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A Spatial Decision Support System for Highway Infrastructure

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Abstract
Modern highways consist one of the main infrastructure of a country and their maintenance in order to achieve the best condition of operation should be a major concern. Extended damage of highway components, i.e. a bridges or tunnels or great slope failure caused by landslides, earthquakes, floods or other causes can produce a disaster that could affect scores of people.

In this paper, a Spatial Decision Support System (SDSS) for deformation monitoring of highway technical works is described. The system uses GIS technology as a base and consists of the following modules:

1. An extended deformation monitoring system based on geodetic and geotechnical instrumentation.
2. Environmental conditions monitoring.
3. Monitoring of construction health (optical and instrumented inspection).
4. A knowledge-based system that analyses all data and makes a rough risk assessment, triggering the alarm for possible immediate failures.
5. An alarm system to ensure the instant/direct authority action.
6. The overall assessment of the results and the final decision level due to geo-informatics solutions.

Keywords
Monitoring, Instrumentation, Risk assessment, Spatial decision system

1. Introduction

A Spatial Decision Support System (SDSS) has been designed to assist a highway maintenance company to assess the information necessary for the technical works and traffic safety as well as to assist decision makers to choose actions.

This paper focuses on the way the system assesses the earthworks, analyze the risk of a possible failure due to earth movements or landslides and prioritize the need to action. Bridge and tunnels due to their constant maintenance needs, are not being evaluated through this system.

2. Decision Support System

The system is using the digital technology to store and share the information and even to measure, evaluate and predict possible risks. But in every aspect of the process, estimation is judged and can be changed by the operator.

The system is realized in five basic steps (Figure 1): Data Collection, Risk Identification and Quantification, Risk Management and Evaluation/ Measurements selection.

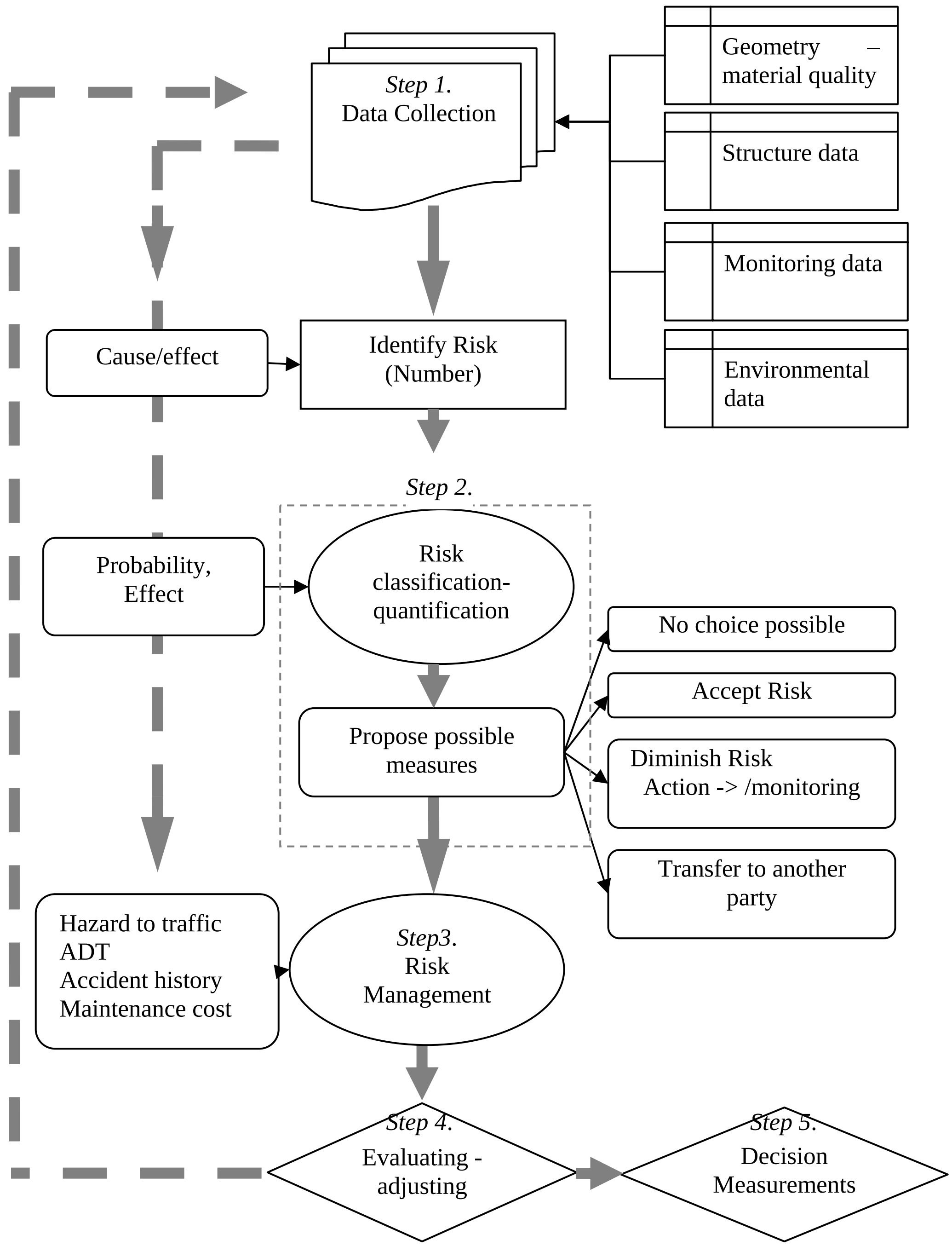

Figure 1: SDSS Structure

2.1 Data Collection

All data described forward are stored in a relational database (RDBMS) connected to a Geographic Information System (GIS).

A crucial necessity for the management control is the segmentation of the project into sections (work sites/ technical works) depending on the type of structure. Nine basic types are used: Bridge, Overpass, Underpass, Tunnel, Cut&Cover, Embankment, Cut, Mixed Earthwork and Building. The database includes all the necessary elements for a rough characterization and the spatial data of every district site (coordinates, chainage).

Especially for the earthworks the database contains construction elements that can be used from the system to calculate the possibility of a stability failure. This feature described in the paper later works as a discrete module that learns from the data being collected.

2.1.1 Visual inspection

The operation of the maintenance is sustained by periodical inspection of the whole project. Daily inspections are taking place by the teams who are responsible for the elementary maintenance and traffic control. There is also an expert group that performs instrumented monitoring and also a thorough visual inspection wherever a possible failure is reported.

The inspectors compose a report with special forms which categorize and rate the possible risk factors. They also record the failure proportions and location (by means of a handheld GPS). The report is supplemented by photos and a rough sketch.

2.1.2 Geodetic and geotechnical instrumentation (monitoring system)

In order to monitor the mechanism of severe geotechnical problems like deep and extended landslides and to ensure the stability in sites where the stability is fragile, an extended monitoring system is deployed.
Depending on the circumstances, the instrumentation consists of a variety of geotechnical instruments, installed in deep boreholes and a network of monuments (control points) for geodetic monitoring.

The main geotechnical instrument used for deformation measurements is the inclinometer, an instrument capable to record the vertical deformation profile with great accuracy. Other instruments with minor range are also used for deformation monitoring, like tiltmeters, crackmeters, strain gauges, horizontal inclinometers. Another instrument with wide usage is the piezometer which monitors the pore pressure fluctuation, the most common cause of earthworks failure. (accelerometers?)

The deformation of the surface of the ground is monitored by geodetic measurements. The methodology used for the measurements depends on the morphology of the area and the special needs of the particular site. In most cases where a landslide area is examined, GPS technology is being utilized. In cases that a structure is included, or a great number of targets is required, total station measurements are frequently combined with GPS observations.

An expert team analyzes the data and updates the results to the database. Due to the multiplicity of the geotechnical characteristics of every site and the different safety factors or trigger values that are valid for a certain earthwork, a numerical risk factor can be provided by the evaluation. To derive this factor, the system uses the categorization of the earthwork, the deformation rates and the depth of the slide.

2.1.3 Environmental conditions monitoring

The most common cause for landslides, or more general earth instability, is the pore pressure increase and this phenomenon is connected to the precipitation of the area. So, in order to establish a learning system that can predict the possibility of a failure, a precipitation monitoring system is required. This system consists of several weather stations and a few automatic acquisition raingauges installed close to the most dangerous landslide areas. In some other places, data is provided by the national whether network. Other environmental parameters, like temperature and wind are also monitored for other reasons like traffic safety but they are not connected to the earthworks stability evaluation.

2.2 Knowledge-Based System

Based on the common geomorphological conditions and construction methodology that characterizes neighbouring sites and the feasibility of the system to analyze spatial data additional to technical ones, a knowledge-based system has been developed to assist the stability evaluation.

2.2.1 Slope failure probability

The data collection and the monitoring results enable the operation of a statistical based procedure that evaluates the probability of instability. The system uses the geotechnical characteristics stored in the database, a deterministic formula for estimating theoretical values of instability and the results of identified deformations to enhance the knowledge of the phenomenon. The formula employs as input the material properties, the earthwork geometry and pore pressure and results into a safety factor value, which is analog to instability probability.

Primarily, detailed data are investigated for sites that have signs of instability. As the system 'learns' and detailed data is recorded to the database correlated with environmental monitoring, the capability of a hazard prediction is constantly increasing. The use of GIS system for the visualization of the information contributes to the manageability of the system.

On Figure 2, an example of stability lines for slope failure is shown.

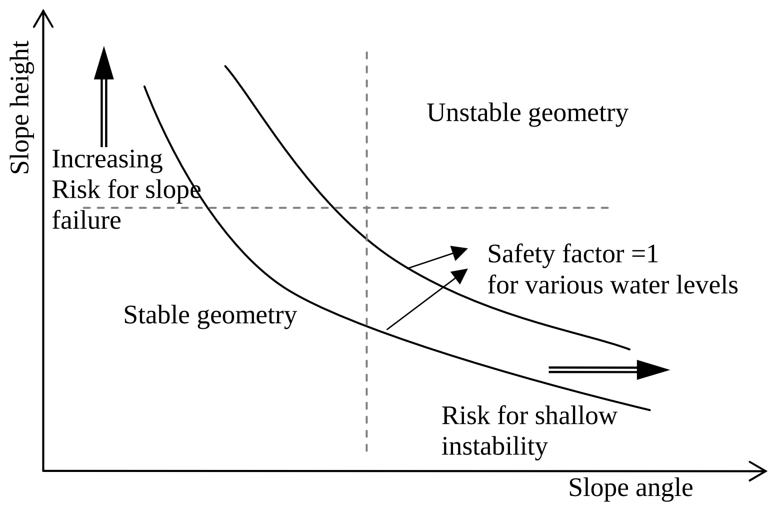

Figure 2: Stability Lines for Clay Slopes

The estimation of failure possibility is based on the theory that a slope displacement progress will follow several stages before a sudden failure due to strength deterioration of the material (Figure 3).

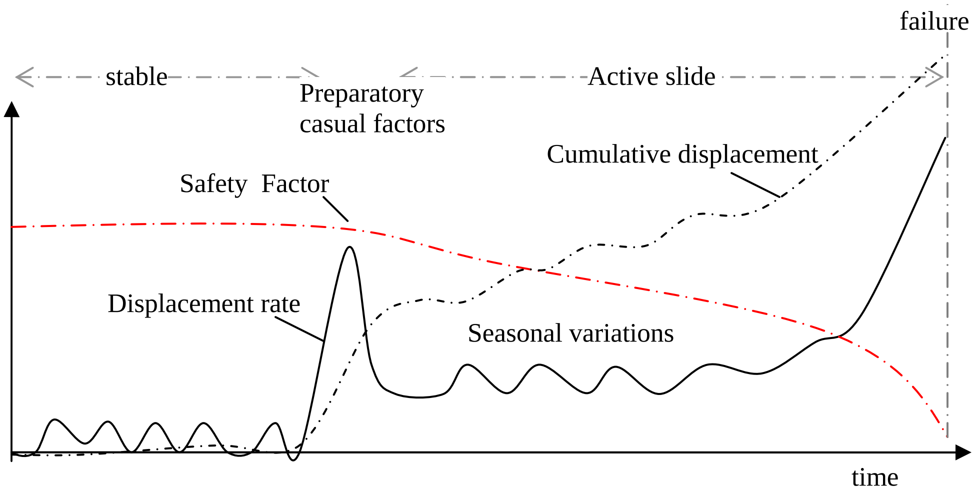

Figure 3: Slope Stability with Time

2.3 Risk Assessment

After the steps of data collection, potential instability has to be classified and quantified due to the potential impact to the road.

For slope instability, the potential impact on the road has been categorized to the following:

Severity of impact	Value of Factor
Damage on slopes but not on surface of the road.	1
Small Damage to the roadway (not affecting main lane or small settlement)	2
Damage on the carriage way that can be locally repaired.	3
Damage that needs immediate rebuild and possible closure of a lane	4
Severe damage that needs reconstruction and detour of the traffic.	5

The probability of a failure (chance of occurring) is also divided into four categories:

Probability of impact	Value of Factor
Very low possibility	1
Low potential of failure – more than five year period to remediation	2
Moderate probability – 1 to 5 year period to remediation	3
High potential of failure – indefinable period of time.	4

Any instability that has already happened is categorized as number 4.

The evaluation of the severity of the potential damage and the estimation of the possibility of occurrence is carrying out by a specialized team of engineers and the estimated factor value can take a decimal value between the main categories. At one site, the same cause may have multiple effects with different possibility.

The quantification of the Risk is derived as a product of the possibility of a hazard and the current consequence. The results are visualized on a graph like the following example:

	Description	Cause	Effect	Probability	Severity cat.	Risk
Site 1.a	Embankment	deep lanslide at foundation,rate~10mm/year	cracks on the surface	3,5	2,0	7,0
Site 1.b	Embankment	deep lanslide at foundation,rate~10mm/year	failure of construction	1,0	4,5	4,5
Site 2	Cut	rockfalls	blockage traffic	3,0	3,0	9,0
Site 3	Embankment	Consolidation	Settlement of surface	2,0	3,0	6,0
Site 4	Cut	mudflow	Cover part of one lane	3,5	3,0	10,5
Site 5	Embankment	wedge failure below roadway	Emb.'s slope damage	2,5	1,5	3,8

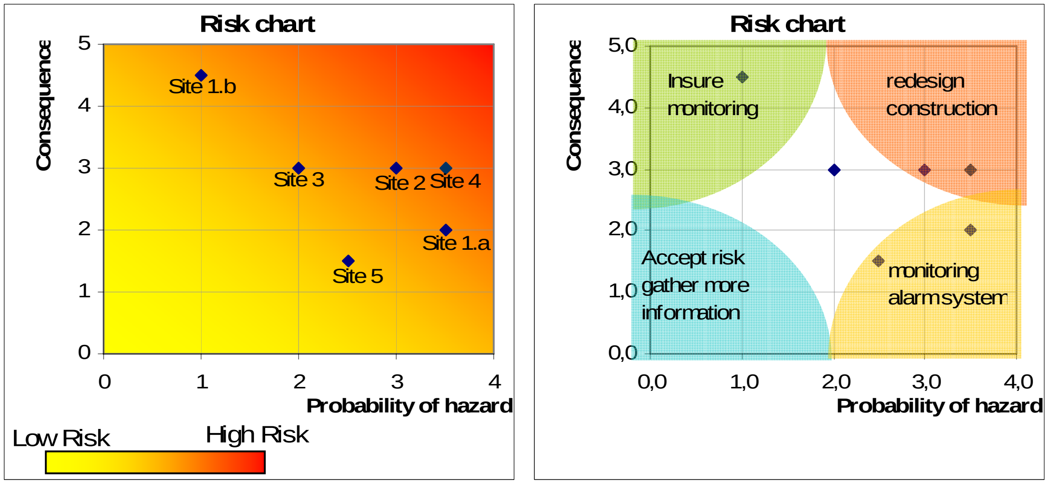

Figure 4: Risk Quantification – Example Risk Chart

The risk analysis gives the engineers a guide for the kind of measures to be chosen. Figure 4 illustrates an example of a risk chart use. The choices for the appropriate kind of measures can be:

- No choice possible: Gather more information
- Accept Risk: Risk/consequences are small enough
- Diminish Risk : Design/Construction, extended monitoring, alarm system
- Transfer to experts: Transfer the solution design to another party.

After one or more different operations are chosen, rough cost estimation has to be input in the system. When the system stores a lot of sites and remediation/maintenance works, the cost/time estimation becomes more efficient.

2.4 Risk Management

The risk qualification and quantification is only one of the factors that have to be taken in account in order to manage an infrastructure like a main national road network.

Other important factors like the maintenance cost, the daily traffic, hazard to traffic (a small instability like small rock falling, doesn't affect the construction but may lead to accidents) are also quantified and composite to produce a hazard score for every investigated site.

The factors that the SDSS is evaluating are:

- Instability Risk
- Hazard to traffic
- Average Daily Traffic
- Accident history
- Maintenance cost.

For every factor a rating criterion from 1 to 4 is established except for Instability Risk which may exceed this score as it has been analyzed previously.

For the rest factors, the following table offers an elementary guide to evaluate a score.

Table 1: Risk Factors

	Value = 1	**Value = 2**	**Value = 3**	**Value = 4**
Hazard to traffic	Visible crack on surface < 1cm wide	Crack or dip on the surface noticeable by a driver (1 to 3 cm wide).	Deformation on surface that makes driver to slow down.	Dangerous deformation on road surface.
Average Daily Traffic	< 2000	2001 - 5000	5001-20000	>20000
Accident history	No accident	Material damage	Injury or 2 minor accidents	More than 3 accidents or fatality
Maintenance cost estimation	Rarely	Annually	Up to 3 times/year	More than 3 times/year.

2.5 Overall Assessment

All the factors are summarized to produce a score for every hazard and site. This score is used to list the sites on priority and measure the necessity for action.

There are also threshold values in scores and in risk assessment, which trigger a software alarm module. This module sends directly messages to the committed officials for immediate investigation and action.

The visualization of the data by GIS helps the decision makers to combine the information with the placement of every site, to estimate the time for a certain authority to act, the additional time cost of the maintenance works, and even to check for detours in case of a severe failure. The same system can produce a standard report for the sites chosen with the detailed information.

3. Conclusions

Infrastructure maintenance is a complex work and often occupies many people from different disciplines and departments. Structure stability is a critical aspect of the maintenance requirement, which is usually undervalued unless it affects traffic. A system that is capable to recognize and evaluate the possible hazards is mandatory.

The SDSS system is using the existing technology in conjunction with the human judgment to cover this mission. The benefits of the system are many. Paper work is reduced, information is standardized and centralized and the work time is shortened. Above all, the integration of various data and different aspects of a hazard helps decision makers to make an overall assessment and prioritize the rehabilitation measurements.

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