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STABILITY OF THE ROCKY SLOPES FACING LARGE RESERVOIRS. INNOVATIVE VERIFICATION AND RISK ASSESSMENT APPROACHES USING 3D POINT CLOUD ANALYSIS – THE CASE OF LA PENNA DAM (AREZZO, TUSCANY, ITALY)

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1. INTRODUCTION

Landslides from rock slopes are characterized by a sudden and rapid development with dynamics for sliding, fall and topple.

These instabilities therefore constitute a serious risk for the management of the reservoirs, related to possible direct damage to the dam's structures, anomalous waves, up to the overflow scenario. Development times of the phenomena are usually incompatible with emptying operations.

It is therefore essential to forecast and elaborate scenarios as precise as possible regarding the stability of the rock faces and the volumes involved, as well as the overall monitoring of the physical state of the rock mass.

Rock instabilities are usually caused by movements along the fracture joints present in the rock mass. Therefore, all the methods for the stability verification and the quantification of unstable volumes are based on the field survey of the joints' orientation.

This information is classically investigated in tedious fieldwork campaigns using a geological compass (Fig. 3).

In the real world, obtaining a description of the rock mass adequate to the objectives of modeling and forecasting the instability with the "classic" field methodology is almost impossible and the resulting models are highly approximate and substantially unreliable. This because the "manual" survey only allows to obtain data on punctual measurement stations, with a limited number of representative joints, and a reduced coverage of the entire mass, usually characterized by significant local heterogeneities.

The survey must also be carried out by personnel on the rope (mountain guides), and this is often not possible for safety reasons, or it can only be carried out in "safe" sectors, therefore not representative of the real risk conditions.

Recent advances in Light Detection and Ranging (LiDAR) instrumentation, and Drone - UAV photogrammetry currently allow quick and accurate 3D data acquisition, yielding on the development of new methodologies for the automatic characterization of rock mass discontinuities.

These methodologies support the analysis of discontinuity systems and joints predisposing instabilities on the basis of a complete coverage of the rock mass, at a level of precision and reliability not comparable with "classic" field survey methodologies, allowing the development of objective and reliable risk models for the reservoir.

The remote survey approach of the rocky front at La Penna dam (Arezzo) is described below. For reasons of synthesis, the subsequent stability analysis refers just to a sample sector of the rock wall ("A" sector in Fig. 1), considering that the methodology was applied to the entire area by the same criteria and technology.

2. LA PENNA DAM CASE STUDY

The La Penna dam, built between 1955 and 1957, on the Arno river, in the municipality of Laterina Pergine Valdarno (AR), is a gravity dam, overflowing with interposed gates. It has an arched shape (R = 139.3 m) and is characterized by the following data (taken from the Maintenance Operation Conditions Sheet).

- height of the dam (pursuant to Ministerial Decree 24.03.82) 36.30 m

- height of the dam (pursuant to Law 584/94) 30.00 m

- maximum retention height 25.50 m

- crowning altitude 206.50 m a.s.l.

- development of the crown 101.00 m

- volume of the dam 42,900 m^3

- reservoir original volume 13 Mm^3

- classification pursuant to D.M. 24.03.82: A.a.1 (ordinary gravity in concrete)

The instability concerns the sector of the rocky slope on the hydrographic right located at a distance between about 100 ÷ 240 m upward from the La Penna dam (Fig. 1).

The slope, starting from the upper surface of the fluvial-lacustrine terrace (ref. Profiles in Fig. 1) at an altitude of about 240 m, has a development of about 36 m compared to the current maximum reservoir level (203.5 m a.s.l.). The observed collapses, endemic over time, concern arenaceous lithotypes, alternating with marly levels of the so-called geological Unit of Falterona, with the involvement of weak thicknesses of fluvial-lacustrine deposits from the top portion.

Anticipating the elements under investigation in the survey, study and stability analysis phases, the failure is on the whole linked in both sectors to:

- alternation of arenaceous banks to more erodible marly levels, with endemic undermining at the base of the arenaceous banks themselves;

- presence of sub-vertical open fracture systems, which allow the subdivision into blocks and their mobilization, following the erosion of the marly levels at the base.

2.1 DISCONTINUITY REMOTE SURVEY

The discontinuity survey was carried out in the overall frame of the landslide risk assessment for the La Penna reservoir and dam. The specific goal was the construction of a model of the fractured rock mass supporting the stability analysis and the quantification / localization of the volumes possibly unstable for collapse / topple.

2.1.1. 3D point cloud survey through Drone – UAV survey

On 09/24/19, on the occasion of partial emptying operations (198.5 m above sea level), an aerial photogrammetric survey was carried out in the specific sector, by Drone - UAV, performing a flight in manual mode (Fig. 2).

Fig. 1
Cliff images and profiles, total height is around 40 m over reservoir average level
Images et profils de falaises, la hauteur totale est d'environ 40 m au-dessus du niveau moyen du réservoir

Images were taken in frontal shooting, with a grid as regular as possible, bidirectional (ref. diagram Fig. 2), with a minimum overlap between adjacent frames of about 75% in the longitudinal direction (“overlap”, flight direction) and at least the 50-60% lateral overlap (“overside”, between strips).

For the correct calibration (georeferencing) of the frames and of the point cloud, a support survey was carried out on known points (GCP: Ground Control Point).

Targets and natural control points were detected with a Leica TS16 total station equipped with a prismless distance meter, enabling a unique topographic reference network to be created.

Pix4D software (Simactive, 2019) was used for the reconstruction of the 3D model. The software searches for the points in common between the photos and proceeds to align them on the basis of the analytical relationships existing between the points in common.

At the end of the processing, the program shows on the screen the points in common (tie points) between the photos that it used for the alignment and that it will use for the construction of the point cloud.

Subsequently, again in the Pix4D environment, we proceeded to frame the cloud on the support topographic survey (ground target net), and subsequent geo-referencing of the point cloud itself.

On the processed and filtered (excluding some vegetated areas) point cloud we proceeded to create polygonal "mesh" surfaces, generating 3D model.

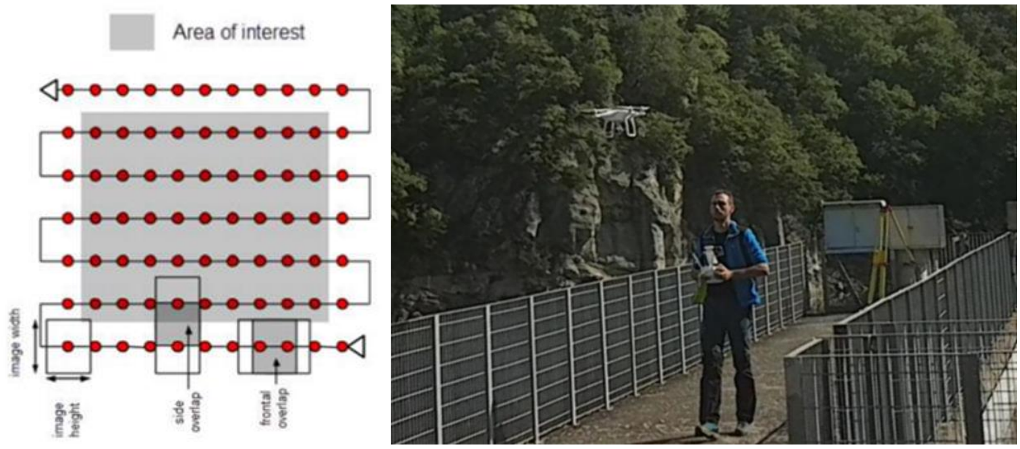

Fig. 2

Layout of the flight plan and frame acquisition. b) positioning of the UAM operator and of the total station for surveying the support network, on the La Penna dam

Schéma du plan de vol et acquisition des photos. b) positionnement de l'opérateur UAM et de la station totale de levé pour le réseau de soutien, sur le barrage de La Penna

2.1.2. Survey of discontinuities, extraction of joints from the 3D point cloud

As previously mentioned, the survey of the discontinuities is usually carried out with a geological compass, detecting the direction and immersion of the plane, placing the cover of the compass on the surface itself (Fig. 3-b). Using a customized version of the well-known CloudCompare software (EDF), it is possible to perform the same measurement on the single plane starting from the 3D model of the rock wall (Fig. 3-a)[1].

However, the complete schematization of the discontinuities in a rock mass requires the continuous and complete definition of all the planes, not always identifiable from the visual observation of the different systems.

For this purpose, the DSE calculation code was tested, capable of "extracting" from the digital model the alignments of points corresponding to the single joints, grouping them in homogeneous clusters from the point of view of orientation.

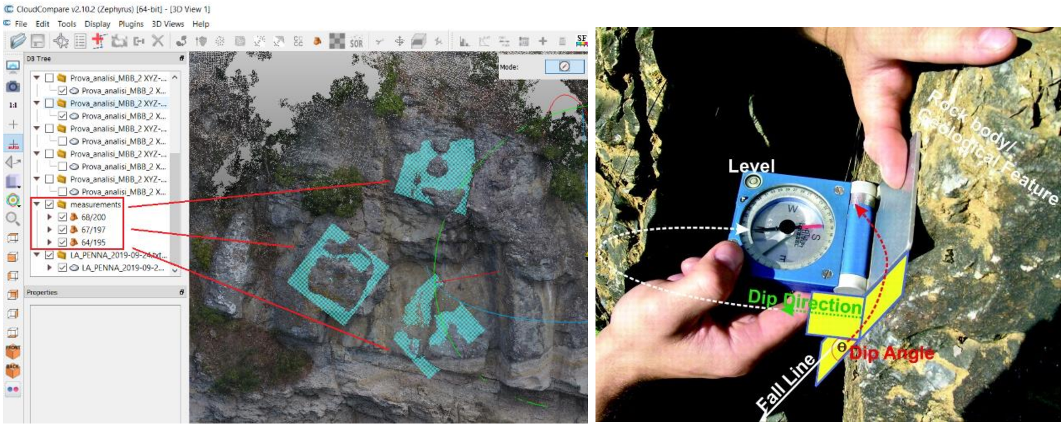

Fig. 3
3D point cloud compass Vs. field compass
Boussole par nuage de points 3D Vs. boussole de terrain

Discontinuity Set Extractor – DSE, developed by Alicante University (E), applies a semi-automatically methodology to identify points members of an unorganized 3D point cloud that are arranged in 3D space by planes.

This method identifies and defines the algebraic equations of the different planes of the rock slope surface by applying an analysis based on [1]:

a) the user-supervised removal of noisy points through the creation of a coplanarity test;

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[1] CloudCompare (developed by Électricité de France EDF) is a point cloud processing software. It has been originally designed to perform comparison between two dense 3D points clouds. Afterwards, it has been extended to a more generic point cloud processing software, including many advanced algorithms (registration, resampling, statistics computation, sensor management, etc.).

b) the semi-automatic identification of discontinuity sets using a Kernel Density Estimation (KDE) Analysis;

c) the automatic extraction of single discontinuities through a density-based clustering algorithm.

2.2 ROCK MASS MODELLING AND DEFINITION OF UNSTABLE VOLUMES FACING THE RESERVOIR

Fig. 5 shows the result of the processing (extraction and clustering of discontinuity plans) carried out in the DSE environment on the sample zone. Analysis is performed over a 2.8E+6 points cloud model (Fig. 4). The classification by joint-set is represented with a continuous chromatic scale (on the right in the image).

Considering the finalization of the stability checks, we opted for an initial classification of the joints in n. 10 "joint sets", meaning a significantly higher number than discontinuity systems normally used for structural analysis.

The above refers to the need, in the practice of stability analysis with a geomechanical criterion, to avoid the calculation with reference to a few average planes representative of systems with strong dispersion, i.e. where stability conditions could result different if calculated assuming the average joint orientation rather than the extremes within the orientation range.

Fig. 6 shows the projection of the same joint systems on a polar diagram (strike/dip [°] reported in the table on the left) .

From a general characterization level, the system J1 ÷ J2, consistent with the position of the slope, J8 ÷ J9 the sedimentation plane (anti-dip slope), J4-J7, and remaining, subvertical fracture joints.

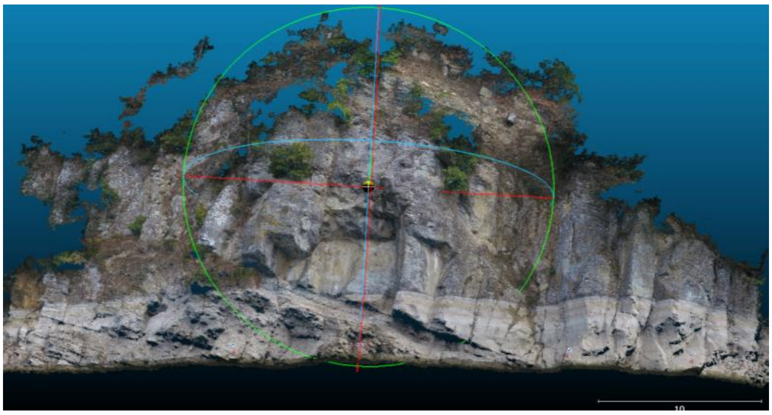


Fig. 4
Three-dimensional model developed in CloudCompare environment
Modèle tridimensionnel développé dans l'environnement logiciel CloudCompare

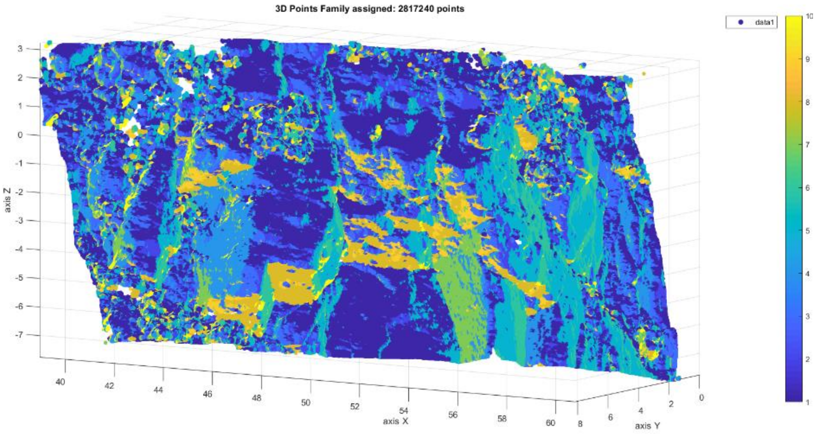


Fig. 5
Projection of discontinuities sets defined by DSE (chromatic scale on the right, stereographic projection on following Fig. 6)
Projection d'ensembles de discontinuités définis par DSE (échelle chromatique à droite, projection stéréographique sur la Fig.6 suivante)

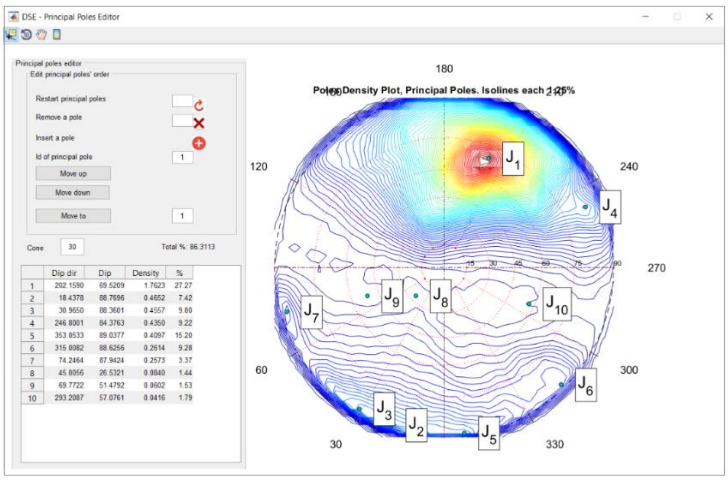


Fig. 6
Stereographic projection on polar diagram of systems 1 ÷ 10 (screenshot software DSE; N.B. the software represents by default North / 0 ° downwards and South / 180 ° upwards)
Projection stéréographique sur diagramme polaire des systèmes 1 ÷ 10 (capture d'écran du logiciel DSE; N.B. le logiciel représente par défaut le Nord / 0 ° vers le bas et le Sud / 180 ° vers le haut)

2.3 SLOPE STABILITY CHECKS, MARKLAND TEST

Starting from the 3D point cloud, the stability analysis was conducted at two levels:

- from the orientation of the joint systems extracted with DSE, a preliminary analysis with Markland Test, leading to the evaluation of the discontinuity sets possibly predisposing collapse (for planar sliding, translation of isolated wedges, topple);

- as for the instabilities related to unfavorable joint geometries (as shown by Markland test results), a detailed analysis in the CloudCompare software environment has been performed, through the 3D modeling of the specific joint systems for the definition of unstable blocks, defined by significant intersections

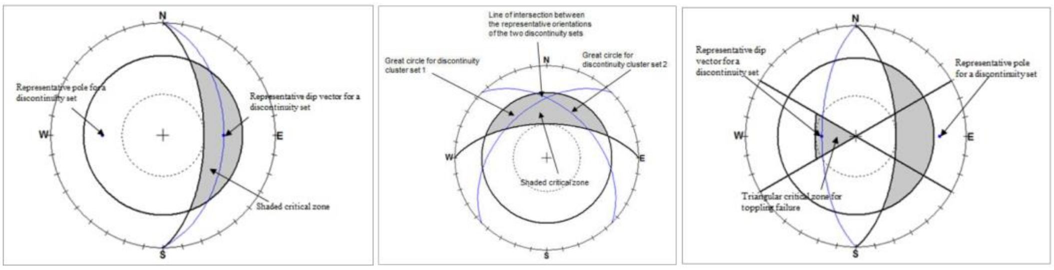
2.3.1. Markland test

The Markland test allows to verify intersections between the plans extracted from point cloud, predisposing phenomena of instability, based on the following standard conditions (Fig. 7):

a: If the representative orientation vector of a system of discontinuity falls within the area indicated in gray (resulting: Discontinuity inclination > joint friction angle ϕ, and Discontinuity inclination < slope front inclination), the condition of potential planar failure exists.

b: If the intersection of the two representative circles of two systems of discontinuity falls within the gray area (area between the friction angle ϕ and the angle of inclination of the face), the condition of potential breakage and collapse of rocky wedges exists.

c: The potential topple condition exists if the orientation vector representative of a system of discontinuity (central point of the arc of a circle in blue) falls within the highlighted triangular sector.



a b c

Fig. 7

Stereographic projection showing the conditions for block mobilization on: a) a planar surface, b: wedge failure, c: topple (Hoek and Bray, 1981, Watts 2003).

Projection stéréographique montrant les conditions de mobilisation de bloc sur: a) sur une surface plane, b: rupture de coin, c: basculement (Hoek et Bray, 1981, Watts 2003).

2.4 RESULTS

Results, as already said, are reported for the sample sector. Fig. 8 shows the stereographic projection, on an equiangular Wulff diagram, of the fracture systems identified through the analysis in the DSE environment from the point cloud. Joint systems J9, J10 have been excluded since, from the single projection in the 3D model, they represent punctual and discontinuous alignments.

From the observation of the diagram, and with reference to the scheme of the stability verification with Markland test referred to Fig. 8, the following is noted:

- the direction and average immersion of the front (Slope) is consistent with the position of the main system of joints (system 1);

- there are no predisposing conditions for breakages on planar surfaces, as none of the single orientation vectors representing a system of discontinuity (central point of the arcs corresponding to the single planes) falls within the "critical zone" indicated in color;

- there are no predisposing conditions for wedge-shaped breaks / unstable wedges; the two systems J7, J4, with intersection in the "critical zone" actually constitute a single sub-vertical system, with dispersion of the planes on the two opposite verges, and do not give rise to unstable wedges;

- there are no conditions predisposing to kinematics for topple.

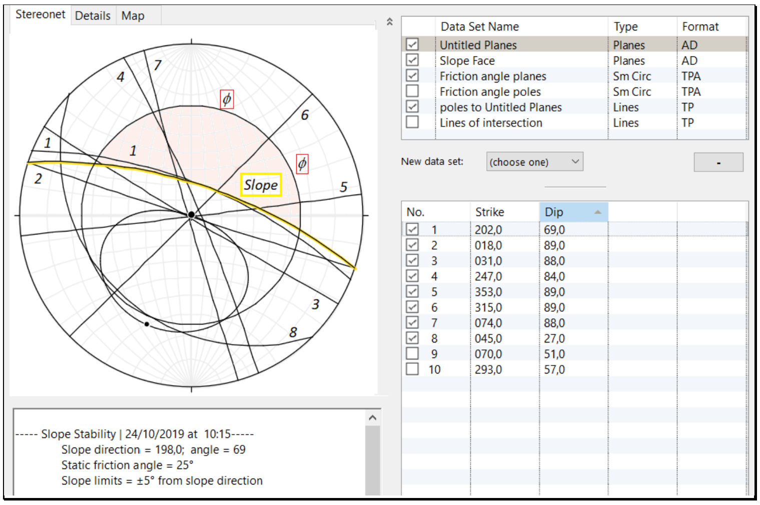


Fig. 8

Stereographic projection of discontinuity systems and stability verification with the Markland test

Projection stéréographique des systèmes de discontinuité et vérification de la stabilité avec le test de Markland

Under the current conditions, the rocky front therefore **does not** present unfavorable joint conditions, predisposing phenomena of instability of rocky prisms.

Conditions of instability can instead derive from differential erosion, also induced by reservoir wave motion.

Erosion, in particular of the marly banks, determines the undermining along the system of joints J8 (stratification plane). <u>This can change stability conditions, causing sub-vertical sliding of blocks</u> delimited by systems J1, J4-J7 (Fig. 9).

Therefore, even in the presence of favorable conditions in geometry of the joints, wave erosion can cause the release and fall of single rocky prism.

This means that:

- on the whole the slope is stable, no significant landslides are expected;

- isolated prism fall is possible, as far as wave erosion proceed.

The extent of the volumes involved in isolated falls, can be analyzed starting from the projection of the individual fracture planes selected in the DSE environment starting from the 3D model, i.e. delimiting volumes between joint sets number J1 and J4-J7. The extracted plans, imported into the CloudCompare environment, can in fact be selected individually to define the volumes underlying the relative intersections. In CloudCompare environment this can be calculated automatically, or “cutting” cloud adding new planes. As for the sample area a plan has been added parallel to J1 system, to consider the location of current traction fractures (Fig. 10-11).

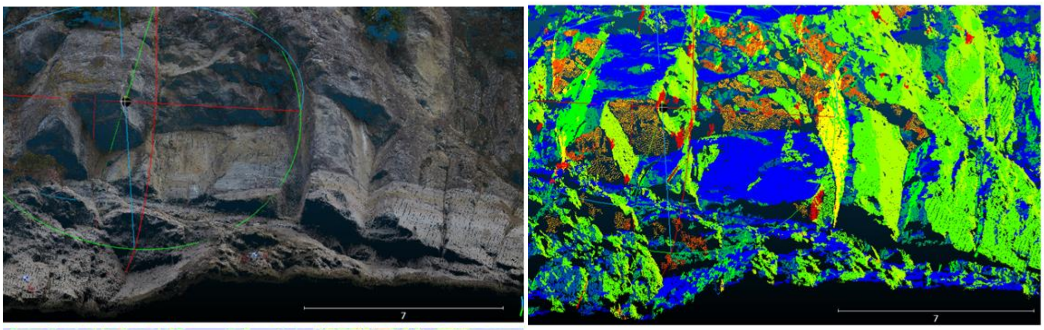


Fig. 9
Surfaces (system 8, dark orange color) from undercutting due to the action of wave motion, resulting in the creation of blocks sliding on the surfaces intersections between systems 1 (blue), 4-7 (green)
Surfaces (système 8, couleur orange foncé) de contre-dépouille due à l'action du mouvement des vagues, entraînant la création de blocs glissants sur les surfaces intersections entre les systèmes 1 (bleu), 4-7 (vert)

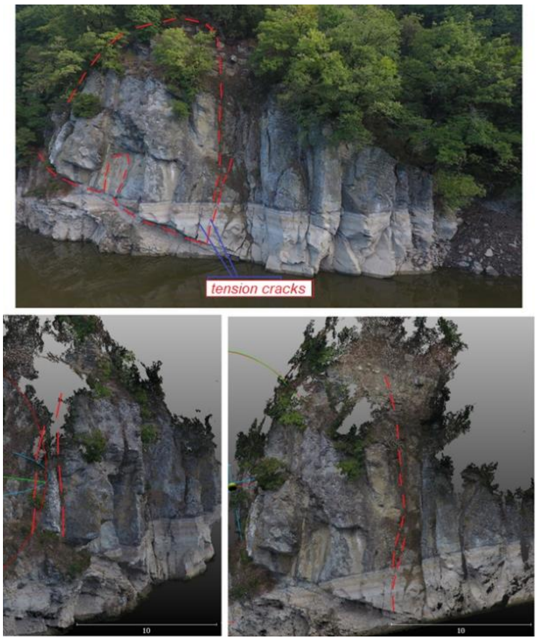


Fig. 10
Delimitation of unstable blocks based on stress fractures, on point cloud and georeferenced image
Délimitation de blocs instables basée sur des fractures de tension, sur nuage de points et image géoréférencée

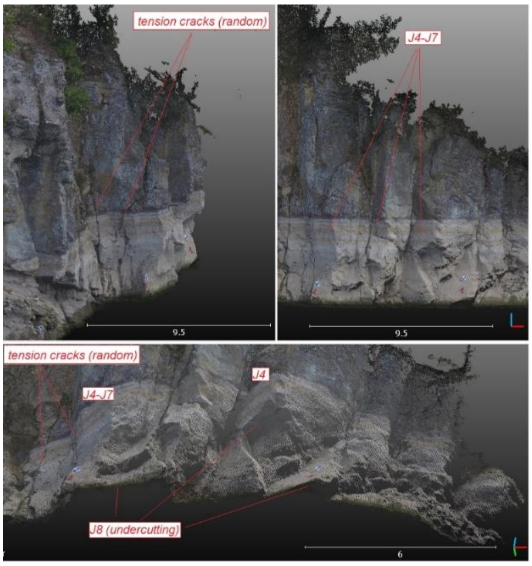


Fig. 11
Delimitation of unstable blocks on 3D point cloud for intersection between tension fractures, sub-vertical joints (systems 4-7) and undercutting surfaces due to wave motion (along joint system 8)
Délimitation de blocs instables sur un nuage de points 3D pour l'intersection entre les fractures de tension, les joints sous-verticaux (systèmes 4-7) et les surfaces de dégagement dues au mouvement des vagues (le long du système d'articulation 8)

2.5 MONITORING BY SEQUENCE OF 3D POINT CLOUDS COMPARISON

The monitoring of a rocky front is generally performed measuring local displacements with high resolution instruments (ex. extensometers, crackmeters).

These technologies allow for accuracies down to <0.1 mm and real-time acquisition and transmission where needed, and are therefore often irreplaceable in the case of high risk related phenomena.

However, the local survey with fixed instrumentation does not allow to visualize the overall deformations of the rock mass, through a complete coverage of the front.

Otherwise this information can be obtained by comparing sets of DTMs from different acquisition dates.

The measurement accuracy at the level of individual DTM points is of the millimeter order, i.e. significantly higher than that of local surveying with fixed instrumentation.

However, the 3D point cloud is made up of an extremely high number of points, for which a random positioning error is assumed, based on the same topographic ground network for all the different surveys. We therefore assume a compensation of the overall error and a consequent high overall reliability of the comparison between point clouds acquired on different dates.

As an example, Fig. 12 shows the comparison (using CloudCompare by EDF) referred to two sets of points, which highlights the overall rotation of the rock block counterclockwise along an approximately sub-vertical central axis.

The comparison between point clouds referring to different survey dates therefore constitutes a fundamental element of interpretation and control of the monitoring data from the local instrumentation.

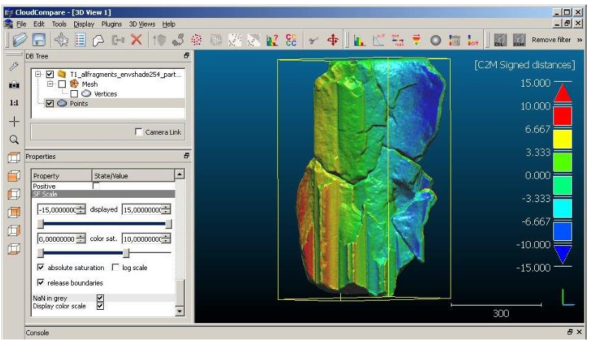


Fig. 12
Typical result of a distance computation process
Résultat typique d'un processus de calcul de distance

3. CONCLUSIONS

3.1 GENERAL CONSIDERATIONS ON THE APPLIED TECHNOLOGY AND ITS POTENTIAL

Evaluating the stability conditions of the rock slopes of a reservoir is frequently a challenging issue, due to the difficulty in obtaining a reliable geomechanical model through the direct survey of the discontinuity joints. Moreover, the direct survey of discontinuities performed by the operators (mountain guides suspended on highline) is frequently not feasible in safety and refers to local measurement stations, just allowing a very rough evaluation of the stability conditions. This is often a crucial issue for reservoirs management, since reliable scenarios of possible collapse cannot be evaluated (as well as related level rise, waves, morphological changes).

The proposed methodology allows to obtain a reliable risk model starting from the remote survey by Drone-UAV, the construction of the 3D point cloud and the subsequent extraction, with a semi-automatic methodology, of single digital models corresponding to the sets of discontinuity joints.

3.2 CASE RELATED CONCLUSIONS – LA PENNA RESERVOIR

The survey and modeling of the discontinuity joints had the purpose of evaluating the possible volumes of rock that could fall into the reservoir, possibly causing waves and level rise. In this paper, for purposes of synthesis, the analysis has been limited to a sample sector of the rock face, representative of the methodology applied on a larger scale.

The model has shown that there are no joint geometries that can determine instability due to the collapse and overturning of rock prisms, i.e. the Markland test for stability is always verified, in all sectors of the rocky front.

The instabilities observed, consisting in the collapse of isolated prisms, occur only as a result of undercutting due to erosion of the marly levels, with the collapse of the overlying arenaceous banks, largely determined by the action of the wave motion and favored by the level fluctuations in the reservoir.

Therefore, problems of instability of large volumes were excluded, resulting compatible with the joints geometry, only the development of "endemic" collapses of blocks and rock portions, as the erosion of the marly levels proceeds. It is therefore the same phenomenology repeatedly observed in the past, precisely "endemic", without significant evolution.

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SUMMARY

Rock slopes stability is one of the most relevant risk factors for the management of dams and large reservoirs. The instabilities for collapse and topple represent insidious phenomena, as they are generally sudden and rapidly developing, able to mobilize large masses, so related to abnormal wave formation as well as possible direct damage to the structures.

On the other hand, the security checks are complex and often not reliable, as they require a detailed assessment of the discontinuities in the rock mass, which is difficult to obtain if not at the level of punctual surveys and where compatible with the conditions of safe access.

The recent improvements of survey technologies by laser scan and Drone - UAV photogrammetry allow to obtain extremely detailed 3D point clouds, to support the analysis of discontinuity systems and joints predisposing instabilities.

This paper presents the application to the case of the ENEL Company dam of La Penna, on the Arno River (Arezzo, Italy), of advanced technologies for the survey by UAV, and the analysis, filtering and clustering of 3D point cloud data, aimed at security checks for rock fall/topple, related to the possible direct exposure of plant structures as well as the generation of hazardous waves.

RESUME

La stabilité des pentes rocheuses est l'un des facteurs de risque les plus importants pour la gestion des barrages et des grands réservoirs. Les instabilités dues à l'éboulement et au basculement représentent des phénomènes insidieux, car ils sont généralement soudains et à développement rapide, capables de *mobiliser de grandes masses, donc liés à la formation d'ondes anormales ainsi qu'à d'éventuels dommages directs aux structures.*

En revanche, les contrôles de sécurité sont complexes et souvent peu fiables, car ils nécessitent d'une évaluation détaillée des discontinuités dans la masse rocheuse, difficile à obtenir sauf au niveau des levés précis et lorsque cela est compatible avec les conditions d'accès sécurisé.

Améliorations récentes des technologies de levé à l'aide de scanners laser et de photogrammétrie par drone permettent d'obtenir des nuages de points 3D très détaillés, pour soutenir l'analyse des systèmes de discontinuité et des joints qui prédisposent à l'instabilité.

Cet article présente l'application au cas du barrage de la société ENEL "La Penna" sur le fleuve Arno (Arezzo, Italie), des technologies avancées de levé par drone et l'analyse, le filtrage et le regroupement des données du nuage de points 3D, destiné aux contrôles de sécurité d'éboulement / basculement de roches, liés à une éventuelle exposition directe des structures ainsi qu'à la génération de vagues dangereuses.

Keywords: reservoir safety, rockfall induced waves, LiDAR, rock mass stability, discontinuity, 3D point cloud, La Penna dam

Mots clé : sécurité des réservoirs, vagues induites par chute de masses rocheuses, LiDAR, stabilité de la masse rocheuse, discontinuité, nuage de points 3D, barrage de La Penna