Challenges and Innovations in Large-Scale Excavation: Inverted-Method Tunnel under the Rimac River in Lima, Peru

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ABSTRACT: This paper presents a case study on the execution of a large-scale excavation and the construction of a tunnel using the Inverted Method (Cut and Cover) beneath the Rímac River in Lima, Peru. To enable the works, it was necessary to temporarily divert the river flow into a provisional channel approximately 10 meters deep, excavated in gravelly soil containing rounded boulders (bolones), characterized as a rocky conglomerate with variable behavior depending on its degree of saturation. The river diversion required the construction of a roller-compacted concrete (RCC) cofferdam and the reinforcement of existing bridges in the surrounding area. The tunnel, with a total length of 1.6 km, was successfully excavated under severe geotechnical conditions, representing a remarkable achievement of Peruvian and Brazilian civil engineering. After the completion of the excavation and installation of the permanent structures, the river flow was redirected to its original course. The paper describes the main stages and challenges of the project, highlighting the technical innovations and mitigation strategies adopted to ensure the stability, safety, and performance of the structure. Finally, it emphasizes the importance of integration between design, geotechnical modeling, and construction supervision, which proved fundamental to the success of tunnels executed in complex fluvial environments.

1 INTRODUCTION

To reduce the recurring traffic congestion in downtown Lima and expand the capacity of the city's road network, a new road complex was designed, whose main structure consists of a tunnel approximately 1,600 meters long, built mostly beneath the Rímac River (Figure 1).

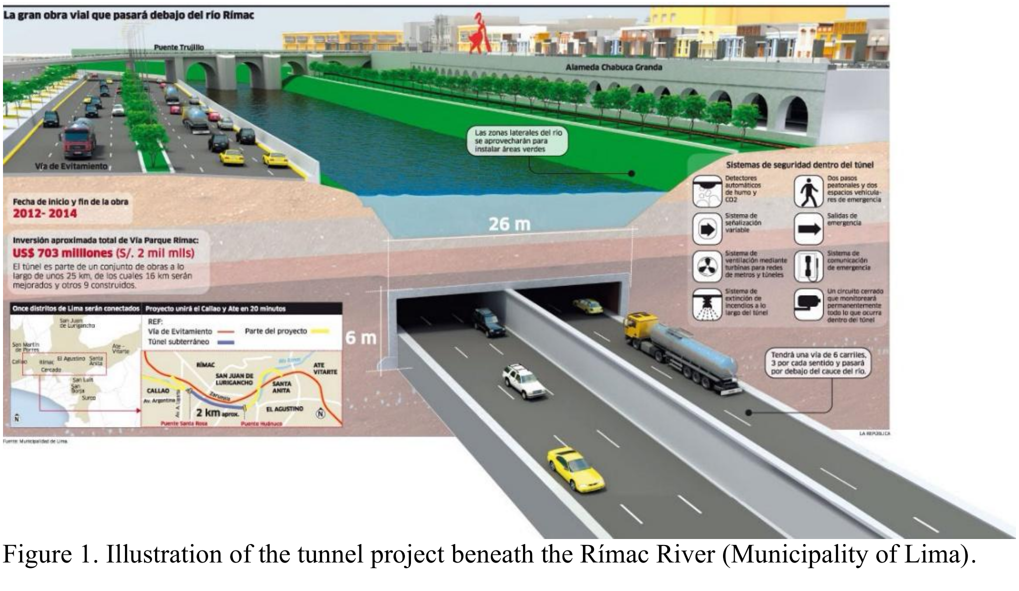

Figure 1. Illustration of the tunnel project beneath the Rímac River (Municipality of Lima).

The project concept was based on the temporary diversion of the river's total flow during the dry season, redirecting it through a provisional channel partially excavated along the right bank of the riverbed. This solution made it possible to construct the tunnel using the Cut and Cover method, under dry-bed conditions.

The main engineering challenge consisted of constructing a 1.6 km tunnel beneath the Rímac River, combined with the execution of foundation works for the viaducts located within the riverbed area.

GeoCompany was responsible for the Construction Technical Supervision (ATO), Project Quality Control (CQP), and for the complementation and adjustment of the executive design.

Among the most significant geotechnical challenges was the characterization and understanding of the local sandy–silty conglomerate, a complex material whose strength and deformability vary significantly with the degree of saturation. Mastering this behavior was crucial to the successful execution and structural safety of the project.

2 LOCAL GEOLOGY

In the area where the project was implemented, the Rímac River crosses Quaternary fluvial deposits, composed predominantly of a conglomerate consisting of rock blocks of variable sizes — generally ranging from 0.15 m to 0.40 m — of igneous or volcanic origin, mainly granitic and andesitic. These blocks are embedded in a sandy–silty matrix, brown to light-brown in color, with occasional interbedded sandy or sandy–silty layers.

Figure 2. Details of the conglomerate found in the excavation area.

2.1 *Geological and Geotechnical Investigations*

Extensive geological and geotechnical field and laboratory investigations were carried out throughout the project area.

As an example, a grain-size distribution analysis of a soil sample indicated 73.2% gravel, 24.9% sand, and 1.9% fines, in material collected at approximately 1.8 meters depth.

CBR (California Bearing Ratio) tests yielded values of 75.0% (for 100% M.D.S.) and 42.0% (for 95% M.D.S.). The maximum dry density obtained was 2.211 g/cm³, and the optimum moisture content was 5.6%.

The borehole drilling campaigns reached depths ranging from 20 m to 50 m, confirming the persistence of the same geological horizon, with only variation in the degree of compaction with depth. The uppermost meter of the profile generally presented a higher concentration of coarse gravel and boulders, along with lenses of less compact sand.

The strength parameters (cohesion and friction angle) were determined from triaxial compression tests performed on samples collected from the Rímac River bed and tested at the Geotechnical Laboratory of the National University of Engineering in Lima (Peru). The results indicated an internal friction angle of 44° and zero cohesion. In-situ permeability tests yielded an average hydraulic conductivity of $K = 8\times10^{-3}$ cm/s.

The laboratory test results showed significantly lower cohesion and friction angle values compared with the behavior observed in the field and were therefore considered incompatible with the actual excavation conditions. This discrepancy was attributed to the difficulty in reproducing, under laboratory conditions, the natural structure of the local soil—a heterogeneous conglomerate of poorly graded rounded boulders, naturally cemented within a sandy or sandy–silty matrix under a certain degree of compaction. The sampling and remolding process disrupted this natural cementation, leading to reduced strength values.

To obtain a more representative assessment of in situ conditions, large-scale direct shear tests were carried out in excavations of approximately 2.0 m × 3.0 m, using central blocks measuring 0.60 m × 0.60 m × 0.40 m. The vertical reaction was applied through a steel beam anchored by vertical tie rods, while the horizontal load was imposed using a hydraulic jack with progressive load increments, monitored by micrometers and vibrating-wire sensors.

Three tests were performed, varying the vertical stress between 0.5, 1.0, and 1.5 kgf/cm². The shear stress–strain curves were obtained up to failure, allowing the determination of the strength parameters of the conglomerate.

The average field results indicated cohesion values ranging from 16.2 to 60.3 kN/m² and an internal friction angle between 35° and 39.4°.

Given the heterogeneity of the rock mass and the high-risk nature of the work, the design parameters adopted were as follows:

Table 1. Material parameters after field investigation.

Material	γ (kN/m³)	c (kN/m²)	φ (°)	E (MPa)
Loose sand and gravel	20,0	1,73	28,69	80
Dense sandy conglomerate	21,5	8,69	32,17	200

3 CONSTRUCTION METHODOLOGY

3.1 *Construction of the River Diversion Dikes*

The execution of the tunnel required the temporary diversion of the Rímac River into a provisional channel, allowing excavation works to be carried out under dry-bed conditions.

Two main dikes were constructed, each with its respective spillway, designed by GeoCompany with the objective of fully diverting the river flow during the dry season. The dikes were built using roller-compacted concrete (RCC), with masonry stone facing and cyclopean concrete sections.

During the flood season, the system allowed excess discharges — greater than 200 m³/s — to flow in a controlled manner through the natural riverbed, without compromising the already constructed structures.

The upstream dike also served to retain rock blocks transported by the current, requiring periodic cleaning to maintain its efficiency. The diversion dike, in turn, was responsible for distributing the flow between the provisional channel and the natural riverbed, depending on the discharge regime.

Figures below illustrate the diversion dikes (a) and the flow partition structure (b).

Figure 3. (a) Diversion channel constructed for the works and (b) diversion dike directing the river flow.

These structures were designed to withstand the transient conditions of the construction period, minimizing the need for reconstruction after the rainy season and ensuring the safety of subsequent excavation works.

3.2 *Slope Excavation*

For the slopes, which reached an approximate height of 14 meters, different stabilization alternatives were evaluated, and the solution adopted consisted of soil nailing, combined with active (tieback) and passive (self-drilling) anchors.

The stability analyses were performed using partial safety factors, and the factor of safety was determined by the limit equilibrium method with the GEOSLOPE software, employing the Bishop (1955) and Janbu (1955) methods.

The initial stabilization system consisted of a 17 cm-thick shotcrete layer, reinforced with two layers of steel mesh, associated with passive anchors arranged in a variable grid (1.5 to 3.0 m horizontally and 2.0 m vertically).

The anchors, ranging in length from 5.7 m to 18.7 m, were executed using 3-inch self-drilling steel bars equipped with tungsten bits.

Since passive anchors rely on mass deformation to mobilize resistance, the behavior of nearby buildings was assessed through finite element numerical modeling (PLAXIS 2D), in order to limit deformations and prevent structural damage.

In sections where the predicted deformations exceeded acceptable limits, active anchors (tiebacks) were employed.

Seismic effects were considered in the design, adopting a design acceleration of 0.31 g, corresponding to a return period of 200 years.

The excavation cycle of the trench for the installation of the tunnel modules was continuously adjusted by the Construction Technical Supervision (ATO), based on topographic monitoring data and field performance observations.

The typical excavation procedure comprised the following steps:

1. Excavation of the conglomerate to the elevation of the anchor line installation, in 100 to 200 m-long sections, depending on soil type and equipment capacity;
2. Initial application of shotcrete, with thickness ranging from 2 to 5 cm;
3. Topographic marking of drill holes for the installation of drains and anchors (average productivity: 100 m/hour);
4. Drilling of anchors and installation of the first layer of steel mesh;
5. Application of a new shotcrete layer, 6 to 10 cm thick (average output: 7 m^3 every 30 minutes);
6. Installation of the second mesh and execution of the final shotcrete layer (with a curing period of approximately 8 hours);
7. Execution of anchor heads, installation of steel plates, application of torque, and full load mobilization.

Although the laboratory cohesion values were relatively low, the slopes remained stable during excavation, showing only slight wind erosion over time. This stability was attributed to the natural cementation of the sandy matrix of the conglomerate and the presence of apparent cohesion.

Given that Lima has an arid climate with almost no rainfall, the absence of infiltration further contributed to slope stability.

Excavations were initially performed in staggered niches, which were progressively widened as the favorable behavior of the ground was confirmed, based on high-precision topographic monitoring.

Based on these observations, the ATO optimized the production cycle, achieving significant productivity gains and enhanced safety during construction.

Figure 4. View of the slope excavation along the construction site.

3.3 *Tunnel*

The construction of the tunnel, approximately 1.6 km in length, adopted the Cut and Cover method, involving open-trench excavation along the bed of the Rímac River, with an approximate cross-section width of 40 meters.

The tunnel was designed with three traffic lanes in each direction, using precast concrete modules combined with in situ cast elements.

To enable the excavations, the river flow was diverted through a temporary reinforced-concrete channel, allowing the work to be carried out under dry-bed conditions.

The river's discharge regime represented one of the main challenges: during the dry season (April to November), average flow rates varied between 20 and 38 m^3/s, but could exceed 200 m^3/s during floods resulting from rainfall and Andean snowmelt.

Accordingly, orthogonal dikes were designed across the riverbed to direct the flow toward the temporary channel (with a capacity of 80 m^3/s), allowing excess flows during peak floods to pass through the natural riverbed, which was protected by the planned retaining structures.

After the completion of excavation and installation of the precast modules, the reinforced concrete raft slab was executed, followed by waterproofing and recomposition of the natural riverbed, restoring the river flow over the tunnel without any noticeable visual or environmental impact.

The tunnel connects to the local marginal roads, which were expanded through the construction of modern viaducts, thereby optimizing urban traffic.

The construction process began with the compaction of the sub-base layer, followed by the execution of an in situ concrete leveling base, waterproofing, reinforcement installation, and casting of the bottom slab.

Subsequently, the precast modules with the lateral walls were assembled in sequence.

The roof slab was built using precast concrete beams and an in situ cast deck, integrated with the external walls and encased within the waterproofing system.

Upon completion, a compacted backfill layer treated against erosion was placed above the slab, restoring the riverbed and reestablishing the normal water flow over the tunnel.

Figure 5. Construction stages of the tunnel, illustrating the final excavation, execution of the bottom slab, lateral walls, and roof beams.

3.4 *Execution of Viaduct Foundations*

During construction, interferences were identified with existing bridges founded on shallow foundations, including a century-old masonry arch bridge of historical significance.

In such cases, reinforcement and underpinning solutions were developed using reinforced concrete micropiles, supported by special foundation blocks individually designed for each pier, ensuring the preservation of the existing structures.

The Construction Technical Supervision (ATO) was responsible for the approval and technical supervision of both shallow and deep foundations associated with approximately ten viaducts forming part of the road complex.

It was verified that some footings were located within the Rímac River bed; considering the erosion studies, local geology, and peak discharge conditions, the ATO recommended replacing them with deep foundations.

Accordingly, groups of bored piles were designed beneath pile caps, protected by steel casing tubes of varying diameters (typically 1.50 m) and depths of up to 20 m.

After an initial learning phase, an average production rate of 20 meters per shift was achieved, even under adverse conditions imposed by the conglomerate's rock blocks.

The introduction of modern cutting and crushing tools, combined with the use of hydraulic clamps for the simultaneous driving of casing tubes, substantially increased the efficiency of the process.

The foundation approval process conducted by the ATO was based on the verification of load-bearing capacity and deformability of the local soil. Continuous core drilling, seismic tests, and DPL (Dynamic Probing Light) tests were performed and interpreted jointly to define the continuity and strength of the subsurface materials.

The responsible geotechnical engineer carried out direct inspections at the foundation level, complemented by small exploratory excavations to validate field data.

When necessary, adjustments to foundation elevations or alternative solutions were proposed, such as the use of micropiles or reinforced pile caps, ensuring the adaptation of the design to actual ground conditions.

The following figure illustrates an example of an executed footing.

Figure 6. Tunnel construction beneath the historic stone bridge.

4 CONCLUSION

The experience described demonstrates that large-scale projects executed in complex geological and geotechnical contexts—such as the heterogeneous sandy conglomerate of the Rímac River—require robust characterization, careful modeling, and constant verification of design assumptions.

The success of construction depends directly on the integration between design and execution, supported by a continuous cycle of technical feedback.

The systematic role of the Construction Technical Supervision (ATO) was decisive for the performance achieved, combining large-scale testing, high-precision topographic monitoring, and dynamic adjustments to the construction methodology, such as the optimization of drilling fluids and the adaptation of the support cycle.

These actions made it possible to control deformations, reduce nonconformities, and maintain productivity, even under adverse conditions.

In summary, the experience confirms that daily technical governance, combined with the capacity for adaptation based on field evidence, is an essential requirement to overcome operational challenges and to achieve the expected levels of safety, efficiency, and performance in high-complexity engineering works.

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