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Landslide danger assessment of large-scale natural slopes – a GIS based approach

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Abstract: This paper presents a GIS based methodological approach for landslide danger assessment, applied to the coast of Dakar. By the combination of analysis, interpretation, and evaluation of geo-morphological, geological and geotechnical data utilizing GIS, valuable results were gained regarding instability factors, slide kinematics, simulation of slope failure and coast dynamics. This led to a thorough assessment and strong reduction of the subjectivity in the slope stability and hazard analysis and to the development of an objective landslide danger map of the SW coast of Dakar. Analysis of the results shows that the slides were influenced by the geotechnical properties of the soil, the weathering, the hydrogeological situation and erosion by waves. The hazard analysis based on this methodological approach has allowed an appropriate and adequate consideration of the multiple factors affecting the stability, the optimization of planning and investment for land development in the city and the elaboration of stabilization measures according to the instability factors.

Résumé: Ce papier présente une approche méthodique d'évaluation et d'analyse les dangers de glissement de terrain basée sur le GIS. Cette approche a été appliquée à la côte de Dakar. L'utilisation de GIS a permis une interprétation, une évaluation et une analyse combinées des données géomorphologiques, géologiques et géotechniques. Ceci a permis d'obtenir d'importants résultats. Ces derniers concernent les facteurs d'instabilité, la cinématique des glissements, la simulation de la rupture des versants naturels et la dynamique de la côte. Cela a conduit à une évaluation minutieuse et à une réduction substantielle de la part de subjectivité dans l'analyse de la stabilité, et aussi à un développement d'une carte de dangers de glissement de terrain de la côte SW de Dakar. L'analyse des résultats montre que la stabilité des versants est influencée par les propriétés géotechniques des sols, l'érosion, les conditions hydrogéologiques et l'érosion par les vagues. L'analyse de la stabilité de versants naturels, basée sur cette approche méthodique, a permis une considération appropriée et adéquate des multiples facteurs affectant la stabilité. Elle a également servi à l'optimisation de la planification et de l'investissement pour l'aménagement des terrains de la ville et à l'élaboration de mesures de stabilisation des versants en tenant compte des les facteurs d'instabilité.

Keyword : Landslide, GIS, Modeling, stability, DTM, Dakar.

INTRODUCTION

Rapid urbanisation and population growth in Dakar are placing increasing development pressure on the available space and, as the more favourable areas are occupied, marginal land such as that on or adjacent to coastal slopes is being developed. The coastal area was avoided in the past because of the exposure to natural hazards like landslides and erosion of the cliffs.

In the context of increasing demands from the population of Dakar for protection against natural catastrophes, particularly coastal landslides, hazard mapping is a valuable assistance tool in decision making. However, it is well known that landslides are often the result of the temporal conjunction of several factors like geological, soil or rock mechanics, hydrogeological, climatic and anthropogenic factors. This means that the difficulties of the stability analysis of natural slopes, particularly coastal cliffs, the survey and study of landslides-endangered areas, the assessment of the causes of slope failures, the evaluation of the landslide hazards as well as the elaboration of stabilization measures are very delicate and complex. Considering the complexity of this problem, only a multi-disciplinary approach for the analysis of this process can deliver satisfactory results in terms of stability analysis and hazard assessment. For this reason, research programs were carried out by the above authors to develop a multidisciplinary approach for landslide danger analysis and mapping and its application to the coastal cliffs in south-western Dakar. This multi-disciplinary approach is based on geological, geotechnical field and laboratory, numerical as well as GIS-analysis methods. The current paper presents the results of the GIS-based landslide danger assessment. The whole multidisciplinary approach, the detailed geotechnical investigations and the results of the discontinuous modeling of the stability of the natural slopes are presented elsewhere (Fall 2000, Fall & Azzam 2000a,b, Fall & Azzam 2001).

METHODOLOGY

Figure 1 shows the developed multidisciplinary analysis methodology for the stability and landslide danger as well as the relationship between the different work steps of the investigations carried out. The method presented includes four main stages.

The first stage includes field and laboratory investigations. Whilst the field investigations dealt with the study of the geological, geotechnical features of the study region, the laboratory investigations were performed with the aim to study the geotechnical behaviour of the soils and rocks present at field regarding the slopes stability. Extensive field and laboratory investigations have allowed the collection of a wide spectrum of data and information regarding the geology, hydrogeology, engineering geology of the study area, the mechanical behaviour of the soils/rocks and the stability of the slopes. The analysis of these data has generated important information on the instability factors that allows a qualitative judgment of the stability of the slopes in the study area. The results of these field and laboratory study were then depicted on topographic maps in large scale (1/500, 1/1000) to develop analog geological, geotechnical, hydrogeological, landslide maps for the study region. All the data obtained from this first stage were then used as input data for the GIS-analysis (i.e. second part).

In the second stage (GIS-stage) of this study, the developed maps were digitized. Thereafter, the digitized data were tested for geometrical imprecision as well as for semantic wrong classifications, and also for their wholeness before their implementation (Fall 2000).

This information combined with elevation data from the digitized topographic maps and large scale aerial photos (1/500, 1/1000) of different ages (1953, 1961, 1981) were stored in a GIS database. To facilitate the data processing and in particular map overlay operations, all the data, stored as ARC/INFO files, were first converted from vector to raster structure and then transferred to a raster-based GIS (ArcView) for subsequent analysis. Thus, integration and a conjunction of the elevation data with the data from field and laboratory investigations have been achieved. The use of GIS-methods allowed a combined evaluation and analysis of the elevation and spatial data, and the results of field and laboratory investigations. The obtained results are related to instability factors, slide kinematics, simulation of slope failure, coast erosion, spatial development of the instable areas and slide mechanisms. The use of GIS has also allowed the identification of old and actual landslides zones in an economic and efficient way.

In the third phase of the study, the stability of the natural slopes that are not affected by instability processes was studied by mean of deterministic analysis and/or numerical modeling. This allowed the quantification of the stability factor or state of these slopes. The results of the stability analysis were then reported on map and integrated into the GIS-system.

Finally, in the last stage of the study, all data derived from field and laboratory investigation, from GIS analysis, and deterministic and numerical stability analysis were integrated and analysed. This led to the development of an objective landslide danger map of the SW coast of Dakar.

This paper is focussing more on the presentation of results of the GIS-based stability analysis. The results of geotechnical field and laboratory field investigation as well as the results of the deterministic and numerical stability analysis are presented elsewhere (Fall 2000, Fall & Azzam 2000a, Fall & Azzam 2001)

DESCRIPTION OF THE STUDY AREA

The investigated region is located on the southwestern coast of Dakar (Senegal). The geology of this region is marked by a long period of volcanism from Tertiary to Quaternary, and by cycles of transgression/regression of the Atlantic Ocean (figure 2). Therefore, the ground and the slopes of south-western Dakar were predominantly built of volcanic materials, sedimentary rock or soils. Hence, five rock types have been identified in the study region. These are loam, limestone, laterite, volcanic tuffs (coarse-grained and fine-grained) and basalt. The outcrops of limestone can only be found at the base of the loam slopes, while the laterite builds crust at the top of the slopes. These materials have been exposed at the coast of Dakar over a long period of geological time, so that they present many signs of weathering (particularly the volcanic tuffs).

The detailed geological survey, based on field and laboratory investigations provided primary information on the discontinuity and the mineral composition of the different rocks. The basalts have a significant joint system and display unstable blocks at coastal cliff crests. The loam and volcanic rock slopes do not show any significant joint systems. Details about the geology of the study area are given in Belion 1980, Dia 1980, Elouard 1980, Fall et al. 1996, Fall 2000.

Regarding climatic conditions, the study region belongs to the Sudanese-Sahel climatic zone. It is characterized by two main seasons: dry season (October to May) with an average temperature of 18°c to 25°c, and a rainy season (June to September) with average temperature between 30°C and 35°C. The rainfall is often stormy and consequently leads to soils erosion. Mean annual rainfall over the period 1960–1970 is in the range of 500 to 900 mm. While over the period 1970 to 1994 the mean annual rainfall is only in the range of 300 to 600 mm (Fall, 2000).

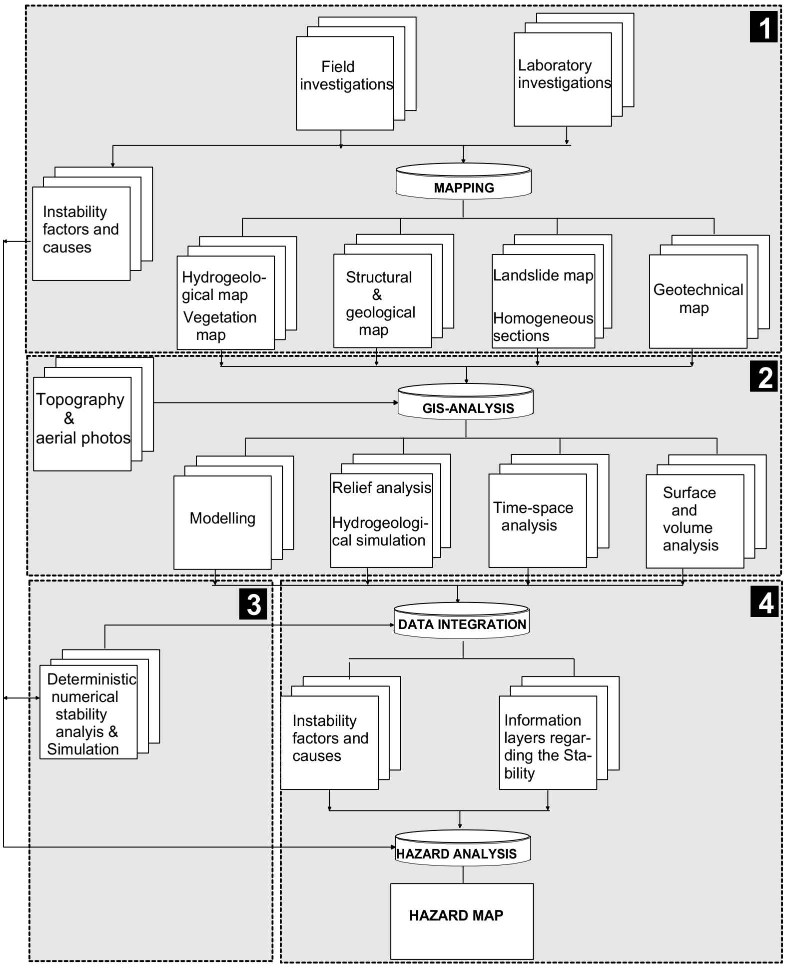


Figure 1. Methodology for the stability analysis: 1, 2, 3, 4 represent different stages of the study

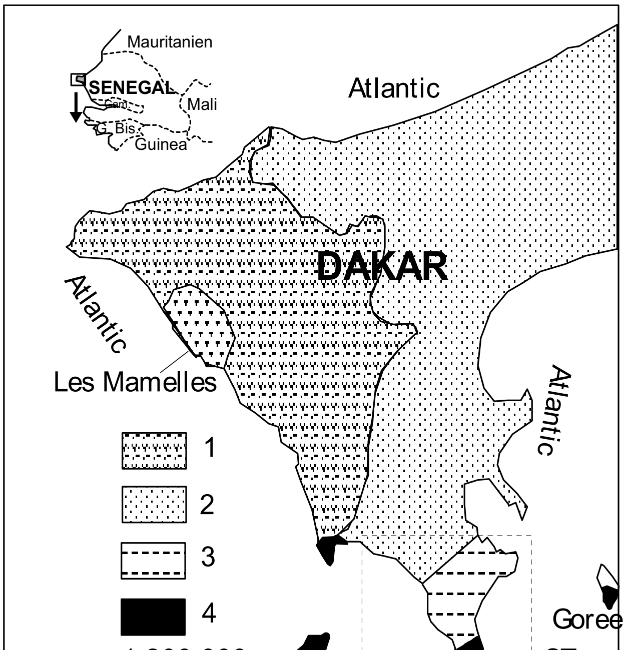


Figure 2. Location and geology of the study area (ST)

1 Volcanic Quaternary; 2 Sedimentary Quaternary; 3 Sedimentary Tertiary; 4 Volcanic Tertiary.

RESULTS OF THE GEOTECHNICAL FIELD INVESTIGATIONS

The geotechnical field investigations carried out were based on the combination of different methods. A geomechanical classification of the rock (basalt) slopes in relation to their stability was carried out along with field landslide mapping. Weathering and its impact on the slopes stability, as well as the affects of sea erosion on the slope's stability were also studied. The hydrogeological condition of the study area was also determined. Then, the combined analysis of the results obtained from the different geotechnical investigations or analysis allowed the description of the engineering geological, hydrogeological and soil and rock mechanics conditions at this coastal region with respect to slope stability or landslides. This also allowed the development of landslide, hydrogeological and engineering geological maps of the study region and the determination of some instability factors. Figure 3 shows the landslide map of the study area in 1997, and the main engineering geological features. Details of the geotechnical field investigation of the stability of the study area are given in Fall 2000, Fall & Azzam 2001.

Generally, the geotechnical field investigations carried out have permitted the identification of the following causes of instability:

- the unfavorable position or orientation of the discontinuities in the basalts. These strongly influence the development of block sliding and block toppling.
- The advanced weathering led to degradation of the geotechnical properties of the volcanic tuffs and to the disintegration of the basalts to soils at the top of the basalt cliffs.
- The undermining of the loam and basalt cliffs by wave erosion.

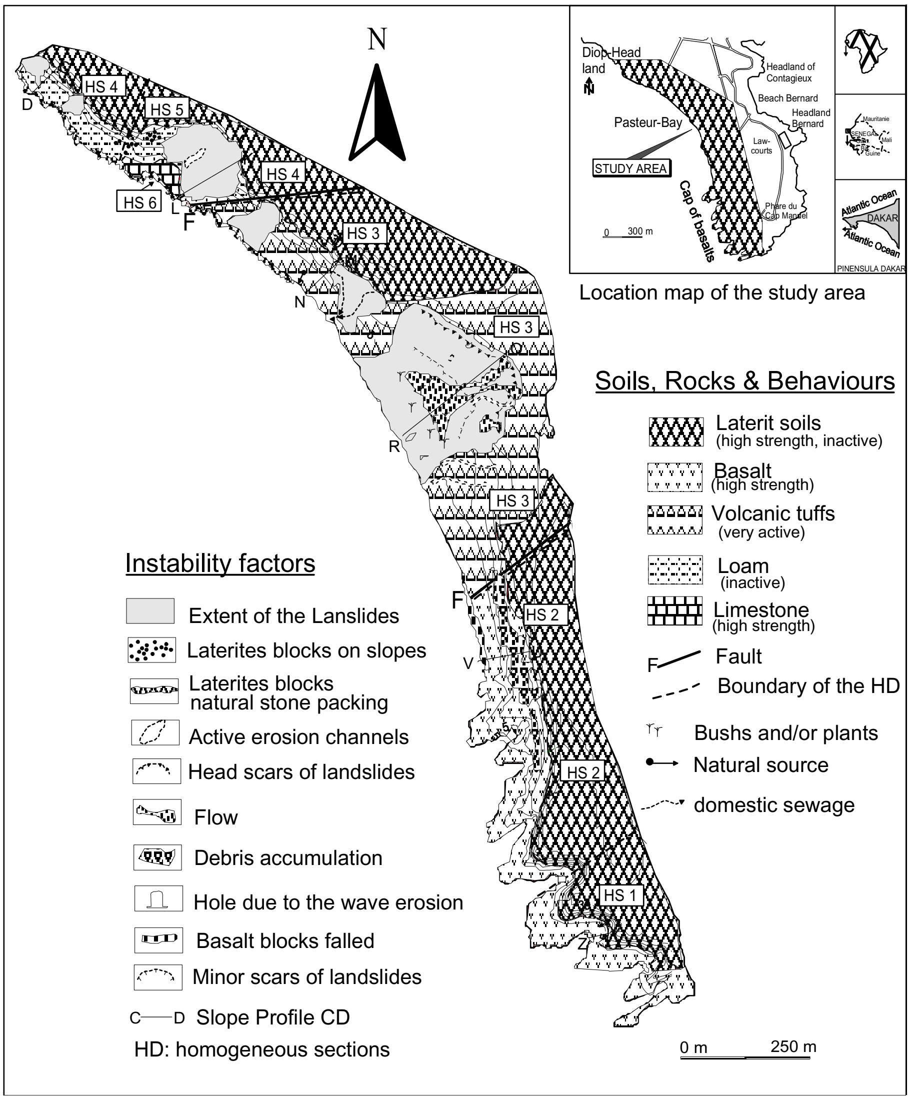


Figure 3. Landslide map and engineering geological conditions in the study area

However, although the geotechnical field investigations have allowed important information about the engineering geological, geomechanical and hydrogeological conditions of the study area to be obtained, and also the identification of some of the causes of instability, they did not enable a quantitative evaluation of the instability processes (landslides, sea erosion, cliff retreat, etc.) in terms of their temporal and spatial distribution and/or development. The data were not sufficient to clarify the historical development of the instability processes in the study area. Also it was not possible, with these geotechnical investigations, to determine the spatial distribution of the rainwater as well as the influence of the hydrogeological conditions on the slope stability. Hence, the GIS methods, presented in section 6, were used to solve the above issues as well as to thoroughly analyse all the instability factors.

RESULTS OF THE GEOTECHNICAL LABORATORY INVESTIGATIONS

The results of laboratory tests describing the geotechnical properties of the soils of the study area are presented in this section. The evaluation of these results provides the precise description of the quality of these soils (regarding slope stability or landslide susceptibility), and consequently allows a geotechnical judgment, as well as analysis of the possible instability processes in the study area, or the ability of old landslides to be reactivated.

To reach the above mentioned objectives, extensive soil mechanics laboratory tests have been performed in order to obtain information about the geotechnical behaviour of the soils. The main results of the geotechnical laboratory investigations are summarized in table 1, figures 4 to 6, and given in Fall 2000, Fall & Azzam 2000, Fall & Azzam 2001.

The results of X-Ray analysis have shown that the volcanic tuffs are rich in montmorillonite, whereas the loam and laterite soils contain mainly kaolinite clays. The different nature and content of clay minerals in these soils strongly influence their activity (figure 4) and consequently their mechanical behaviour (figure 5 and 6).

Indeed, the results of the laboratory tests conducted on the volcanic tuffs have shown that these tuffs, which contain montmorillonite as the clay mineral display high plasticity, activity (Fall 2000, Fall & Azzam 2000b) and ability to absorb water. Their shear strength is low and not favorable for slope stability (table 1, Fall 2000, Fall & Azzam 2000b). A large shear displacement (20 to 28 cm) was necessary to reach the residual state of the volcanic tuffs (Fall 2000, Fall & Azzam 2000b). This is coupled with an important fall of the peak shear strength to the residual strength (brittleness index I_B~ 50 to 70%; I_B calculated according to Bishop 1967). This is caused by the strong reorientation of the montmorillonite particles by large shear displacement. Hence, the presence of montmorillonite in the volcanic tuffs increases the risk for slope instability. It was observed in the field that cliff sections where such clays are predominant, like the volcanic tuffs, are more affected by landslides than others. The slide mechanism appears to be progressive, since a major reduction of the peak shear strength to a very low residual value occurs during the movement and the infiltration of water into the slope during the rainy season causes a general drop of the shear strength. Due to their low residual shear strength, the reactivation of relict landslide in the volcanic tuffs will be easy.

In contrast to the volcanic tuffs, the loam and laterite soils show low plasticity, low activity (Fall 2000, Fall & Azzam 2000b) and low ability to water absorption as well as higher shear strength values because of the absence of swelling clay minerals. These materials (loam, laterite soils) are also characterized by a relatively low brittleness index (I_B~5-15%) and a short shear displacement to reach the residual shear strength (figure 6, table 1). The latter is also relatively high (28 to 32°). This high residual shear strength is not favorable for an eventual reactivation of loam material affected by landslides.

In conclusion, the results of geotechnical laboratory tests and analyses of the properties of the soils present in the study area suggest that the clay mineral composition of these soils exert a profound influence on the physical and mechanical properties of these materials, which in turn affects the susceptibility to slide and also the susceptibility of reactivating old landslide areas. The results of this study have allowed the classification of the volcanic tuffs as liable to slide and the loam and laterite soils are not liable to slide (table 1). These results are reported on an analog map, then digitized and finally implemented in the GIS-system.

Table 1. View on some geotechnical properties of the soils present in the study area.

		Loam	**Volc. tuffs, coarse**	**Volc. tuffs, fine**	**Laterite soils**
present clay mineral	*no swelling*	kaolinite	traces	traces	kaolinite
	swelling	no	montmorillonite	montmorillonite	no
Soil mechanical behaviours	*plasticity*	not plastic	plastic	plastic	not plastic
	activity	not active	active	very active	normal
	water absorption	mean	high	high	low
Shear strength	φ*(°)	30,9	25,4	19,5	34,9
	φ_r*(°)	28,7	10,2	8,1	32
	Peak dec.(%)	23	35	62	-
	S. R. (%)	11	52	68	11
Judgment regarding the susceptibility to slide		not liable to slide	liable to slide	very liable to slide	not liable to slide

v.: volcanic; *Results from Ring shear test; Peak decrease: decreasing of the peak strength by infiltration of water into the slope during the raining season; S.R.: Strength reduction from peak to residual

GIS-BASED STABILITY ANALYSIS

Figure 4 gives an overview of the different primary information layers, and the different analysis methods used for the GIS-stability analysis. It shows also the different presentation forms of the results. The primary information or data layers in the GIS-database are divided into geometry and attributes data. Ten primary layers of information have been used in the present analysis. As shown in figures 1 and 4, these layers include geology information (lithology, structural geology), relief data (elevation in years 1953, 1961, 1981), landslides information (landslide map in year 1997), vegetation data (distribution of the vegetation in the study area), hydrogeological data (groundwater level, natural and domestic source, etc.), the geotechnical soils map (soils with their geotechnical properties, different homogenous sections determined). The attributed data included: the type and geotechnical properties of the soils and rocks, the weathering degree of these materials, the type of vegetation, etc. The digital relief analysis, mapping, surface overlaying and intersection, computation of surface and curvatures or volume, and statistical analysis are the most important methods used in the present GIS-based stability analysis.

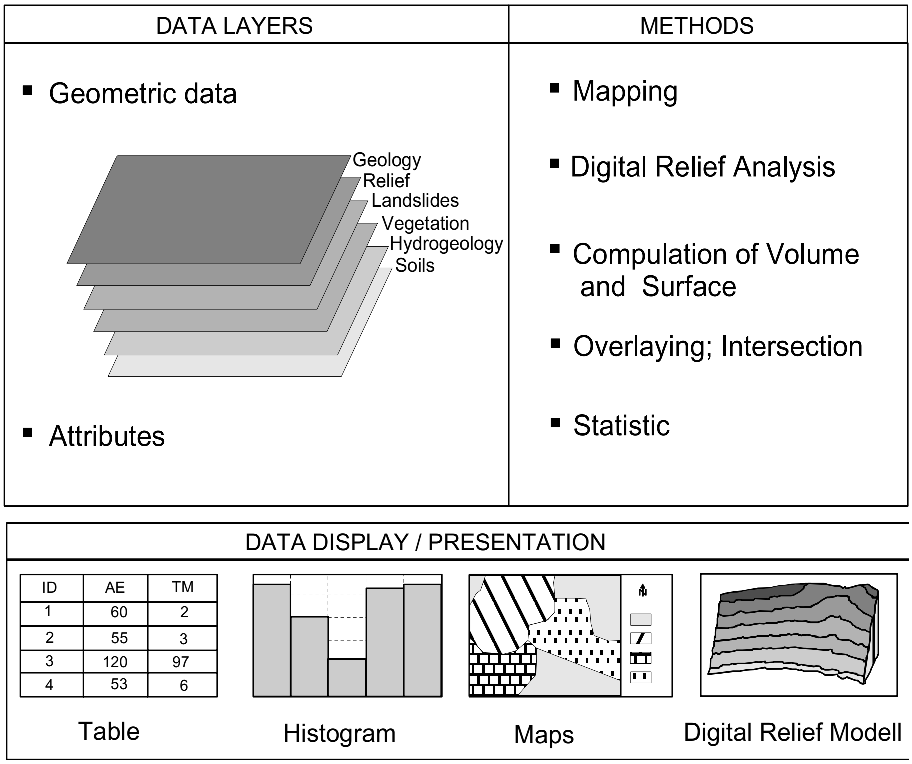


Figure 4. Flowchart of landslide hazard analyses based on GIS methods.

The use of GIS-methods allowed a combined evaluation and analysis of the spatial data and the results of geological, geotechnical and hydrogeological investigations. This has enabled valuable information to be gained regarding the stability of the study areas. Indeed, the use of GIS has allowed us to:

- qualitatively and quantitatively evaluate the instability processes in their temporal and spatial distribution or development;
- analyse and quantify the historical development of the landslides areas;
- study the relationship between the hydrogeological conditions in the study region and the development of instability process;
- study the relationship between landslides and the geotechnical properties of the soils or rocks present in the study;
- quantify the erosion by the sea wave.

The main results of this GIS analysis are presented in the following sections. More detailed results are given in Fall 2000.

Geomorphological evolution of the study area

In order to analyse the geomorphological evolution of the slopes, three-dimensional modeling of the relief of the study area was performed. This led to the development of 2 m gridded Digital Terrain Models (DTM) of the study region in the years 1953, 1961 and 1981. Figures 5 and 6 show the DTM of the study area in the years 1953 and 1981. These figures puts demonstrate that landslides have caused significant changes of the relief at the Pasteur bay (outcrop of volcanic tuffs) and Camp Dial Diop (outcrop of loam slopes).

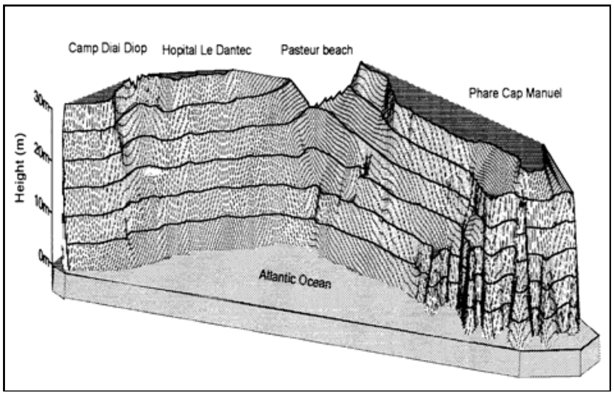


Figure 5. DTM of the study area in year 1953.

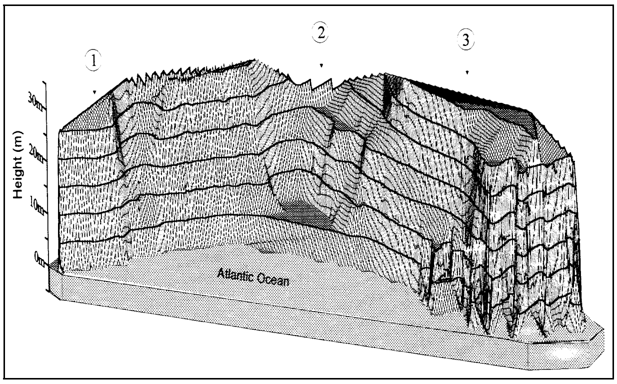


Figure 6. DTM of the study area in year 1981

1 Cliff fall and transport of the slid mass by the sea; 2 Slides and building of accumulation zone at the slope base; 3 Region developed for settlement; no visible morphological changes of the basalt cliffs.

Slope and cliff retreat

In order to quantitatively evaluate the retreat of the slopes or cliffs in the study area because of the occurred instability processes, morphometric data were derived from the DTM of different ages. This has allowed a reconstruction of the slope profiles before and after the landslides. The comparison of the reconstructed slope profiles of different ages led to the determination of the average cliff recession in the corresponding period. Figure 7 shows, the methods used for the modeling of the slope or cliff retreat, while some results of the analysis of the cliff recession are summarized in figure 8. It was demonstrated that the tuff slopes have retreated 10 to 60 m between 1953 and 1981. This is in accordance with the poor geotechnical properties of the volcanic tuffs. The recession of the loam cliffs in this period was 10 to 20 m. The basalt cliffs show the lowest recession because of their high strength.

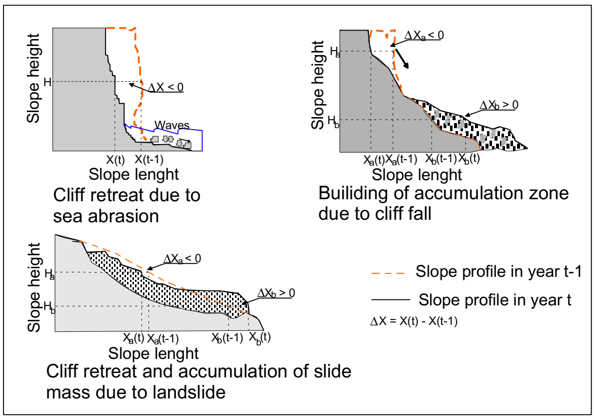


Figure 7. Principles and methods used to model the slope or cliff retreat.

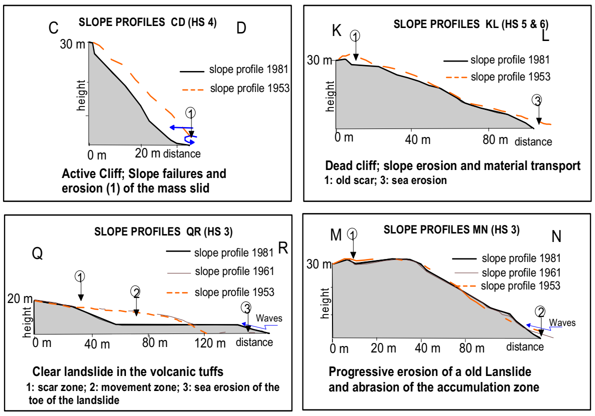


Figure 8. Example of sequential changes of the slope profiles at the study area (HS: homogeneous sections, see figure 3).

Reconstruction of the historical landslides areas

In order to define and judge the spatial development of the landslide areas in the study region, historical landslide maps were reconstructed comprising the pre-dimensions and pre-location of the sliding areas and the slope movement types. Figure 9 shows the used method for the reconstruction of the historical landslides area. This reconstruction is based on the numerical calculation of the variation of the elevation data of the study area from 1953 to 1981 (figure 9). Thus, by means of the digital elevation data of this coastal region in the years 1953, 1961 and 1981, the relief variation and level difference ($\Delta H = \Delta Z$) between 1953 and 1961 as well as between 1961 and 1981 were computed. The variation and the landslides that occurred during the corresponding period were visualized and mapped. The results show that almost no slope movements occurred in the volcanic tuffs between 1953 and 1961, whilst the loam cliffs show falls and toe erosion due to wave activity. Only after 1961 did large slope movements occur in the volcanic tuffs. These slides were later reactivated by subsequent erosion and debris flows. This is shown by figure 10, which represents a digitally reconstructed landslide map of the study area for the year 1981.

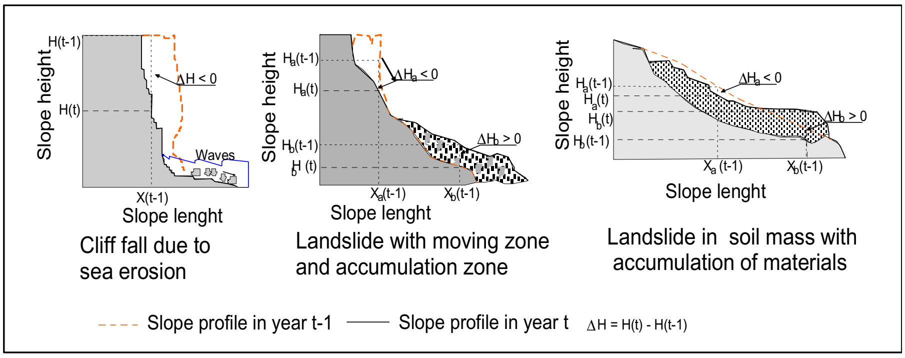


Figure 9. Principles and method used for the reconstruction of the historical landslide zones in the study area.

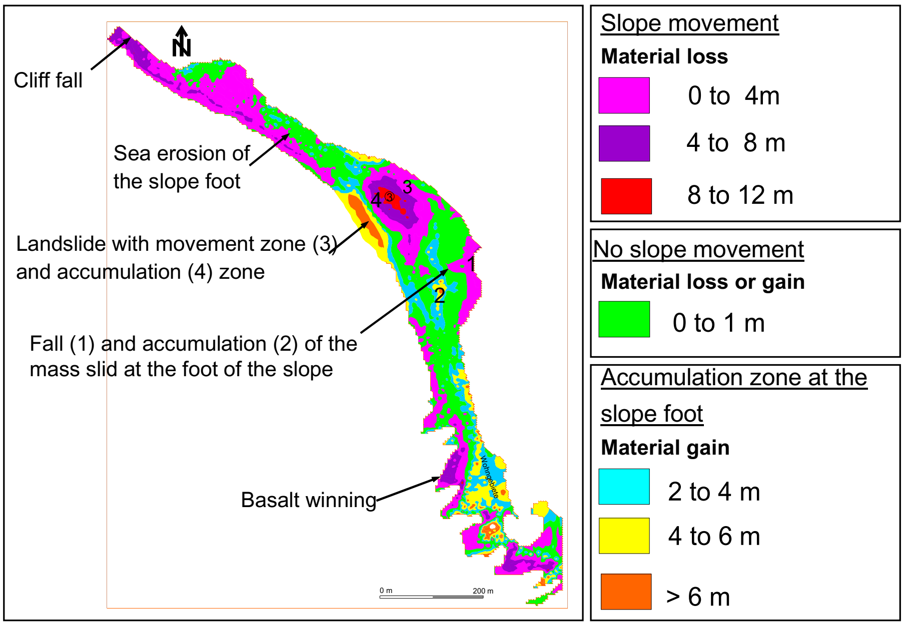


Figure 10. Digital reconstructed landslide map of the study area for the year 1981.

Relationship between landslides and hydrological conditions

According to the hydrogeological investigations carried out, groundwater is only present at the northern part of the homogenous section 3 (figure 3) and its level is deep. A high fluctuation of the groundwater level is unlikely due to the low rainfall. But the surface flow of rainwater can have serious consequence on the stability of the slopes in the study area (e.g. tuffs have a high water absorption capacity). Hence, in order to analyse the relationship between the hydrological conditions and the development of slope movements, the flow direction of surface or rain water and its converging zones were computed and determined. For the modeling of the flow direction of the surface water, the terrain gradients, the slope dip and the elevation differences were used as basic parameters. These parameters are derived from the computed DTM of the coastal region. The obtained results demonstrate and emphasize a clear correlation between the flow direction of the rain water and the development of slope movements or landslide areas, particularly in tuff slopes (figure 11). This can be explained by the fact that the infiltration of the surface water into expansive soils such as tuffs leads to a significant decrease of the shear strength as demonstrated by the geotechnical laboratory investigations (table 1, Fall 2000).

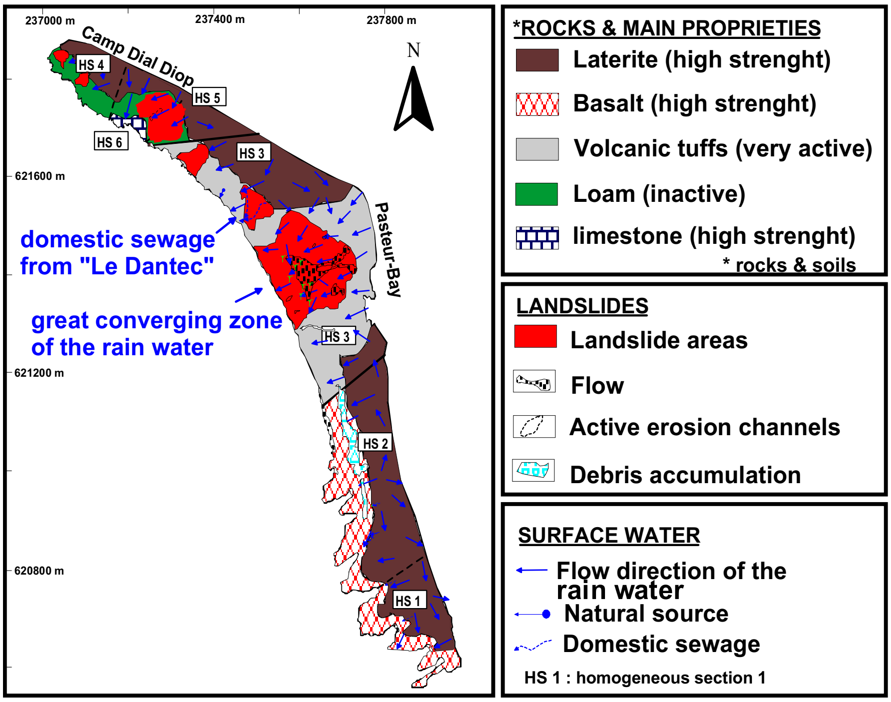
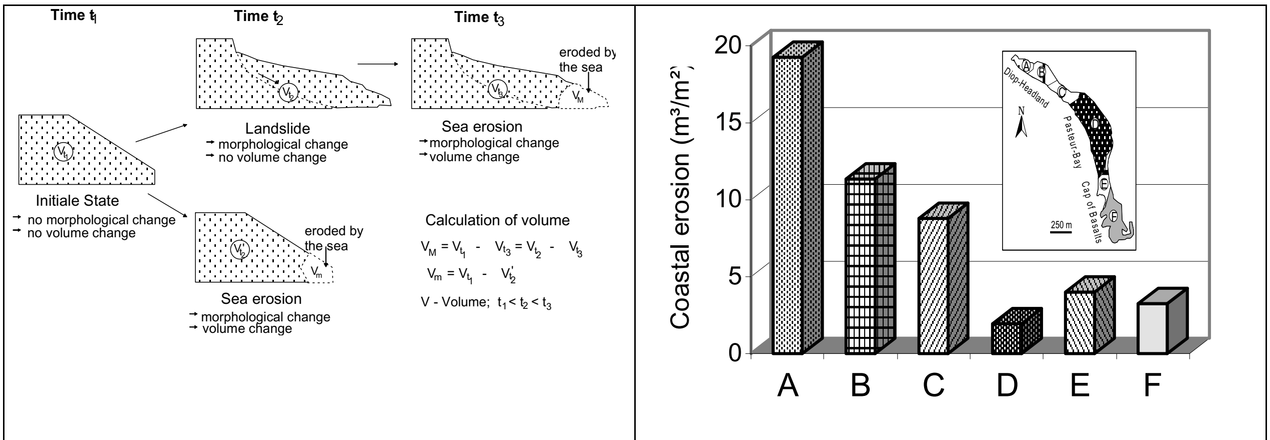


Figure 11. Visualisation of the relationship between landslides areas and the hydrological conditions in the study area.

Sea erosion

The effects of sea waves at this coastal region can be particularly severe. Wave impact causes toe erosion and removal of previous failure material leading to retrogressive erosion of the whole cliff profile (figures 3, 6). The utilization of the computed DTM for this coastal region from 1953 and 1981 allows the calculation of the cubature changes of the slopes. This also gives a quantitative analysis of the toe erosion, the estimation of the denudation effects, and the material transport due to the coastal erosion.



a-Principles and methodology

b- Soil erosion by the waves

Figure 12. Quantitative evaluation of the sea erosion at the coast Dakar from 1953 till 1981.

Figure 12-a shows the methodology for the quantitative evaluation of the sea erosion in the study area, while the results of this analysis are summarized in figure 12-b. The latter demonstrates that the wave activity has a destructive effect on the stability of the loam cliffs. The material erosion due to the wave activity at the Diop-headland which is developed in the loam is more important than soil erosion in the bay of Pasteur where the volcanic tuffs outcrop. The basalt cliffs are little affected by coastal erosion, because of their high strength.

Relationship between soils properties and landslides

In order to evaluate the temporal expansion of the instable areas in the study region as a function of the geotechnical properties of the soils, the percentage ratio of the unstable areas was derived for every soil type unit as a weighted summation of the landslide areas existing in the unit compared to the whole unit area (figure 13). The obtained results (figure 14) permit the susceptibility to slide of the different materials to be assessed. This study led to the following main conclusions:

- Because of their unfavorable geotechnical properties, the volcanic tuffs should be characterized as very susceptible to sliding. They show an average expansion of their unstable areas of 29 % per year between 1951 and 1961 and of 1,6 % per year between 1981 and 1997.
- The loam should be considered as not susceptible to slides but to cliff falls and wave erosion. The annual expansion of the unstable areas in the loam amounts only to 0,3 to 0,4 %, since the instability mechanism here is not the expansion of instable areas, but the loss of land.
- The enlargement of unstable area in the basalt is insignificant.

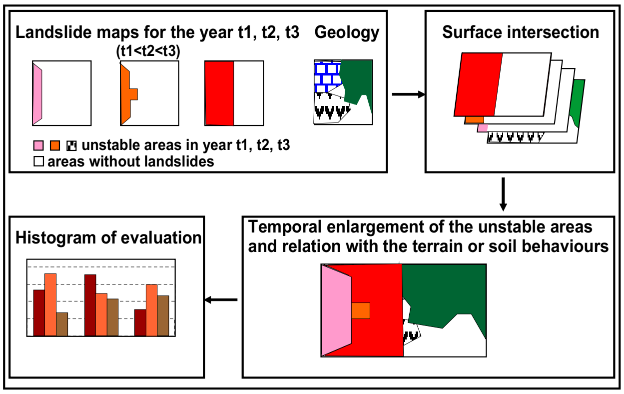


Figure 16. Principles and methodology for the evaluation of the time- and material-dependent expansion of the unstable zones in the study area.

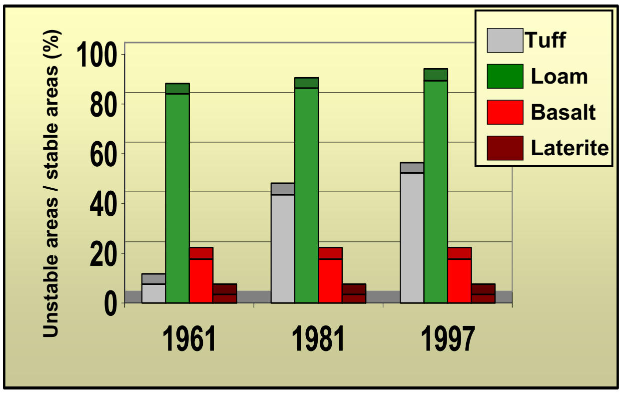


Figure 17. Time and material-dependent expansion of the unstable zones in the study area.

*slide area **1961 is compared with 1953

In conclusion, this GIS-based analysis of the stability of the study area has demonstrated that several slope movements occurred in this coastal region from 1953 to 1997. The main causes of the slope failures are the geotechnical behaviours of the soils, the hydrological conditions (rain water, domestic sewage) and the destructive and erosive activity of sea waves. The wave activity leads to cliff recession, excavation and sliding as well as to material transport away from the toe.

STABILITY CALCULATION AND LANDSLIDE DANGER MAP

Stability analysis and calculation

The field and laboratory investigations as well as the GIS-based stability analysis have enabled the analysis of the landslides that occurred in the study region. The slopes affected by landslides were classified as unstable. The stability of the slopes that are not affected by landslides was determined with limit equilibrium methods or discontinuous numerical modeling.

The limiting equilibrium method was used to calculate the factors of safety for the loam and tuff cliffs which are not affected by slope movement. Slope stability factors can be computed according to several deterministic methods. The latter can give relatively different values of safety factor. Hence, the safety factors of the loam and tuffs slopes were calculated according to four methods: Fellenius (1927), Janbu (1954), Morgernstern-Price (1965), and Bishop (1967). The corresponding potential failure surfaces were also determined. The potential failure surface with the lowest safety factor was considered as the most likely failure surface. The lowest calculated factor of safety was used to judge the stability state of the correspondent cliffs. The factor of safety calculations have indicated that almost all slopes which are not presently affected by slope movements, are relatively stable. Only some cliffs in the northern part of the study area should be considered as potentially unstable, because their lowest factor of safety is between 0.8 and 1.0. But the stability of the cliffs in the northern part of the study area may be influenced by groundwater levels. The stability analysis shows that a 10 m higher groundwater level has significant effects on the stability of the cliffs in this section.

In order to analyse, calculate and evaluate the deformation and the stability of the basalt cliffs, analytical and numerical stability analyses were carried out. The analytical calculations are based on the limit equilibrium method. The factors of safety of the potential sliding and toppling blocks, identified by the geomechanical classification and geostatistical analysis of the failure mechanisms, were calculated. A parametric analysis was also performed to evaluate the sensitivity of the safety factor to variations in unit weight, strength parameters, hydrostatic pressure and block size. Generally, the results of this analysis method show that the basalt cliffs should be considered as stable. Only during the rainy season, very small wedges and topple blocks, located at the top of the basalt cliffs may become active.

For mathematical modeling of the basalt cliffs a distinct element model (DEM) with completely deformable blocks has been performed using the UDEC code (Hart & Cundall, 1992). Using discontinuous modeling this allowed the stress distribution to be analysed along with the stability conditions of these cliffs. In addition these analyses simulated the failures mechanisms as well as the stability of the cliff cave (located in HS 2, figure 3) formed by destructive wave activity. Sensitivity analyses on critical input parameters, such as discontinuity shear strength, stiffness, and geometry were performed to assess their influence on the model behavior. The obtained results generally show that the basalt cliffs are stable. The discontinuities and their shear strength parameters highly influence the stability. The hole caused by the wave impact and toe erosion results in unstable wedges in the cave side wall and the roof.

Landslide danger map

All results obtained from the computation of the safety factor were then integrated into the GIS-system. The combination of these results with those from field and laboratory works as well as from GIS-stability analysis, and the processing, integration and analysis of all the results have led to the development of a landslide hazard map of this region. On the danger zonation map, the terrains were classified according to the hazard level. The landslide hazard information is presented in formats that are accessible to non-specialist decision-makers. This facilitates planners and administrators to make correct decisions at the planning stage of a development project. The results of the landslide hazard map are presented in Fall 2000, Fall & Azzam 2001.

SUMMARY AND CONCLUSIONS

The goal of this work was the development of a multidisciplinary approach for landslide danger analysis and then to study the stability of the costal cliffs in Dakar (Senegal) as well as to develop a landslide danger map for this region. For this purpose the results of the field and laboratory work were analysed and then digitized for input into a GIS. The results of the field and laboratory investigations, and of the GIS analysis were then used to calculate and analysis the stability of slopes that are not affected by landslides. The integration of all results into the GIS system allowed the development of an objective danger map of the SW coast of Dakar. By using the developed methodological approach, valuable results were gained regarding instability factors, slide kinematics, simulation of slope failure and coast dynamics. This led to a thorough assessment and strong reduction of the subjectivity in the slope stability and hazard assessment. Of course, the result and numerical values are still influenced by the subjective nature of the original information. The analysis of the results shows that the slides were influenced by the geotechnical properties of the soil, the weathering, the hydrogeological situation and the erosion by the waves. However, it can be concluded that, the hazard analysis based on this multidisciplinary approach allows an appropriate and adequate consideration of the multiple factors affecting the stability, and consequently an objective and effective judgment of the stability of natural slopes.

REFERENCES

BELLION, Y. 1987. Histoire géodynamique post-paléozoïque de l'Afrique de l'Ouest. D'aprés l'étude de quelques bassins sédimentaires (Sénégal, Taoudenni, Iullemmeden, Tchad). Thèse doctorat es Sciences Univ. d'Avignon et des pays de Vaucluse, 222 pp.

BISHOP, A. W. 1967. Discussion Session 2. Shear strength of stiff clay, Geotechnical Conference, Olso.

DIA, A. 1980.Contribution à l'étude des caractéristiques pétrographiques, pétrochimiques et géotechniques des granulats basaltiques de la Presqu'île du Cap-Vert et du plateau de Thiés. Thèse 3e cycle Univ. Dakar, 183 pp.

ELOUARD 1980. Excursion géologique, sous-sol de Dakar. Labo Géo. Fac. Sc. Univ. Dakar, 2-12.

FALL, MAM, DIA, A., FALL, MEÏ., GBAGUIDI, I., LO, P.G., DIOP, I.N. 1996. Un cas d'instabilité de pente naturelle: le versant des Madeleines - Presqu'île de Dakar (Sénégal): Analyse, Cartographie des risques et prévention; *In international Journal of IAEGE* **53**. 29-38.

FALL, M 2000. Standsicherheitsanalyse der Küstenhänge in Cap Manuel (Dakar, Senegal) mit Hilfe ingenieurgeologisch-geotechnischer Untersuchungen und GIS-technologischer Methoden. *Journal Wiss. Mitt. des Institutes Für Geotechnik.*, Heft n° **2000-2**, 187 pp.

FALL, M. & AZZAM, R. 2000a. Ingenieurgeologische und numerische Standsicherheitsanalysen der Basaltkliffe in Dakar, *International Journal Felsbau*, n°1/2001, K 8266, 51-57.

FALL, M. & AZZAM, R. 2000b. Analyse der Stabilität der Küstenhänge in Dakar mit Hilfe GIS-technologischer Methoden. *Journal Wiss. Mitt. des Institutes für Geotechnik*, TU Freiberg, Germany, Heft 2000-1, 34-35.

FALL, M. & AZZAM, R. 2001. An example of multi-disciplinary approach to landslide assessment in coastal area. International Conference on Landslide. *In proceedings International Conference on Landslides: Causes, Impacts and Countermeasures*, June 17-21, Davos, Switzerland.

FELLENIUS, W. 1927. Erdstatische Berechnungen mit Reibung und Kohesion. Ernest Verlag, Berlin.

HART, R. D., CUNDALL, P., A. 1992. Microcomputer programs for explicit numerical analysis in geotechnical engineering. *Proc. Int. Sem. Num. Methods in Geom.*, Moscow.

JANBU, N. 1954. Stability analysis of slopes with dimensionless parameters. *Harvard Soil Mechanics Series*, **46**, 81 S., Harvard.

MORGENSTERN, N.R. , PRICE, V.E. 1965. The analysis of the stability of general slip surfaces. *Geotechnique* **15**, n°1, pp. 79-93.

SKEMPTON, A. W. 1953. The colloidal activity of clays. In: Proc. ICSMGF, Zürich 1953.