GEOTECHNICAL AND NATURAL HAZARD MAPPING ON URBAN AND OUTER URBAN PLANNING

Alexandre Oliveira Tavares, Dep. Earth Science, F.C.T. University of Coimbra, Portugal

ABSTRACT
The area studied represents an area of recent urban and outer urban occupation. Human activity has produced a state of disturbance with a general increase in instability related to geomorphic processes. Geological and geotechnical characterisation and the inventory and mapping of mass movement have made susceptibility evaluation possible. A methodological evaluation, using GIS technology, has identified the factors determining instability and indicated three relative levels of composite susceptibility with cartographic expression. Outcome mapping will have repercussions on land use and planning.

RÉSUMÉ
La région étudiée correspond a une occupation urbaine et péri urbaine récente. Les activités humaines ont déclenché un état de perturbation avec une augmentation générale de l'instabilité en rapport avec les processus géomorphiques. La caractérisation géologique et géotechnique et l'inventaire et la cartographie des mouvements en masse ont permis une évaluation de la susceptibilité. L'évaluation méthodologique, basée sur la technologie SIG, a conduit à l'identification des facteurs déterminants sur l'instabilité et a établi trois niveaux relatifs de la susceptibilité composée, avec une expression cartographique. La cartographie résultante doit être réfléchie sur l'utilisation et la planification du territoire.

1. INTRODUCTION

Urban and outer urban occupation usually generates a state of disturbance with non-equilibrium between forms and processes (Toy and Hadley, 1987). This state increases incidences of instability, displaced mass materials and economic and social losses (Aleotti and Chowdhury, 1999).

Geotechnical characterisation and an integrated management approach to natural hazards must be adopted and applied to planning nationwide. The general public demands progress towards a post-disturbance period and this is also a goal for technicians and decision makers.

To this end, a large-scale physical characterisation and a susceptibility analysis were developed for the area studied. The outcomes of the hazard mapping will have repercussions on land use, will influence planning and building regulations and will indicate local physical restrictions (Fookes, 1987; Tavares and Soares, 2002; Lateltin, 2002; Thierry and Vinet, 2003).

2. GENERAL DESCRIPTION OF THE AREA

The municipality of Coimbra is located in central Portugal, has an area of about 316Km^2, a population of over 140,000 and in recent decades has shown a large increase in human occupation.

The area studied is characterised by a confrontation between the metamorphic Precambrian units of the Hesperian Massif and the Lusitanian Meso-Cenozoic sedimentary basin. To the east, altitude exceeds 500m and presents average slope angles of over 26%, in contrast with the gentle slopes in the sedimentary units in the west that have a minimum altitude of 8m in the large Mondego river valley.

These geological contrasts determine wide variations in lithological unit outcropping, structural features, morphological characteristics, drainage setting and hydrological nature, which have created difficulties when they have been incorporated into land use and comprehensive planning.

2.1 Human occupation

Historically the area has centred on the city of Coimbra, which presents a high urban occupation surrounded by outer urban territories, and others which are essentially rural in character. Since the 1970s, large-scale radial urbanisation has taken place, together with the construction of important road infrastructures and facilities. A comparative analysis of the past two decades shows the urban area has doubled (an increase from 42Km^2 to 95Km$^{2)}$), and this correlates with the processes of peri-urbanisation and rurbanisation.

This development also shows a profoundly changing relationship between human occupation and physical factors (Tavares and Soares, 2002) with: (1) progressive development in areas with severe slope steepnesses; (2) the new relevance of lithological units (Jurassic marl-limestone alternation and Cretaceous sandstones and mudstones) as opposed to the traditional occupation units (Triassic conglomerates and sandstones and Lower Jurassic dolomitic-limestones); (3) the breakdown of the historical limits for occupation, as outlined by cartographic contours and fault valleys; (4) urban growth in areas intermittently inundated or with superficial water tables; (5)

a move into areas with evidence of instability associated with geomorphic processes.

The above features have created evident changes in landscape, with an increase in the magnitude and frequency of geomorphic processes and a surface extension of disturbance, reflecting a general state of disequilibrium. The active disturbance has special relevance in the outer urban areas in the north, southwest and east of the city of Coimbra.

2.2 Geological and geotechnical characterisation

In morphological terms there is a contrast between the uplift area in the east, with incised valleys that have slope steepnesses frequently over 26%, and a gentle dipped and depressed area to the west. One of the main morphological and hydrological marks is the Mondego river, which flows from an upstream-incised valley to a large downstream valley floor (with a maximum width of over 4800m and a deposit thickness of over 40m) (Tavares, 1999).

From a geological point of view, the area studied is represented by a thrust-system, uplifted in the east, and gently dipped and depressed in the west by N-S faults.

In the eastern uplift area, metamorphic units (Precambrian – Ordovician/Silurian) represented by phyllite, greywacke, shale and quartzite can be observed. Faults strike N-S, NW-SE and NE-SW, with large throws generating a strong topographic expression with deep valleys.

Three foliated geotechnical units can be defined, where faults and folds bring down the shear strength. The foliated metamorphic units present a general heterogeneity in sequence, layer thickness between L_{34} and L_{45}, general fracture intercept F_4, uniaxial compressive strength S_2 – S_{34} and a degree of weathering between W_{12} to $W_{45,}$ related to the distance to major faults and folds (according ISRM, 1981).

To the west, there is a sedimentary sequence defining a gentle dipping monocline, where faults with strikes N-S, NE-SW to ENE-WSW, NW-SW to NNW-SSE and E-W generate blocks with a noticeable thickening of the lithological units.

The Upper Triassic conglomerates, sandstones and mudstones, represent the sequence base, on which Lower/Middle Jurassic units are superimposed, represented by dolomitic limestones and claystones and by thick limestone and marl-limestone alternations. The detritical Triassic units are characterised by $F_{12\text{-}3}$, $S_{34\text{-}45}$, $W_{2\text{-}4}$, and present thick pelitic lenses of about 100cm, which can have zero to moderate plasticity when associated with smectite clay.

The Upper Triassic and Lower Jurassic dolomitic limestones and claystones have a high variability of thickness of calcareous layers ($L_{23\text{-}L45}$) and pelitic lenses (1-500cm). The limestones present a fracture intercept values of $F_{23\text{-}45}$, S_{23} and W_{23}; the claystones have moderate plasticity (5-18% PI) and free swelling (4-18%) due to the vermiculite and smectite clay minerals.

To the west, there is a thick Jurassic series (of about 300m) with marls, marl-limestones and limestones, which is affected by faults, dipping strata or thrown blocks. Seven lithological units have been individualised (Tavares, 2003) with general marl-limestone alternations but with a high variability of thickness of calcareous layer (L_3-L_5) and of marl or pelitic lenses (1-250cm). The limestones and marl-limestones present fracture intercept values from F_{34} to F_{45} and uniaxial compressive strength S_{23}-S_3, The marl and pelitic lenses have low to high plasticity (4-23% PI), 4-17% free swelling values, and high variability of $CaCO_3$ contents (20-76%). The dominant clay mineralogy is Illite and kaolinite but vermiculite, smectite and chlorite are also present. The degree of weathering varies between W_{12} to W_{45} and is related to the thickness of marl/pelitic lenses or to the distance from major faults.

In the farthest western area, Cretaceous and Tertiary conglomerates, sandstones, mudstones and limestones can be observed. The four units present have a general heterogeneity of sequence or an alternative character as calcareous units. The pelitic lenses can reach a thickness of 5m. The sandy-conglomerates usually have zero to moderate plasticity and low to moderate free swelling (0.4-15%). However, the red sandy-claystone unit presents low to high plasticity (5-40% PI) and free swelling (3-32%). Smectite, together with kaolinite and illite, represents the dominant clay mineralogy.

All these units are covered with large superficial Plio-quaternary deposits represented by sandy-conglomerates or tuffs and travertines. Torrential deposits can present moderate plasticity, with 10% free swelling, in opposition to the fluvial deposits with little or no plasticity or swelling.

In contrast to the strong slope angles, high drainage density (4.0-5.0 Km/Km^2 and 5.0-7.3 Km/Km^2) and low infiltration rates in the east, the sedimentary units in the west present general slope steepnesses of below 16%, with a large area of <2,5% in the Mondego floodplain. The detritical and calcareous units present a general drainage density of under 4 Km/Km^2 (the dolomitic limestones and tuffs and travertines have average values of under 2.0 Km/Km^2, associated with karst forms) and mid to high permeability (the highest values are recognized in the Cretaceous sandstones and Quaternary sandy-conglomerate deposits).

2.3 Instability processes

Instability processes related to mass movements have been historically observed and described in the area studied. These processes bear particular relevance to the recent anthropogenic occupation and a general state of reactivation was produced during the 2000-2001 winter, leading to severe damage and loss. The long-lasting period of rainfall that occurred, involving high cumulative rainfall records, generated an active state of disturbance with an increase in the occurrences, amount and rate of movement.

A description of instability processes (WP/WLI UNESCO, 1993a; WP/WLI UNESCO, 1993b) and triggering factors recognised in the area indicates the following:

Falls and translational slides are recognised in most of the substratum units but especially in the metamorphic rocks (close to major faults and folds or in the relativity narrow zone of magmatic intrusions) and the dolomitic limestones (within pelitic lenses, close to major faults and sinkholes filled by red sands with moderate plasticity). The factors triggering these types of movements are chiefly slope cutting, due to road and building excavation.

Rotational slides in different states of activity are essentially recognized as involving the marl-limestone alternations and claystone-dolomitic limestone alternations, usually associated with faults. The slope angles of the affected areas have a large range of values (8-16%; 16-26%, >26%) and frequently have a northern aspect. The triggering factors are mainly human activity involving cuts in potentially unstable slopes for road and house building, alterations to the vegetation cover and changes in drainage or infiltration capacity. Rotational slides, inactive relict to active, can also be observed in the Cretaceous sandy-mudstones, which present moderate to high plasticity, namely in conjunction with fault patterns and related to human slope cutting or river bank erosion.

Lateral spreads can be observed in fractured dolomitic limestones ($L_{45}F_{45}$, ISRM 1981) alternating with moderately plastic clays (with thickness layers of 1-180cm) and in limestones ($L_{45}F_{45}$, op. cit.) alternating with moderately plastic marls (with thickness layers of 10 to 250cm). Marl-limestone alternation units also present lateral spread movement when the marl lenses are over 50cm thick. These movements are related to average slope angles ranging between 8-20%, northern slope aspects, and bare or sparse vegetation cover. The main factor triggering this type of movement is rainfall.

The debris and earth flow inventory map suggests three main lithological domains which have typical field drainage and morphological slopes: (1) metamorphic units when moderately to highly weathered (W_{34}) and associated with slopes over 26% and gully erosion; (2) the interbedded sandy-mudstones of the Upper Triassic with low vertical permeability correlated with slopes over 16%, frequently with northern slope aspects; (3) Plio-Quaternary sandy-conglomerate deposits especially those on red sands (with moderate plasticity and low compactness) on colluvial/slope deposits and on anthropogenic fills. The main triggering factors are rainfall (especially when seasonal water courses are changed), human slope cutting and the destruction of plant cover.

Gully and rill erosion (Fannin and Rollerson, 1993) occurs particularly in the tiny Jurassic marl-limestone alternations and the calcareous marlstone presenting slopes under 16% and a specific development within the S and W slope aspects. These types of erosion are directly related to the marl content and occur in inverse proportion to the thickness of the layer (Tavares, 2004, awaiting publication). Gully is also observed in the cretaceous white sandstone with low superficial compactness and the sandy-mudstones with strong variations in vertical permeability.

Karst subsidence and sinkholes, frequently filled with Plio-Quaternary materials, have been identified in Jurassic units as dolomitic limestones, marls and marly limestones, and calcarenites to calcirudites. Karst forms have also been recognized in the superficial tuffs and travertine deposits. Associated with these forms, falls and translational movements related to old quarries and recent human slope cuts can be observed.

3. METHODOLOGICAL SUSCEPTIBILITY AND VULNERABILITY EVALUATION

A methodology for hazard evaluation associated with geomorphic processes was developed using GIS technology, which enabled composite identification of areas with growing levels of susceptibility (Brabb, Pampeyan and Bonilla, 1972; Irigaray and Chacon, 1996; Tavares, 1999 acceptation) that will have repercussions on land use and comprehensive planning.

The database, with two levels of attributes, included: a lithological map (outcropping units, cartographic contour density map) a geotechnical soil and rock zoning, structural map (tectonic network density map) a digital terrain model (hypsometric, slope steepness and slope aspect maps), the hydrological network (drainage density), the agricultural and ecological areas under protection, multi-spectral Landsat satellite imagery classification (surface moisture map, surface temperature map. artificial areas and quarries with little or no vegetation cover). An inventory of evidence of mass movement (falls, slides, lateral spreads, flows, gully erosion, karst subsidence and sinkholes) was also produced and mapped.

The degree of exposure (IUGS, 1997) was established in relation to the percentage of human occupation and the road infrastructure density maps. This methodological evaluation is represented in Figure 1.

The data management for hazard evaluation identified twenty-five physical factors which determine instability associated with geomorphic processes. The selected factors were analysed by means of qualitative scales and weighted according to field observations. In tables 1, 2 and 3 the determining factors are described.

The factors were grouped into three main classes according to lithological, morphological and structural and hydrological factors in order to display three preliminary susceptibility maps, as suggested in Figure 1.

The relevance to land use of this intermediate suscepti-

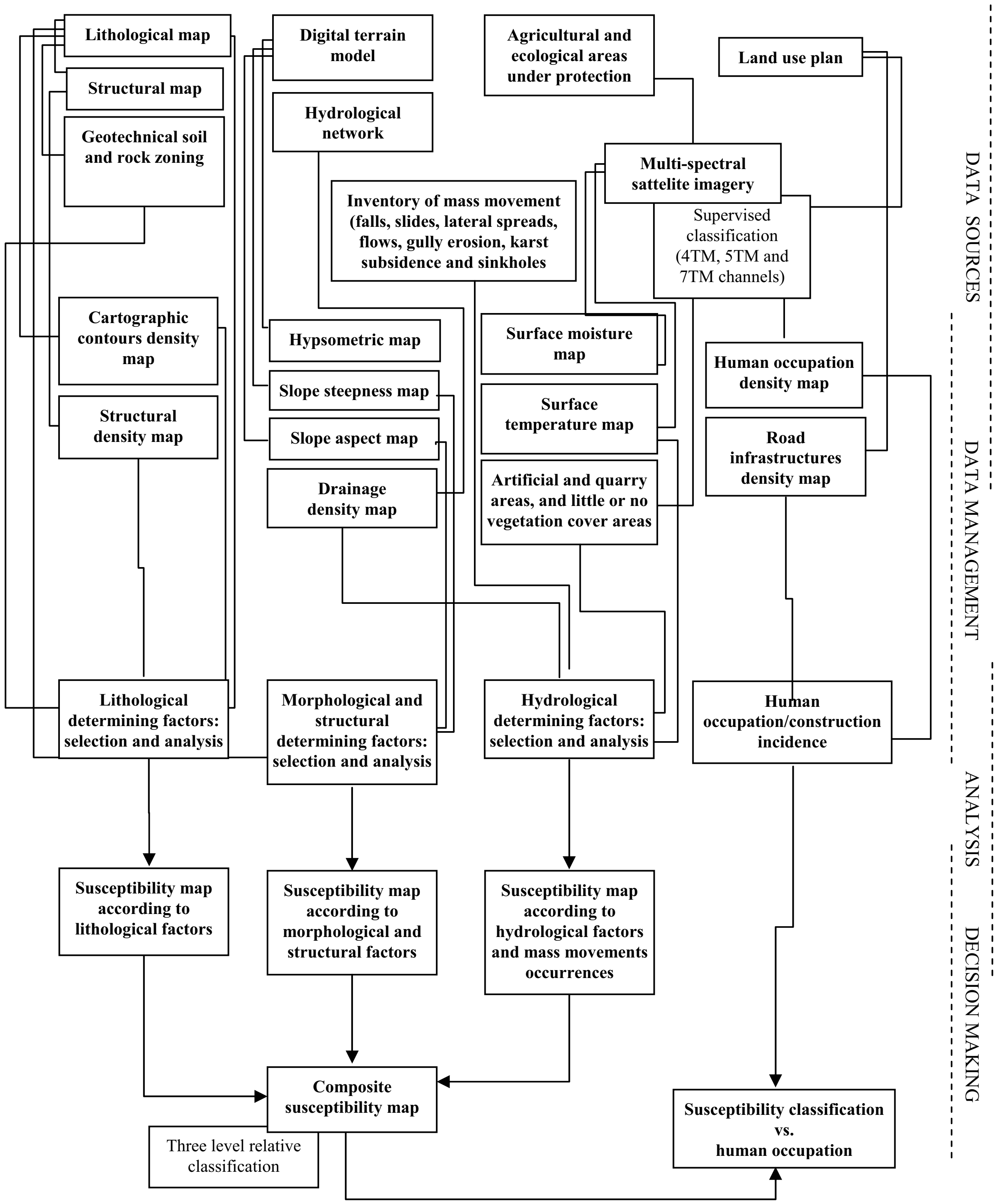

Figure 1. – Methodological susceptibility evaluation in an urban and outer urban area (the municipality of Coimbra)

bility evaluation and selection of determining factors arises out of the fact that it is the best and easiest way to define local physical restrictions and create planning and building regulations. The inventory of occurrences of mass movement was added to the hydrological factors because *in situ* evaluation made it clear that rainfall was important as the main triggering factor in instability.

Table 1. Lithological factors affecting instability

Factors	
High cartographic contours density (Km/Km^2)	]2.5 – 4.5]]4.5 – 8.1]
Low compactness on the surface detritical deposits	
Mechanic anisotropies in the foliated metamorphic materials	
Heterogeneity of unit facies sequence	
Presence of peat materials	
Sequence alternation with marl or claystones	
Low uniaxial compressive strength	<20MPa
Medium to high degree of weathering	W_3 to W_5
Low thickness of limestone layer	<20cm
Grading heterogeneity of detritical sediments	

Table 2. Morphological and structural factors affecting instability

Factors	
Slope steepness (%)	]8 - 16]]16 - 120]
Facets with northern aspect	
High structural density (Km/Km^2)	]1.0 – 3.5]]3.5 – 7.3]
Folded structures on foliated materials	
Close fracturing intercept	<20cm

Table 3. Hydrological factors affecting instability and mass movements inventory

Factors and occurences	
High drainage density (Km/Km^2)	]4.0 – 5.0]]5.0 – 7.3]
Areas under construction or quarrying areas, and areas with little or no vegetation cover	
High surface temperature from satellite imagery	
Superficial water table	
High permeability of surface detritical deposits	
- Gully and rill forms	
- Rotational slide features	
- Rockfall and translational slide features	
- Lateral spread and flow features	

Figures 2, 3 and 4 represent the three intermediate susceptibility maps according the group of instability factors. These maps express three classes of evaluation, which represent an increase in determining factors present in the area.

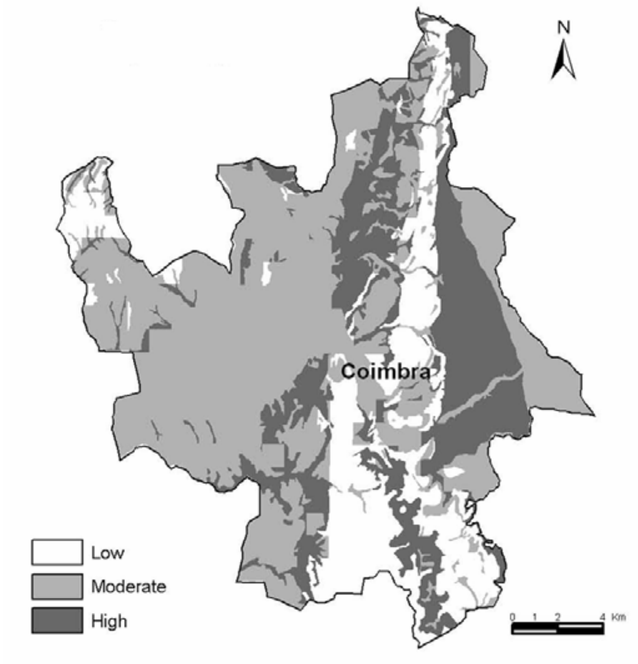

Figure 2 – Susceptibility according to lithological factors

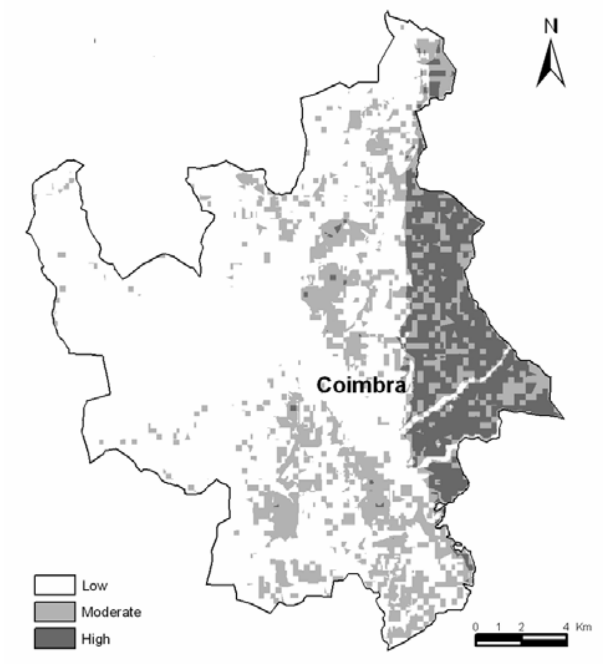

Figure 3 – Susceptibility according to morphological and structural factors

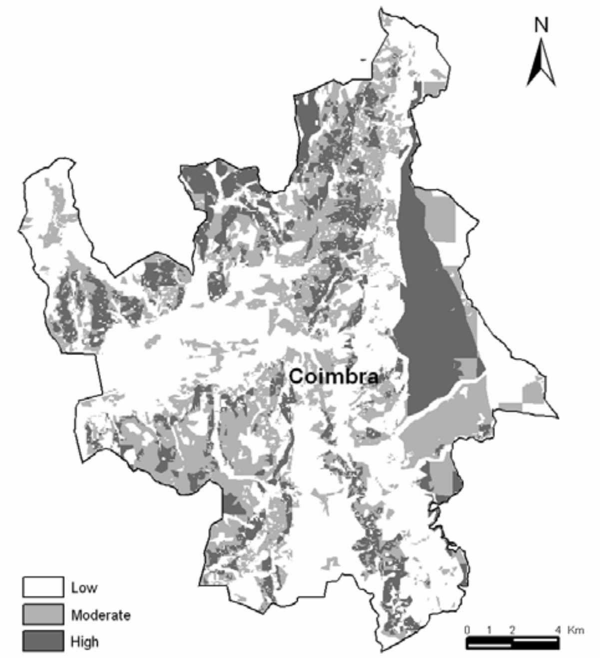

Figure 4 – Susceptibility according to hydrological factors and occurrences of mass movement

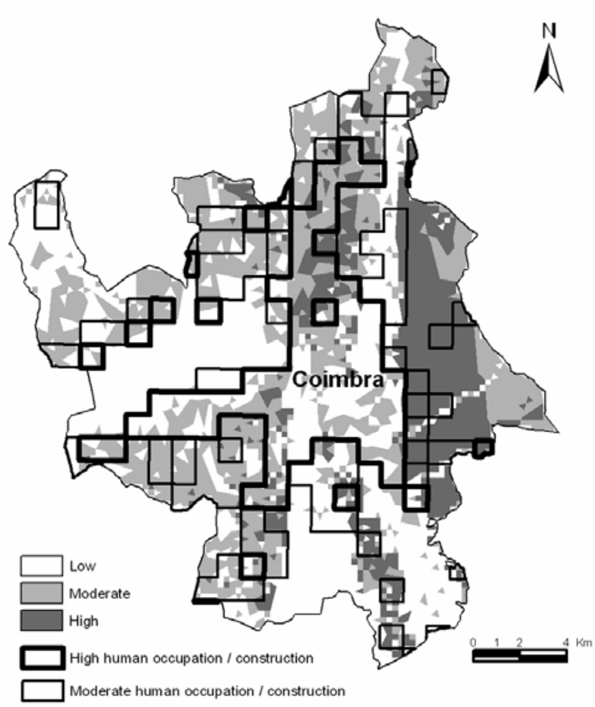

Figure 5 – Composite susceptibility vs. Human ocupation

Figure 2 shows that the lithological factors influencing the geomorphic processes are important in most of the area, and especially relevant in two meridian corridors.

Morphological/structural determining factors are important in the eastern areas, according to Figure 3. Hydrological factors and occurrences of mass movements are relevant in the eastern meridian area, and in several areas in the southeast, southwest, north and northwest, as shown in Figure 4.

It was possible to create a final susceptibility map using data retrieval and analyses from the preliminary susceptibility evaluation. The ArcView software displayed a composite surface map, whose hierarchical reclassification enabled areas with a given index value to be identified. These areas were classified according to three ascending levels of susceptibility (low, moderate and high), as shown in Figure 5

In Figure 5, incidences of occupation/construction are also represented, which makes the evaluation of relative vulnerability possible (IUGS, 1997).

4. CONCLUSION

Field recognition and mapping and *in situ* and laboratory testing have led to a better understanding of the physical characteristics of the area. A large amount of geological and geotechnical information is available nowadays in relation to land use and comprehensive planning.

A large inventory of mass movement has been created, which includes identification of features, evaluation of state and distribution activity, characterisation of typology and displaced volume and the relative triggering factors.

The preliminary and final susceptibility mapping enabled a land capability classification to be created, together with the identification of local physical restrictions, which will be incorporated into planning regulations.

The composite susceptibility outcome indicates the low representation of areas with high susceptibility, and the importance of moderate levels in outer urban areas.

The methodological susceptibility evaluation also showed a progressive human movement into areas with growing levels of susceptibility, threatening historical areas characterised by low levels of susceptibility and better geotechnical proprieties.

5. REFERENCES

Aleotti, P. and Chowdhuray, R. 1999. Landslide hazard assessment: summary review and new perspectives. Bull. Eng. Geol. Environment, 58, 1, pp. 21-44.

Brabb, E. E.; Pampeyan, E. H. and Bonilla, M. G. 1972. Landslide susceptibility in San Mateo County, California. U.S.G.S., Misc. Field Studies Map MF-360.

Cruden, D. M. and Varnes, D. J. 1996. Landslides types and processes. In Turner, A.K., Schuster, R.L. (ed), Landslides: Investigation and Mitigation. Transportation

Research Board, National Research Council, Sp. Report 247, Washington DC, pp. 36-75.
Fannin, R. J. and Rollerson, T. P. 1993. Debris flows: some physical characteristics and behaviour. Canadian Geotechnical Journal, 30, pp. 71-81.
Fookes, P. G. 1987. Land evaluation and site assessment (hazard and risk). In Culshaw, Bell, Cripps & O'Hara (ed), Planning and Engineering Geology. Geological Society Engineering Geology, Special Publication nº 4, pp. 273-282.
Irigaray, C. and Chacón, J. 1996. Comparative analysis of methods for landslides susceptibility mapping. In Chacón, Irigaray & Fernández (ed.), Landslides. Balkema, Rotterdam, pp. 373-384.
ISRM 1981. Basic geotechnical description of rock masses (BGD). International Journal Rock Mechanics Mining, Science & Geomechanics Abstracts, 18, pp. 55-110.
IUGS 1997. Quantitative risk assessement for slopes and landslides – the state of the art. In Cruden & Fell (ed.), Landslides Risk Assessement, Balkema, Rotterdam, pp. 3-35
Lateltin, O. J. 2002. Landslides, land-use planning and risk management: Switzerland as a case-study. In R. McInnes & J. Jakeways (ed.), Instability, planning and management, London: Thomas Telford, pp. 89-96
Tavares, A. O. and Soares A. F. 2002. Instability relevance on land use planning in Coimbra municipality (Portugal). In R. McInnes & J. Jakeways (ed.), Instability, planning and management, London, Thomas Telford, pp. 177-184.
Tavares, A. O. 1999. Condicionantes físicas ao planeamento. Análise da susceptibilidade no espaço do concelho de Coimbra. Univ. Coimbra Thesis, Portugal, p. 346 + 26 maps.
Tavares, A. O. 2003. Caracterização das unidades líticas carbonatadas na região de Coimbra. In Portugal Ferreira (ed.), A Geologia de Engenharia e os Recursos Geológicos, Coimbra: Imprensa da Universidade, pp. 333-343
Tavares, A. O. 2004. Landslides and gully erosion in Jurassic marl-limestone areas (Central Portugal). IX International Symposium on Landslides, Rio de Janeiro (in press).
Thierry, P. and Vinet, L. 2003. Mapping an urban area prone to slope instability: Greater Lyons. Bull. Eng. Geol. Environment, 62, pp. 135-143.
WP/WLI UNESCO 1993a. A suggested method for describing the activity of a landslide. Bulletin Intern. Association of Engineering Geology, 47, pp. 53-57.
WP/WLI UNESCO 1993b. Multilingual landslide glossary. International Geotechnical Societies, Canadian Geotechnical Society (ed.), Richmond: BiTech Publishers Ltd.