Instability and geotechnical problems of steep rock slopes east of Cairo

Azza M. Elleboudy
Professor of Geotechnical Engineering, Faculty of Engineering-Shobra,
Cairo, Benha University, Egypt

ABSTRACT
Mokattam Plateau, east of Cairo, has been affected by successive rock slope failures. Retreat of the plateau edges caused considerable damages to several buildings and to the main road along the cliff. Mokattam is capped by limestone interbedded with shale that has an detrimental impact on the stability of the steep rock slopes. The present work deals with the assessment of geotechnical hazards in this area. It covered the failure modes, joint patterns, topographic parameters, boundary stresses, landslide features, rockfall mechanism, location and geometry of potential sliding planes and triggering factors. Establishing monitoring and early warning systems, and rehabilitation procedures were suggested to save the endangered structures existed near the retreating cliff. Assessment of the rockfall potential and application of engineering technology designed to prevent movement or to control movement once begun were considered.

RÉSUMÉ
Plateau Mokattam, à l'est du Caire, a été affecté par des défaillances de talus rocheux successifs. Retraite des bords du plateau a causé des dommages considérables à plusieurs bâtiments et de la route principale le long de la falaise. Mokattam est plafonné par interstratifiées de calcaire avec de schiste qui ont une action néfaste sur la stabilité des pentes rocheuses abruptes. Le présent travail traite de l'évaluation des risques géotechniques dans ce domaine. Elle a porté sur les modes de défaillance, les modèles communs, les paramètres topographiques, des contraintes limites, des glissements de terrain, chutes de pierres, mécanisme de l'emplacement et de la géométrie de facteurs plans de glissement et de déclenchement potentiels. Établissement d'une surveillance et des systèmes d'alerte précoce, et les procédures de redressement ont été suggérées pour enregistrer les structures en voie de disparition existait près de la falaise effondrement. Évaluation du potentiel de glissements de terrain et l'application de la technologie d'ingénierie visant à empêcher tout mouvement ou de contrôler le mouvement une fois commencée ont été pris en compte.

1 INTRODUCTION

Rockfalls are the fastest type of mass movement and are common in mountainous areas near cliffs of weathered, faulted, or jointed bedrock on steep slopes, or where cliffy bedrock ledges are undercut by erosion or human activity. The loss of support from underneath, or detachment from a larger rock mass destabilizes the rocks and gravity does the rest. The criteria for rockfall are an exposure of fractured rock, gravity, and a slope steep enough that when a rock detaches or dislodges from the cliff, it will move rapidly down the slope. The rock sizes vary from gravel to boulders (Figure 1). Complex interactions between physical and geoenvironmental parameters of both the rock and the slope cause the falling rocks to move down the slope at high velocities, seemingly random and erratic manner that endangers people, buildings, vehicles, or highways in the path of the rockfall.

A new suburban area has been developed on Mokattam plateau that overlooks Cairo from the eastern side. The plateau level is higher than the average elevation of Cairo by 180 m. Cracks in buildings located near the cliff were noted and rockfalls along the western and southern edges of the plateau frequently occurred (Figures 2 and 3).

Rockfall is a natural catastrophic erosion process that occurrs in such steep terrain. Human activities frequently increase the frequency and volume of rockfalls. Vibration from blasting and earthquakes can trigger rockfalls as can changes in surface and ground water conditions (Elleboudy, 1985).

Figure 1. Example of rockfall massive blocks, (USGS). http://pr.water.usgs.gov/public/venezuela)

Figure 2. Rockfalls along the western cliff

2 ROCK SLOPE CHARACTERISTICS

Mokattam Plateau is composed of a thick succession of sedimentary carbonates and argillaceous rocks that belong mainly to middle and late Eocene. These include clayey marl and shale layers interbedded with limestone members. At the top of this formation, a limestone cap exists. This cap is severely jointed and subjected to falling along the cliffs. It is underlain by a thick shale member. The stratigraphic section is then composed of successive layers of limestone and shale (Elsohby and Elleboudy, 1993). Jointing is an important characteristic of the plateau. Some of the joint sets are closely spaced in a way that accentuates rockfall along the southern escarpment and in the vicinity of the faults. The intersections between sets of joints occasionally give a blocky appearance for some limestone beds outcropping on Mokattam plateau. Moreover, they represent weak zones along which movements can reoccur (Volkwein et al. 2011).

Figure 3. Sattellite image of Mokattam rockfall

3 GEOTECHNICAL INVESTIGATION

Several site investigations were conducted along the southern and southwestern cliffs. Most boreholes revealed that the rock formation consisted of jointed weathered limestone, followed by a thick succession of shale, underlain by a hard limestone stratum. The laboratory tests were concentrated mainly on the shale layer, since the limestone samples gave a compressive strength of more than 5MPa in the intact condition and the strength of the intact rock does not contribute significantly in the case of fractured or jointed rocks (Elleboudy, 1999b). The axial swelling of shale samples ranged from 25% to 30%. The swelling pressure varied between 550 and 700 kPa. The x-ray diffraction analysis confirmed the shale’s expansive nature due to the presence of high percentage montmorillonite (Abouleid et al., 1987).

4 ROCKFALL MECHANISMS

Study of rock slope movements can take very different configurations and mechanisms such as rock topple, block slide, rotational failure, wedge failure and slide (Lambert and Nicot, 2011). They can involve a variety of materials ranging from hard rock to weak shale, and can result from a variety of phenomena. Slope movement could be defined in four different stages: (a) the pre-failure stage, including deformations associated with changes in stresses and strains, and displacements associated with progressive failure; (b) the onset of failure characterized by the formation of a continuous shear surface through the entire rock mass or by the separation of an unstable rock mass from the slope (rock fall or toppling); (c) the post-failure stage, which includes movement of the rock mass involved in the rockfall, from just after the onset of failure until it essentially stops; and (d) the reactivation stage, when the rock mass slides along one or several pre-existing shear surfaces. This reactivation is generally occasional. Continuous movements with seasonal variations of the rate of movement, which are the rule in some countries and geological environments, represent a peculiar situation that might be associated with reactivation since these movements occur along well-defined shear surfaces.

5 ROCKFALL CAUSATIVE FACTORS

Rockfalls are caused by the loss of support from underneath or detachment from a large rock mass (Figure 4) due to various factors. Progressive deterioration of the western and southwestern rock slopes has occurred in recent years after the rapid urban development of Mokattam Plateau. At least four major rockfalls took place along the cliffs since 1960. Buildings on the cliff were endangered and cracked due to loss of foundation support (Figure 5). The main road bordering the western cliff was damaged. Many parts of the road cracked and fell down the slope (Fig. 6). The deterioration of rock and the alternation of its physical and chemical properties were due to several factors.

Figure 4. Newly detached rock mass at Mokattam cliff

Figure 5. Endangered building due to slope failure

Figure 6. Road collapse at the western edge of Plateau

4.1 Massive Rock Blocks

Rockfall is common where there are cliffs of massive broken, faulted, or jointed rock. Rock mass is a discontinuious medium due to the presence of fault, joint, shear plane, bedding plane, cleavage and schistosity. These inherent and induced geological features, produce separate rock blocks as in the top limestone layer capping Mokattam Plateau. Moreover, the joint sets and their orientation, joint characteristics, and the orientation of slope face with respect to the joint sets may help in activating the rockfall. In addition, the differences in temperatures between night and day, winter and summer, among other weathering processes develops pressures capable of wedging apart contiguous blocks of massive rock and facilitates their fall.

4.2 Steep Slope

The geometry of the slope; the high altitude and the steep angle of the southern and southwestern slopes of the plateau (slope angle in most parts is between 60^o and 90^o), contributed to the severity of the problem. The over-steepness of the slope aggravates the active natural rockfall process and cause increased movement or falling of the detached rock blocks.

4.3 Shale Strata

Shales constitute about one-half of the volume of sedimentary rocks in the Earth’s crust (Franklin, 1981). Shale is a fine-grained detrital sedimentary rock, formed by the consolidation of clay and silt. It is characterized by finely laminated structure, which imparts fissility approximately parallel to the bedding. It is composed of an appreciable content of clay minerals and detrital quartz. Shales are by far the most pervasive problematic degradable rock. The presence of shale strata interbedded with limestone layers is a major causative factor for rockfall in Mokattam. Shales that contain a high percentage of clay become weak and slippery when wet. The result is a reduction of static friction at the base of overlying metastable blocks. This can cause slippage, which leads to forward movement and results in subsequent falling of top limestone blocks.

The dark gray fissile shale in this plateau consists of laminated heavily overconsolidated clay layers with seems of sands, silt, and gypsum (Elleboudy, 2002). The urban development of Mokattam resulted in rapid Geoenvironmental changes. Surface water and water from defective sewers and water supply pipes percolated through the limestone cracks and joints to the underlying shale (Figure 7). It softened the shale and decreased its shearing strength. This process along with the orientation of bedding planes, when dipping towards the cliff, created slip surfaces at the base of the limestone blocks.

Moreover, the expansive nature of the shale, which contained an average of 37% montmorillonite, exerts when wet, a high swelling pressure on the limestone blocks. The removal of the lateral confinement as a result of the preceding slides encourages the expansion of shale in the horizontal direction towards the cliff. The increase of surcharge load near the cliff due to construction of the road and the adjacent buildings enhanced the movement towards the slope. The growth of gypsum crystals between the shale layers also added to the swelling potential of shale. However, the seeping water might also have dissolved some gypsum crystals and weakened the fabric of the shale strata (Goodman, 1993).

Figure 7. Seepage through rock cracks

4.4 Dynamic Forces

Equilibrium of unstable blocks in rock slopes can be upset by shock from natural earthquakes, blasting, or movement of heavy vehicles. The resulted dynamic forces aggravate the situation and accelerate the slope failure. Earthquake can produce thundering rockfalls moving at high velocities. In Mokattam case, earthquake ground shaking and vehicles excess vibrations are major triggering factors for slope failures.

4.5 Blast Damage

Blast damage from large production blasts in adjacent quarries, have extended many tens of meters into the rock mass behind the slope face. This blast damage is due to rock fracture and joint opening as a result of the dynamic stresses induced by the blast. In addition, penetration of gas pressure from the blast can open existing discontinuities for considerable distances from the face. This damage causes loosening of the rock mass with a consequent reduction in strength.

Vertical rock cutting and blasting that take place in adjacent quarries may remove support for overlying or overhanging rock resulting in conditions conducive to rockfall (Figure 8).

4.5 Caves and Caverns

Natural man-made caves and caverns are spread in Mokkatam Plateau limestone formation. They comprise zones of weakness in rock structure (Elleboudy, 1999a). Their presence adds to the rockfalls causative factors, especially if they exist near the cliff. An example of these caves is shown in Figure 9.

4.6 Bedding Planes

Occurrence of inclined bedding planes, joints, and shear zones along the cliff creates planes of weakness, which provides conditions of instability and potential failure.

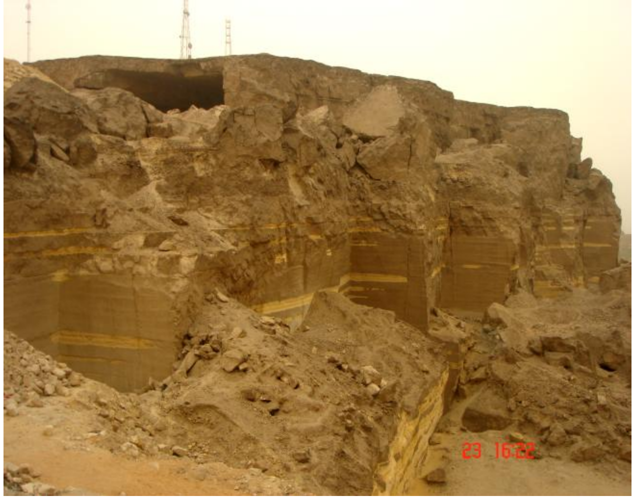

Figure 8. Quarries in Mokattam Plateau

Figure 9. Caves in Mokattam

Moreover, the intersection of joints exposed on the face of the slope helps to form separate loose limestone blocks. The layers of limestone and shale at the western and southern cliffs show regional bedding direction dipping slightly towards the cliff. The inclined bedding provides planes for the sliding of loose rock blocks to fall over the cliff. The presence of a prominent joint/fracture between limestone and shale layers at the top of the slope acts as sliding surfaces through which most of the weathered and weak layers that are exposed on the surface slide down slope.

5. ROCKFALL MITIGATION

5.1 Face Trimming

The steep face of the slope, which is vulnerable to sudden detachment of rocks, was mitigated to prevent dislodged rock from falling off the vertical cliff. The steep vertical cuts with loose overhanging blocks were leveled and the loose rock was removed.

5.2 Shotcrete

Since the rocks have multiple open joints and are likely to widen over time, the application of steel fiber reinforced shotcrete (SFRS) of 70 mm thickness is suggested to stabilize the rock slopes. Steel fibers are very efficient compared to other material fibers such as asbestos, nylon or polypropylene and glass due to their high tensile strength and adherence to concrete. The SFRS provides measures to prevent the rock blocks from moving off the slope and also will prevent the weathering of the rock slope. Weak planes or zones, cracks and joints, may be grouted to prevent percolation of water. Consolidation grout is effective for controlling seepage flow in any discontinuities in the rock mass (Kikuchi, 1999).

5.3 Guard Net

Rockfall protection with flexible steel net systems has significantly increased compared with other protective measures because of its advantageous ratio of energy absorbing capacity and cost (Figure 10). A steel cable net of aperture size (300 mm x 300 mm) could be draped over the face of the slope down to the toe to slow erosion and catch falling rocks.

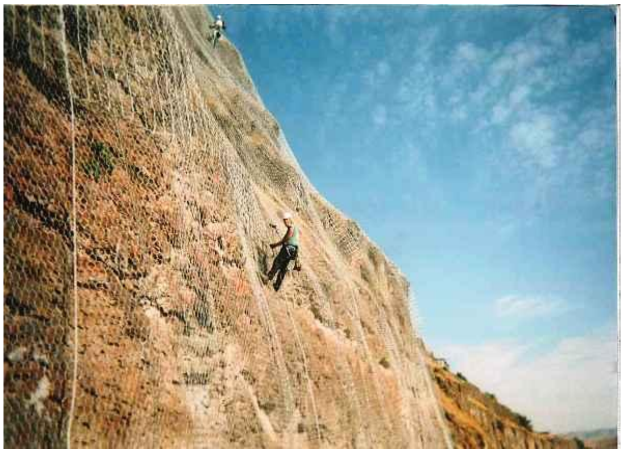

Figure 10. Cable net spread on the face of the slope

Guard mesh could also be used at the toe of the slope to capture the falling rocks. Steel-net systems consist of wire-ring nets or diagonal-rope nets, steel cables could be utilized as fences to separate the rock slope from roads or other structures threatened by the rockfall, and trap the falling rocks before causing any damage (Figures11 and 12).

5.4 Rock Reinforcement

To stabilize potential rockslide and rock falls, rock bolts and anchors could be installed. If any improvement in the rock mass response is essential, it is carried out economically by introducing rock bolts, rock anchors or rock dowels. Various types of rock bolts could be used to stabilize the detached and loose rocks such as mechanically anchored rock bolts, grouted rock bolts, grouted cable bolts, and friction anchored rock bolts.

Figure 11. Gard mesh protecting road from rockfall

Figure 12. Catch fence of wire-ring net near slope toe

Rock anchors are applicable when compressive, uplift or pull-out forces, or lateral supports are required to stabilize a structure or rock mass on-ground or underground. Active anchors support the rock fully and immediately, while passive ones develop increasing support with the deformation of the rock (Figure 13).

5.5 Leakage control

One of the most influential factors was the remarkable change in the moisture regime in such arid rocks. The seepage of water through rock layers and fractures was obviously noticed on the face of the slope. Therefore, constructing watertight pipes with flexible joints, leakage proof sewer system, and a proper drainage network for quick removal of percolating moisture to direct the surface water away from the cliff are important.

Figure 13. Rock Anchor on slope face

6. ASSESSMENT OF ROCKFALL POTENTIAL

Using the rating method suggested by Nicholson and Hencher (1997) for the assessment of the deterioration of the rock slope, gave a deterioration rating of almost 60% which indicates a class of high susceptibility to failure. Therefore, efforts should be made to estimate where, when, and with what severity future rockfalls will occur. Assessment of rockfall susceptibility by integrating statistical and physically based approaches was suggested by Frattini et al. (2008).

6.1 Rockfall Susceptibility Mapping

Remote sensing techniques for landslides and rockfalls investigations are undergoing rapid developments. The possibility of acquiring 3D information of the terrain with high accuracy and high spatial resolution is opening up new ways of investigating the rockfall phenomena. Recent advances in sensor electronics and data treatment make these techniques affordable.

The two major remote sensing techniques that are exponentially developing in landslides investigation are interferometric synthetic aperture radar (InSAR) (Colesanti et al. 2003; Squarzoni et al. 2003), and light detection and ranging (LIDAR) (Jaboyedoff et al. 2009; Slob et al. 2002). InSAR techniques are usually ground-based (Tarchi et al. 2003) or satellite-based (Singhroy 2009), and only rarely airborne. InSAR techniques are mainly dedicated to the detection and the quantification of small displacements over large areas. LIDAR (or laser scanning) provide high-resolution point clouds of the topography and has several applications that range from mapping to monitoring deformation, landslides or rockfall displacements (Abellan et al. 2010). The joint use of terrestrial laser scanning (TLS) and SAR techniques can help to understand rockfall phenomena, as is discussed by Teza et al. (2008).

6.2 Monitoring Slope Movements

Monitoring surface displacements of rock slopes is simpler than in soil slopes because the displacements can be considered as rigid body transformation (Monserrat and Crosetto, 2008). As a consequence, it is easier to identify and decompose the movements as a combination of translations and rotations of different parts of the slope. Extensometers installed for continuous measuring of landslide movement are more efficient than periodic measurements. If the rate of movement is known to increase regularly, then instability and potential future movement can be assessed for the purpose of issuing landslide hazard warnings. Data can be retrieved by regularly visiting the site. However, significant disruption, such as splitting of the ground, could destabilize the operation of the extensometer. For very rapid movement as in rockfalls, the initial displacement might happen only seconds or minutes before the accelerated failure. Nevertheless, such measurements could provide useful data for warning systems.

3 CONCLUSIONS

Mokattam Plateau has experienced several rockfalls at various critical locations on the southern and southwestern cliffs. This problematic area, overlooking Cairo from the east, was subjected to detailed study to delineate the causes of rockfalls and recommend practical solutions. The rockfall phenomenon has been investigated from geological, geotechnical, and environmental perspectives. Based on field observations and investigations, the most probable causes and mechanisms of rockfalls are the presence of massive broken and jointed rock at the surface, underlain with layers of expansive shale which becomes weak and slippery when wet and exerts a swelling pressure on the limestone blocks. The result is a reduction of static friction at the base of overlying metastable blocks. The geoenvironmental changes due to urban development of Mokattam increased the surface water and leakage from defective sewers and water supply pipes. Water percolates through the limestone cracks and joints to the underlying shale and decreases its shearing strength.

This facilitates the slippage of top limestone blocks. Moreover, the bedding planes, when dipping towards the cliff, accelerates the movement of the limestone blocks. The swelling pressure aggravates the movement of the limestone blocks and pushes them towards the cliff. The dynamic forces from earthquakes, blasts in adjacent quarries, and vibrations from vehicles near the cliff and at the toe of the slope exacerbate the situation.

Suitable protection schemes, remedial processes, and rockfall preventive measures such as leakage control, face trimming, application of steel fiber reinforced shotcrete, guard steel cable net draped over the face of the slope, guard mesh and catch fence at the toe of the slope to capture the falling rocks, and rock reinforcement by bolts and anchors are recommended. Rockfall preventive measures are not intended to avoid the movement of blocks but to improve the stability of the rock slope, eliminate some of the triggering factors, and control sudden occurrence of rockfall.

Landslide susceptibility maps can identify the potential rockfall hazard zones and delineate the areas with growing instability problems. A Monitoring system is vital in detecting surface displacements and providing useful data for warning to be issued to evacuate people and decrease the loss of lives.

REFERENCES

Abellan, A., Vilaplana, J., Calvet, J., Blanchard, J. 2010. Detection and spatial prediction of rockfalls by means of terrestrial laser scanning modelling. *Geomorphology*, 119:162–171.

Abouleid, A., Elleboudy, A., Hafez, H., Eid, H. 1987. Some geotechnical properties of Mokattam shale. *Journal of the Egyptian Society for Soil Mechanics and Foundation Engineering*, 2: 1-6.

Colesanti, C., Ferretti, A., Prati, C., Rocca, F. 2003. Monitoring landslides and tectonic motions with the permanent scatterers technique. *Engineering Geology*, 68:3–14.

Elleboudy, A. M. 1985. Analysis of Mokattam rockfalls. *11th International Conference of ISSMFE*, San Francisco, California, USA, 4: 2321-2324.

Elleboudy, A. M. 1999a. Foundation problems on cavernous limestone formation. *9th Int. Congress on Rock Mechanics*, Paris, France, 1: 455-460.

Elleboudy, A. M. 1999b. Geoenvironmental factors influencing the deterioration of shale in a rockslope. *International Symposium on Slope Stability Engineering*, Matsuyama, Japan, 1: 103-106.

Elleboudy, A.M. 2002. Building safely on shale formation near the cliff edge. *9th International Congress of Association for Engineering Geology*. Durban, South Africa.

Elsohby, M.A., Elleboudy, A. M. 1993. Instability of natural slope in interbedded limestone and shale. *5th International Symposium on Landslides*, Lausanne, Switzerland, 1: 121-123.

Francklin, J. A. 1981. A shale rating system and tentitive applications to shale performance. *Transportation Research Record*, *TRB*, Washington D.C., USA, 790: 2-12.

Frattini, P., Crosta, G., Carrara, A., Agliardi, F. 2008. Assessment of rockfall susceptibility by integrating statistical and physically based approaches. *Geomorphology*, 94:419–437.

Goodman, R. E. 1993. *Engineering Geology: Rock in Engineering Construction*. John Wiley & Sons, Inc. New York.

Jaboyedoff, M., Oppikofer,T., Locat, A., Locat, J., Turmel, D., Robitaille, D., Demers, D., Locat, P. 2009. Use of ground-based LIDAR for the analysis of retrogressive landslides in sensitive clay and of rotational landslides in river banks. *Canadian Geotechnical J*ournal, 46:1379–1390.

Kikuchi, K. 1999. Grouting effects on deformability of several types of rock masses. *9th International Congress on Rock Mechanics*, Paris, France, 2: 1377-1380.

Lambert, S., Nicot, F. 2011. *Rockfall Engineering*. Wiley/ISTE Ltd., New York/London.

Leshchinsky, D. and Perry, E.B. 1987. A design procedure for geotextile reinforced walls, *Geosynthetics '87*, IFAI, New Orleans, LA, USA, 1: 95-107.

Monserrat, O., Crosetto, M. 2008. Deformation measurement using terrestrial laser scanning data and least squares 3D surface matching. *ISPRS Journal of Photogrammetry and Remote Sensing*, 63:142–154.

Nicholson, D.T., Hencher, S. R. 1997. Assessing the potential for deterioration of engineered rockslopes. *Engineering Geology and Environment*, Balkema, Rotterdam, 911-917.

Singhroy, V. 2009. Satellite remote sensing applications for landside detection and monitoring. *Landslides - Disaster Risk Reduction*, Springer, Berlin/Heidelberg, pp 143–158.

Slob, S., Hack, H., Turner, A. 2002. An approach to automate discontinuity measurements of rock faces using laser scanning techniques. *ISRM EUROCK 2002*, Funchal, Portugal, 1: 87–94.

Squarzoni, C., Delacourt, C., Allemand, P. 2003. Nine years of spatial and temporal evolution of the La Valette landslide observed by SAR interferometry. *Engineering Geology*, 68:53–66.

Tarchi, D., Casagli, N., Fanti, R, Leva, D., Luzi, G., Pasuto, A., Pieccini, M., Silvano, S. 2003. Landslide monitoring by using ground-based SAR interferometry: an example of application to the Tessina landslide in Italy. *Engineering Geology*, 68:15–30.

Teza, G., Pesci, A., Genevois, R., Galgaro, A. 2008. Characterization of landslide ground surface kinematics from terrestrial laser scanning and strain field computation. *Geomorphology*, 97:424–437.

Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., Dorren, L., Gerber, W., Jaboyedoff, M. 2011. Rockfall characterization and structural protection—a review. *Jounal of Natural Hazards and Earth System Sciences*, 11:2617–2651.