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Large-scale land-suitability mapping in the GIS environment for the construction site of the University Olympic Village in Izmir (Turkey)

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Abstract

Participants of the 23rd University Olympic Games held in Izmir (Turkey) were hosted in a Universiade Olympic Village that had to be newly constructed. A risk analysis has been performed to assess potential engineering problems at the envisaged construction site. The risk analysis was largely based on a new, large-scale land-suitability map that was prepared in the GIS environment with much detail for this type of construction work. Information was collected from several maps, in combination with mapping in the field, drilling and seismic data. Geological, geotechnical, geophysical and morphological data were then superimposed on these analyses. This sequence of overlay analyses was performed with the help of GIS software (MapInfo Professional 7.5); this resulted in five hazard maps. Risk points (1–11) were then attributed to the different zones in the five digital hazard maps.
A land-suitability map indicating the suitability for envisaged constructional activities was subsequently obtained in the form of an overlay of the five hazard maps, thus allowing to calculate a total risk for each zone on this map. The land-suitability map that was thus obtained, has been prepared for a 1:1,000 scale development plan; such a large scale is uncommon in this context.

Keywords: Land-suitability map, hazard maps, risk assessment, GIS, Turkey

Introduction

The Izmir Metropolitan Municipality had reserved a site of 0.5288 km^2 at the southern rim of Izmir Bay (Fig. 1) to accommodate the sport competitors in a Universiade Olympic Village. Artificial terraces had to be constructed as basements for 2-, 4- and 8-floor buildings. This required firm ground conditions, and the steeply inclined site had therefore to be investigated to find out whether they were geotechnically suitable and/or whether specific parts were more suitable than others.

Geological, geophysical and geotechnical studies formed the basis of a land-suitability map of the envisaged construction area; it was prepared with the help of Geographical Information Systems (GIS). The study com-

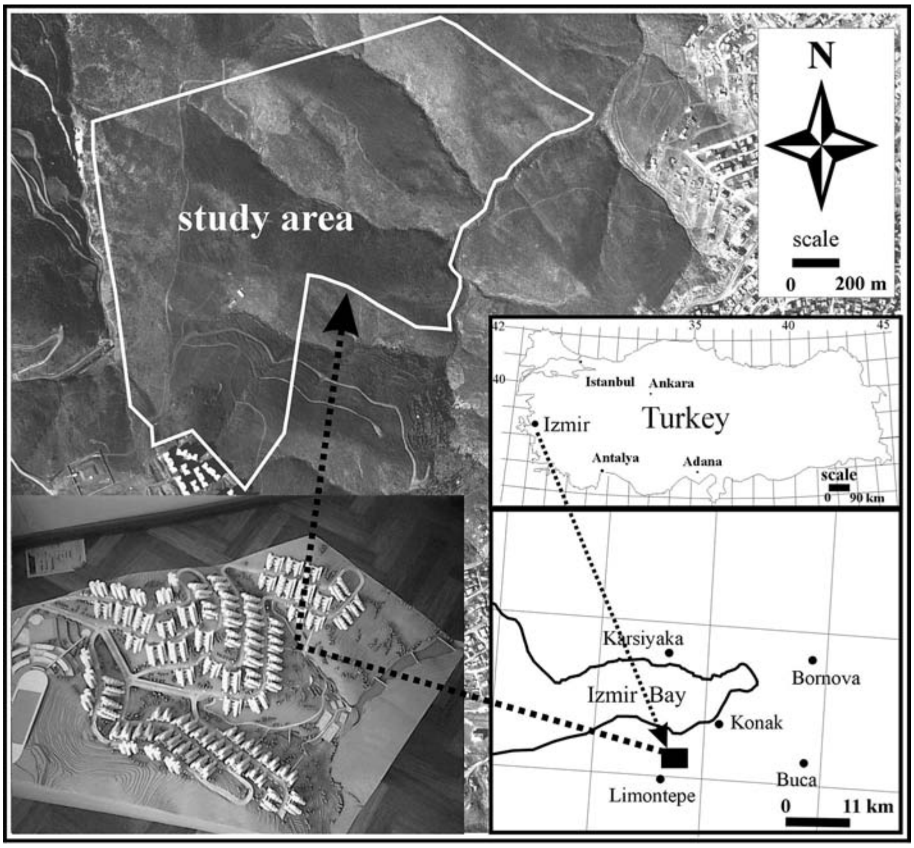


Fig. 1. Location map, aerial photograph and 3-D model of the study area.

bined engineering-geological and geophysical data by applying an overlay process in the GIS environment at the uncommonly large scale of 1:1000. Because the successful methodology followed can be understood satisfactorily only if the reasons for the various steps are clear, we also provide a short overview of the main problems to be dealt with, the successive steps to find solutions for these problems, and the outcomes. More details will be provided in a separate contribution devoted to the risk analysis carried out.

Engineering problems

The substratum of the construction area consists of sandstone/shale alternations (Koca & Kıncal, 2004; Kıncal, 2005; Kıncal & Koca; 2009); the sandstones outcrop with high-angle slopes; the shales have lower slope angles (10–20°). There are also some volcanic rocks. The boundaries between the sandstones and shales vary in depth, even within a few metres. Both the sandstones and the shales have joint sets, mainly in two sets with strikes that are almost perpendicular to one another. The volcanics show also two joint sets. The joints may help initiate failure of the steep slopes, which are locally covered by gravity-transported slope deposits with a thickness of 1.5–7.0 m. The steepness of the terrain (more than 45% of the area is steeper than 20°) was considered to be a critical parameter. The steep slopes might pose problems due to insufficiently controlled water runoff and to erosion.

Another potential problem was the groundwater level: boreholes indicated in many places a static groundwater level close to the surface, and elsewhere at depths of 6–10 m. These shallow groundwater levels might result in flooding of the deep foundation pits necessary for the construction of the multi-floor buildings.

Almost half of the drillings carried out penetrated lenses of graphitic shales, which do not outcrop in the study area. Geophysical surveys confirmed the shale occurrences and determined their horizontal extent. These shales do not only form local aquitards, but also can induce instability as they behave as soil if they are saturated with water.

Not less important is that horst-and-graben structures are common in this region. Recent earthquakes indicate that the region is now mainly affected by a tensile tectonic regime. In addition, the Aegean region, with its active tectonic structure, forms the epicentre of earthquakes that may also affect the study area.

Methods

The preparation of a land-suitability map was considered the best approach to assess the suitability of the site for the construction of the Olympic Village. Land-suitability maps are a special type of engineering geological maps, and present – in commonly schematic form – all components of the geological environment that are necessary for adequate land-use planning and for construction activities. With respect to the latter, a land-suitability map was thought to be optimum if showing three zones: (a) suitable zones, (b) second-choice zones (only provisionally acceptable), and (c) unsuitable zones for building. Such a map should be based on the combination of all relevant – mainly engineering-geological – parameters. This combination could be realized by using an overlay process in the GIS environment at a scale of 1:1000. This must be considered an uncommon procedure, as engineering-geological studies for an overlay process in the GIS environment tend to be made at 1:5000, 1:10,000 or even smaller scales, for instance at the level of a catchment area.

The preparation of land-suitability maps has been internationally standardized (IAEG-UNESCO, 1976). The standardized methodology was followed during the present study, but with an integrated approach in several steps. First, the available data relevant to the local geology (lithology, tectonic setting), geophysical (seismic) data, subsurface layering and geotechnical soil characteristics were compiled; the thematic maps were prepared in the GIS environment.

The ability to integrate data from two or more sources using a map overlay is perhaps the key function of any GIS, as it allows constructing a new layer (Heywood et al., 2002). One can distinguish three major categories of approaches to GIS-based land-use suitability analysis in the literature: (1) computer-assisted overlay mapping, (2) multi-criteria evaluation methods, and (3) soft computing or geocomputation methods (Collins et al., 2001). The computer-assisted overlay mapping technique (category 1) was used in the present study.

Computer-assisted overlay techniques were developed some decades ago as a response to the limitations of mapping and combining large datasets by hand (MacDougall, 1975; Steinitz et al., 1976). We used this technique to combine data from a number of maps in order to prepare a set of new maps that are termed 'hazard maps' in the following. For the preparation of these hazard maps, raster background images (scanned from topographical, geological, groundwater and slope maps, as well as from geophysical maps showing spatial peak ground-acceleration, site-amplification and S-wave velocity values) were digitized to form layers in vector data (Kıncal, 2005). GIS enables the end user to carry out a complete land-use planning and seismic-risk assessment at regional, sub-regional and local scale (Jimenez et al., 2000). All analyses for the present study were carried out at a local scale.

The use of GIS

In order to obtain all required data for the hazard map on the basis of which suitable construction sites should be selected in the study area, geological, geophysical and geotechnical studies based on borehole data were, like some previous surveys, carried out. It is beyond the scope of the present contribution to detail here the various types of research that were carried out – using GIS – for obtaining the data for the various layers of the maps. Both the methods followed during the investigations and their results will be dealt with in a separate contribution. In the present context it seems sufficient to mention that the following types of investigations have been carried out: (1) determination of rock strength and stability, (2) geophysical profiling, (3) analysis of borehole data, (4) laboratory tests, (5) determination of the engineering properties of the graphitic shales, and (6) estimates of the bearing capacity for foundations in the various rock types.

For this purpose, 1:1000 scale engineering-geological, groundwater-table and slope-zoning maps – each consisting of four sheets – were prepared first. Then, the following geophysical maps were prepared by conducting seismic studies: (1) a distribution map of S-wave velocities (V_s), (2) a distribution map of the Poisson's ratios (ν), (3) a distribution map of the site amplification, (4) a distribution map of the peak ground-acceleration, and (5) a distribution map of the natural period. Each of these maps formed one layer in the GIS process.

In this context, it should be mentioned that the Poisson's ratio (ν) was investigated because it provides the relationships between the elasticity modulus (E), the rigidity modulus (G) and the wave velocities V_p and V_s:

$$E = G \times \frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2} \qquad \text{(Kramer, 1996)}$$

where $G = \gamma \frac{V_s^2}{100}$ and $\gamma = 0.31 \times V_p^{0.25}$

(γ = unit weight);

$$\nu = \frac{0.5 \times (\frac{V_p}{V_s})^2}{(\frac{V_p}{V_s})^2 - 1} \qquad \text{(Bowles, 1988).}$$

where ν is the Poisson's ratio.

These formulas show that the elasticity modulus increases if the rigidity modulus and the wave velocity V_s increase.

Initially, the five geophysical maps were digitised and the data thus obtained were integrated into hazard maps. This means that

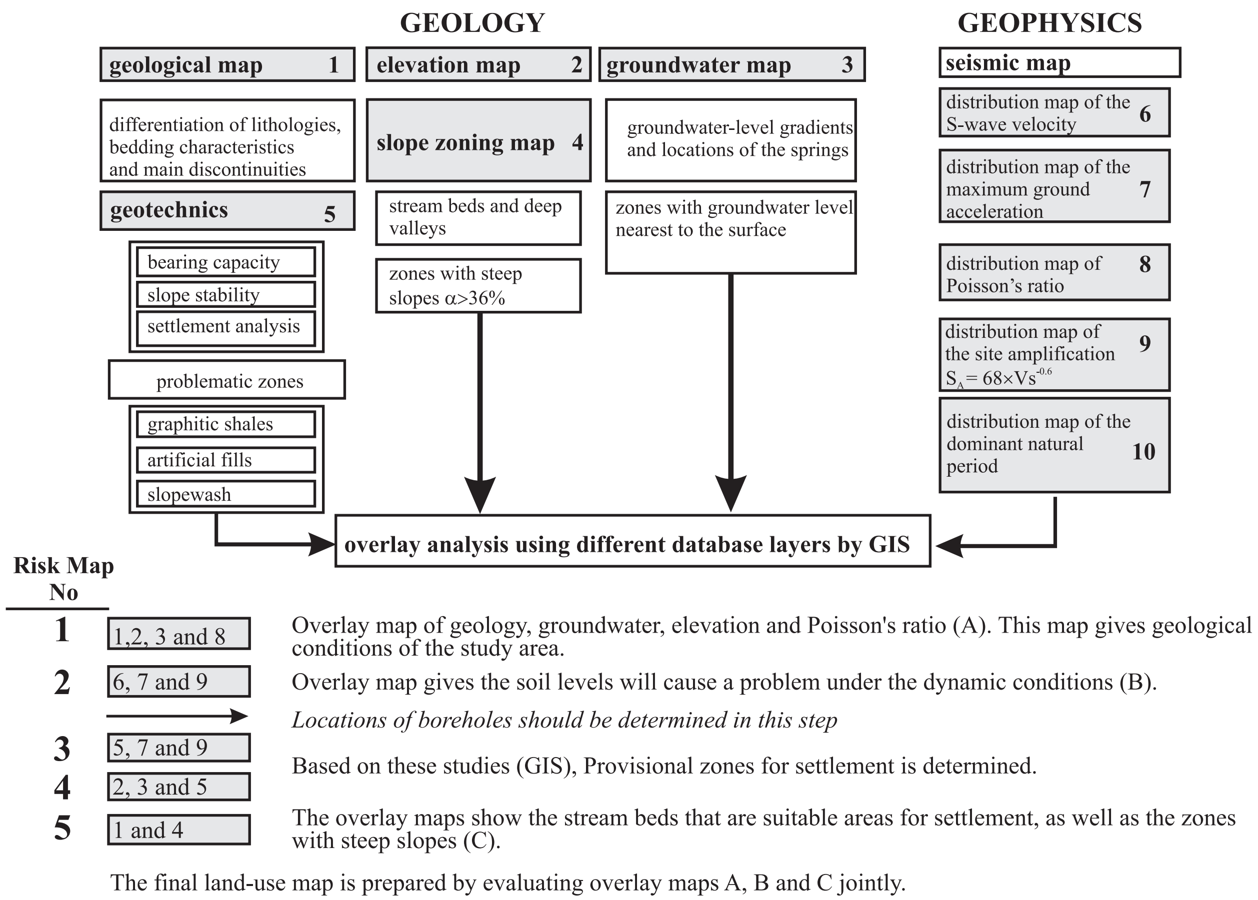


Fig. 2. Flowchart of the methodology adopted.

plane coordinates were transformed into UTM (3 degrees) coordinates. Then, a next GIS-related process was implemented according to the flow chart shown in Figure 2. MapInfo Professional 7.5 software (MapInfo, 2006) was used for overlaying different layers to obtain the hazard maps. Finally, a land-suitability map (Kıncal, 2005) for geotechnical purposes was obtained by considering the areas on the hazard maps. This detailed (1:1000) map indicated that the soil levels would pose a problem for the construction of the Olympic village.

Preparation of the land-suitability map

The various investigations yielded GIS-related data that were subjected to overlay processes in the way presented in Figure 2. For the present study, first risk points (also known as 'grade points') were allocated for each digital map layer in the database. This resulted in five hazard maps, which jointly contained the data needed for the preparation of the required land-suitability map.

Preparation of the hazard maps

Each of the five hazard maps has been created by combination of three (out of the ten available) layers, and 5 or 6 risk points were appointed to each layer. As the overlay process that has been applied involved five sets of overlay combinations, five hazard maps have been obtained (Fig. 3). The five individual hazard maps each indicate how large the risk of a specific hazard (e.g. slope failure) is at a specific place; the combined risk values of the five maps result ultimately in a land-suitability map from which it can be deduced which areas are suitable for construction activities, which areas are 'second choice', and which areas are unsuitable.

Hazard map I (Fig. 3-a), which was constructed by an overlay combination of groundwater + Poisson's ratio (v) + geology data, shows the areas where the groundwater table is close to the surface. The Poisson's ratio is larger than 0.36 where the depth of the groundwater level is less than 4.0 m below the surface.

Both Hazard map II (Fig. 3-b), composed by an overlay combination of the S-wave velocity (V_s) + the maximum ground-acceleration (a_{max}) + the site amplification (A), and Hazard map III (Fig. 3-c), made from overlays of a_{max} + A + presence of graphitic shale, represent areas where the soils pose a problem with respect to the bearing capacity under dynamic conditions. Generally, rock types such as graphitic shale, highly weathered shale, slope wash and artificial fills are the main constituents in the surficial layers of these zones. Particularly the zones with V_s values of 200–400 $m \cdot s^{-1}$, maximum ground-acceleration values (a_{max}) of 0.09-0.10 $cm \cdot s^{-2}$ and site-amplification (A) values of 1.14–1.22 s^{-1} can cause several problems for engineering activities. If these zones also have steep slopes, the construction of buildings should be avoided (unsuitable area for settlement). Additionally, lives and property are at risk if houses are built on these unstable slopes.

Hazard map IV (Fig. 3-d), composed by combining the overlays groundwater + elevation + graphitic shale, shows the zones that are classified in the present study as 'second choice' because there may be problems with the bearing capacity.

Hazard map V (Fig. 3-e), which has an overlay combination of geology + slope + elevation, comprises stream beddings that form 'unsuitable areas' for settlement, and steep (~ 20°) slopes that constitute a 'second choice' for settlement. Particularly where sandstone outcrops, the slopes are steep; shale and slopewash give rise to much less inclined surfaces. It should be noticed that strips of 12.5 m wide at each side of the streams have been taken as buffer zones, which are evaluated as 'unsuitable areas' for settlement purposes.

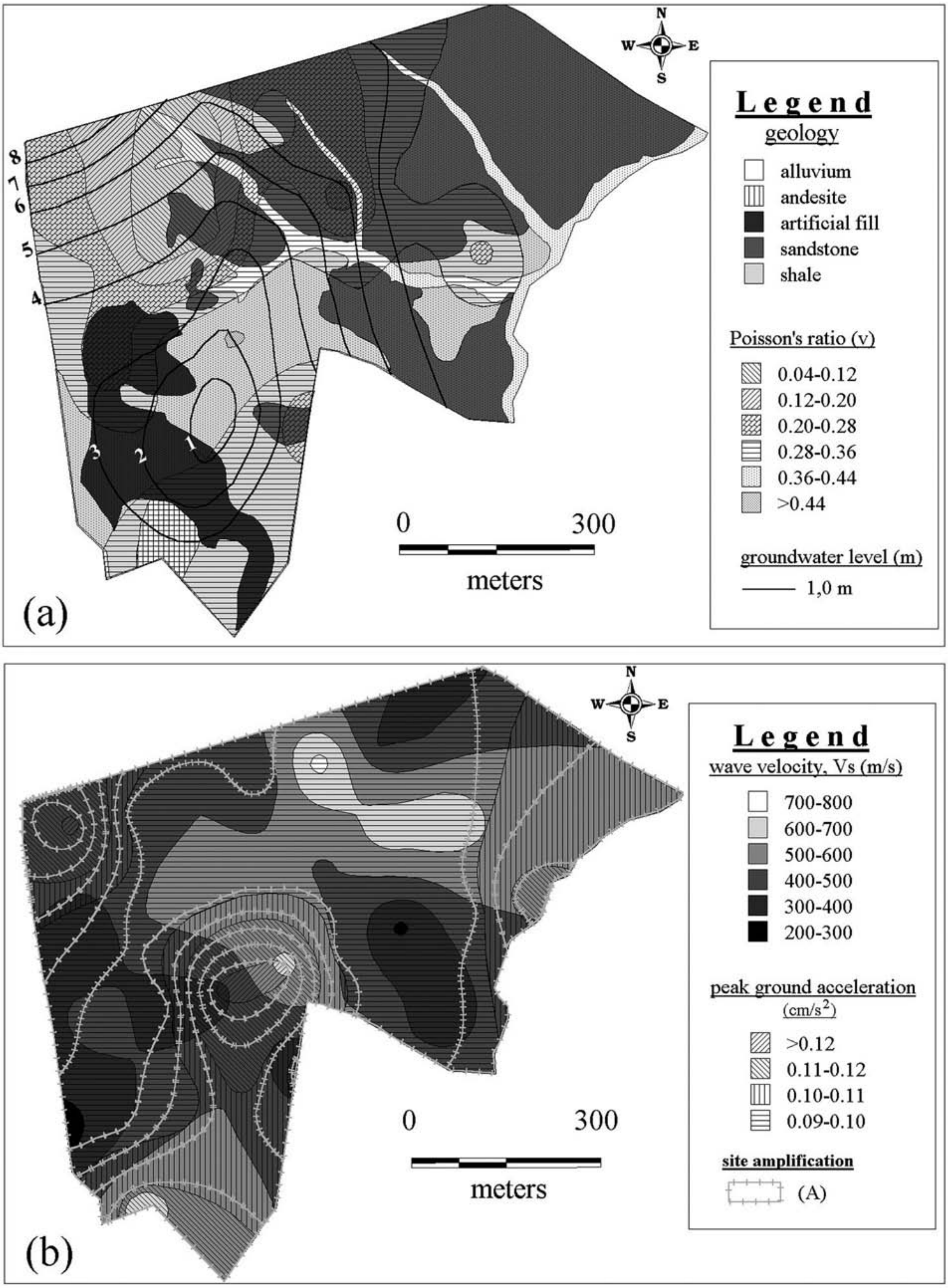
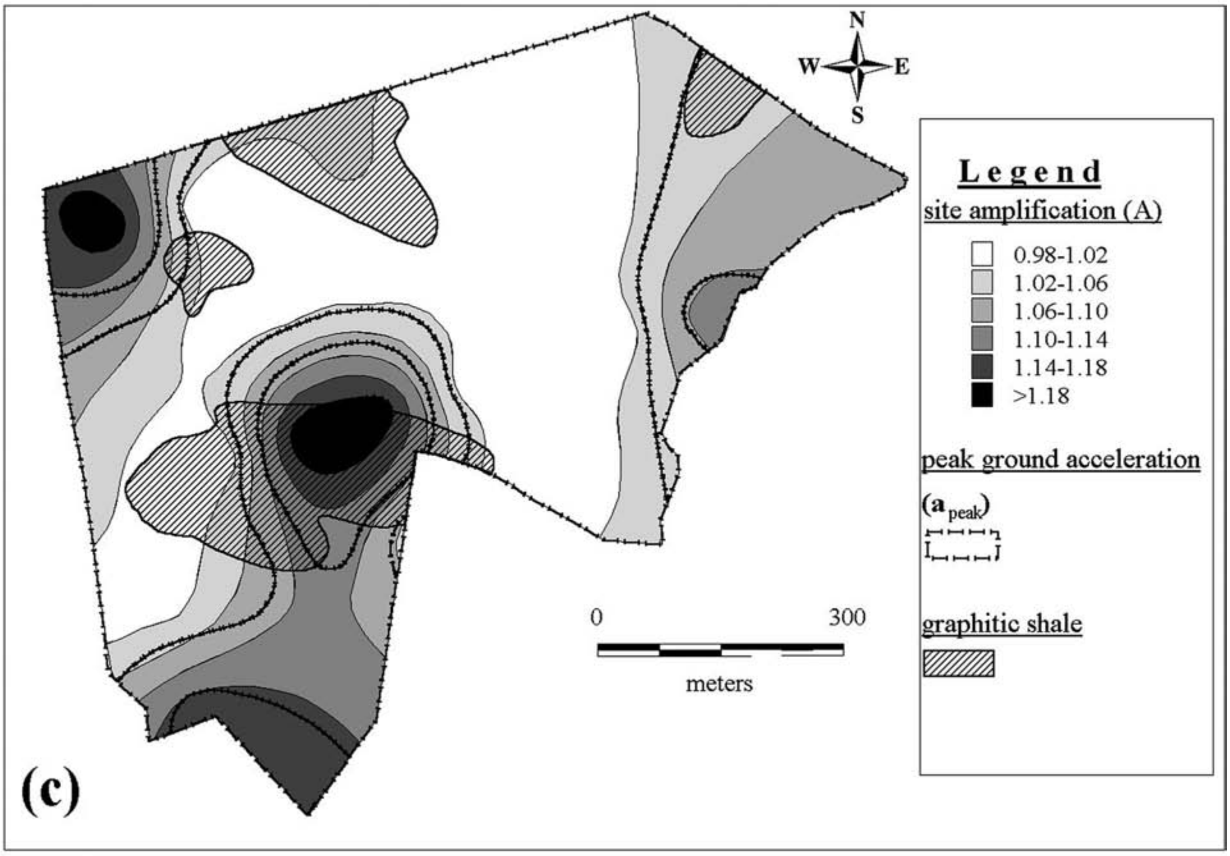
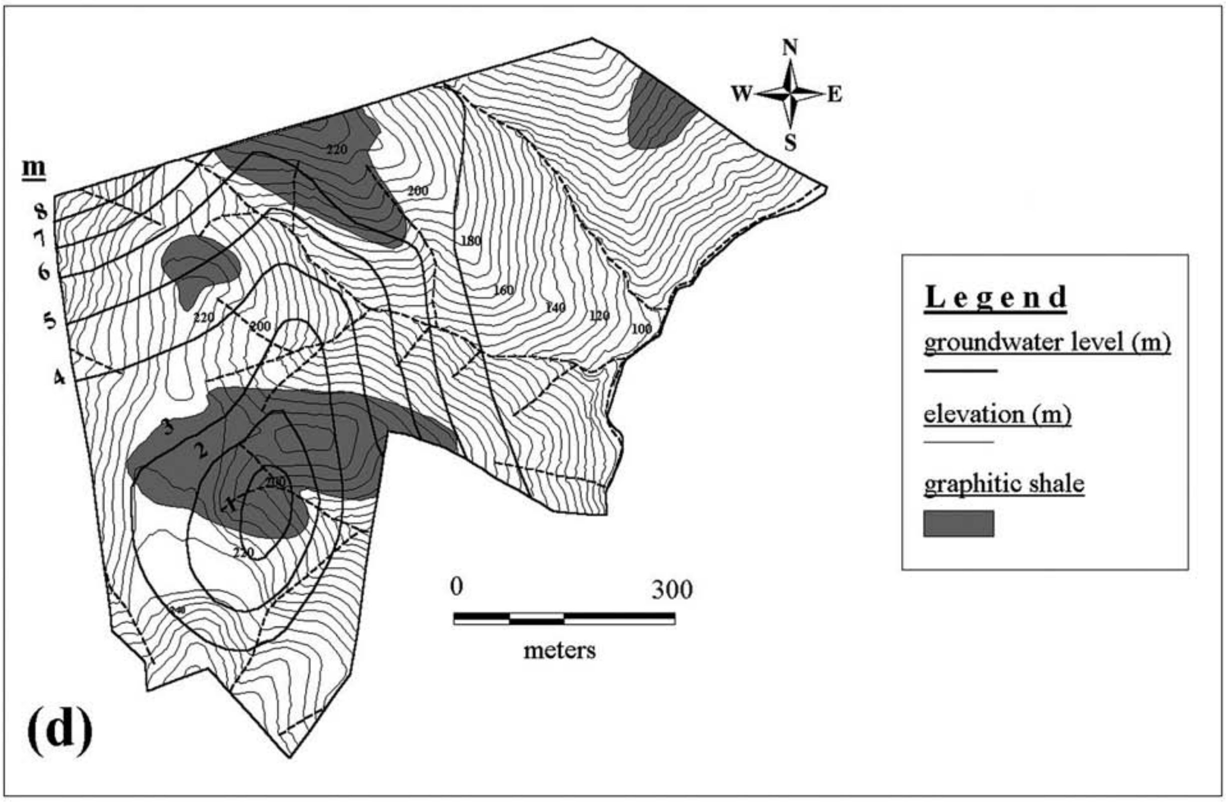


Fig. 3. Hazard maps.
a: Overlaid map of groundwater, geology and Poisson's ratio.
b: Overlaid map of wave velocity, maximum ground-acceleration and site-amplification.





c: Overlaid map of graphitic shale, maximum ground-acceleration and site-amplification.
d: Overlaid map of groundwater, topography, valleys and graphitic shales.

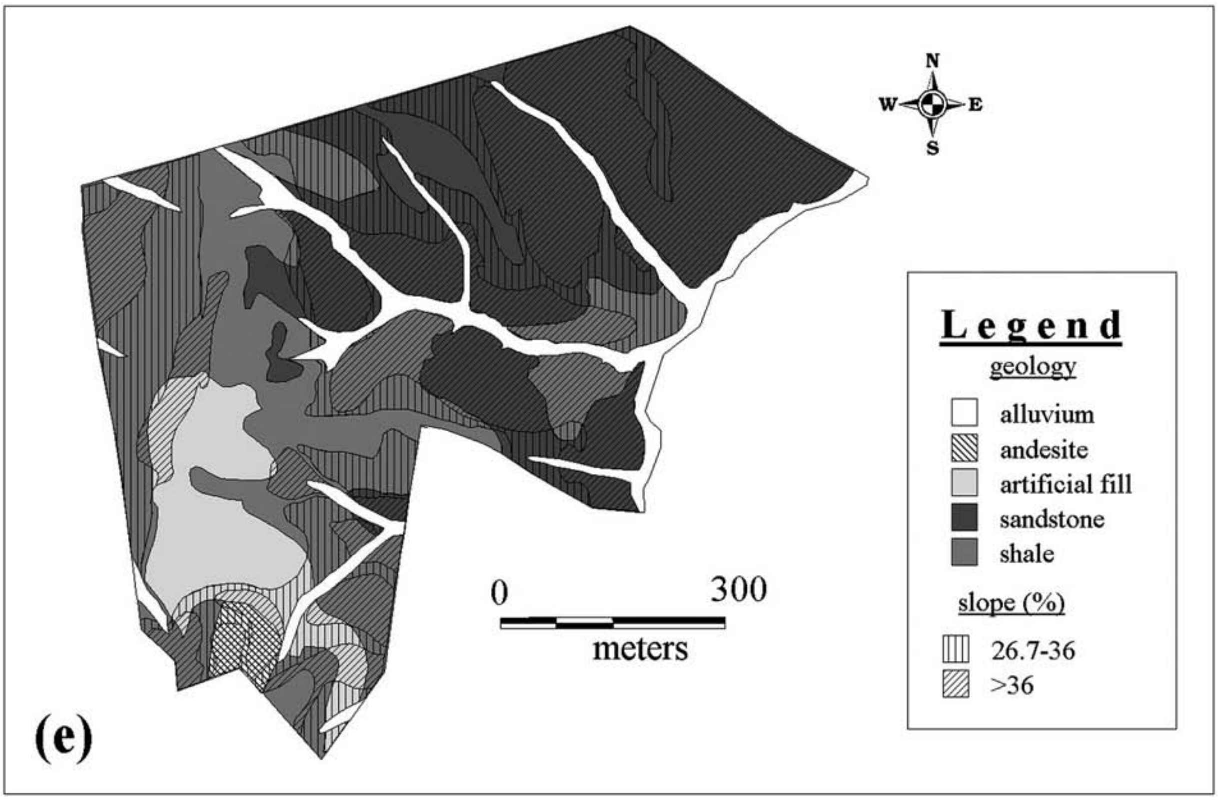


Fig. 3. Cont.
e: Overlaid map of geology and slope.

Relative quantification of suitability

After having prepared the above five hazard maps, the relative problematic character of each parameter involved was determined. This was done by giving risk points to zones with characteristics between specific values (Table 1). The more (potential) problems a specific characteristic yields, the more points have been attributed to it. In general, a characteristic that got more than 5 risk points should be considered as unsuitable or second choice. To give an impression of these 'boundary values', the following characteristics resulted in five or more risk points:

- lithology: shale, graphitic shale, artificial fills and slopewash;
- groundwater level at 0–4 m;
- slopes of over 20° ;
- S-wave velocity less than 400 $m{\cdot}s^{-1}$;
- maximum ground acceleration less than 0.11 $cm{\cdot}s^{-2}$;
- Poisson's ratio over 0.36;
- site amplification over 1.4;
- stream beds and buffer zones.

The risk points for the individual parameters have been added in the overlay analysis. If the total number of risk points found by this addition was between 13 and 18, the pertinent zones have been classified as second-choice zones in which soil improvement and reinforcement techniques should be applied to increase the bearing capacity of the soil and the stability of steep rock slopes. If the total number of risk points was less than 13, the pertinent zone was classified as suitable for settlement purposes. The zones with more than 18 risk points (by definition everywhere outside the zones mentioned above) were classified as unsuitable for settlement purposes. Thus, a final land-suitability map was obtained (Fig. 4). A computer program has been written in Q-basic language to determine the various zones in each hazard map. Minimally three parameters must be selected to run the program.

Conclusions

The land-suitability map for the Izmir Universiade Olympic Games village was prepared on the basis of five hazard maps. Critical areas (risk-point value >13) of each hazard map have been overlaid by MapInfo Professional 7.5 GIS software to obtain this land-use map. A computer programme was written in Q-Basic language in order to determine the suitable and the second-choice areas. The zones on the land-suitability map that indicate suitability for the construction of the buildings to house the Olympiade participants cover a surface area of 0.32708 km^2, which is 61.85% of the entire area. The second-choice zones cover a surface area of 0.1195 km^2, which is 22.60% of the entire area, and unsuitable areas cover 0.0822 km^2, which is 15.55%. The great detail in which the designated area for the Olympic Village could be subdivided into suitable, second-choice and unsuitable zones for construction activities results from the preparation of GIS-based maps at the uncommonly large scale of 1:1000.

Obviously, the procedure followed for the preparation of this map depended entirely of (1) the purposes of the study (assessment of the suitability of the study area – or parts of it – for the construction of buildings of a previously established size and number of floors) and (2) the local conditions. Consequently, the procedure followed for this study cannot be applied universally: the choice of parameters to be investigated (both in the field and in calculations) should depend on both aspects. In many cases, however, the procedure followed here, working at a 1:1000 scale, will provide a sound basis for decisions about measures that should be taken to avoid catastrophic events due to an insufficient engineering-geological evaluation.

Table 1. Risk points given for the various database layers.

peak ground acceleration		wave velocity		site amplification		Poisson's ratio		groundwater level (m)		geological map		slope-zoning map (%)	
a_{max} ($cm \cdot s^{-2}$)	risk points	V_s ($m \cdot s^{-1}$)	risk points	(A)	risk points	$\nu = V_p / V_s$	risk points	GWL	risk points	GM	risk points	SM	risk points
-	-	-	-	0.98<A≤1.02	1	0.04<ν≤0.12	1	10<GWL	1	-	-		-
a_{max}> 0.13	2	600<V_s≤700	2	1.02<A≤1.06	2	0.12<ν≤0.20	2	8< GWL ≤10	2	sandstone	2	SM≤8.7%	2
0.12<a_{max}≤0.13	3	500<V_s≤600	3	1.06<A≤1.10	3	0.20<ν≤0.28	3	6< GWL ≤ 8	3	andesite	3	8.7%<SM≤17.6%	4
0.11<a_{max}≤0.12	4	400<V_s≤500	4	1.10<A≤1.14	4	0.28<ν≤0.36	4	4< GWL ≤ 6	4	shale	4	17.6%<SM≤26.7%	6
0.10<a_{max}≤0.11	5	300<V_s≤400	5	1.14<A≤1.18	5	0.36<ν≤0.44	5	2< GWL ≤ 4	5	slopewash	5	26.7%<SM≤36%	8
0.09<a_{max}≤0.10	6	200<V_s≤300	6	1.18<A≤1.22	6	0.44<ν	6	GWL ≤ 2	6	artificial fill	6		
-	-	-	--	-	-	-	-	-	-	graphitic shale	8	36%≤SM	11

Hazard map no	*overlay combination*	*Hazard map no*	*overlay combination*
Hazard map I	groundwater + ν + geology	Hazard map IV	groundwater + elevation + graphitic shale
Hazard map II	V_s + a_{max} + (A)	Hazard map V	geology + slope + elevation
Hazard map III	a_{max} + (A) + graphitic shale		

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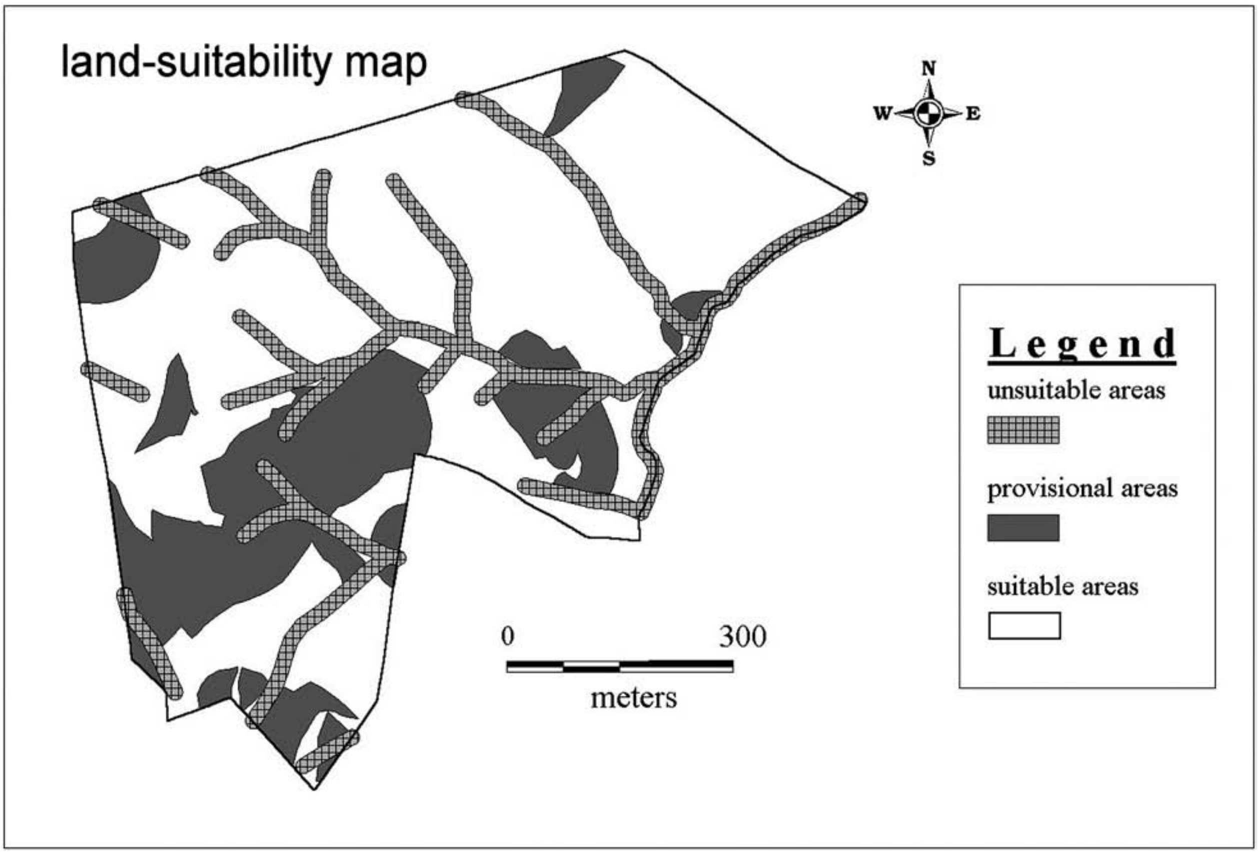

Fig. 4. Land-use map obtained as a result of overlay functions in GIS.

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