Developing on-line monitoring systems for geological hazards for large construction works

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Abstract: Control of geological hazards is obligatory for managing large industrial units and linear constructions, such as plant facilities, gas and oil pipe-lines. The Institute of Environmental Geoscience of The Russian Academy of Science (IEG RAS) have developed on-line monitoring systems of geological hazards for a large number of constructions.

An on-line computer-based system of geological hazards (underflooding, karst, and landslides) was designed for Moscow.

The main scientific problems of the monitoring systems include:

- The problem of combined control,
- The problem of representativiness,
- The problem of immediacy,
- The problem of adaptivity.

A software package to estimate the probability of geological hazard impact on construction is a promising component of the monitoring systems. Based on mathematical models of landscape morphological patterns scientists of IEG RAS developed a probability estimation technique for a wide range of processes, including soil subsidence, karst, landslides, and thermokarst. Random process theory was used for developing the on-line estimation technique of impact probability for following cases:

- Linear constructions,
- Area constructions,
- Little (point) constructions.

A similar monitoring system was developed for the Russian-Turkey gas-transport system (GTS) "Blue Stream".

Resume: L’estimation des risques géologiques est obligatoire pour contrôler de grandes unités industrielles et constructions linéaires. L'institut de Geoscience environnemental de l'Académie russe de la Science (IEG RAS) développe des systèmes en ligne de surveillance des risques géologiques pour un grand nombre de constructions.

Un système informatisé en ligne des risques géologiques (eau souterraine, karst, et éboulements) a été conçu pour Moscou.

Les problèmes scientifiques principaux des systèmes de surveillance incluent :

- le problème de la commande combinée,
- le problème de la représentation,
- le problème de l'urgence,
- le problème de l'adaptabilité.

Un progiciel pour estimer la probabilité de l'impact géologique de risque sur la construction est un composant prometteur des systèmes de surveillance. Basé sur les modèles mathématiques des scientifiques morphologiques de modèles de paysage d'IEG RAS a développé une technique d'évaluation de probabilité pour un éventail de processus, y compris l'affaissement de sol, le karst, les éboulements, et le thermokarst. La théorie de processus aléatoire a été employée pour développer la technique en ligne d'évaluation de la probabilité d'impact pour des cas suivants :

- constructions linéaires,
- constructions de secteur,
- peu constructions (de point).

Un système de surveillance semblable a été développé pour le Conduit de gaz Russe-Turquie "Jet bleu".

Keywords: environmental geology, geological hazards, database systems, remote sensing, risk assessment.

INTRODUCTION

Environmental control is an obligatory condition for exploitation of large linear constructions, such as gas pipelines, oil pipelines, and others. The environmental control includes control for groundwater and natural geological hazards, such as landslides, karst, and underflooding. Main requirements to the monitoring systems of the large linear constructions results from their extension, durable exploitation time, changing conditions, and high safety requirements. The system must work in changing environment across a large area, fulfil an integrated control for the whole geological environment, and perform on-line data processing.

The Institute of Environmental Geoscience of RAS used the named principles and methods for developing the integrated environmental monitoring systems, such as the monitoring system of geological hazards for gas pipeline "Blue Stream" (Russia-Turkey), as well as a number of other major gas pipelines and other objects.

DESIGN OF THE MONITORING SYSTEM

The Main Scientific and Managerial Problems

The main problems are: integration, representativeness, responsiveness, and adaptability of the monitoring system.

The problem of integration deals with area and time optimization of measurement mode for monitoring a set of interrelated but different geological components with different variability. The problem of responsiveness deals with realizing rather short measuring cycle. The problem of adaptability includes structure and operating changes of the monitoring system according to changing nature environment and the engineering construction.

The Main Principles of the System

The monitoring system is based on the following principles:

- The system executes the combined control over the entire set of observed geoenvironment components.
- The information measurement system combines contact and remote control methods, permitting wide areal coverage and observation extrapolation.
- The system uses a method of obtaining and processing data based on the existing natural relationships of different environmental components (wide use of indicative properties of vegetation).
- The system controls the current state of the observed geoenvironmental components and makes dynamic assessments of its development, (i.e. by the retrospective analysis, and comparison with predicted variation in the observed component status).
- The system operates in the on-line environment enabling regular communication exchange between all system elements and on-line information.
- The structure and operation of the environmental monitoring system are tailored to the modifying environmental conditions and construction development.

Structure and Composition of the System

In order to satisfy the named requirements the most rational structure of the on-line integrated monitoring system should include:

- Data collecting net,
- Data managing subsystem,
- Data transfer subsystem.

Data collecting net (DCN)

This should combine certain types of measuring units, such as automatic control stations of geological processes, visitation control stations, mobile control at vehicles or helicopters, and remote sensing control. Automatic control stations are used for ground spot monitoring of rapid processes, such as seismic events and landslides. For example, an automatic control station of landslides consists of groundwater gauges, seismic acoustic control, and inclinometers. Data transfer could be performed by radio or phone or cellular phone. Visitation control stations and mobile control are used for ground spot monitoring of middle speed processes, such as waterlogging, landsliding, and others. The control in the visit regime is performed using automobiles, floating facilities or helicopters equipped with required measurement devices (electric level gauge and GPS-equipment). The information is registered manually. Remote sensing data are used for area control of non-rapid processes, detecting new areas of hazardous processes and interpolation of the ground data. In addition, the remote sensing method permit us to adapt the monitoring system, to reveal new centres of hazardous geological processes (new landslides, collapses, etc.), which, if necessary are controlled at the surface. Spectral or multispectral, airborne or space images are used with resolution better than 2.5–0.5 m pixels.

The posts of automatic landslide control used in monitoring systems of a number of gas pipelines and intended for the on-line regime operation will be incorporated into this system as examples of automatic control posts. These posts provide the control of the following parameters:

- The seismic-acoustic emission level,
- The groundwater level,
- The soils and rock massif movement (by tracing the position of the long axis of inclinometer).

The control over seismic-acoustic emission allows us to obtain movement indications at the preliminary stage of landslide development, i.e., 2-3 days before the active landslide movement. The groundwater level control provides the information on the most important landslide factor and recalculates the parameter of landslide stability. The rock-massif movement control provides information about the start of active landsliding phase. The indicated parameters are controlled in boreholes drilled in the landslide body on the landslide-prone slope. The appropriate registering gauges are installed in boreholes. The equipment of each borehole provides the control of only one parameter.

Control stations may include the following components:

- The points of seismic acoustic emission control,
- The points of inclinometric control;
- The points of groundwater level control,
- The complex of primary data collection,
- The alignments of geodetic control consisting of geodetic landmarks.

The following registering complexes are installed at control points and are equipped with the appropriate sensing units:

- The seismic acoustic control unit,
- The inclinometric control unit,
- The groundwater level control unit.

For visiting operations, different equipment is used, mounted on an automobile or a helicopter. The automobile is equipped with a computer -based automatic work place of mobile geological control (AWP-GC). This soft-hardware serves for collecting and on-line processing of data at specific sites of geological hazards when developments occur. For example, in steppe regions, hazardous geological processes affecting the gas transportation pipeline control can be remotely observed through the following processes:

- The displacement of landslide bodies and their separate blocks,
- Bogging, overmoistening, and alteration of water body outlines,
- Changes in collapsible and land subsidence depressions,
- The growth of erosion landforms,
- Abrasion,
- Accumulative processes on shoals,
- Appearance of groundwater discharge sites,
- Soil salinization,
- Technogenic impacts (new traffic routes, dumps, etc.)

The indicative principles of image interpretation permit us to obtain data on geoenvironment components using indirect signs. The procedure of remote survey data processing is based on a wide use of computer processing.

Data managing subsystem (DMS)

This controls the DCN and deals with collecting, transferring, processing, and storing monitoring data in the system. DMS also makes mathematical modelling of natural and man-caused processes including ecological forecast. The core of DMS is GIS and a database with special software, for example a module of ecological hazards development. Adaptability is an important characteristic of the system, which allows it to change the structure and operating mode according to changes of the environment.

The data are processed at a computer-based work place of a geologist (AWP-G) elaborated in IEG RAS. The AWP-G software is based on GIS-technology. It includes the following:

- The unit of complex data analysis (SKAD)
- The unit of landslide stability assessment,
- The software complex for data exchange.

The AWP-G dataware includes the following:

- The general data package,
- The detailed data package.

It is used:

- for control-stations sites,
- for centres of the most hazardous geological processes,
- by the geological profiles.

The general data package represents the set of informational layers characterizing the variation in environmental conditions along the entire pipeline route within the band controlled by the geological hazard monitoring system. The detailed data package for the control-station site or the geological hazard development centre represents a set of information layers describing the status of the mobile geoenvironment components at the given site and the modifying factors.

The unit of complex data analysis is intended for the combined analysis of data on the current stage and dynamics of various environment components both of cartographic and attributive character of various detail levels. The block is one of the main elements in AWP-G and operates in interactive regime. The unit operates in MapInfo program. The combined-analysis complex is intended for solving the following problems:

- analysis of geological hazards development for predicting
- revealing of hidden sources of anthropogenic impact on the environment
- Generalization of monitoring data
- Comprehensive assessment of geoenvironment conditions
- Compiling reports on the conditions of the territory under control.

The input data for the unit operation include the entire set of graphical and attributive data on geoenvironment conditions at the linear engineering structure provided by the monitoring system. The data-processing deliverables include the materials on complex analysis and assessment of geoenvironment conditions in the observed territory.

The last version of SKAD is intended for performing the combined data analysis. It includes the following:

- Visualization of the observation data package according to target area designation at a smaller scale
- Visualization of the engineering-geological cross-section data package according to the target cross-section line designation in the map
- Visualization of a photographic image by the target shooting point and data designation
- Aerial image visualization by the designation of target central point
- Building the graph of parameter variation (the water level, the seismo-acoustic emission intensity, etc.) according to target control post and time interval designation
- Building the graph of geodetic profile and reference point alterations according to the designation of target measurement dates and profiles
- The inquiry realization by the parameter and the time interval
- The prediction of the outlines of the varying object area (collapsing or waterlogging area, etc.) according to the designation of two initial object outlines and the forecast date.

The unit of landslide stability determination is intended for the assessment and prediction of the stability of the controlled landslide sites by the regime and target designations.

The following are the input data necessary for the unit operation:

- The current relief elevation
- The current groundwater table level.

Also used are:

- The position of sliding surface of the landslide body
- The parameters of physical and mechanical properties of soils and rocks occurring within the limits of the controlled landslide site (the internal friction angle (φ) – *degrees*, cohesion (c) – (t/m^2))
- The seismicity of the region, where the controlled slope is located.

The processing deliverables comprise the following:

- The values of slope stability coefficients
- The landslide pressure values for the given combination of ground layers and groundwater in the slope
- The new position of the sliding surface of the landslide body.

The software data-exchange unit is used for exchanging information between AWPs (both mobile and stationary) as well as with the external data sources.

The software unit provides:

- Receiving information and filling up the measurement database
- Exchange with electron messages confirming information exchange and compiling the message database
- Receiving of cartographic, measurement and text information coming from the external information sources (dump outlines, data interpretation materials, etc.) and filling in the database.

Future System Development

The prospects in future development of on-line monitoring systems of hazardous geological processes are as follows:

- Broadening of the hardware and equipment base, in particular, the development of measurement equipment, providing the automatic on-line control of reference geodetic marks displacement
- The development of methods and software means for the on-line calculation of probability of impact and risk assessment.

THE ASSESSMENT OF THE IMPACT PROBABILITY

Mathematical Modelling as a Base for the Assessment

The assessment of the Impact probability of linear engineering structures is one of the latest developments in this field based on the methods of landscape mathematical morphology. The mathematical model gives a solution for a task of a linear construction affected by a process, forming the morphological structure of diffusive type. These are the processes developing from isometric sites (initial isolated areas of process development) randomly located within some region. Processes of this type develop under uniform conditions and include karst, subsidence, thermokarst and aeolian process. Here, we call these exogenic geological processes "*diffuse processes*".

Assumptions of the Model

The model is based on the following assumptions.

- The appearance of a new site during any time within any clear area is an occasional event independent of other sites and the probability of this is directly proportional to the time period and the area.
- The probability that two or more sites occur is negligibly small in comparison with appearance of the only one site.
- A new site cannot appear within another site.
- Changes of a new site of isometric form are described with an occasional process $F_0(x, t)$ (the probability density $f_0(x, t)$).
- Different sites change independently on each other.
- Site increasing can stop after reaching a critical limit (size) with distribution F (x). Then the site stops to increase and immediate "degeneration" takes place. The critical size does not depend upon other sites.

The Model Solutions

The mathematical model gives a solution for a task of a linear unit affected by a diffuse process. The resulting distribution for a number of diffuse process sites is a Poisson distribution with a free parameter as it follows from the first assumption:

$$P(k) = \frac{[\gamma(t)S]^k}{k!} e^{-\gamma(t)S} \tag{1}$$

Where $\gamma(t)$ is an average number of sites per unit area at time t, S – the given area.

Let us take a linear construction (of length L) crossing a uniform section under the diffuse process in question. Let the section be an infinite band of corresponding width (L), perpendicular to the linear construction. We need to analyse the distribution for a number of intersections of the linear construction with active sites of the diffuse process.

Let us consider a band of a finite length 2R. The probability that at least one of the named sites touches the linear construction depends upon its radius and the distance between its centre and the construction. Thus, the probability is

$$\alpha = \int_0^R [1 - F_1(x,t)] \frac{dx}{R} \tag{2}$$

The probability that v sites touch the linear construction, if a total number of sites within the band is k, is

$$P(v,k,R) = \binom{k}{v} \alpha^v (1-\alpha)^{k-v} \frac{(2\gamma(t)RL)^k}{k!} e^{-2\gamma(t)RL} \tag{3}$$

Correspondingly, the number of touches for a random number of the sites within the band can be obtained by summing over *k* and is

$$P_R(\nu) = \frac{(2\alpha\gamma(t)LR)^{\nu}}{\nu!} e^{-2\alpha\gamma(t)LR} \tag{4}$$

The expression for the infinite band results from the limit in the previous equation if R→+∞, and taking into account that

$$\lim_{R\to+\infty} \alpha R = \int_0^{+\infty} [1 - F_1(x,t)]dx = \lim_{R\to+\infty} x[1 - F_1(x,t)] + \int_0^{+\infty} x f_1(x,t)dx \tag{5}$$

Thus we get

$$\lim_{R\to+\infty} \alpha R = \bar{r}(t) \text{ and } P(\nu) = \frac{[2\gamma(t)L\bar{r}(t)]^{\nu}}{\nu!} e^{-2\gamma(t)L\bar{r}(t)} \tag{6}$$

Where $\bar{r}(t)$ is an average site radius at time t.

Therefore, the resulting distribution for the number of impacts from sites of the diffuse process on a linear construction is a Poisson distribution with a free parameter. The parameter is equal to the product of the length of the linear construction by the distribution density of sites and their average diameter.

The parameter is equal to a product of a linear unit length by distribution density of sites and their average diameter.

$$\gamma_l = 2\gamma(t)\bar{r}(t) \tag{7}$$

Besides, an impact probability for a linear unit is

$$P_{dl} = 1 - \exp[-2\gamma(t)\bar{r}(t)L], \tag{8}$$

Where *L* is length of the linear unit.

Taking into account possible impact on the construction by the active sites, which turned into degenerated ones to a point of time t, one can get :

$$P_{dl}(b) = 1 - \exp\{-2[\gamma(t)\bar{r}(t) + \gamma_{dg}(t)\bar{r}_{dg}(t)]L\}, \tag{9}$$

Where $\gamma(t), \bar{r}(t)$ are an average number and average radius of active sites per unit area at moment *t,* while $\gamma_{dg}(t), \bar{r}_{dg}(t)$ is the same for degenerate sites.

Let us find *an average impact risk for a linear construction* of length *L*. Risk is considered an average of the distribution for length of linear construction segments affected by the active process. Let us find an average length of a linear construction segment within an active site.

The probability for the segment length being greater than *x* is

$$P(\xi > x) = \int_{\frac{x}{2}}^{+\infty} \frac{1}{\nu}\sqrt{\nu^2 - (\frac{x}{2})^2} f_1(\nu,t)d\nu = \frac{x}{2}\int_{\frac{x}{2}}^{+\infty} \sqrt{1 - (\frac{x}{2\nu})^2} f_1(\nu,t)d\nu \tag{10}$$

Where f_1(x,t) is the distribution density of radii of active sites at a point of time *t* if a stop factor exists.

By converting, one can derive the value distribution for impact on a linear construction by one site of the diffuse process.

$$F_{rl}(x,t) = 1 - \frac{x}{2}\int_1^{+\infty} \sqrt{1 - \frac{1}{u^2}} f_1(u\frac{x}{2},t)du \tag{11}$$

Taking into account the finite moment of the second order

$$\int_0^{+\infty} xf(x)dx = \int_0^{+\infty} [1 - F(x)\}dx \quad ,$$

One can get

$$\overline{r_l}(t) = \int_1^{+\infty} \frac{x}{2} \int_1^{+\infty} \sqrt{1 - \frac{1}{u^2}} f_1(u\frac{x}{2}, t)dudx \quad . \tag{13}$$

By converting one obtains

$$\overline{r_l}(t) = \int_1^{+\infty} \frac{2}{u^2} \sqrt{1 - \frac{1}{u^2}} \bar{r}(t)du \quad , \tag{14}$$

This means that the average impact by one site is

$$\overline{r_l}(t) = \bar{r}(t)\frac{\pi}{2} \tag{15}$$

Taking into account equation (16) for the probability of impact on a point of the linear construction one can find the average risk value:

$$R_l(L) = \{1 - \exp[-\gamma(t)s(t) - \gamma_{dg}(t)s_{dg}(t)]\}L \tag{16}$$

The given model can be practically used for engineering construction impact probability assessment and evaluation of possible damage. Let us consider an example of linear construction impact probability assessment such as a pipeline.

Let us determine thermokarst impact probability for a straight linear construction of length (L) and operating time (T) within a uniform area of a plain developing under thermokarst and fluvial erosion processes. The impact probability results from product of the two probabilities.

$$p = p_1 p_2 \tag{17}$$

The first one P_1 is the impact probability for an engineering construction due to growth of the thermokarst sites that had appeared before the construction was built. The second probability takes account of an impact from new sites, which originated after the construction was built.

The first probability takes into account independence of thermokarst sites development from each other and is given by the product:

$$p_1 = \prod_{i=1}^{m} [1 - F^0(r_i, \nu_i, T)] \tag{18}$$

where r_i is a distance between the center of existing and the linear construction,
ν_i is i thermokarst site radius,

$$F^0(x, \nu, t) = \int_{-\infty}^{x} f^0(u, \nu, t)du \tag{19}$$

Where f_0(x, ν, t) is the possibility that the site get radius not more than x after time t, and at initial radius v. Hence f_0(x, ν, t) is a function of transition probabilities in case when the diffuse process in question is described with the Markov stochastic process. As it comes from the mathematical model for the morphological pattern of thermokarst and fluvial erosion plains [2], the necessary function is given by the equation:

$$F^0(x,v,t) = \int_0^x \frac{1}{\sqrt{2\pi}\sigma u\sqrt{t}} \exp\left[-\frac{(\ln u - \ln v - at)^2}{2\sigma^2 t}\right] du \tag{20}$$

The second probability P_2 is obtained from the following assumptions.

Let a site appears at moment t from the interval [0,T] on the distance x from the linear construction. The impact probability for a linear construction is determined by the probabilities that the critical size (stop-factor) and the radius of the site are larger than the distance to the linear construction.

$$\alpha = \int_0^T \int_0^R [1 - F(x)][1 - F_0(x,t)]] \frac{dx}{R} \frac{dt}{T} . \tag{21}$$

The probability that v sites touch the linear construction, if the total number of sites within the band is k, is

$$P(v,k,R,T) = \binom{k}{v} \alpha^v (1-\alpha)^{k-v} \frac{[2\lambda(1-P)TRL]^k}{k!} e^{-2\lambda(1-P)TRL} \tag{22}$$

Where λ is an average number of sites, occurring within a unit area per unit time.

After summing over k and proceeding to we get the expression for the impact probability of an engineering construction:

$$P_{dl}(L) = 1 - \exp[-2\beta(T)\lambda(1-P)L] , \tag{23}$$

where $\beta(T)$ is determined by the equation:

$$\beta(T) = \lim_{R\to+\infty} \alpha RT . \tag{24}$$

It is easy to see that taking into account (36) one can get its analytical formula:

$$\beta(T) = \int_0^T \int_0^{+\infty} [1 - F(x)][1 - F_0(x,t)]] dx dt . \tag{25}$$

This formula can be defined concretely according to the obtained results (Viktorov 2005), basing on the radii distribution function for thermokast sites of a thermokarst and fluvial erosion plain (lognormal distribution)

$$F_0(x,t) = \int_0^x \frac{1}{\sqrt{2\pi}\sigma u\sqrt{t}} \exp\left[-\frac{(\ln u - at)^2}{2\sigma^2 t}\right] du \tag{26}$$

And the distribution function for the critical value

$$F(x) = 1 - \exp(-\pi\gamma x^2) , \tag{27}$$

Where γ is the average density of fluvial sources. Direct substitution yields:

$$\beta(T) = \int_0^{+\infty} \exp(-\pi\gamma x^2) \int_0^T [1 - \Phi\left(\frac{\ln u - at}{o\sqrt{t}}\right)] dt dx , \tag{28}$$

where $\Phi(t)$ is the Laplace function. It is possible to simplify this equation:

$$\beta(T) = \frac{T}{2\sqrt{\gamma}} - \int_0^{+\infty} \exp(-\pi\gamma x^2) \int_0^T \Phi\left(\frac{\ln u - at}{o\sqrt{t}}\right) dt dx \tag{29}$$

It is easy to see that impact probability for linear constructions is determined by parameters α, σ, λ, P, γ . All these parameters can be detected rather precisely from repeated air-borne or space-borne high precision photogrammetry. We get the necessary parameters from the equations:

$$a = \frac{M_2 - M_1}{t_2 - t_1},\ \sigma = \frac{\sqrt{D_2 - D_1}}{t_2 - t_1},\ \lambda = \frac{n_2 - n_1}{(t_2 - t_1)S},\ P = \frac{S_t}{S},\ \gamma = \frac{m}{S} , \tag{30}$$

Where t_1,t_2 is the time of the first and second surveys, M_i is the average radii logarithm of the thermokarst sites (lakes) within the testing area at the corresponding time of the survey, D_i- is the logarithm radii variance of the thermokarst sites (lakes) within the testing area at the corresponding time of the survey, S is the total testing area, S_i is the part of the testing area occupied with the thermokarst sites, m is the number of fluvial sources within the testing area.

CONCLUSION

The suggested quantitative assessment technique of impact probability for large linear construction on the base of mathematical morphology of landscapes can be used for the software module of on-line risk assessment in frame of the monitoring system for geological hazards.

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