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WOC3-3B Integrity of gas transmission systems

SLOPE STABILIZATION FOR THE CAMISEA GAS PIPELINE SYSTEM USING FOUNDATION STRUCTURES BASED ON DEEP PILES IN SOFT SOIL

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ABSTRACT

The experience obtained during the operational and maintenance stage of the CAMISEA Pipeline Transportation System (SDT in Spanish), property of TGP in Peru, which extends 729 Kms from the Tropical Jungle in the province of Cusco to the Coast of Lima through a pipe that transports natural gas, has allowed for the evolution and optimization of the design, construction and maintenance processes that focus on the stabilization of the slopes in the right of way (ROW) through which pipelines transport NG and LNG. The NG pipeline has a length of 557 Km and the LNG pipeline has a length of 729Km including a 105 Km loop.

The soils of the Peruvian rainforest are susceptible to landslides, most of which are triggered by water. In order to control this mass removal process, structures have been designed and built to withstand rainfalls of 270 mm in 12 hours and a yearly accumulated amount of more than 6 500 mm/year. There are two very distinct seasons: a rainy period between October and April and a dry period between April and October. In addition, landfills created during the construction period over soft soils along the first 210 Km, variable gradient slopes and altitude changes in short stretches, are become true engineering challenges that need to be overcome to ensure the geotechnical stability of the pipeline system.

Another challenge we face is the difficulty of access to the maintenance areas, because they can only be reached by helicopter. This reduces solutions to just a few choices for the building of retaining walls, including gabion walls (bags filled with soil/cement or stone), reinforced soil wall, piles of steel or a combination of these alternatives. They are usually employed along with works that focus on an efficient management of runoff and subsurface flow (like French filters, geo-drainages filters, drainage trenches, collect channels, etc.).

The instability problems usually occur on the side dumps created during the construction phase of the pipeline system – usually made of non-consolidated soil. These dumps, as mentioned above, are characterized by thicknesses sometimes of 6 m or 8 m, and require removing large amounts of

ground material to find the competent soil or the rock layer where the foundations of the retaining structure can be built.

The process of stabilization jobs goes from design through construction and comprises the following steps:

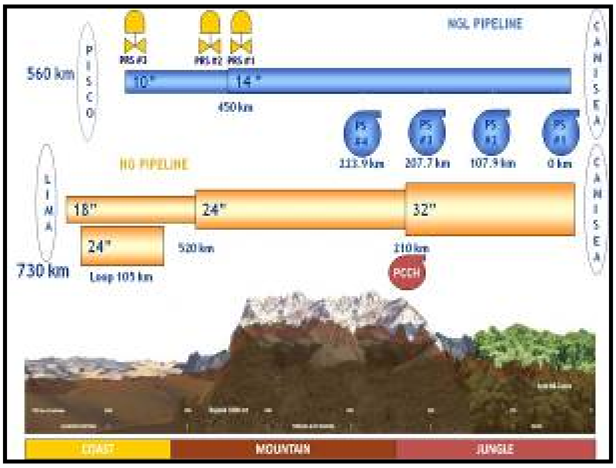
- Detailed topography of areas under study.
- Verification of whether the pipeline is affected by the removal of ground material.
- Analysis of pipelines integrity.
- Study of soil.
- Modeling and stability analysis using Slide 5.0 for the initial conditions.
- Definition of possible work alternatives.
- Modeling and stability analysis for actual conditions of proposed jobs.
- Verification of internal stability of the works.
- Election of the best alternative (technically, environmentally and economically speaking).
- Construction.
- Post-construction work monitoring.

The great difficulties of making large earthworks and excavations to find competent strata for the foundations of conventional structures (gabion walls/concrete walls), as well as the environmental impacts in the Amazon region and the deadlines imposed by the rainy period of the year (stabilization jobs are performed in the dry season), an innovative alternative was considered, suitable for remote sites: piles founded in competent soil, traditionally successfully applied in soft grounds, combined with retaining structures (gabion walls /reinforced soil). Soil studies and slope stability analysis are performed to ensure its applicability on a case-by-case basis.

One of the major innovations of this slope stabilization system on soft soil is the effect and soil densification process by pile driving. This soil-pile system becomes a treatment for the optimization of the mechanical conditions of soils, resulting in a reliable and environmentally viable retaining structure.

1 BACKGROUND

The Camisea Pipeline Conveying System consists of two parallel pipelines: the first one carries natural gas (NG; 730 km) and the second one carries liquid natural gas (LNG; 560 km). The system starts in Malvinas (Cusco) in the Amazon basin and, whilst the LNG pipe finishes at Lobería beach (Ica region); the NG pipe ends at the City Gate located in Lurín (a suburb of Lima).



The geographical, geological and atmospheric characteristics of the territory crossed by the pipeline (rainforests, highlands and coastal desert) make it different from other pipelines in the world in terms of complexity. Its highest point reaches 4 860 m. above sea level in the Peruvian Andes.

The first 200 km are the most challenging for the operation, as they are located on waste soft ground, with gradients of more than 45°, exposed to rainfall over 6.000 mm a year, apart from the logistics problem of no road access for the transport of personnel, materials and equipment – so that maintenance activities are done by helicopter.

The piping is designed to withstand low longitudinal stress due to pressure and movement caused by thermal stress. These stresses almost reach – but rarely exceed – the limits established by ASME B31.4 and ASME B31.8 about ***54 per cent of the Specified Minimum Yield Strength*** (SMYS) for longitudinal stress. Additionally, the slight elastic curvature imposed by the installation of a pipeline inside an imperfect trench, rarely concerns the involved people. These “ordinary” longitudinal stresses are not considered a problem in stable grounds where no extreme cycles are involved. On the other side, wherever there is significant ground movement of failure, the existing stresses can become as high as to lead to piping failure. In such areas, permanent supervision of the pipeline to prevent failure is necessary.

In most cases, as knowledge and experience about the types and characteristics of soil involved in the path of the pipeline increase thanks to a committed and constant supervision, deep technical studies and analysis of soils, early intervention and forecast can prevent problems related to mass removal.

Though, in geographically and geologically complex soils, extraordinary and unexpected events can occur, leading to pipeline failure. This is the case of the Camisea pipeline system in Peru.

When the main risk in a pipeline system is associated with ground, a strategy of ground control must be designed to minimize that risk and, if necessary, perform slope stabilization works. To do so, it is necessary to use a time- and resource-saving technology suitable to local geography and restriction of access, such as retaining structures founded on piles – which is addressed in this paper.

2 AIMS

The main aim of this paper is to present and disseminate the successful experience in slope stabilization based on retaining structures founded on piles that the Camisea pipeline system has acquired.

In its first 200 km, located in the middle of the Amazon Jungle, this pipeline faces logistical challenges, such as the absence of road access to the right of way (ROW), and a time frame limited to the dry season between April and October. So, this technology represents a new approach in pipeline systems.

The implementation process of this technology, including design, construction and monitoring is illustrated with examples.

3 METHODS

3.1 Topographic, geological and geotechnical characteristics of the Camisea pipe system in the rainforest.

3.1.1 Topography

- *Slight/mild gradient terrain:* Undulate plains, divided alluvial terraces, lower undulate hills, undulate slight gradient hills and rounded hills.

- *Mild gradient terrain:* Mild gradient slopes, ample slopes, low divided and cliffy hills, alluvial “V” valleys.

- *High/very high gradient terrain:* Cliffy high gradient slopes, alluvial slopes (slope deposits), high long narrow hills, long cliffy top lines. These kinds of terrain cover the remaining 75 % of the corridor. Long cliffy top lines and high long narrow hills are among the most challenging.

3.1.2 Geological and geotechnical characteristics

From a geological point of view, the entire section located in the Jungle is on a soft rock substrate which correspond to low durability – or high degradability – materials in the typology of rock mechanics for tropical ground.

Durability characteristics mentioned above are related to the behavior of rocks facing weathering agents, in particular moistening or saturation and drying cycles that are typical of alternate rainy and dry seasons in tropical territories. Once exposed to the atmosphere, as they are during the construction process, these materials rapidly debase and lose shear-resistance or get divided into their stratification layers or in its diaclases (discontinuity of the rocky mass), become fragmented and can finally collapse.

The cover over the rocks present in the Jungle stretch predominantly consists of a low density mixture of silt, sand and gravel. These materials easily and highly become eroded, depending on the gradient – frequently deep, as mentioned.

It is important to point out that the presence of side stocks in the juLNGe section, where fine and cohesive soils are predominant. These features determine the mechanical behavior of soils – mainly instability caused by water saturation.

3.2 Typical geotechnical problems affecting the Camisea pipeline system in the rainforest

Among identification of factors triggering mass removal in the underground, the various geo-shapes are outstanding. So, it becomes particularly critical being able to distinguish along slopes, depressions or concavities followed by protrusions or bulges on the terrain, escarpments or scratches, mainly caused by water saturation. Saturation and gravity are the most important factors regarding the said geo-shapes because saturation leads to loss of shear strength and, when volume and weight of soils increase, the potential for landslides also increase.

In connection to the above mentioned, besides managing the control of water run-off during maintenance jobs, the geotechnical area also identifies and takes remedial actions for movements of masses, such as: rotational, translational, multiple and complex slides, land flows, slides, etc. D. J. Varner's Slope Fault Movement Classification System (1978) is applied in the project. To identify and describe the cases in a clearer manner, the system is complemented with Skempton and Hutchinson's (1969) system. That classification process is performed first by visually inspecting the ROW in detail. Continuous surveillance teams are implemented; they travel all along the pipeline in its Jungle section during the rainy season. Figure 3-1 graphically shows the main types of slides that occur at the Camisea pipeline system.

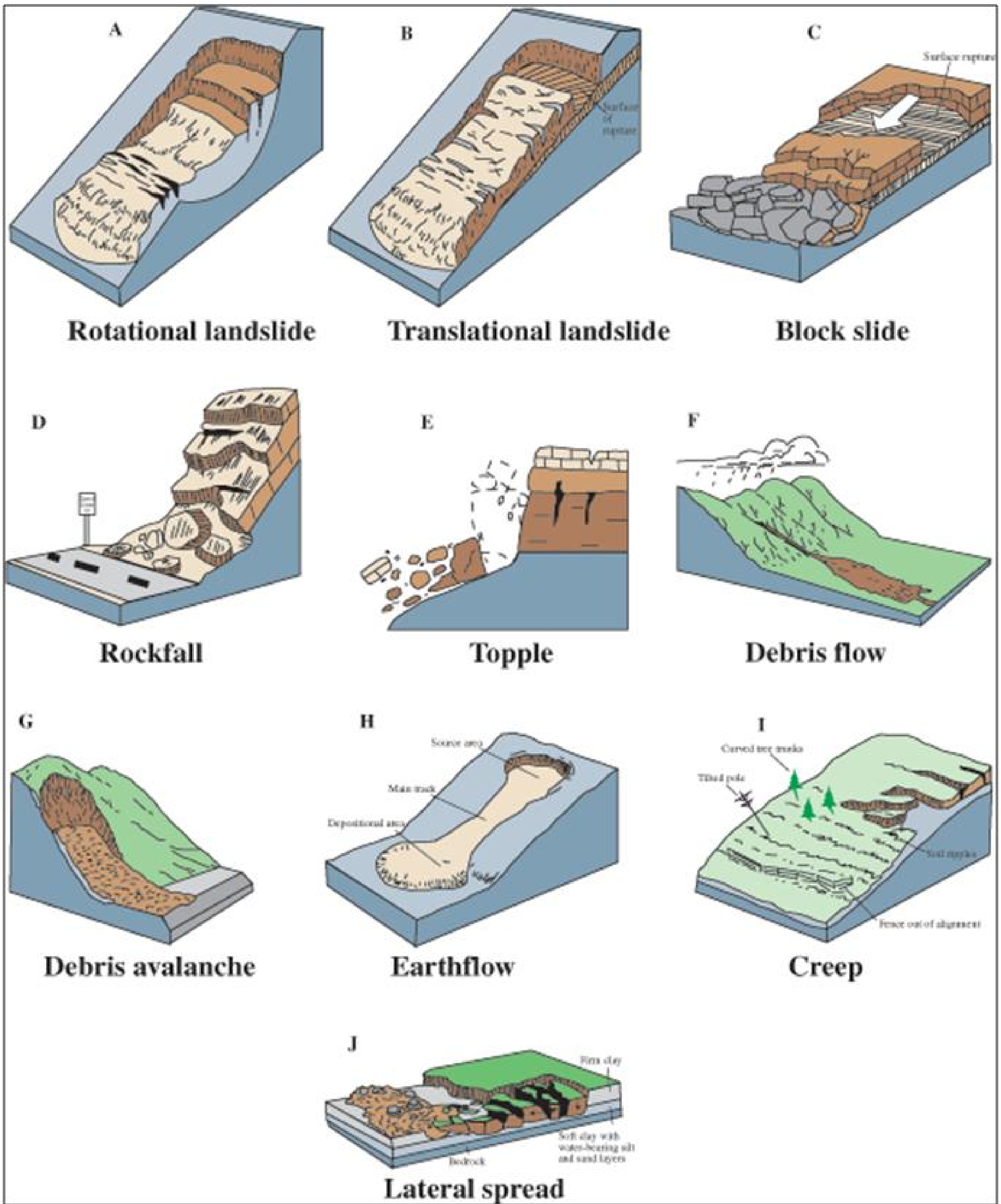


Figure 3-1 – Frequent types fault slope fault movements[1]

Among the causes of the processes of mass removal on the pipeline system, the following must be considered:

- The mount topography of the Andes.
- Soil where particle rearrangement is constantly taking place due to seismic activity.
- Presence of material stocks in simple display, created during the construction phase.
- As a consequence of the latter, soils have low shear strength parameters.

[1] *(Varnes, 1978) Prepared on the base of: Varnes, David J,. 1978; "Slope Movement Types and Processes", Chap. 2, Schuster R. L.&y Krizek R. J., editors, 1978, "Landslides Analysis and Control". Special Report , 176. Transportation Research Board. National Academy of Sciences, Washington, D.C.*

- Geologically young tropical soils, easily debased when in contact with water and during earthquakes, in addition to loss of deforestation – where forests are crucial to soil stability in extremely erodible soils.
- Heavy rainfall in a relatively short period of time (November – April), typical in the rainforest area, speeds up processes.
- There are rocky masses showing different degrees of alteration and meteorization.
- The hydraulic behavior of basins has changed by the presence of the ROW, because the replacement of native plant species by imported grass has changed the run-off patterns.

3.3 Management system for the assurance of geotechnical stability

In order to assure the geotechnical stability of the ROW and the pipeline, a management system has been developed to identify geotechnical problems and to take repair, maintenance and monitoring actions on a preventative and early treatment approach, thus reducing their critical level. The main elements of the system are the following:

3.3.1 Threat identification system

It consists of a continuous surveillance of the ROW in order to identify geotechnical problems mainly triggered by rainfall - cracks on the ROW, bulging, escarpments, drainage blocking (detected when the out coming water amount decreases noticeably), dislocation of cutoff drainages (water collecting ditches transversely arranged) and of longitudinal canals, increase of erosion processes on the relief outlets of the ditches, erosion at river crossings, etc. The information collected by the surveillance groups is then classified and sorted to assess the risks. On the other side, this information is greatly worthy and valuable to gather knowledge on how the built structures have been behaving the over the past seasons.

3.3.2 Risk assessment

A risk matrix is applied to prioritize and decide where to start geotechnical remedial jobs. This matrix helps in sorting geotechnical works establishing how critical they are. The methodology consists of the evaluation of the geo-integrity parameters along with the probability of failure using an in-field analysis, as well as establishing the severity of the failure that is likely to occur. Finally, the risk of the failure is assessed on a *semi*-quantitative basis.

3.3.3 Design of works

A priority table and the concerned design engineering work are preformed according to the risk levels, using geotechnical tools such: underground exploration, laboratory testing, mathematical modeling and instrumentation.

3.3.4 Execution of works

The execution of the geotechnical stabilization works are performed on a yearly basis during the dry season (between April and October).

3.3.5 Monitoring and surveillance

Once the dry season is over and the stabilization works are completed, a continuous monitoring is performed during the rainy period of the year (November-April), conducting permanent inspections, topographic monitoring and instruments located at key spots (inclinometers, piezometers and strain gages).

3.4 Design of geotechnical works

The ground where the pipeline was installed essentially consists of non-rigid materials and must rather be considered, at a certain degree, flexible materials. On the slopes, the soils are known to be creeping – an extremely slow flow that occurs at rates between 1 and 6 cm a year in the northern hemisphere mild-weather regions, and between 1 and 10 cm a year in tropical regions as that where the first stretch of the Camisea pipeline is located.

Rigid structures – such as rebar concrete retaining walls – rarely endure undamaged under the said conditions (crack or collapse are common). Gabion walls or rock counterbalance structures must then be used as they are more tolerant to deformations. Both the fill of the gabion walls and the rock reinforcements are frequently replaced with bags filled with soil/cement, as durable strong rocks are scarcely found in the region. This type of structure is flexible and tolerates noticeable deformations, compatible with pushes and deformations of the ground which supports the structure or of the contained/retained soil.

Under such environmental conditions, the key criteria concerning maximum push or displacement are to minimize ground movement to reach an amount of efforts and deformations that the pipeline can tolerate within proper safety ranges. So, following structures are built to meet those criteria:

- Undersurface drainage, including synthetic geo-drainage filters, at depths between 2 and 3 m, or at least to the deepest point of the duct. Concerning deep drainage, draining trenches have been introduced and excavated using excavators, these can be brought to depth of 4 and 5 m – in any case, above 3 or 3,5 m. Where piezometers have been installed, trenches are installed at depths determined by the water table established by these instruments.
- Surface drainage systems: cut-offs, collecting canals, outlets, canalization of natural water streams.
- Energy dissipation systems in torrent beds crossing the area or in the lower part of it.
- Laminar erosion is controlled using structures such as trenches or crossed wooden dams, bags with soil/cement or rock fill.
- Deepening of river beds that cross the ROW or that are natural drainages in the critical area. This favorably accounts – sometimes even surprising – for the reduction of the level of the water table in the long run.
- Reduce to the minimum possible the displacement of the ground by means of discharge terracing at the top of the displacement; installation of drainage systems and retention/containment works.
- Construction of counterbalance stocks at the bottom of slopes which have already shown rotational/translational fault surfaces.
- Reduce the overload caused by refill noticeable thicknesses that lead to the consolidation of soft founding soils - and to the resulting settlement of the ROW, which can on its turn lead to vertical deformation of the pipes – by removing proper or practical thicknesses of materials. These thicknesses depend on the calculated magnitude of the required pressure relief, on the topography of the area, on the density of soils and of the availability of areas suitable for permanent disposal of these remaining materials.
- Retaining/containment structures of various types, as gabion walls of soil/cement, walls of reinforced soil, gabion walls deeply founded on piles – driven into competent strata.
- Revegetation of slopes by natural means helped by using geosynthetic materials and biosheets.

In order to design the works above described – once decided which ones are to be built according to the prioritization and the risk matrix – a normal geotechnical engineering processing is conducted with some important variations due to the complexity of the solutions that must be adopted in relation with available logistics.

In this paper we will focus on the retaining/containment structures founded on piles.

3.5 Design process for retaining structures founded on piles

In the rainforest region there are many areas like side stocks and slopes near the ROW with heavy gradient where landslides occur due to heavy rainfall. In this region, competent soils are commonly found at depths of 5 m or more. Therefore, it is important to implement deeply founded structures (piles) that can guarantee the stability of the work, by transferring the loads of the retaining/containment wall to the most adequate layer in the underground (rock) – given the impossibility to use conventional containment structures due to the magnitude of the slides, the environmental and logistical restrictions, and the need to keep integrity of the pipeline.

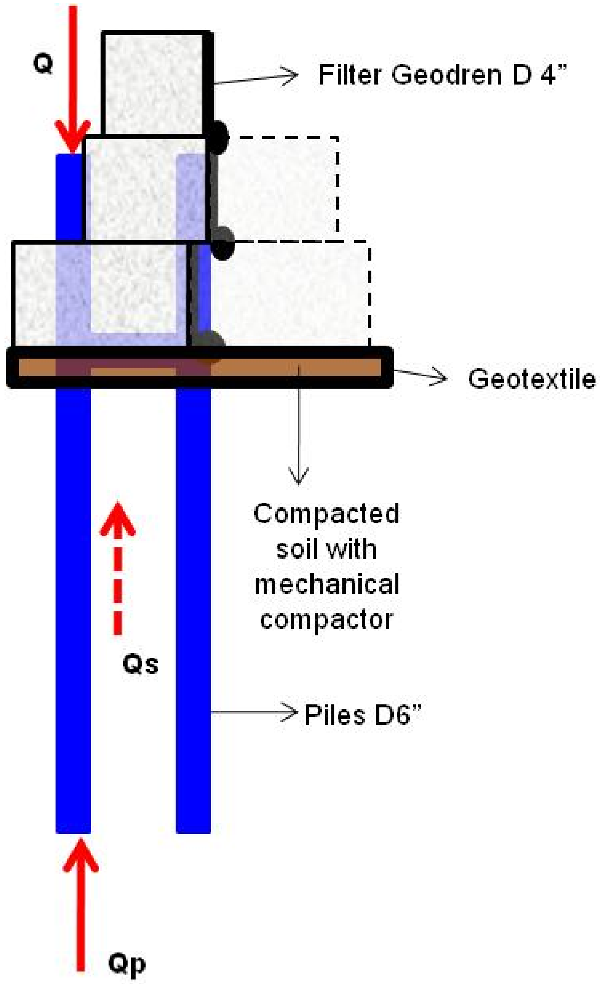


Figure 3-2 – Retaining structure (gabions) founded on driven steel piles

This system is used either as a part of a slope stabilization work or as an alternative to isolate a backwards slide heading the pipeline area. The choice will depend on the characteristics of each work area.

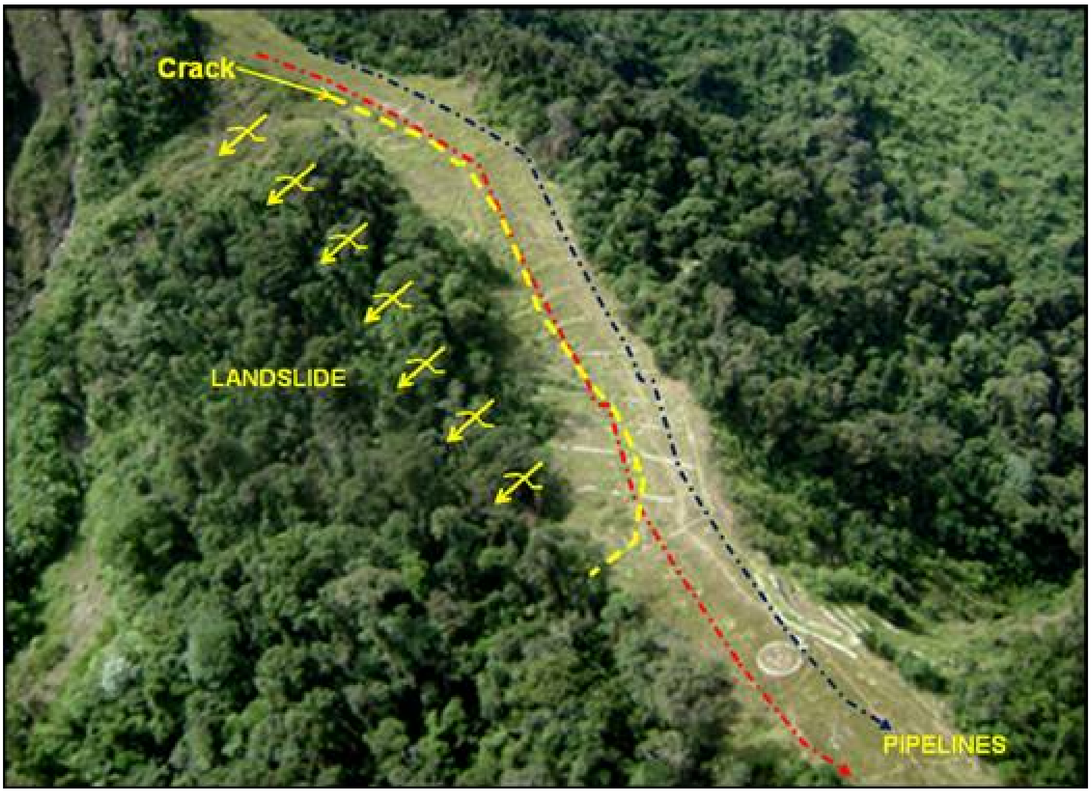


Figure 3-3 – An example of a landslide on a slope at the ROW

Each of the activities performed for the design of the retaining walls founded on piles is now described.

3.5.1 Topographic survey

A topographic survey is conducted not only to map cracks, escarpments and other indicators of geotechnical instability but also (and in accordance to the characterization of movements) to establish that the moving ground mass can involve any of both pipelines – or if there is no certainty that any of them has been reach by the movement.

As part of the job, the pipeline is first found in the field, using the *as-built* dr awings or the construction register. Then, in-site exploratory testing pits are practiced to certainly establish the precise location and the depth to which the pipeline is buried.

The topographic survey is also necessary to establish the critical profiles later used for finite-element modeling and to set the limit balance under both current conditions and after works completion, in order to validate the stability of the latter.

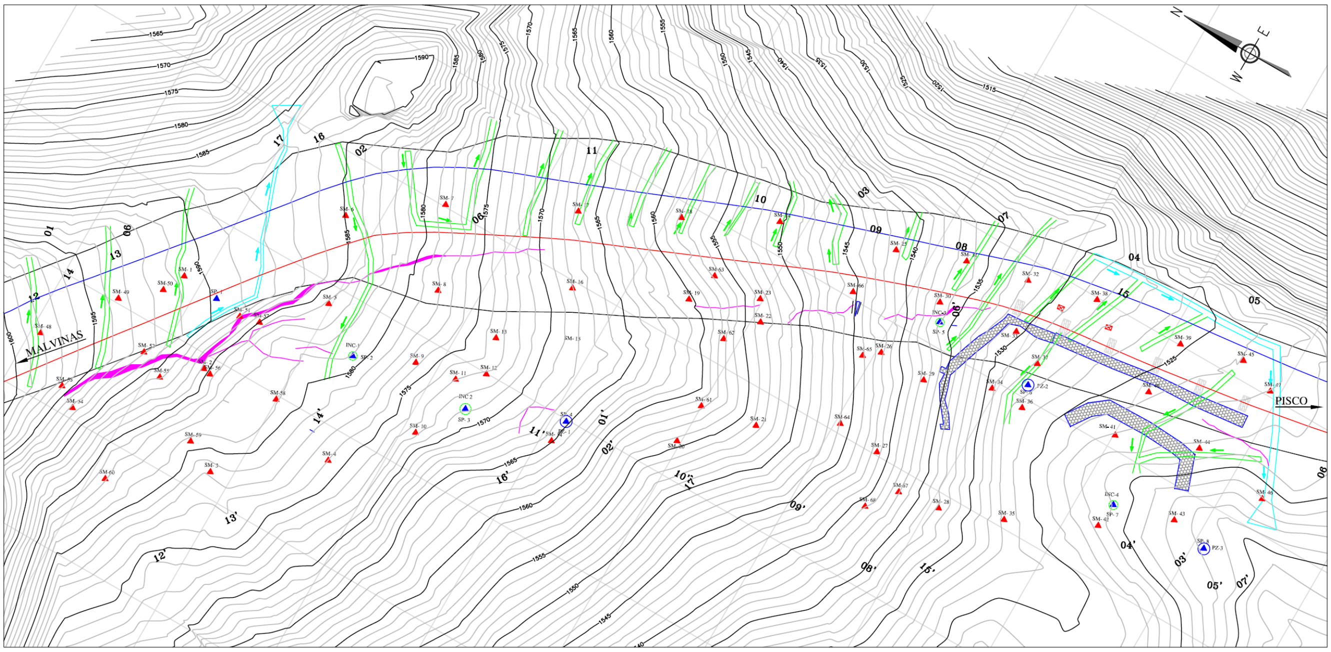


Figure 3-4 – Topographic survey of the area and location of SPT points

3.5.2 Exploration of the underground

The exploration of the underground - SPT (Standard Penetration Testing) - is performed along with the topographic survey; for the SPT samples of soils are analyzed in the soil mechanics lab at the base of COGA in the Jungle.

The stratographic profiles of the area under study are obtained from the exploration and the SPT testing, while the soil strength parameters (friction angle and cohesion) are taken from the laboratory.

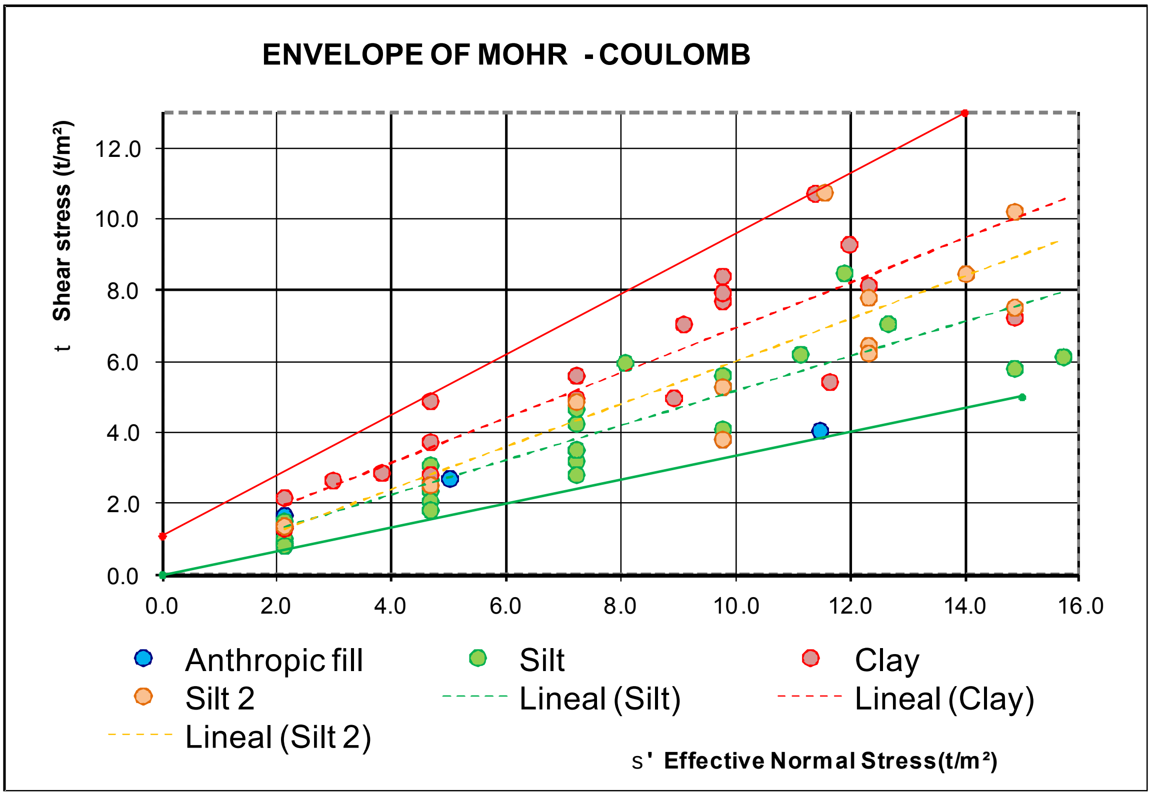


Figure 3-5 - Ratio of SPT testing

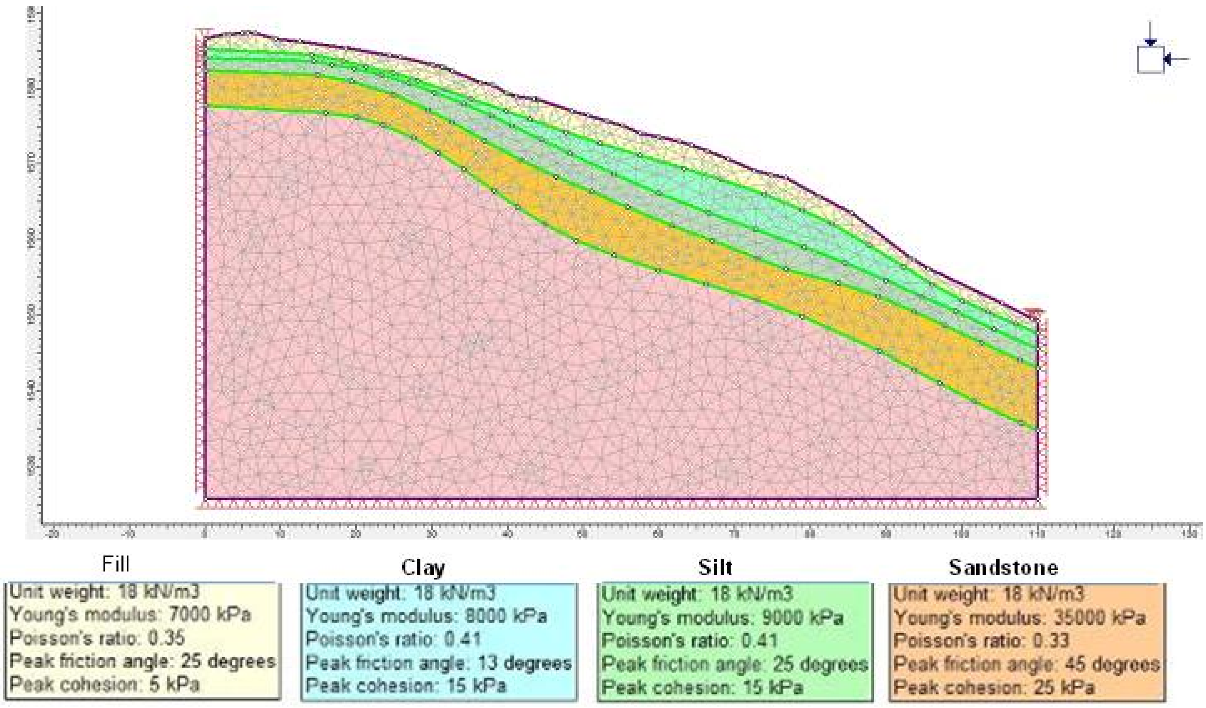


Figure 3-6 – Stratographic profile of the slope used for modeling by means of a finite elements software

3.5.3 Stability analysis of slopes and design calculations

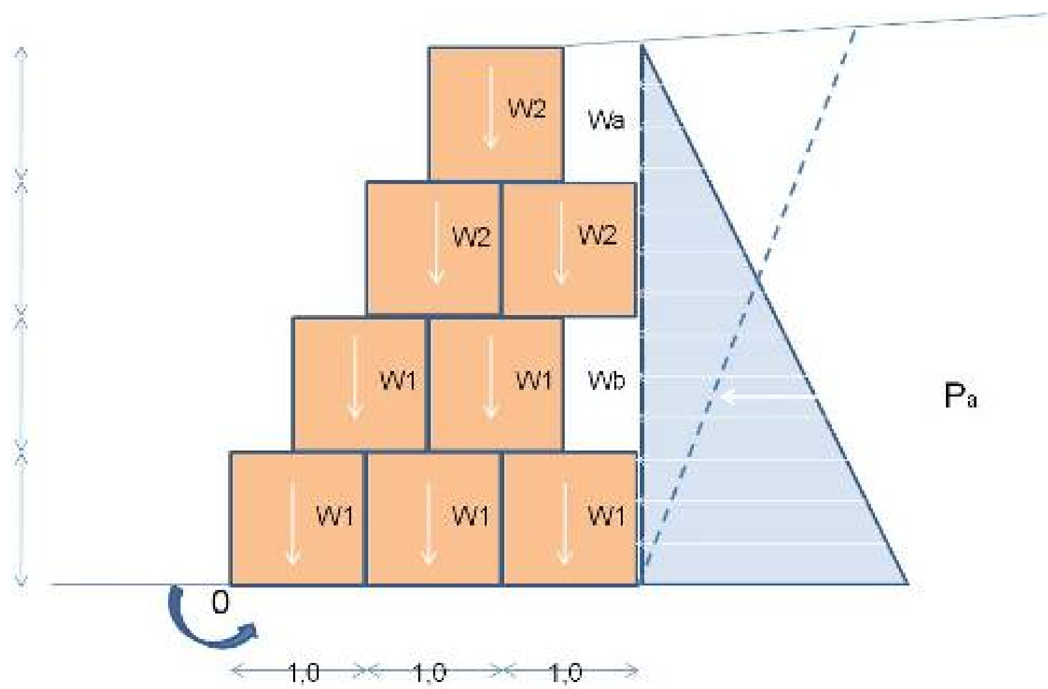
Strengths of acknowledged soils (internal friction angle and cohesion) are calculated using laboratory tests and data from the pipeline. Then, the most critical sections in terms of gradient and thickness of soft materials are used to calibrate and define the mathematical models and obtain the safety factors for the slope with the designed works. To get this result, various scenarios are modeled using the Slide v.5.0 software (limit balance) and Phase 2 (efforts and deformations), by de Rock science. The best design option is selected upon the results.

In order to perform the stability analysis maximum and minimum values of the shear strength parameters are considered, by means of random combinations of pairs of data on cohesion and friction, assuming a uniform variation of the parameters. Despite the values of the parameters are mostly in the middle of the scale (in most cases, showing a normal distribution), the assumption of a uniform distribution of the parameters of strength, guarantees to take into account the extreme values of the materials with which most critical safety factor are obtained or the values for allowable efforts and deformations. Such modeling is performed for both the conditions presented by the slope at the time of analysis (Failure) and projected conditions to the execution of works (Stability).

The process of checking the stability of the walls takes into account the minimum values for the safety factors:

- Revision for overturning with respect to the top of the wall.
- Revision of the fault for slides along the base. (As the gabion wall is anchored at the pile system and both work as one piece, we consider that this condition is met).
- Revision of the fault for load capacity of the base (given that the piles on which the gabion is embedded must reach the rocky strata, we consider that this condition is met).

Numeric models used to check the stability of the wall:



Coefficient of active earth pressure Müller – Breslau (Static) K_A	$K_A = \dfrac{\mathrm{sen}^2(\alpha+\phi')}{D_A\ \mathrm{sen}^2\alpha\ \mathrm{sen}(\alpha-\delta')}$ $D_A = \left[1+\sqrt{\dfrac{\mathrm{sen}(\phi'+\delta')\,\mathrm{sen}(\phi'-\beta)}{\mathrm{sen}(\alpha-\delta')\,\mathrm{sen}(\alpha+\beta)}}\right]^2$
ψ	$\psi = \tan^{-1}\left(\dfrac{a_h}{1-a_v}\right)$
Coefficient of active earth pressure Mononobe – Okabe (Pseudo-Static) K_{AE}	$K_A = \dfrac{(1-a_v)\,\mathrm{sen}^2(\alpha+\phi'-\psi)}{D_A\ \cos\psi\ \mathrm{sen}^2\alpha\ \mathrm{sen}(\alpha-\delta'-\psi)}$ $D_A = \left[1+\sqrt{\dfrac{\mathrm{sen}(\phi'+\delta')\,\mathrm{sen}(\phi'-\beta-\psi)}{\mathrm{sen}(\alpha-\delta'-\psi)\,\mathrm{sen}(\alpha+\beta)}}\right]^2$
Total Thrust Müller – Breslau (Static) K_A	$P_A = K_A \dfrac{\gamma H^2}{2} - 2\,c'\,H\sqrt{K_A}$
Total Thrust Mononobe – Okabe (Pseudo-Static) K_{AE}	

$$\beta < (\phi' - \psi)$$

$$\psi = \tan^{-1}\left(\frac{a_h}{1-a_v}\right)$$

β = **Soil-Horizon angle**
α = **Wall-Horizon angle**
δ' = **Forces-Normal wall face angle**
a_h = **Horizontal ground acceleration. Earthquake**
a_v = **Vertical ground acceleration. Earthquake**

Figure 3-7 Free-body scheme of forces acting on the wall. Equations to calculate the active pressure and the total push

To calculate the active push, we have:

$$K_a = \frac{1 - sen\,\emptyset}{1 + sen\,\emptyset}$$ Coulomb (Static)

$$E_a = 1/2\gamma h^2 K_a$$

For the overturning momentum:

$$M_v = E_a\, x\, d$$

For the stabilizing momentum:

$$W_T = W_1 + W_2 + W_3 + W_4$$

With these data we can then calculate the overturning and the slide safety factor:

$Fs = M_R / M_V$ Overturning safety factor

$Fsv = u\,(W_1 + W_2 + W_a + W_b)/E_a$

$Fsv = \tan\phi\,(W_1 + W_2 + W_a + W_b)/E_a$ Slide safety factor

In both cases, it works with minimum safety factors of 1,5. This analysis only assesses the self-weight stability and the diverse forces that may affect the structure.

For pile calculation, to verify its capacity by top and friction. Additionally, minimum embedding length of the pile into the competent ground is checked.

$$Q = Q_p + Q_s$$

$$Q_p = A_p\,(C_u \cdot N_c + \sigma_{vo})$$

$$Q_s = \sum (\Delta L)\, a_s\, C_u$$

Qp: Load at the Tip
Qs: Shaft Load

A_p: Area of pile (m2)

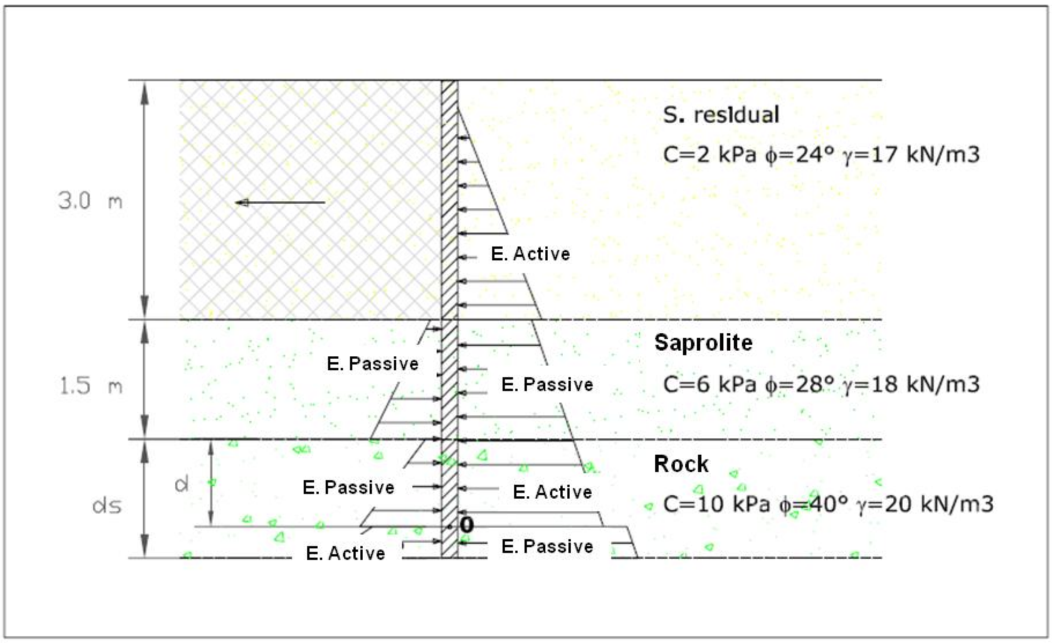
C_u: Undrained shear strength (ton/m2)

N_c: Dimensionless factor of the bearing capacity equation

σ_{VO}: Total effort on the tip of the pile (ton/m2)

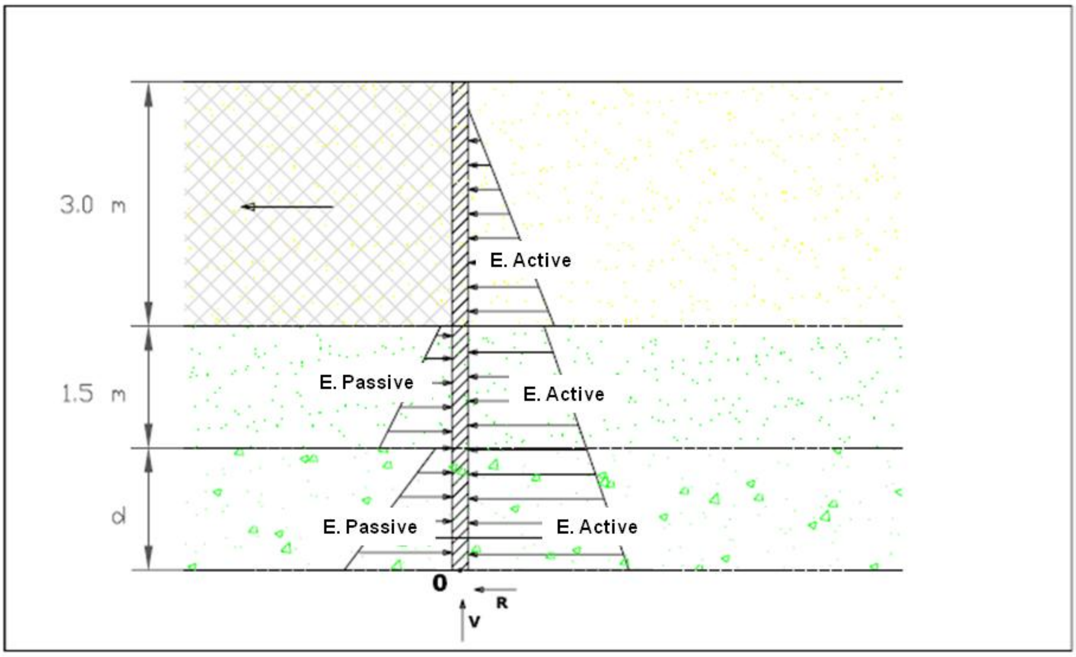
ΔL . a_s: Longitudinal area of the pile (m2)

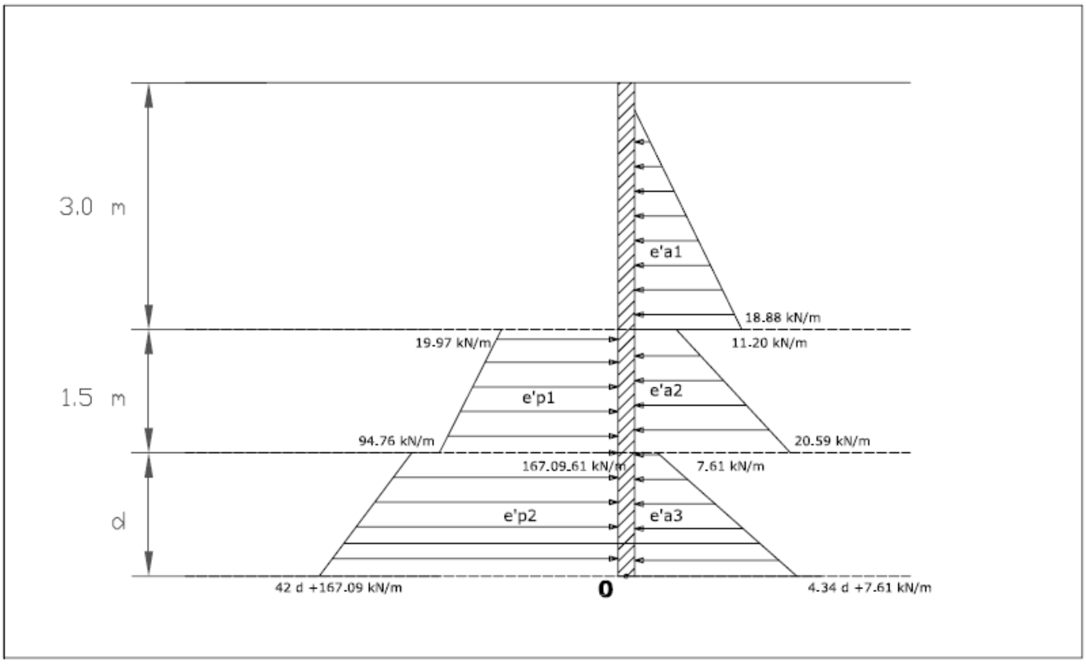
For the minimum length of pile driving:



$$K_a - \frac{1 \quad sen\,\emptyset}{1 + sen\,\emptyset}$$

$$\sigma'_v = \gamma Z E_a = \sigma'_v K_a - 2c'\sqrt{K_a}$$





$$0 = e'_{a1}\left[(3-0.36)\left(\frac{1}{3}\right)+1.5+d\right] + e'_{a2}\left(1.5\left(\frac{1}{3}\right)+d\right) + e'_{a3}\left(\frac{d}{3}\right) - e'_{p1}(1.5\left(\frac{1}{3}\right)+d) - e'_{p2}(\frac{d}{3})$$

$$\mathbf{0 = 42.66 - 8.33d - 34.59d^2 - 9.49d^3}$$

$$0 = e'_{a1}(2.38+d) + e'_{a2}(0.5+d) + e'_{a3}\left(\frac{d}{3}\right) - e'_{p1}(0.5+d) - e'_{p2}(\frac{d}{3})$$

By solving the cubic equation we obtain:

$$d = 0.902\ m$$
$$d_s = 1.2d$$

Later on a stability analysis is performed suing the finite element software, in which the model is en calibrated according to real field conditions.

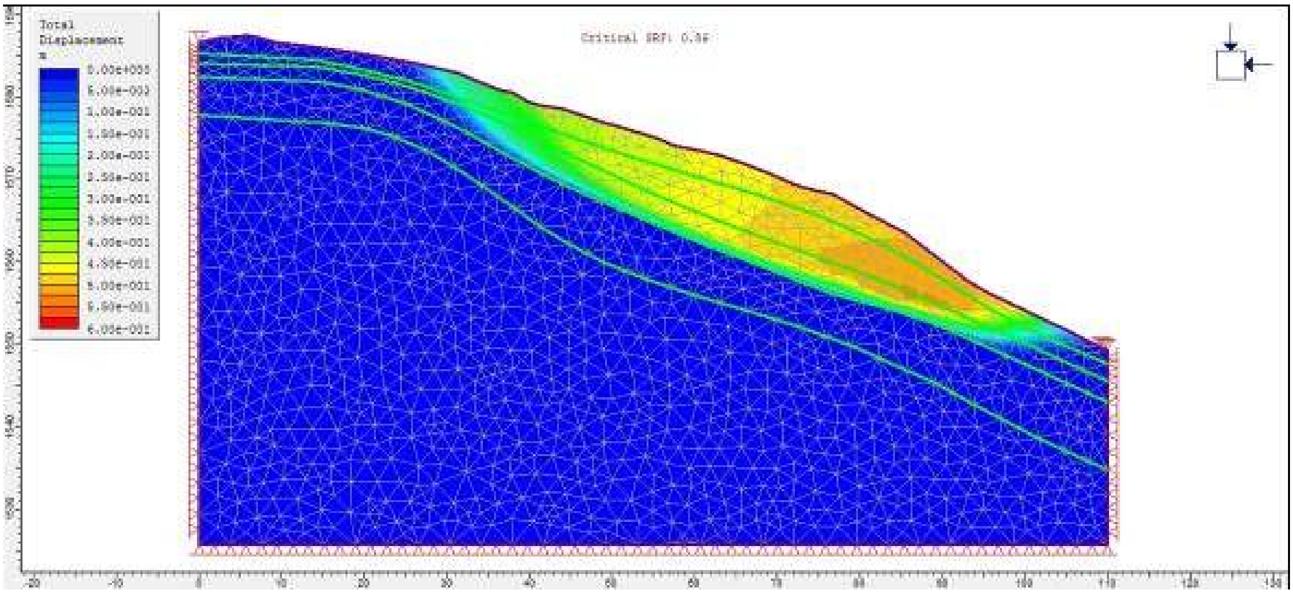


Figure 3-8 - Efforts and deformations under initial conditions on the slope

Stabilization works are entered into the model and strength and deformations are observed to be within allowable ranges in the area of interest for the project.

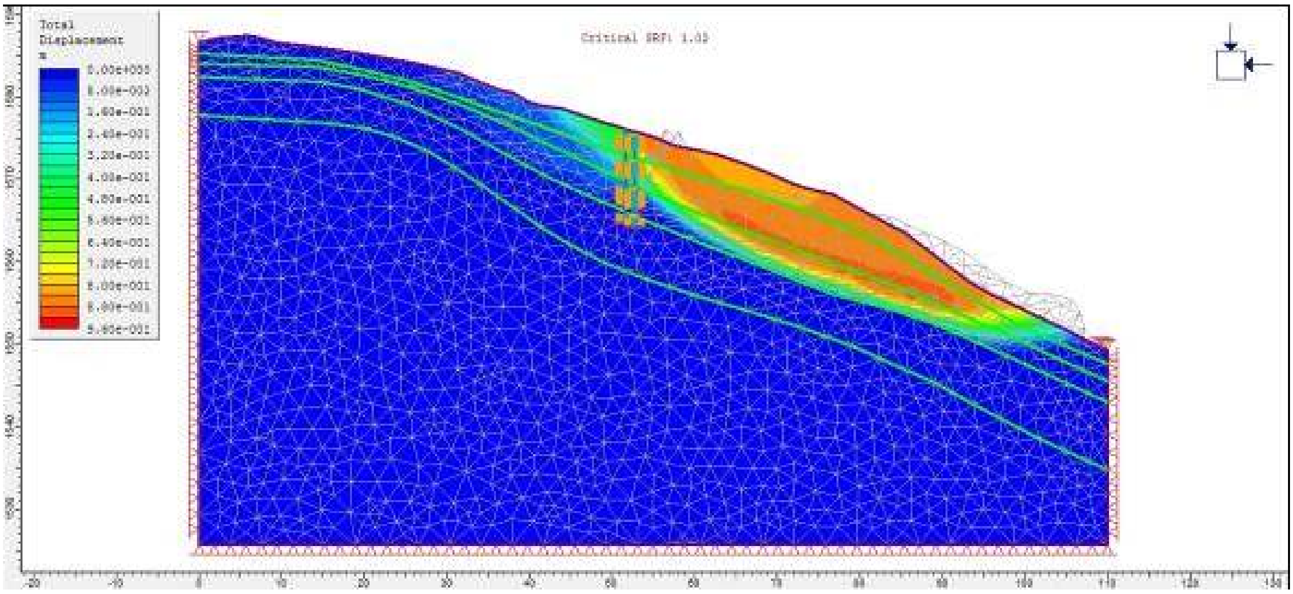


Figure 3-9 – Scheme including the works

As shown in Figure 3-9, the pile system transfers the instability area to the lower part of the slope. This analysis shows that the proposed structure does isolate the ROW from movement.

3.6 Work Plan

Once the works are defined, a comprising document is issued presenting all data from analysis and calculations used in the design and construction plans. Construction methods, the required resources and the involved environmental, safety considerations are also addressed in this document. Figures supporting the design – which is based on known geotechnical methods - are also included in the document.

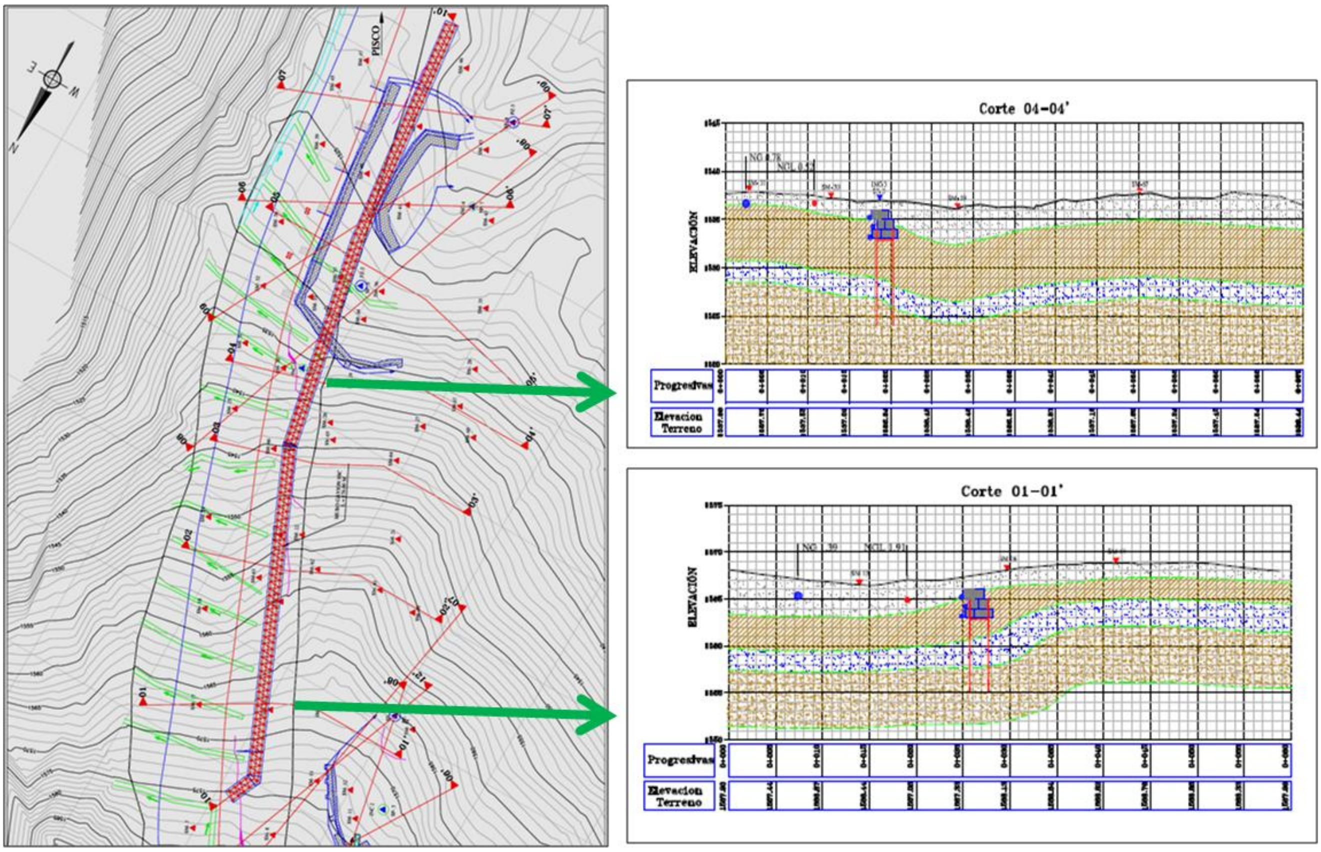


Figure 3-10 - Example of design drawings

3.7 Construction process

3.7.1 General information

There are crews organized for this task and which preferably work in the dry season (between April and October). These crews can count up to 600 people, who are organized and scheduled along with the other resources within a master plan, involving the execution of every work plan, as well as logistics deployment ranging from the construction of temporary camps next to the ROW to hiring helicopters for transportation of personnel, food, materials, equipment and other items required for the job. The entire operation is done in the dry season and needs to be completed before the next rainy season.

3.7.2 Driven piles foundations

Along the entire gabion walls to be built, piles are driven into the ground until competent soil is reached (in accordance with soil studies). 6" diameter steel piles are employed on the Camisea pipeline, considering the equipment available for this job (Cat 312 caterpillar loader). The piles are then braced among all of them in a staggered arrangement (see Figure 3-15).

3.7.2.1 Excavation for driving of piles

In general, excavations are done leaving temporary slopes not over 45º and not higher than 4-5 m. The excavated material is then protected with polypropylene sheets to prevent wetting caused by rainfall. The bench is 3 m wide, and a filter system is installed there to allow drainage and prevent saturation with water.

This practice aims at ensuring the piles to reach the depth established on the design.

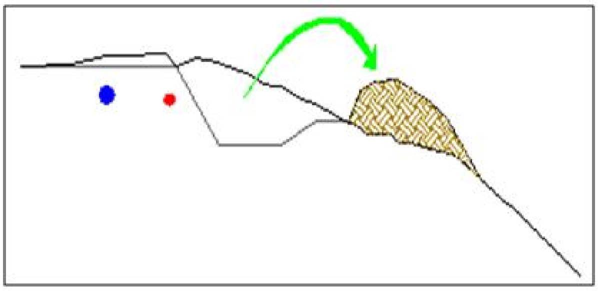


Figure 3-11 Excavation for the driving of piles

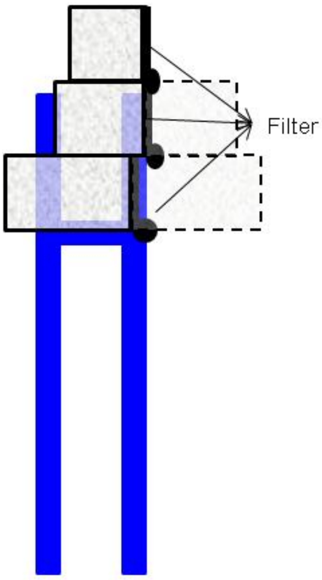


Figure 3-12 Construction of filters

3.7.2.2 Driving-in of piles

Once the excavations is done, D=6" steel piles must be driven into the ground (in three-bobbin configuration) strongly braced with 6" welded pipes.

In Figure 3-14 geometry and arrangement of piles and bracing are shown in detail. The depth of drive-in shall vary according to drawings.

An air-transported CAT-312 excavator is used to do the job, arranged for this kind of work.

Figure 3-13 – Driving of piles

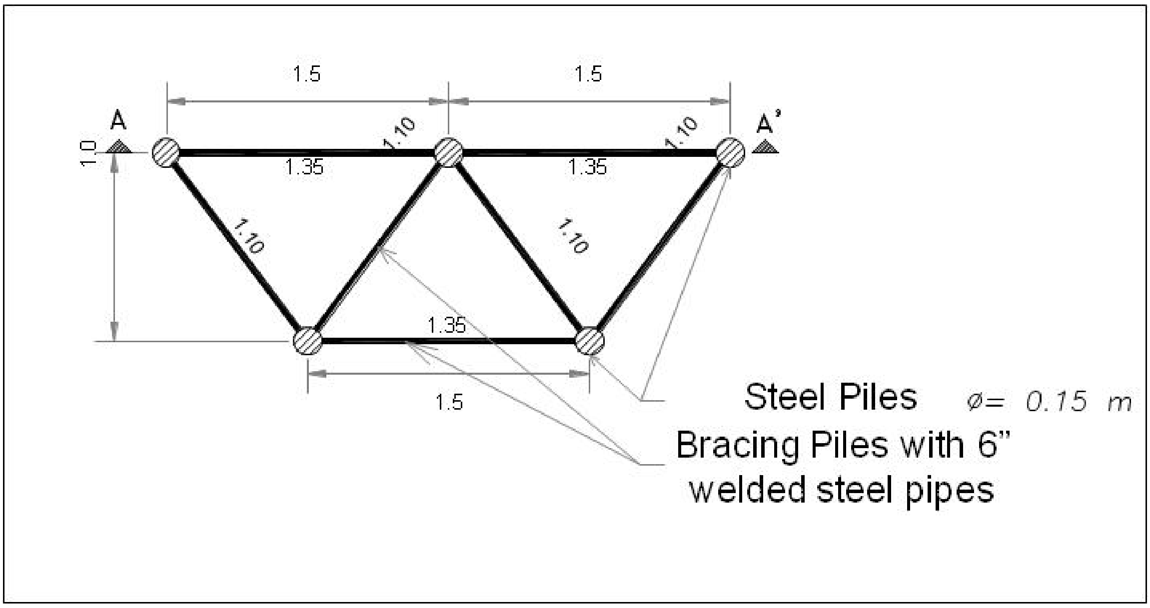


Figure 3-14 – Arrangement of piles and bracing.

Figure 3-15 – Bracing of piles

3.7.2.3 Construction of the gabion wall

Once the bracing of the heads of the pile system is completed, a gabion wall shall be built using bags with soil/cement or stone, if available. The arrangement of the gabions depends on the height and there must always be a 2 m overlap between the heads of the pile arrangement and the gabion body. The filling of the soil/cement bags is done using the waste material resulting from the cuts performed to drive the piles into the ground.

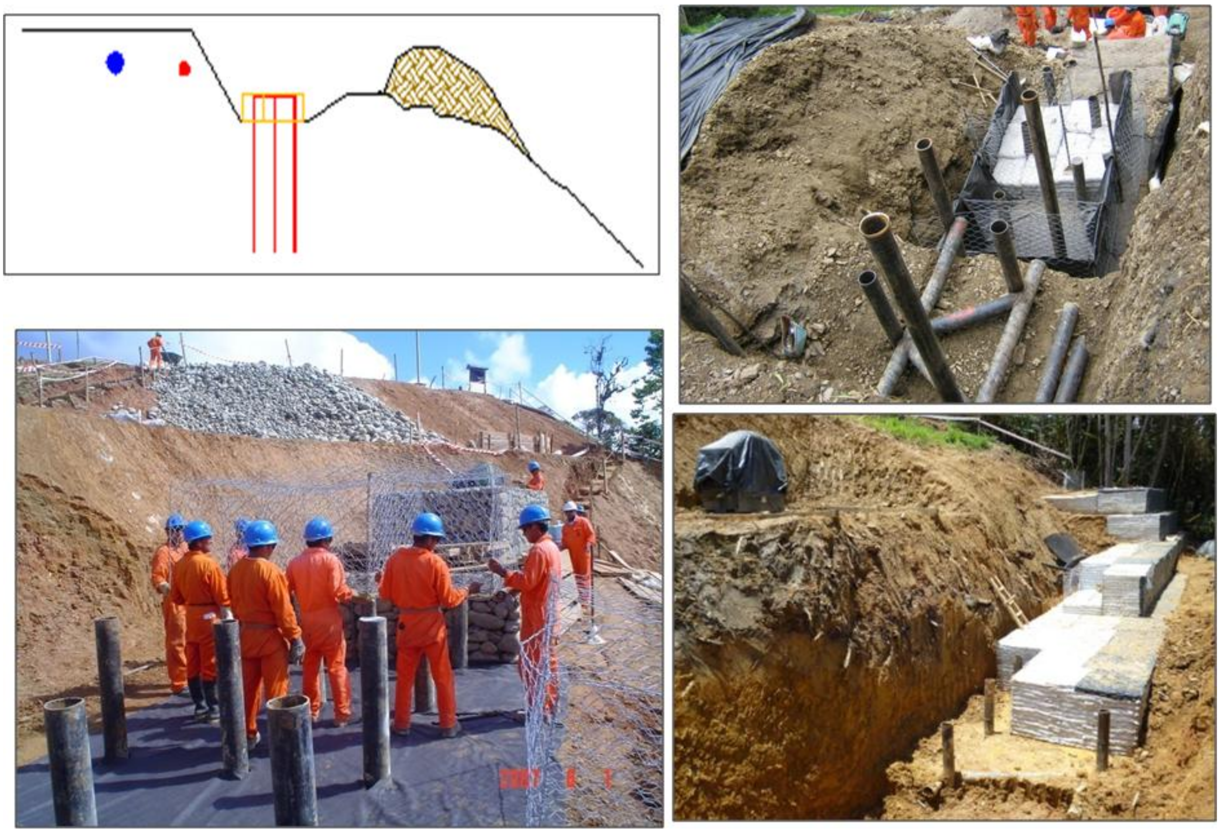


Figure 3-16 – Assembly and construction: first level of gabions

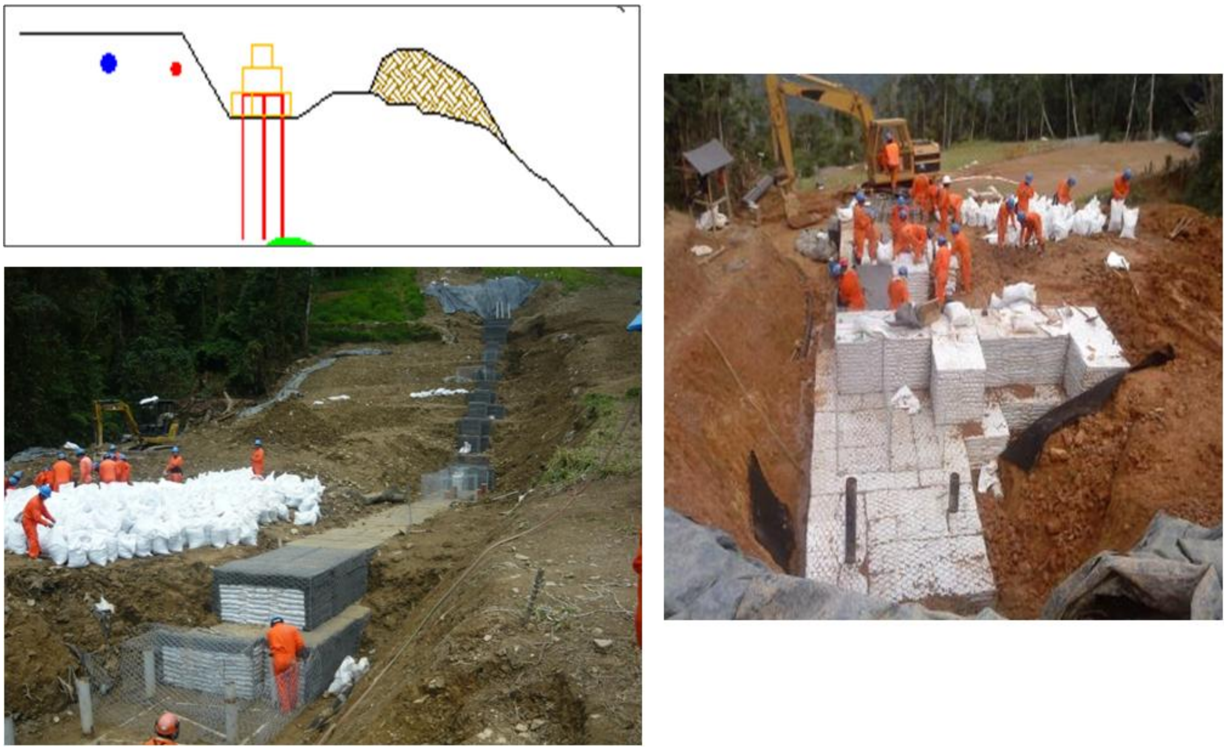


Figure 3-17 – Assembly and construction: next level of the gabion

Figure 3-18 – General view of the completed work

3.8 Monitoring of Works

Once the remedial jobs are completed, monitoring of the structure begins, so as to verify its performance ensuring the integrity of the pipes.

The monitoring activity is done installing topographic dots (monuments) located on the structures already built or on the ground. The readings are performed in periods not over a month, using previously established points known to have no movement as control points. By comparing both groups of points, eventual movements are detected on structures or on the ground. Upon these readings action is taken to carry on with the monitoring or more detailed studies on the integrity of the structures.

At the points which the integrity and geotechnical official consider to be critical for the pipeline system, additional monitoring is performed besides the topographic monitoring using inclinometers, piezometers and strain gages.

Inclinometers and piezometers are installed at different locations in the area where the geotechnical event is known to occur. Those are placed at depths between 10 and 30 m. Data concerning horizontal movement in the depth is obtained through them in order to establish the fault horizons. The latter are then associated with the depth of the water table obtained by the piezometers.

The strain gages are installed on the pipeline and data concerning strength in the three axes is obtained. Eventual presence of pressure from the ground is established to exist.

4 CONCLUSIONS

It is important to say that, under the particular access conditions and the logistics challenges at the Camisea pipeline system, a specific method or technique was developed from geotechnical engineering, though adapted to the characteristics of the site, looking for the optimization of the available resources and guaranteeing efficiency and suitability of works.

Usually, piles are employed in geotechnical engineering to give sturdy foundations to structures that otherwise could not be supported by soft soils; their main job is to convey the loads from the surface to deeper strata where firm anchorage can be found. Particularly, in the case under study, beyond conveying the loads from softer soils to stronger ones, piles se must work as a retaining and confinement of materials. Both combined actions produce two different effects on terrain: on one hand, driving metal pieces with a much higher shear resistance than soil into unstable terrain and anchored into rock, the whole system becomes an only structure that neutralizes the kinetics of the ground. On the other side, driving steel piles into the ground creates an area with higher shear strength than before, due to the increase of density and cohesion of soil. So, the farther from the pile structure, the lesser the cohesion of soil – which becomes evident where the goal is not to stop the movement of soil, but to isolate the area inside the right of way from the ground outside it. In this case, evidence shows that faults do not go through the pile system; moreover, the fault does not usually affect the nearby soil even outside the pile system but only as materials are less influenced by the confinement effect of the system.

From a technical and practical point of view, it is evident that the implementation of this type of structure does work; but one of its assets is the optimization of resources, because even under extreme outside conditions, steel piles are almost as strong as other systems using different materials (reinforced concrete, for example) but with the advantage of lower costs. Of course, this choice lays closer to safety limits and poses a challenge to engineering – improvement of processes, optimization of resources and quality assurance, as part of our job.

5 REFERENCES

Ingeciencia, 2009. Zonificación Geotécnica del Gasoducto de Camisea - Tramo Selva. (Draft).

Senamhi, 2007. Ministry of Defense, Peru's National Meteorological Service, Corporative Studies of Rainfall in the rainforest of the Camisea gas pipeline and historical files of Senamhi.

Coga, 2007. Rainfall data of the pluviometric seasons located along the Camisea gas pipeline for 2006. Compañía Operadora de Gas del Amazonas.

Varnes, D.J. (1978). "Slope Movement Types and Processes". In: Schuster R.L. and Krizek R.J., Editors, "Landslides - Analysis and Control". Special Report 176, Transportation Research Board. National Academy of Sciences, Washington D.C.

Suarez Jaime (2009). Libro Deslizamientos-Análisis Geotécnico.

Deere and Patton, 1971. Slope stability in residual soils. Fourth Pan-American Convention of Soil Mechanics and Engineering of Foundation, Vol I, Puerto Rico, U.S.A. 1971.

Exponent, 2006. Appendix C Hybrid Risk Technical Memorandum, Draft Interim Report of the Camisea Pipe Lines in Perú. December 20, 2006.

Normas Colombianas de Diseño y Construcción NSR98, 1998. Capítu lo H.4 Diseño Geotécnico, tabla H.4-3 - Muros de Contención. Colombia, 1998.

Velásquez Fernando, Martínez Gustavo, 2009, Geotechnical Stabilization of a Pipelines System in Mountain and tropical soil, 24th World Gas Conference, Octubre 6-9, Buenos Aires Argentina.