Analysis of Deformations of Gravel Columns in Tailings Dams Using the Finite Element Method and Constitutive Equations

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Abstract. In this research, the analysis of the deformations of the gravel columns applied in the foundation of the dam's regrowth of the centerline method is developed. The purpose is to guarantee its stability against the potential liquefaction phenomenon induced by a seismic event, construction and external loads. The configuration of the centerline method dam has a part of the foundation in sedimented tailings material upstream and downstream it has a stable foundation. For the analysis of the gravel columns and the structure, the mechanical and geotechnical properties of the original materials (tailings) and gravel that is part of the column, as well as the fill materials that make up the structure of the dam, have been considered. In view of the problems identified, we propose that the application of gravel columns is an optimal alternative that improves the short and long term consolidation time of the sediment tailings upstream of the dam.

The results obtained from the modeling analysis in the Plaxis 2D program determine that it improves the shear strength and reduces settlements or deformations. It allows the release of pore pressure stresses through the gravel columns that function as a vertical subdrainage system.

As for the initial modeling without gravel columns.

Keywords: Tailing's dam · Liquefaction · Gravel columns · dam stability

1 Introduction

In recent years, Peru has become one of the main countries where mining operations generate toxic waste from metallurgical processing, generally a mixture of fragmented earth, rocks, minerals, water and high concentrations of chemicals that are transported through pipelines and deposited in purpose-built dams. During disposal, the tailings slowly decant and form a stratified deposit composed of coarse and fine solid materials [1].

In the last decades, very serious tailings dam failures occurred that have caused environmental, social and economic damages. Peru is one of the countries with tailings dams of surprising sizes "very large, among the largest in the world, such as Antamina, one of the highest, the "Cerro Verde and Quebrada Honda, to the south".

Most tailings dam failures are induced by seismic events that trigger displacements and/or deformations due to increased interstitial pressures generating the potential development of liquefaction. Moreover, it is the main factor influencing instability, it is concluded that failure mechanisms directly affect the instability of the containment structure causing an increased risk of collapse [18]. The main cause of dam failures is the liquefaction phenomenon, so international standards have classified the type of tailings dams and the consequences of environmental impact. And with the assigned classification they recommend considering seismic and hydraulic criteria in their design to provide greater safety [21].

Peru is a highly seismic country due to its location in the Ring of Fire. The construction of tailings dams is allowed by the downstream and central line method, prior verification and validation of the vulnerability of these dams to the eventual liquefaction of the sands. Dam safety and proper tailings management must also be ensured. In addition, a dam breach simulation is required because it allows to evaluate the possible displacement of the structure and to identify possible affectations that may influence the stability of the tailings dam regrowth dam.

The objective of this research article is to present a viable alternative for improvement, by incorporating gravel columns in the foundation of the tailings dam re-growth dam whose design is the centerline method. Its application allows greater stability because it offers resistance when receiving loads of greater magnitude. Our contribution consists of making use of gravel columns whose main function is to provide a vertical drainage system that reduces the impact of liquefaction phenomena in the tailings dam. It is sought that tailings dams acquire greater stability against various seismic events, liquefaction, settlements and displacements, for the same reason that the tailings material undergoes different consolidation processes over time. In this research paper, the analysis of the deformations of the gravel columns installed in the tailings dam dike will be carried out using the finite element method and empirical equations.

2 Evaluation of Geotechnical Data

To evaluate liquefaction, it is necessary to consider the historical, geological, compositional criteria (type of soil, type of material) based on the SPT (standard penetration test) and CPTu (static penetration test in situ) tests [15] of the tailings dam to be studied.

The gravel columns act as vertical drains since they have a higher permeability than the natural soil, so this effect reduces the increase of pore pressures, which are generated when the water table rises above the dam [4]. It is also important to consider the plasticity of the gravel columns, the settling process and the dissipation of excess interstitial pressures [6].

The methodology of this research is of the explanatory type and is developed in four stages covering in detail the specific objectives. These stages consist of the conceptual review of tailings dams built by the central line method, the collection of information from laboratory data, the numerical analysis of the drainage columns that are incorporated into the tailings dam and the verification of the behavior of dams.

To perform the deformation analysis of the gravel columns implanted in the tailing's dams, firstly, all the information such as the geotechnical properties of the materials that
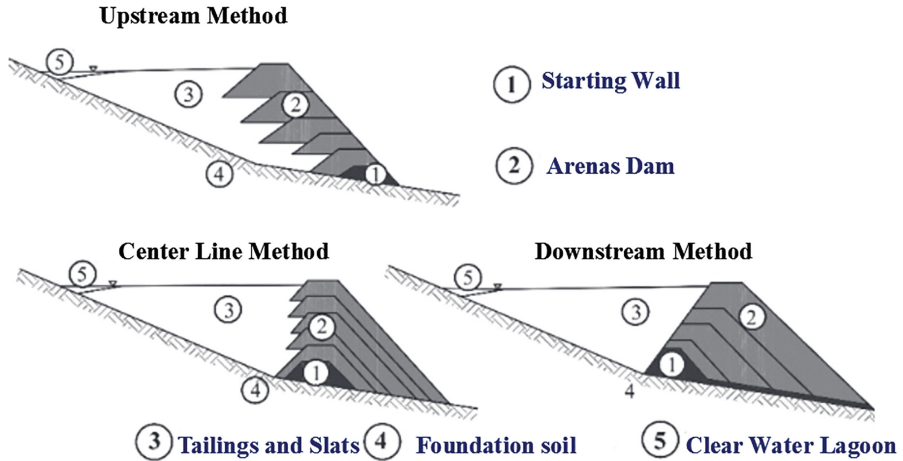
Upstream Method

Fig. 1. Typical tailings dam sections according to their growth method.

compose the containment dam and the gravel columns were collected. Secondly, the empirical evaluation of the deformation was carried out using the proposed method [7] and [8]. Thirdly, the modeling was applied using the finite element method with the help of the Plaxis 2D program, taking into account the most critical conditions. Finally, the obtained values of the deformation of the gravel columns were compared to determine the degree of improvement they bring to the structure (check dam).

2.1 Information Gathering and Case Description

Information is available on the central line method dam and the characteristics of the materials of which it is composed. These dams are built with a part of the tailings material as foundation, in addition, the fill material is used as backfill material which goes through a mechanical process of classification and disposition in the deposits. In seismic zones, the most used method of regrowth is the downstream and centerline method, both methods have similar processes in the starting dam, being more feasible to install the drainage system.

In the dams of the centerline method during its regrowth, part of its foundation is on compacted tailings, therefore, to improve the foundation it was implemented with gravel columns. With their incorporation, the deformations and displacements that could be generated by the effects of external loads and the phreatic level of the tailings will be evaluated (Fig. 1).

The dam under investigation has characteristics of the centerline method, which considers a starting dam, following the guidelines of the downstream method, and then proceeding with a centerline growth. In the successive growths of the centerline method, gravel columns were installed in order to improve the stability of the foundation and to evaluate the deformations and displacements that could be originated.
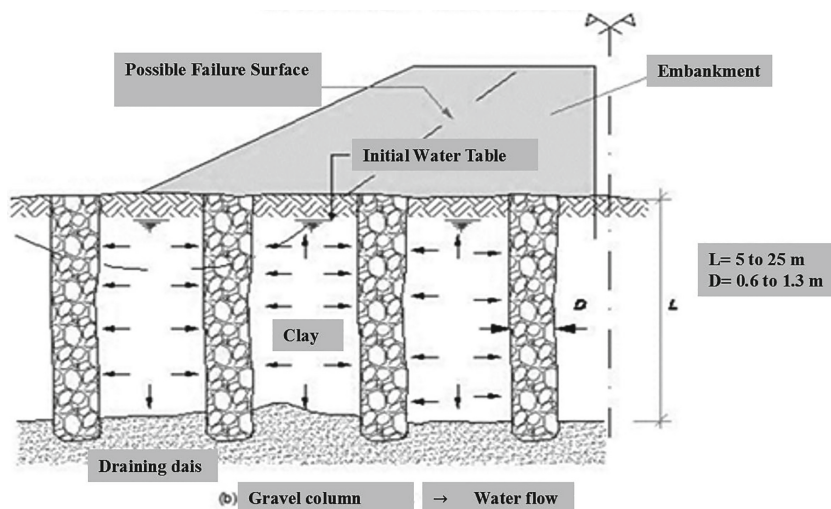
Fig. 2. Gravel columns configuration. Fuente: Oteo, C. (2011)

2.2   Characterization and Evaluation of Gravel Columns in Tailings Dams

In order to proceed with the analysis, a literature review was previously carried out based on regulations, design manuals and documents such as research articles, journals and national and international congresses associated with the design of tailings dams and gravel columns.

Gravel columns are considered as one of the common methods to improve or reinforce the geotechnical characteristics of soils with low bearing capacity. In order to accelerate the soil consolidation process, have gravel columns with a vertical drainage system, reduce settlements and mitigate the potential for seismic liquefaction (See Fig 2).

One of the advantages of gravel columns is their draining capacity, which allows to dissipate pore pressure and accelerate the consolidation process. In addition, it reduces the development of the liquefaction phenomenon and induces a combined effect of a vertical underdrainage system and improves the shear resistance of the soil.

2.3   Configuration of Gravel Columns and Tailings Dams

The design of gravel columns requires detailed information because a variety of elements influence their calculation, which are described below.

- Gravel particle size and friction angle.
- Distance between columns, according to the chosen mesh (2 to 10 m).
- Diameter of the gravel columns (0.40 to 1.50 m) having a direct relation with the characteristics of the surrounding soil.
- Depth and construction process.

On the other hand, there are different gravel column design methods. This research will be based on the gravel column method [8] which is based on the vibrosubstitution proposals [2] [21].

The method proposed by [21] is based on obtaining the improved soil parameters considering the mechanical characteristics of the original soil deduced from the geotechnical report and from the gravel columns themselves. From the data obtained, he proceeds to perform the settlement calculations of the improved foundation. In 1995 he modified and improved his proposal considering the following points:

- The vertical deformation of the soil is that corresponding to edometric conditions, i.e., it has lateral confinement.
- Rigid-plastic state of the gravel columns.
- Plastic limit state.
- Thrust coefficient at rest is 1.
- Radial soil-column pressure

In his proposal [21], he considers more real parameters for the design, such as the oedometric modulus of the soil-column, substitution ratio and gravel data. [13].

[2], is based on Priebe's approach, improves his proposal by considering an elastic analysis for gravel columns, proposing two situations in the short and long term. It considers soil parameters in drained and undrained conditions, respectively. The result of the analysis determines that the soil-column stress distribution is variable (see Fig. 3).

The determination of column areas for major loads such as the retaining dike of a dam uses regular meshes (square, triangular and hexagonal), with the triangular mesh being optimal.

The concept is based on the interaction that exists between the soil and the gravel columns, the characteristics of the soil (angle of internal friction φ_s, cohesion C_s and modulus of elasticity Es) and the characteristics of the gravel columns (angle of internal
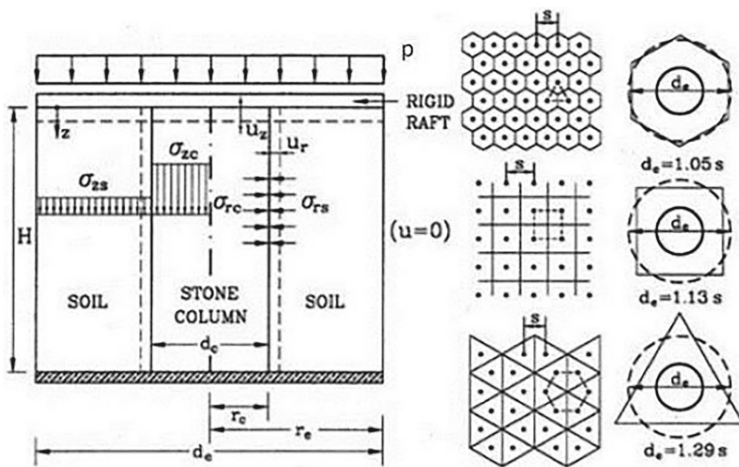

Fig. 3. Unit cell characteristics and equivalent diameter [Original] [2, 7].

friction φ_{col}, cohesion C col and modulus of elasticity E_{col}) are considered, to finally obtain the soil stability improvement through the combined soil and gravel column parameters (φ^*, c* and E*). [11].

The method used allows to determine from the parameters obtained (friction angle φ^*, cohesion c* and modulus of elasticity E*) a detailed study of deformations, settlement and displacement in the soil.

It is necessary to take into account in the calculations the influence of the soil improvement parameters surrounding the gravel column. The analysis can be performed through the unit cell concept.

The diameter of the gravel columns is based on the mechanical characteristics of the surrounding soil. For our research, all the geotechnical studies carried out on the dam are considered, including the CPTu, SPT and laboratory tests. To ensure that the equivalent diameters are optimal, they are verified by numerical modeling of stability.

The equivalent diameter is obtained from the following equation:

- Malla triangular

$$d_e = 1.05s \tag{1}$$

- Malla cuadrada

$$d_e = 1.13s \tag{2}$$

- Malla hexagonal

$$d_e = 1.29s \tag{3}$$

The most determinant parameter in the analysis of gravel column treatments is the substitution factor (ar), [11] which represents the percentage of soft soil replaced or displaced by the columns:

$$a_r = \frac{A_c}{A_t} = \left(\frac{d_c}{d_e}\right)^2 \tag{4}$$

Generally, it is proposed to use equilateral triangular meshes, because they cover a higher treatment density.

For the analytical calculation of settlements of the gravel columns, the following formula was used:

$$\beta = \frac{1}{n} = \frac{S_C}{S_0} \tag{5}$$

Siendo:

- S_c Asiento de columnas
- S_0 Asentamiento sin columnas.

The final settlements to be determined will comprise a variation largely due to the type of soil being improved. Therefore, the stresses produced by the effect of loads and overloads generate the instantaneous deformations of the columns and as a response, the improvement and dissipation of stresses that are supported by the columns are obtained. In [11] they carried out studies of gravel columns where they analyze simultaneously the following points:

- The consolidation process
- Deformations in the columns
- Deformation in the adjacent soil

Elastic deformations during plastic deformations of the columns are neglected (case of columns without bagging). The silt stratum (representative) is taken for the analysis of the gravel column:

For the lateral confinement analysis, it is necessary to obtain the value of the soil thrust coefficient, since from this it is determined that the higher the thrust coefficient at rest the higher the lateral confinement of the gravel and soil columns.

$$K_o = 1 - \sin \varphi \tag{6}$$

Donde:

- K_0 : Ground buoyancy coefficient
- φ_s : Soil friction angle

El Módulo Edométrico Del Suelo (E_{ms}) In [11] it is mentioned that, in a strict sense, with the presence of gravel columns, the soil is no longer laterally confined (edometric conditions). To obtain the average modulus (Eq. 7), radial stress is not considered, but vertical stress is considered in a practical way.

$$\frac{1}{E_{ms}} = \frac{\varepsilon}{\Delta\sigma_{zs}} = \frac{C_c}{\Delta\sigma_{zs}(1 + e_o)} \log \frac{\sigma'_{zso} + \Delta\sigma_{zs}}{\sigma'_{zso}} \tag{7}$$

Donde:

s_z: Seat with columns.

$\Delta\sigma_{zs}$: Total seat.

σ'_{zso}: Average Initial Tension.

According to investigations [10], the quotient between the load increase and the Oedometric Modulus represented the average unit strain for the two layers, fill and sand. The partial strain is obtained from the product of the average unit strain times the initial thickness.

With Eq. (7) it is possible to calculate the average strain of the "silts" stratum (Table 1).

Table 1. Oedometric parameters of soils.

Stratum	$\Delta\sigma$ (kPa)	E_{ms} (MPa)	ε (%)	H_O (m)	ΔH (cm)
Filling	120	10.4	1.2	1	1.2
Silts	120	3.1	3.8	4.5	17.1
Sands	120	14.8	0.8	3.5	2.8

Table 2. Parameters of gravel columns.

Column data and parameters	Values
Mesh type	Triangular
Axis separation distance from columns	s=2.20 m y 2.50 m
Diameter of the chosen column	D_c=1.00 m y 1.20 m
Column length	L_c=7.00 m y 8.00 m
Elastic modulus of the column	E_c=75 MPa
Friction angle	$\boldsymbol{\phi}_c$=40°
Poisson module	ν=0.30

3   Analysis and Results

The application of gravel columns in the foundation of the tailings dam increases the shear resistance that is supported by the soils and it is determined that the average oedometric modulus is lower.

With the Table 2 Presents the final configuration of the gravel columns, which are applied to the reclaimed tailings dam foundation using the centerline method.

La Table 3 Presents the results of the percentage of substituted material after incorporating the gravel columns.

3.1   El módulo edométrico del suelo (E_{ms})

Tables 4, 5 and 6 presents the results of oedometric modulus of gravel column analysis for the tailings dam foundation material.

3.2   Assessment of Gravel Column Settlement

The settlement and displacement calculation covers different geotechnical parameters such as: specific gravity, friction angle, cohesion, soil permeability, Young's modulus, Poisson's coefficient, thrust coefficient and dilatancy for the soil as well as for the gravel

Table 3. Diameters substitution factor, using the triangular grid.

Diameter (m)	Separation between columns, to axes (m)	Equivalent diameter $D_e = 1.05s$	Length (m)	Substitution factor $a_r = (D_c/D_e)^2$
0.90	2.10	2.21	3.00- 6.00	17%
1.00	2.20	2.31	7.00	19%
1.20	2.50	2.63	8.00	21%

Table 4. Results of oedometric modulus of gravel columns in the foundation.

Stratum	$\Delta\sigma$ (kPa)	E_{ms} (MPa)	ε (%)	H_O (m)	ΔH (cm)	Seat with columns: s_z (cm)	Mean initial voltage: σ'_{zso} (kPa)
Silts	120	3.1	3.8	4.5	17.1	119	38

Table 5. Seat reduction factor

Substitution factor $a_r = (D_c/D_e)^2$	Seat reduction factor β
17%	0.69
19%	0.66
21%	0.63

Note: Source: Own elaboration

column material. These determined parameters are input data for the modeling of the Plaxis 2D and analytical program.

In his recent research on gravel columns [20], presents a reliability analysis for gravel columns where he mentions that the probability of failure occurs in small groups of columns or under a small foundation area as opposed to when it is placed massively in large extensions of area, which applies to a tailings dam foundation that maintains an extensive area longitudinally.

The improvement is optimal, due to the variability that exists in the silver configuration and the characteristics of the gravel columns themselves.

According to the calculations obtained, it is determined that the greater the area replaced by the gravel columns, the greater the stability of the tailings dam foundation.

3.3 Geotechnical Parameters of Materials

The tailings dam foundation consists of tailings material deposits upstream of the dam. The geotechnical characterization of the deposited tailings was defined based on information obtained from research articles and soil laboratory reports.

Table 6 presents the summary of the geotechnical parameters of the materials used in the modeling of the tailings dam deformation analysis in the Plaxis 2D program.

Table 6. Geotechnical parameters of the tailings dam

Parameter	Und	Rocky basement	Castling	Stage 1,2,3 and 4	Existing dam	Old tailings	New tailings	Uncontrolled fillers	Gravel column
Saturated specific weight (γ_{nosat})	(kN/m^3)	27	22	22	20	19	18	20	14
Unsaturated specific weight (γ_{sat})	(kN/m^3)	28	23	23	21	20	19	21	21
Elastic modulus (E)	(kN/m^2)	3.82×10^5	1.23×10^4	3.5×10^4	3.5×10^4	0.94×10^4	0.94×10^4	0.55×10^4	7.50×10^4
Poisson module v	-	0.20	0.25	0.20	0.20	0.20	0.20	0.30	0.30
Cohesion (c)	(kN/m^2)	225	0	10	10	50	40	10	0.003
Friction angle (ϕ_c)	(°)	32	40	42	42	0	0	35	40

Note: Source: Own elaboration

3.4   Analysis of Deformations by the Finite Element Method

With the input data presented in Table 7, we proceeded to perform the modeling and subsequent deformation analysis of the tailings dam.

The deformations obtained from the gravel columns are shown in Fig 4, Fig 5, and Fig 6. The displacements originated during the evaluation of the gravel columns are located at the foundation of the growth dam on the upstream slope of the embankment, reaching values in the order of 0.010×10-6 m and 47.638×10-6m. As for the maximum deformations and/or settlements, values between 36.575×10-6 m and 47.937×10-6 m were obtained. These results are mainly seen in the foundation of the embankment along the upstream slope just where the gravel columns are supported.

The results obtained determine that the displacements originated in the slope upstream of the dam is fundamentally translational because it has probably been caused by the reduction of the shear strength of the saturated tailings material or the product of the development of the liquefaction phenomenon.
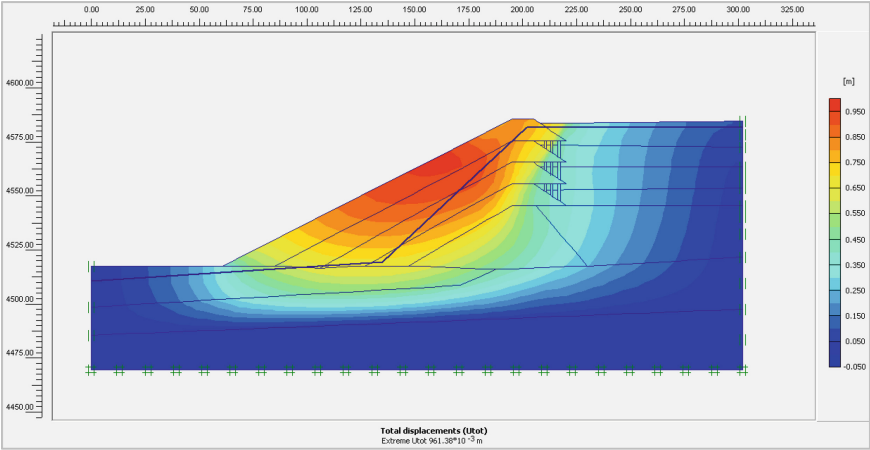
Fig. 4. Column Stresses. Source: Own elaboration
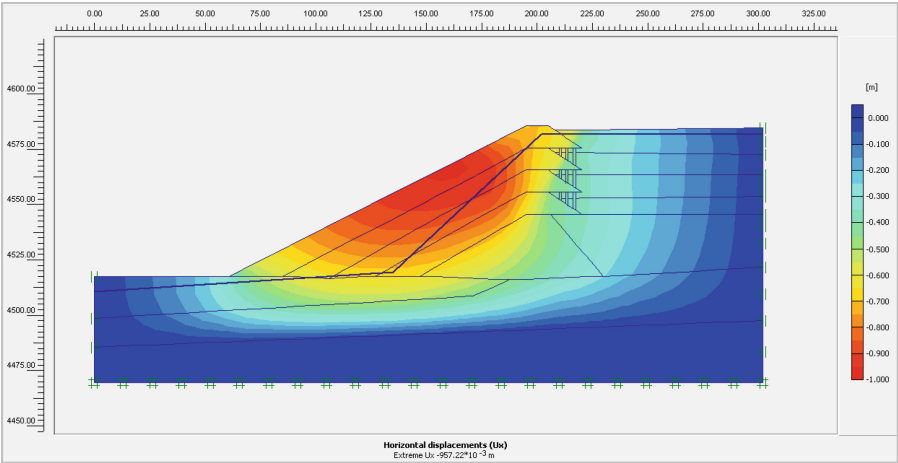

Fig. 5. Horizontal Displacement Ux. Source: Own elaboration

After obtaining the results of the deformation analysis. We proceed to perform the analysis of the percentage (%) of improvement of the gravel columns. The Table 7 Presents the improvement factor of the gravel columns applied in the tailings dam foundation.
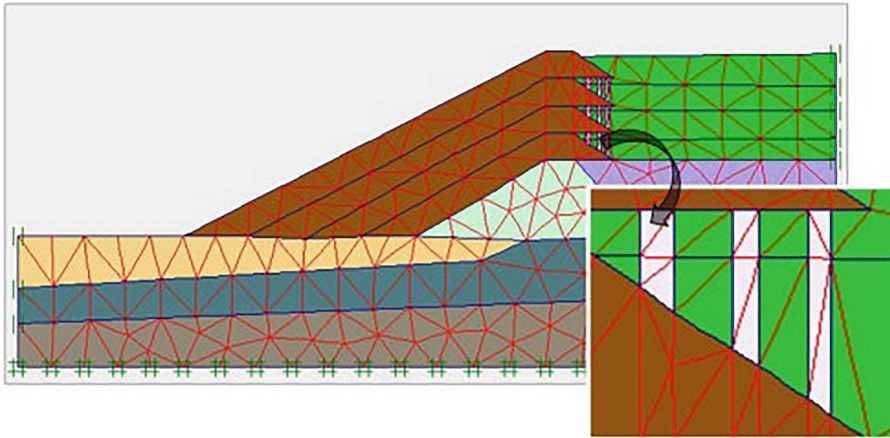
Fig. 6. 2D PLAXIS for finite element analysis of the gravel columns at the Centra Line Method tailings dam. Source: Own elaboration

Table 7. Results of settlements of gravel columns

Substitution factor $a_r = (D_c/D_e)^2$	Active thrust coefficient K_{ac}	Depth factor $f(v_s, a_r)$	Initial improvement factor n_0
17%	0.406	1.03	1.44
19%	0.271	0.96	1.86
21%	0.217	0.91	2.28

Source: Own elaboration

4   Conclusions

The results obtained indicate that the values of the maximum deformations and/or settlements are between 36.575 × 10-6 m and 47.937 × 10-6 m for a free bode of 2 m.

The determined diameters of the gravel columns in the foundation of the embankment are of 1.00 m and 1.2 m. Also, according to the results, the increase of the bearing capacity is perceived as the length of the column increases column length increases.

The results obtained for the improvement factor range from 1 to 3, with 1 being the minimum. Therefore, the improvement factor is verified to be optimal for the application of the gravel columns, having 2.28 as the maximum value.

It was determined that the maximum horizontal and vertical static displacements are 0.219 m at the base of the dam and 0.234 m at the crest, respectively. However, the relative horizontal displacements are in the order of 0.001 m to 0.025 m, while the vertical ones are from 0.034 m to 0.047 m.

As in our research the improvement is carried out on a soil stratum that has a fine content greater than 12%, it was proposed to use a geosynthetic (geotextile) in order to obtain a good lateral confinement and keep the structure fixed.

Finally, the deformation of the gravel columns installed in a tailings dam when a liquefaction event is generated has been analyzed and as a result improvements are obtained by consolidation in the short and long term, as well as the reduction of the development of the liquefaction phenomenon in the face of a seismic event or other movement that may affect the regrowth dam of a tailings dam of the central line method.

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