Landslide susceptibility in small villages situated in the marly Betic Cordillera: A case study

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Abstract: The Betic Cordillera includes a number of formations where marls and clays predominate and therefore are subjected to slope instability processes, which are active during rainfall periods usually in the form of shallow earth flow and complex landslides. These slides combine planar slide and plastic flow mechanisms. During the last 25 years development of Andalusia has occurred under the umbrella of European financial support. This has caused an increase in urban areas. Many small country villages are growing and landslide incidences are increasing. This is causing municipality plans to establish the distribution of the unstable areas for the new urban land-use planning.

The case study in Villanueva de San Juan (South of the Seville province close to the boundaries with Malaga and Cadiz provinces, Western Andalusia, Spain) is related to new Land-use Planning by the municipality after a number of landslides occurred in this town during the last heavy rainfall periods through 1996 and 1997. The geology in this region is Sub-Betic and Circum-Betic units composed of a series of marls, marly limestones and clays, covered by postorogenic deposits of sands and bioclastic sandstones. Landslides damaged a high number of the houses in the villages. The distribution of landslides and slope creep were analysed using a combination of aerial orthophotos and field surveys. A GIS application in ArcGIS (ESRI) was implemented using a 2 m vertical resolution DEM, conbined with morphologic parameters of the damaged urban area, including elevation, slope aspect and angle, and solar exposition. A detailed landslide inventory at a scale of 1:5.000 in the urban area and 1:10.000 was digitised. Geotechnical data were obtained from a number of boreholes with soil sampling, SPT tests as well as other field and laboratory tests. A superficial hydrology map of the drainage network and data about the depth to the water table from boreholes was also obtained. A GIS susceptibility map of the urban area was produced from which recommendations for a new land-use plan and landslide control and mitigation measures were proposed.

Résumé: Les Cordillères Bétiques inclut plusieurs formations où prédominent les marnes et les argiles et par conséquent sont soumises à des processus d'instabilité habituellement actif pendant les périodes de pluie intense. Ces processus se pressentent souvent en forme d´écoulement peu profond et glissements de terrain complexes. Ces glissements combinent les mécanismes translationnels et écoulement plastiques. Pendant les derniers 25 années le développement de l'Andalousie s'est produit sous le support financier européen. Cela a causé une augmentation des régions urbaines. Beaucoup de petits villages grandissent et les fréquences des mouvements de versants augmentent. Cela pousse les projets municipaux d'établir la distribution spatiale des zones instables pour son aménagement du territoire urbaine. Cette étude réalisée en Villanueva de San Juan (Sud de la province de Séville, Espagne) est en rapport avec le nouvel aménagement de territoire municipal après l'observation de plusieurs glissements de terrain que se sont produit principalement dans cette ville pendant les dernières périodes d'intenses pluies en 1996, 1997. Du point de vue géologique cette région est constitué principalement des unités Sub-Betic et Circum-Betic composées d'une série des marnes, calcaires marneux et argiles, couverte par des dépôts post-orogéniques de sables et calcarenites bioclastiques. On analyse la distribution des mouvements de versants en utilisant les données obtenus a partir de travail de terrain et de l'interprétation des photographies aériens. On a confectionné une application SIG (ArcGIS, ESRI) avec un MDE de résolution verticale de 2 m et on a réalisé la modélisation des paramètres morphologiques de la région urbaine endommagée, y compris élévation, pente, illumination et exposition de versants. Un inventaire de mouvement de versant a été réalisé et digitalisé a échelle 1:5.000 dans la région urbaine et 1:10.000 dans les alentours. Les données géotechniques ont été obtenues à partir sondages avec échantillonnage du sol et des essais SPT en plus des essais de laboratoire. Une carte de l'hydrologie superficielle avec les donnes de la profondeur de niveau phréatique a été obtenue a partir des mesures réalisées dans différents points d'observation. Comme résultat final, on obtient une carte de susceptibilité aux mouvements de versants a partir de la quel on a formulé des recommandations pour la nouvelle plan d'aménagement de territoire pour éviter les effets des mouvements de versants dans la zone urbain..

Keywords: landslides, geographic information systems.

INTRODUCTION

The Betic Cordillera includes a number of units where marls and clays predominate and therefore are subjected to slope instability processes. These are active during rainfall periods usually in the form of shallow earthflow and complex landslides which combine planar slide and plastic flow mechanisms. During the last 25 years the urban areas of many of the small country villages have expanded and the incidence of landsliding has increased. This has prompted the local authority to determine geologically unstable areas for the new urban land-use planning. This research discussed in this paper was conducted to fulfil the requirements of the City Council of the village of Villanueva de San Juan (Province of Seville) for designing a tool that could assist in the preparation of new land-use planning. An area larger than the village was examined in order to obtain a wider view of the instability processes affecting the urban lots. After available technical information about landslides and related geotechnical problems in the town was obtained, several areas were selected for additional study.

GEOLOGY AND HYDROGEOLOGY OF THE STUDY AREA.

The village of Villanueva de San Juan (Sevilla) is situated in the Northeastern Betic Cordillera where two main tectonic domains are represented: the External Zones (Sub-Betic Zone) and the Internal Zones (Circum-Betic or flysch zones). Also, after a post-tectonic unconformity several sedimentary units of Tertiary and Quaternary ages outcrop (Baena et al. 1981).

In the Sub-Betic Zone, are several Triassic formations that are mainly clays and sandstones of red and green colours. There are gypsum layers in some particular outcrops at the northern limit of the zone, “Red layers” of marly clays, marly limestones and white and salmon-coloured marls, usually cover the Triassic materials.

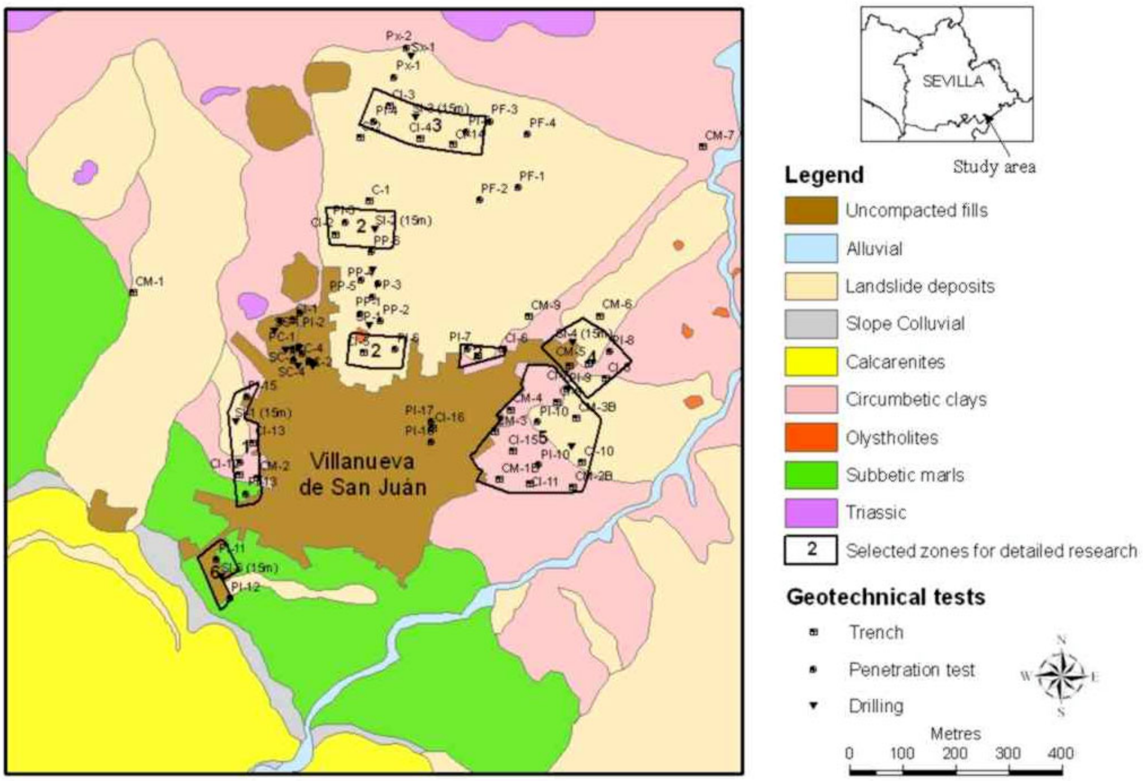

Figure 1. Geology of the study area and distribution of the selected areas for intensive geotechnical research.

The Circum-Betic materials, thrust over the Sub-Betic units, (called “Flysh ultras”by Baena et al. 1981), are represented by dark green clay with some scattered red colours and olistoliths. Units of brown soils frequently cover this domain which is difficult to identify. Megablocks of olysthrosmic breccia exist that have angular or sub-rounded pebbles of variable size (0.1 to several meters) that are composed of limestone or dolostone with chert, oolitic limestones, etc. all of them Jurassic in age. This formation includes the “Aljibe” sandstones and “Microcodium” limestone that are of Paleogene age. The post-tectonic formations overlying the Sub-Betic units show horizontal or sub-horizontal layers of sandstone and calcareous sandstone that are ~150 m. Covering all of the units previously described are Quaternary deposits of alluvial, colluvial or landsliding origin that are widespread in the region.

The fluvial network within the study area is dominated by two streams converging to the Corbones river, a subsidiary of the Genil river, which is one of the main subsidiaries of the Guadalquivir river. The main aquifer in the region is the limestone unit which gives place to the Peñón de Algámitas and Sierra de Tablones (IGME, 2003) and supplies the necessary drinkable water. There are some other minor aquifers wihin the calcareous sandstones at the southern border of Villanueva de San Juan. These drain to the North through a number of fracture planes. There are many springs in the boundary between this porous material and the underlying Sub-Betic marls.

This geological setting of porous and deformed calcareous sandstones out-cropping in the middle and upper side of the hills overlying marl units which appear at its base, is unsuitable for development from a geotechnical point of view because of the saturation of the upper part of the marls which clearly reduce the slope stability at the foot of the hills.

GEOTECHNICAL FEATURES OF THE SELECTED AREAS

At selected sites shown in Figure 1 six rotary drills were conducted down to a depth of 15 m, 32 SPT tests were made, 29 unaltered samples obtained and 90 metres of inclinometer tube were installed. Also 18 dynamic penetrations maintained up to the rebound level were performed and 16 trenches excavated with extraction of 30 disturbed and 12 undisturbed samples. During the "in situ" testing campaign 33 temporal measures of the depth to the water table were made. All the data obtained were interpreted with reference to existing geotechnical reports compiled from different civil works projects conducted in the village.

In five of the rotary drill sites, flexible vertical casings were installed and an inclinometer probe used to obtain measurements on three separate occasions: 09/11/04 (start), 19/11/04, 29/11/04 and 15/12/04. The measured deviation of the bores from the vertical line resulting from the drilling works was lower than 2º which was considered acceptable. The readings of the inclinometer probe show some deformation at the base of boring SI-2 (depth 14.5 m) on the west side of the village (Figure 1) and a deviation A+ above this point. This implies an accumulated maximum deformation of 5 mm over the observation time and an average of 30 – 40 mm/year. In the B axis a displacement is observed although minor with component B-. To complement to the inclinometer probe, control rigid tubes were introduced in the bores (9th and 10th November, 2004) to check for the existence of deformations in the installed casing. No significant deformation was observed in any of the tubes.

Using the results from field instruments and laboratory tests five different geotechnical units where recognised each of which will now be described.

Unit 1. Heterogeneous uncompacted fills with organic argillaceous soil: This unit has an average thickness of ~1 m although in some parts may attain more than 5 m. It includes soils of types CL, GC or MH (Unified Soil Classification System, USCS). The number of blows in dynamic penetration tests are below 10. Their consistency is soft to medium and the relative density is loose to medium.

Unit 2. Brown-greenish clay with pebbles: This unit is a result of the weathering of the underlying formations, slope wash and the accumulation of small earth and mud flows. The observed thickness varies from 3.5 to > 8 m. Underlying locally weathered marls and clays of Tertiary age, may be interpreted as belonging to this unit as the SPT offer very similar profiles. The unit is represented mainly by high plasticity clay CH with a moisture content several points above a liquid limit of 110%. The measured SPT N-values are between 2 and 16 bpf although most of the tests indicate N values below 10 bpf. The strength properties of the unit were investigated using shear box (UU, CU, UD and UD tests) and triaxial tests (CU) from which the properties obtained, under CU conditions averaged effective cohesion and friction angle of c_u= 94 kPa and ϕ = 15º . Under CD conditions the average c_u = 38 kPa and ϕ = 23 º.

Unit 3. Homogeneous brown-greenish clay: This unit is Tertiary in age, derived from weathered materials from both the Circum-Betic and the Sub-Betic tectonic domains. It outcrops in the majority of the study area usually below Unit 2 and with a thickness ranging between 8 and 13 m. In most of the excavated trenches the base of the unit was not attained. Unit 3 is a high plasticity clay (CH) with liquid limit above 113% in some samples. The average moisture content is usually slightly below the LL value. The geotechnical profile in this unit shows a sudden increase of the SPT N-values between 15 and 40 bpf (in average). In all these tests no rebound level was measured. The remarkable difference in the number of blows (and its rapid increase with depth) measured in the penetration tests compared with those made in the Circum-Betic or Sub-Betic materials is the main criteria used to distinguish between these units. The relative density in undisturbed samples is variable between medium and hard although on average it is denser in samples obtained from the Sub-Betic or Circum-Betic units. The average of the effective strength parameters in CD conditions obtained from shear box and triaxial (CU and CD) tests are c_u= 34 kPa and ϕ = 23º. The residual strength shows cohesion and an effective friction angle below the range of 8 to 14º.

Unit 4A. Circum-Betic: This unit is a brown-greenish clay with middle to high plasticity. It lies unconformably, above Sub-Betic materials in the southern part of the study area, or the Triassic in the northern part, with a thickness greater than 15 m in places. It is composed of soils of types CL, MH, ML and CH. Small blocks of olistolith and scattered layers of silts and sands give way to 10% sand and 8% gravel in the extracted disturbed samples. This unit therefore has a coarser grain size than units 2 and 3. The fine fraction indicates clay of middle to high plasticity with LL values above 78%, although the moisture content is several points below this amount, corresponding to the position of the water table below the unit. The measured relative density is quite homogeneous in the different samples and denser than in units 1-3. The CU shear box tests give c_u = 85 kPa and ϕ = 16º, while the CD test gives an average c_u = 50-70 kPa and ϕ = 19º – 30º. At residual shear strength the cohesion was negligible and friction angles below 20º were measured.

Unit 4B. Olistoliths. Clay, marl, sandstone and limestone: The thickness measured in the field is not representative since the tectonic setting of the unit is like a "floating body" embedded into the Circum-Betic domain. The lithologies composing these bodies are unequally distributed amounts of clay layers and fragments of sandstone and micro-breccia. Most of the dynamic penetration tests conducted on this unit produce sudden rebounds showing the abundance of the rock fragments.

Unit 5. Sub-Betic. This unit is Brown greenish to pink marly clays with sand of middle plasticity. It only outcrops in the southern part of the study area where it is very easily identified by higher angled slopes than those in the surrounding areas. Unit 5 is tens of metres thick (Baena et al. 1981) and during the geotechnical reconnaissance only the upper few metres were tested. The disturbed samples show 20% sand grains of calcareous composition and a medium plasticity with LL values below a 47.8% corresponding to CL. The measured moisture content in undisturbed samples is several points in percentage below the LL value, with moisture-consistence relationships close to those observed in Unit 4A. Also two SPT tests in this unit finished even more quickly than in Unit 4A with bpf rebounds which were interpreted as corresponding to a very high relative density.

Along with the geotechnical testing in the selected study areas, detailed mapping of the geological, geomorphic and geotechnical units was conducted at scales ranging from 1:5,000 to 1:10,000. First a geological survey was accomplished using stereoscopic pairs of recent and older aerial pictures to establish the evolution of the local morphology. Then the boundaries between the different units projected into the preliminary survey map were adjusted to the results of the geotechnical research. Also a field survey was completed to collect data about the structural geology, geomorphology, shallow soil covers and weathering of the existing outcrops, for inclusion in the maps. The final delimitation of the previously described geotechnical units is one of the results of this mapping process. In Figure 2, several cross sections of the units are shown.

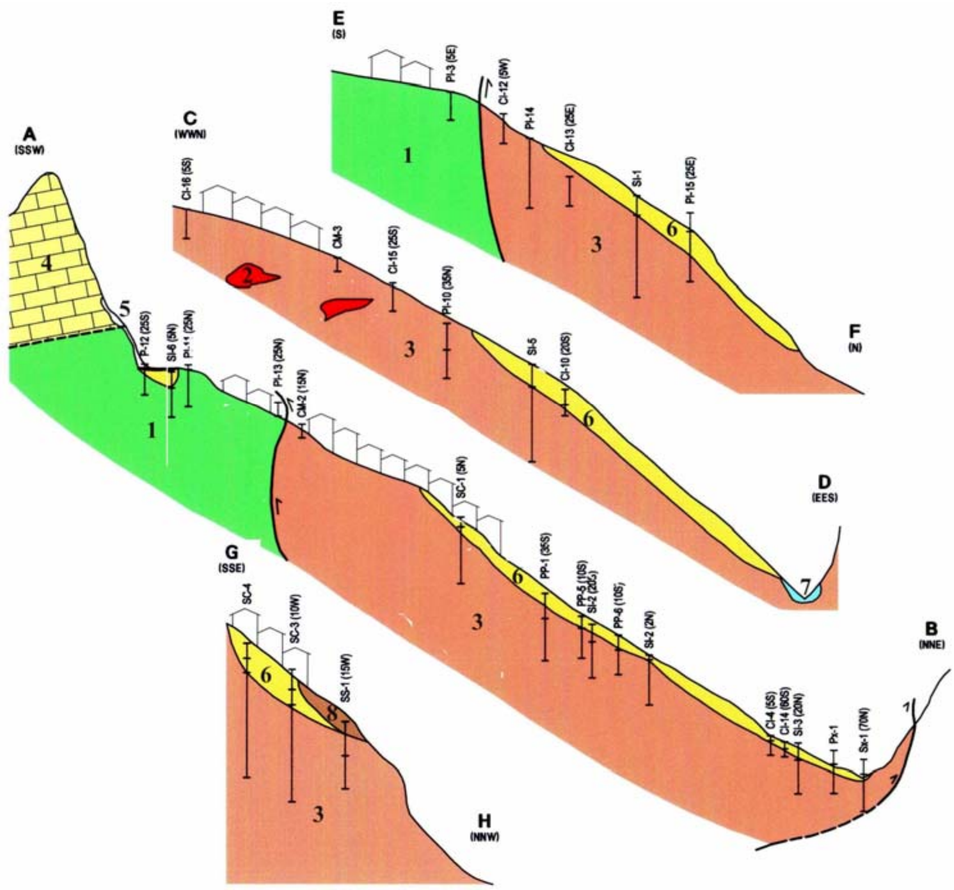

Figure 2. Structural setting of the different geotechnical units. 1: Sub-Betic marls. 2: Olistoliths. 3. Circum-Betic clay. 4: Calcareous sandstones. 5: Slope colluvial. 6: Landslide deposits. 7: Alluvial. 8: Uncompacted fills. Section AB (NS through the village). Section CD (Zone 5). Section EF (Zone 1). Section GH (Zone 2).

LANDSLIDE SUSCEPTIBILITY IN THE STUDY AREA.

Landslide inventory map

Using the aerial photo-interpretation and field survey, complemented with the results of the geotechnical research, an inventory of landslides was prepared (Figure 3) based on the classification of Varnes (1978). The following landslide types were distinguished:

Earthflows: These cover 41% of the total mapped landslide masses having a total surface area of 293744 m^2. Located at the south side of the village, these earthflows affect the local cemetery and a swimming pool. In the head zone of earthflow´s Sub-Betic marls are usually found to be out-cropped. Flow processes are evident on the margin of the Las Mujeres stream and in some other minor streams. Our geotechnical tests and field observations indicate that around the main scarps of earthflows there are clear rupture planes below which the exposed soil appears undeformed.

Creep: Evidence of creep occurs over 58% of the total surface affected by landsliding processes, (415396 m^2). Materials in which creep is observed are mainly Circum-Betic weathered clays. Evidence of creeping is most easily recognized as "terracettes" on rural slopes but can be difficult to make out in built-up areas. Within the village there is evidence of misalignment of walls and pavements. The swelling behaviour of the clays and the water infiltration are responsible for these deformations which occur to a depth of 4 - 5 m, below which no evidences of deformations are observed. The main difficulty in mapping the creeping zone was to delimit clear boundaries between affected and non-affected areas.

Rockfalls: These represent only 1 % of the total surface affected by landslide in the study area (7160 m^2) occurring on the scarps of the calcareous sandstones that outcrop in the upper part of the village.

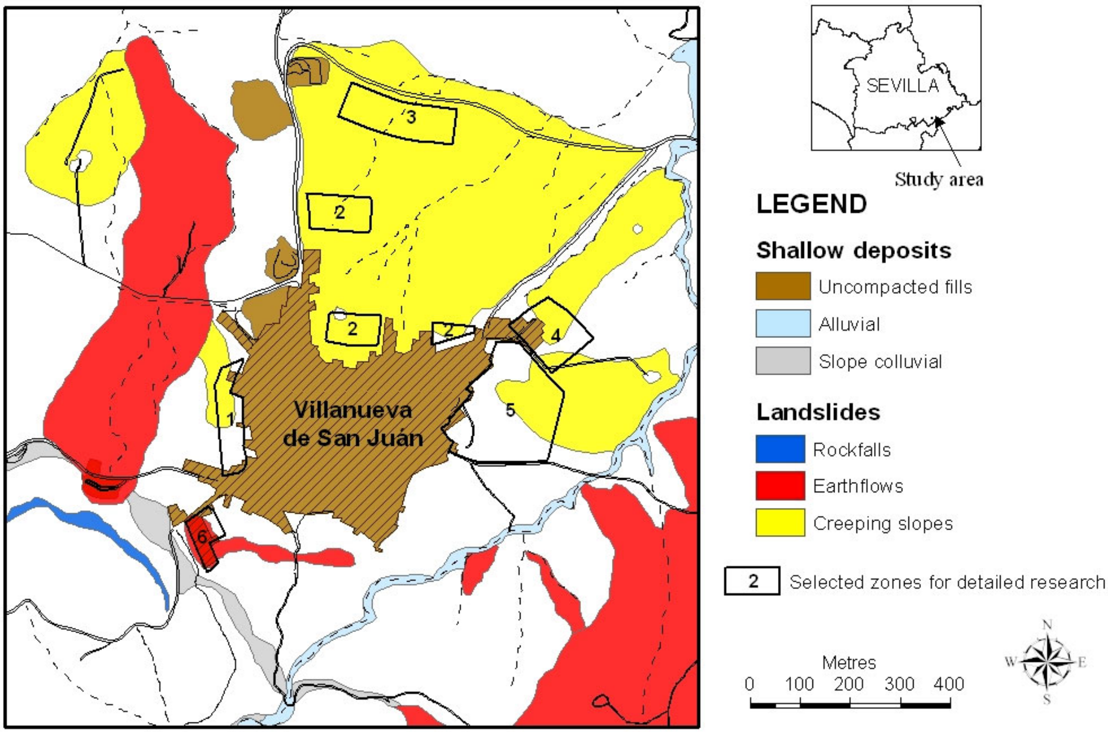

Figure 3. Landslide inventory in Villanueva de San Juan (Seville, Spain).

Susceptibility analysis using a model of planar failure in an infinite slope.

It has previously been shown before that planar failure occurs in different slopes head where several earthflows have developed. This has established the failure mechanism in the beginning of the landsliding process. Several excavated trenches and bore samples from our study show a planar boundary underlying the slope unit affected by swelling and creeping deformations. These observations support the application of a model of a planar slide on an infinite slope (Taylor 1948). Due to the simplicity of this model it has been widely applied in GIS analysis and modelling of landslides for dynamic conditions (e.g. Jibson 1993, Jibson et al. 1998, 2000, Luzi et al. 2000, Refice & Capolongo 2002) or static conditions (e.g. Dietrich & Montmogomery 1998, Van Westen y Terlien 1996, Venkatachalam et al. 2002, Frattini et al. 2004, Lan et al. 2004, Xie et al. 2004).

Using data we have obtained around Villaneuva de San Juan we have tested a planar failure equilibrium approach to examine factors of safety in the surrounding slopes. We used a raster grid approach with cells of 2x2 meters to obtain a model of the study area by introducing into the equation the established geotechnical parameters, and the geometrical and water table conditions for the study area. As in Corominas and Santacana (2003), the slope factor of safety is determined for each grid cell following a well known equation and the cells are taken as fully independent from each other. Landslide susceptibility is determined from the factor of safety value providing a method for examining how prone each 2x2 m cell is to develop a landslide. The factor of safety values were classified into three levels: high, medium, and low susceptibility and used to produce a map of landslide susceptibility. Upon completion of this susceptibility map, it was validated against field observations of actual ground conditions in the study area.

Figure 4 shows that 25% of study zone (504592 m^2), has high susceptibility, 30% (596292 m^2) has low susceptibility and 44.37% a moderate susceptibility. Taking into consideration the urban area alone 7% is classified as being of high susceptibility (12396 m^2) distributed in three different sectors, which includes the damaged swimming pool. The moderate susceptibility zone represents 29 % (49472 m^2) and the low susceptibility zone 63 % (108828 m^2) of the total area. Within the areas 1 to 6 (Figures 1 and 5) 1,4 and 5 have moderate to low landslide susceptibility while 6 is highly susceptible.

To further validate our landslide susceptibility map, a cross analysis between the safety factor map reclassified into three classes and the landslide inventory map showing rupture scars was performed. For this, the degree of adjustment was calculated using the equation (Irigaray et al. 1999):

$$GA = \frac{Zi / Si}{\sum Zi / Si}$$

where: Zi: surface of the rupture in the i susceptibility class. Si: surface of the i susceptibility class.

The smaller the degree of adjustment in the low susceptibility class (relative error) and the higher the degree of adjustment is in the higher susceptibility classes (relative right guess), the greater the quality of the map. The results in Table 1 show that a high coincidence occurs between the earthflow rupture zones and the higher susceptibility zones with a very low relative error (approximately a 5%). This appears to validate the use of the infinite slope model for analyses of landslides where the early rupture mechanism is very close to a plane failure. However, the relative error increases in zones affected by creeping processes indicating that the infinite slope model is not appropriate.

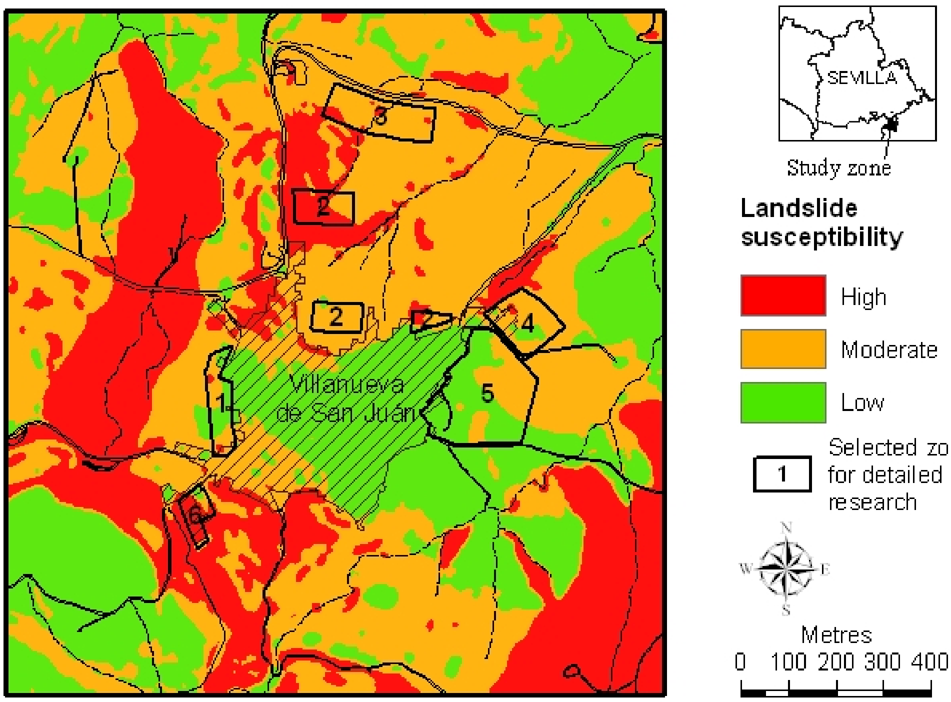

Figure 4. Landslide susceptibility map of Villanueva de San Juan (Seville, Spain).

Table 1. Degree of adjustment for earthflow and creep zones.

Susceptibility (SF values)	Earthflow rupture zone	Creep zones
High (>1,2)	69.1	46.1
Moderate (1-1,2)	25.5	43.9
Low (<1)	5.4	9.9

CONCLUSIONS

Our geotechnical research of the study areas and the mapping of the geological and geotechnical features, allow different geotechnical units to be distinguished based upon USCS soil types, values of effective friction angle and cohesion, thickness as well as water pressures. Five units were identified: 1. heterogeneous uncompacted fills with organic argillaceous soil; 2. brown-greenish clay with pebbles; 3, homogeneous brown-greenish clay; 4A, Circum-Betic brown-greenish clay with middle to high plasticity; 4B, Olistoliths, clay, marl, sandstone and limestone; 5, Sub-Betic brown greenish to pink marly clays with sand of middle plasticity.

The most unstable unit is number 4 (A and B), the location of which should be avoided where possible in future land-use planning of new urban areas. The incidence of landslides has been analysed, mapped and then modelled using an plane failure on an infinite slope constrained with with geotechnical and hydrological data from field and laboratory tests. A calculation of safety factor (SF) was made in grid cells of 2 x 2 meter and a susceptibility map was produced in which cells with SF below 1 (high susceptibility), between 1 and 1,2 (moderate susceptibility) and above 1,2 (low susceptibility) were distinguished. The landslide susceptibility map was assessed to be useful for the examination of earthflows but not for creep processes.

Several simplifications were assumed in this research. First, the failure model and safety factor calculations were applied to a grid of cells of 2x2 m wide, with every cell calculated independent of each other. Although there were direct field observations and tests that showed planar failure in earthflows, further development of these landslides involved plastic strain which may be not expressed by the plane failure model. The same failure model was used to compute safety factor values in cells affected by creeping, which it is not a process of landsliding but instead a very slow evolution of the slope morphology in soils bearing expansive clay and silt where swelling and shrinkage take place along with changes in the moisture content. Therefore it may be considered inappropriate to use this approach to model displacements in these soils. Nevertheless, the existence of 4 to 5 m of the soil profiles affected by creep along with the planar setting of this lower boundary provides an opportunity to use the model, bearing in mind the possible inaccuracy of the results. An additional limitation is the lack of data about the capillary behaviour of the water table in silt and marly clay bearing units and the more that likely existence of negative pore pressures which were totally disregarded.

Despite these limitations, and some other concerning the number and distributions of the field tests, or the statistic signification of the obtained disturbed and undisturbed soil samples, the results of the safety factor and susceptibility analyses shown in table 1 and figure 5 fit fairly well to the observed distribution of previous landslides. We therefore consider them useful in delimiting areas where geotechnical works of stabilization should be necessary for urban development (high susceptibility zone), areas where the susceptibility is low and therefore it may be suitable for urban development and areas where still site detailed geotechnical studies should be necessary in order to decide about the local instability conditions and remedial works for urban development (moderate susceptibility). Approximately 25% of the study area has high landslide susceptibility, with more that 7% of the village in this class. For future urban development only areas 1, 4 and 5 have low landslide susceptibility.

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