Rockfalls in Eocene flysch rock mass: geomechanical aspects of remediation of abandoned quarries in Central Dalmatia

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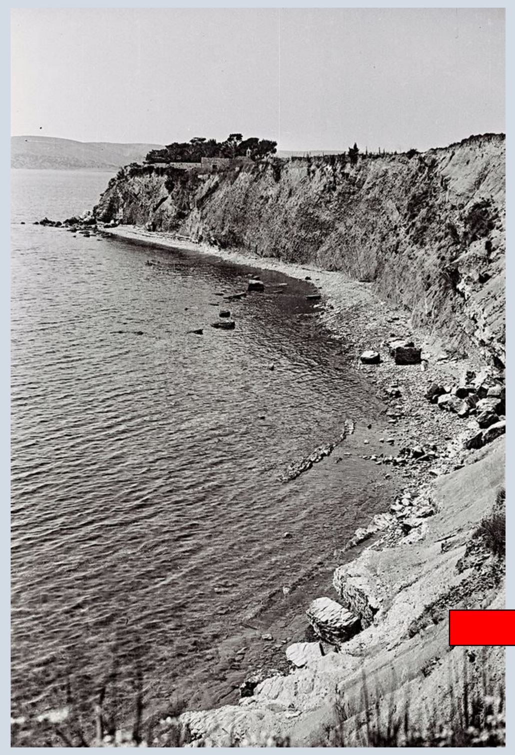
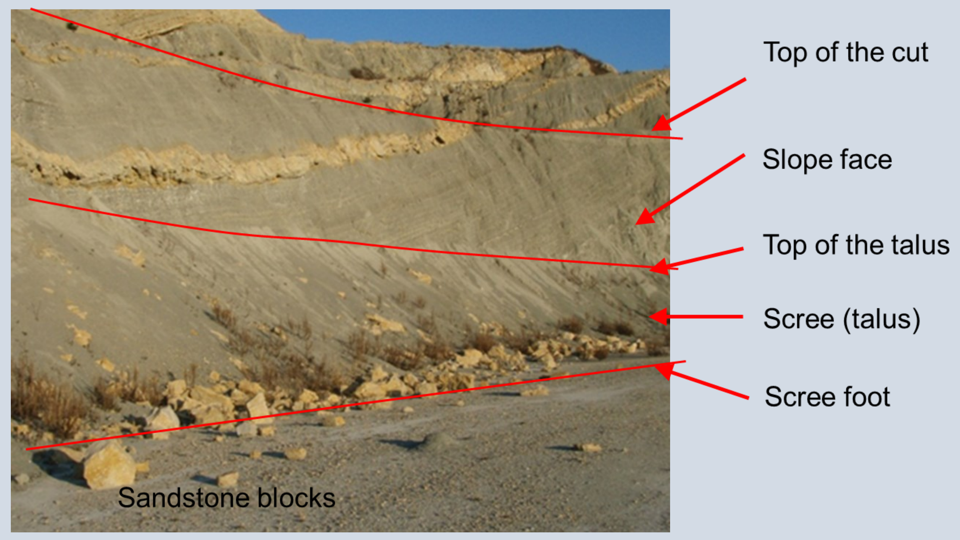
Introduction



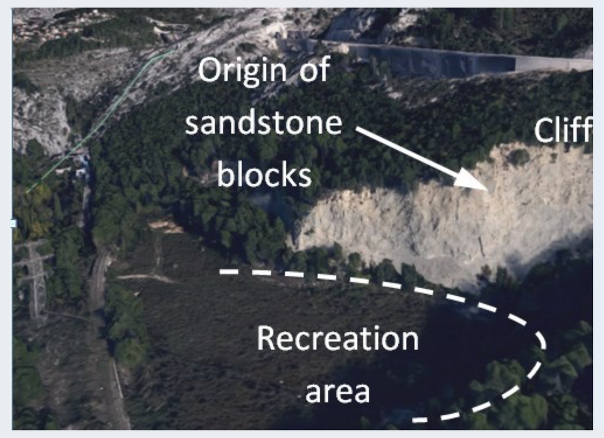
Flysch is a typical example of heterogeneous rock mass with layers of different mechanical properties. Even though they are formed by sedimentation and originally were horizontal, since flysch was suitable for tectonic shaping, layers that are often bent or inclined at various dip angles from 0 to 90 degrees can be encountered. While for homogeneous rock masses the process of weathering and erosion on cut slope is relatively predictable, and it can be well described by mathematical models of recession, for heterogeneous profiles this task is significantly more complex and sometimes unpredictable. Flysch members whom are more resistant to weathering, depending on the dip and dip angle of the layer, usually remain for longer time on the slope face and overhang like a "console". When the console becomes sufficiently long, the bending moment separates the blocks create rockfall that threatens the space below the slope (Miščević and Vlastelica, 2014). At the same time less resistant members, which are previously eroded form under or above more resistant members, create an scree (talus) at the bottom of the slope, thus making a very specific slope profile of different rapid changing of geometry of the slope (Vlastelica et. al, 2016a). tion parameters are favourable (it consists mainly of disintegrated ture, talus is prone to sliding in case of extreme loading conditions. loading and calculation of stability to sliding are made, considering ences (rainfall, earthquakes, etc.).



ground properties and relatively Even though talus material restitu- marl), because of its quasi stable na- Additional considerations about its build-up and environmental influ-

Pilot location

As a typical example of this situation, an abandoned quarry Majdan (Croatia) in flysch rock mass was selected, as it is intended to be reused as a recreation area. On the eastern side of the quarry slopes are up to 50 meters high and inclined more than 70 degrees, with large sandstone layers overhanging on the top. Considering that a solution with minimum investment was requested, that would ensure both maximum space for recreation area, and sufficient safety factor for rockfall hazard, multiple scenarios and types of remediation measures were investigated. Detailed survey by terrestrial laser scanner was made to ensure detailed profiles for 2D kinematic analysis, as well as to detect the erosion intensity and rate of scree accumulation at the bottom of the slope. Ground parameters necessary for kinematic analysis of future rockfalls were obtained by retrograde analysis of previously detected rockfalls on this and couple of other sites in the nearby area.



To determine the need for additional protection elements, as well as their efficiency, it is necessary to calculate the path of detached unstable blocks. Since there is no previous observation of the amount and frequency of rockfalls at investigated site, the probability approach of the simulation of the rockfall using the Monte Carlo method and the Rockfall (Rocscience) software was used for the analysis of possible trajectories.

Table 1. Selected restitution parameters

Parameter	Slope face	Talus	Plateau
Normal coefficient of restitution - R_N	0.5	0.3	0.25
Tangential coefficient of restitution - R_T	0.9	0.6	0.55
Dynamic friction coefficient	0.5	0.5	0.4
Rolling Friction	0.4	0.6	0.5

The mass of the characteristic sandstone block is m=2500 kg, as it is calculated by thickness of sandstone layer, observed shape of previously detached blocks and density of sandstone r= 2700 kg/m^3.

After defining input data, global stability control is performed assuming a solid sliding body according to one of the available limit boundary methods using Slide 6.0 (Rocscience) and in accordance with Eurocode 7, design approach 3. Calculation is carried out by assuming circular slip surfaces according to Bishops method, with the automatic search of critical sliding surfaces (with the lowest security factor) for defined boundary conditions. Possibility of on-circular sliding surface for general anisotropic material - discontinuous flysch (different surface properties along discontinuity at an inclination range ±10° and in the remainder of the rock mass) is also checked. According to the Croatian Seismological Map (HRN EN 1998-1: 2011 / NA: 2011) the site is located in the area with expected maximum horizontal acceleration of 0.22 g. For the seismic design of the structure soil class is A (flysch rock mass).

Characteristic values of material shear strength properties and unit weight (for flysch rock mass and talus) are determined as presented in Table 2. (Miščević and Vlastelica, 2009; Vlastelica et al., 2016b)

Table 2. Characteristic values of material properties

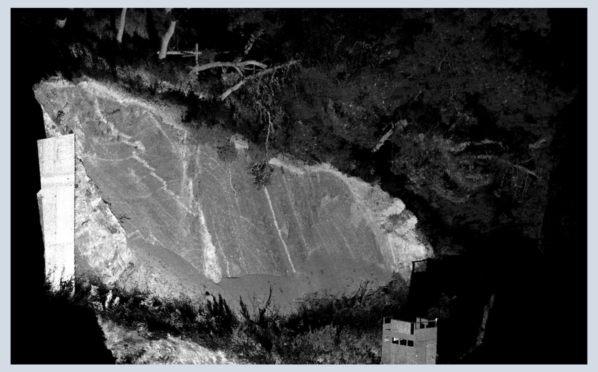
	c_k (kPa)	ϕ_k (°)	γ (kN/m^3)
Flysch rock mass	130	35	24
Talus	5	30	18

Methodology

Terrestrial laser scanning

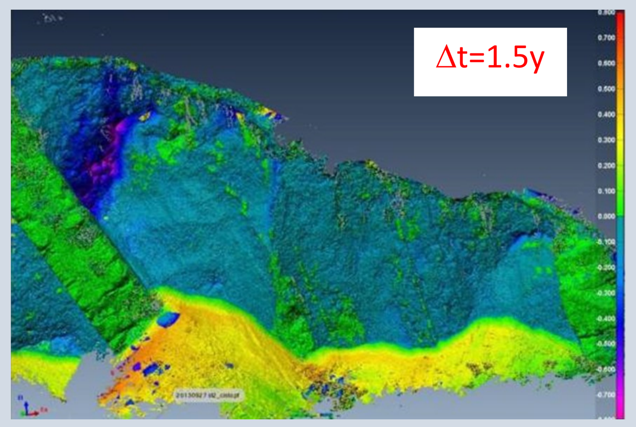
Result: Point cloud

Cloud of points with app 4 million points (Pilot location „Žnjan 1")

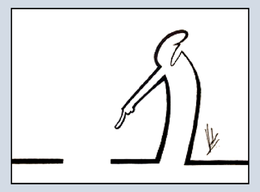


Valuable results:
(x, y, z) and Intensity of return-beam

Also important: 3D comparison



PC_0 → S_0 → PC_1, PC_2, ⋮, PC_n (Δt_1, Δt_2, ⋮, Δt_{n-1}) → PC_i vs S_0 → 2D



Input parameters for forecast models

Comparison of point clouds from different epochs

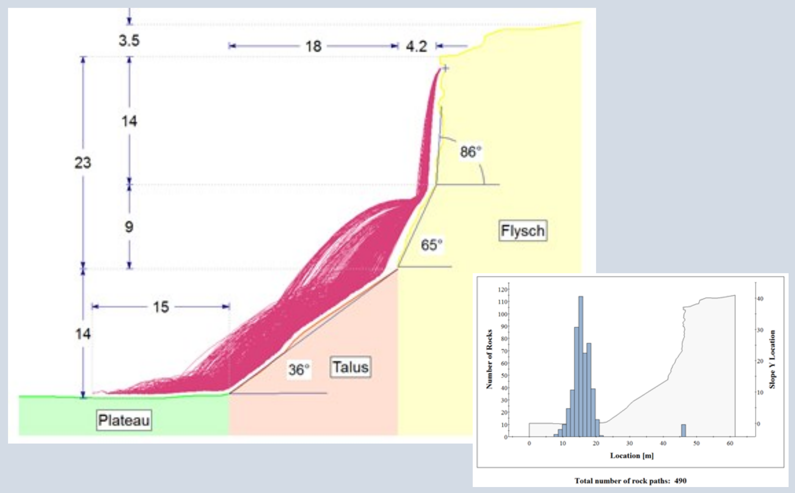
- The first collection of data (Cloud of points, TIN) → 3D comparisons
- … The new epoch of measurement (New cloud of points, After 6 months, 1 year, …) → 3D comparisons
- The initial geometric characteristics required for modeling → Define necessary input parameters (c, $R_{y,s}$ ili $R_{g,s}$) → 2D models (Mathematical models)
- The initial geometric characteristics required for modeling → 2D models (Mathematical models)

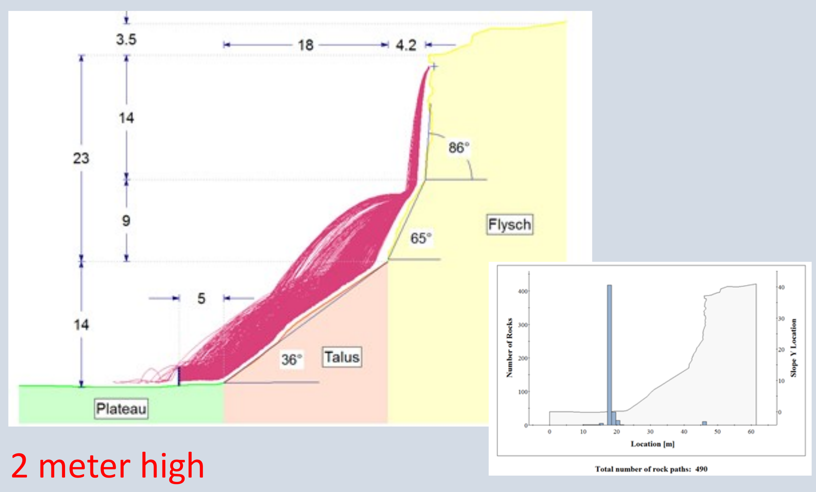
Calculation procedure (Vlastelica, 2015)

- The initial geometric characteristics for selected location (TLS) → Parameters for Fisher-Lehmann model (c and $R_{y,s}$) from similar sites → Forecast of geometric characteristics for each ΔT_i (Δt=0, 5 , 10, 20, 50, 100 y)
- Restitution parameters R_N, R_T → Rockfall analysis (Rocscience/Rocfall) → Results (for current and future slope development)
- + Global factor of safety (+ local for talus) ← Shear strength (c, φ)

Results

Rockfall analysis ΔT=0



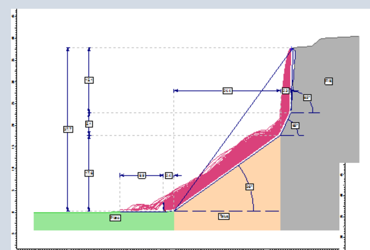


2 meter high gabion barrier

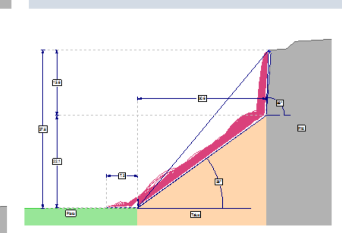
Rockfall analysis ΔT>0

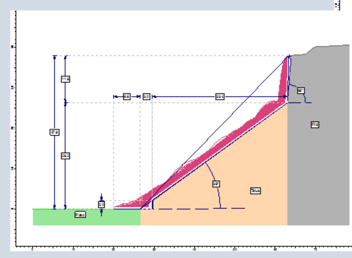
Year	ΔT (years)	Barrier height (m)	No of blocks that jump over barrier (od 500)	No of blocks that jump over barrier (%)	Trajectory endpoint without barrier (m)	Trajectory endpoint with barrier (100%)(m)	Trajectory endpoint with barrier (95%)(m)
2017	0	2	11	2,2	17,6	7,2	Barrier
2022	5	2	7	1,4	15,9	8,5	Barrier
2027	10	2	9	1,8	21,8	13,4	Barrier
2037	20	2	14	2,8	14,7	9,9	Barrier
2067	50	2	15	3,0	10,1	7,5	Barrier
2077	60	2	48	9,6	9,2	9,2	4,8
2117	100	2	494	98,8	10,0	9,5	7
2117	100	3	208	41,6	10,0	9,6	6,3
2117	100	4	15	3,0	10,0	9,3	Barrier

ΔT=20 years



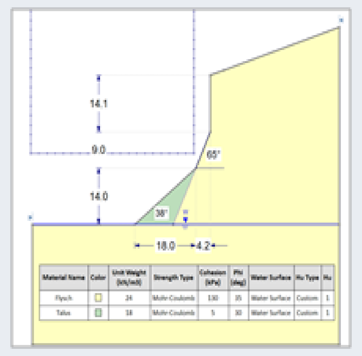
ΔT=50 years



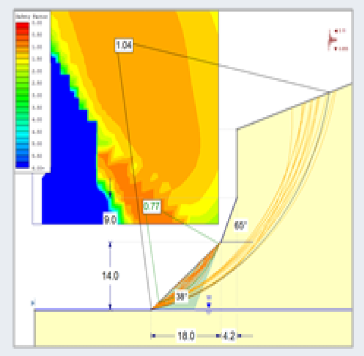


ΔT=100 years

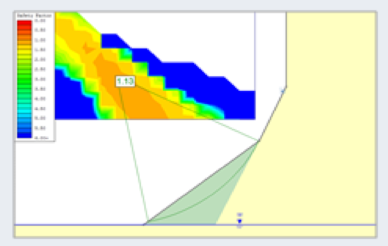
Global stability ΔT=0



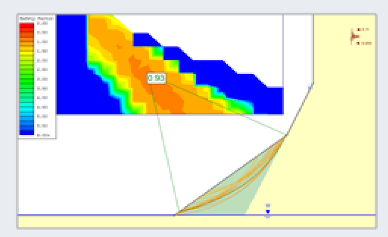
Global stability model



Results of the analysis (EC7)
F_S=1.04 (talus F_S=0.77)



Sliding stability of talus material (without EC7)
F_S=1.13



Sliding stability of talus material (introduced seismic action) F_S=0.93

Similar for other ΔT

Conclusions

- Abandoned quarries in flysch rock mass in Dalmatian area provide a new public resource as they are state owned, however funding for their remediation is usually very limited, so protection against rockfalls has to be dealt without conventional (expensive) geotechnical structures.
- Even though talus material restitution parameters are favourable (it consists mainly of disintegrated marl), because of its quasi stable nature, talus is prone to sliding in case of extreme loading conditions.
- Because it cannot satisfy the minimum factor of safety when using EC 7, and the additional build-up of newly eroded material changes the slope geometry, an occasional maintenance of talus zone is necessary.

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