

Application of Soil Mechanical Response Units (SMRU) in regional landslide hazard assessment

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with 4 figures and 2 tables

Summary. Traditional landslide hazard mapping approaches combine basic input variables such as lithology, vegetation, morphometric characteristics (slope, curvature, etc) with measures of probability of landslide occurrence. This study defines and describes *Soil Mechanical Response Units* (SMRU) for use as input parameters and is thus a combined heuristic and soil mechanical approach to landslide hazard assessment. SMRU's were delimited using a Geographical Information System (GIS) to combine equal geological and lithological characteristics. Their plausibility was tested in the field. Regolith samples were taken in the field for each SMRU, and subjected to direct shear testing to derive values of cohesion and angle of internal friction. These were used, in combination with morphometric parameters derived from a digital elevation model (20 m-resolution), to calculate Factors of Safety. These were used for regional landslide hazard analysis.

This approach has been tested at the northwestern Tertiary escarpment of Rheinhessen, Germany. In winter 1981/82 the test site (45 km²) experienced considerable damage caused by 42 landslides. Verification of the established hazard model was performed using these failures and shows the successful application of SMRU's and their use in regional landslide hazard modelling.

Zusammenfassung. Anwendung bodenmechanischer Reaktionseinheiten (SMRU) in der regionalen Bewertung von Hangrutschungsgefahren. Traditionelle Methoden der Gefahrenzonierung durch Hangrutschungen kombinieren Informationen der grundlegenden Eingangsvariablen (Lithologie, Vegetation, Geomorphometrie) mit wahrscheinlichkeitstheoretischen Modellen des Auftretens von Hangrutschungen. Die vorliegende Untersuchung definiert und beschreibt bodenmechanische Raumeinheiten (SMRU) als Eingangsparameter und kombiniert heuristische Modelle mit bodenmechanischen Modellen. Die BMRE's wurden durch eine Verschneidung von ähnlichen geologischen und lithologischen Charakteristika in einem Geo-Informationssystem (GIS) gewonnen und im Gelände auf Plausibilität überprüft. Die für die Berechnung des Standsicherheitsfaktors benötigten bodenmechanischen Parameter wurden durch direkte Schertests bestimmt. Die für jede bodenmechanische Raumeinheit ermittelten Werte werden in die weitere Gefahrenanalyse durch Hangrutschungen integriert. Die Scherfestigkeit des Materials ist für jede bodenmechanische Raumeinheit berechnet worden. In Kombination mit einem Digitalen Höhenmodell (20 m-Auflösung) konnte der Sicherheitsfaktor auf Pixelgröße im regionalen Maßstab modelliert werden. Diese Methode

ist an der nordwestlichen Schichtstufe von Rheinhessen getestet worden, in dem es zur Jahreswende 1981/82 zu einem Ereignis kam, bei dem im hier beschriebenen Untersuchungsgebiet (45 km²) 42 Hangrutschungen auftraten. Das aufgestellte Naturgefahrenmodell wurde anhand dieses Ereignisses verifiziert und zeigt Möglichkeiten der Anwendung der BMREs und ihren Einsatz in der regionalen Naturgefahrenmodellierung.

1 Introduction

Despite the existence of a growing number of regional landslide hazard models, there remain still serious problems concerning the dualism of analytical (site specific, local) and regional modelling. Therefore one of the major topics of spatial hazard assessment is to include as much soil mechanical data into regional scales as is possible and reasonable (HUTCHINSON 1993). In view of the great spatial variability of data, it is "... illusory to seek complicated models that call upon sophisticated behaviour laws, but for which not enough parameters are accessible." (LEROI 1996). In addition to the spatial variability of geotechnical parameters, the variability in time and space of pore water pressures is important. However, this variability is only marginally reflected in conventional calculated factors of safety (ALEOTTI & CHOWDHURY 1999). Access to parameters and spatial data is temporally, financially and technically limited, and methods and models need to be chosen with such accessibility as criteria. Systematic uncertainties arise both from the fact that the number of test sites and field and laboratory tests is finite and because testing equipment and methods are not perfect (ALEOTTI & CHOWDHURY 1999).

The hazard mapping procedure can involve different spatial scales, ranging from local to regional, with different methods being employed for each scale (LEROI 1996). To solve the problem of regionalising geomechanical point data from specific samples *Soil Mechanical Response Units* (SMRU's) have been introduced. This approach originates from the concept of *Geomorphological Terrain Units* (GTU) (DIKAU & JÄGER 1995) and follows closely conceptions published by STYLES & HANSEN (1989) and HUTCHINSON (1993). SMRU's can be defined by characteristic spatial properties and have a distinct span of statistical variation in their geotechnical properties. In contrast to the GTU concept, primarily based on landform morphometry, SMRU's are based on those attributes which are supposed to have a strong influence on the behaviour of the material under stress conditions. Underlying lithology, regolith thickness and the genesis of overlying material are the chosen attributes in the present study. Rather than landslide hazard, resulting maps represent landslide susceptibility which is defined as the possibility that a landslide will occur in a particular area on the basis of the local environmental condition (ALEOTTI & CHOWDHURY 1999, BRABB 1984).

2 Previous work

In the test area different approaches to regional landslide hazard assessment have been taken. The first regional scale stability map was published by KRAUTER & STEINGÖTTER (1983), delineating potentially unstable areas by a manual combination of landslide locations and bedrock lithology. First approaches to transform this model into a digital form using digital

terrain models and GIS technologies were presented by DIKAU (1990a), and have been spatially expanded and supplemented with a spatial and temporal landslide inventory (GLA 1989) by JÄGER & DIKAU (1994). JÄGER (1997) produced a regional scale landslide hazard map by implementing geological information, vertical and horizontal curvature, slope angle and landslide position on a slope (upper, mid, lower slope) in a statistical regression model. Classes within each parameter were defined using failure rate analysis (ANIYA 1985). Model building used degrees of freedom and the likelihood-ratio-test as criteria. The final model which represents the situation best in the study area, used slope angle, slope position and lithology as model input parameters. Despite the fact that the final hazard map was based on a digital elevation model (DEM) with a coarse resolution (40m), highest landslide hazard classes on upper slopes were able to be verified with the field evidence of landslide occurrence in these locations.

A different approach to define landslide susceptibility was taken by DIKAU (1989, 1990b) using morphometric analysis. The region was analysed with respect to characteristic terrain units, which were compared with landslide occurrence. It could be demonstrated that steeper parts of the mid slopes were particularly prone to landsliding (DIKAU & JÄGER 1995).

3 *Study area*

The study area is located at the northwestern part of Rheinhessen (Fig. 1) and described in more detail by GLADE et al. (this issue). Bedrock lithology consists of clays and marls (Oligocene) and overlying Miocene limestone which is topped by Plio-Pleistocene sands, gravels and loess. landslide failure typically occurs in the clay-rich Oligocene material (DIKAU & JÄGER 1995), which is considered to be overconsolidated (KRAUTER & STEINGÖTTER 1983). Progressive physical and chemical weathering leads to reduction of shear strength and higher susceptibility to landsliding.

The soil material is strongly influenced by the morphology of the region. Hollows, concave footslopes and the partially scarped foreland are covered by colluvium, originating from both landslides and slope wash processes. Soil profiles are stratified by successive deposition rather than through pedogenetic horizonation. The convex scarps and ridges are covered by immature erosional soils which are slightly developed. Undisturbed material, which shows no morphological evidence of loading or unloading by deposition or erosion respectively, can be found both on the plateau top and in flat valley parts. It is assumed that thickness and genetic development of overlying regolith material has a strong influence on the angle of internal friction of the bedrock.

Landslides have occurred throughout the basin for centuries (GLA 1989, KRAUTER & STEINGÖTTER 1983). Five years of precipitation above the long-term annual mean lead to 212 landslide failures between December 1981 and January 1982 (STEINGÖTTER 1984). In the 45 km² study area of this investigation, 42 slopes failed in this event. According to the Rheinhessen landslide inventory (GLA 1989) the mean shear plane depth of the landslides within this study area is approximately 4 m.

Recent analysis demonstrates, however, that landslides movement is not exclusively episodic, as the landslide inventory suggests (GLA 1989). GLADE et al. (this volume) demon-

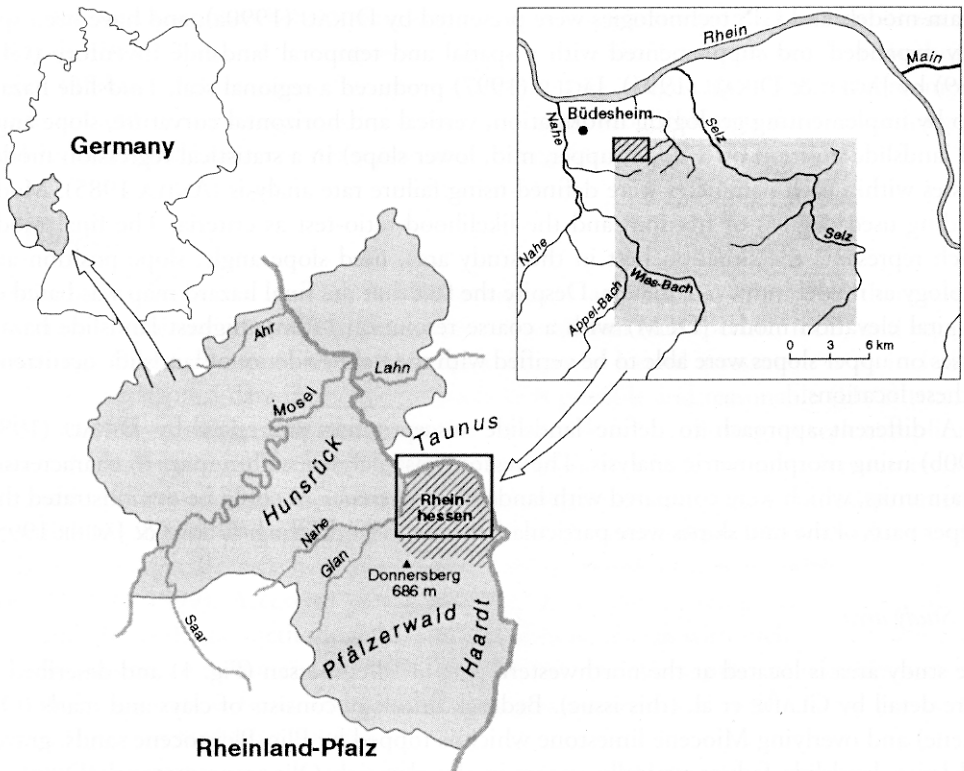


Fig. 1. Location of the Rheinhessen region (crossed area is location of study area, referred to in Fig. 2).

strate a continuous movement behaviour of landslides in Rheinhessen. These movements seem to have not been recognised, and thus were not included in the landslide inventory, possibly because these slow movements do not create noticeable damage. As previous studies have shown, however, landslides constitute a local and regional problem in Rheinhessen and should be analysed in more detail using new approaches to regional landslide hazard assessments.

4 Methods and data

The concept of *Soil Mechanical Response Units* (SMRU) is developed in analogy to *Hydrological Response Units* (HRU), which define areas of similar hydrological conditions determined by soil types and land use or land cover (ROSS et al. 1979, ROSS et al. 1982, SHANTHOLTZ et al. 1990). These HRU's allow the computation of spatially distributed rainfall excess and infiltration. This concept has been adapted to geomorphological purposes by STYLES & HANSEN (1989) and DIKAU & JÄGER (1995). This study approaches the problem of spatial distribution of soil mechanical parameters through the delineation of 2-dimensional objects

Table 1. Composition and characteristics of input variables defining the Soil Mechanical Response Units. Refer to text for explanation.

SMRU	Lithology Description	Stratigraphic units	Soil Characteristics	Soil types
5	Gravel and sand of high permeability	Alluvium, alluvial deposits, aeolian sand, Pliocene sand and gravels, quartz gravel	Immature and slightly developed erosional soils	Regosol, Rendzina, Pararendzina, Pelosol
7	Regolith of high thickness	Colluvium	Immature depositional soils	Colluvium, Alluvial Soils
8	Marls and clay, low permeability and overconsolidated	fresh water marls, brackish water marls, sand, septarian clay (Oligocene)	Immature and slightly developed erosional soils	Regosol, Rendzina, Pararendzina, Pelosol
11	Limestone, high permeability	<i>Corbicularis, hydrobia inflata</i> (Miocene)	Immature and slightly developed erosional soils	Regosol, Rendzina, Pararendzina, Pelosol
12	Limestone, high permeability	<i>Corbicularis, hydrobia inflata</i> (Miocene)	Mature soils	Brown earth, Para-brown earth, Latosol, Chernozem

of similar soil mechanical behaviour, defined as SMRU's. The underlying assumption herein is that the spatial variability of the test area is captured by the unit variability. Soil mechanical behaviour is determined through testing undisturbed soil samples. Representative sample locations have been identified based on local expert knowledge in combination with a map of SMRU's. Test results have been applied to respective SMRU's, which were then used for regional scale analysis.

In general it can be summarised that the smaller the spatial scale of discretization or the higher the number of classes of input parameters, the higher are the data requirements of a model. By definition, terrain units must be mappable at effective cost over the entire region through criteria which are as objective as possible (CARRARA et al. 1995). GIS has the ability to combine, select and use different terrain units for the analysis cheaply and easily and is consequently used within this analysis.

Lithology and soils have been used as input variables for defining SMRU's. The lithology was classified using soil physical parameters such as permeability, internal friction, cohesion and plasticity characteristics. According to the hypothesis that thickness and genetic development of regolith is significantly influenced by bedrock, genetic soil types were used within this study. Inherent in genetic soil typology is the implication of position of the respective soil type within the landscape. For example, colluvium can generally mostly be expected to occur at either toes of a slope or in depressions.

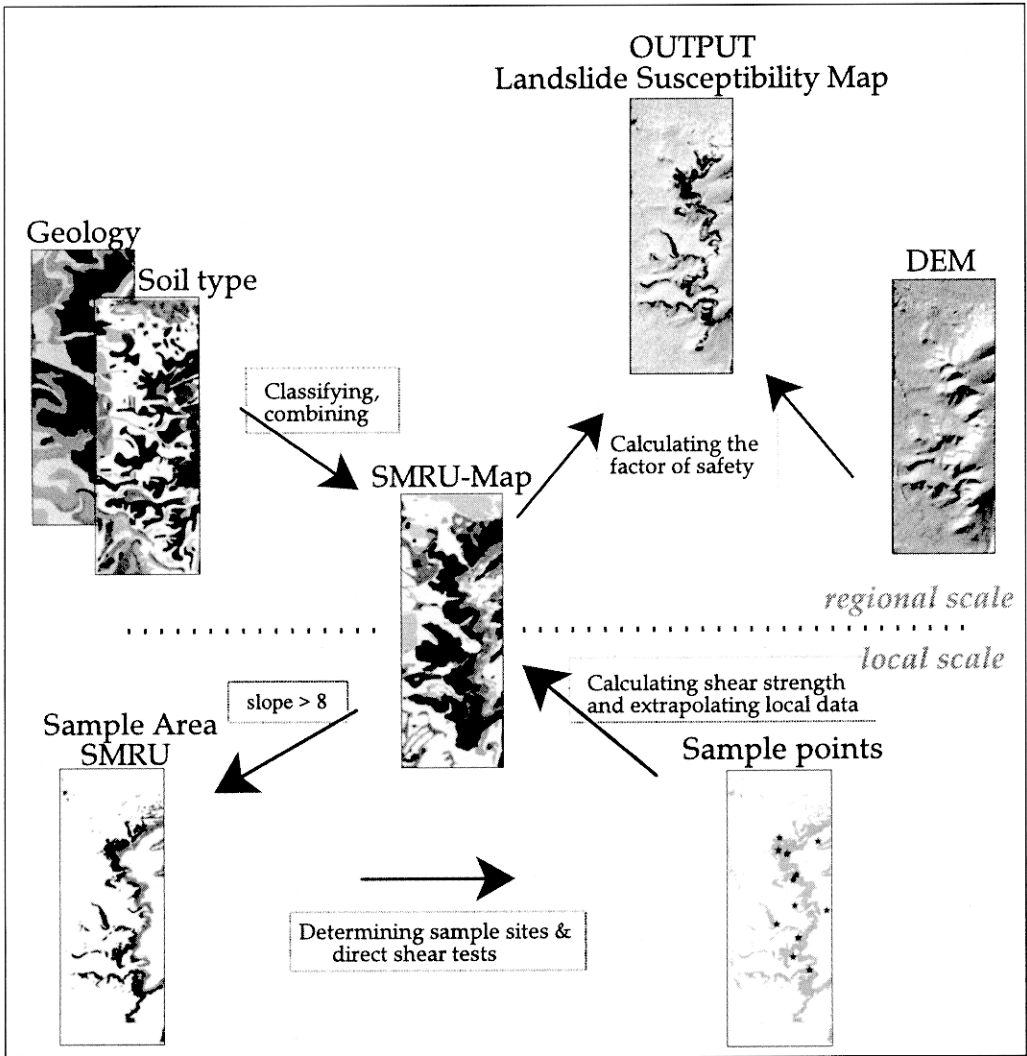


Fig. 2. Generalized scheme of model building, data collection and analysis for a landslide susceptibility model based on Soil Mechanical Response Units.

From a total of 12 SMRU's, five predict landslide occurrence significantly. Other units do not show any landsliding. These are on slopes lower than 8° and are regarded as not highly susceptible to future failures under natural conditions. Consequently, these units have been excluded from sampling and soil mechanical tests. Table 1 shows the units delimited by the described method and their supposed characteristics (please refer to Fig. 2 for location of units).

The regional SMRU concept allows statements on shear strength of material at a given depth, i.e. the susceptibility of the material to landsliding. The final result of the model is a

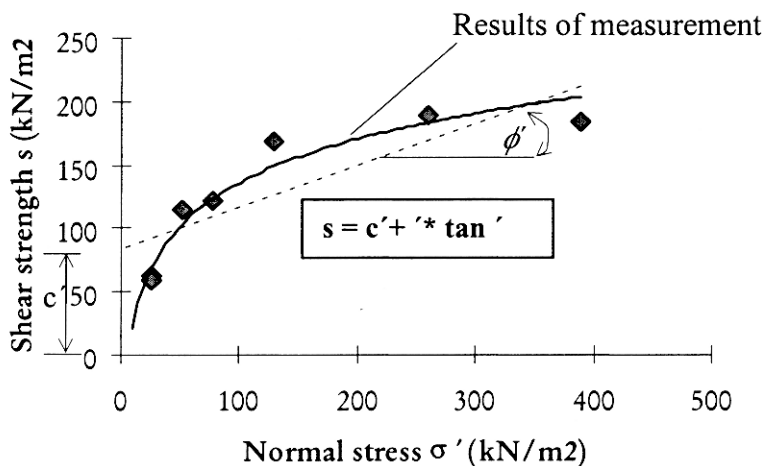


Fig. 3. Curved failure envelope and derived shear strength parameters. Shear strength is calculated over a limited stress range by the Coulomb-Terzaghi shear strength equation (TERZAGHI 1925). (Note: s refers to shear strength (kN/m^2), c' to effective cohesion (kN/m^2), σ' to effective normal stress (kN/m^2), ϕ' to effective angle of internal friction ($^\circ$).)

landslide susceptibility map as defined by BRABB (1984). However, prediction is restricted to potential spatial occurrence of landslides. To include temporal probabilities of occurrences, climatic conditions have to be examined more closely in relation to reported landslide occurrence. Although the next logical step is to include such probabilistic data, available landslide data for this area are not detailed enough to undertake such an approach (GLADE et al., this volume).

Fig. 2 shows the landslide susceptibility modelling process as it has been implemented in the study (refer to Fig. 1 for location within the study area). SMRU's were defined by combining information on lithology and soils. Sample locations were selected for characterisation of SMRU's considered to be significant for landsliding, i.e. those with slope angles greater than 8° . Collected samples were analysed in a soil mechanical laboratory. Resulting soil mechanical parameters include effective cohesion (c'), angle of effective internal friction (ϕ') and dry density (γ) and allowed calculation of shear strength for each SMRU. Slope angle was extracted from a 20 m digital elevation model and the Factor of Safety was calculated for each unit.

Material derives its strength from the contacts between particles which can transmit normal and shear forces. The shear strength is fully mobilized when a soil element can only just support the stresses imposed on it and large plastic deformation is occurring (NASH 1987). Fig. 3 shows a typical curved failure envelope. Shear strength is calculated over a limited stress range by the Coulomb-Terzaghi shear strength equation (TERZAGHI 1925).

Strength parameters were derived from laboratory test using a direct shear box under drained conditions. At least three samples were taken from each location within each SMRU. Sampling locations were distributed over the whole study area and were restricted to sites that

had not experienced landsliding, ensuring that the angle of shear resistance was not already reduced to its residual value. According to the landslide inventory (GLA 1989) the shear plane is assumed to be in 4 m depth. Undisturbed samples were collected from the bottom of boreholes using 10 cm diameter core cylinders.

To make predictions about stability of slopes a quantitative assessment had to be applied. There are several models calculating the state of stability, ranging from two dimensional limit equilibrium models to very complex 3-dimensional multivariate models which are only applicable for very small areas. Limit equilibrium models assume a two-dimensional failure, i.e. slope is assumed to be infinitely long with an inclination (β) to the horizontal. The infinite slope model (HENKEL & SKEMPTON 1954) is suitable for translational landslides where the shear plane is approximately parallel to the ground surface. Because these failures are the most common in the study area, this model has been applied in this study. The physical model is used to calculate the Factor of Safety on a pixel basis and is therefore very suitable for a use in a raster GIS (e.g. the GRID module in Arc/Info).

The subsurface hydrological conditions are assumed invariant along the shear plane. This assumption seems reasonable considering the very low infiltration capacities of the Oligocene mud- and claystones (KRAUTER et al. 1983). The pore water pressure (u) is modelled as the ratio m (dimensionless) of water table depth to regolith depth (VAN WESTEN & TERLIEN 1996). The buoyancy effect of positive pore water pressure bears rather than applies weight, therefore the stress it provides is negative. Back analysis of 42 first-time failures from the 1981/1982 event delivered most significant results with a critical m value of 0.35, which was consequently applied in further analysis.

5 Results

Test results of derived average soil strength parameters are given in Table 2. In total, 52 samples have been analysed under three different normal loads for each sample.

Despite the variability within each class, data show distinctive differences. Thus this regional approach to defining *Soil Mechanical Response Units* seems to work satisfactorily. The object based information on soil strength parameters was transferred to pixel based values. As

Table 2. Soil strength parameters derived by direct shear tests of undisturbed samples for different SMRU's.

SMRU	Eff. angle of internal friction ϕ' (°)	Standard Deviation s	Effective Cohesion c' (kN/m ²)	Standard Deviation s	Dry density γ (kg/m ³)	n
5	41.7	3.9	66.9	14.2	1813.8	10
7	21.4	2.7	76.6	3.6	1605.9	11
8	12.9	2.1	88.9	11.6	1586.6	12
11	24.9	13.2	46.7	2.7	1396.2	9
12	25.4	10.3	61.9	5.9	1407.9	10

previously discussed, water table height represented by m was assumed to be 0.35. Including slope angle derived from the DEM into analysis, the Factor of Safety (FOS) was calculated for each pixel. Resulting values were classified into three categories of stability. Pixel with a FOS >1.8 were predicted to be stable, between 1.8 and 1.3 marginally stable, and <1.3 actively unstable under the 1981/1982 event conditions. These classes were successfully applied to slope stability modelling by SELBY (1993) and CROZIER (1989).

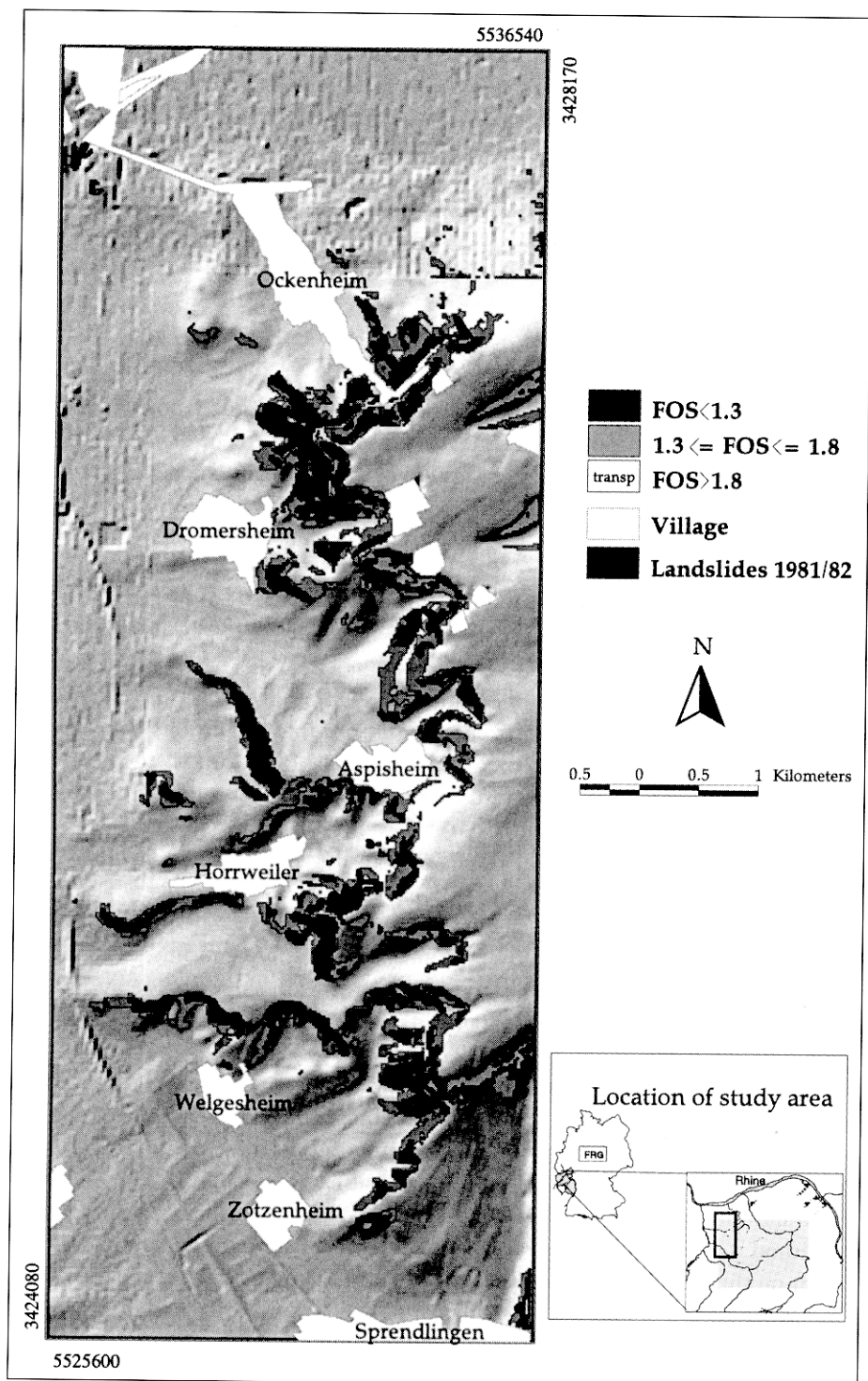
Fig. 4 shows the resulting landslide susceptibility map based on Factor of Safety calculations for SMRU's. Landslide occurrences during the Dec.1981/Jan.1982 event are included for reference purposes.

6 Discussion

Comparison of the calculated susceptibility classes with the landslide failures of 1981/1982 shows good results concerning the quality of the model. 64.3 percent of the landslide scars lie in the part of the study area which was classified as actively unstable, 26.2 in the marginally stable area and 9.5 percent in the stable area. The relatively high number in the latter category can be explained by high anthropogenic components. These relate in particular to slope cuts for road construction or residential developments and function as causative factors. In contrast, model outputs relate to 'natural' conditions only. High susceptibility was calculated for the Oligocene marls and clays covered by immature erosional soils (SMRU No. 8). This material is overconsolidated, thus it still contains strength related to previous loads, which have been eroded during the last thousands of years. Overconsolidated material should be treated with caution because stored strength from previous conditions is believed to be released with time (BROMHEAD 1979, SAKELLARIADI et al. 1996, SKEMPTON 1970). Shear strength decreases gradually upwards towards the surface in overconsolidated material which could favour further shallow slope failure.

Qualitatively comparing the present results with former investigations (DIKAU & JÄGER 1995, JÄGER 1997), all approaches defined the escarpment as being highly susceptible to landsliding. In contrast to the multivariate statistical model presented by JÄGER (1997), more areas are delineated as stable in this study. Within these areas, no landslides occurred during the 1981/82 event. As the current model is less dependent on slope and geomorphometric positions, but more related to strength parameters, zones of classified factors of safety seem much more differentiated.

Nevertheless, inherent in this approach are uncertainties, in particular related to the assumptions which had to be made. The spatial variability of shear strength parameters within the SMRU cannot be reduced without a higher amount of subsurface investigations. This means in turn that the quality of this kind of regional hazard models is determined by the degree to which the spatial variability of the input parameters can be minimized. In some ways the method is quite objective, because the number, size and nature of the classes is strictly dependent on the criteria chosen for classification of the input parameters (CARRARA et al. 1991).



7 Conclusion

The combination of deterministic and regional modelling, i.e. the addition of soil mechanical data into regional landslide hazard assessment is a promising approach to physically based susceptibility modelling at the regional scale. Even in areas without any evidence of recent landsliding processes, which prohibits statistical back analysis of critical conditions responsible for failures, this approach is suitable for susceptibility assessment and prediction of future landslide activities under changing environmental conditions. Final judgement of the quality of the developed model, however, can only be made after a future landslide-triggering rainstorm occurs.

Besides promising results, various questions have arisen through the study. These are identified here, and should be incorporated into further research objectives. Further studies have to be undertaken in particular with respect to:

- defining the critical size of a SMRU,
- providing input data compiled in the same spatial format,
- including further hydrological information such as height of ground water table or soil moisture condition in different topographic locations,
- linking soil moisture conditions with climatic parameters and/or patterns,
- including vegetation into analysis, because vegetation will influence soil strength through root development (PRESTON & CROZIER 1999), soil moisture conditions and additional normal load, and finally
- using more advanced slope stability models into analysis to reflect natural settings more appropriately.

Nevertheless, at this preliminary stage determination and application of *Soil Mechanical Response Units* in landslide hazard assessments has shown promising results for the Rheinhessen test site and has allowed more detailed regional interpretation than previously undertaken in statistically based regional landslide hazard modelling.

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Fig. 4. Landslide susceptibility map based on SMRU's. Refer to text for explanation of boundaries for Factor of Safety (FOS) and water table height of $m=0.35$. Safety zones are overlaid with a 20 m Digital Elevation Model. (Note: For the most northern and western parts of the image, a 40 m DEM was available only.)

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