Rock mass quality and landslide hazard evaluation in the northern Mexico City urban zone

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Abstract: In the middle of the Mexico City Basin there is a cluster of volcanic domes forming a circular morphological feature known as the Sierra de Guadalupe (SG). They are characterized by steep accumulations of lava flows, and pyroclastic and volcanic avalanche deposits. A natural steep morphology and modification of slopes by quarry exploitation a century ago make the zone susceptible to landslides. At the present, the Mexico City urban zone has growth all around the lower hills of the sierra in an irregular and non-planned manner, including inside the open pits of the quarries. Anthropogenic factors such as inadequate drainage, gardening and vibration by heavy vehicles make these urban settlements highly susceptible to landslide hazards (wedge failure, planar sliding and rock falls).

The paper describes an evaluation of rock mass quality and anthropogenic factors affecting the stability at 26 sites. The modifications to the slope by quarry exploitation increase the landslide hazards, due in particular to blasting creating short, non-persistent discontinuities with large apertures and no infilling. This can result in block falls and slide failure of wedges after the end of quarrying activities. A good correlation is observed between RMR and landslide mechanisms. In those sites with large discontinuity spacing (>1m) and few fracture families, the RMR is between 56-75 (Fair to Good quality) and toppling, wedge failure and rock fall of blocks are observed. On the other hand, at sites with a large number of fracture families, small discontinuity spacing (few centimeters), and especially the presence of non-welded pseudo-bedding and faulting, there are low RMR values (Fair Rock quality), giving place to rock avalanches and detritus flow.

Résumé: au centre du bassin de la ville de Mexico se trouve un amas de dômes volcaniques formant un corps de morphologie circulaire appelé Sierra de Guadalupe. Ces amas sont caractérisés par des accumulations de coulées de lave et de dépôts d´avalanches et pyroclastiques avec pente raide. Étant donné sa morphologie naturelle et les modifications apportées aux pendages suite à une exploitation carrière il y a une centaine d´années cette zone est susceptible aux glissements de terrains. Actuellement, la zone urbaine de la ville de Mexico s´est agrandie de manière irrégulière et sans planification autour des plus basses collines de la Sierra de Guadalupe, jusqu´à l´intérieur des carrières à ciel ouvert.

Ces établissements urbains sont très susceptibles à des glissements de terrain (coin et planaire mécanismes, chute de roches) et cela est dû à des facteurs anthropogéniques tels que un drainage inadéquat, le jardinage, les vibrations causées par des véhicules lourds.

On effectue, dans le cadre de ce travail, l´évaluation de la qualité du massif rocheux et la description des facteurs affectant la stabilité de 26 sites différents. Les conséquences occasionees aux pendages par l´exploitation de carrières augmentent les risques de glissements de terrain, particulièrement à cause de l´effet de détonants : soit court, peu résistant aux discontinuités á ouverture ou bien large et sans remplissage. Ainsi que La chute de grands fragments rocheux et de coins après la venue d´activités dans les carrières et antérieures à l´emplacement irrégulier des établissements urbains. On a pu observer une forte corrélation entre le facteur RMR et les mécanismes de glissements. Le facteur RMR de ces sites à larges espacements (plus de 1 m) et quelques familles de fractures, se situe entre 56 et 75 (qualité régulière à bonne). On a pu observer toppling, coins, et chute de grands fragments. Par ailleurs, la présence de beaucoup de familles de fractures des petits espacements (de quelques centimètres), particulièrement la présence de ouvert pseudo-litages et faille diminuent le facteur RMR de façon significative à faible qualité ce qui provoque place à des avalanches de cailloux et des écoulements de détritus.

Keywords: igneous rock, engineering properties, abandoned quarries, landslides, geological hazards

INTRODUCTION

The Sierra de Guadalupe (SG) is one of the central sierras of the Mexico City Basin (Figure 1). Its volcanic origin is related to sixteen volcanic centers such as domes and stratovolcanoes and the related deposits (lahars, volcanic avalanches, ash flows, and ash falls) affected by NE-SW and E-W faults that affect these volcanic structures (SEGEOMET, 2004). The SG is located at the limit of several municipalities and between two states. Gustavo A. Madero municipality belongs to the Federal District and it is located at the southern part of the SG. The rest of the Sierra is located in Mexico State, in the municipalities of Tultitlán, Ecatepec, Tlalnepantla, and Coacalco. The Mexico City Metropolitan Geological Survey (SEGEOMET, 2004) performed a previous project where they identified and characterized the landslide hazard in the Mexico State portion of the SG. That project was used as a guide for the geomechanical characterization and selection of critical sites. The critical sites correspond mostly with the steepest slope angles (>30°) (Figure 2), naturally originating from faulting and lava flow fronts, and mostly modified by quarry activity. Several sites show slope failures: rock falls, rock avalanches, and wedge failures close to the earliest and most precarious urban settlements. The population around of the municipalities where the SG is located has grown eighteen times from the 1960´s to the year 2000 (INEGI; 1960, 2000) in an irregular manner and there are settlements with no-services in the southern and eastern portions of the SG. The lack of urban planning in the settlement expansion towards the hills of the SG makes them susceptible to landslide hazards. In fact several rock falls and house collapse have been reported by neighbors during rainy seasons. In order to quantify this hazard we performed rock mass characterization of 26 sites around SG to obtain the rock mass rating, RMR (Biewnawski, 1989) by using the scanline method for sampling characteristics of discontinuities (Priest, 1993). The data collection allow us to define the site conditions and find possible correlations between RMR and failure mechanism (rock flow, rock fall, sliding, toppling) as input for slope stability analysis and generation of deterministic hazard maps.

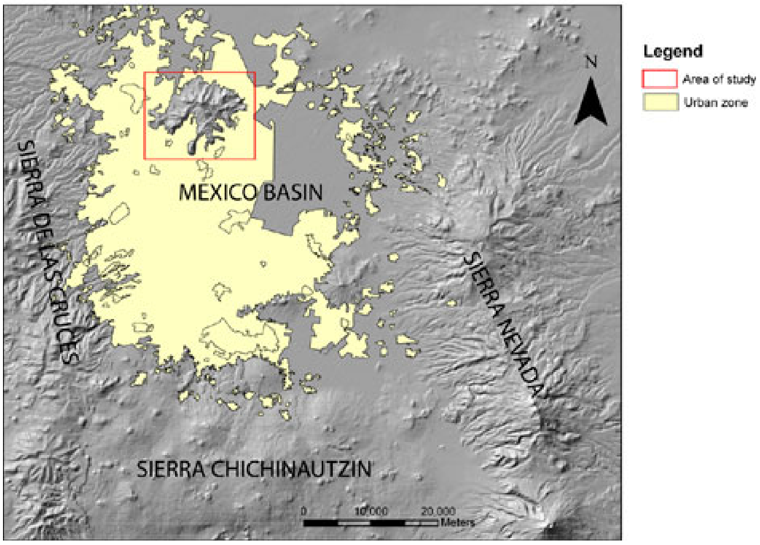

Figure 1. Location of the area of study inside the Mexico basin and the urban zone of Mexico City.

METHODOLOGY

The SG landslide inventory map was generated by the Mexico City Metropolitan Geological Survey (SEGEOMET, 2004). They report 192 sites with actual or potential landslides only in the Mexico State portion of the SG. We defined the overall critical sites mainly on the basis of urban zone limit, slope angles, and the inventory map (Figure 2 and 3). Critical sites were defined as those with slopes steeper than 30°, proximity to the urban area limit (≤ 400 m), and presence of landslides. Many of these sites are located in the S-SE portion of the SG such as Chiquihuite, Cerro La Tabla, La Presa, Cerro Gordo, Tlayacampa, Tenayo, and Chalma de Guadalupe (Figure 2).

The geomechanical surveys were performed on 26 sites around the SG (Figure 3) at different volcanic units of andesitic, dacitic, and rhyolitic composition, originating from volcanic activity of domes and stratovolcanoes of Miocene age (Lugo-Hubp and Salinas-Montes 1996). At each site we sampled characteristics of discontinuities according to the scanline method described by Priest (1993) and obtained attitude, aperture, JRC value (Barton, Lien & Lunde 1974), infilling, water presence, semi-length of joint traces in order to identify and characterize the joint families at each site. In sites where lavas have bedding-like flow structures two lines were performed. One line was parallel to bedding (mostly horizontally) where fractures were the predominant discontinuities along the scanline. A second line was perpendicular to flow structures, crossing mainly bedding-like planes. Diagram contours were generated to obtain a characteristic attitude of fractures. RQD values were calculated from the scanline using the theoretical relationship established by Priest and Hudson (1976). The strength of the rock was evaluated by performing irregular-lump point load tests (ASTM 5731-95) on samples collected for each site. Where flow structures are present, directional point load tests were performed, parallel and perpendicular to bedding. Figure 4 presents the discontinuity analysis of data collected from the Cerro Gordo site and the way the information was analysed to evaluate the Rock Mass Rating (RMR) (Biewniaski 1989) for all the points. Each RMR parameter was rated on the basis of the most frequent and RMR lowest-rated value of analysed data e.g., if two joint families are present at the site the spacing used to evaluate RMR was the smaller most frequent space of the two families.

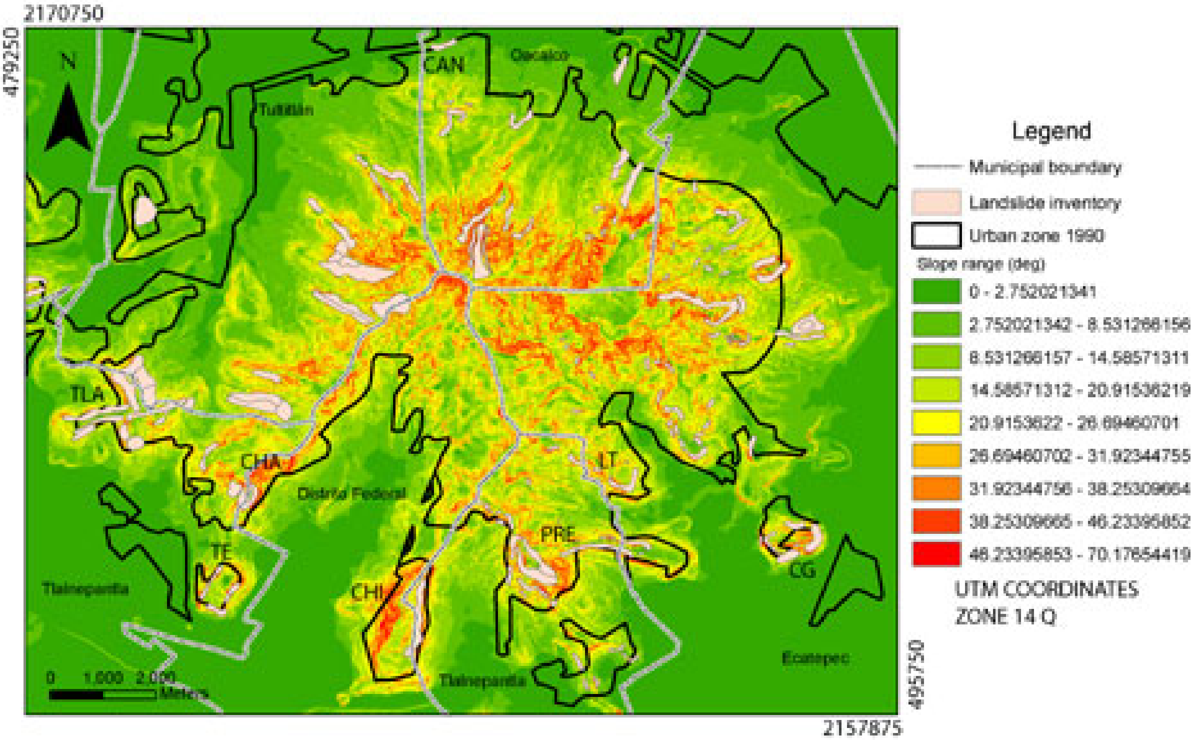

Figure 2. Slope map of the Sierra de Guadalupe along with urban zone limits, municipal boundaries, and landslide inventory (SEGEOMET, 2004). Some of the critical zones are labelled. LT: Cerro La Tabla; CHI: Cerro Chiquihuite; CHA: Chalma de Guadalupe; TE: Cerro Tenayo; TLA: Tlayacampa; PRE: La Presa; CG: Cerro Gordo; CAN: Cantera NW

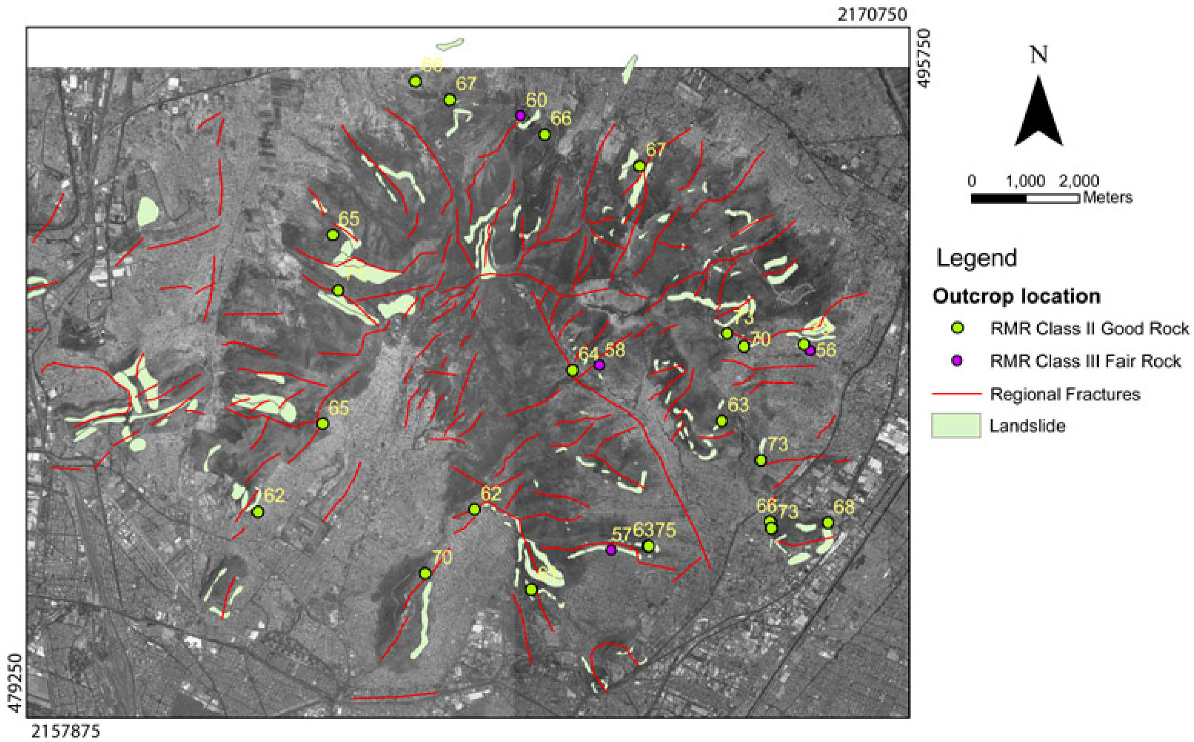

Figure 3. Locations of surveyed points and their relative position to regional lineaments and landslides (SEGEOMET, 2004). Associated numbers are the corresponding RMR values (for 5 sites the values are parallel to bedding RMR).

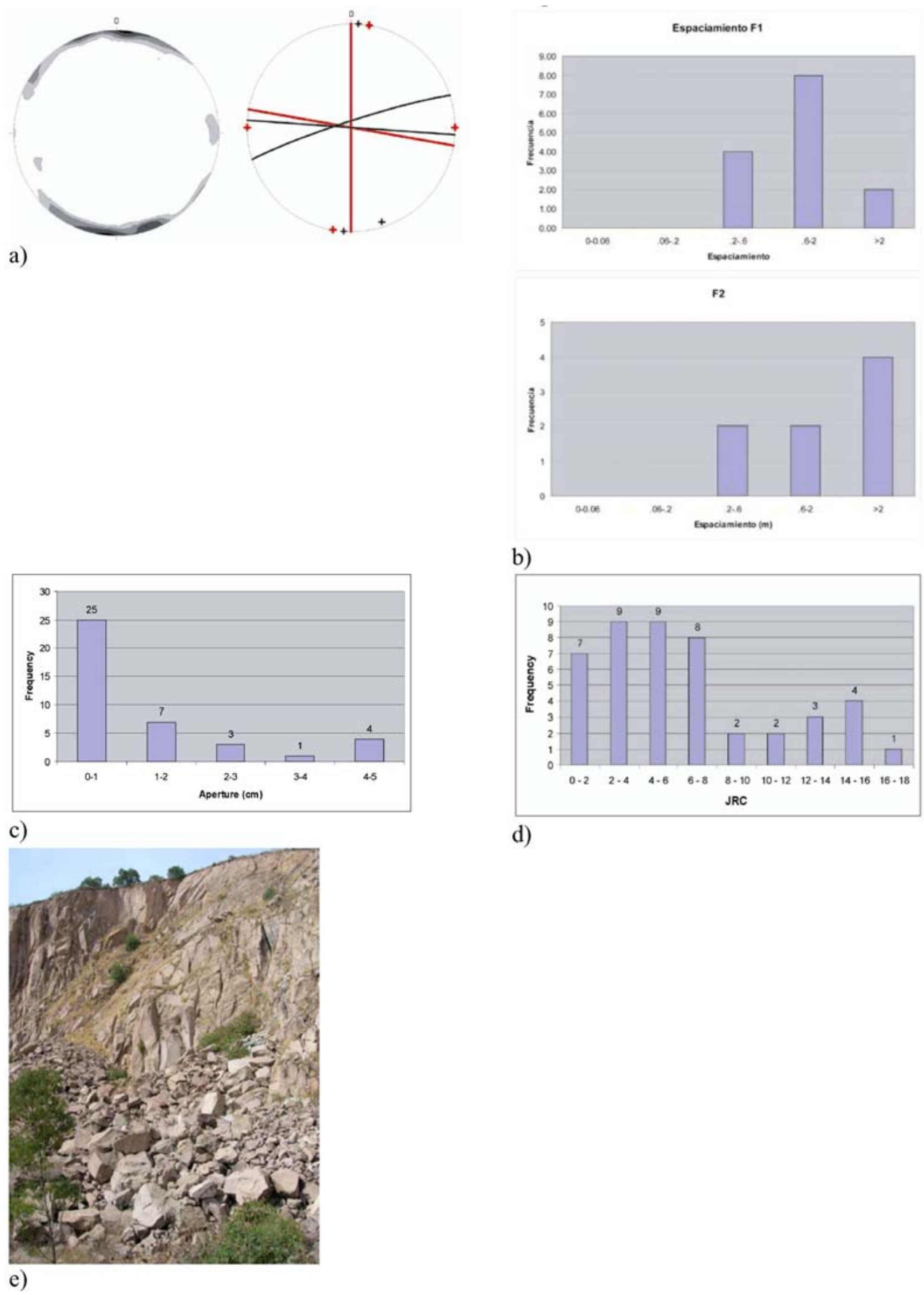

Figure 4. Example of collected data processing for Cerro Gordo location. a)stereogram and great circle of two joint families F1,F2; b)spacing histogram; c)aperture histogram; d)JRC histogram; e) sliding rock blocks that failed at the site

RESULTS

Rock Mass Quality and associated sliding mechanisms

The range of RMR values is shown in the histogram in Figure 5. Scanlines are differentiated between those with no-bedding and parallel to bedding (26 scanlines), and those perpendicular to bedding (7 sites), to assess the effect of the flow structures. The former category always has RMR ratings in the Good Rock class. The lines perpendicular to bedding are on the limit between Good Rock and Fair Rock (55-66). Lines parallel to bedding have large discontinuity spacing, since they cross mostly fractures, and low Point Load Strength Index, while lines perpendicular to bedding have low RQD due to the small bedding spacing. This low RQD value is compensated with the favourable conditions of no infilling, slight weathering, and, sometimes, long persistence of flow structures. This compensation makes the final RMR's slightly different between parallel and perpendicular to bedding surveying directions when the second is present, but the tendency is to lower the quality to Fair Rock (Figure 5). The minimum and maximum RMR parameter rates for lines parallel and perpendicular to bedding are shown in Table 1.

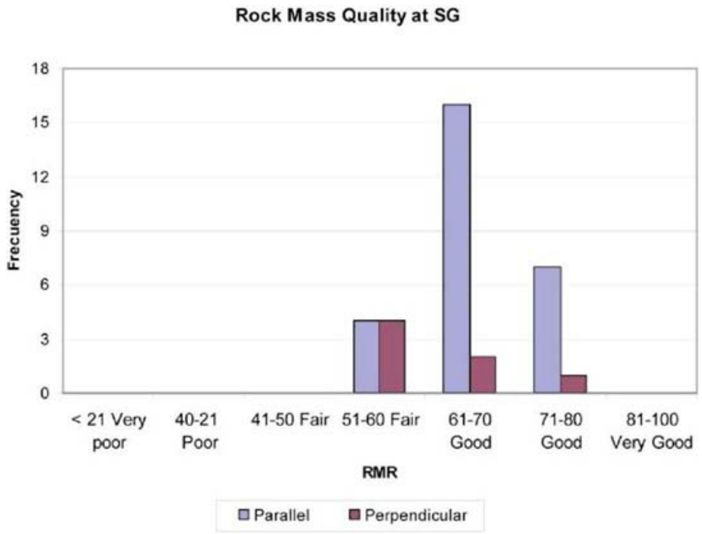

Figure 5. Frequency histogram for RMR values at SG. Blue bars refer to scanlines parallel to bedding and red bars refer to five sites with scanlines perpendicular to bedding

Table 1. Summary of minimum and maximum rates for the different RMR evaluation parameters at the SG

RMR parameter	Parallel to bedding	Perpendicular to bedding
RQD	100-96 %	97-47 %
Point Load Strength Index (Is 50)	8.8- 2.5 MPa	8.8-1.33 MPa
Spacing of discontinuities	0.2-0.6 m	<0.06 m
Discontinuity Length	3-10 m	3-20 m
Aperture	0-50 cm	0 cm
Roughness (JRC)	0- 14	0-4
Infilling and weathering	slightly weathered with none or rock infilling – highly altered (sheared) and gouge or soils	slightly weathered with no-infilling
Groundwater	damp	damp
Number of joint sets	5-1	predominance of bedding
RMR	75-56	72-55

The largest RMR values are related to outcrops with a large fracture spacing and homogeneous crystalline texture. In these rock mass conditions, slides are related to the edges of lava flows where cooling fractures form columns with rock falls and toppling. However, at many of these sites with high rock mass quality, there are quarry pits that were active almost a century ago and abandoned 30 years ago. The use of explosives generated short, open fractures, from a few to tens of centimeters. Despite this large aperture and non-persistent joints, the point load index of the rock mass is high and fractures that show short persistence generate medium size unstable blocks of 1-5 cubic meters, and in addition to the natural rock falls and toppling, sliding wedges are generated. Some of these wedges are up to 500 cubic meters, forming rock avalanches with blocks that have moved up to 80 meters from the toe of the slope, as at Cerro Gordo west and southeast (Figure 4e) quarries. Large falling blocks are predominant at steep slopes, producing very high kinetic energy that reach high velocities in very short horizontal distances. This is the case of Almarcigo Norte, Chiquihuite and La Tabla (Figure 2).

The fair rock mass quality is associated with several geological factors: the presence of bedding-like lava flow structures with a spacing of a few centimeters, highly fractured fault zones, or non-welded pyroclastic units with large blocks in a fine matrix. Bedding-like structure was the most frequent factor diminishing the rock mass quality from Good to Fair, not only because of the spacing, but also, because of the lower value of the Point load Index parallel to the bedding direction. In sites where the bedding-like structure is present, detritus flow is another characteristic sliding mechanism. In general, when flow structures are absent, the lowest RMR values (Class III Fair rock) are related to regional fractures and from the field evidence these sites correspond mostly to faulting zones (Figure 3).

The eastern flank of the SG is mostly at the ecological reserve and state park, where settlements are restricted. The slopes at this flank vary from 8 to 20 degrees (Figure 2) and soil cover develops from 20 cm to 1.5 meters. Shallow soil slides develop at the rock-soil interface as creep or circular slides. Several of these slides affect the main road access of the park and some slope cuts at the park limits.

Triggering landslide factors

At the present day the irregular settlements of the northern portion of Mexico City surround the SG (Figure 1). In most of the cases the settlements are at the head and/or the toe of natural slopes and abandoned quarries. In the case of settlements at the head of scarps, human activities modify the natural conditions, affecting the stability by lack of adequate drainage for residual waters and construction of streets and houses on unstable rock blocks. At settlements at the toe of slopes, both natural and anthropogenic factors trigger slides. Heavy rain has triggered several rock falls and wedge slides, destroying houses at sites such as Chalma de Guadalupe (CHA) and Chiquihuite (CHI) (Figure 2). This is indicative that, at sites with steep slopes, modifications of pore water pressure are critical. In several old quarries, wedge sliding and rock falls were generated after the slope was modified by the mining activity and slope modifications from natural conditions must be planned in future construction projects. In sites where toppling was observed, only a few large blocks were rotated and the triggering mechanism was not obvious, nor was it obvious for detritus flows.

CONCLUSIONS

The Rock Mass Rating (RMR) values at SG range from the high values of Class III Fair Rock to Class II Good Rock. Fair rock is related mostly to bedding like structure and proximity of faults, passing from Good to Fair rock quality. Detritus flows are common where the bedding-like flow structure is present.

Because of the volcanic origin of the Sierra de Guadalupe the most common sliding mechanism are rock falls, toppling and wedge sliding in lava flows. The critical zones are those with urban settlements on steep slope conditions mainly at the south and eastern flanks of the SG. In most of the cases, natural steep slopes have their origin as fronts of lava flows or by faulting. If settlements are at the toes of such natural steep slopes rock fall is critical because of the high kinetic energy of a block impact. The other natural factor generating steep slopes and low rock mass quality is regional fractures and faulted zones. The previous occurrence of rock falls during heavy rain seasons shows the importance of pore water pressure as a natural triggering mechanism in these steep slope zones. When slopes are modified by human activity by quarry exploitation, the existence of failures inside the open pits of the quarries implies that these sites very susceptible to the modifications of natural slope conditions and settlements at the toe and head of slopes are at high risk. Any future slope modification by human activity must consider the impact of pore water pressure and slope conditions.

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