Development of a Decision Support System for Managing Unstable Terrain: Calculating the Landslide Risk of Slopes

Luc Jouneau[1)] and Alexia Stokes[1,2)]
1) INRA, LIAMA-CASIA, Zhonguancun Dong Lu 95, P.O. Box 2728, Haidian District, 100080 Beijing, China (jouneau@liama.ia.ac.cn)
2) AMAP, TA40/PS2, Boulevard de la Lironde, 34398 Montpellier Cedex 5, France (stokes@liama.ia.ac.cn)

Abstract

Based on an already existing slopes decision support system (*SDSS*), we developed a new platform for managing unstable slopes and calculating the risk of slope failure, with an emphasis on vegetated slopes. This *SDSS* can be modified by the expert to include personal data, models and databases. The end user can then access this information through a rule-based system. The output given by the *SDSS* is in the form of landslide risk and mitigation strategies. In a case study, we show how a general slope stability model can be incorporated by the expert and accessed by the end user. Mitigation strategies are given in the form of links to help files, providing advice to the end user. The system is discussed with regard to the functioning of the *SDSS* and how the system could be expanded further.

Keywords: slope stability, SDSS, forest, expert system, logistic regression model, SLIP4EX

Introduction

The need to produce sufficient quantities of food and the development of infrastructure to transport it to the markets leads to the cultivation and modification of slopes that have often been neglected due to their poor suitability for these purposes. Such changes can lead to slope instability and the ensuing degradation may lead to an irrecoverable loss of soil quality by erosion or mass movements. If predictions concerning global change prove to be correct (UNEP, 2002), more and more extreme weather events will occur, resulting in increased flooding, landslides, erosion and storms. Therefore, mitigation strategies are needed urgently to better manage slope instability problems. However, such planning and management strategies must be cost-effective and sustainable in the long-term, especially for use in rural areas (Stokes et al. 2004). Therefore, it is necessary to develop decision support tools to help the eco-engineer decide how best to manage a slope, depending on the existing problems, location, type and use of the slope.

A Decision Support System (DSS) is an interactive computer program that utilises analytical methods, such as decision analysis, optimisation algorithms and program scheduling routines for developing models to help decision makers formulate alternatives, analyse their impacts and interpret and select appropriate options for implementation (Rao and Kumar 2004). Rule-based management systems can offer the end-user, stakeholder or local government authority, the opportunity to better approximate current or proposed management options more easily, especially as they relate to dynamic conditions in forests or farms (Shaffer and Brodahl 1998).

Several DSS for managing slope stability and soil erosion problems exist already (Lawrence et al. 1997, Dragan et al. 2003, Barac et al. 2004, De la Rosa et al. 2004, Sarangi et al. 2004, Mickovski and Van Beek 2005). Geographic information system (GIS) modelling of landslide hazard (Lazzari and Salvaneschi 1999), erosion (Huang et al. 2003) and environmental vulnerability (Li et al. 2006), has recently provided decision support tools for water resources management and land use. However, such tools are of limited utility if end-users do not have access to GIS models or data and the necessary expertise to run the DSS (Walker et al. 1995). Therefore, expert and rule-based DSS (Shaffer and Brodahl 1998) lend themselves well for use by end-users who either do not have significant computer expertise; whose needs for information are not continuous or who have little time to spend on elegant but complicated DSS (Crist et al. 2000). Hence, we are currently developing a simple, open-source, rule-based expert system, freely available on the internet. Our DSS will be based on a DSS previously developed by Mickovski et al. (2005) and Mickovski and van Beek (2006). This Slopes Decision Support System (*SDSS*) was created using an existing geotechnical Decision Support System platform called ConFound©(Toll and Barr 2001). The *SDSS* gives expert advice on how to manage vegetated slopes over the long-term with regard to landslides, erosion and wind storms. However, this DSS does not lend itself to new or evolving situations e.g. if an end-user wished to add a module on flood management in a particular environment, the software is closed, therefore such new criteria could not be added easily.

pp. 543–552

In any DSS, the decisions will only be as good as the information on which they are based. As the applications of a DSS are outpacing the available databases and simulation models, there is an increasing reliance on expert opinion for information on resource management systems (Lawrence et al. 1997). Therefore, background research carried out on the expert information used in the DSS should be thorough and the DSS should be validated by real data and case studies. Few data exist which include a complete classification of landslides, soil type, hydrological factors and vegetation type (e.g. Lee 2004, Lee and Dan 2005, Lee and Talib 2005). In a complex study, Lee (2004) examined 107 landslides in Korea using IRS satellite imagery and field surveys. Several topographic, geological and vegetation parameters were included in the database. Using a logistic regression model, Lee (2004) was able to predict landslide susceptibility depending on a mixture of certain variables. However, if only local ground data are available, it is also possible to use geotechnical models to calculate slope stability in the form of safety factors (FOS) e.g. SLIP4EX (Greenwood 2006), Slope W (http://www.geo-slope.com/) or STABL (http://www.ecn.purdue.edu/STABL/). Nevertheless, the requirements of such models necessitate the use of detailed soil mechanical data which is not always readily available to the end-user. Therefore, a DSS platform which allowed the expert to either include their own model[jl1], or to choose from a selection of models, would be extremely useful.

In this paper, we outline the structure of a new DSS platform for managing slopes and give examples of how landslide susceptibility can be calculated using data from Lee (2004) and the model SLIP4EX (Greenwood 2006). The end user can input data concerning the slope and soil type, vegetation and meteorology of his/her site. The output of the DSS will give a susceptibility index of slope failure, depending on these data and the model used. The overall functioning of the DSS is discussed along with how the system could be expanded further.

Materials and Methods

Development of the Decision Support System

The Slopes Decision Support System (*SDSS*) developed by Mickovski et al. (2005) and Mickovski and van Beek (2006) consists of an explicit Knowledge Base (KB) and analyses data using symbolic logic involving user input parameters, and an ability to explain the output decision in a way understandable for the user. The basic software package provided an environment in which both the KB could be created and entered hierarchically by the expert (*SUPERVISOR* mode), and where this information can be explored interactively by the user (*END USER* mode). Using this logic, a new DSS platform has been developed, which cannot only be used for slope stability analyses but can also be used as a tool for any purpose where decision logic is required. In this paper, we shall present both the DSS platform and the new version of the *SDSS*, which is dedicated to slope stability analyses.

The DSS platform is based on two software elements:

* A standalone java user interface where the *SUPERVISOR* can define the content of the KB.
* A web application, in which the *END USER* can enter context specific data and read advice deduced by the DSS from the rules defined in the KB.

The framework of this DSS is composed of three main elements: input, rules-set and output. Input provided by the *END USER* will lead to changes in the state of the rules-set, which will in turn lead to validation or invalidation of output as deduced from the KB pre-defined by a *SUPERVISOR* (Figure 1).

The *SUPERVISOR* can fully document elements defined in the KB e.g. name, description, link to an external web site etc. This information is thus displayed in the *END USER* web application.

Using the SUPERVISOR mode

The *SUPERVISOR* is the expert who can define rules-sets, input and output types. Very little computing knowledge is required to use this mode. However, the *SUPERVISOR* should judge how best to elicit the *END USER*'s preference information and how to use this information to guide the end user to the best applicable solution (Chen and Lin, 2003). Therefore, the first step to take when using *SUPERVISOR* mode, is to decide input type.

Deciding input type

Input can be defined in two ways, either:

* *END USER* input: a value or a set of values given by an *END USER* and consisting of context specific data e.g. slope angle, soil type, rainfall, land use etc. The *SUPERVISOR* must decide which constraints

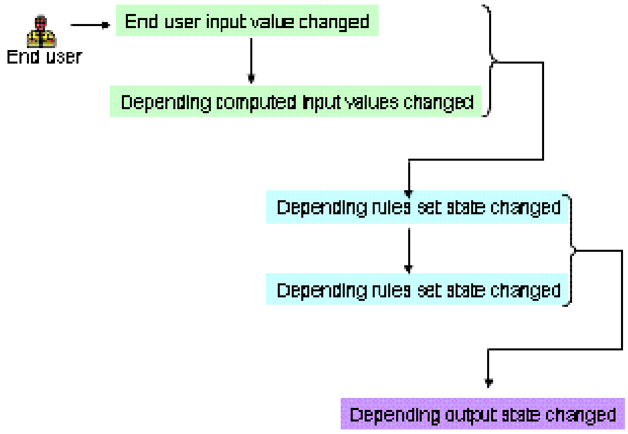

Fig. 1. Flow chart showing how an end-user's input will change the state of the rules-set which in turn influences the output of the DSS.

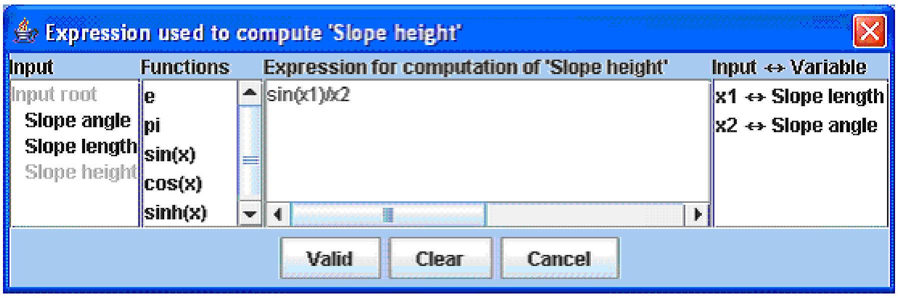

Fig. 2. Interface to enter mathematical expressions by the *SUPERVISOR*

apply i.e. single or multiple values, data type (text, number, decimal) or a list of acceptable values should be provided.

* Computed input: a value computed by the system and depending on other input.

Computed input can be defined in several ways, e.g. as a mathematical expression involving other input, which is either given by the end-user or computed by the DSS (Figure 2).

Computed input may also use a distribution of scores where a score is associated with each input value. Scores are given by the *SUPERVISOR*, who defines them according to personal data, model coefficients or even qualitative field experience. Using a previous study in the literature, we can use regression coefficients from a landslide probability model as an example of a score (Lee 2004). Using IRS satellite imagery and field surveys in the Janghung region of Korea, Lee (2004) examined 107 landslides and calculated the area ratio for landslide occurrence and non-occurrence for a given factor e.g. slope angle, vegetation type, soil type etc. Lee (2004) then used a logistic regression model with a binary variable as the dependent variable representing the presence or absence of landslides. The probability of a landslide event occurring could then be estimated. The logistic regression coefficients derived for each parameter can then be used as examples of scores in our *SDSS* (Figure 3). For example, scores for land use type range from -5.8363 (water) to 0 (barren land).

Weights can also be associated to the input (Figure 3). The weight assigned to an input is decided by the *SUPERVISOR*, depending on the influence of the given input on the whole scoring computation. If all input data n are equally important, the weight of each will be the sum of weights/n. Some input may have unequal weights, depending on the importance of those data. The weight used can be qualitative, depending on the *SUPERVISOR*'s personal experience with the problem, or can be quantitative. Using the data and logistic regression model developed by Lee (2004), an example of a quantitative weight could be the slope angle regression coefficient derived from the multivariate analysis of the presence or absence of landslides on the independent variables (Figure 3).

Using classic logic in DSS analysis, we can use Equation 1 to determine the distribution of a computed input for a given factor, depending on the scores and weights assigned to each variable. This distribution of computed input value is therefore an indicator of landslide risk:

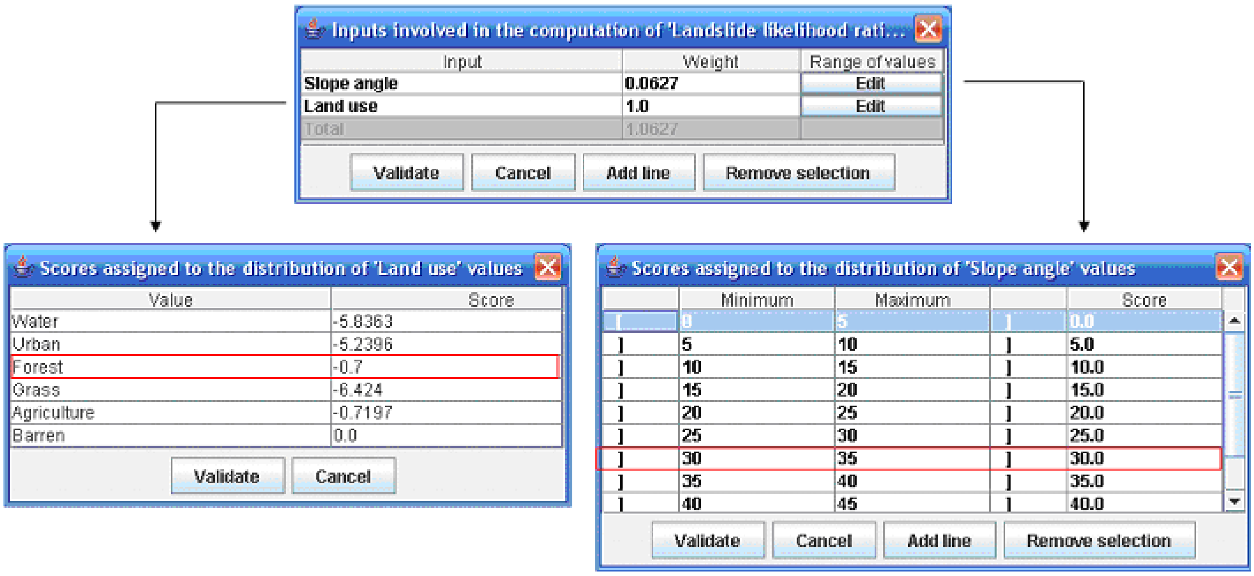

Fig. 3. Interfaces used to enter score values and a specific weight for each input involved

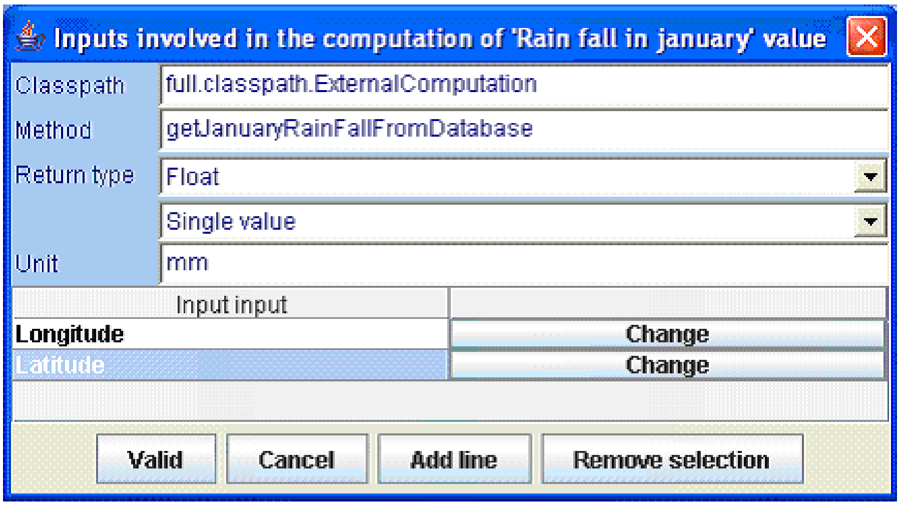

Fig. 4. Interface to define external java method used for the computation of an input

$$\text{Landslide risk} = \sum(\text{weight} \times \text{score}) \tag{1}$$

If in a given case study, slope angle is 34° and the land use is "forest," the score assigned to slope angle will correspond to a class of slope value angles (Figure 3), as in Equation (4) of Lee (2004). The score for forest is −0.7, and the weight for slope angle is the logistic regression coefficient determined by Lee (2004), whereas the weight for land use is 1, as all data are equally important. Therefore, equation 1 becomes:

$$(0.0627 \times 30) + (1 \times -0.7) = 1.81 \tag{2}$$

This ratio can then be compared to a value in the rules-sets (see below), to interpret whether the landslide risk of 1.81 is high or not, and whether remedial measures need to be taken at the site.

Further examples of computed input can include access to databases using an external java method. For example, if longitude and latitude are defined as end-user input, and if the system has access to a rainfall database, the *SUPERVISOR* can define computed input for precipitation at the time of a landslide event (Figure 4).

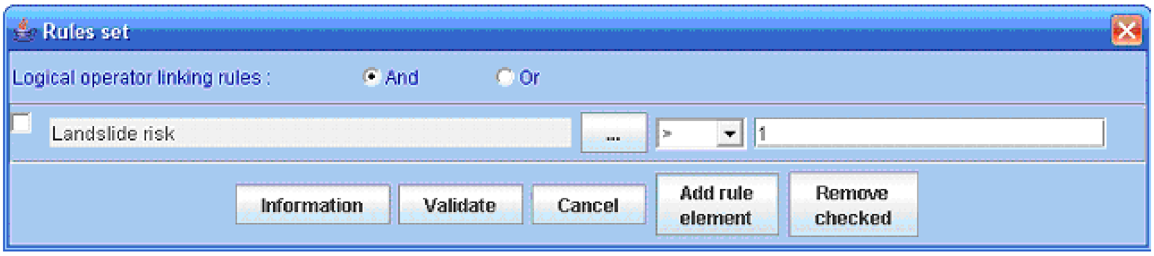

Fig. 5. Definition of the rules-set "Landslide risk"

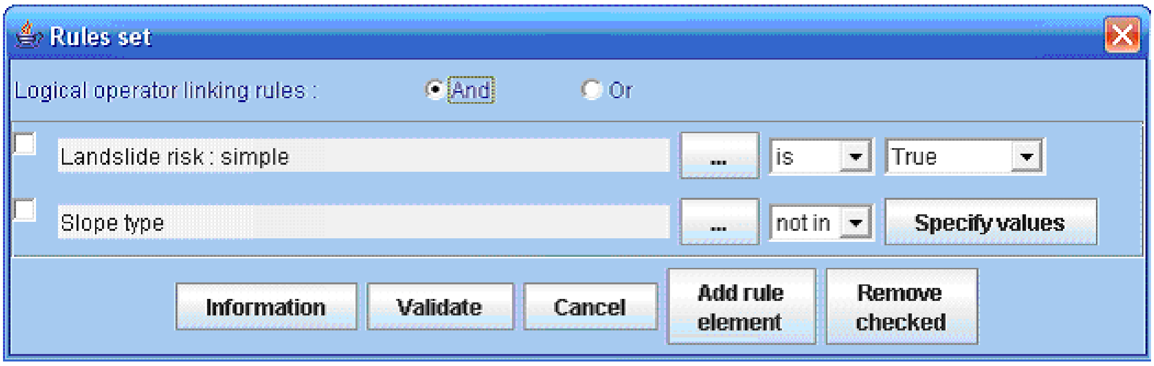

Fig. 6. Definition of the rules-set "Landslide risk + slope type"

The use of rules-sets

Rules-sets link input (description of context) and output (strategy or hazard; see next section) together. Parameters in the form of input values are compared to a given value or set of values. The result of the comparison will decide the state of the rules-set. A rules-set is a set of rules linked by either AND or OR logical operators (Figure 5). A rule is composed of three elements:

1) a left hand part which can be an input or a rules-set,
2) a comparison operator $(=, >, <, ...)$,
3) a right hand part consisting of value(s) to be compared with the left hand value of the rule

As the left hand part can refer to a rules-set previously defined in the KB, the *SUPERVISOR* can begin defining simple rules-sets with increasing accuracy (Figure 6).

The use of a previously defined rule-set and being able to select AND or OR logical operators allows us to define any possible logical expression. The state of a rule can be either TRUE, FALSE or UNKNOWN (Table 1). A rule is in the state UNKNOWN, if the value of the input involved in the rule is not known. This situation may occur either because the value is an *END USER* input, and no data have been provided, or because it is a computed input and values of some of the input involved are not known.

Output given by the DSS

An output is described as either a probability of hazard or a strategy to avoid the hazard within the framework of a given DSS. For example, in the *SDSS* developed by Mickovski et al. (2005) and Mickovski and van Beek (2006), a hazard output can be *Soil Mass Movement*, *Rockfall* or *Windthrow Hazard*. The mitigation strategies given by the *SDSS*, which also exist in this version, concern techniques and management strategies to fix soil using vegetation (for details see Mickovski et al. 2005, Mickovski and van Beek 2006).

For a given output, the *SUPERVISOR* provides a list of rule-sets. For each one, he/she should give a comment explaining to the *END USER* the implication of this rule if its state is TRUE or FALSE (Figure 7).

This information is of utmost importance, because for a particular strategy, the statement 'FALSE' can have several meanings:

* the end user should not apply this strategy
* the strategy will have no effect

Table 1. The state of a rules-set is decided depending on whether rules are in the TRUE, FALSE or UNKNOWN states and the logical operator linking the rules.

Logical operator linking rules	**Rules-set state**		
	TRUE	**FALSE**	**UNKNOWN**
AND	All rules are in TRUE state	At least one rule is in FALSE state	At least one rule is in UNKNOWN state
OR	At least one rule is in TRUE state	All rules are in FALSE state	All rules are in UNKNOWN state

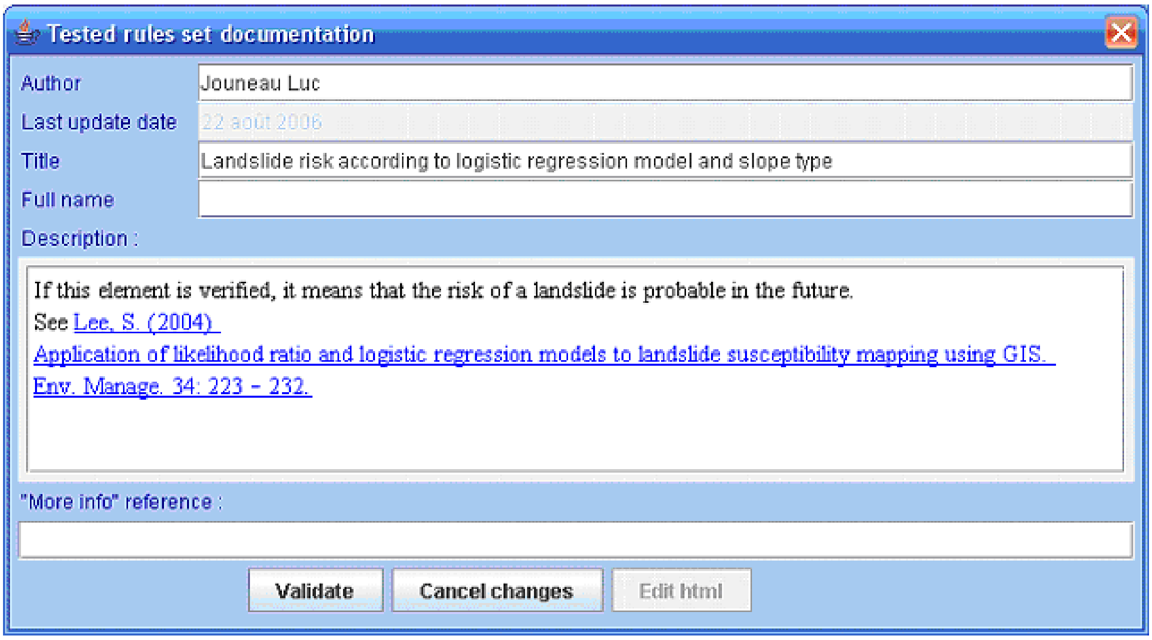

Fig. 7. Example of output whereby the *SUPERVISOR* states that the rule is TRUE and gives a reference to Lee (2004) to explain the implications of this state.

* the strategy is not applicable to the context

This rules-set is therefore the key that will help the *END USER* to understand the likelihood of hazards on his site and the strategy to deploy to avoid them.

The *SUPERVISOR* should also provide a confidence level to each rules-set involved in the output (Figure 8). This confidence level will indicate to the *END USER* whether the *SUPERVISOR* is confident or not in what he is describing or modelling. If we have an output involving the two rules-sets shown in Figures 5 and 6, as the second rules-set had one more input, it will be more accurate in the evaluation of the output. Therefore, its confidence level should be higher than that associated with the first rules-set (Figure 8).

Using the END USER mode

Once the *SUPERVISOR* has defined the content of the KB, he/she can access the web site where the *SDSS* server is freely available. An *END USER* can then access the web site where he/she selects the KB of interest. The web page invites the *END USER* to enter input data corresponding to the specific context of their situation (Figure 9). Depending on the data entered, the *SDSS* evaluates the state of the rules set, and decides which of the output are accurate for the *END USER*'s particular situation (Figure 9).

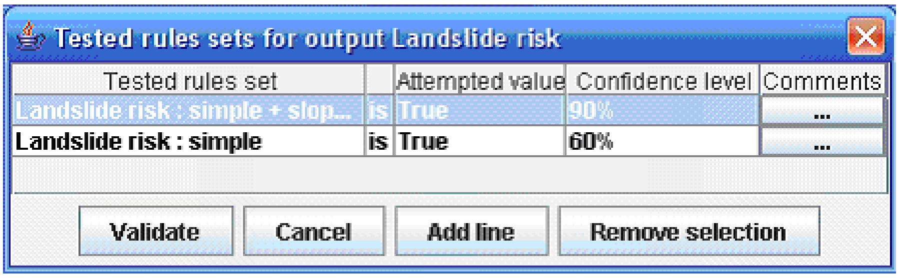

Fig. 8. The confidence level is only 60% when one input is added to the rules-set but increases to 90% when a second input is added.

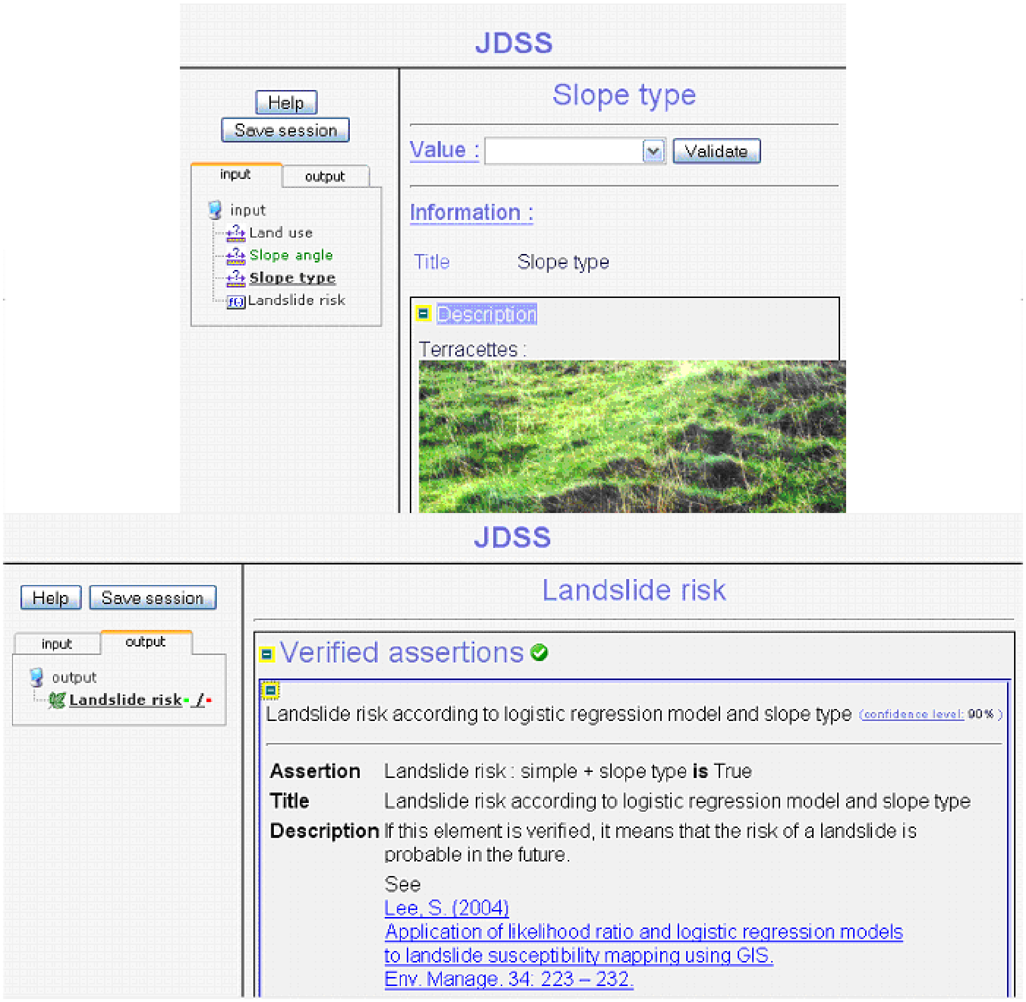

Fig. 9. The *END USER* can enter data depending on the specific context with which he/she is concerned. The *SDSS* then evaluates the landslide risk.

Case study — Incorporation of a general slope stability model

As an example of how the *SDSS* can be used by other users to incorporate their own models or data, we have integrated the computer program SLIP4EX into the *SDSS*. SLIP4EX is a straightforward program developed for routine slope stability analysis and the assessment of the contribution of vegetation to slope stability (Greenwood 2006). Once parameters are fed into the program, stability calculations and comparisons of Factors of Safety using different methods of analysis are carried out. Geosynthetic reinforcement may be included and vegetation effects such as enhanced cohesion, changed water pressures, mass of vegetation, wind forces and root reinforcement forces are readily included in the analysis.

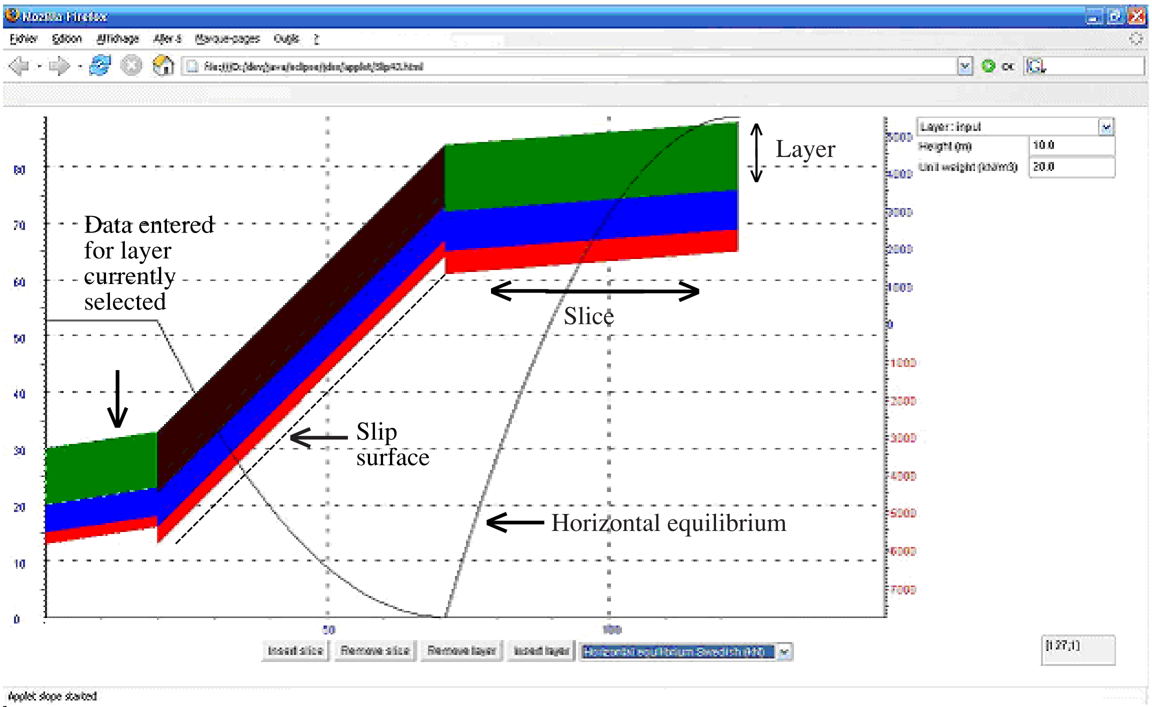

Fig. 10. The *END USER* enters height, angle and weight data for each slice (three shown) and each layer (three shown). The Factor of Safety (FOS) is calculated by SLIP4EX and the black line shows how the horizontal equilibrium decreases with increasing slope angle and height at the second slice, before increasing again when the third slice is reached. The slip surface (dotted line) is located underneath the layers in question.

To use SLIP4EX, the slope stability problem should be drawn out to scale, with the single slip surface defined (Figure 10). Slice (up to 15 slices allowed) dimensions with up to three soil layers, and the angles between the base of each slice and the horizontal (Figure 10), are scaled from the diagram. Appropriate soil and water parameters are then assigned for each slice. The notation used and details of the dimensions are given in Greenwood (2006). The prepared slice data is then input manually, which calculates the forces acting on each slice of the analysis and the total forces acting on the slip surface. SLIP4EX then calculates the Factor of Safety (FOS) of the slip surface using different geotechnical methods (using methods by Greenwood, Bishop and Janbu — see Greenwood 2006). The Factor of Safety is calculated both in terms of moment equilibrium and horizontal force equilibrium where appropriate.

In the example (Figure 10), for the selected layer, slope angle is 10°, height is 10 m and the unit weight of each layer differs (shown by differences in colour). The FOS calculated for the entire slope was 0.33, therefore the likelihood of this slope to fail is quite low. The helpfiles of the *SDSS* can then be consulted with regard to mitigation practices for the slope in question.

Conclusions

The *SDSS* is simple and easy to use, even with limited technical knowledge. Freely available on the internet (http://liama.ia.ac.cn), it is ideal for experts around the world who wish to incorporate their own parameters, models, knowledge and databases. It is hoped that experts and users will adapt the *SDSS* to their own situations, whether that be soil mass movement risk, debris flow, erosion or storm hazard, and then propose to the authors to upload their versions onto the web site, where other users may also access them. The type of user which could benefit from such a system would not just be professionals and engineers, but also local authorities, stakeholders and students. As a learning tool, the *SDSS* is particularly useful, especially when models e.g. SLIP4EX can be run with different types of data. The help files have also been compiled by several experts in the fields of ground bio- and eco-engineering in the previous version of the *SDSS* (Mickovski et al. 2005, Mickovski and van Beek 2006) and combine in-depth engineering theory with practical methodology for slope management.

In the future, we plan to implement other DSS in our platform, to see if it can support several types of logical analysis models. We also wish to use our own data and models in the *SDSS*, therefore we are currently building a database of landslides, similar to that collated by Lee (2004). Shallow landslides and soil slips in the Sichuan province on the eastern edge of the Tibet-Qinghai plateau, China, are being examined. Parameters measured include soil type, slope angle, size and depth of slip, exposition, basic hydrology and vegetation type on or adjacent to slip. From the analysis of these parameters, we hope to determine which are important with regard to landslide risk, and then implement these results into the *SDSS*. Simultaneously, we are collecting data from a number of sites in the Sichuan, close to where landslides have been measured for the database. We will then use these data as input to SLIP4EX, to determine the FOS on slopes similar to those where landslides or shallow slips have recently occurred. By combining the results, we should be able to estimate or confirm the major factors contributing to slope stability in the regions being studied.

Although the help files associated with the *SDSS* are extensive, with guidelines as to how to manage certain slopes in given circumstances, it is necessary to continuously update the helpfiles, as new results and research are being published. If the *SDSS* is modified for use in different geographic regions, it is also imperative for the *SUPERVISOR* to include information and mitigation strategies for that particular location. Nevertheless, it is hoped that the *SDSS* will be a useful tool for slope stability analyses, and its free access will allow for collaborative studies between both researchers and professionals, in particular with regard to vegetated slopes.

Acknowledgements

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