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A Case of Singular Geotechnical Failure for Industrial Structures in the Peruvian Andes

A. Carrillo Gil
Principal Professor, National University of Engineering

R. Torres Vega
Member of the Board, A. Carrillo S.A., Consulting Engineering, Lima, Peru

SYNOPSIS During the rainy season of 1982, foundation distress was occurred at several recently completed and still incomplete structures of an important mine project located in the Peruvian Andes. When the tailings thickener was tested an unexpected settlement started, some cracking was observed in the slab, and the central pier settled and tilted. The nature of the distress suggested the failure occurred as the result of the combined effect of a long term seepage under the bearing foundation soil and due to its different degree of compaction. This paper presents the characteristics of these problems as both foundation and fill materials, the probably failure mechanisms and a discussion of geotechnical design criteria to solving them.

INTRODUCTION

The Peruvian Mine Project is located on a flange jungle area in the South Andes of Peru. The mine industrial zone consists of several buildings sited in an area of rugged terrain. The building layout is illustrated in figure 1. The underlying soil conditions are reasonably good, being older terrace deposits. Locations for the major plant structures and their relationship to the original topography are indicated in the same figure. Extensive fills and cuts were necessary because of the topography, some of the fills were as deep as over 15 meters, this area is rugged an montainous.

The Tailings Thickener Tank, Shop/Warehouse building and conveyor belt foundations, constructed from the end of 1980 to early 1982, were inspected in detail because foundation distress was noted by May 1982. The failed structures were placed on fill portions of the site. There were not fails in the structures placed in cut areas, thus, there was a striking difference between the behavior of structures placed on fills or on cuts.

Therefore, several investigation works and reviews started after the failure. This paper attempts to cover the essential details, the unfortunate change of the original design and discussion of the probably failure mechanism of this case study. General recommendations and foundation corrections are presented. It is point out here that this paper has been prepared by one of the reviews and reflects the authors' standpoint and experience of the Peruvian Andes Conditions.

2. NATURAL CONDITIONS OF THE SITE AREA

2.1 Geologic Features

The mine project site is located in an area of rugged terrain in the Peruvian Andes. The area, called "Pampa", is a river alluvial terrace and it is thought that debris cone material of small canyons are accumulated in the surface. The adjacent hill in the east side, presents a colluvial and residual granitic material making its debris slope. The area is characterized by folded and faulted sedimentary rocks where the Paleozoic Copacabana formation is the general rocks type in the area. Colluvial with residual granitic material or thick accumulations of river alluvium deposits with siltstones and lime-stones fills the relative flat site area between the mountain slopes and topographic rise.

During the Superior Cretaceous the development of the geologic conditions of site area was initiated. The orogenic activity continue with more intensity during the Inferior Tertiary, when the Copacabana formation rocks started to folding, faulting and uplift. After the Trias-Jurassic Period the uplift of a granitic body occurred. The development of the geologic conditions of the alluvial terrace was during the Cuaternary Period and the deposition of geologic units are associated with the main river of this area. In addition the erosive geodynamics of the cuaternary have been intense.

During the surface geological mapping four major lithologic units which occur at or near the surface at the site were identified: Copacabana formation, which is the general rock type in the area; colluvial and residual granitic material; landslide debris and river-alluvium deposits with siltstones and limestones. There are not evidences of a granitic intrusion in the site; however the geological map of the area shows a granitic outcrop, we argue this statement from the geomorphology point of view and from our studies of the area.
Figure 1. General view of the site plant area and location of the damaged structures.

Figure 2. Topography and geology map of the site region.

Qt: Siltstones and Limestones
Qta: Colluvial and residual granitic debris
F: Paleozoic Copacabana Formation
2.2 Topography Features

The topography configuration of the site area, where is located the new industrial plant depends on the Copacabana formation and on the alluvial deposits with residual granitic material resulting that of half of a bowl-shaped basin. The hills which surround the site for 180 degrees have slopes at angles between 30 and 40 degrees. The elevations range from about 2,300 meters above mean sea level (MSL) at the point where topography flattens to 3,200 meters (MSL) at the crest of the basin. The construction site, where the mill and related structures are built, ranges in elevation between 2,275 and 2,325 meters (MSL), being the site area about 200 meters wide by 1,300 meters long. The site area extends to the original eastern edge of the basin and in some places even slightly beyond. From this edge the land surface drops steeply from about 2,275 meters (MSL) at the crest of the gorge to 2,000 meters (MSL) at the river level.

The construction of plant facilities involved excavations and fills. The fill material were placed to form three terraces for the plant site at approximate elevations of 2,290, 2,300 and 2,305 meters (MSL).

2.3 Ground Conditions

Figure 3, are typical boring logs from the plant site. The investigation of the soil condition was made before the construction works started.

Stratigraphically, the ground at the construction site consists of debris cone material and river-alluvial layers, lying in that order from the surface.

The debris material averages 1 meter in thickness and consists of sandy silts with siltstones.

Under this layer is the river-alluvial layer which has a thickness of approximately 34 meters. In general, the alluvial layer in the construction site is thick and exhibits considerable stratigraphic variation. This layer is sublayered into an upper part of gravels and siltstones in sandy silt matrix down to 11 meters in average and into a sand layer with poor grain size distribution, mixed with stones and gravel down 35 meters.

2.4 Climate Characteristics

The climate at the site area changes remarkably from dry season to wet season. During rainy season there are large thunderstorms which can drop a heavy rainfall in a short time and front storms which sometimes rain for all day long, continuing for days. Rainfall and wind erosion effect the site and there are not facilities to quantify the rain patterns.

2.5 Earthquake Features

Peru is located in the Circum-Pacific Earthquake zone a seismically active region. The site area is considered within zone 2 (medium seismicity) of the Peruvian seismic zonation as shown in Figure 2.

From the analysis and investigations carried out in the site area it has been stated that in case of earthquake should not be possible the occurrence seismicity - generated landslide as in another areas locate within zone 1, no such landslides have been documented in the site area. Also should not be possible the occurrence of densifications nor liquefactions of the natural soil due to its actual compaction and its, dry condition.

There are not evidences of potential for development of creep landslide movements.

Figure 3: Typical soil profile
3. SITE CONSTRUCTION

3.1 Site subsurface features
The Plant site is actually placed on an area underlain by alluvial terraces with residual granitic material and debris associated with colluvial material. For the construction it was required the placement of significant thicknesses of fill material and, relatively minor cuts, to form three terraces levels at approximate elevations of 2,290, 2,300 and 2,305 meters (MSL). The areas in which fill back was placed are also shown in Figure 1. The deepest excavation was conducted at the crusher building where approximately 30 meters were removed. Throughout the remainder of the site excavations were less than 5 meters fill thicknesses in the conveyor belt foundation area ranged about 3 meters, in the Shop/Warehouse area ranged from about 3 to 9 meters with fill thicknesses in the southeastern portion of the thickener up to 15 meters.  

The majority of fill material was obtained from debris. Rocks larger than 4 inches were supposed to be removed before compaction. From the modified Proctor compaction test the reported results were generally in excess of 95 percent of the maximum dry density. Rough grading work began in January, 1980 and finished in August, 1980 except for the tailing thic kener area. From 1981-82 the final filling was completed.

3.2 Drainage Conditions
From the aerial photograph interpretation study, the area has a dendritic drainage with radial type due to the drainage of the terrace surrounded hills area convergings to the site area, the water that reaches the terrace drains as ground water. During the rainy season the excess of rain water flows in the surface, specially through two gullies which forms two debris cones crossing the site area.

The modifications made to the site for construction of plant facilities supposed the change of originally existing ground water pathways and existing surface drainage patterns. However, the tendency of the water is to flow through the groundwater original pathways. Thus in spite of the modifications for the construction the ground - water pathways did not change, it is believe that it still flows through the gullies which cross the site area.

4. CHANGES TO THE ORIGINAL DESIGN

Under some considerations, the field engineers were allowed to make certain design changes on the locations of the structures.

The displacement of the structures are approximately to the southeastern direction, being the displacement to the south side ranged from 26 to 83 meters and to the east side ranged from 10.50 to 24 meters. The minimum resultant displacement from the original design is 28 meters and a maximum of 84.6m. Figure 4.

Therefore as a result of the modifications the characteristics of the bearing layer were changed due to the thicknesses of the fill material placed to form the terraces.

The elevation of the tailing thickener platform was also changed from 2284.14m. to 2,290m. and the displacement to the southeastern side was approximately 44 meters. Thus, entirely central piler foundation was supposed to be embedded into original ground, but due to design changes the foundation required small excavation on the extreme north side of the tank site and placement of fill throughout the rest of the tank.

The Concentrator building was also moved to S.E. about 41 meters and the platform elevation were is placed was changed from 2,301 m. to 2,306 m. so, the building is partially supported on cut and partially on fill. By the original design it was required only excavation.

The location of the Shop/Warehouse building was changed to the S.E. about 85 meters and its original platform elevation changed from 2,305m. to 2,300m. The bearing layer for this building in the original design was partially cut and partially filled. With the new location it is entirely filled.

Here, is interesting to point out that the displacement of the structures is to the slope of the filled gully, which crosses the site area as was described above. Thus, the design changes increased the depth of the filled bearing layer of failed structures which are placed on natural ground water pathways, increasing the potential for saturation of site soil. See Figure 5.
5. THE FAILURE DESCRIPTION

As a start in the failure study, specific information was obtained from the owner, consultants engineers, and constructors, concerning (1) laying out on the plan of structure the observed fails; (2) all available information in the project files, including grading plans and building plans; (3) field density testing during construction and results of these tests were available, (4) recording settlement of the failed structures.

Detailed field surveys was carried out of the fill and natural ground surfaces in the vicinity of the distressed structures. Several observation pits were excavated adjacent to the tailing thickener tank and Shop/Warehouse building.

5.1 Tailing Thickener Tank

The site area of the Tailing Thickener Tank is near the head of a gully on the southeast side of the "pampa". The bearing layer was described above, Figure 6 shows a section through the tank area. Fill was placed in the tank side area from the beginning of 1980 to mid of the same year. Fill construction was halted prior to reaching final grade and was completed by the fine grading contractor rather than the rough grading contractor. During construction test results indicated 95 percent or greater of the laboratory Modified Proctor reference density.

The cracks were filled with mastic, after the tank was partially filled with water. By December 1981 the installation of the tank mechanical equipment was finished and by May 1982 was checked for operation with no water. At this time, approximately 1/2 of the design foundation pressure was applied to the center pier.

By the middle of May, 1982, the tank was filled with water to a depth of about 5m, measured at the center pier. After few hours, it was reported that all the water drained out of the tank into the underlying soils. Many new cracks appeared in the tank slab (Figure 7). The central pier settled, tilted and cracked the adjacent slabs. The thickener takes bent and contacted the bottom of the tank. The settlement at several points of the tank were measured and the result is indicated in the same figure. The result of the ground settlement measurements carried out on surrounding ringwall and inner slab area of the thickener tank shows that in addition to the center pier settlement and floor slab cracks, the outer ringwall had also settled at the southeast quadrant and had elevated at the northwest quadrant as are shown in Figure 7.

![Fig. 6. Cross section of the thickener area](image1)

![Fig. 7. Slab cracks and rate of settlement](image2)
From the observation pits adjacent to the center pier foundation, it may be seen very wet and soft debris fill overlying alluvial deposits with residual granitic material; below the foundation of the center pier was encountered angular to subangular and slightly rounded granite cobbles embedded in a sandy silt matrix.

It was observed direct contact of several boulders and cobbles with the foundation block. In three of the observation pits was seen settlement of the fill away from the overlying slabs with settlements of about 40 mm.

It is noteworthy to mention that the tunnel has the southeast direction where the fill is more than 15 meters depth and the settlement of the structure in this quadrant was about 70 mm., the largest of this failed structure.

5.2 Shop/Warehouse Building

The bearing layer of the shop/warehouse building is fill material. This fill varies from about 3 meters to 9 meters in thickness. See Figure 8.

![Figure 8: Fill conditions of the Shop/Warehouse Building bearing layer.](image)

The building is a steel frame, one-story structure approximately 30 meters wide and 128 meters long. The roof system is supported by trusses spanning the short dimension. The roof trusses are supported by two rows of exterior columns and a center row of columns. The foundation for the exterior columns are a grade beam widened at each column location to form a footing and pier. The foundation for the center columns are individual shallow foundations.

By the beginning of March, 1982, it was observed that one of the roof truss members was significantly twisted.

Settlement checks were made of the building column piers and these checks indicated settlements from 18 mm. to 120 mm. throughout the entire building area. During about 2 months the settlement were monitored and when it was recorded that little additional settlement was occurring the repair works started.

From the survey carried out it was seen that the footing settlements have not occurred independently of the floor slab nor connecting grade beams between the exterior columns. In two cases there is an indication of cracking in the center of a grade beam between two columns that means the possibility of greater settlements at the footing.

It is seen that the grade beams which carry little load have settled same as the columns.

Is interesting to point out that maximum amount of settlement has been recorded where maximum amount of fill was placed. Thus in most cases, columns on the east side of the building have settled more than those on the west side.

The observation pits excavated adjacent to the columns shows the fill material consisted of a wet landslide debris and contains both hard and loose zones in the walls of the observation pits. In one of the observation pits it was encountered a void under the column footing, probably related to an adjacent electrical duct which was filled with clean coarse stone.

On the basis of our field and the recorded data it seems that the shop building settled basically as a unit.

5.3 Foundation Belt Conveyor

The bearing layer of three conveyor belt foundation is fill material. By early January, 1982, the foundations of the conveyor belt experienced settlements. It is interesting to mention that among all the conveyor belt foundation the failed ones were founded on fill material with about 3 meters of thickner.

As it was pointed out the three described failed structures were supported partially or totally on fill material, which fill the same gully which crosses the site area. No other structures within the plant site are known to be experiencing settlements. Few if any, of the other plant structures are supported on fill material. In all cases the observation pits showed high percentage of gravel bigger than the allowable size and disagreement between the results of the field density test during construction and performed by the authors after occurred the fail. See Figure 9.

![Figure 9: Observation pit showing the excavated material.](image)
6. PROBABLE MECHANISMS OF FAILURE

On the basis of the above studies, we believe that the modifications made to the site for construction of plant facilities such as thick fills and interruption of natural ground-water pathways and existing surface drainage patterns, have increased the potential for saturation of site soils. It is seen that during rainy season ponding rainwater around the plant structures gradually seeped into the fill material filling the gaps and started the undermining of the footings, causing them to settle somewhat under their own weight.

It is also seen that during the rainy season the excess of rain water flows in the surface specially through two gullies and that one of the gullies, which has a thick fill, cross the site area under the failed structures, it is believe that in spite of the modifications, the tendency of the water is to flow through the original existing ground water pathways and existing surface drainage patterns. See Figure 10.

Thus, it seems apparent that the failure resulted from the combined effect of the poor drainage system of the site and uncontrolled fill which weaken the soil, starting the undermine of the footing and probably piping, a process by which the fill material is eroded internally due to the underground flowing water crossing through the failed structures site area.

From the geotechnical work carried out, there area not evidences of landslide potential in either natural deposits or the fill material, related with the failure mechanisms.

7. REPAIR WORKS

Since the influx of the rain-water is directly related to settlements which have been observed at several structures, as stated above, it was necessary to review the entire drainage water patterns at the site and provide a suitable drainage system promoting better removal of the water.

Therefore, to remove the surface water, the areas around the main structures were sealed with asphalt (this areas were not less than 2 meters wide with a minimum slope to the trenches of 2%) and all the surface drainage system was reviewed and improved in order to provide for rapid removal of the heavy rains common during the rainy seasons. To intercept the subsurface water due to infiltration of surface water uphill from the site it was recommended the construction of a subdrainage system in the hill's walls which bound the mill site to collect the water and route the collected water away from the site area.

The two areas considered the most critical are the Tailing Thickener and the Shop/warehouse areas.

To repair the Central pier foundation of the Tailing Thickener it was necessary to improve the bearing layer soil under the central pier through the injection grouting of cement and provide additional foundation support, taking care of the correct foundation level. As the central pier has extremely tight tolerances for differential settlement, the total structure level was changed.

After reconstruction of the central pier foundation, the failed slab was covered with a bituminous material with variable thicknesses due to the settlement of the slab. This thicknesses should be corrected in the future if additional settlements appears.

As the settlements of Shop/warehouse building were due to settlement of the fill material, it is thought that additional settlement could occur and there is no technique which would allow its estimation, thus the building columns were jacked to raise the building back to plan elevation, making possible the correction of future settlements.

8. CONCLUSIONS

1. The analysis show that the original design site selection and geotechnical studies were appropriate and extensive.

2. It should be noted that the new location of the structures without sufficient consideration of the effects of differing structures site geological conditions affected their behavior.

3. The failure investigations could not be as deeper as should be desirable, due to the short available time to give the retrofitting recommendations.

4. The thickener pier foundation tilting may be caused by lateral variations in soil compaction beneath the base foundation.
5. Thick fills have been placed in an uncontrolled fashion in two gullies at the edge of the pampa. The failed structures were placed along one of these filled gullies, being the settlement of the fill material due to its own weight resulting from the effects of water soaking into the fill.

6. Due to infiltration of surface water uphill from the site, water can move through the subsurface and enter the site area.

7. The fundamental cause of failure may be regarded as a combination of climatic factors and design decision that taken together, permitted the failure to develop. The main climatic factor was the lack information about past rainfall average records. The design decision was the locations of the structures total or partially on a filled gullies.

8. Summarizing, under difficult conditions, an unfortunate choice of structures location together with less than conventional precautions was taken to ensure the adequate behavior of the structures, and these situations finally led to their failure.

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