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THEORETICAL CONCEPT AND PRACTICAL IMPLEMENTATION OF THE NEW INTEGRATED METHODOLOGY FOR LANDSLIDE HAZARDS EARLY WARNING SYSTEMS

ABSTRACT

The global climate changes and continued expansion of land use result in a tangible raise of the landslides frequency and intensity. Landslides are an important component of a number of major natural disasters and are charged with far greater losses than it is generally recognized. Usually, they are referred to in connection with floods, earthquakes or volcanoes eruptions with the losses from landslides often exceeding all other damages from a general disaster. During the last decade (from 2000 to 2009), the natural disasters damaged and destroyed about one million objects directly affecting nearly 2.5 billion people around the world. Every year in Europe about 20 major landslides occur, and this considerably exceeds the number of floods, earthquakes and hurricanes. Early warning systems are an effective tool for preventing and mitigating the risks associated with the occurrences of various types of threats (including landslides). The paper presents and describes the concept and practical implementation of the new integrated methodology (NIM) for early warning systems (EWS), which is based on the integration of modern monitoring technologies and comprehensive numerical modeling of an object under study. The basic concept of an EWS installed on landslides is that the elements at risk, especially people being away from the dangerous area, must have sufficient time to evacuate, if an imminent collapse is expected. Therefore, the effective EWS shall include such four main sets of actions: monitoring of the observed object activity, i.e. the data collection and transmission, as well as the equipment maintenance; the analysis and modeling of the observed and studied object; warning, i.e. the dissemination of simple and clear information about the observed object; the effective response of risk exposed elements; full understanding of risks. The examples of the practical application of the proposed integrated methodology to various construction projects and natural and technological systems are given, including 1) the Central Livadia Landslide System and Livadia Palace, 2) a system for landslide hazard areas monitoring in the Kharkiv region; and 3) a landslides early warning system using unmanned aerial vehicles as a specialized monitoring system for shear deformations.

KEYWORDS: Concept, methodology, hazard early warning, monitoring and numerical modeling.

ТЕОРЕТИЧНА КОНЦЕПЦІЯ ТА ПРАКТИЧНА РЕАЛІЗАЦІЯ НОВОЇ ІНТЕГРОВАНОЇ МЕТОДОЛОГІЇ СИСТЕМ РАННЬОГО ПОПЕРЕДЖЕННЯ ПРО ЗСУВНУ НЕБЕЗПЕКУ

АНОТАЦІЯ

Глобальні кліматичні зміни і триваюче збільшення землекористування викликають помітне збільшення частоти та інтенсивності зсувів. Зсуви є важливою складовою низки значних стихійних лих і несуть відповідальність за набагато більш великі втрати, ніж загальновизнано. Зазвичай часто про зсуви згадують у зв'язку з повенями, землетрусами або виверженнями вулканів навіть при тому, що втрати від зсувних руйнувань можуть перевищувати всі інші збитки від загальної катастрофи. Протягом останнього десятиліття (з 2000 по 2009) стихійні лиха пошкодили та зруй-

нували близько одного мільйона об'єктів, що безпосередньо торкнулося майже 2,5 млрд людей в усьому світі. Щорічно у Європі трапляється близько 20 великих зсувів – значно більше, ніж повеней, землетрусів та ураганів. Системи раннього попередження про небезпеку є ефективним інструментам для запобігання та пом'якшення ризиків, пов'язаних з виникненням різного типу загроз (зсувів у тому числі). У статті представлена і описана концепція та практична реалізація нової інтегрованої методології систем раннього попередження, яка заснована на інтеграції між сучасними технологіями моніторингу і всебічним чисельним моделюванням досліджуваного обєкту. Основна концепція EWS, встановлених на зсувах, полягає в тому, щоб елементи, котрі схильні до ризику, особливо люди, що знаходяться далеко від небезпечної зони, мали достатньо часу для евакуації у випадку очікування неминучого колапсу. Тому дійова і ефективна EWS повинна включати в себе чотирі основні набори дій: моніторинг активності об'єкта спостереження: збір даних, передача і обслуговування обладнання; аналіз і моделювання досліджуваного об'єкта; попередження - розповсюдження простої і зрозумілої інформації про об'єкт спостереження; ефективна реакція у відповідь елементів схильних до ризику; повне знання ризику. Наведено приклади практичної реалізаії запропонованої інтегрованої методології для різних будівельних об'єктів та природно-техногенних систем: 1) Центральна Лівадійська зсувна система та Лівадійський палац, 2) система моніторингу зсувонебезпевних ділянок Харківської обл., 3) система раннього попередження зсувів з використанням безпілотних літальних аппаратів в якості спеціалізованої системи моніторингу зсувних деформацій.
КЛЮЧОВІ СЛОВА: концепція, методологія, раннє попередження про небезпеку, моніторинг, чисельне моделювання.

INTRODUCTION

The global climate changes and continued expansion of land use result in a tangible raise of the landslides frequency and intensity. Landslides are an important component of a number of major natural disasters and are charged with far greater losses than it is generally recognized. Usually, they are referred to in connection with floods, earthquakes or volcanoes eruptions with the losses from landslides often exceeding all other damages from general disasters. During the last decade (from 2000 to 2009), the natural disasters damaged and destroyed about one million objects directly affecting nearly 2.5 billion people around the world. Every year in Europe about 20 major landslides occur, and this considerably exceeds the number of floods, earthquakes and hurricanes [1].

In the USA all states and territories suffer from landslides and other soil problems. Moreover, in 36 states the landslide hazard has changed from moderate to extremely dangerous. Landslides in the United States are a serious hazard and every year result in significant human and financial losses amounting from 25 to 50 deaths and from one billion to three billion dollars damages [2]. In Ukraine landslides are on the top in terms of caused losses and their number has increased by 1.3 times over the last 15 years and approximately by 3 times during 30 years [3].

Massive landslides were observed in Kyiv in April 2014: "The landslides have again become more active in Kyiv. Soil already slumps at 131 sites all over the city (last year there were 125 such areas). Experts say the city could be threatened by large-scale land slips, because caving soil can damage roads, houses, water supply system, heating mains and gas pipelines" [4].

The landslide hazards study requires the answers to two fundamental questions:

1. "Where and when can landslides occur?" and
2. "How to avoid them or mitigate their consequences?"

The early stage of the landslide hazards automated study has begun with a variety of monitoring systems, the main role of which was to collect information about an object or phenomenon under study.

The term "monitoring" originates from the English verb "to monitor" (to check, supervise, watch or keep track of) derived from Latin monit - 'warned' or monere - to warn, admonish or remind. In a variety of scientific and practical activities, the method of observation has been used for a long time as a method of knowledge acquisition based on relatively long-term, purposeful and systematic perception of objects and phenomena of the surrounding environment. The brilliant patterns of the nature observation management were described in the first century AD in the Natural History (Naturalis Historia) by Pliny the Elder (Gaius Plinius Secundus). The work was divided into 37 books organized into ten volumes. They covered topics including astronomy, geography, geology, zoology, botany, mineralogy etc. and became the most complete encyclopedia until the Middle Ages [5].

The organization of observations of the hydrocarbon oxide content in coal mines air in England and Belgium more than 100 years ago can be considered as the environmental monitoring historical beginning. For those observations canaries, guinea pigs and cockroaches were used as some kinds of sensors [6]. The systems for recording and accumulating information are the simplest forms of monitoring or of monitoring systems (MS). The historical sciences, which gather and analyze the data on historical facts and events, seem to be the oldest among such systems. In the 20th century, due to the modern information and analytic bases and the computerization of all fields of science and technology, the monitoring systems have spread everywhere, including technology [7], economics [8], medicine and sociology [9], public administration etc [10-11].

There are many various definitions of monitoring, for instance:

1. Monitoring (Latin monitor - who reminds or warns) is a complex system of observations, assessments and predictions of changes in the states of a technical object or its individual elements and nodes under the various actions influences.
2. Monitoring can be understood as the continuous observation of system component elements or the system as a whole to establish their development regularities, forecast the development, make the managerial decisions and control their implementation results [12].
3. Seismo-acoustic monitoring is based on the observation of the seismo-acoustic wavefield of the object under study. At present the physical, geological and methodological principles of seismo-acoustic monitoring [13] are being developed. They will provide for the possibilities to detect and interpret the seismic wavefields variations by the available hardware, methodological and computational tools [14].
4. Monitoring can be regarded as a set of operations on data collection, accumulation and transformation in order to extract from them an information in a form, which can best satisfy the information needs of the user, and with the maximum possible computerization of its following components [15]:
   - content-related component covering the information technology processes of preparation and design including problems statement, used models and methods of applied mathematics and information support;
   - functional component including complex documenting, circulation and processing of information;
   - system activities component formalizing the human activities structural units, including reasoning, interactive modeling abilities, procedures and technologies, in compliance with a powerful computing base, i.e. system-wide and hardware equipment.

The purpose of monitoring is to determine the time points, at which the deviations from the normal operation of the object under study occur. The main role in monitoring belongs to the information system for the observations and assessment of object current state and trends of technical state (TS) variation under the operating conditions. The amount of experimental data obtained during monitoring constitutes the scientific basis for planning the measures to resume the technical state and the optimal methods to achieve this goal (by time, cost, parts and mechanisms replacement necessity etc.).

The main task to be solved in the monitoring process is the detection and assessment of the recorded field deviation from the stationary state. But prior to this, at a preliminary stage, it is important to study and find the stationary state characteristics. The mathematical modeling use makes it possible to assign a certain set of technical state indicators, which correspond to the normal or optimal state of the object under study, to a given natural or technical object. To identify the object state by means of analysis, the most informative indicative parameters, the combination of which represents the state of the object under study, should be selected. For observations the indicative areas, nodes and mechanisms, that is, areas with the most dynamic (or, on the contrary, stable) state variations can also be chosen. In the process of monitoring, the indicative parameters actual values shall be recorded [16 and 17].

In 2001 the President of the National Academy of Sciences of Ukraine, the academician B.E.Paton in his report on the problems of constructions, buildings and equipment resources in Ukraine presented at the scientific and practical conference "Reconstruction of buildings and structures. Experience and problems" noted that in recent years a new direction of the continuous monitoring of the state of the most loaded elements, the failure of which can cause significant consequences, has been developed in order to improve the critical structures safe operation. ***Special systems for monitoring*** the structures state have been worked out. They allow estimating both the actual loading (for example, in case of earthquakes) and the degradation of the structural elements resistance against real loads. A wide range of such solutions relating to bridges, dams, tunnels, bridge railroads etc. and taking into account the requirement of their reliable service during a period from 50 to 100 years are known in the USA and Europe. Such systems differ in the type of sensors and the saturation of an interface for recording, storing, transferring and processing measurement results. The equipment should meet the high requirements of performance reliability during long service life. A very important issue is cost, since in the real structures the number of "hot spots", that is, the sensors installation places, can reach several thousands. Nevertheless, the costs of such systems for monitoring the structures state can be fully compensated by means of the accidents risks reduction, which now is well understood in the advanced economies of the world. Monitoring should be an integral part of any meaningful activity. The lack of monitoring leads to a loss of the link between an activity and its results, which, after all, inevitably leads to emergencies occurrences.

In view of the fact that monitoring systems relate to the information technologies field, since 2001 they have undergone very thorough changes. As a result, the information technologies, hardware and strategies for landslide analysis and soil disaster risks mitigation require permanent and continuous improvement by various means, including landslide hazard early warning systems (LH EWS).

CONCEPT OF THE EARLY WARNING SYSTEMS NEW INTEGRATED METHODOLOGY (EWS NIM)

As defined by the UN International Strategy for Environmental Disaster Reduction (UN International Strategy for Disaster Reduction, UNISDR 2009), the Early Warning System (EWS) is "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss" [18].

This general definition can be applicable to any danger and does not contain a direct reference to landslides. Regardless of the definition and the hazard considered, EWS is used to reduce the risk by affecting the impact on exposed elements. The basic concept of EWS installed on landslides is that the elements at risk, especially people being away from the dangerous area, must have sufficient time to evacuate, if an imminent collapse is expected.

Therefore, an effective EWS shall include such four main sets of actions [19]:

- Monitoring of the observed object activity, i.e. the data collection and transmission, as well as the equipment maintenance;
- The analysis and modeling of the observed and studied object;
- Warning, i.e. the dissemination of simple and clear information about the observed object;
- The effective response of risk exposed elements; full understanding of risks.

The key to the successful application of landslides EWS is the system ability to identify and measure in real time a limited number of important indicators called precursors that precede landslide catastrophic movements including disturbances and collapses. The recent advances in the development of control and measuring equipment in conjunction with GPS and photogrammetric techniques have increased the potential for obtaining the highly reliable measurements of various parameters, which then can be used to detect landslide activity preceding the entire slope breakage [20-28].

It is quite obvious that whenever the mechanics and instability mechanism of a particular slope are ignored, it may be difficult or simply impossible to rely solely on the analysis based on the surface displacements and velocities measurements. Therefore, it is necessary to describe the landslide forerunners for the purposes of early warning about soil movements [29-31].

As EWS in its components is time-sensitive or stochastic errors susceptible, it is necessary to develop the EWS designing methodology, which will determine the methods for integrating the monitoring information sources, identifying the potential hazard thresholds and assessing the associated risks within the frameworks of an explicit cause-and-effect analysis. Since both the corresponding forerunners and the landslides characteristic elements can vary depending on the landslide type and its location (urban, rural or mountainous areas), each EWS can be tailored for each particular landslide area to be investigated.

The **LH EWS NIM** is usually based on a real-time monitoring of the landslide surfaces displacements and displacements velocities (I), as well as on the realistic numerical prediction of their behavior (II), i.e., the methodology is ensured by the use of these both approaches (I&II) taken together.

The **LH EWS NIM** consists of four main components shown in the block-diagram of fig. 1.

Each module performs certain functions. The surface displacements and velocities are chosen here as precursors, although the methodology architecture has been designed to ensure compatibility with a wide range of precursors that would be used for the various types of landslides. The LH EWS methodology includes four main elements as follows:

1. Special monitoring module;
2. Integrated monitoring module;
3. Module of characteristics description and mathematical modeling;
4. Module of analysis (verification).

Modules 1 through 3 are the input data sources for the decision-making algorithm (orange dotted frame at the bottom of the flowchart). The algorithm allows the continuous assessment of hazard levels and identifies the appropriate actions to be taken to ensure an adequate safety level for elements exposed to risk.

In Fig. 1 there is also the time scale (t_0, t_1, t_2 and t_3), which should be as follows:

t_0 can be considered as the initial control time. For the first occurred violation of a soil, the value of t_0 represents a period of time prior to landslides emergence. For a dormant or potential landslide, t_0 represents the landslide reactivation time;

t_1 is a time directly from the moment immediately after t_0 to about the next three days;

t_2 is a time from 3 to about 20 days after t_0;

t_3 is a time exceeding 20 days after t_0.

The special monitoring module (1) is the first to be triggered and to ensure the EWS setting at t_1 period when the critical conditions require the warning system immediate activation. Modules 2 and

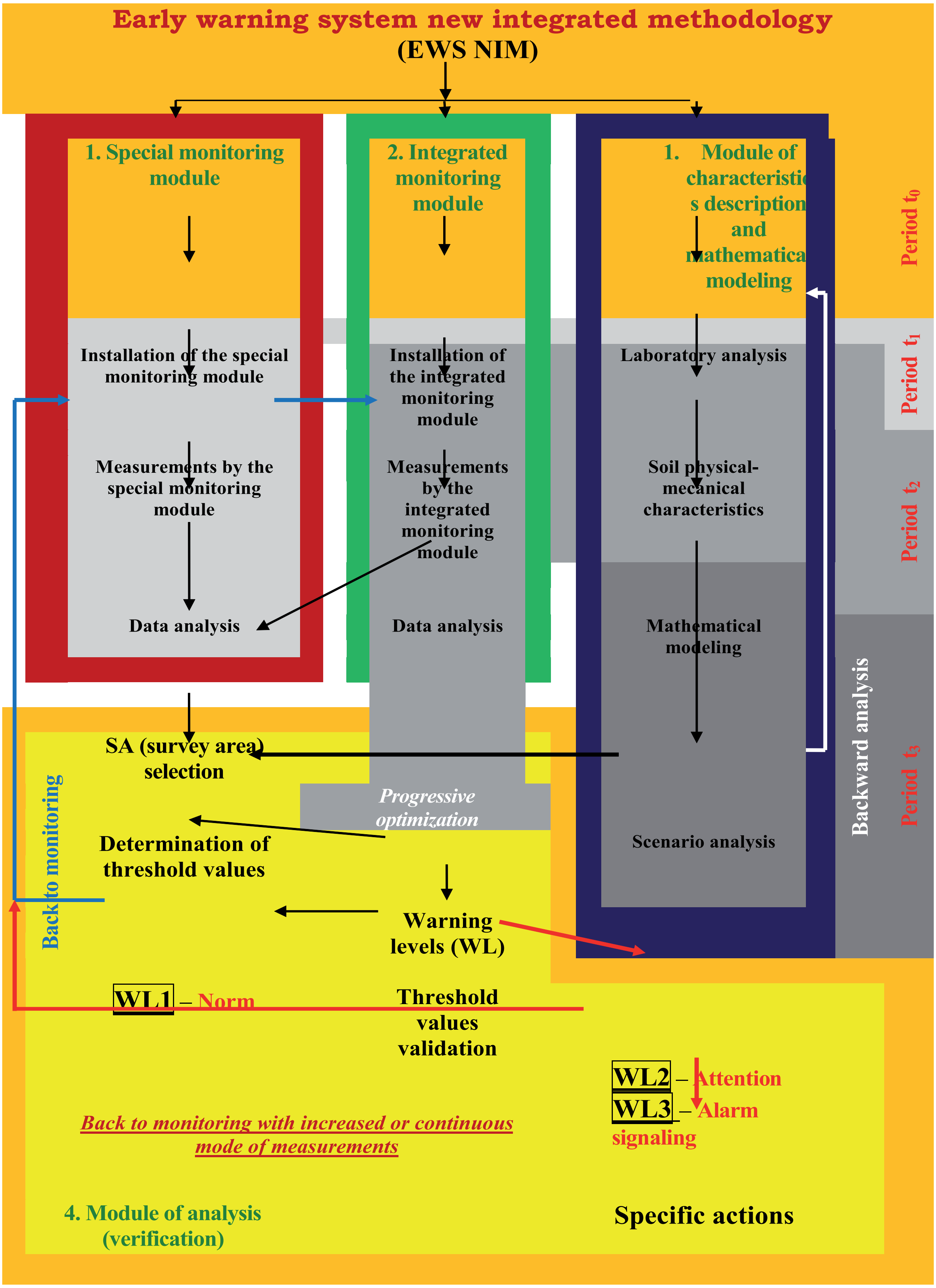

Figure1 – LH EWS NIM block-diagram

3, which perform the general monitoring (2) and characteristics description and modeling (3), can be started simultaneously, but this requires additional time to provide for the feedback (outputs) useful for the EWS optimization.

For instance, among all known landslide monitoring systems there is the GBInSAR system, which is unique due to its radar capabilities for measuring the surface bias field and velocity with millimeter accuracy over the entire landslide (or pit surface) practically in real time with a detection frequency of several minutes under any weather conditions without the necessity of any contact sensors installation on a landslide [32-33]. These functions allow obtaining the maps of the monitored area displacements and velocities in a few hours after the system setting (t_1). The possibility of obtaining the displacement maps, which are updated every 10 minutes or less, fully meets the real-time monitoring system requirements, especially in emergency conditions, and is an important additional advantage of such a monitoring system [32-33].

The integrated monitoring module (2). The integrated monitoring module covers all operations related to the installation, collection and processing of data obtained from the geotechnical instruments (piezometers, inclinometers, extensometers, crack measuring devices etc.) arranged on the landslide and from the additional remote sensing equipment (i.e., a ground-based laser scanner, tachometers, photogrammetric devices etc.) that can be used to monitor the landslides [34-35]. The equipment arrangement on the site also implies the need for the staff and mechanisms to have an access to the works on the control points installation. Due to the time constraints, the availability of data from the standard monitoring module generally differs by a few days or weeks (t_2) after the occurrence of the first ground failure. If the devices are equipped with sensors that perform an effective procedure of data analysis in real time, it is possible to get a significant reduction of time required to get to the "core" algorithm of the decision-making unit.

The module of characteristics description and modeling (3). This module performs field studies (geological, geomorphological, structural and geophysical), laboratory tests on undisturbed and broken rocks and numerical modeling for the study of landslide triggering conditions and its evolution scenarios. All these activities usually require some time and their execution takes from one week to several months (t_2-t_3) after the landslide occurrence. The time spent for field surveys and on-site investigations is generally proportional to the level of detail. Field studies and on-site tests may begin within some days or weeks after the onset of instability (t_1), but to obtain reliable results, which will be used at the next stages (t_2), the basic time is required. Geotechnical laboratory tests also require some time to ensure the valid geomechanical parameters for numerical modeling. Laboratory tests, however, are a fundamental stage for obtaining the quantitative characteristics of undisturbed and broken rocks properties and provide the input parameters for numerical modeling. The selection of tests to be necessarily carried out is based on the soil physical and mechanical characteristics and the mechanism leading to this landslide instability.

Once the undisturbed and broken rocks characteristics determination is completed, the process of numerical modeling of the slope instability (t_3) may begin. Since the landslides analysis is often complicated because of the geometry or topography, material anisotropy, nonlinear behavior, stresses within slopes and the related processes presence (e.g., hydromechanical behavior), numerical modeling is the only solution that will properly use and take into account all these interactions.

The reverse analysis process [36, 37] based on the monitoring data obtained by GBInSAR or conventional monitoring methods, as well as the continuous calibration of numerical and physicomechanical parameters allow using with increased confidence the mathematical modeling results in the landslide scenario analysis for early warning purposes. Therefore, the numerical modeling results can forecast the landslide kinetic energy, displacement and velocity of a moving mass, its depth and final configuration after the deposition.

Verification module (4). The verification module is the last component, which represents the decision-making algorithm in the integrated methodology. It provides for a set of operations necessary for the constant and continuous determination of real-time hazard levels associated with the observed object of instability using data from at least one of the previously described analysis modules. The module of decision-making in compliance with the time variable can be ready for analysis performance within the interval from t_1 (a few hours after the landslide beginnings) to t_3 (several weeks) depending on the particular combination of chosen analysis modules. In this sense, it does not present any special restrictions as to the time of its operation activation.

The results of GBInSAR and other monitoring modules operation are consistent with the landslide kinematics determination and the subsequent interpretation of landslide displacement models. Various areas in complicated landslides may be characterized by different types of movements, velocities and volumes, and may manifest various short- and long-term behaviors under the actions of various "triggers" (e.g., precipitation). This can be explained by the introduction of the "Region of Interest" (ROI) concept. The ROIs are the landslide parts characterized by a uniform kinematic behavior (i.e., type, direction, displacement and velocity of motion) and a certain degree of activity.

After the ROI is determined, the next step in the algorithm is the selection of the threshold values that will be used in the decision-making algorithm. The general criteria for choosing adequate threshold values include the necessity to predict the landslide evolution scenario (or slope degradation modes) and the time required for a competent response. In the proposed methodology in the case of information unavailability, for instance, from the landslide monitoring network, the verification module is activated only via the radar monitoring module (time point t_1). As a consequence, the threshold values will be conservative to a large extent and will be selected by the method of expert ratings assessment. As the first data of GBInSAR monitoring are becoming available, it becomes possible to analyze the time series for various points of the landslide under study to gradually optimize the previously selected threshold values. At time point t_2 (from days to weeks after the landslides occurrence) this improvement can be ensured by other general (standard) monitoring data. The further and more reliable optimization of the threshold values, which will be taken for the landslide long-term monitoring, should be carried out at the time point t_3 based on the results of the characteristics description and mathematical modeling module (3).

In the proposed methodology, a typical set of three warning levels (WL1, WL2 and WL3) is used and, consequently, a two-threshold system (attention and alarm) is adopted (see table 1).

Each level of warning is then associated with the state of the landslide activity (normal or seasonal activity, increased activity or possible collapse) and activated by exceeding the corresponding threshold (boundary) value. For each warning level there is a set of responses that indicates, which actions (i.e., "What to do?" and "Who is responsible?") should be activated to mitigate the landslide hazard. A comprehensive consideration of specific actions is far beyond the scope of this report, since social, economic and political aspects that can be learned only from specific interdisciplinary risks assessment studies shall be taken into account. In the proposed scheme, the responses associated with each warning level have a feedback with the monitoring modules (1-3). When a certain threshold level is reached, the measurement frequency increases under the alarm condition until the maximum frequency of sensors scan is obtained and continuous monitoring is ensured. Once the hazard levels (warnings) and the corresponding threshold values are defined, the verification module (4) continuously compares in real time the results of the measurements in the selected quantity of ROI data with predetermined threshold values. The software is able to display in real time the maps of displacements and velocities generated during the processing, as well as to make the hazard level maps of controlled landslide area available on-line.

Table 1 - Warning levels accepted for an early warning system [38]

Warning level	Desription	Trigger	Response
WL1 – norm	Seasonal or long-term change of characteristics – **Seasonal activity**	Seasonal thresholds values are not exceeded	The standard measurement frequency. The check of seasonal variations.
WL2 – Attention	Changes of characteristics according to seasonal trends – **Increased activity**	Exceeding of relative threshold values	The measurement frequency increase. The preparation to the alarm raise.
WL3 – Alarm signaling	Acceleration of characteristics changes – **Collapse is probable**	Exceeding of relative threshold values and/or expert ratings	The maximum frequency of measurements. The twenty-four-hour observations. The manpower resource is necessary. Communicating with the population. The preliminary elaborated plan of actions to be implemented.

THE PRACTICAL IMPLEMENTATIONS OF THE LANDSLIDE HAZARDS EARLY WARNING SYSTEMS NEW INTEGRATED METHODOLOGY (LH EWS NIM)

1. As the first illustration of the LH EWS NIM practical embodiment the project «System of monitoring the Central Livadia landslide system (CLLS) and Livadia Palace» [34, 39, 40] implemented during 2002-2014 (Project Chairman Yu.I.Kaliukh) can be taken. In this project unit 2, unit 3 and partially unit 4 of the four units of the LH EWS NIM were implemented.

To study the CLLS geological environment state the monitoring system was developed and technically implemented on the computer. Heliogenic parameters included solar activity, changes in temperature and humidity regimes, the nature and intensity of precipitation, wind activity etc. The data were manually loaded into the computer. Lithogenic parameters were presented by a set of conditions and factors characterizing the mechanism and dynamics of changes in the equilibrium state of the CLLS slopes. The system performed the following actions:

1. Control of the CLLS reference points displacements by means of landslide surface visual observations and subsequent manual loading of information into the PC.
2. The continuous real-time monitoring of the deviation angle changes evolution for selected areas and zones within the landslide massif with the use of high precision electric inclinometers, filtering of electrical signals, converting of analog signals into a digital code by means of the analog-to-digital converter (ADC) and data real-time downloading into the PC.

The processing of the measurement results showed the following facts [41-44]:

1. The southeastern wing of the Livadia palace performs continuous waves relative to a certain intermediate position. These vibrations are of a noticeable periodic nature with a period being defined as twenty-four hours. The daily vibrations amplitude varies within the range of approximately 1.5 angular minutes, that is, about 45 angular seconds to every side away from the intermediate position. The vibrations are directed relative to the transverse building axis.
2. Sometimes (for instance, on February 13-14, February 26-27 and March 22-23, 2002), the Livadia Palace tilt angle increase was recorded. In those cases, the amplitude increased to 6 angular minutes. The calculation results showed that the usual daily vibrations were 1.9 mm to each side from the intermediate position, but on the mentioned days the vibrations were about 4.2 mm to each side from the intermediate position.
3. The exact correlation of those factors with the Livadia Palace civil structures dynamics was not proved because of the frequent forced breaks in the monitoring system operation. Such breaks were caused by the necessity to fulfill the mandatory requirements of the Security Service of Ukraine during the various official events of the All-Ukrainian and local (Yalta and Livadia) levels in the Livadia Palace and preliminary preparations for them. Since January 2014, the monitoring of the CLLS and the Livadia Palace has been completely ceased because of the Crimea occupation by Russia.

2. The project "System of GIS-monitoring of the landslide hazard slopes in Kharkivska oblast by means of ERS" [45–47] implemented during 2008-2011 (Project Chairman A.N.Trofymchuk) can be taken as the second illustration of the LH EWS NIM practical embodiment. In this project the unit 1, partially unit 3 and partially unit 4 of the four units of the LH EWS NIM were implemented.

As the basis for the proposed structure of the landslide hazard slopes information system the proprietary database and GIS (fig. 2) were taken. The developed database had an information and reference character and contained the brief information about fifty-two certificates of the Kharkiv region landslide areas and the data on the total precipitation during twenty years from 1983 to 2002 at the Kharkiv region meteorological stations. The database information could be used for the rapid assessment of landslides formation risk. The GIS contained the multilayer information on relief, gradients of slopes, hydrographic network, roads, landslide areas etc.

It was found that with the decrease of the distance between a road and landslide areas, the number of landslides increases. Despite the fact that the Kharkiv region territory is relatively small in size, its main part is struck by the landslide processes, which should be constantly monitored.

The GIS adaptation to the existing database of the Kharkiv region landslide hazard massifs (LHM) facilitated the clarification of the following connections: "landslides density - area flooding", "the number of landslides - the amount of precipitation", "slump deformations - slope gradient", "slump

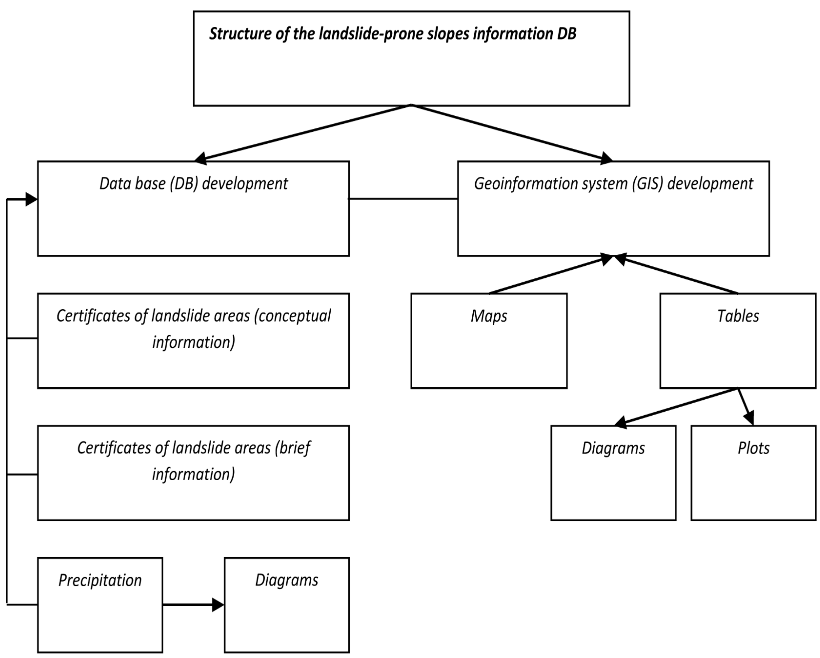

Figure 2 – Structure of the landslide hazard slopes information database

deformations - seismic loads", "density of landslides - density of the road network". On the most part of the Kharkiv region territory, the LHM areas flooding, precipitation and anthropogenic factors have the dominant effects on the landslides evolution or activation.

Firstly, a water table rise due to natural and anthropogenic factors is recorded almost wherever numerous landslides are observed. Anthropogenic factors can include the violations of sewer systems of buildings, low efficiency and hydrological imperfections of drainage systems, storm-water sewerage systems failures etc. Secondly, it is possible to observe the various economic activities with the significant violations of control standards (cutting of LHM slopes, lands ploughing for agricultural use in the vicinity of the landslide deformations manifestations, trees removal on slopes etc.). Thirdly, the dynamic impact on LHMs is rising because of the intensification of traffic density and transport speed, increase of transit freight traffic and respective roads surfaces loads, reduction of the distances between roads and slopes etc.

When processing the information available from the DB of landslide manifestations in the Kharkiv region districts, which has been obtained earlier, it became clear that there was no valid correlation between the landslide areas and landslides quantities.

That fact can be caused by several reasons including the unreliability of landslides information, shifting (increase) of landslides activation, secondary factors of influence, stale data etc. All of that requires the new approaches and modern information technologies application to the LHM data collection and processing etc., as well as the on-line acquisition of operational information. To solve those tasks, the advanced software tools are necessary for the landslide hazard assessment at the local and regional levels based on a systemic combination of the analysis of unmanned aerial vehicles (UAV) cartographic information, space images taken by means of Earth remote sensing (ERS), mathematical modeling results and GIS-technologies outputs. The new GIS model should contain multilayer information on the relief, slopes gradients, hydrographic network, roads, landslide areas and others.

3. At present, the paper authors develop “System for the UAV- monitoring of landslide slopes”. In 2017 O.A.Klimenkov defended his dissertation where the preliminary studies of the LH EWS NIM units 1-4 using the unmanned aerial vehicle (UAV) were implemented at the theoretical and methodological levels [45, 46]. The new approaches and modern information technologies application to the collection and processing of data on potentially dangerous landslide massifs etc. and the on-line obtaining of operational information require the improvement of existing software for the landslide hazard assessment at local and regional levels based on a systemic combination of UAV cartographic information analysis, satellite images taken by means of the Earth remote sensing (ERS), mathematical modeling and GIS technologies [45].

Despite the continuous improvement of the aerospace ERS tools, such aerospace photography has well-known methodological limitations, which are determined, first of all, by the impossibility of photographing at any time and in any place depending on the weather conditions and on account of satellites orbits geometry. The preconditions for the UAV use as a new photogrammetric tool include the disadvantages of two traditional ways of the remote sensing data acquisition by means of space satellites (space photography) or manned aircrafts (aerial photography) (fig. 3).

Satellite observations allow the images acquisition with a publicly accessible maximum resolution of 0.5 m, which is insufficient for large-scale mapping (fig. 3.a). Moreover, it is not always possible to find the cloudless photos in archive. In case of customized photographing, the promptness of data acquisition may be lost. The operators and distributors often do not exhibit the flexible pricing policies as to the relatively compact areas. Traditional aerial photography carried out from aircrafts (Tu-134, An-2, An-30, Il-18, Cesna and L-410) or helicopters (Mi-8T, Ka-26 and AS-350) requires high economic costs for maintenance and fueling, which leads to the increase of a final product value.

The application of standard aircraft systems is uneconomic in the following situations:

1. The photography of small objects and small areas. In such cases, the economic and time costs of work organization related to a photographed area unit significantly exceed the similar parameters of the large areas photography (particularly for objects at a considerable distance from an aerodrome);
2. The necessity to carry out regular photographing for monitoring the extended objects, including pipelines, transmission lines or traffic arteries.

It should be noted that the technology of aerial photography from UAV has been largely worked out [46, 47]. Currently, most of the existing and operating UAVs are intended for air reconnaissance and surveillance by taking photos and videos.

The vertical and horizontal axes show the area covered by photographing and the operativity and relevance of the data received, respectively. As can be seen from the figure, the materials of satellite acquisition have the maximum coverage, but their applicability is insignificant. Sometimes the space images of certain territories are waited for months.

The aerial photography and aerial laser scanning have a higher applicability and accuracy, but cover the smaller areas as compared to satellite acquisition. Also, both of the above mentioned methods of taking photos are expensive. The use of UAVs is a)

b)

c)

Figure 3 – Satellite observation data
a. The low resolution image from the Google Earth service
b. Superimposition of the aerial photo made from "Dozor-2" UAV
c. A high-resolution photo segment

justified in cases when it is necessary to quickly obtain accurate information about a locality at a small area. In addition, taking into account the cost of each of the solutions, UAVs get the very advantageous scoring and are optimal in some cases in terms of financial costs. Thus, the plus points of UAVs use are as follows: economic efficiency; possibility of taking photos from small altitudes and in the vicinity of objects and, therefore, obtaining the high resolution images; immediate imaging and the possibility of UAV usage in zones of emergency without any risk to the pilots' lives and health.

The use of UAVs for solving the tasks of emergency areas aerial surveillance (such as monitoring of the Fukushima-1 NPP condition as of March 16, 2011 after the radiation accident (fig. 4)) is the most cost-effective, safe and operational means of environmental monitoring. It is evident from fig. 4 that only the second power unit building has some small external damages; but the buildings of the Fukushima-1 NPP third and fourth power units suffered greatly.

Figure 4 – The photograph (DigitalGlobe) of the first four power units of Fukushima-1 NPP as of March 16, 2011

CONCLUSIONS

1. The concept and practical implementation of the Early Warning System (EWS) new integrated methodology, which is based on the integration of modern monitoring technologies and

investigated object comprehensive numerical simulation, is presented and described.

2. The actual and efficient EWS shall perform four main sets of the following actions:
   - The monitoring of the behaviour of an object under observation, i.e. data collection and transfer, as well as equipment maintenance;
   - The analysis and modeling of the investigated object under observation;
   - Warning, that is, the dissemination of simple and clear information about the object under observation; and
   - The effective response of risk-exposed elements; full understanding of risks.
3. The new integrated methodology of landslide hazard EWS includes four main elements as follows:
   - Special monitoring module.
   - Integrated monitoring module.
   - Module of characteristics description and mathematical modeling.
   - Analysis (verification) module.
4. The time scale (t_0, t_1, t_2 and t_3) should be as follows:
   - t_0 can be considered as the initial control time. For the first-in-time soil violation, the t_0 value represents a period of time before the landslides occurrence. For a dormant or potential landslide, the t_0 value represents the time of its reactivation;
   - t_1 means approximately three days period from the moment immediately after t_0;
   - t_2 is a period from 3 to about 20 days after t_0;
   - t_3 means more than 20 days after t_0.
5. The proposed methodology uses a typical set of three warning levels (WL1-WL3), therefore, a dual-threshold system (attention and alarm) is adopted. Each level of warning is related to the landslide activity state (normal or seasonal activity, increased activity or possible collapse) and becomes activated when the corresponding threshold (boundary value) is exceeded. For each alert level, there is a set of responses to indicate, which actions should be activated for mitigating the landslide hazard (i.e., "What to do?" and "Who is responsible?").
6. The integrated methodology was tested and proved to be effective in managing the Torgiovannetto di Assisi rockslide. The warning thresholds and danger threshold were identified and applied to create a EWS in an experimental mountain landslide area [38].
7. The following examples of practical implementation of the proposed integrated methodology for various construction objects or natural and man-made systems are presented: 1) the Central Livadia landslide system and Livadia Palace; 2) the system for landslide hazard areas monitoring in Kharkiv Region, and 3) the systems of early prevention of landslides with the use of unmanned aerial vehicles as the specialized systems for monitoring the deformations due to landslides.

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