Proceedings of the 9th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2024)
Chestnut Conference Centre - University of Toronto, Toronto, Canada – June 13-15, 2024
Paper No. 206
DOI: 10.11159/iccste24.206

Evaluation Of The Stress History In A Tailings Dam Raising Stages: A Study Based On Finite Element Method (FEM) Methodology

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Abstract - Tailings dams are complex geotechnical structures that require a thorough analysis of their stability. The traditional method for assessing stability, the Limit Equilibrium Method (LEM), focuses on calculating the factor of safety (FS), but omits critical aspects such as the stress distribution along the regrowth process. The finite element method (FEM), based on the strength reduction technique (SSR), is an alternative that allows calculating the FS and understanding the real behavior of the slope, by analysing stresses along the different raises stage. In this study, the FEM method was used to simulate the Ancash tailings dam, Peru. The simulation allowed obtaining detailed information on the stress states to which the soil foundation is subjected at each stage of regrowth. The results obtained in terms of displacements and stresses provided a more accurate understanding of the failure mechanism to which the slope may be subjected. It was concluded that the FEM method demonstrated its superiority over the traditional LEM approach, as it provides a more complete and realistic appreciation of the behavior of the slope body at different stages of its development.

Keywords**:** Finite element, limit equilibrium, strength reduction, Plaxis 2D, numerical model, tailings, stress distribution

1. Introduction

Currently, tailings dams have emerged as a global concern due to their increasing incidence of failure. According to [1], of the 1800 mines recorded in the last 100 years, tailings dams show an alarming failure rate of 1.2%, compared to 0.01% for conventional water dams. This problem has become a critical issue worldwide. Although various methodologies exist to assess the stability of these structures, most focus on the Limit Equilibrium Method (LEM), which simplifies slope behavior by assuming simultaneous failure of the entire structure. However, this approach overlooks critical aspects, such as internal stresses generated by increased tailings loads during the different stages of construction. In addition, it represents a limitation in that it does not allow obtaining stresses at specific points of the structure, which omits crucial information to evaluate the stability of the dam.

To address this need to assess the stability of these complex structures more realistically, several authors have explored more advanced approaches, such as the Finite Element Method (FEM), supported by numerical models that provide a more accurate representation of the reality of the structures. For example, [3] demonstrated the successful application of the FEM approach using the Plaxis 3D program to evaluate the stability of rock slopes in a mine in Iran. This finding relates to research [5], which presented a methodology using FEM together with Plaxis 2D software to calculate deformations and locate shear forces in soft clay slope stabilization, concluding that FEM provides data on construction feasibility and reliability of stabilization alternatives when evaluating deformations. In addition, researchers such as [6], [7] and [8] analyzed the stability of road slopes in India using the FEM , evaluating multiple typical slopes. These authors concluded that FEM outperforms LEM in effectiveness, highlighting the importance of identifying zones of major stress concentration and displacements. In a similar vein, [9] and [10] reached the same conclusion when evaluating rock slopes. However, in all previous investigations, only the deformations in the last construction phase have been analyzed, resulting in obtaining only global results of the stresses, thus preventing a detailed knowledge of the evolution of the stresses in the structure. For this reason, this research focuses on providing a comprehensive assessment of the structural integrity of the dam by analyzing the historical stresses. This will allow detecting any significant variations that may indicate possible critical stress points, which is essential to prevent possible catastrophic failures and ensure the safety of the infrastructure, especially considering the potentially devastating consequences of a tailings dam failure. In addition, minor stresses will be analyzed in order to understand the overall response of the dam to different stages of regrowth over time. This will reveal deformations that, although they do not represent an immediate danger, could indicate load redistribution problems. To this end, strategic control points will be established along the central axis of each dam section. This methodology, supported by the FEM Method and Plaxis 2D software, will allow the development of a numerical model that will shed light on how the stresses in the dam have evolved from its initial construction to its current state of regrowth.

1.1. Study case

In this case study, information on the tailings dam slope in the Ancash region of Peru is used. The dam is currently undergoing regrowth and stores 28.4 million cubic meters of tailings. The dam is located at an elevation of 935 m, with a maximum height of approximately 105 m and a downstream slope of 1.75H:1V, along with three intermediate berms of 2 m wide, resulting in an overall slope of 5H:1V as shown in Fig. 1. The current conditions of the structure are not the most favorable, due to the constant heavy rainfall in the area, thus generating a high risk for the surrounding populations.

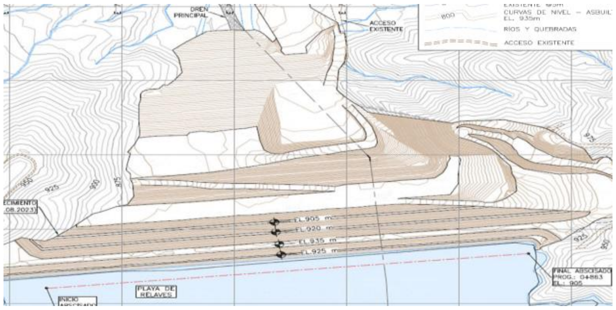


Fig. 1: Plan view of the study area.

2. Numerical simulations

A two-dimensional analysis was carried out, in which it is assumed that it is subjected to a plane state of deformations, this analysis section corresponds to section B-B as shown in Fig. 2. Section B-B was considered one of the most critical of the structure because it crosses the dam in one of its highest regions, in addition it presents compressible and saturated geotechnical materials, according to the reports obtained. For the configuration of the properties of the numerical model in Plaxis 2D, the "Plane Strain" model and "15-Noded" elements were chosen for greater accuracy in the representation of stresses and deformations. Also, constraints related to the model boundary conditions were identified which are x_{min}=0 m, x_{max}=400 m; y_{min}=770 m, y_{max}=940 m.

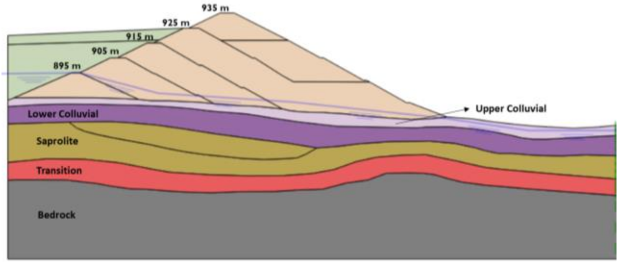


Fig. 2: Tailings dam analysis section

2.2. Definition of dam section materials.

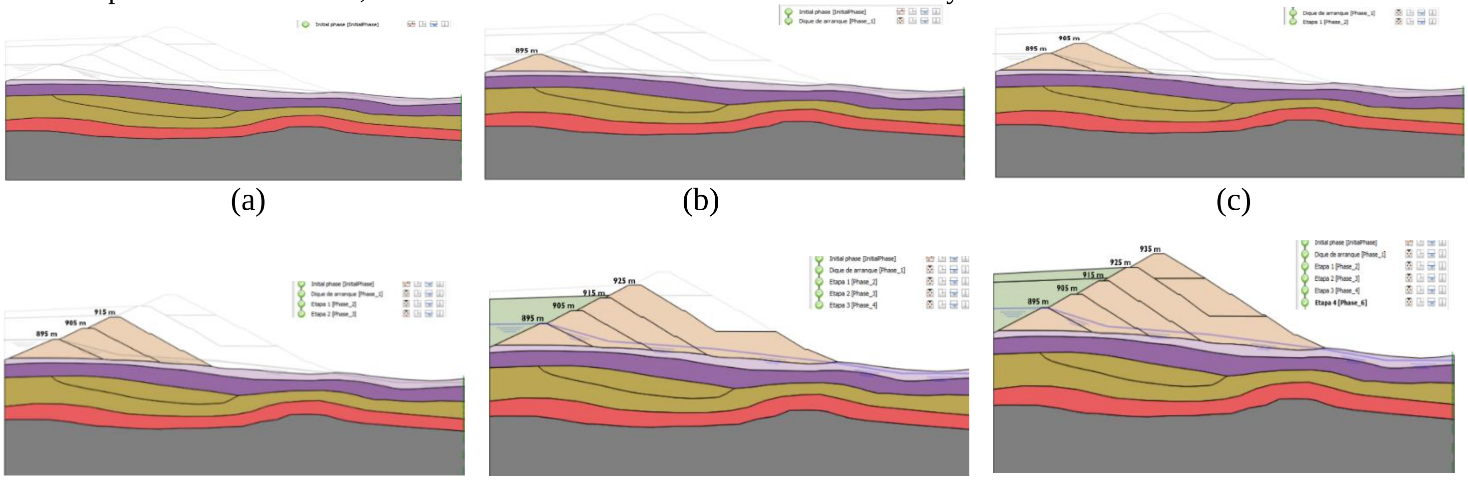
The geotechnical characterization of the materials that make up the dam was carried out mainly based on the Field Program 1 obtained from the reports of the company Demos. In the case of the tailings, there is no characterization in terms of strength, so the company provides us with geotechnical parameters. Additionally, it is considered that the material used for the construction of the dam is of the earthfill type. The soil foundation materials, the fill dam and the tailings were characterized according to the investigations obtained where samples were collected and sent to a laboratory for testing. The tests were as follows: Unified Soil Classification System (SUCS), specific gravity (GS), moisture content (W), liquid limit (LL), plastic limit (LP) and unit weight (PU). Tests results can be seen in Table 1.

Table 1: Geotechnical characterization of the soil foundation and dam fill

Material		SUCS	GS	W %	LL [%]	LP [%]	PU [kN/m3]
Upper Colluvial	🟪	GM-SM	2.70	13	30	20	20
Lower Colluvial	🟪	SM-SC	2.68	25	30	21	21
Saprolite	🟫	SM-SC	2.68	18	35	24	18
Transition	🟥	-	-	-	-	-	26
Bedrock	⬛	-	-	-	-	-	26
Starter Dam and Dam Raises	🟧	-	2.73	-	29.7	29.7	-
Lower and upper tailings	🟩	ML	2.82	29.4	NP	NP	14.4

2.3. Creation of construction stages

The construction process is divided into six fundamental stages. The first stage involves the formation of the soil foundation, detailed in Fig. 3a and composed of five analysis strata defined in Table 1. The initial stage addresses the starter dam at an elevation of 895 meters, observed in Fig. 3b. Stages 1 and 2 focus on the dam raise with elevations of 905 and 915 meters, respectively, as visualized in Fig. 3c and Fig. 3d. Stages 3 and 4 focus on the dam raise at 925-meter and 935-meter elevation, each with a corresponding tailings level, evidenced in Fig. 3e and Fig. 3f. Stage 4 encompasses all the construction phases of the structure and the soil foundation. This stage will allow us to calculate the total principal stresses σ_1 and σ_3 in the final phase of the structure, which will be crucial to evaluate the stress history.



(a) (b) (c)

(d) (e) (f)

Fig. 3: (a) Tailings dam analysis section; (b) Initial stage – Starter dam at 895m elevation; (c) Stage 1 - Dam raise at elevation 905m; (d) Stage 2 – Dam raise at elevation 915m;(e) Stage 3 – Dam raise at elevation 925m;(f) Stage 3 – Dam raise at elevation 925m.

2.4. Definition of Constitutive Models

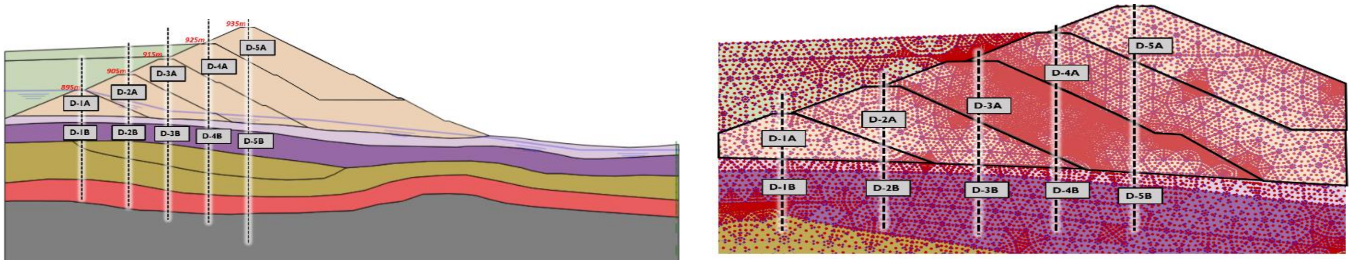
The numerical calibration of the geomechanically behaviour of the materials comprising the analysis section was performed using the Mohr-Coulomb constitutive model for all the soil foundation materials except for the bedrock, which follows the linear elastic model. The definition of the constitutive model and the input parameters for each material is based on the behavior recorded in the reports provided by the company Demos during the geotechnical characterization process. The mechanical parameters used in the model are presented in Table 3.

Table 3: Parameters of the Mohr-Coulomb

Material		E [kN/m^2]	ν' [-]	c' [kN/m^2]	ϕ' [°]	ψ [°]
Upper colluvial	🟪	50000	0.12	1	32	0
Lower colluvial	🟪	50000	0.13	1	32	0
Saprolite	🟫	80000	0.30	1	30	0
Transition	🟥	160000	0.30	150	32	0
Bedrock	⬛	450000	0.20	-	-	-
Upper and lower tailings	🟩	10000	0.35	0	12	0
Starter dam and dam raises	🟧	50000	0.35	5	35	0

2.5. Definition of control points

In this case, ten control points were defined, of which five were distributed in the dam fill according to each heightening of the dam (identified as D-1A, D-2A, D-3A, D-4A, D-5A), i.e. it was decided to place a control point in each of the raise of the dam in order to evaluate the stresses produced in each of them and thus be able to perform the historical analysis of stresses in the different construction phases of the dam under study. On the other hand, the remaining five control points were located in the soil foundation, specifically in the upper colluvial material, in order to be more conservative, since this material is one of the most critical in the stratigraphy. The location of these points also considered the dam raises (points D-1B, D-2B, D-3B, D-4B, D-5B). The projection of the control points can be seen in Fig. 4 (a,b)



(a) (b)

Fig. 4: (a) Overall view of the 10 control points; (b) Enlarged view of the 10 control points

2.6. Determination of total principal stresses

Since the purpose is to evaluate the stress history both in the dam fill and in the soil foundation according to each stage of raise, it is necessary to know the total principal stresses σ_1 and σ_3 for each of the monitoring points, this was carried out in the Plaxis 2D software. To determine each of the stresses in the Plaxis 2D software, the construction stages corresponding to each of the monitoring points were activated. Table 4 shows the summary of the stages that were activated in Plaxis according to the monitoring point and the corresponding dam raise. We will detail the process to be followed for the control point D-1A, since the procedure for the other points is the same. First, with the help of Plaxis 2D, we generate the total stress curve σ_1 or σ_3 (depending on the analysis to be performed) versus the calculation steps of the program. For this procedure we will perform the example of the major total principal forces σ^1 at the control point D-1A. Subsequently, we configure the stress curve to be generated by the program in such a way that these stresses are those that occur only in the stage corresponding to the control point under analysis. For example, for point D-1A, the stage to be activated is "Starting dam", which corresponds to elevation 895 msnm, as shown in Table 4 below. Once the stages corresponding to the control point under analysis have been selected, we obtain the stresses σ_1 generated, from which for the final evaluation we will take the stress of the last software calculation step as shown. In the same way, we obtained stresses σ_1 and σ_3 for the various control points by activating their respective construction stages. We recorded the stress generated in the last calculation step in an Excel database to properly interpret the results.

Table 4: Control points according to construction stages and regrowth.

Active Stages / Regrowth (msnm)	Control Points at the Dam Fill and Soil foundation				
	D-1A, D-1B	*D-2A, D-2B*	*D-3A, D-3B*	*D-4A, D-4B*	*D-5A, D-5B*
Initial Stage - 895	X	X	X	X	X
Stage 1 - 905		X	X	X	X
Stage 2 - 915			X	X	X
Stage 3 - 925				X	X
Stage 4 - 935					X

2.7. Total principal stress ratio σ_1/σ_3

In order to perform an analysis of the principal stress ratio σ_1/σ_3, it was decided to evaluate the soil foundation since there is a greater sensitivity compared to the dam fill; therefore, only the control points D-1B, D-2B, D-3B, D-4B and D-5B will be evaluated. Since an analysis will be performed considering the stresses in the soil foundation points in each of the construction stages of the dam, the criteria to activate these stages in the Plaxis 2D software to obtain the stresses can be seen in Table V, which shows that in all the construction stages, all the control points defined in the soil foundation will be evaluated. The process to obtain the stresses is the same as in the section "Determination of total principal stresses".

Table 5: Control points according to construction stages and regrowth.

Active Stages / Regrowth (msnm)	Control Points in the Soil foundation				
	D-1B	*D-2B*	*D-3B*	*D-4B*	*D-5B*
Start-up Dam - 895	X	X	X	X	X
Stage 1 - 905	X	X	X	X	X
Stage 2 - 915	X	X	X	X	X
Stage 3 - 925	X	X	X	X	X
Stage 4 - 935	X	X	X	X	X

3. Back-analysis

3.1. Total principal stresses σ_1/ σ_3

Table 6 shows the total major principal stresses generated at the control points located in the dam fill for certain construction stages. The stresses σ1 generated at control point D-1A for the construction stage of the starter dam is 136kN/m2; however, upon raising the dam to elevation 905 msnm (stage 2), the stresses σ1 increase 35.47 kN/m2 with respect to the previous stage, resulting in a σ1 of 172.40 kN/m2 generated at point D-2A. As for stage 2 corresponding to elevation 915 msnm, the stresses evaluated at control point D-3A increase by 52% with respect to the stresses generated at point D-2A, which is a significant increase due to the large number of tailings stored in this new stage. Finally, in the last stage corresponding to the regrowth at 935 msnm, the stress σ1 at point D-5A is 319.89 kN/m2, where a decrease can be observed with respect to the previous point, due to the fact that at that point the tailings storage is not taken into account, because when the model was evaluated the level of tailings was not yet significant. Likewise, Table 6 shows the minor principal stresses σ3 also in the control points located in the dam fill, the behavior of these stresses is similar to that of the major total principal stresses σ1, except for points D-2A and D-3A, since between these points there is a decrease in stress σ3, This is due to the fact that point D-2A is located very close to the water table, while point D-3A is farther away, so that the hydrostatic pressure of the water produces a decrease in the σ3 due to the oppositions of these pressures.

Table 6: Total major and minor major stresses in the dam fill

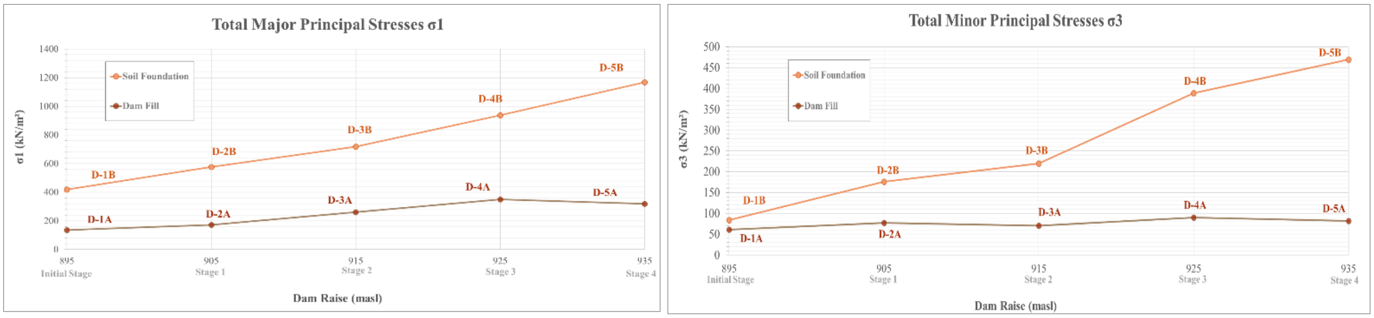
DAM FILL				
Control Point	Construction Stage	Dam Raise (msnm)	σ_1 (kN/m^2)	σ_3 (kN/m^2)
D-1A	Start-up Dam	895	136.93	61.00
D-2A	Stage 1	905	172.40	77.02
D-3A	Stage 2	915	261.40	70.50
D-4A	Stage 3	925	350.14	89.68
D-5A	Stage 4	935	319.89	81.48

Table 7 shows the major total principal stresses at the points located in the soil foundation, specifically along the colluvial material. It can be observed that at control point D-1A, the stresses generated due to the starter dam that reaches up to 895 msnm, is 419.99 kN/m2, while the stress at control point D2A due to the 905 msnm heightening, is 577.01 kN/m2, for the other control points in their respective stages of heightening an increase in stress σ1 can be observed, the average increase of stresses at one control point with respect to the previous one is 30%. This indicates that, for each 10-meter raise of the dam, the colluvial material suffers a stress increase of approximately 30%. Likewise, Table 7 shows the minor principal stresses σ3, which showed a similar behavior to the stresses σ1, since the stresses at points D-1B, D-2B, D-3B, D-4B and D-5B increase by 111%, 25%, 77% and 21% with respect to the previous one, which indicates that the colluvial soil supports higher stresses σ_3 as the dam raises.

Table 7: Total major and minor major efforts at the soil foundation of the dam

SOIL FOUNDATION				
Control Point	Construction Stage	Regrowth (msnm)	σ_1 (kN/m^2)	σ_3 (kN/m^2)
D-1B	Start-up Dam	895	419.99	83.58
D-2B	Stage 1	905	577.01	176.18
D-3B	Stage 2	915	718.93	219.79
D-4B	Stage 3	925	937.35	388.64
D-5B	Stage 4	935	1168.93	469.73

The stresses obtained were plotted and can be seen in Fig. 5a, showing their trend. For the dam fill it is observed that from the starting dam stage to stage 3 corresponding to elevation 925 msnm there is an increase, which is greater between stages 2 and 3, due to the presence of tailings; however, it is evident that for point D-5A in the last stage of regrowth there is a decrease in the stress σ1, which is attributed to the fact that the tailings do not generate any stress at this control point. Finally, it was evidenced that there are higher stresses in the soil foundation due to the weight of the dam fill. Likewise, the total minor principal stresses σ3 were plotted according to the corresponding regrowth, as can be seen in Fig. 5b. As can be seen, in the soil foundation the stresses σ3 increase in all the construction stages, which does not occur in the dam fill, since in construction stage 2 corresponding to the regrowth 915 msnm, the stress in the dam fill suffers a decrease due to the water table near point D-3A. At point D-5A, due to the fact that the tailings do not generate stresses at that point, there is a decrease, while at the points located at the soil foundation only increases occur.



(a) (b)

Fig. 5: (a) Total major principal stresses σ1 of the levee body and soil foundation.; (b) Total minor principal stresses σ3 of the levee body and soil foundation.

3.2. Total principal stress ratio σ_1/σ_3

An analysis was performed to evaluate the σ_1/σ_3 ratio in the soil foundation zone, as it was observed that there is a higher sensitivity in this zone due to colluvial material. Table 8 shows the stresses σ_1 and σ_3. Regarding the stresses σ_1, it can be observed that at control point D-1B the stress produced by the starter dam is 419.99 kN/m^2, while at the same point when the regrowth that reaches 905 meters above sea level is built, the stress increases to 528.55 kN/m2. Already for construction stage 3 that reaches elevation 915 msnm, the stress increases by 21.21 kN/m^2 with respect to the previous stage; however, for stage 3 where there is a significant presence of tailings, the increase is greater reaching a stress σ_1 of 851.21 kN/m^2. Finally, in the last stage of regrowth, which reaches 935 msnm, a stress of 937.87 kN/m^2 is produced. Similarly, the minor principal stresses σ_3 generated at the different soil foundation control points increase as the dam is being built.

Table 8: Major total principal stresses in the dam soil foundation

Construction Stages/Recreation (msnm)	σ_1 (kN/m^2)					σ_3 (kN/m^2)				
	D-1B	*D-2B*	*D-3B*	*D-4B*	*D-5B*	*D-1B*	*D-2B*	*D-3B*	*D-4B*	*D-5B*
Start-up Dam - 895	419.99	285.81	181.06	185.54	202.60	127.94	103.79	83.58	81.35	96.26
Stage 1- 905	528.55	577.01	452.15	286.18	206.55	161.29	176.18	137.82	105.57	99.72
Stage 2- 915	549.76	757.21	718.93	617.34	432.38	168.18	231.55	219.79	188.57	133.06
Stage 3- 925	851.21	955.78	953.34	937.35	853.88	454.71	440.73	395.63	388.64	372.93
Stage 4- 935	937.87	1056.46	1082.90	1150.87	1168.93	481.34	464.78	435.44	454.24	469.73

Fig.6 shows the results obtained for stress σ_1 and σ_3 for each of the soil foundation control points. As can be seen, they have a directly proportional relationship, as the stress σ_1 increases, the σ_3 also increases, this is due to the fact that in each of the stages a greater amount of dam material is added to make the embankments and at the same time, a greater amount of tailings are stored, which is reflected in the fact that the soil foundation supports greater stresses, both minor and major.

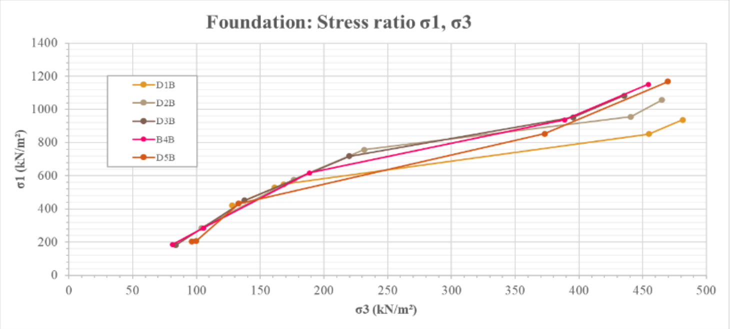


Fig. 6: Stress ratio σ_1 and σ_3 in the soil foundation

4. Conclusion

First of all, the variation of the principal stresses along the different stages of regrowth can be highlighted, with a variation being observed with the increase of tailings. This highlights the importance of considering the temporal of stresses for a complete assessment of dam stability. Also, the importance of a correct assignment of the geotechnical parameters must be considered, since the geotechnical properties of the soil play a crucial role in the response of the dam to the applied loads, in this case the heightening and tailings. Understanding these properties is essential for a correct and accurate analysis of stability indicators, such as stresses, otherwise the results obtained would not be credible or realistic and, in turn, Plaxis 2D would not be able to perform the calculations correctly. Furthermore, it is of utmost importance to know the constitutive models and to choose the most appropriate one according to the conditions of the dam under study, as observed in the present case, Mohr Coloumb was mostly used in drained conditions.

From the evaluation of the historical total principal stresses in the tailings dam, it was observed that the variation of these stresses in some cases was due to the presence of tailings or in other cases to the water table. Evidently, the stresses were much higher in the control points that were defined in the soil foundation compared to those located in the dam fill, since the soil foundation supports a greater weight.

Finally, this study provides a good contribution, since it provides a solid basis for the design of tailings dams, highlighting the importance of evaluating the evolution of stresses during each construction phase. The results offer highly relevant information for other similar projects, such as future enlargements of the analysed dam. It also highlights the need for careful management of geotechnical conditions in tailings storage structures.

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