Groundwater constraints in quarries exploitation: a coupled approach by means of geotechnical and hydrogeological modelling to deep existing gravel pits

MATTEO BERTI[1], ROBERTO PEDRON[2], ALESSANDRO SIMONI[1] & ANDREA SOTTANI[2]

[1] Dipartimento di Scienze della Terra e Geologico-Ambientali, Università di Bologna,
Via Zamboni 67, 40126 Bologna, Italy; E-mail: berti@geomin.unibo.it
[2] Sinergeo S.r.l., Contrŕ del Pozzetto 4, 36100 Vicenza, Italy; E-mail: info@sinergeo.it

Abstract: The deepening of existing quarries below the water table may cause variations on hydraulic heads distribution and determine potential slope stability hazard. Results of numerical modelling analyses on flow nets and slope stability criteria during the excavation development are described.

Key words: aquifer simulation model, groundwater balance, phreatic surface, gravel pit, slope stability.

INTRODUCTION

During the last decades the growing demand of inert building materials has lead to an exploitation of natural resources, which has not paid attention to environmental conservancy. In the "Padano-Veneta" plain (NE Italy) there is a powerful alluvial layer mainly formed by sands and gravel. This structure forms an important and valuable unconfined aquifer that is used as drinkable water resource. During the last decades this territory has been intensively exploited which have lead to an indiscriminate opening of many gravel pits, most of which have developed even below the aquifer level. This study is aimed to deliver a contribution favouring the use of pre existent pits and already below the water table.

RESULTS AND DISCUSSIONS

From hydrogeological point of view the opening of a pit with interception of the groundwater table determines modifications of piezometric surface. Following the void produced by the exportation of alluvial porous media, the hydraulic transmissivity of the dug sector theoretically becomes infinite[1]. Within these conditions a growth of discharge in transit can be observed, which is proportional to the digging length. Maintaining the area dimensions constant within different hydrogeological environments, we analysed the problems concerning the growth of hydro inflow following different deepening phases. Different hydrogeological environments are synthesized by three unconfined aquifers differing in hydraulic conductibility (K= 3e-02, 3e-03 and 3e-04 m/s). Using computing code for every phase of aquifer deepening starting from undisturbed situation, we proceeded the computing of water budget inside the all domain of analysis for the three different hydrogeological contests. The results show that the growth of one order of the K parameter leads to the

---

Scientific paper

growth of the same order for discharge in transit. The most interesting aspect could be observed in Figure 1: within the all domain the growth of discharge-in-transit percentage follows a pseudo asymptotic rule. For example, the 10 % interception of saturated thickness leads to a 61 % growth of flow percentage in relation to the greatest possible growth (100 %), which could be obtained by completely intercepting the alluvial porous media in the aquifer. The 50 % interception of saturated thickness indicates the possibility to reach a percentage growth of capacity of more than 90 %. The results of different extractive sites demonstrate that the major effects on hydro structure produced by aquifer diggings are substantially reached during the first phases of aquifer interception.

The classical approach for performance of a slope stability design (referred to Mohr-Coulomb failure criterion and to some form of the limit equilibrium method) is connected with numerous uncertainties in the case of the low stress environment where pit slopes and weakly bonded granular materials are characteristic, such as in the high Venetian plain. The soil strength determination is identified as a major deficiency in design practice. Excavated material is a sand-gravel mixture (containing 70 % of gravel, 20 % of sand and 10 % of silt and clay on average) that shows a dense, packed structure as the result of the wet-deposition in an alluvial-fan environment. Friction angles (ϕ’) obtained by reconstituting the soil matrix at minimum relative density range from 33° to 35° and are well in the range of the natural repose angle of the loose mixture mounds. The natural soil exhibits most likely much larger frictional strength, but uncertainties do not allow less conservative predictions. Similar problems affect the estimate of effective cohesion (c’). The apparent stability of near-vertical cuts in emerged slopes reveal the presence of a certain cohesive component of the shear strength, but it is almost impossible to obtain representative samples for laboratory tests. Therefore the back-analysis of slopes behaviour were used to estimate a minimum value of c’ for a given friction angle (33°<ϕ’<35°). Values of about 25-30 kPa were obtained for emerged slope, while much lower c’ (≈5 kPa) was computed for submerged cuts. This difference may indicate that inter-particle bonding do not result from mineral

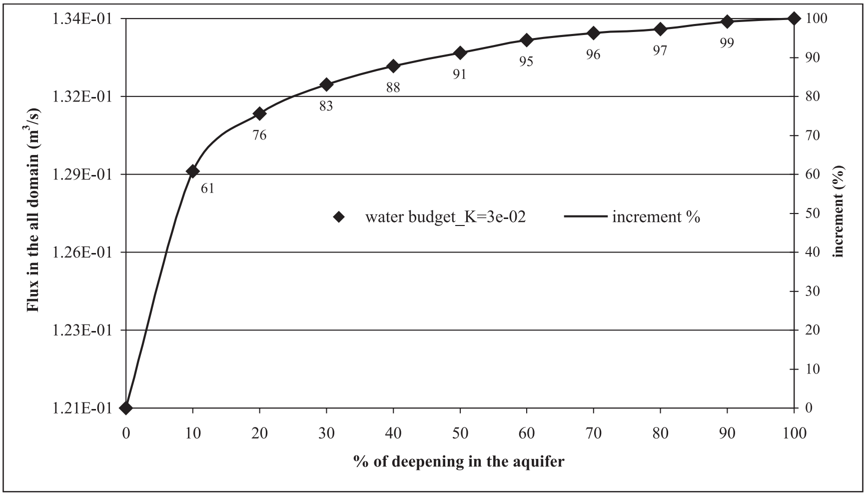

Figure 1. Effects of deepening in the water budget of model domain

cement but from weak attractive forces between grains, probably developed during the drying process of the silt-clay fraction. In long-term submerged conditions the cohesion tends to disappear and the soil mostly behaves as a pure granular material. For this reason two different design values of c' were used for the emerged and submerged parts of pit slopes, as suggested by back-analysis.

As regard the stability of submerged slopes, we compared the results obtained by limit equilibrium methods with finite-difference modelling. The comparison points out two questions that refer 1) to potential errors in the computation of the safety factor that may arise using some limit-equilibrium methods based on assumptions about interslice shear forces which are not adequate for submerged slopes, and 2) to limitations of limit equilibrium methods in the analysis of heterogeneous slopes composed of soil with very different mechanical properties. The model used for the comparison is a typical design slope with a height of 30 m and a dip of 30°. Figure 2 summarizes the results of the analysis in terms of critical safety factor computed by different methods as a function of gravel friction angle.

Factor of safety for the finite-difference modelling has been determined by using the shear strength reduction technique[2]. As can be seen, in case of a homogeneous gravel slope (Figure 2/A) all three considered solutions of the limit equilibrium method (Janbu simplified, Bishop simplified, Morgenstern-Price) tend to slightly overestimate the safety factor. However, computed values are only 1 %-7 % higher than those obtained by finite different modelling (a small error compared with the uncertainties in the estimate of shear strength properties). It is interesting to note that more rigorous methods that include interslice shear forces,

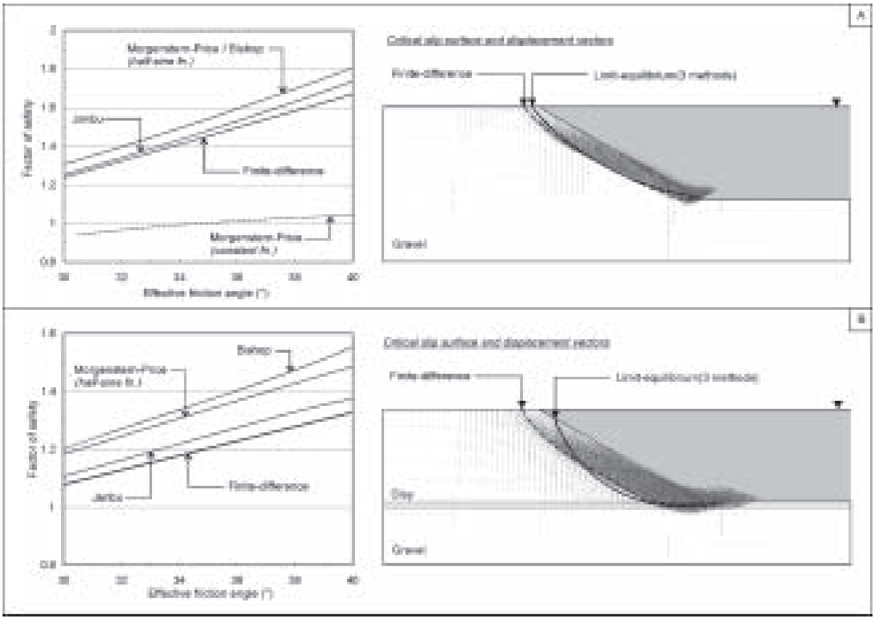

Figure 2. Comparison between limit-equilibrium and finite-difference analysis of a sample design slope (H=30 m; b=30°). Soil properties: 1) effective cohesion of the gravel, c'=5 kPa; 2) effective cohesion of the clay, c'=0 kPa; 3) effective friction angle of the clay, f'=20°; 4) thickness of the clay layer=2 m

such as the Morgestern-Price, give reasonable results only if a proper interslice function is used (compare the results obtained with half-sine and constant function in Figure 2/A). The choice of the interslice force function is a crucial point in the analysis of submerged slopes - since we expect no shear between the slices within the water, the function must be able to reduce the shear component, right as the half-sine function does. Of course this is not an issue for other simplified methods (JANBU, BISHOP), since these methods ignore interslice shear forces. Limit equilibrium methods perform worst in case of a heterogeneous slope with a thin weak layer (Fig. 2/B), a rather common situation in quarry. The percentage difference between the analytical and numerical values of the safety factor almost double, reaching 14 % for the Bishop method at high friction angles. Similar results for a slope with a weak layer in the foundation were reported[3] - a safety factor of 1.50 according to Bishop's method and 1.34 according to numerical modelling, with a relevant error of about 11 %. Numerical models usually determine a lower (and more realistic) safety factor because the critical failure surface is found automatically and it is not necessary to specify the shape of the failure surface in advance. Since the failure mode for complex slopes is generally more complex than simple circles or segmented surfaces, the difference in safety factor may be relevant. This may be clearly seen in Figure 2, where the discrepancy between numerical and circular slip surface (and consequently between the factors of safety) is much more heavy in case of the heterogeneous slope, where the failure is controlled by the weak clay layer.

CONCLUSIONS

The difficulties connected with the opening of new quarries suggested to evaluate the deepening effects of existing ones. The analyses demonstrated that the main disturbance in the local groundwater balance occurs in the first phase of excavation below the water table. Afterwards, the impact of deepening on the aquifer becomes negligible, following a pseudo-asymptotical behaviour. Regarding the slope stability, deepening of an existing quarry results in a stability conditions decrease with slope height. However, the increase of height for a submerged slope is much less critical than for an emerged or partially submerged slope, mostly because of the presence of an external water table. Its presence decreases the shear stresses acting on the potential slip surface while do not significantly affect the effective normal stress. The main problems that may arise from deepening are related to the presence of weak soils at depth. Limit-equilibrium and numerical stability analyses have been successfully used to design the submerged slopes in the study area.

REFERENCES

[1] AVANZINI, M., BERETTA, G. P. (1991): Il sistema idrodinamico "falda-cava" in relazione alla struttura idrogeologica. *1° Conv. Naz. Giovani Ricercatori in Geologia Applicata*. Gargnano (BS), 22.-23.10.1991.

[2] LORIG, L., VARONA, P. (2000): Practical slope stability analysis using finite-difference codes. In: "*Slope Stability in Surface Mining*" (HUSTRULID ET AL., eds.), Society for Mining, Metallurgy and Exploration, pp. 115-124.

[3] DONALD, I. B., GIAM, S. K. (1988): Application of the nodal displacement method to slope stability analysis. *Proc. of the Fifth Australia-New Zealand Conference on Geomechanics*, Sydney, pp. 456-460.