the slope
- The installation of inclinometers in geotechnical boreholes throughout the slope
- The installation of multi-level vibrating wire piezometers in geotechnical boreholes

Figure 8 shows the location of the instruments installed during the investigation program. A failure surface was identified based on the inclinometer and prism results. The approximate location of the failure surface is shown on Figures 9 and 10. Behind the main part of the wall, the failure surface ran mostly along the contact zone between the bedrock and the overlying LSG material. Below the toe of the slope and the pit floor, the failure surface was about 70 m below ground.

The piezometer installations that were made as part of the remediation program are also shown on Figure 8. The piezometer results identified strong artesian pressures in bedrock below the failure surface, as shown in Figure 9 and 10. At the toe of the slope, the total head in the material immediately below the level of the failure surface was up to 35 m above the bench level. In the material above the failure surface, the total head was about 5 m below bench level. Input of the observed water levels into a limit equilibrium analysis identified that the high water levels were creating a very low factor of safety for the slope (analyzed at less than 1.1). Sensitivity analysis indicated the factor of safety could be significantly improved by lowering of the water pressures, particularly in the material immediately below the failure surface.
Figure 8. Map showing piezometers installed as part of the investigation program.

Figure 9. Geologic cross sections through 2C Zone 1.
The two zones (Zone 1 and Zone 2) were defined based on the on-going interpretation of the prism and inclinometer data, and observed cracking in the upper part of the slope and above the crest. The approximate area of movement is shown in Figure 11. While each zone had different movement vectors, the water pressure profile was similar for both zones. Therefore, the slope depressurization plan was similar for both zones.
6 Remediation plan

The results of the geotechnical analysis were used to develop a remediation plan for the slope. The remediation plan had three basic components, as follows:

- To repair cracking in the surface water diversion channel around the crest of the pit in order to reduce the possibility of surface water directly entering the upper slope materials
- To construct a buttress immediately north of the Zone 1 area to help stabilize the movement in the short term
- To carry out a pilot hole and production well drilling program to lower water pressures in the bedrock below the failure surface, and to gradually reduce water pressures in the overlying LSG material through the creation of a downward gradient in water pressure

Repairs to the diversion channel around the crest of the pit were initially achieved by using a temporary dam in the upstream channel and placing bypass lines above the main area of cracking. The remediation work is shown in Figure 12. The temporary measure provided immediate remediation for surface water infiltration while the movement and cracking was still occurring. More permanent repairs to the channel by infilling of the cracks and re-lining of the base of the channel were subsequently carried out following a reduction in the rate of movement and when the propagation of new cracks ceased.

![Figure 12. Remediation work for the surface water diversion channel above the crest of the slope.](image)

Drilling of pilot holes identified open fracturing with the potential for high yielding remediation wells in both the Zone 1 and Zone 2 areas. As a result, the progressive installation of five remediation wells was planned to achieve the required slope depressurization. The plan involved testing and evaluating each new well, and interactively adjusting the program based on the testing results. All five remediation wells were installed on the 3,588L step-out bench which was 24 m above the lowest Phase 2C pit floor level. The wells were constructed...
by drilling 20-inch diameter holes and installing 14-inch diameter casing and screen. The remediation wells were numbered LQPW-38 through 42. Their completion details are listed in Table 2. Their location is shown on Figure 13. Figure 14 shows the Phase 2C area and the East high wall, looking south. Figure 15 shows the Phase 2C area and the East high wall, looking north.

Table 1. Completion details of the LQ2C pilot holes and remediation wells.

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<tr>
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<th>Pozo</th>
<th>Prof.</th>
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Figure 13. Map showing location of pilot holes and remediation wells.
Figure 14. Photograph of the LQ2C area looking south, showing the buttress and remediation wells in the 3,588L bench.

Figure 15. Photograph of the LQ2C area looking north.
The buttress was constructed immediately to the north of the Zone 1 area and the area of the production wells using 2.1 million tons of waste rock material. The toe was placed on the 3,588L step out bench, with some overspill occurring to the bench below. The maximum height of the buttress was 44 m. The goal was to first use the buttress to help provide initial stabilization of the slope, then use depressurization to provide long term stabilization in the Zone 1 and Zone 2 areas to the south of the buttress.

7 Monitoring and results of remediation

The pumping hydrographs from the remediation wells are shown in Figure 16 for Zone 1 and Figure 17 for Zone 2. The individual yield of all wells was good. The combined pumping rate reached a maximum of about 100 l/s in Zone 1 and about 65 l/s in Zone 2. The water level response is shown on the same hydrograph. Up to 150 m of drawdown was achieved within a period of 2-3 months in Zone 1. A similar amount of drawdown was achieved within a similar period in Zone 2.

The wells produced all their ingress from zones of fracturing within the bedrock, within the interval from about 40-100 m below the level of the failure surface. Pumping from the bedrock reversed the upward total head gradient in the lower part of the failure, as planned. The result of this was a gradual drainage of the LSG material overlying the failure surface. A map showing the drawdown achieved in all piezometers is shown in Figure 18.

Progressive reduction in the inclinometer movements and slowing of the prisms was coincident with the progressive increase in drawdown, as shown in Figure 19 and 20. Following achievement of maximum of drawdown in each zone, movement rates in the prisms generally slowed to rates of 2 mm/day or less. There has been no significant increase in movement since the start of the depressurization program.

Figure 16. Hydrograph of pumping rate in Zone 1, plus piezometer hydrographs.
Figure 17. Hydrograph of pumping rate in Zone 2, plus piezometer hydrographs.

Figure 18. Map showing drawdown achieved as a result of pumping from the remediation wells.
Figure 19. Plots of inclinometer data showing reduction in movement rate.

Figure 20. Plots of prism data showing reduction in movement rate (LQ2C – Zone 2).
8 Conclusions

Slope depressurization was used as a successful method to help stabilize the East high wall of the La Quinua 2C pit. The program involved a detailed site investigation to characterize hydrogeological conditions, to determine the optimum method to stabilize the slope, and to set target levels for depressurization. The target levels were achieved by pumping from a total of five remedial wells. Pumping from the wells reduced the pore pressure on the failure surface by up to 1,500 Kpa (about 150 m head).