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GRAPHICAL METHOD FOR THE ANALYSIS OF ROCK SLOPES IN URBAN AREAS

Méthode graphique pour l'analyse de talus rocheux en zone urbaine

Graphische Methode für die Analyse von Felsböschungen in Stadtgebieten

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SYNOPSIS

The purpose of the paper is to apply a three-dimensional graphical method to the slope analysis in weathered schists that constitute the hills surrounding Caracas, the capital of Venezuela. The method was applied to a particular urban zone with an area of one million square meters. The result was used to draw a map showing areas with different degrees of stability related to the three-dimensional arrangement of discontinuities within the topographic constraints.

ZUSAMMENFASSUNG

Die Absicht dieser Arbeit ist es, für die dreidimensionalen Analysen der Böschungs-Stabilität der verwitterten Schiefer, aus denen die Hügel in der Umgebung Caracas, der Hauptstadt Venezuelas, bestehen, eine graphische Methode zu verwenden. Die Methode wurde an einer spezifischen städtischen Zone mit einer Fläche von einer Million Quadratmeter angewendet. Das Ergebnis wurde benützt, um eine Stabilitätskarte zu zeichnen. In dieser werden Flächen mit verschiedenen Stabilitätsabstufungen gezeigt, die sich auf die dreidimensionelle Lage zwischen den geologischen Ungleichförmigkeiten und topographischen Oberflächen beziehen.

RESUME

Cette communication concerne l'application d'une méthodologie graphique pour l'analyse tridimensionelle de la stabilité de talus dans les schistes altérés, qui constituent les collines autour de Caracas, capitale du Vénézuéla. Cette méthodologie a été appliquée à une zone spécifique urbaine sur une superficie d'un million de mètres carrês. Les résultats ont été utilisés afin de tracer une carte montrant les zones dont la stabilité varie en rapport avec la répartition tridimensionnelle des discontinuités à l'intérieur des contraintes topographiques.

INTRODUCTION

In the rocky areas characterized by a highly anisotropic mechanical behavior, owing to the presence of surfaces of lesser resistance, systematically arranged in the rock mass, the parameters which decisively control the stability of the slopes, naturaly or artificially formed, are of two principal orders:

- On one hand, the parameters of shear strength (cohesion and friction which may develop along the length of the different surfaces of lesser resistance or planes of geological discontinuity.
- On the other hand, the reciprocal location between these planes of discontinuity and the planes of the free surfaces of the rock mass: the faces of the slopes.

In particular, concerning the problem of the stability of the slopes in rock masses, at least three possibly characteristic situations can be defined:

a) *Stable kinematic conditions*. This is the relative location in the space between the planes involved in the problem, which does not give rise to the existance of any freedom for all the structure. These, consenquently, result stable, independently of the characteristics of shear strength that may develop.

b) *Conditions of kinematic instability and of mechanical stability*. When the geometric conditions of kinematic instability are present, the shear strength that can develop along the surface of the different planes of discontinuities involved, intervenes to prevent the movement. When these resistant forces are greater than the unstabling forces, the slope will be stable.

c) *Conditions of kinematic and mechanical instability.* If besides verifyin situations of kinematic instability, it happens that the unstabilizing forces are superior in intensity to those of resistance, then the slope will be unstable.

It is known (Hoek and Bray, 1974; Goodman, 1976) that the techniques of hemispheric projection form an extremely convenient and simple instrument for the representation in a plan, based on a network, of the complicated phenomena of geometric interaction in the space between the structures involved in the problem of the three-dimentional analysis of slopes in rock masses. At the same time, it is also convenient and simple to introduce,by use of a graphical method, the effects of the shear strength, in its frictional and even cohesive component and finally, the most advanced methods permit the complete quantification of the problem, even determining the numeric values of the safety factors and of the effects of eventual non-gravitational external forces.

DESCRIPTION OF THE METHOD

The analysis procedure presented here is especially effective when applied to relatively vast areas, on which a territorial zoning is desired, based on the stability of the slopes that compose them.

The topographic scales used are generally small to medium (specifically, the author has used the method, with satisfactory results, on scales of 1:1000, 1:2000 and 1:5000), and the approach of the procedure of the elaboration and analysis of the situation, was carried out on statistical and probabilistical bases. At the same time, the results are given in terms of different degrees of geological-*ricks* of instability.

The immediate consequence of aforementioned is the efficiency and reliability of the results of such a stud which are closely linked to the abundance and the representantivity of the data to be used as inputs of the problem.

These inputs, in the initial phase of the analysis, are the location in the space and the geologic-geotechnical nature of the structural discontinuities present in the rock formations of the area (the first family of planes) and, the location in the space of the planes that form the topographic gradients of the same area (the second family of planes).

The fundamental stage of the procedure is to analyse the geometric interaction existing between the different planes of the first family and then between these and the second familiy of planes. This analysis allows certain interesting aspects of the problem to be made evident and can lead to the quantification and topographic location of the phenomena in its integrity.

In order to illustrate the method of the analysis, direct reference must be made when it is applied in the zoning of risks, in an area of approximatelly one million square meters, on which a residential urban zone is to be developed.

Namely, an area located in the hills in the south-east of the valley of the city of Caracas, Venezuela, whose geologic ambient corresponds with the *Las Mercedes Formation of the Caracas Group*. This was originally described by Aguerrevere and Zuloaga (1937) as a series of calcareous schists with zones of graphite, locally micaceous, which outcrop in a fairly weathered state in the area under study.

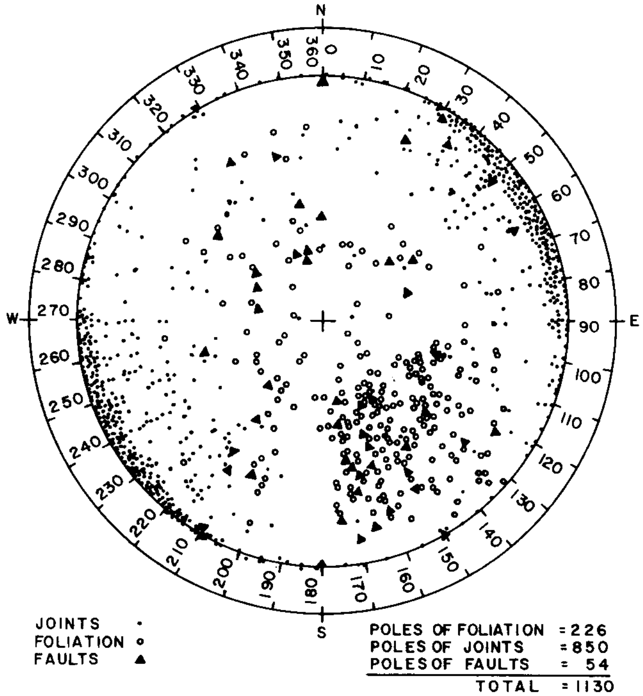

Fig. 1 Plot of poles of discontinuities. Equatorial equal-area projection.

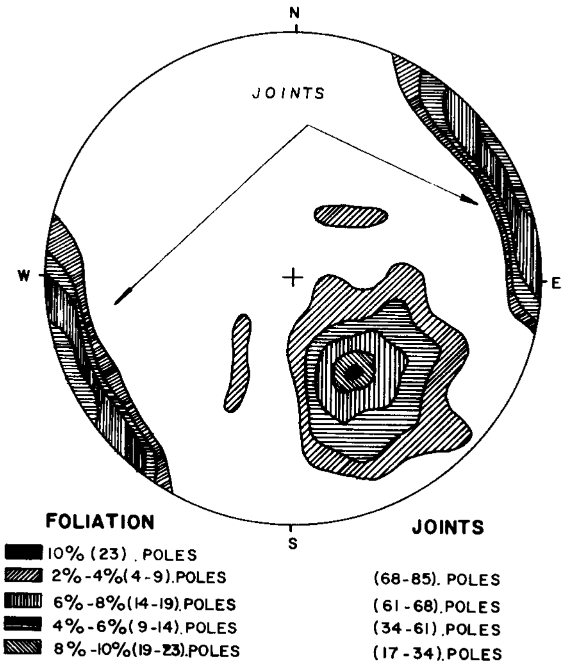

Fig. 2 Contour diagram of discontinuities: joint, foliation and faults.

The rocks present in all the area belong to one lithological gruop, thus allowing all the structural data obtained in the geologic survey of the field to be treated as one entity in this example.

This information consists of the location and geomorphologic description of the main structural accidents existing which, for succesive elaboration, are diferentiated in foliation joints and minor faults. Figure 1 presents the diagram of the concentration of poles, based on Lambert's equal-area network, of all the observed discontinuities (1130 poles).

Figure 2 presents the corresponding countour diagram which permits to observe the existence of two distinct patterns of discontinuities: the first corresponds to the planes of foliation and the second to the planes of joints; the minor faults follow a pattern similar to that of the foliation.

As a complement, useful for future consideration, in figure 3 and 4 respectively, the envelope of the great circles of the foliation planes and of the planes of joints, are reported. Also outlined, in both diagrams, is the common area of the two envelopes, which represent the zone of the network in which the intersections between the two families of planes of discontinuities area located, or in other words, the zone in which the lines of all the possible structural wedges present in the area under study, fall.

Until now, has been analyzed and arraged the first geometric parameter: the structural aspect. It now remains to analyze and arrange the second geometric parameter of the problem: the topographic aspect.

In order to do this, it is convenient to imagine the hills which form the area, as a collection of a great number - of small slopes, each one of which represents a small portion of the side, crest or base of the relief.

Each elementary plane thus established, is characterised by a well defined value of dip and an equally well defined value of strike; this is the bearing of each elementary area of the gradients.

At this point, follows the quantification of the problem, or rather, of the definition and localization of the corresponding geometric characteristics of strike and dip, direction for each one of these ideal slopes which are generally quite numerous.

For this purpose, we proceed to elaborate a map of the gradients which, besides being characterized by the values of dip of each area, contains the information relative to the bearing of the gradients, or rather, the dip direction of each elementary plane.

In this example which is being illustrated, four classes of dip and eight classes of dip direction were used. All of these are shown in figures 5 and 6 where by means of diagrams, the quantified results of this analysis of the area being studied, are given. For example, there may be observed a dip direction of the gradients, predominatelly towards the N-NE and an almost complete lack of gradients towards the W. With respect to the angle of dip, we note that those of the category 28°-35° predominate. The flat areas are excluded from the calculations of the percentages in the diagram of dip, while they are taken into consideration in the percentage calculations in the diagram of dip direction allowing the latter to give us an exact idea of the portion of non-level territory in the area being studied.

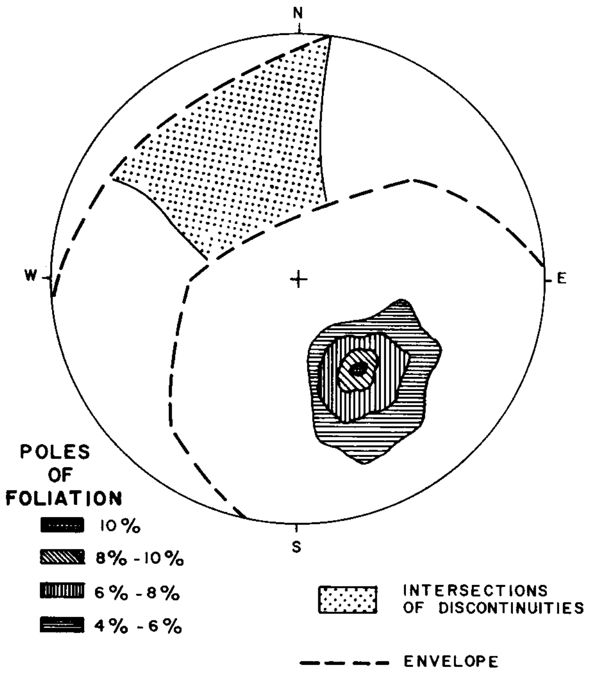

Fig. 3 Envelope of great circles of foliation and area of intersections foliation-joints.

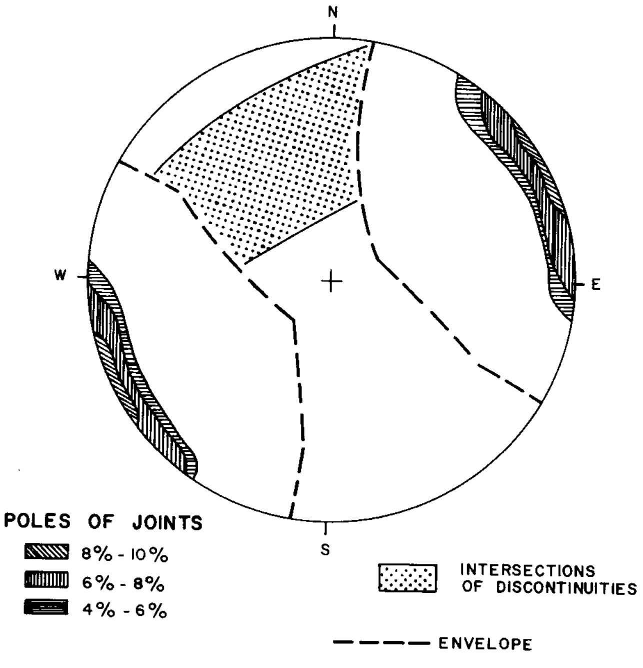

Fig. 4 Envelope of great circles of joints and area of intersections joints-foliation.

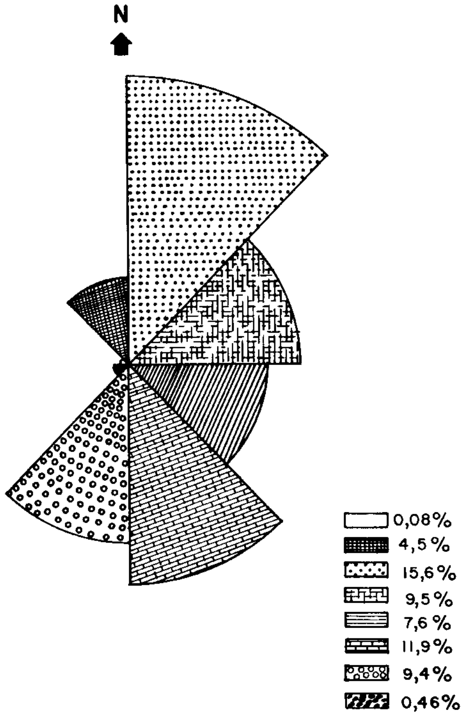

Fig. 5. Distribution of dip directions or dip azimuth of topographic gradients

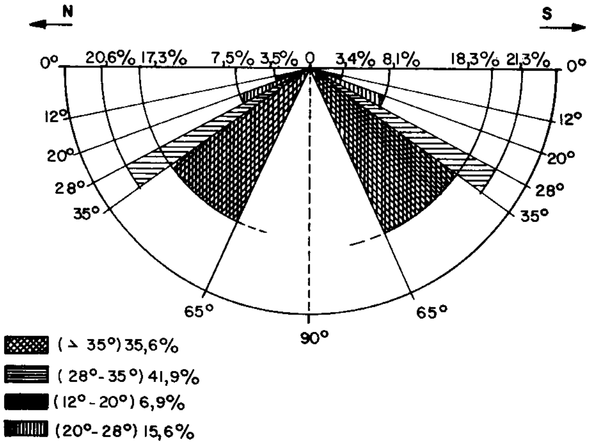

Fig. 6. Distribution of true dip of topographic gradients.

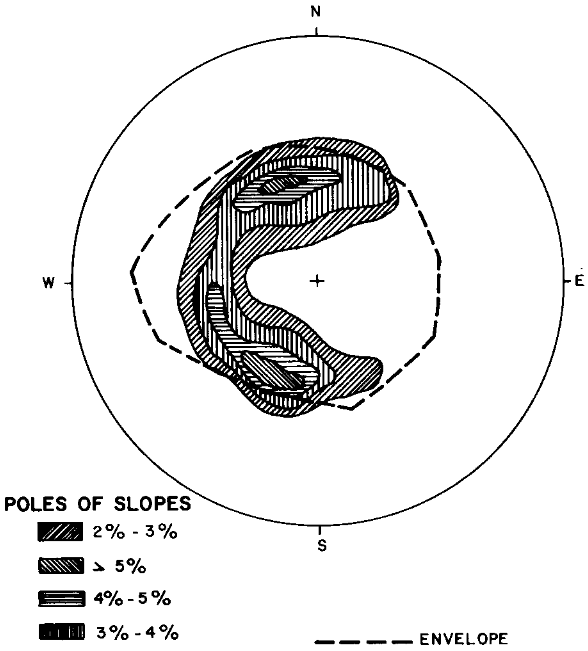

Fig. 7. Contour diagram and envelope of great circles of topographic gradients.

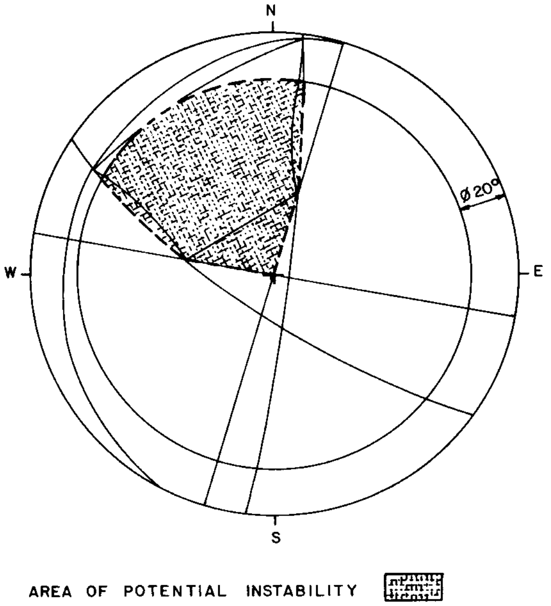

Fig. 8. Stereo plot of great circles representing limit stable slopes.

It can now be used in an original form, the idea by which the relief of the rock has been associated with a group, made up of small slopes which, geometrically, are no more than planes, whose bearing is known with sufficient precision.

On the other hand, this group of planes can be shown in the hemispheric projection by means of a simple diagram of the concentration of poles, which, in turn, allows the making the corresponding diagram of countour of poles of the gradients an the envelope of the corresponding great circles. These same elements are reported in figure 7 for the example that is being illustrated.

At this point, follows the confrontation of all the geometric factors involved in the problem and quantified in the aforementioned stages.

Referring to the three (a.b.c.) characteristic situations possible in the stability of rock slopes, it is worth while, on one hand, to individualize the stable kinematic conditions, so as not to bother with them further and, on the other hand, to individualize which, among the unstable kinematic conditions, can and can not constitute mechanical instability.

In effect, it is possible in a phase of general zoning as in that which is being analyzed, to take to into consideration a minimal value of the frictional parameter of the shear strength along the different surfaces of discontinuity analyzed and thus also to set aside the slopes that become stable, with the mere contributions of a minimal friction, reducing even more, the cases to be analyzed in more detail, for being potentially and effectively unstable.

In order to make this step, by means of the sequence of hemispheric projections, it is sufficient to trace, in the diagram, a concentric circle with the network which marks the value of the angle of friction available, from the periphery towards the centre.

In figure 8, the area must not be intercected by the great circles of the stable slopes, is outlinded in the manner thus described. Successively the new simple mechanical elaboration which is detailed, prosecutes:

- Superimpose figures 7 and 8.
- Trace the figure outlined by the envelope of the planes of the gradients and by the area of the potentially unstable slopes.
- Outline the section of contour diagram of the poles of the gradient corresponding only to those poles whose great circles form part of the outlined figure in the previous step. In other words, among all the existing gradients, individualize the poles of those planes whose great circles intercept the figure mentioned in the previous step, along its entire extention.

The result is figure 9, where we may observe that:

a) The area of the location of the intersections (foliation-joint) which are potentially unstable (because they possess an angle of dip lesser than that of the slopes) represents around 50% of the total area of the location of these intersections.

b) The area of the contour of poles of the gradients which are potentially unstable, (as they possess an angle of dip greater than that of the lines of wedges) represents almost 22% of total area of the contour of the gradients poles.

c) As a result of (a) and (b) the *probably* unstable slopes (for which the two unfavourable conditions area verified simultaneously) will be around 11% of the total existing in all the area studied, (obviously only of all those reported in the countour diagram and corresponding to inclinations superior to those of 20°).

At this point, the procedure of analysis, which has been illustrated with reference to the stability of the structural wedges, must be repeated, also in order to analyze the stability relative to the two systems of existing discontinuities, considered as planes in a separate form, following exactly all the same steps already described.

In this particular case, these other analisis is of secondary importance, owing to the fact that, first of all, the joints area pseudo-vertical and second, the foliation planes cause unstable situations coincidents with those already individualized by the wedges. Consenquently, the situations shown in the previous point (c) will not suffer important variations, neither in quality nor quantity.

Once the problem is quantifid in the form described, there remains simply its placement in the area, in order to achieve a greater benefit in its application. This last operation is inmediate, considering that we already posses all the necessary information. The results are reported in the plan of figure 10, called *The Map of Stability Analysis*, which summarizes all the principal aspects involved in the problem. (The figure represents only a limited portion of the plan which, in the example in question, was originally elaborated on a scale of 1:2000).

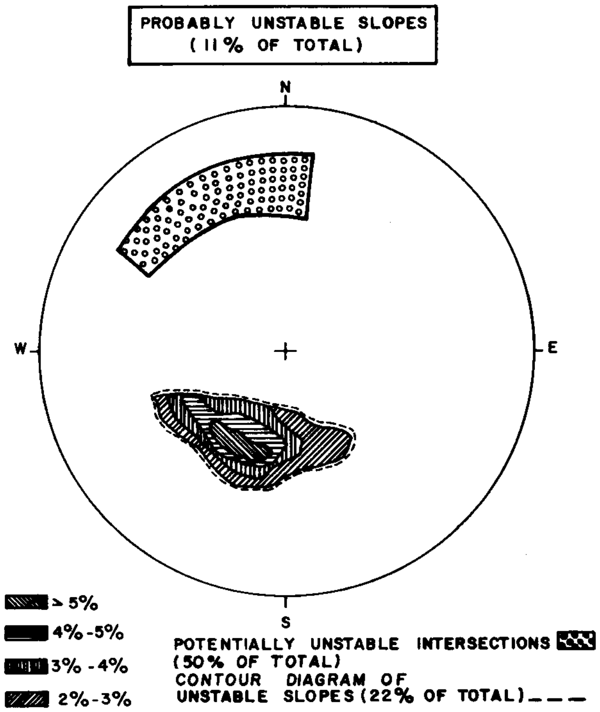

Fig. 9 Contour diagram of poles of potencially unstable slopes and area of potentially unstable intersections joint-foliation.

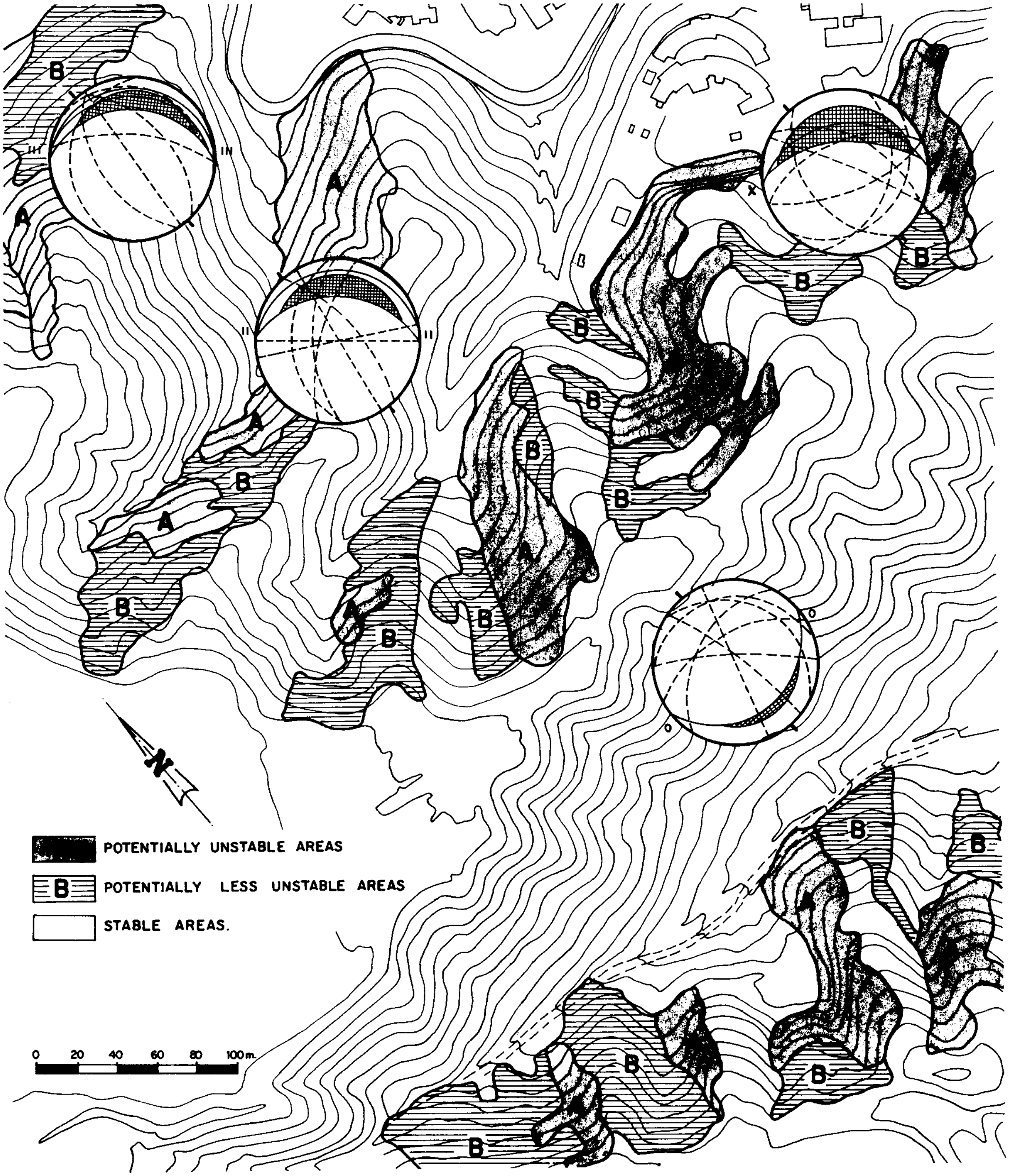

Fig. 10. *Partial representation of the "The Maps of Stability Analysis". The original map was elaborated on a scale of 1:2000. The total area was approximately one million square meters.*

In spite of having been able to realize a more detailed zonification, or rather, individualizing a great number of possible categories as the large amount of information available would have permited, it was preferable to use a zoning of only three categories, considering the degree of precision available and above all, considering the practical purpose of the use of such an analysis. In other words, a more detailed subdivision at this stage and at this scale of study would perhaps result in pure academic speculation.

For the example illustrated, the following categories of zonification have been used:

a) *Zones of potential geometric-structural instability;* which comprise slopes with strike-sub-parallel to that of the foliation structures and dipping at an angle greater than 28° in the same direction as the discontinuities.

   At the same time, these zones contain slopes with gradients greater than 28°, on whose faces outcrop intersection lines of discontinuities with a direction pseudo-perpendicular to the strike of the slopes; similarly, slopes with gradients greater than 35°, on the face of which outcrop intersection lines of discontinuities with a non-perpendicular direction to the strike of the slope.

b) *Zones of potentially reduced geometric-structural instability;* these comprise slopes with gradients greater than 35° and on the face of which enentually may outcrop intersection lines of discontinuities whit a pseudo-parallel strike to the slope. Also included, at the same time, are slopes with gradients greater than 28° and on the face of which outcrop discontinuities with a non-parallel strike of the slope.

c) *Zones of geometric-structural stability;* which comprise slopes with gradients lesser than 28° and slopes with steeper gradients which are situated in such a way as not to permit kinematic conditions of instability, owing to the favorable location of the geological structures.

Once the zonification of the area has been completed in the described manner, it may pass to the more detailed phase of analysis, in which it will proceed to carry out localized calculations of stability for the zones and the specific slopes belonging to the areas with a greater potential of instability.

CONCLUSION:

A method for the zonification of urban areas based on the geological risks has been presented.

The result is the elaboration of a "Map of stability analysis" in which the total area is separated in three zones: potentially unstable areas, potentially less unstable areas and stable areas.

The method is based on the use of the techniques of hemispheric projections for graphical three dimensional analysis of the stability of rock slopes characterized by surfaces of lesser mechanical resistance and a frankly anisotropic behaviour.

In fact, in those geotechnical conditions,the fundamental factor for the control of stability is the number, location and characteristics of the discontinuities, and it is possible and easy to introduce in the proposed analysis, the effects of other factors that can concur to define the stability conditions: hidrology, external and seismic loads and others.

On the other hand, in certain cases, the stability of the area depend essentially on factors that escape from a analysis such as the proposed in this paper. For example, when the processe of external geodynamics are very active: erosion, surface runoff, regional landslides, etc.

In those cases, however, the result produced by the method described can be considered as an important contribution to the complete definition of geological risks in urban areas.
It is not the purpose of this study to described the aforementioned detailed analyses, which were carried out using the routine methods of the graphical techiques of hemispheric projections, taking into account for each specific geometry of the slope, the corresponding existing discontinuities,with their respective parameter or shear strength (friction and or cohesion), which may develop. (Perri, 1979).

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