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Rock and stone weathering at Citadel fortifications, Gozo (Malta): benefits from terrestrial laser scanning combined with conventional investigations

D. Tapete, G. Gigli, F. Mugnai, P. Vannocci, E. Pecchioni, S. Morelli, R. Fanti, and N. Casagli
Department of Earth Sciences, University of Firenze, Firenze, Italy (deodato.tapete@unifi.it)

Military architecture heritage is frequently built on rock masses affected by slope instability and weathering processes, which progressively undermine the foundations and cause collapses and toppling of the masonries. The latter can be also weakened by alteration of the stone surfaces, as a consequence of the interactions with the local environmental conditions. These conservation issues are emphasized for those sites, whose susceptibility to structural damages is also due to the similarity between the lithotypes constituting the geologic substratum and the construction materials. Effective solutions for the protection from such a type of phenomena can be achieved if the whole "rock mass – built heritage system" is analyzed.
In this perspective, we propose a new approach for the study of the weathering processes affecting historic hilltop sites, taking benefits from the combination of terrestrial laser scanning (TLS) and conventional investigations, the latter including geotechnical and minero-petrographic analyses. In particular, the results here presented were obtained from specific tests on the fortifications of Citadel, Gozo (Malta), performed in co-operation with the Restoration Unit, Works Division, Maltese Ministry for Resources and Rural Affairs and the private company Politecnica Ingegneria e Architettura.
The Citadel fortifications are built at the top of a relatively stiff and brittle limestone plate, formed by Upper Coralline Limestone (UCL) and overlying a thick Blue Clay (BC) layer. Differential weathering creates extensively fractured ledges on the cap and erosion niches in the strata beneath, thereby favouring block detachment, even rockfall events, such as the last one occurred in 2001. The locally quarried Globigerina Limestone (GL), historically employed in restoration masonries, is also exposed to alveolization and powdering, and several collapses damaged the underwalling interventions.
Since the erosion pattern distribution suggested a correlation with the structural setting of the rock mass and the mineralogical properties of the limestones, an overall weathering study was carried out, by combining surface surveys with analyses of the inner structure. A holistic TLS point cloud of Citadel, produced by Consorzio Ferrara Ricerche of the University of Ferrara and made available by the Restoration Unit, was exploited to perform a 3D quantitative kinematic analysis of the entire rock mass. Each sector was classified in relation to the probability of occurrence of instability mechanisms, among which plane failure, block toppling and wedge failure. The latter was found associated with the highest index measured (30%), followed by the flexural toppling mechanism (17%), providing a confirmation to the field survey and the results of geotechnical analyses. The integration with geologic and diagnostic investigations (e.g., boreholes, thin section observations) highlighted the intrinsic weaknesses of the rocks and stones to weathering, with a quite unexpected higher susceptibility to erosion and disaggregation characterizing the inner layers. Hence, the textural appearance of the erosion surfaces, the rock/stone structural properties and the TLS-based classification of the cliff sectors were mutually correlated, and the most unstable areas were mapped. As main implication for the conservation, on site monitoring system (i.e. biaxial inclinometers and crack gauges) was installed and targeted restorations have been properly designed.