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A COMPREHENSIVE DESIGNATION OF TAILINGS STORAGE DAMS – A CASE STUDY OF THE SANGAN IRON MINE PROJECT IN IRAN

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Abstract: Tailings storage dams are considered to be one of the most essential facilities in mining projects. In metal mines, after blasting the rocks, the blasted ore is transferred to specific industrial plants for processing operations. During such operations, a large amount of pollutant tailings are inevitably generated. Those tailings must be safely stored in previously constructed storage dams. In this research, a storage dam has been designed to store the tailings of the Iranian Sangan Iron Mine project. The geometry and capacity of the dam were designed to minimize the construction works and to maintain the stability of the facility. To assess the stability of the proposed storage dam, a numerical analysis was performed for both static and dynamic loading conditions. The results showed that the embankment is stable under these two different loading conditions. Hence, the proposed design can be successfully adopted for the construction of a tailings storage dam in the project. In addition, the methodology presented in this research can be used by geotechnic engineers to design safe tailings storage dams in mining projects.

Keywords: tailings dam, waste disposal, mining impacts, numerical modelling, slope stability analysis

1. Introduction

The large volume of waste tailings produced by the mining industry has always been an important issue. Such tailings may lead to the contamination of the lithosphere, and hydrosphere. For instance, the acid drainage, the transfer of dangerous elements to the surface and underground water sources, and the elimination of the natural landscapes are some of the corresponding environmental impacts [1, 2].

In recent years, one of the most significant issues of the global mining industry has been the storage of tailings produced during extraction and processing operations. In order to store the produced tailings, storage dams must be built in the vicinity of the mining sites. Due to the nature of the tailings stored in the dam, any leakage or failure of the dams will have adverse environmental consequences. In some conditions, the occurrence of those environmental impacts even leads to potential biological damage in the region for a long time [3–6].

As well as those potential environmental impacts, there have been a number of reports about the mechanical failure of tailings dams [7–11]. The most frequent dam failures have been reported in the US and European countries [8]. However, those reports are a minor part of the occurred failure problems in mines since mining companies do not report such accidents in many countries. This is mainly due to the governmental regulations or the fear of the companies about the consequences of the announcement of such events. Some dam failures stem directly from the design process. Hence, during the early designation, a good understanding of the in situ geological, and geotechnical characteristics of the site is needed. Moreover, to predict the potential failures in the dams, numerical simulations can be effectively utilized [12].

The Sangan iron mine is near the town of Sangan in northeastern Iran. In the mine, a storage dam had been already constructed to store the tailings produced during operations. However, due to the new explorations in the area, there is a need to construct new tailings dam storage. The objective of this research is to address the design of a new tailings storage facility for this mine. The storage dam will be constructed by a combination of the excavation and development of an embankment immediately downstream of the excavation.

The storage dam has been designed so that it can be constructed in three stages, attempting to evenly distribute the amount of excavation, the excavation fill, and the construction schedule. This will reduce the initial capital costs for the facility development. Stage 1 will be constructed to accommodate two years' worth of tailings storage (approximately 3.5 Mm^3), after that the next stage will be required to ensure the tailings deposition can continue without concern of exceeding capacity of the first stage embankment dam. Stage 2 will have the capacity to store approximately an additional 6 Mm^3 and will store tailings production from Year 2 to approximately Year 6. Stage 3 will be the final stage, storing an additional 6.6 Mm^3 and extending the life of the cell to a total of approximately 11 years.

Apart from the construction procedure, the stability of the dam embankment has been analyzed under both static and dynamic loading. Dynamic analysis of storage dams are essential in the dam designation phase [13]. The numerical simulations were carried out in SLOPE/W software. The safety factor of the embankment has been calculated in different conditions. The obtained results confirm the stability of the proposed storage dam for the mine.

2. Project description

2.1. Geographical location

The site is located in the province of Khorasan Razavi in northeast Iran, approximately 20 km east-northeast of the city of Sangan. Figure 1 illustrates the location of the conducted project.

2.2. Geology and morphology description

The Sangan iron mine is situated on a broad alluvial plain in the south of the Sangan Mountains. The plain has a gentle slope from the north towards the south. The slope of the plain ranges between 2% and 5% from the north towards the southwest. In addition, water erosion has caused channeling in the plain. The elevation in the vicinity of the proposed tailings storage dam varies between 1010 m and 1120 m from the southernmost to the northernmost, respectively.

The proposed tailings storage dam is situated in the south of other facilities of the mine. Moreover, the iron-containing reserves are located in the mountainous terrain to the north of the tailings storage dam. The ore body is situated approximately 5 km from the tailings facility and extends up to an elevation of approximately 1700 m.

The Sangan mine is situated in highly tectonically active formations. The main ore body is in the form of Hematite (Fe_2O_3) and Magnetite (Fe_3O_4) minerals. From the geological era perspective, the igneous rocks date back to Oligocene to Precambrian. In the area, large-scale faults are presented as well.

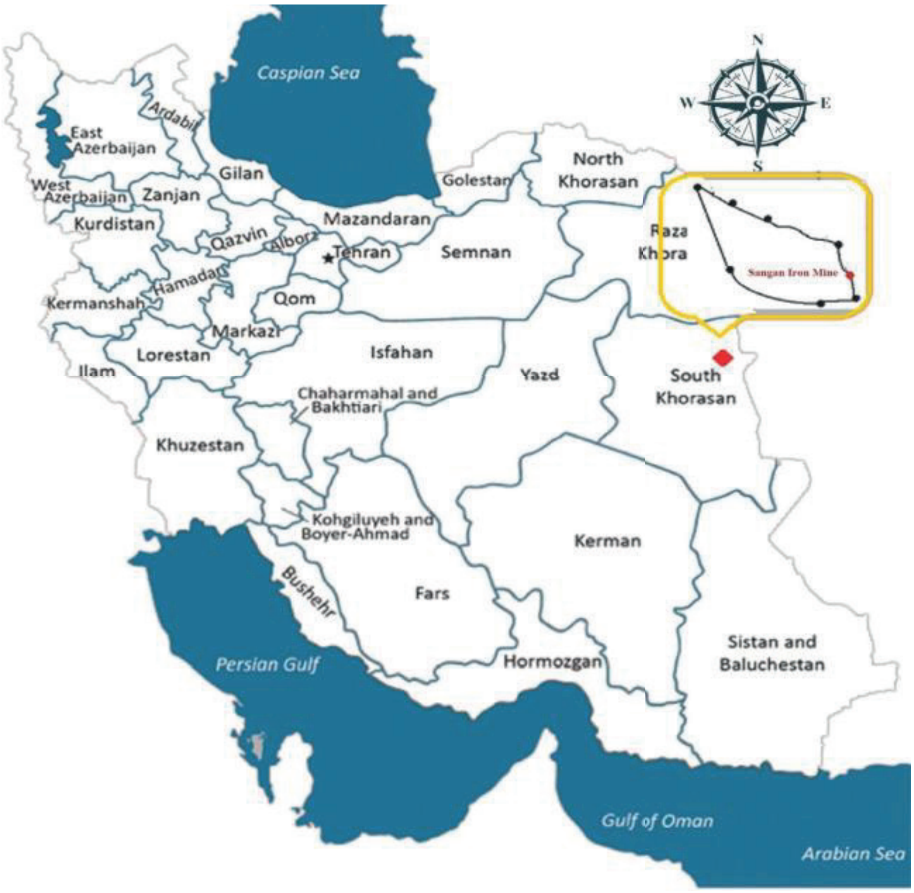

Fig. 1. The location of the Sangan iron mine project

The alluvial soils consist of sand and gravel with various fine contents that are dense, and exhibit evidence of cementation that may be associated with the varying percentages of gypsum in the local soils. Moreover, the level of the groundwater was reported nearly 25 m below the surface of the ground.

2.3. Geotechnical characteristics

The subsurface conditions were assessed by both test pitting and drilling boreholes. Four boreholes were drilled in the vicinity of the proposed storage dam. The objective of the boreholes was to study the conditions at the proposed location, and to evaluate the soil as well as groundwater characteristics. Standard Penetration Test (SPT) blowcounts were used to measure the density of the subsurface soils. Moreover, the hydraulic conductivity testing was carried out at two of the four completed holes. Two standpipe piezometers were installed in two separate boreholes.

The groundwater characteristics were regionally investigated [14, 15]. The investigation identified an aquifer within the alluvial deposits derived from the adjacent uplifted proterozoic blocks. The regional aquifer did not extend to the mine site or the proposed tailings storage dam area [14].

Furthermore, based on the results of the samples, the gypsum content of the in-situ soil was around 2%. It is noticeable that Gypsiferous soils containing in excess of 6% of gypsum are typically not deemed acceptable for use as structural fill [16].

The geotechnical information derived from the above-described investigations was the basis for the main subsurface condition conclusions made for the dam design.

3. Tailings dam design

3.1. Construction process

Due to the gentle sloping alluvial plain on which the tailing storage facility will be located, a combination of excavation and earth-filled embankment configuration is envisaged to be the most logical and feasible method of constructing the storage dam. The excavated material from the respective dam will be used to construct the three embankments. Figure 2 shows a plan of the dam with three designed cells, namely Cell 1, Cell 2, and Cell 3. All of the produced tailings should be pumped to the tailing storage facility by spigotting and then deposited in these cells. A diversion ditch and a diversion berm have also been designed to control and divert the surface runoff from the catchment basin in which the tailings dam will be located. Further design considerations and recommendations that support the feasibility level of the engineering efforts are presented in this research.

In this study, only the designation of Cell 1 is presented. The designation of the Cell 2 and Cell 3 will be conducted after completely filling Cell 1 with the maximum amount of tailings. In other words, it is more reasonable to design Cell 2 and Cell 3 based on the future production volume of tailings by the processing plant. A plan view along with a vertical cross-section of Cell 1 are shown in Appendix A and Appendix B, respectively.

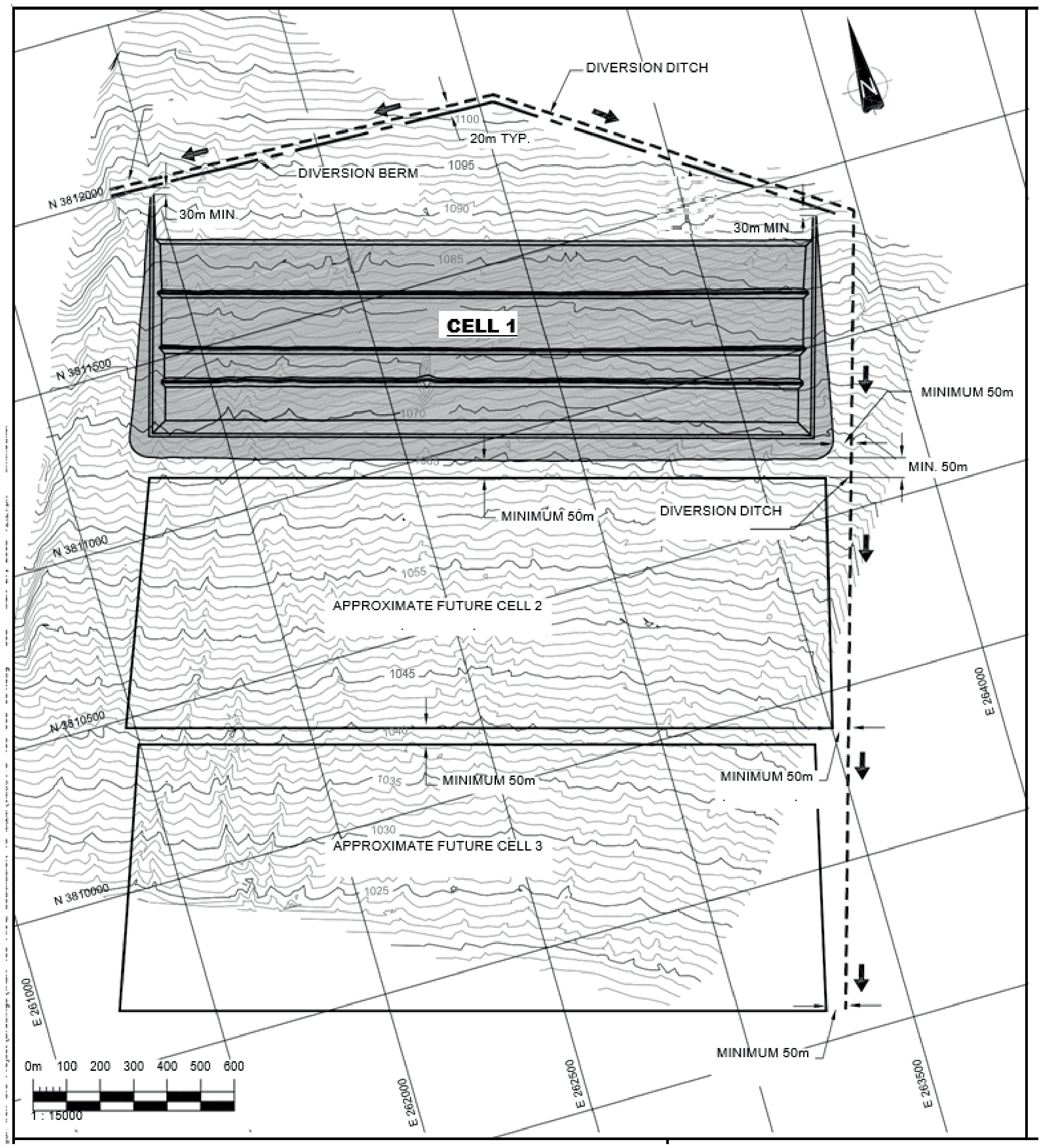

Fig. 2. The geometry of the proposed tailings dam. Note that the dam has been divided to three cells: Cell 1, Cell 2, and Cell 3

3.2. Dam sizing considerations

Under normal operating conditions, Cell 1 consists of tailings, runoff (between the cell and the water diversion system), direct precipitation, and diversion ditch leakage (assumed to be 5%). The criteria used to determine the appropriate size for the tailings storage facility was based on the tailings production rates and assuming that the water diversion system would be capable of redirecting runoff water from a 100-year event with a 24-hour duration.

The whole dam is expected to accommodate a minimum of 16.1 Mm^3 of tailings in approximately 11 years of storage at envisioned milling rates. The storage quantities per stage of the proposed dam development are shown in Table 1.

Regarding the dimensions of Cell 1, it is supposed that the beaches slope increased at an angle of 1% from the embankment towards the end of the facility. This slope is considered for the crest planning, so during the wet season, the water pound would be developed at the north of the impoundment.

Following completion of the embankment construction, an accurate as-built survey must be conducted. The beach slope should also be monitored to confirm the 1% slope and development of the water pond. An Elevation versus Storage Volume curve was generated for Cell 1 using the prismoidal method to calculate the volumes between two surfaces. The EaglePoint and AutoCad software packages were used to determine the elevation storage curve. Storage volumes were calculated from the curve presented in Figure 3.

Cell 1 has been designed to include 1 m of freeboard to protect overtopping of the dam by flooding and wave run-up; however, due to the natural slope of the ground, 2 m of freeboard is required for Stage 1 development asthe external embankment arms on the eastern and western ends of the storage facility would not entirely encompass the tailings, or the water pond. Crest elevations for Stages 1, 2, and 3 have thus been determined to be 1079 m, 1086 m, and 1092 m, respectively.

Table 1. Tailings storage per stage of development

Construction Stage	Tailings Storage Capacity [Mm^3]	Years of Operation
Stage 1	3.5	2
Stage 2	6.0	4
Stage 3	6.6	5
Total	16.1	11

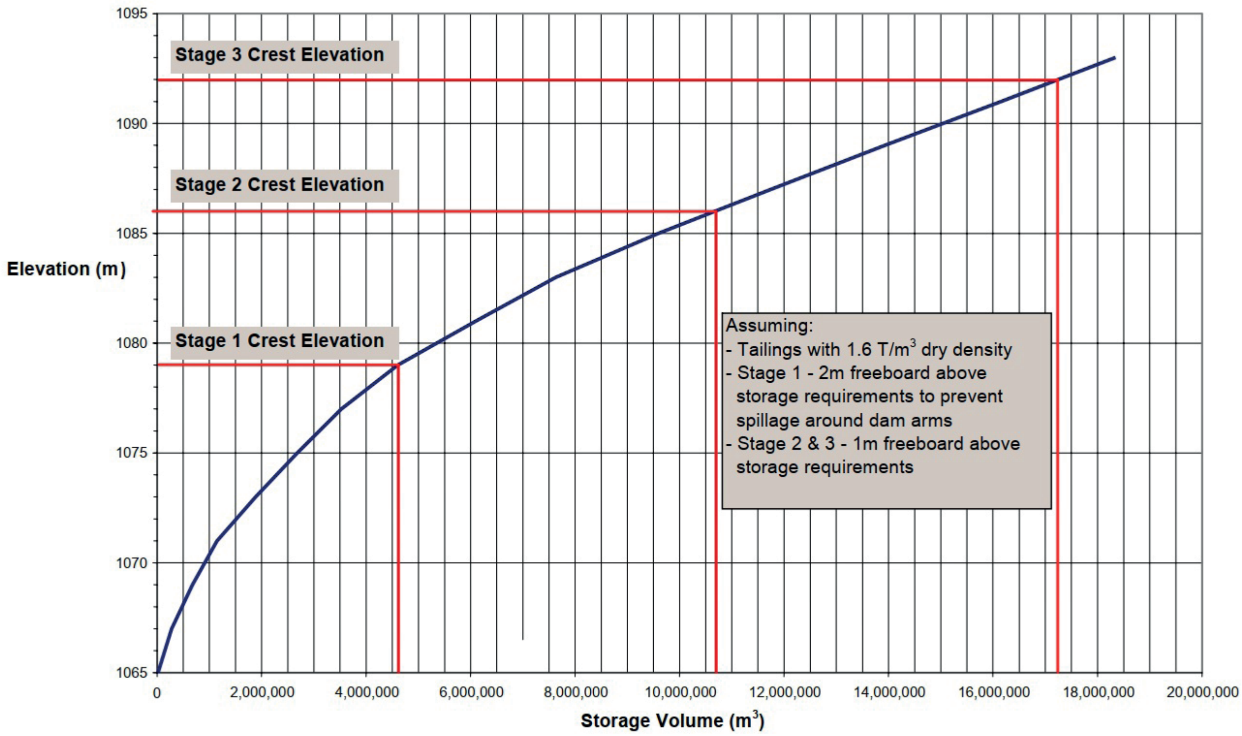

Fig. 3. Elevation-storage curve of the proposed Cell 1

4. Stability evaluation of tailings dam

The stability assessment for the embankment of the Cell 1 has been considered for two general scenarios. Scenario one strictly addresses the stability of Stage 1 during operations. The second scenario considers both the operational and long-term stability of Stage 3 (final configuration) of the Cell 1. Figure 4 shows a vertical cross section of the modeled embankment in Stage 1 and Stage 3.

Variable factors will affect the realized phreatic regime within the embankment and include both the arid climate and methodology of the tailings deposition. The primary uncertainty in the stability assessment was the phreatic condition within the filled embankment at the various stages of the Cell 1 development. For this reason, the surface modelled for Stage 1 was conservative (considered to be a relatively high surface within the embankment).

On the other side, for the analyses related to the Stage 3 configuration, two phreatic surfaces were used that were deemed potential representative bounds. Stage 2 was not analyzed because Stage 3 is considered to be more critical as it will be susceptible to both operational (short-term) and long-term stability (post closure). Short-term stability for Stage 2 is expected to be essentially identical to that of Stage 3. Stage 3 has been assessed using both an estimated relatively high phreatic surface as well as a more likely low phreatic surface within the embankment. Due to the design similarities between the Stage 2 and Stage 3, results obtained from the Stage 3 are considered applicable to Stage 2. Any further stability work deemed required prior to or during construction of the subsequent stages should use the behavior of the tailings embankment observed during the operation of Stage 1.

Static stability analyses were completed for the downstream portion of the starter dam (Stage 1). Both stability analyses, including static and pseudo static, were completed for the downstream portion of the final embankment configuration (Stage 3) of the Cell 1 embankment. The static stability analyses were also carried out for the internal excavation berms within the impoundment that will be created during the excavation activities associated with the material development. These internal excavation berms do not pose any long-term stability concerns as they will be covered with tailings as the impoundment is filled.

The following sections present the methodology, assumptions, and results of the stability analyses.

4.1. Safety factor design criteria

The static stability of the Cell 1 embankment and internal excavation berms was quantified in terms of a factor of safety (FoS) determined using 2D limit equilibrium analyses. The FoS design criteria for the dam and interm berms are as listed below and conform to the International Committee on Large Dams (ICOLD) guidelines which is used throughout the world as the following criteria:

- FoS > 1.3 for the short-term construction conditions (when excess, construction-induced pore pressures might exist within the dam fill).
- FoS > 1.5 for the long-term steady state (i.e., closure) conditions.

The pseudo-static stability analysis for the downstream portion of Stage 3 was evaluated using a peak ground acceleration (PGA) of 0.3 g and a design earthquake magnitude of 7.5.

4.2. Liquefaction potential of foundation

Liquefaction is a phenomenon where loose, saturated, generally cohesionless soils undergo significant strength and stiffness loss in response to the strain softening derived from the transient loads such as earthquake ground motions [17].

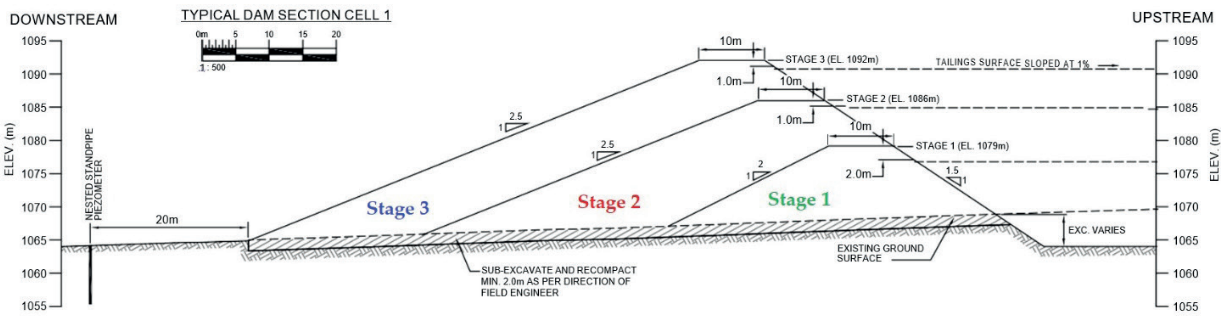

Fig. 4. A vertical cross-section of the Cell 1 embankment during the different completion stages, i.e. Stage 1, Stage 2, and Stage 3. The numerical modelling was performed for Stage 1 and Stage 3

Liquefaction of both foundation and embankment materials is not considered to be a threat to the embankment stability at the Sangan site because of the in-situ density of the foundation soils and the prescribed density of the embankment fills. In addition, for the in-situ foundations, the water level below the impoundment is located approximately 25 m to 30 m below the existing ground surface, and the soil above the water table is unsaturated. As a result, liquefaction assessment was not deemed necessary for the proposed development site.

4.3. Stability modelling assumptions and methods of analysis

The computer program SLOPE/W was utilized to determine the safety factors applying the method of slices (limit equilibrium theory) with the Morgenstern–Price, half sine interslice force function. The limit equilibrium methodology used assumed that:

- The materials behave as Mohr–Coulomb materials (e.g. that the strength will be a function of the effective stress level, apparent cohesion, and the internal friction angle).
- The safety factors are the same for all slices (slices are in equilibrium).

The method of slices breaks a given potential slip surface up into a specified number of slices. Each slice is subjected to its self-weight, the downslope component of which creates a driving force, and the normal component which contributes to the shear resistance of the slice, any external loads, and the forces, both vertical and horizontal, exerted on the slice by neighboring slices. All downslope components of these forces combine to create the driving force, and the available shear resistance of the slice creates the resistance. The factor of safety for any given slice is the resistance divided by the driving force.

In order to model earthquake loading, pseudo-static analyses based on the limit equilibrium theory were carried out. The Morgenstern–Price method of slices was used, and an additional horizontal driving force was applied. A semi-empirical approach was utilized to estimate the deformation to which the embankment might experience if subjected to design earthquake loading [18]. This is a screening-level method used to determine whether more complex dynamic analyses are needed.

The Makdisi–Seed approach requires the determination of the critical yield acceleration, k_y, which represents the seismic coefficient that creates a force that affects the safety factor of unity as determined using limit equilibrium slope stability analysis. This yield acceleration is then compared to the site seismicity (e.g., PGA) and an empirical estimate of the resulting deformations is obtained. Yield accelerations were determined using SLOPE/W for each of the critical failure surfaces and are discussed in more detail in the Chapter 5.3.

All of the modelled soil types were assumed to behave as Mohr–Coulomb materials. The parameters pertinent to the soil material used during the analysis are tabulated in Table 2.

Table 2. Soil material properties used in stability analyses

Material	Bulk Unit Weight [kN/m^3]	Friction Angle [°]	Undrained Shear Strength Ratio
Embankment Fill	21.5	34	N/A
Upper Layer	21.5	34	N/A
Lower Layer	20	34	N/A
Tailings	16	0.1	0.1[1]

[1] Strength determined as a function of overburden where $S_u/\sigma'_v = 0.1$, where:
S_u = undrained strength,
σ'_v = effective vertical consolidation stress.

The numerical modelling was carried out on an embankment section that had the maximum height. Several specified slip surfaces through the tailings, dam fill material, and through the dam crest were assessed. The analyses also included computer generated grid and radius slip surfaces, which attempts to find various slip surfaces with the lowest stability situations within a given range. More detail is presented in the following sections.

5. Results of numerical simulations

5.1. Static stability analysis of Stage 1

As previously discussed, the stability of Stage 1 was assessed with a relatively high phreatic surface entering the embankment at the maximum elevation of the tailings, and exiting the embankment near the Stage 1 toe. The phreatic surface modelled within the Stage 1 embankment is likely more conservative than those conditions that will actually occur during the operations. The phreatic surface developed within the embankment will be a function of how the facility will be operated. For this reason, as the operating criteria are only truly established upon the commencement of the project, a conservative approach was adopted in choosing the phreatic surface for the Stage 1 embankment.

The specified slip surfaces within the embankment were estimated and analyzed to complement the numerous computer generated Grid and Radius solutions. Seven specified slip surfaces and the candidate phreatic surface are shown on Figure 5.

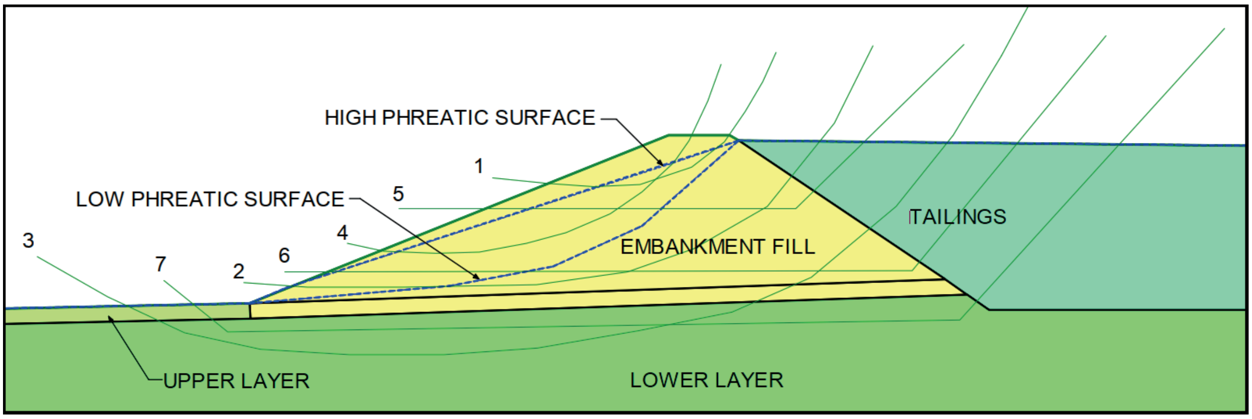

Fig. 5. Stage 1 specified slip surfaces and phreatic surface

The factors of safety computed for the static analysis of Stage 1 are presented below in Table 3. The table does not include the factors of safety computed for the internal excavation berms; however, the berm configurations do meet or exceed the operating design criteria factor, or FoS of 1.3. As it can be seen in the below table, all factors of safety are higher than 1.3 implies that the embankment is stable in stage 1. The critical FoS was for specific surface 4 equal to 1.7.

Table 3. Soil material properties used in stability analyses

Stability Scenario	Candidate Failure Surfaces	Computed FoS	Design Criteria FoS
Stage 1	Grid and Radius	1.8	1.3
	Specified Surface 1	3.6	1.3
	Specified Surface 2	3.8	1.3
	Specified Surface3	3.8	1.3
	Specified Surface 4	1.7	1.3
	Specified Surface 5	12.6	1.3
	Specified Surface 6	6.8	1.3
	Specified Surface 7	4.8	1.3

5.2. Static stability analysis of Stage 3

Static stability analyses were also completed for Stage 3 of the Cell 1 embankment. The analyses considered two different scenarios, each having different phreatic surfaces within the embankment that may develop based on the operational procedures and seepage behavior. Scenario 1 included a conservatively high phreatic surface. This phreatic surface entered the embankment at the maximum elevation of the tailings, and exited the downstream face of the embankment 2 meters above the round surface. The phreatic surface assumed for the second scenario entered the embankment at the maximum elevation of the tailings, and exited the embankment at the toe. Moreover, it was slightly concave in shape. Both phreatic surface conditions are shown on Figure 4. The specified slip surfaces analyzed for both scenarios are similar to those shown in Figure 4.

The static factors of safety computed for the two scenarios of Stage 3 are presented in Table 4. As noted, the factors of safety for the internal berms within the impoundment are not presented in the table but all met or exceeded the operating design criteria of 1.3. According to Table 4, all factors of safety satisfy the stability of the embankment in Stage 3. The critical specified phreatic surface was surface 4 for Scenario 1, with a safety factor equal to 1.6.

Table 4. Static stability analyses results of Stage 3

Stability Scenario	Candidate Failure Surfaces	Limit Equilibrium FoS	Design Criteria FoS
Stage 3 Scenario 1 – High Phreatic Surface	Grid and Radius	1.6	1.5
	Specified Surface 1	2.6	1.5
	Specified Surface 2	1.7	1.5
	Specified Surface3	1.9	1.5
	Specified Surface 4	1.6	1.5
	Specified Surface 5	4.8	1.5
	Specified Surface 6	3.8	1.5
	Specified Surface 7	3.2	1.5
Stage 3 Scenario 2 – Lower Phreatic Surface	Grid and Radius	1.8	1.5
	Specified Surface 1	2.8	1.5
	Specified Surface 2	2.4	1.5
	Specified Surface3	2.3	1.5
	Specified Surface 4	2.0	1.5
	Specified Surface 5	5.6	1.5
	Specified Surface 6	4.6	1.5
	Specified Surface 7	3.7	1.5

5.3. Seismic deformation of Stage 3

The Makdisi-Seed approach allowed an estimate of potential permanent dam crest deformation as a result of the design seismic loading. This was completed for each specified candidate failure surface for Stage 3 of the embankment using the PGA of 0.3 g. The results of the deformation estimates are tabulated in Table 5. According to this table, it can be deduced that the maximum estimated crest displacement is 11 cm for the specified failure surface of 4. However, even with this deformation, the embankment was stable during the applied seismic loadings in numerical simulation.

Table 5. Pseudo static stability analyses results of the embankment in Stage 3

Stability Scenario	Candidate Failure Surface	Static FoS	Yield Acceleration k_y	Ratio of Yield Acceleration to Maximum Average Acceleration k_y/k_{max}	Estimated Crest Displacement [mm]
Stage 3	1	2.6	0.375	1.25	<0.5
	2	1.7	0.180	0.60	10.0
	3	1.9	0.190	0.63	9.0
	4	1.5	0.155	0.52	11.0
	5	4.8	0.370	1.23	<0.5
	6	3.8	0.305	1.02	<0.5
	7	3.2	0.280	0.93	<0.5

6. Discussion

A successful designation of the mining tailings storage dams needs to consider different aspects, especially the geological and geotechnical characteristics of the preplanned land for the dam construction [19]. Furthermore, appropriate capacity and geometry of the dam must be determined based on the mine operational production as well as the reduction of the capital cost. Moreover, analytical or numerical simulations can be carried out to estimate the dam embankment stability during various static and dynamic loading conditions. Some previous studies have reported the close agreement between the numerical analysis results and the field observations during seismic events [20].

In the current study, a new tailings storage dam for the Sangan iron mine project was designed, and all above-mentioned aspects were considered. The results of the stability analysis indicated that the embankment will be stable under different loading conditions. Moreover, the current study confirms the effect of both static and dynamic loadings on the stability of the mining tailings dams as previously reported by some researchers [20–27].

The stability analysis also indicated that if a low phreatic surface was maintained within the fill embankment, the structure would be stable for the subsequent stages of the dam development; however, the results also indicated that the design criteria may not be readily achievable if a very high phreatic surface is allowed to develop within the embankment. Therefore, monitoring the dam will be important in maintaining the stability criteria for the embankment.

In addition, as observations are made during the operational phase of Stage 1, the performance of the embankment and seepage characteristics can be evaluated. If the observations suggest that the phreatic surface was too high within the embankment, solutions to ensure the stability of the embankment may be required. Conceptually, increasing the stability of the embankment may be carried out by reducing the downstream slope from what is currently proposed. Furthermore, the installation of a drain would be a less expensive method for lowering the phreatic surface within the fill embankment. Further evaluation for the design and configuration of the subsequent stages will need to be reviewed by the geotechnical engineer once Stage 1 performance is evaluated. It should be noted that conducting the stability analysis of the dam is not only necessary during the active operational time of the dam, but also during the abandonment of the facility [19].

7. Conclusions

In this research, a new tailings storage dam was designed for the Sangan iron mine project located in Khorasan Razavi province in Iran. The incentive for such a design was that the previous storage dam of the mine has been completely filled by the produced tailings. The new proposed designation has been established based on the ore production plan, in-situ geological and geotechnical characteristics, and on-site engineering experience. As well as the geometry and storage capacity of the dam, numerical simulations were also performed to analyze the stability of the dam embankment under both static and dynamic loading conditions.

Based on the numerical results, it was deduced that the dam embankment is stable under both static and dynamic loadings. All of the calculated safety factors were higher than the minimum required safety factor considered for the dam design. The lowest safety factor for the embankment belonged to the pheratic surface number 4. This pheratic surface was the surface whose start and the end spots were situated entirely on the embankment slope; however, even if such a pheratic surface occurs in the embankment slope, the safety factor is higher than the minimum allowable one. Hence, the stability of the embankment is guaranteed during its operational lifetime.

In addition, an accurate survey of the tailings surface will be required to calculate the annual volume of the tailings deposited. Given this information, coupled with the tailings tonnage from the mill, the density of the tailings can be calculated, and the anticipated volume of the deposited tailings can be verified to ensure there will be appropriately staged storage for the tailings. Regular monitoring of the dam impoundment will verify the assumptions used in the design phase. Moreover, it will provides opportunities for optimization during the production phase of the project.

In the Sangan region, intense rainfalls periodically occur. Thus, for future works, it is recommended that the influence of such intense rainfalls on the stability of the dam be analyzed. Unusual rainfall incidents have been indicated as the reason for some mining tailings dam failures [7].

As well as the Sangan iron mine project, the current study can be utilized by other mining companies to design and construct safe tailings storage dams.

Author Contributions: "Conceptualization, M.S.; methodology, M.S.; software, M.S.; validation, M.S.; formal analysis, M.S.; investigation, M.S.; resources, M.S.; data curation, M.S.; writing – original draft preparation, M.S. and K.M.; writing – review and editing, M.S. and K.M.; visualization, M.S. All authors have read and agreed to the published version of the manuscript."

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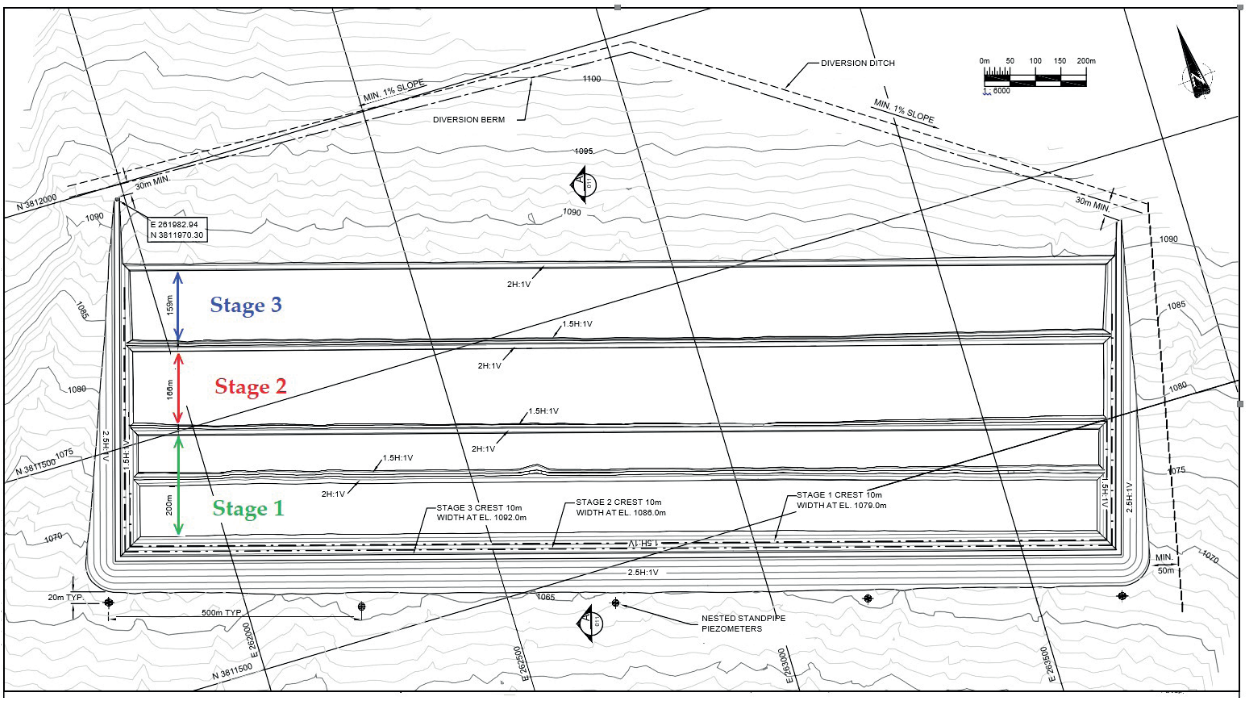
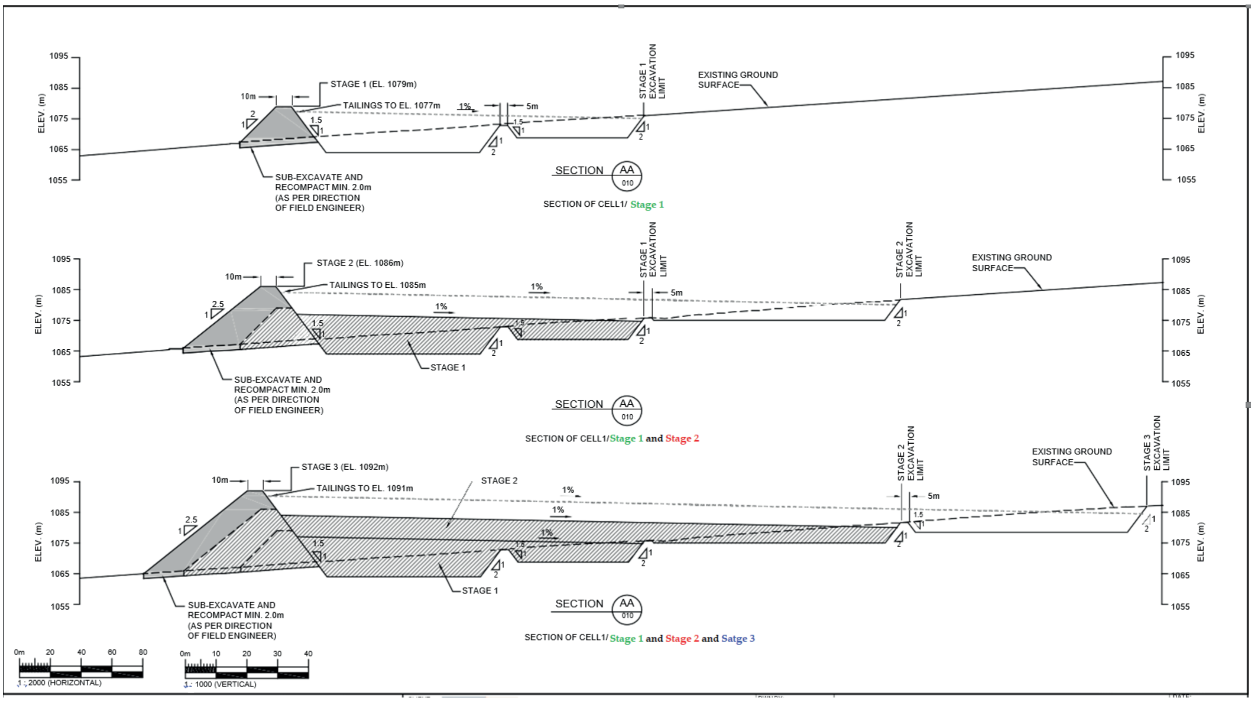
Appendix A: The layout of Cell 1 in the plan view. The different stages of the dam construction are depicted as Stage 1, Stage 2, and Stage 3. The underlying layout has been intersected by the vertical A-A plane. The corresponding section is depicted in Appendix B



Appendix B: The vertical section of A-A (see the Appendix A) on Cell 1. The three different stages of the dam construction, i.e. Stage 1, Stage 2, and Stage 3 are shown in the map



References

[1] Stefaniak K., Wróżyńska M.: *On possibilities of using global monitoring in effective prevention of tailings storage facilities failures*. Environmental Science and Pollution Research, vol. 25, 2018, pp. 5280–5297. https://doi.org/10.1007/s11356-017-0995-x.

[2] Chattopadhyay S., Chattopadhyay D.: *Coal and other mining operations: role of sustainability*, [in:] Malhotra R. (Ed.), *Fossil Energy*, 2nd ed. Encyclopedia of Sustainability Science and Technology Series, Springer, New York 2020, pp. 333–356. https://doi.org/10.1007/978-1-4939-9763-3_864.

[3] Armstrong M., Petter R., Petter C.: *Why have so many tailings dams failed in recent years?* Resources Policy, vol. 63, 2019, 101412. https://doi.org/10.1016/j.resourpol.2019.101412.

[4] Hatje V., Pedreira R.M.A., de Rezende C.E., Schettini C.A.F., de Souza G.C., Marin D.C., Hackspacher P.C.: *The environmental impacts of one of the largest tailing dam failures worldwide*. Scientific Reports, vol. 7, 2017, 10706. https://doi.org/10.1038/s41598-017-11143-x.

[5] Lèbre É., Corder G.D., Golev A.: *Sustainable practices in the management of mining waste: A focus on the mineral resource*. Minerals Engineering, vol. 107, 2107, pp. 34–42. https://doi.org/10.1016/j.mineng.2016.12.004.

[6] Aghili S., Vaezihir A., Hosseinzadeh M.: *Distribution and modeling of heavy metal pollution in the sediment and water mediums of Pakhir River, at the downstream of Sungun mine tailing dump, Iran*. Environmental Earth Sciences, vol. 77, 2018, 128. https://doi.org/10.1007/s12665-018-7283-z.

[7] Azam S., Li Q.: *Tailings dam failures: a review of the last one hundred years*. Geotechnical News, vol. 28(4), 2010, pp. 50–54.

[8] Rico M., Benito G., Salgueiro A.R., Díez-Herrero A., Pereira H.G.: *Reported tailings dam failures: a review of the European incidents in the worldwide context*. Journal of Hazardous Materials, vol. 152(2), 2008, pp. 846–852. https://doi.org/10.1016/j.jhazmat.2007.07.050.

[9] Lyu Z., Chai J., Xu Z., Qin Y., Cao J.: *A comprehensive review on reasons for tailings dam failures based on case history*. Advances in Civil Engineering, 2019, 4159306. https://doi.org/10.1155/2019/4159306.

[10] Davies M.P.: *Tailings impoundment failures: are geotechnical engineers listening?* Geotechnical News, vol. 20(3), 2002, pp. 31–36.

[11] Kossoff D., Dubbin W.E., Alfredsson M., Edwards S.J., Macklin M.G., Hudson-Edwards K.A.: *Mine tailings dams: Characteristics, failure, environmental impacts, and remediation*. Applied Geochemistry, vol. 51, 2014, pp. 229–245. https://doi.org/10.1016/j.apgeochem.2014.09.010.

[12] Geppetti A., Facciorusso J., Madiai C.: *Tailings dams numerical models: A review*, [in:] *Proceedings of the 7th World Congress on Civil, Structural, and Environmental Engineering (CSEE'22)*, Avestia Publishing, 2022, pp. 1–7. https://doi.org/10.11159/icgre22.241.

[13] Harper T.G., McLeod H.N., Davies M.P.: *Seismic assessment of tailings dams*. Civil Engineering, vol. 62(12), 1992, pp. 64–66.

[14] Ansari: *Summary Report on Groundwater Exploration in Sangan Iron Ore Area*. July 1992.

[15] Ansari: *Hydrogeological Studies within areas of erecting Tailings Dams of Sangan Iron Ore Mines*. February 1993.

[16] Day R.W.: *Geotechnical and Foundation Engineering: Design and Construction*. McGraw-Hill Professional, 1999.

[17] Vick S.G.: *Planning, Design, and Analysis of Tailings Dams*. BiTech Publishers, Richmond, Canada 1990.

[18] Makdisi F.I., Seed H.B.: *Simplified procedure for estimating dam and embankment earthquake-induced deformations*. Journal of the Geotechnical Engineering Division, vol. 104(7), 1978, pp. 849–867. https://doi.org/10.1061/AJGEB6.0000668.

[19] Zardari M.A., Mattsson H., Knutsson S.: *Numerical modelling for stability of tailings dams*. Conference paper presented at the Grundläggningsdagen 2013. http://ltu.diva-portal.org/smash/get/diva2:1010447/FULLTEXT01.pdf.

[20] Ishihara K., Ueno K., Yamada S., Yasuda S., Yoneoka T.: *Breach of a tailings dam in the 2011 earthquake in Japan*. Soil Dynamics and Earthquake Engineering, vol. 68, 2015, pp. 3–22. https://doi.org/10.1016/j.soildyn.2014.10.010.

[21] Chakraborty D., Choudhury D.: *Seismic behavior of tailings dam using FLAC^{3D}*, [in:] Han J., Alzamora D.A. (eds.), *Geo-Frontiers 2011: Advances in Geotechnical Engineering (GSP 211): Dallas, Texas, USA*, *13–16 March 2011*, Geotechnical Special Publication, no. 211, American Society of Civil Engineers, Reston 2011, pp. 3138–3147. https://doi.org/10.1061/41165(397)321.

[22] Meisheng F., Laigui W.: *A tailings dam dynamic stability study based on numerical simulation*, [in:] *2011 International Conference on Consumer Electronics, Communications and Networks: (CECNet 2011); Xianning, China, 16-18 April*, IEEE, Piscataway 2011, pp. 1002–1005. https://doi.org/10.1109/CECNET.2011.5769336.

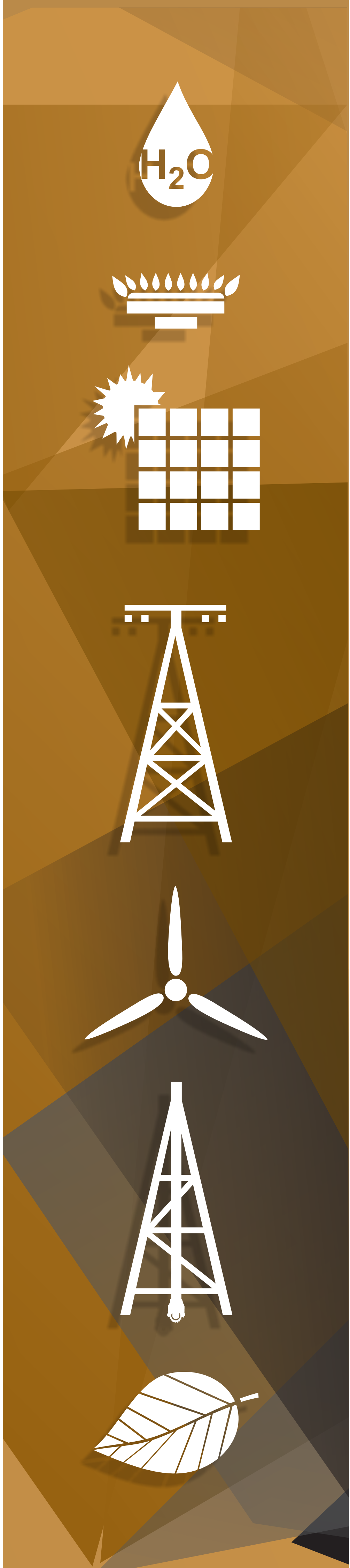
[23] Wang T., Zhou Y., Lv, Q., Zhu Y., Jiang C.: *A safety assessment of the new Xiangyun phosphogypsum tailings pond*. Minerals Engineering, vol. 24(10), 2011, pp. 1084–1090. https://doi.org/10.1016/j.mineng.2011.05.013.

[24] Barrero A.R., Taiebat M., Lizcano A.: *Application of an advanced constitutive model in nonlinear dynamic analysis of tailings dam*, [in:] *GeoQuebec2015: 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*, University of British Columbia, Vancouver, Canada 2015. https://www.kz.srk.com/sites/default/files/file/ALizcano_AdvancedConstitutiveModelInAnalysisOfTailingsDam_2015.pdf.

[25] Xu B., Wang Y.: *Stability analysis of the Lingshan gold mine tailings dam under conditions of a raised dam height*. Bulletin of Engineering Geology and the Environment, vol. 74, 2015, pp. 151–161. https://doi.org/10.1007/s10064-014-0602-z.

[26] Zardari M.A., Mattsson H., Knutsson S., Khalid M.S., Ask M.V., Lund B.: *Numerical analyses of earthquake induced liquefaction and deformation behaviour of an upstream tailings dam*. Advances in Materials Science and Engineering, 2017, 5389308. https://doi.org/10.1155/2017/5389308.

[27] Naeini M., Akhtarpour A.: *Numerical analysis of seismic stability of a high centerline tailings dam*. Soil Dynamics and Earthquake Engineering, vol. 107, 2018, pp. 179–194. https://doi.org/10.1016/j.soildyn.2018.01.019.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