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Methodology for the Prevention of Critical Failures in Iron Ore Stockpiles: A Case Study

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Abstract

Throughout the iron ore production chain, the material undergoes several transfers, making stockpiling essential for reserve formation, process support, or product homogenization. However, due to the artificial geometry of stockpiles slope, there is an inherent risk of structural failure, which may cause significant damage to nearby facilities, equipment, and personnel. Considering the scarcity of methodologies focused on minimizing the risk of failures in iron ore stockyards, this study proposes a preventive approach aimed at reducing critical events. A multidisciplinary team was assembled to identify, evaluate, and analyze the main risk factors associated with stockpile stability. Based on the data collected, a methodology was developed to guide operational procedures and improve risk management in stockyards. A case study was conducted focusing on iron ore stockpiles in Brazil, a country with a strong mining tradition. After implementing the proposed methodology, significant improvements were observed, including the elimination of critical stockpile failures. These results confirm the methodology's effectiveness and highlight its potential to enhance safety, operational reliability, and risk control in mining stockyard operations.

Keywords

Iron Ore Stockpiles, Failure Prevention, Risk Management, Operational Safety, Sustainability, Multidisciplinary Approach

1. Introduction

The mineral extraction industry is essential for the advancement and development of civilizations, providing the raw materials that support the energy, metallurgical, chemical, construction, and high-tech industries. Mining transforms ores into useful products through a series of extraction and processing stages. Throughout this process, ores undergo multiple transfers—from extraction at the mine, through processing facilities, to the final consumers. Therefore, stockpiling becomes necessary to ensure continuous operations during rainy seasons, system shutdowns, transportation waits, or product homogenization to meet quality standards.

The most commonly used storage method in mining is stockpiling, which allows for storing large quantities at relatively low costs. However, it requires specific guidelines and criteria, and it has limitations that may demand special care. One critical risk in ore stockpile projects is potential pile failure, which can significantly impact personnel safety and equipment integrity (Hawley & Cunning, 2017). Past incidents have demonstrated the vulnerability of stockpiling processes but are often treated reactively, without systematic methodologies to prevent future failures.

Ensuring safety during ore handling, particularly regarding pile stability, demands a thorough understanding of associated factors and their impacts. Only then is it possible to define and standardize controls to eliminate risks and mitigate effects. Ore pile failures, like those shown in **Figure 1**, not only pose fatality risks but can also cause permanent harm to people (Moraes da Gama et al., 2014). Financially, a pile collapse at a port with a single loading line and two-yard machines could cut shipment capacity by 50% for up to a year, resulting in millions in material damages.

Figure 1. Failures in ore stockpiles. (a) Stockpile failure at the EMO Dry Bulk Terminal (Rotterdam, 2022); (b) Stockpile failure at the EMO Dry Bulk Terminal (Rotterdam, 2022); (c) Stockpile failure (Brazil, 2018); (d) Stockpile failure (Brazil, 2018); (e) Stockpile failure at an operational port (Brazil, 2018).

To prevent or minimize critical events, it is crucial to implement control measures based on operational, geotechnical, hydrological, and geological aspects. Understanding pile behavior is key to defining safe operational criteria. Additionally, developing procedures to standardize best practices and guide teams is vital. The absence of inadequacy of control measures can lead to serious, often preventable accidents.

Thus, applying a management methodology that enhances stockpiling operation reliability, reduces pile failure risks, and minimizes impacts is essential for the sustainability of mining processes. This work aims to propose a methodology to prevent critical iron ore stockpile failure events and mitigate potential effects on people, equipment, and business sustainability.

2. Iron Ore Stockpiling

Throughout the entire mining process, iron ore undergoes a series of transfers, starting from extraction at the mines, moving through processing facilities, and continuing until it reaches the final consumers. As in other industrial sectors, the mining industry requires the storage of raw materials, intermediate products, and finished goods. According to Chaves (2012), several reasons justify the need for stockpiling in mining operations:

a) To build reserves to support operations during periods of heavy rainfall, scheduled shutdowns, or mine emergencies;

b) To create buffer stockpiles between operations with different processing rates or schedules, ensuring a constant feed to the subsequent unit operations;

c) To wait for the availability of transport systems to transfer the ore to its destination;

d) To homogenize the material feeding certain beneficiation plant units, minimizing variations in feed characteristics and, consequently, reducing process control issues.

Stockpiling in mining operations can occur in three main forms: in railway wagons, silos, or piles. Ferreira (1989) similarly states that the storage of bulk solids can be done in silos or yards, further classifying storage as either open-air or indoor stockpiling. For iron ore specifically, the most commonly used method is open-air stockpiling, as it allows for the accumulation of large quantities of material over extended periods at relatively low cost. Moreover, stockpiles can assume various shapes—such as conical, prismatic, trapezoidal-section prisms, or circular/semicircular-section prisms—depending on the product characteristics, available physical space, and equipment used.

The stockpiling process of iron ore presents particular features, since the material generally arrives at the stockyard in batches. A batch is composed of parcels of ore with different characteristics, blended to obtain an average composition. Consequently, it is necessary to homogenize the batch to concentrate the desired valuable content for commercialization. This is achieved during stockpile construction by systematically distributing the material along the pile in successive elementary layers, ensuring that the entire stockpile reflects the targeted blend characteristics.

Figure 2 illustrates that, although each element of the stockpile has specific properties, any cross-section perpendicular to the pile's axis will statistically present the same average composition, indicating effective homogenization. There are different pile construction methods aimed at homogenization. However, not all stockpiles are intended for this purpose; some are simply designed for storage. Therefore, selecting the appropriate pile formation method requires evaluating not only the need for homogenization but also the advantages and disadvantages of each method, especially regarding stockpile stability and storage capacity.

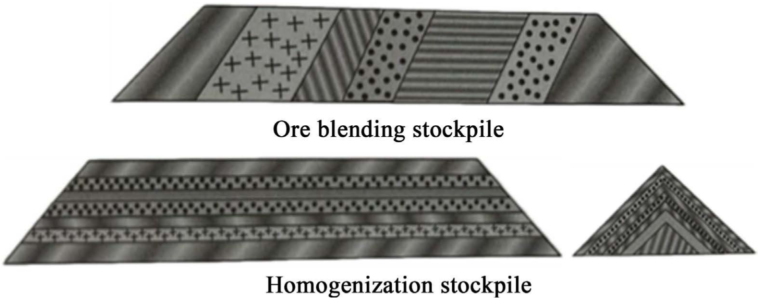

Figure 2. Ore stockpile homogenization (Chaves, 2012).

2.1. Methods for Stockpile Construction

Chaves (2012) notes that there are different stockpile construction methods, and their applicability varies according to the volume of material to be handled, the storage location, ease of maintenance, process efficiency, the type of equipment to be used, and the level of care given to the operation.

According to Guaranys et al. (2013), stockpiling methods involve stacking multiple layers on top of each other along the longitudinal axis of the pile. The most common methods are chevron, windrow, and cone shell, as illustrated in **Figure 3**. The selection of the appropriate method must be made carefully to address the specific characteristics of the material to be stockpiled, the equipment to be used, the stacking area, and the potential need for ore homogenization.

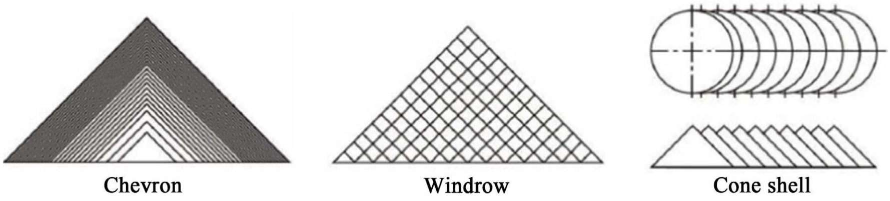

Figure 3. Main stockpiling methods (Chaves, 2012).

2.2. Issues Related to Stockpile Storage

According to Leal Filho (1994), the stockpiling process presents a number of issues that must be considered to ensure the success of the operation. It is therefore essential to study the stacking and reclaiming methods, as well as the characteristics and limitations of the process. Leal Filho (1994) identified several common problems associated with stockpile storage, including:

- Dust Emission: This can hinder equipment performance and cause discomfort to workers. Additionally, material loss due to dust dispersion may alter the characteristics of the stored product.
- Particle Size Segregation: During transfer via conveyor belts and especially when the material is dumped onto the pile, coarser particles tend to roll to the sides and accumulate at the base, while finer particles concentrate in the center and rear. This causes variations in both particle size distribution and reclaim flow.
- Compaction: Cohesive materials under prolonged pressure tend to clump together, making them difficult to reclaim. This is common with fine, moist iron ore.
- Moisture Content: Moisture affects handling during both stacking and reclaiming. Since stockpiles are exposed to the weather, their moisture level is directly impacted, affecting product quality, operational performance, and stability.
- "Dead" Material: This refers to residual material that requires heavy equipment for reclaiming, increasing operational costs and possibly compromising product quality and storage efficiency.

Additionally, stockpiles are inclined surfaces and can suffer mass sliding, impacting nearby personnel and equipment. Slopes, whether natural or artificial, may become unstable (Gerscovich, 2012). Thus, ore piles can be classified as artificial embankment slopes (Abrantes & Costa, 2019). Gerscovich (2009) identifies instability mechanisms as either load increase or strength reduction. According to CGEE (2010), iron ores differ greatly due to their genesis, resulting in declining ore quality—lower iron content and higher alumina and phosphorus—making it sometimes impossible to eliminate instability causes, thus requiring control measures.

3. Case Study

The study on the prevention of ore stockpile failures was conducted at an iron mine located in Brazil. The stockpile formation is carried out using three stacker-reclaimers (SR) with a maximum stacking rate of 8000 t/h, and two additional units with a maximum rate of 7000 t/h. Stacking operations take place across ten open-air storage yards, with a total storage capacity of 2.6 million tons. The starting point of the study was the mapping of the main areas responsible within the operational processes of the storage yards, as illustrated in **Figure 4**. A team was formed, composed of representatives from the aforementioned areas, named the Stockyard Technical Management Group (STMG), with the initial objective of investigating the main causes of stockpile instability (**Figure 4**). The first step was to collect data on critical stockpile failure events that had occurred in the storage yards.

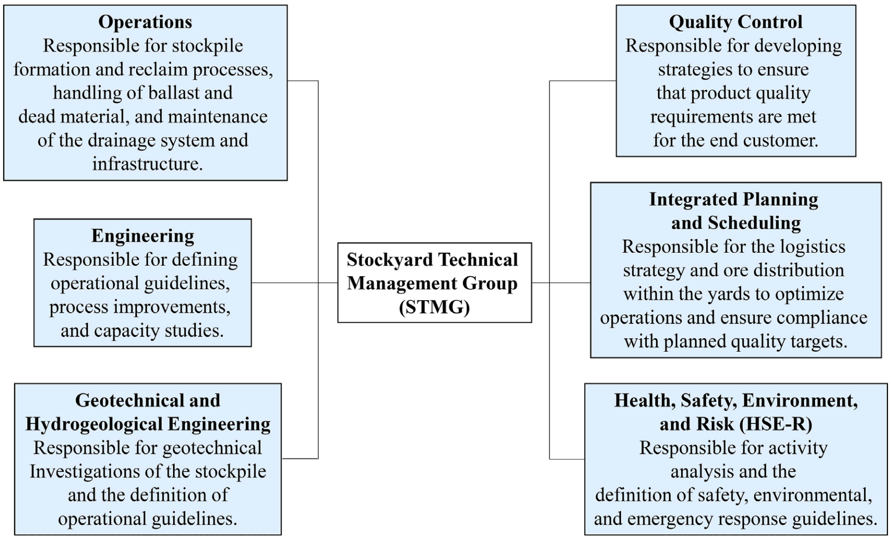

Figure 4. Technical group involved in the stockyard management methodology.

3.1. Identification of Risk Factors

To support this analysis, a set of guiding questions was developed to identify which factors are most closely related to past failure events in the product stockyards:

1) Is there mass removal from the sides or base of the pile that alters its structure?

2) Is there an external load acting on the pile?

3) Are natural or artificial vibrations present in the storage yards?

4) Does the yard foundation show signs of settlement or low load-bearing capacity?

5) Do inherent product characteristics (texture, geometry, structure) affect pile stability?

6) Are weathering processes influencing the pile's structure?

7) Is there water level rise in the yard, causing accumulation at the pile base?

8) Can moisture variations influence suction and affect stability?

Responses from the mapped areas identified several key risk conditions:

- Mass Removal: Sampling at the pile base or sides (Figure 5) can significantly alter its geometry and undermine the structural support of upper layers.
- Vibrations: Both seismic activity and heavy equipment traffic can induce horizontal accelerations that, combined with gravity, may destabilize the pile.
- Foundation Issues: Poor compaction or inadequate drainage (Figure 6) reduces bearing capacity, making the foundation unable to support the pile's weight.
- Material Variability: Stockpiles often consist of ore from multiple sources with varying granulometry, moisture, and clay mineral content (Figure 7), which affect stability.
- Heterogeneous Layering: Adding ore to an existing or partially reclaimed pile (Figure 8) may create geometric imbalances, especially if materials differ in properties.

Figure 5. Modification of the stockpile structure.

Figure 6. Stockyard foundation with low bearing capacity.

Figure 7. Characteristics of the Products Present in the Stockpile.

Figure 8. Addition of ore to an existing or partially reclaimed stockpile.

- Weathering: Rainwater infiltration (**Figure 9**) can saturate the ore, reduce particle cohesion, and alter slope geometry, increasing the risk of failure.
- Water Accumulation: Rising groundwater or poor drainage (**Figure 10**) can

saturate the pile base, decreasing its shear strength.

- High Moisture Content: Excessive moisture (**Figure 11**) may alter pore pressures, reducing effective stress and increasing susceptibility to instability.
- External Loads: While added loads on slopes can trigger instability, this is rarely an issue in stockpiles, as no equipment operates on their tops, and their geometry prevents water accumulation.

Figure 9. Influence of weathering on the stockpile.

Figure 10. Weathering influence on the stockpile and base saturation.

Figure 11. Stockpile with high humidity.

These identified conditions provide critical input for risk mitigation strategies in stockyard management. In the studied area, vibration was excluded as a contributing factor, since there are no blasting activities, subsidence, or significant seismicity. Only the transit of equipment and trains occurs. Observations indicated that neither equipment movement near stockpiles nor train passage caused any changes in stockpile behavior. There are no records of failures related to these activities. Design assessments of the storage yards show that the foundations were treated and replaced with hydraulic fill, with no history of stockpile failures due to foundation conditions. Therefore, stockpile failures are considered to be associated with mass removal, product characteristics, pile geometry, drainage deficiencies, water accumulation at the base, and high ore moisture content.

3.2. Preventive and Mitigating Controls

Based on the risk assessment, the STMG proposed control measures to both prevent stockpile failures and mitigate their effects if they occur. The main controls are outlined below:

1) Sampling Procedure: Though not routine, sampling is required to assess moisture content and Transportable Moisture Limit (TML). A formal procedure was established: sampling must be done exclusively by stacker-reclaimer (SR), prohibiting manual or excavator use. The sampled area must be isolated during operations.

2) Stockpile Geometry: To ensure equipment safety, a minimum buffer zone between the pile and track slope is established, based on material type and yard configuration. This setback accounts for potential flow in case of failure. Base width is constrained by equipment and yard geometry, while pile height depends on the repose angle of the ore.

3) Ore Quality Parameters: High moisture combined with fine particles (<0.15 mm) may lead to negative suction pressures and apparent stability. To prevent this, ore used for stacking must have moisture below 11% and less than 50% fines.

4) Stockpile Reformation Requirements: Building a new pile on unrecovered material can compromise stability, especially with high moisture and fine content. Reformation is allowed only when:

- The base is prepared (removal of residual ore and drainage ensured),
- Residual and new ore meet moisture and granulometry limits,
- Sinter feed is not stacked over pellet feed,
- No water pooling exists near the pile.

5) Drainage System Maintenance: Surface drainage (longitudinal/transversal) directs water away from storage areas. Maintenance includes reshaping yard slopes and clearing ditches to channel runoff to sediment basins, preventing water accumulation around piles.

6) Yard Preparation Prior to Stacking: Post-recovery, residual ore (dead ore) remains. Its characteristics may differ from the new material, forming weak layers. This material must be moved to the center of the stacking axis using designated

equipment, a process known as stockpile cleanup.

7) Execution of stockpile cleanup: It involves redistributing leftover ore into 3-meter-high cones or rows in the central pile area. If the residue is wet and immobile, the pile must be treated as a reformed structure and follow respective criteria.

8) Pile Stability Assessment: Evaluating pile stability is critical for planning. Simulations help define optimal stacking criteria, enable geometry adjustments, and support capacity increases.

9) Operational Criteria for Pile Formation: Pile construction must follow yard-specific geometry and positioning. The chevron stacking method is adopted for better homogenization and drainage. A minimum setback between pile and equipment track is ensured, based on broken mass projection studies.

10) Operational Criteria for Pile Recovery: Recovery must maintain product quality but can impact subsequent operations. Improper benching or recovery in long benches during rainy periods can hinder stockpile cleanup or lead to water infiltration. Standardized recovery procedures are necessary.

11) Mass Flow Projection Study: Simulations of failed mass behavior determine ideal pile positioning and geometry to ensure that, in case of failure, material remains within the yard, avoiding areas used by personnel and equipment.

12) Safety and Emergency Response Measures:

- Access Control: Only authorized and trained personnel may enter yards. Barriers restrict unauthorized entry.
- Traffic Rules: Clear guidelines for the movement of people, vehicles, and equipment.
- Emergency Response: Plans and resources are in place for incident management. Regular drills are conducted to identify improvement opportunities.
- Infrastructure Maintenance: Includes upkeep of berms separating stockpile and access areas, as well as signage and internal roads.

3.3. Implementation

With preventive and mitigating controls defined, implementation began with the development of a model to assess compliance with established requirements. Two evaluation questionnaires were created: one for process management and another for on-site assessment.

The process and management section focused on planning, organization, and control activities, using a quantitative scoring system based on the level of implementation. The technical-operational section assessed field implementation through visual inspections, reflecting current on-site conditions.

Diagnoses were conducted by the STMG team across all ten storage yards. Based on results, an action plan was developed to address gaps. A routine was established for tracking progress and applying corrective actions. At the end of the implementation phase, new assessments measured improvements. Standardized solutions were adopted for compliant areas, and a new plan was launched for outstanding requirements.

3.4. Results

Following the implementation of the preventive and mitigative controls defined by the STMG for preventing critical iron ore stockpile failures and mitigating risks to personnel and equipment, significant improvements were observed in both operational process management and yard operating conditions. Based on diagnostics carried out at the start and end of a one-year implementation period, process and management compliance improved from 41% to 82%, while technical-operational compliance rose from 35% to 78%. These improvements reflect the effectiveness of the adopted methodology.

Among the improvements observed, notable enhancements were seen in drainage systems. Figure 12 compares conditions before and after the intervention: (a) shows a silted drainage channel incapable of capturing runoff, whereas (b) illustrates an effective channel post-rainfall, successfully redirecting water to sedimentation basins. Stockpiles also exhibited no water accumulation at their base.

Figure 13 highlights yard preparation improvements. Initially (a), residual material from a previous stockpile was present with an uneven base. After intervention (b), the yard was leveled, and residuals were redistributed to ensure proper slope toward drainage channels, which were also maintained.

(a) Before implementation (b) after implementation

Figure 12. Drainage system before and after the implementation of controls.

(a) Before implementation (b) after implementation

Figure 13. Yard preparation for storage.

The construction and upkeep of surface drainage channels, combined with regular stockpile residue removal (stockpile cleanup), enabled gravitational drainage of rainwater, reducing waterlogging, pile instability, and deviations in ore moisture quality.

Yard infrastructure was enhanced through regular access road leveling, installation of signage indicating risks, traffic direction, speed limits, operational marker identification, and emergency assembly points. Controlled access was established, restricting entry to authorized personnel only. Additionally, a mandatory safety training for yard access was introduced. Stability and runout studies were essential for defining pile geometry and safe stacking/reclaiming criteria. These were standardized and communicated to operators.

Over the one-year period, no critical stockpile failures affecting people or equipment were recorded, validating the strategy. Minor face displacements occurred but remained within the designated storage area, posing no operational risk (**Figure 14**). Based on the tested methodology, the outcome of the study is the flowchart presented in **Figure 15**.

Figure 14. Displacement of the stockpile face after the implementation of controls.

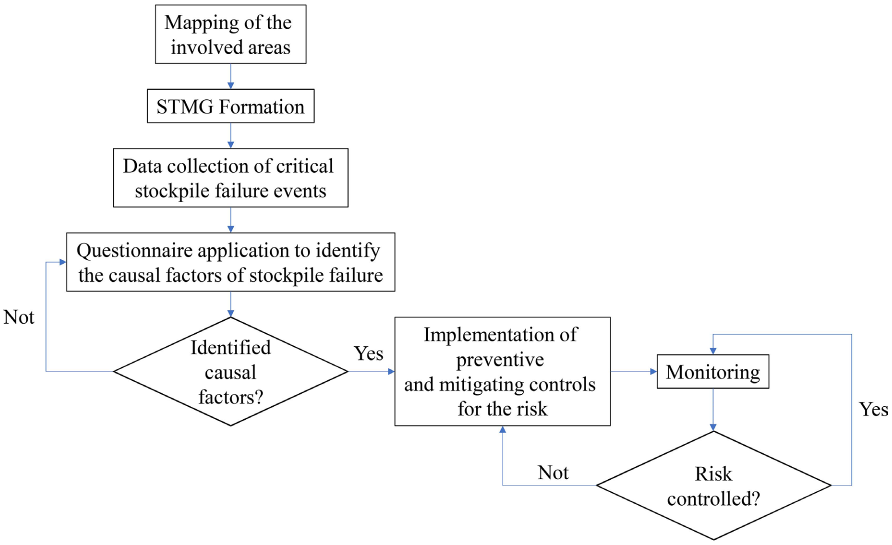

Figure 15. Methodology for preventing ore pile failures.

4. Conclusion

The triggering mechanisms of slope instability addressed in this study are typical of artificial embankments and, therefore, applicable to iron ore product stockpiles. However, unlike tailings or waste dumps, product stockpiles have a short residence time in storage yards, are not manually compacted, and may undergo changes in slope geometry. Despite this, there is a noticeable lack of technical studies focused specifically on ore product piles.

The methodology developed in this study for defining and implementing preventive and mitigative controls for critical stockpile failure events proved effective, resulting in zero critical incidents in the stockyards. Although some minor events occurred, the failed mass remained within the stockpile area, with no risk to personnel or equipment.

As not all criteria have yet been fully implemented, further improvements are expected in operational processes, potentially reducing the occurrence of non-critical failures. Despite the positive safety outcomes, the new pile geometry guidelines—particularly height reduction—led to a decrease in storage capacity by approximately 120 Kt.

The main objective of the study was achieved: the proposed methodology is effective for preventing critical failures in iron ore stockpiles and mitigating safety and operational risks.

The formation of a multidisciplinary team—STMG (Stockyard Technical Management Group)—comprising professionals from operations, engineering, geotechnics, health, safety, environment, and emergency response, was essential for success. Key contributing factors to stockpile instability identified were: pile structure alterations due to additional stacking, weight accumulation at the top, ore geotechnical characteristics, inefficient drainage, and water accumulation.

Preventive and mitigative controls included: proper base preparation, residue management, quality parameters for pile formation, reform criteria, yard drainage, stability and runout studies, and operational safety standards.

This methodology, based on diagnostics, monitoring, and standardization, proved effective and offers a valuable reference for preventing ore stockpile failures.

To enhance the scientific robustness and practical applicability of the proposed methodology, future research should systematically address its limitations by considering a broader range of geological, geotechnical, and operational conditions that may affect its performance. Expanding the dataset to include lithological units from different mining sites and geotectonic settings would enable a more rigorous validation of the derived parameters and support the assessment of their transferability across contexts. Additionally, sensitivity analyses involving variations in stability criteria, boundary conditions, and input data uncertainties are recommended to quantify the influence of each factor on model outputs. Such approaches would contribute to a more comprehensive understanding of the constraints and optimal applicability domains of the methodology, thereby improving its reliability and scientific soundness.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding authors upon reasonable request.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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