



A UNIFIED 4D UAV PHOTOGRAMMETRY METHODOLOGY FOR MINE DUMP SLOPE MONITORING, DISPLACEMENT ANALYSIS AND TIME DEPENDENT FACTOR OF SAFETY EVALUATION

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Abstract: Landslides of mine dump slopes are recognized as high-consequence hazards in surface mining. They occur due to the rapid construction from heterogeneous waste materials, the continuous evolution of their geometry during dumping, and the strong influence of foundation conditions and hydromechanical triggers on stability. Uncrewed aerial vehicles (UAV) photogrammetry has increasingly been adopted for the frequent acquisition of high-resolution 3D representations of dump morphology, enabling safer and more efficient monitoring and engineering assessment. Nevertheless, deformation mapping derived from multitemporal point cloud differencing is commonly treated independently from mechanistic stability analysis, thereby limiting its value for predictive hazard interpretation. In this study, a unified 4D (x,y,z,t) framework is proposed in which multitemporal UAV point cloud comparison is integrated with displacement estimation procedures, together with 3D limit equilibrium and strength reduction numerical modeling for time-dependent factor of safety (FoS), evaluation, and operational warning tier definition. The framework is conceived in a form suitable for software-based implementation and is intended for the direct use of site point clouds and geotechnical parameters. Through further research and targeted programming development, it could be translated into an executable workflow capable of generating outputs such as spatial displacement fields, volumetric change distributions, FoS surfaces, and risk classifications to support proactive dump slope management and hazard mitigation.

Keywords: UAV drone; Mine dump; Slope stability; Hazard assessment; Open pit mining; Geotechnical monitoring

1. Introduction

Mine dump slopes are among the most complex and potentially dangerous man-made landforms in open pit mining. Unlike cut slopes in intact or partially weathered rock, dumps are formed by progressive placement of fragmented waste material with variable grain size, density, moisture content, compaction state, and shear strength. [1, 2]. Their geometry evolves continuously as new material is tipped, spread, reworked, or eroded, and their stability is influenced not only by the visible slope angle but also by dump height, internal layering, dumping sequence, toe support, and foundation behavior [3, 4]. Weak basal materials, low bearing capacity, and stress concentration near the toe may produce progressive movement even when the surface form appears visually acceptable [2, 3]. For this reason, mine dumps must be treated as evolving systems rather than fixed geometric objects.

The recent expansion of UAV photogrammetry has significantly improved the monitoring of surface mine slopes and dumps. Repeated UAV surveys can capture dense 3D point clouds and high-resolution surface models at a temporal frequency that is difficult to achieve with traditional ground surveying alone [5, 6, 7, 8, 9]. The uploaded literature shows that UAV methods are now used for stockpile modeling, surface

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reconstruction, slope monitoring, erosion mapping, reclamation assessment, and broad safety evaluation across the mine life cycle [10, 11, 12, 13]. In addition, review papers emphasize that UAV systems provide important advantages in hazardous or inaccessible terrain because they reduce direct field exposure while preserving high spatial detail [8, 9, 14].

At the same time, multitemporal point cloud processing has matured considerably. Classical cloud to cloud, cloud to mesh, and DEM differencing methods can identify geometric change between successive epochs [15, 16, 17, 18]. More advanced approaches have been proposed to reduce the influence of roughness, outliers, and registration error, and to estimate true 3D displacement vectors rather than only distances measured normal to the surface [16, 17]. These developments are particularly important for mine dumps, where movement may occur not only outward from the slope face but also downslope along the surface or within deforming depositional lobes. Dense displacement mapping therefore offers far more insight than a limited set of isolated monitoring points [15, 18].

However, a clear gap remains in current practice. In many studies, UAV outputs are used to map morphology, displacement, or volume, while geotechnical stability analysis is undertaken separately, often with simplified or outdated geometry [5, 6, 7, 8, 9, 14]. Conversely, some dump stability studies use numerical or analytical models without direct coupling to repeated surface observations [2, 3, 4]. As a result, valuable monitoring information is not fully translated into engineering interpretation. A crest loading zone may be detected, for example, but not explicitly connected to an increase in driving forces. A toe bulge may be mapped, but not incorporated into a revised FoS analysis. A local erosional gully may be identified, but not interpreted as a possible trigger of geometry degradation or drainage concentration [6, 7, 10].

The objective of this study is therefore to define a practical methodology that unifies repeated UAV monitoring with geotechnical stability interpretation in a single 4D framework. Here, 4D means that geometry and kinematics are evaluated as functions of space and time. Each UAV epoch contributes to an evolving representation of the dump, and each update can be transferred into a stability model that yields a new FoS distribution and warning status. The proposed framework does not replace geotechnical judgment. Rather, it improves the timing, spatial resolution, and mechanical relevance of that judgment by integrating geometry, displacement, volumetric change, and stability in one workflow. This makes the method suitable for operational mine monitoring, progressive hazard detection, and future case study implementation with free software [4, 6, 8, 9, 14].

The proposed methodology is organized as a sequence of linked operations. The important feature is that each stage is not independent. Every product from one stage becomes an input to the next stage, so that the final FoS and warning outputs remain physically connected to the observed dump geometry.

In practical terms, the proposed framework is conceived as a workflow that can be implemented through a sequence of interoperable processing stages. Repeated UAV surveys provide the image data required for photogrammetric reconstruction, from which multitemporal point clouds and surface models may be generated. These geometric products may then be aligned, compared, and analyzed for displacement and volumetric change, after which the updated slope geometry may be transferred to a geotechnical model for factor of safety evaluation. Finally, the geometric and mechanical outputs may be interpreted together to support hazard recognition and warning assignment. This practical workflow perspective is important because it frames the methodology not only as a conceptual integration of monitoring and stability analysis, but also as a structured basis for future executable implementation in applied mine dump assessment.

The present study is positioned primarily at the level of methodological development. Its contribution lies in the formulation of an integrated framework that connects multitemporal UAV based geometric monitoring with geotechnical stability evaluation in a unified analytical structure. Accordingly, the paper focuses on the conception, internal logic, and implementation pathway of the methodology itself, while full case study application and site specific validation are identified as the next stage required for testing, calibration, and broader practical demonstration.

2. Unified 4D Methodology and Factor of Safety Evaluation

The proposed methodology is organized as a sequence of linked operations. The important feature is that each stage is not independent. Every product from one stage becomes an input to the next stage, so that the final FoS and warning outputs remain physically connected to the observed dump geometry.

2.1 Step 1: Multitemporal UAV data acquisition

The purpose of this stage is not simply to obtain aerial images, but to generate repeatable 3D datasets that can be compared over time. Flight planning should therefore prioritize geometric consistency. High image overlap, stable flight altitude, appropriate ground sampling distance, and reliable georeferencing are essential [5, 6, 7, 9]. If the mine has RTK or PPK capability, this improves direct geolocation. If not, a sufficient number of well distributed ground control points should be used. The survey interval depends on risk level and operational needs. In a stable dump, monthly or quarterly surveys may be sufficient. In an active or high risk dump, weekly or even event-based surveys after intense rainfall or rapid deposition may be justified [8, 9, 14]. The output of this step is a set of overlapping images for each survey epoch $t_1, t_2, \dots, t_n$.

2.2 Step 2: Photogrammetric reconstruction

Using structure from motion and dense image matching, each UAV dataset is converted into a dense point cloud, a digital surface model, and an orthomosaic. Mathematically, the surface at epoch is represented as:

$$P(t_k) = \{(x_i, y_i, z_i)\}_{i=1}^{N_k} \quad (1)$$

where each point carries the spatial coordinates of the reconstructed dump surface. At this stage, it is important to understand that the point cloud is not yet ready for deformation analysis. Before any comparison between epochs, all clouds must be expressed in the same spatial reference frame and their internal error structure must be checked [6, 15, 16].

2.3 Step 3: Registration and quality control

After the 3D point cloud has been created for each survey epoch, it must be ensured that all point clouds are expressed correctly within the same coordinate system. This operation is referred to as registration. If registration is not performed adequately, differences between two epochs may be interpreted as slope movement even when they are only caused by imperfect alignment.

The objective of registration is therefore straightforward: before deformation is measured, the different point clouds must be made geometrically consistent. In practice, this means that small offsets in position and orientation must be corrected so that one epoch can be meaningfully compared with another. Such corrections may involve small shifts in the horizontal or vertical directions and, where necessary, small rotational adjustments. Once this process has been completed, the point clouds can be treated as surfaces belonging to the same spatial reference frame.

This stage is necessary because even if the mine dump had not moved at all, two photogrammetric point clouds acquired on different dates would still not be perfectly identical. Small differences may arise from georeferencing uncertainty, camera positioning, image matching noise, or local reconstruction error. For that reason, direct comparison between epochs must not be undertaken before the alignment quality has been checked.

Registration may be supported by ground control points, by RTK or PPK georeferencing, by stable or quasi-stable sectors, or by refinement procedures such as Iterative Closest Point. In many practical applications, RTK-supported acquisition, optionally strengthened by a limited number of ground control points, may provide a sufficiently reliable common reference for multitemporal comparison. The reliability of such an approach is further improved when the number of epochs increases, because repeated surveys allow systematic behavior to be distinguished more clearly from isolated noise. Its reliability is also strengthened when the interpretation is based on tendencies through time rather than on a single small displacement value observed between only two epochs.

An additional point is that alignment error may often be recognized from its spatial pattern. If the apparent difference between two epochs is caused by a general registration error, it will usually appear in a systematic way across most or all of the point cloud. In other words, a broad and coherent shift affecting the entire surface in a similar manner is more likely to indicate imperfect alignment than real geotechnical displacement. By contrast, actual slope movement is expected to appear as a localized or mechanically meaningful spatial pattern, such as crest retreat, toe bulging, or concentrated deformation in specific sectors of the dump. The distinction between these two cases is important for the interpretation of multitemporal results.

The quality of registration may be summarized by the root mean square error:

$$RMSE_{reg} = \sqrt{\left(\frac{1}{m}\right) \sum_{j=1}^m \|p_j^{obs} - p_j^{ref}\|^2} \quad (2)$$

where m is the number of control or check points, p_j^{obs} is the observed position of point j , and p_j^{ref} is the corresponding reference position. This quantity expresses the typical magnitude of the remaining alignment error after registration.

If the registration error remains large, then apparent deformation may simply reflect imperfect alignment rather than actual displacement. For that reason, the registration error must be significantly smaller than the movement that is intended to be detected. A displacement of only a few centimeters, for example, cannot be interpreted with confidence if the residual registration uncertainty is of the same order. Only after the point clouds have been brought into a sufficiently consistent frame and their internal alignment quality has been verified can deformation analysis be considered reliable.

2.4 Step 4: Surface change and displacement estimation

After registration has been completed and its quality has been verified, the comparison between epochs can be undertaken in order to quantify surface change and displacement. At this stage, the objective is to determine where the dump surface has changed, by how much it has changed, and whether the observed differences are consistent with meaningful deformation patterns.

The simplest comparison is based on the nearest distance between the two point clouds. In this case, the distance assigned to point i is written as:

$$d_i^{c2c} = \min_j \|p_{i,t_2} - p_{j,t_1}\| \quad (3)$$

This quantity represents the minimum distance between a point in the later epoch and all candidate points in the earlier epoch. Such a comparison is straightforward and computationally efficient, and it can provide a first estimate of geometric change. However, it is sensitive to point spacing, surface roughness, and local noise, and therefore it may not always reflect true physical displacement.

For rough mining surfaces, a more robust estimate may be obtained by measuring change along the local surface normal. In this case, the signed displacement is written as:

$$d_i^n = (\bar{q}_{i,t_2} - \bar{q}_{i,t_1}) \cdot \mathbf{n}_i \quad (4)$$

where $\bar{q}_{i,t_2}$ and $\bar{q}_{i,t_1}$ are local average positions around the comparison point and $\mathbf{n}_i$ is the unit normal vector. This formulation is advantageous because it reduces the influence of roughness and avoids a direct comparison between isolated noisy points. Instead, the change is evaluated between local neighborhoods, which generally leads to a more stable estimate of surface separation.

Nevertheless, normal-based displacement must not be interpreted as the full movement of the surface. It expresses only the component of displacement projected onto the local normal direction. If the real movement occurs mainly outward from the slope face, the normal component may capture it well. However, if the motion is predominantly parallel to the slope surface, the normal displacement may remain small even when the true movement is significant. For that reason, normal distance methods may underestimate actual kinematic behavior when tangential or downslope movement dominates.

A more complete representation is obtained when the full 3D displacement vector is estimated:

$$\mathbf{u}_i = p_{i,t_2} - p_{i,t_1} = (u_{x,i}, u_{y,i}, u_{z,i}) \quad (5)$$

with magnitude:

$$|\mathbf{u}_i| = \text{sqrt}(u_{x,i}^2 + u_{y,i}^2 + u_{z,i}^2) \quad (6)$$

This vector formulation is more informative because it expresses both the magnitude and the direction of movement. It is therefore more suitable for the interpretation of downslope creep, toe spreading, crest retreat, local slumping, or settlement. However, true vector estimation is more demanding than simple distance computation, because direct point-to-point correspondence between epochs is not naturally contained in a point cloud. A point cloud represents the surface geometrically, but it does not preserve the identity of individual material points between survey dates.

For this reason, the reliable detection of local patch movement, especially when it is approximately parallel to the surface, generally requires correspondence-based procedures rather than simple distance metrics alone. In such cases, local neighborhoods or surface patterns must be matched between epochs so that the movement of the same patch can be inferred in three dimensions. This is more difficult than ordinary cloud comparison, but it is necessary when the aim is true kinematic interpretation rather than only geometric separation. In practical terms, conventional software such as CloudCompare is well-suited to robust surface

change detection, including cloud-to-cloud and M3C2 type comparisons, whereas full patch tracking or vector-based correspondence is more commonly achieved through custom workflows implemented in programmable environments.

The results of this step may therefore take several forms, depending on the level of detail required and the quality of the data. These include maps of nearest surface difference, maps of signed normal displacement, fields of 3D displacement vectors, and zones of concentrated deformation. In all cases, the purpose remains the same: to transform repeated geometric reconstructions into interpretable kinematic information. This stage is therefore the point at which the methodology moves from a simple representation of dump geometry to an evaluation of how the dump is actually behaving through time.

2.5 Step 5: Volumetric change analysis

After the geometric differences between epochs have been identified, the associated volumetric change can be evaluated. The purpose of this step is to determine where material has been added, where it has been removed, and the total magnitude of these changes over the area of interest. In the context of mine dumps, this information is important not only for geometric documentation but also for the interpretation of loading, redistribution of material, toe bulging, erosion, and other processes that may influence stability.

For a continuous surface representation, the volume difference between two epochs may be written as:

$$\Delta V = \iint A (z(t_2)(x, y) - z(t_1)(x, y)) dA \quad (7)$$

where A is the area over which the comparison is carried out, and $(z(t_2)(x, y))$ and $(z(t_1)(x, y))$ are the surface elevations at location (x, y) for the two survey dates. Positive values indicate that the later surface is higher than the earlier one, whereas negative values indicate that the later surface is lower.

In practical applications, the comparison is commonly performed on a gridded representation of the surface. In that case, the volume difference may be approximated as:

$$\Delta V \approx \sum (r = 1)^M (z(t_2, r) - z(t_1, r)) a_r \quad (8)$$

where r denotes the grid cell, M is the total number of cells, a_r is the area of cell r , and $z_{t_1, r}$ and $z_{t_2, r}$ are the elevations assigned to that cell at the two epochs. This discrete formulation is particularly suitable for digital surface models derived from UAV photogrammetry and may be implemented directly in raster-based workflows.

The interpretation of volumetric change must be undertaken both in spatial and numerical terms. A positive volume change near the crest may indicate continued dumping or surcharge loading. A positive change near the toe may be associated with bulging, spreading, or accumulation of displaced material. Negative volume change in localized channels or surface incisions may indicate erosion or material removal. For this reason, volumetric change must not be treated only as a bulk quantity, since its spatial distribution may provide insight into the mechanisms affecting the dump.

This step also provides an important link between geometric monitoring and geotechnical interpretation. Areas that show significant volumetric gain or loss may be compared directly with displacement fields, slope geometry, and later factor of safety calculations. In this way, volumetric change contributes not only to the description of morphology, but also to the recognition of patterns that may be relevant to hazard development.

As with displacement analysis, the reliability of volume estimates depends strongly on the quality of the preceding steps. Errors in registration, surface interpolation, roughness representation, or data density may introduce apparent volume differences that do not correspond to real material change. Consequently, volumetric results must be interpreted together with data quality controls and with an understanding of the detection limits of the survey. When these conditions are satisfied, volumetric change analysis provides a direct and operationally useful measure of the temporal evolution of the mine dump surface.

2.6 Step 6: Transfer of observed geometry to the stability model and assignment of geotechnical parameters

After the geometric evolution of the dump has been quantified, the most recent observed surface must be transferred into a form suitable for stability analysis. The purpose of this step is to ensure that the factor of safety is evaluated on the basis of the actual current geometry of the dump rather than on an outdated design profile or an idealized section. This is important because mine dumps evolve continuously during deposition, and changes in crest position, slope angle, toe geometry, and local relief may significantly influence stability conditions.

The observed surface derived from UAV photogrammetry is therefore adopted as the active geometric basis of the geotechnical model. In practice, this surface may be represented as a triangulated mesh, a gridded

surface, a set of representative cross sections, or a numerical model domain suitable for limit equilibrium or strength reduction analysis. In this way, the morphology measured in the field is translated directly into a computational form that can support stability calculations.

Once the geometric form of the model has been established, geotechnical parameters must be assigned to the dump body and, where relevant, to the underlying foundation. The principal parameters required for stability analysis are:

- the effective cohesion c' ,
- the effective friction angle φ' ,
- and the unit weight γ .

Depending on the level of detail of the model, these properties may be assigned uniformly or may vary according to material type, construction stage, stratigraphic zone, or inferred spatial domain within the dump. When additional information is available, pore pressure conditions, water-related effects, or interface properties may also be incorporated.

This step is especially important because the mechanical response of the dump cannot be inferred from geometry alone. Similar slope forms may behave very differently depending on the shear strength and weight of the waste material and on the condition of the supporting ground. In some cases, the most critical mechanism may develop not only within the dump mass itself but also along the base of the dump or within a weak foundation layer. For that reason, foundation conditions must be considered wherever such information exists, since neglect of a weak basal or subgrade zone may lead to an unrealistically high estimate of stability.

Where sufficient geotechnical data are available, the model may be populated with site-specific parameter values obtained from laboratory testing, field investigation, previous studies, or engineering characterization of the dumped material. Where such data are limited, the same workflow may still be applied in a scenario-based form by assigning representative parameter ranges and by evaluating the corresponding sensitivity of the stability results. In that case, the factor of safety must be interpreted as a relative or conditional indicator rather than as a uniquely calibrated site value.

This step therefore establishes the direct link between geometric monitoring and geotechnical assessment. The measured dump morphology is converted into a stability model, and the relevant material and foundation properties are assigned so that factor of safety calculations can be carried out on a geometry that reflects the current state of the slope. In this way, the methodology moves from observation of change to mechanical interpretation of its consequences.

2.7 Step 7: Factor of safety calculation through strength reduction analysis

After the observed geometry has been transferred to the geotechnical model and the required material properties have been assigned, the stability condition of the dump can be evaluated through factor of safety analysis. In the present framework, one of the principal approaches adopted for this purpose is the strength reduction method. This approach is particularly suitable for complex dump geometries because it does not require the critical failure surface to be imposed in advance. Instead, the slope response is allowed to develop numerically as the available shear strength is progressively reduced.

The method is based on the Mohr–Coulomb representation of shear strength, which may be written as:

$$\tau_f = c' + \sigma'_n \tan(\varphi') \quad (9)$$

where τ_f is the available shear strength, c' is the effective cohesion, σ'_n is the effective normal stress, and φ' is the effective friction angle. In the strength reduction procedure, the material strength is not increased or decreased in a physical sense for forecasting a specific future condition. Rather, it is reduced numerically in a controlled manner in order to identify how much strength reserve is present in the current slope configuration.

The reduced parameters are written as:

$$c_r = \frac{c'}{F} \quad (10)$$

$$\tan(\varphi_r) = \frac{\tan(\varphi')}{F} \quad (11)$$

where F is the trial strength reduction factor, c_r is the reduced cohesion, and φ_r is the reduced friction angle. For each trial value of F , the numerical model is solved again using the same geometry, loading, and boundary conditions. As F increases, the resisting capacity of the material decreases. The critical state is approached when the model can no longer maintain equilibrium, typically as indicated by loss of numerical convergence, rapid increase in displacement, or development of a continuous plastic failure mechanism.

The corresponding critical value is taken as:

$$FoS_{SRM} = F_{crit} \quad (12)$$

This procedure provides a direct numerical measure of the stability margin of the current dump state. If only a small reduction in strength is sufficient to produce failure, the slope is close to its limiting condition. If a much larger reduction is required, a greater reserve against failure is implied. In this sense, the method offers a numerical equivalent of the conventional factor of safety concept, expressed not as an imposed loading path but as the amount of strength reduction needed for failure to occur.

It is acknowledged that instability in an operating mine dump may develop in reality through increasing load, changing geometry, rising pore pressures, or other adverse processes rather than through uniform physical weakening of the material. However, the strength reduction method remains appropriate because it evaluates the reserve stability of the actual monitored slope configuration at each epoch. The effect of real morphological evolution is incorporated through the repeated updating of the slope geometry from UAV observations, while the strength reduction procedure is used to determine how close that updated geometry is to failure under the assumed material conditions.

For this reason, the method is particularly well-suited to the proposed time-dependent framework. It allows factor of safety values to be recalculated for each monitored stage of dump development without prescribing a single fixed failure surface in advance. In this way, the observed geometric evolution, together with the assigned geotechnical parameters, is converted into a mechanical estimate of stability that can be compared directly through time.

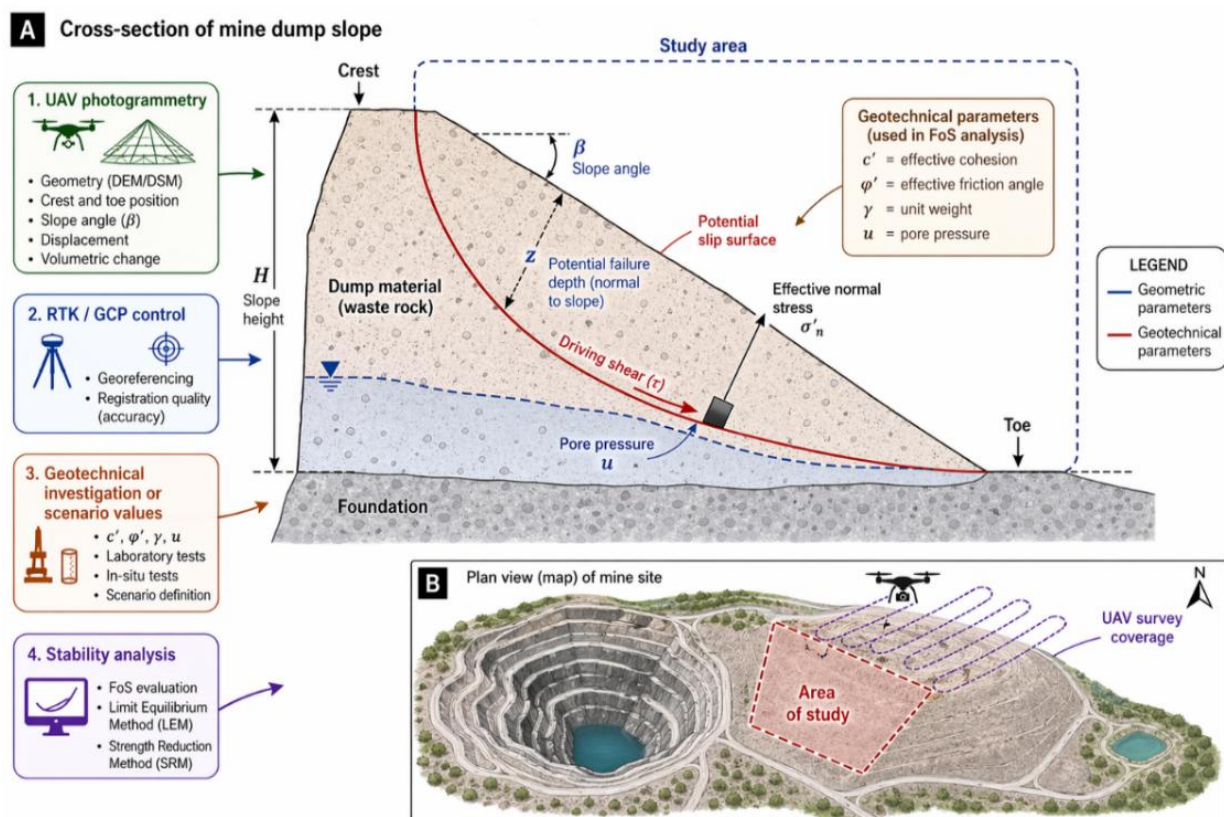


Fig. 1. Mine Slope SRM visualization

2.8 Step 8: Integrated interpretation and warning tier assignment

After displacement fields, volumetric change distributions, and factor of safety results have been obtained, these outputs may be interpreted together in order to support practical hazard evaluation. The purpose of this step is not to replace the factor of safety, which remains the principal mechanical indicator of stability, but to translate the combined monitoring and modeling results into an operationally useful classification of concern. In this sense, the warning tier functions as a light interpretive layer built on top of the main outputs of the methodology.

The need for such a layer arises from the fact that the factor of safety, although fundamental, does not by itself describe the full observed behavior of the dump. A low factor of safety is already a warning condition in

mechanical terms, but deformation monitoring may provide additional evidence on whether instability is localized, persistent, or intensifying through time. Conversely, a sector may show measurable displacement or volumetric redistribution while still maintaining a factor of safety above the limiting condition. For this reason, a simple combined interpretation may be useful, particularly in an operational setting where monitored sectors must be prioritized for attention.

In the proposed framework, the factor of safety remains the primary basis for warning assignment, while observed displacement and volumetric change provide contextual support. A practical and intentionally light formulation may therefore be adopted by defining a warning score for sector s at epoch k as:

$$W(s, k) = w_F I_{F(s, k)} + w_D I_{D(s, k)} + w_Q I_{Q(s, k)} \quad (13)$$

subject to:

$$w_F + w_D + w_Q = 1 \quad (14)$$

Those are normalized indicators for factor of safety, displacement, and volumetric change, respectively, and w_F, w_D, w_Q are their corresponding weights. In order to preserve the central role of stability analysis, the largest weight is assigned to the factor of safety term.

A simple normalized factor of safety indicator may be written as:

$$I_{F(s, k)} = \min \left(\max \left(\frac{F_{warn} - FoS(s, k)}{F_{warn} - 1}, 0 \right), 1 \right) \quad (15)$$

where $FoS(s, k)$ is the calculated factor of safety and F_{warn} is a warning reference value greater than 1. In this form, the indicator approaches zero when the factor of safety remains comfortably above the warning threshold and increases toward one as the factor of safety approaches the limiting state.

The displacement and volumetric change terms may be written as:

$$I_{D(s, k)} = \min \left(\frac{D(s, k)}{D_{ref}}, 1 \right) \quad (16)$$

$$I_{Q(s, k)} = \min \left(\frac{|DV(s, k)|}{Q_{ref}}, 1 \right) \quad (17)$$

where $D(s, k)$ is the representative displacement magnitude of the sector, D_{ref} is a reference displacement value for normalization, $DV(s, k)$ is the volumetric change associated with the sector, and Q_{ref} is a reference volumetric threshold. These two terms are not intended to override the factor of safety, but rather to indicate whether the monitored sector is also expressing geometric or kinematic evidence consistent with deterioration.

For practical implementation, the warning tier may then be assigned in a simple manner. A low concern class may be associated with sectors for which the factor of safety remains comfortably above the warning threshold and only minor deformation is observed. A moderate concern class may be assigned where the factor of safety decreases, localized displacement becomes identifiable, or volumetric redistribution begins to concentrate in a mechanically meaningful area. A high concern class may be assigned where the factor of safety approaches the limiting range and is accompanied by persistent displacement, crest retreat, toe bulging, or clear concentration of volumetric change. If required, a critical class may be reserved for sectors in which the factor of safety reaches or falls below unity, especially when this condition is consistent with observed deformation.

A practical classification of the composite warning score may be defined in four levels;

- Values of W below 0.25 may be interpreted as representing low concern, indicating that the monitored sector exhibits limited evidence of instability under the adopted criteria.
- Values between 0.25 and 0.50 may be classified as moderate concern, suggesting the presence of measurable but not yet strongly critical warning features.
- Values between 0.50 and 0.75 may be interpreted as high concern, reflecting a more significant combination of adverse indicators and a greater likelihood of ongoing deterioration.
- Values exceeding 0.75 may be classified as critical, corresponding to sectors that require the highest level of attention within the monitoring framework.

Notwithstanding this classification, sectors for which the calculated factor of safety approaches or falls below unity should be regarded as alarming irrespective of the composite warning score, since such values indicate that the slope is at or near the limiting mechanical condition.

The final outcome of this step is therefore not a replacement of stability analysis, but an integrated statement of condition. Sectors with low factor of safety, especially when accompanied by persistent displacement and localized volumetric redistribution, may be recognized as the highest priority for monitoring and intervention. Sectors with a higher factor of safety and limited geometric change may be classified as lower concern. The warning tier thus provides a practical bridge between multitemporal UAV observation, factor of safety evaluation, and operational slope management, while remaining deliberately light and subordinate to the primary geotechnical interpretation.

3. Software implementation

The proposed methodology may be implemented through a combination of freely available software environments, each supporting a distinct part of the workflow. Because the framework includes photogrammetric reconstruction, multitemporal surface comparison, volumetric analysis, geotechnical parameter handling, factor of safety calculation, and integrated interpretation, its practical realization is most naturally organized as a sequence of interoperable tools rather than as a single software package.

For the photogrammetric component, software such as OpenDroneMap or MicMac may be used for image alignment, camera orientation, dense point cloud generation, digital surface model production, and orthomosaic derivation. These environments are appropriate for repeated UAV surveys and are capable of generating the multitemporal surface representations required for geometric monitoring. For point cloud registration, comparison, and local change analysis, CloudCompare is well suited to the needs of the framework, since it supports point cloud visualization, registration refinement, cloud comparison, and normal based or M3C2 type distance estimation. At the spatial analysis stage, QGIS may be used for raster processing, sector-based organization of the study area, volumetric differencing, spatial overlay, and map production.

The transfer from geometric monitoring to stability analysis may be approached through additional computational implementation. In particular, the extraction of representative geometries from the monitored surface, the assignment of geotechnical parameters to selected sectors or model domains, the repeated calculation of factor of safety across survey epochs, and the generation of integrated warning indicators may be facilitated through dedicated scripts. Such scripts may be written to connect intermediate outputs, standardize the processing sequence, and support repeatable application of the methodology under different case study conditions.

Accordingly, the methodology is compatible with a modular software pathway in which the principal stages are carried out with available free tools, while further investigation and script development may be undertaken to formalize the links between stages and to increase the degree of automation. This implementation structure is consistent with the interdisciplinary character of the framework and provides a practical basis for future case study application, refinement, and executable realization.

4. Discussion and Conclusions

This study presented a unified 4D methodology for the monitoring and stability evaluation of mine dump slopes using multitemporal UAV photogrammetry, geometric change analysis, and factor of safety assessment within a common framework. The aim was to move beyond the separate use of repeated surface models and to show how observed geometric evolution may be linked directly with the mechanical interpretation of slope condition through time.

It is important to distinguish between the definition of the methodology and its validation under field conditions. In the present work, the former is addressed through the analytical formulation of the workflow, the explicit connection between geometric and mechanical stages, and the identification of implementation pathways. By contrast, the latter requires application to one or more case studies, together with comparison against observed slope behavior, independent measurements, or other reference evidence. The current paper therefore establishes the methodological basis upon which such validation may be carried out, rather than presenting validation itself as already completed.

The methodology was structured so that repeated UAV surveys provide the basis for reconstruction of the dump surface at successive epochs, followed by registration, surface comparison, displacement estimation, and volumetric change analysis within a common spatial reference frame. These geometric outputs are then

connected with geotechnical parameter assignment and factor of safety evaluation through limit equilibrium or strength reduction procedures. In this way, monitored morphology, observed deformation, and modeled stability are treated as related aspects of the same evolving system rather than as isolated analytical products.

A key contribution of the proposed approach is the direct use of the current observed dump geometry in the stability analysis. This is important because mine dumps evolve continuously during deposition and may develop changes in crest position, slope angle, toe geometry, and local relief that are not represented by idealized or outdated sections. By incorporating UAV-derived geometry into the geotechnical model, the framework provides a more realistic basis for time-dependent factor of safety assessment and for interpretation of progressive deterioration. At the same time, the methodology explicitly recognizes that geometric observation alone is not a direct substitute for geotechnical characterization. For this reason, displacement and volumetric change are not interpreted as standalone proxies for failure, but as monitored indicators whose significance depends on material behavior, parameterization, and the adopted stability model.

The study also highlighted that displacement and volumetric change outputs must be interpreted carefully. Surface difference mapping and normal based comparison are valuable for identifying geometric change, but they do not always represent the full three-dimensional kinematics of slope movement. In addition, the reliability of early deformation interpretation depends on registration quality, reconstruction consistency between epochs, and the magnitude of the observed change relative to survey uncertainty. The stability component is similarly dependent on the representativeness of the adopted geotechnical parameters, pore pressure assumptions, and the adequacy with which the updated geometry captures the controlling failure mechanism. For this reason, the framework should be understood as a structured methodology for integrated assessment, whose results are conditional upon the quality of both the geometric and geotechnical inputs.

In implementation terms, the methodology is compatible with a modular software pathway based on free tools for photogrammetry, point cloud comparison, and spatial analysis, complemented where needed by dedicated scripts for geometry transfer, parameter handling, repeated factor of safety calculation, and integrated interpretation. The framework is therefore presented as methodologically defined and suitable for future executable implementation, while its full automation and field scale deployment remain natural next stages of development. Likewise, where site specific geotechnical data are limited, the methodology remains applicable in scenario-based form, with factor of safety interpreted as a conditional stability indicator rather than as an absolute deterministic value.

Overall, the proposed framework shows that UAV based geometric monitoring and geotechnical stability analysis can be combined into a single methodology for proactive mine dump assessment. Its present contribution lies in the formal integration of monitoring, geometric change analysis, and stability evaluation into one coherent workflow. Further work may focus on script-based implementation, controlled benchmarking, and application to case studies for calibration and validation under varied geological, hydrological, and operational conditions.

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Conflicts of Interest

The authors declare no conflicts of interest.

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