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Vulnerability of critical infrastructures to rock fall hazard: the case of the Wastewater Treatment Facility of Tolo, Greece.

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The nature and extent of the risk associated with rockfall in steep terrains is a function of the local terrain conditions such as the structure of the rock, the slope stability and the geological processes that lie underground. Furthermore, climate, and weather-related phenomena can alter the local conditions and affect an area's risk. These variables make the assessment of hazard more difficult, especially when specific infrastructures are situated at the site and support measures are required to be adopted. The HSGME has performed numerous studies on rockfall hazard assessment at cliffs of broken, faulted or jointed rock. Among them there exist cases of steep bedrock layers undercut by activities of man for infrastructures developments, mining works etc. In these last cases humans and infrastructures are subjected to serious threat from detached falling rocks (Konstantopoulou et al., 2015). The available support systems for mitigating this risk have the ability either to stabilize the slope or to dissipate the kinetic energy of falling rock. Due to the lack of an official design code, these systems are designed primarily by experience and engineering judgment which often makes the design rather conservative.

In this study, assessment of rockfall hazard along a 300m long manmade cliff at Tolo, Naflio (Greece) is presented. The area is of specific interest due to fact that the foot of the 10 to 110m high cliff hosts the local wastewater treatment plant (WTP) of Tolo, consisting of clarifiers, aeration tanks and other supplementary infrastructures. The WTP plant was decided to be situated at the specific site, a few meters from the seaside of Tolo, to minimize wastewater transportation cost for disposal to the sea.

Geology of the site

According to the Geological Map (sheet 'Nafplion', IGME, 1970; scale 1:50.000) the area consists of Triassic limestone. Tectonically the area is dominated by folds, thrusts and faults, mainly normal that contribute to the morphological structure of the wider area of the trench of Argolis. The limestone rock mass is blocky to thickly bedded, moderately fractured. Randomly intersecting discontinuities include bedding, joint systems, fractures and open cracks caused by blasting practices during the preparation of the site for the facility construction. Also, several overhanging rocks were detected along the cliff (Figure 1).

Stability analysis of the rock cliff

Stability analysis of the cliff required evaluation of the rock structure. The compressive strength of the rock material ranges between 13.8-28.3MPa, based on experimental tests performed at the Lab. *Lithos* of IGME. Furthermore, detailed in situ evaluation of the rock mass characteristics (RQD parameter, spacing of discontinuities, condition of discontinuities and groundwater conditions) permitted the estimation of the Rock Mass Rating (RMR, Bieniawski, 1989) ranging between 52 and 70, corresponding to fair to good quality rock mass. Yet, the contoured plot of the rock discontinuities orientation (presented by poles) is shown in Figure 2 (*Schmidt net)*. Kinematic analysis of slope concerning three critical slopes along the cliff were carried out using the Dips v.5.1 software (Rocscience) taking into consideration the orientation of discontinuities and the shear strength of the potential sliding surface (angle of friction). The results indicated that several wedges of dimensions 0.2m^3 to 36m^{3}are free to slide or topple along all the three critical slopes.

Figure 1: Left: Extended fractured rock slope close to one of the clarifiers of the facility. Right: Overhanging rocks.

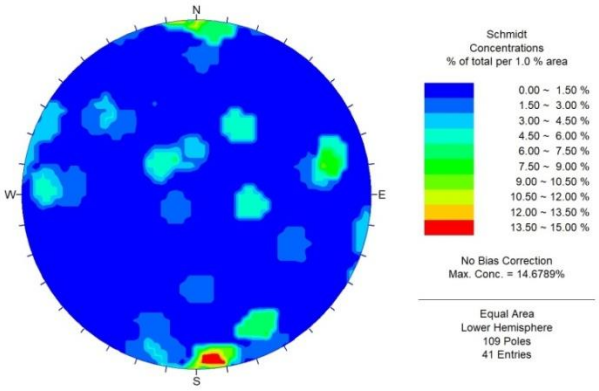

Figure 2: Contoured plot of 109 poles of discontinuity orientation of the examined rock and their concentrations (Schmidt stereonet projection, Dips v.5.1).

Rockfall Hazard Assessment

The outcomes of the stabilty analysis confirm that the various parts of the WTP are subjected to rockfall instabilities. The associated rockfall hazard varies depending on the height of the slope, as well as on the thickness of the inner zone and was considered to be medium to high (Figure 3) suggesting the need of remedial measures. Based on the indentified characteristics of potentially unstable rock mass, analyses of the motion of detached rocks were conducted with Rocfall 4.0 software (Rocscience) on the most critical profiles close to the facility parts. As anticipated, rockfall trajectories suggest that all the facility parts (buildings, tanks etc) are at risk, and also provide evidence that certain types of measures, as for instance mechanical removal of overhanging rocks or installation of fence that require a certain spatial margin between the slope and the facility to be protected, should be excluded for the necessary margin does not exist. Given this conclusion, the remaining suitable measures proposed for the site is wire mesh and rock bolts installation of specific characteristics.

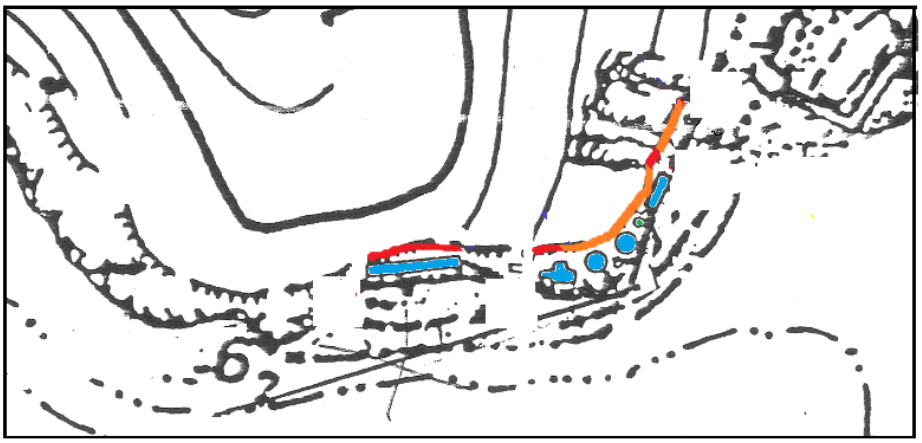

Figure 3: Rockfall hazard map along the WTP of Tolo. Orange line indicates the length of the cliff need to be supported (medium risk). Red lines correspond to locations of extended overhanging rocks of high risk. The facility parts are drawn in blue (the background map is a topographic map provided by the Municipality of Nafplio).

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