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The dynamic model of the geodetic control network as a research tool of the state of earthen structures

The article deals with the problem of application of the dynamic model of the geodetic control network in monitoring the subsidence of earthen structures. A tentative model of a control network coupled with a soil environment functioning model has been presented herein alongside an organization pattern of measuring and control works. Against such background the purposefulness of the use of the suggested algorithm in monitoring the condition of earthen structures has been discussed together with specification of the conditions that should be satisfied to make the use of the algorithm possible.

1. *Introduction*

Geotechnological experience in the line of non-invasive research methods and successful geodetic monitoring of the movements of complicated engineering objects have provided inspiration for detailed discussion. A rich literature on the subject pertaining to the importance of geodetic measurements while investigating into the condition of structures of various kinds and the model of a control network (chiefly the dynamic one) as an analyzing tool of measuring data, encourages for searching for new domains of the application thereof. Following the experience of many authors (e.g.: [1], [3], [4], [5], [8], [11]) an attempt has been made [12] to check up on if and to what extent the dynamic model of the geodetic control network, a tool time and again used in integrated large objects displacements monitoring systems, might be applied in an extended analysis of measuring results of displacements of smaller objects (upon the example of earthen road structures). An "extended analysis" will be conceived herein as the physics of a phenomenon, approached as a deformation process determining factor, being taken into account in numerical analysis of geodetic observation results.

Discussion has been narrowed down to the so called dynamic model of the control network, due to the fact that only such a model makes it possible to numerically evaluate the physical parameters of an object, basing directly upon the results of geodetic measurements. The most frequently applied static and kinematic models of geodetic networks may be treated as special cases ify those guidelines with the help of the collected observations. This might be remarkably significant especially if it is not possible to verify the guidelines by means of soil survey *in situ*.

Discussion of the controversial adjective "dynamic" used as referred to the notion of the model of the geodetic control network will be disregarded herein, due to limited space. However, it is worthwhile to point out now that appropriate literature provides us with many interpretations of the term, which every now and then leads to misunderstandings, in interdisciplinary contacts in particular.

2. *The specific character of earthen structures*

Among other engineering objects earthen structures (embankments in particular) are characterized by the specific role of physico-mechanical soil parameters (both of the constructing base and building material) determining the strength of the soil as a structure. Unlike for inst. steel structures the strength parameters of an earthen one may change, due to which even under unchanged exploitation conditions (i.e. at the same operational load) significant deformations of such an object may occur. This is why the state of a dynamic system which includes an earthen structure should be approached slightly different. As it is, the impact of exciting forces upon the response of the system is more complicated here, moreover it is determined by the values of soil parameters, which — as it were — play the role of the "catalyst" or "inhibitor" of the deforming process.

In Figure 1 state x of the system connected with an earthen structure, determined by occurring enforcement u, may be interpreted as a direct, although unmeasurable response of the system covering the controlled object together with its surroundings. It is possible to determine it thanks to analysis of control measuring results taken within a geodetic network which make up a collection of available responses. State vector x may be in turn, by means of a back analysis, the basis for determination of the values of loads u. However, the scheme of the dynamic system connected with an earthen structure should take into account, apart from the set of exciting forces, also the inherent features of the object which influence the character of its response and the deforming process, described by symbol z. Those values, together with loads u, may be subject to estimation in the process of the back analysis.

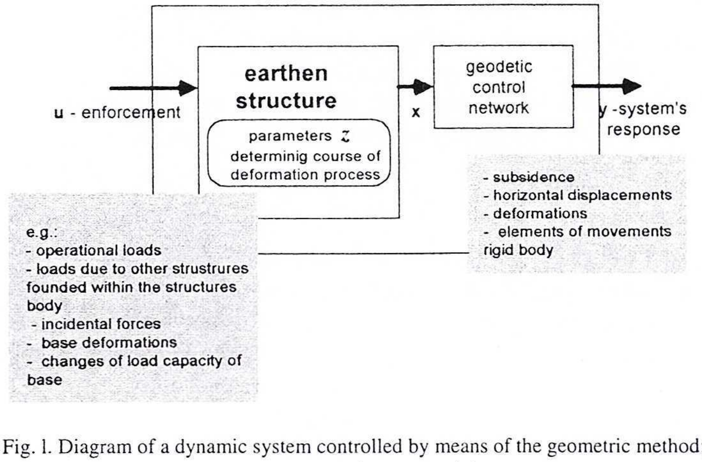


Fig. 1. Diagram of a dynamic system controlled by means of the geometric method; an earthen structures being a part of the system

3. *The characteristics of the suggested model*

The tentative dynamic model of a geodetic control network, developed on the basis of [12], has been discussed below. The testing of the model has been carried out upon simulated examples and a real object which was a railway embankment and the dyke of the dam "Grabownia" of the storage reservoir "Rybnik".

Elementary assumptions

- Account being taken of the Papo-Perelmuter concept [10], separation of the geodetic work-out of the measuring material and application of its results in the estimating process of the parameters that characterize the research object in its physical aspect, has been taken for granted.
- Due to the need to apply displacement values referred to immobile surroundings of the object, a rigid reference system has been assumed as appropriate.
- Stability of the reference system for assumed time intervals has been taken for granted.
- Due to the non-linear character of most mathematical relationships describing ground phenomena, while approximating displacement values, application of the full form of the mathematical formula describing the relationship (set of soil parameters) $\Rightarrow$ (displacement) has been assumed as necessary, as analogous to Chen-Yang's "back analysis" concept [2].
- For selected calculating periods stability of forcing factors has been taken for granted alongside stability of the sources thereof and stability of the ground parameters that are being looked for.
- For selected calculating periods a single reference moment of determined displacement values has been assumed.
- It has been assumed that the *a priori* form of the correction covariance matrix of the equation of state is unknown. Bearing in mind that the estimating incorrectness of the values of free terms in correction equations is the linear function of the incorrectness of displacements determined by control measurement and the incorrectness of the approximate values thereof, determined from the assumed model relationships, estimations of the values of the elements of correction covariance matrix of the equation of state will be accomplished on the basis of the following formula:

$$\mathbf{C}_w = \mathbf{C}_{\hat{x}} + \mathbf{C}_M \tag{1}$$

where: C_w correction covariance matrix of the equation of state;

$\mathbf{C}_{\hat{x}}$ – quasi-observation covariance matrix, i.e. displacements of check points, determined on the basis of direct measurement data;

$\mathbf{C}_M$ – covariance matrix of approximate displacements values calculated on the basis of the assumed model of deformation process

$\mathbf{C}_M$ – assumes the form of a diagonal matrix of diagonal elements

$$(\mathbf{C}_M)_{i,i} = \left[\sum_{j=1}^{lz} \left| \frac{\partial f(z,c)}{\partial z_j} \times (\Delta z)_j \right| + \sum_{k=1}^{lc} \left| \frac{\partial f(z,c)}{\partial c_k} \times (\Delta c)_k \right| \right]^2 \tag{2}$$

z – variables of the functions of the model (process parameters) of approximate values z_0 determined with tolerance;

c – constants of the functions of the model (e.g. values of constant forces of system p, time t approached parametrically, other values of the character of function parameters) determined with tolerance Δc,

The model of an earthen structure as a dynamic system whose responses are observed by means of a geodetic measuring network, account being taken of all the foregoing assumptions, will assume form of the following system of equations:

$$\bar{x}_i = \bar{x}_0 + f_i(p, z_i, t) + w_i, \mathbf{C}_{w_i} \tag{3a}$$

$$l_i = A_i x_i + v_i, \mathbf{C}_{l_i} \tag{3b}$$

solved under the following conditions:

$$v_i^{\mathrm{T}} \mathbf{C}_{l_i}^{-1} v_i = \text{minimum}$$

$$w_i^{\mathrm{T}} \mathbf{C}_{w_i}^{-1} w_i = \text{minimum}$$

where:

$$x_i = \bar{x}_i - x_0 \tag{4}$$

$$x_i(\sum_{j=1}^{i} m_j \times 1) = \begin{bmatrix} x_{i-1}(\sum_{j=1}^{i} m_j \times 1) \\ x_a(m_a \times 1) \end{bmatrix} \tag{5}$$

$$l_i(\sum_{j=1}^{i} n_j \times 1) = \begin{bmatrix} l_{i-1}(\sum_{j=1}^{i} n_j \times 1) \\ l_a(n_a \times 1) \end{bmatrix} \tag{6}$$

$$\mathbf{A}_i(\sum_{j=1}^{i} n_j \times \sum_{j=1}^{i} m_j) = \begin{bmatrix} \mathbf{A}_1 & & & \\ & \mathbf{A}_2 & & \\ & & \cdots & \\ & & & \mathbf{A}_i \end{bmatrix} \tag{7}$$

$f(p, z, t)$ (stands for the function describing the dependence of changes of coordinates of the state (position) of a check point of the network and forcing factors $\boldsymbol{p}$, physical parameters z and time t;

$\bar{x}$ – state coordinates vector within the measuring space;

x – state coordinates change vector within the measuring space (displacements);

z – vector of system's unknowns, here: physical (for inst. geotechnic) parameters, determining the course of deformation process; in accordance with our assumptions this is the quantity that affects the state of the system within period <0, i >, presumption on its approximate value being based on the result of the solution of the system for epoch i–1;
w – equation of state corrections vector, or quasi-observation corrections vector (input random disturbance vector) ;
$\mathbf{A}$ – observation corrections equations matrix (response or output matrix) determined within a rigid reference system;
l – vector of changes within appropriate geodetic observations;
v – observation corrections vector (vector of output random disturbances);
$\mathbf{C}_w$ – equation of state corrections covariance matrix (corrections to model w);
$\mathbf{C}_l$ – observation covariance matrix.
$i \in <1, k>$, k stands for the number of measuring epochs, a – measuring epoch index.

The state of the system at a successive measurement (moment i) is determined by its initial state, forcing factors (at zero dynamics of the changes of those quantities), and the values of factors regarded as the system's unknowns (physical parameters of a given object) at the time between previous and current measurements (3a).

Formulas (5)-(7) display the system's memory on the history of its changes expressed by responses $\boldsymbol{x}$ of the system itself and geodetic observations $\boldsymbol{l}$.

Linearization of function $f(\boldsymbol{p}, z, t)$ according to unknown z through the first two terms of its development into a Taylor series having been assumed for approximate value $z_{0_{i-1}}$ leads to the following forms of model relationships:

$$\boldsymbol{x}_i = f_i(\boldsymbol{p}, z_{0_{i-1}}, t) + \mathbf{M}_i(\boldsymbol{p}, z_{0_{i-1}}, t)dz_i + w_i, \mathbf{C}_{w_i} \tag{8a}$$

$$\boldsymbol{l}_i = \mathbf{A}_i \boldsymbol{x}_i + v_i, \mathbf{C}_{l_i} \tag{8b}$$

$\mathbf{M}$ stands for the matrix of the physical model of a given process (so called sensitivity matrix [6]) which satisfies the following:

$$\mathbf{M}(\boldsymbol{p}, z, t) = \frac{df(\boldsymbol{p}, z, t)}{dz} \tag{9}$$

index i-1 at approximate value z_0 means that its structure is based on the knowledge of the system of the preceding epoch.

Solution to system of equations (8a) at boundary conditions (8b) is a discreet case of the so called multipoint boundary value problem (MPBVP) solved with the help of the Gauss-Newton quasi-linearization method [6], [7]. Application of increments dz instead of complete values z is advantageous due to the fact that it protects the calculating process against possible disproportions within the orders of quantities of particular elements of vector z.

Appropriate covariance matrices having been assigned to the equations of system (8) express the uncertainty that accompanies the construction of the model of a physical phenomenon and limited trust in the measuring results as measurable effects:

$\mathbf{C}_w$ – equations of state corrections covariance matrix (corrections to the model) $\boldsymbol{w}$;
$\mathbf{C}_l$ – observation covariance matrix.

It is noteworthy to mention the fact that significant disproportions in the values of diagonal elements of matrices of both the foregoing types have been recorded in test examples. This proves a considerably greater inner coherence of geodetic measurements as compared with the modelling results of a physical phenomenon.

Determination of estimator $d\hat{z}$, which minimizes standard, $w_i^T \mathbf{C}_{w_i}^{-1} w_i$ with simultaneous minimization of standard $v_i^T \mathbf{C}_{w_i}^{-1} v_i$ is the calculating aim.

The following expression is the solution to system of equations (8):

$$d\hat{z}_i = (\mathbf{M}_i^{\mathrm{T}} \mathbf{C}_{w_i}^{-1} \mathbf{M}_i)^{-1} \mathbf{M}_i^{\mathrm{T}} \mathbf{C}_{w_i}^{-1} (\hat{x}_i - f_i(z_{0_{i-1}})) \tag{10}$$

$$\hat{z}_i = z_{0_{i-1}} + d\hat{z}_i \tag{11}$$

its covariance matrix looking thus

$$\hat{\mathbf{C}}_{d\hat{z}_i} = (\mathbf{M}_i^{\mathrm{T}} \mathbf{C}_{w_i}^{-1} \mathbf{M}_i)^{-1} \mathbf{M}_i^{\mathrm{T}} \mathbf{C}_{w_i}^{-1} \mathbf{C}_{\hat{x}_i} \mathbf{C}_{w_i}^{-1} \mathbf{M}_i (\mathbf{M}_i^{\mathrm{T}} \mathbf{C}_{w_i}^{-1} \mathbf{M}_i)^{-1} \tag{12}$$

$$\hat{\mathbf{C}}_{\hat{z}_i} = \hat{\mathbf{C}}_{d\hat{z}_i} \tag{13}$$

Values of displacements $\hat{x}_i$ specified on the basis of geodetic measurements have been determined from equation (8b):

$$\hat{x}_i = (\mathbf{A}_i^{\mathrm{T}} \mathbf{C}_{l_i}^{-1} \mathbf{A}_i)^{-1} \mathbf{A}_i^{\mathrm{T}} \mathbf{C}_{l_i}^{-1} l_i \tag{14}$$

$$\mathbf{C}_{\hat{x}_i} = (\mathbf{A}_i^{\mathrm{T}} \mathbf{C}_{l_i}^{-1} \mathbf{A}_i)^{-1} \tag{15}$$

The general shape of the model permits different practical solutions. According to the amount of measuring data and the purpose of appropriate analyses, it is possible to combine differences of results of direct geodetic measurements:

- from two successive epochs,
- from two optional epochs, e.g. input (first) measurement and current one:
- from many epochs in the following order: successive measurement – preceding measurement,
- from many epochs in the following order: successive measurement – input measurement.

This makes it possible to estimate the unknown parameters of the system for different time intervals, which extends the range of analyses of values of those unknowns.

Once a certain data configuration has been created, it is necessary to construct matrix **M** (matrix of deformation process mathematical model). This task consists of two independent issues:

- specification of functional dependencies $f(p, z, t)$ which make up the model's basis; this will be vested in a cooperating specialist (geotechnician, hydrogeologist, constructor, etc.);
- presentation of determined values of derivatives $\frac{df(p,z,t)}{dz}$ in a numerical table according to the assumed calculating purpose and the analyzing manner of calculating results.

The second issue consists in creation of an appropriate configuration of derivative values within numerical table **M** in accord with the needs of definite analyses. In order to illustrate the foregoing, we will describe the creation of multi-epoch table **M** for the following case:

a) stability of estimated unknowns z between extreme measuring epochs having been assumed,
b) no such assumption having been taken.

Case a

number of unknown parameters of the dynamic system: s
number of controlled points: m

Within a k-epoch system matrix **M** will assume the following form:

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_1 \\ \mathbf{M}_2 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{M}_k \end{bmatrix} \quad \text{dimension } (km \times s) \tag{16}$$

Case b

number of unknown parameters of the dynamic system: $s' = ks$
number of controlled points: m

Within a k-epoch system matrix **M** will assume the form of a quasi-diagonal matrix

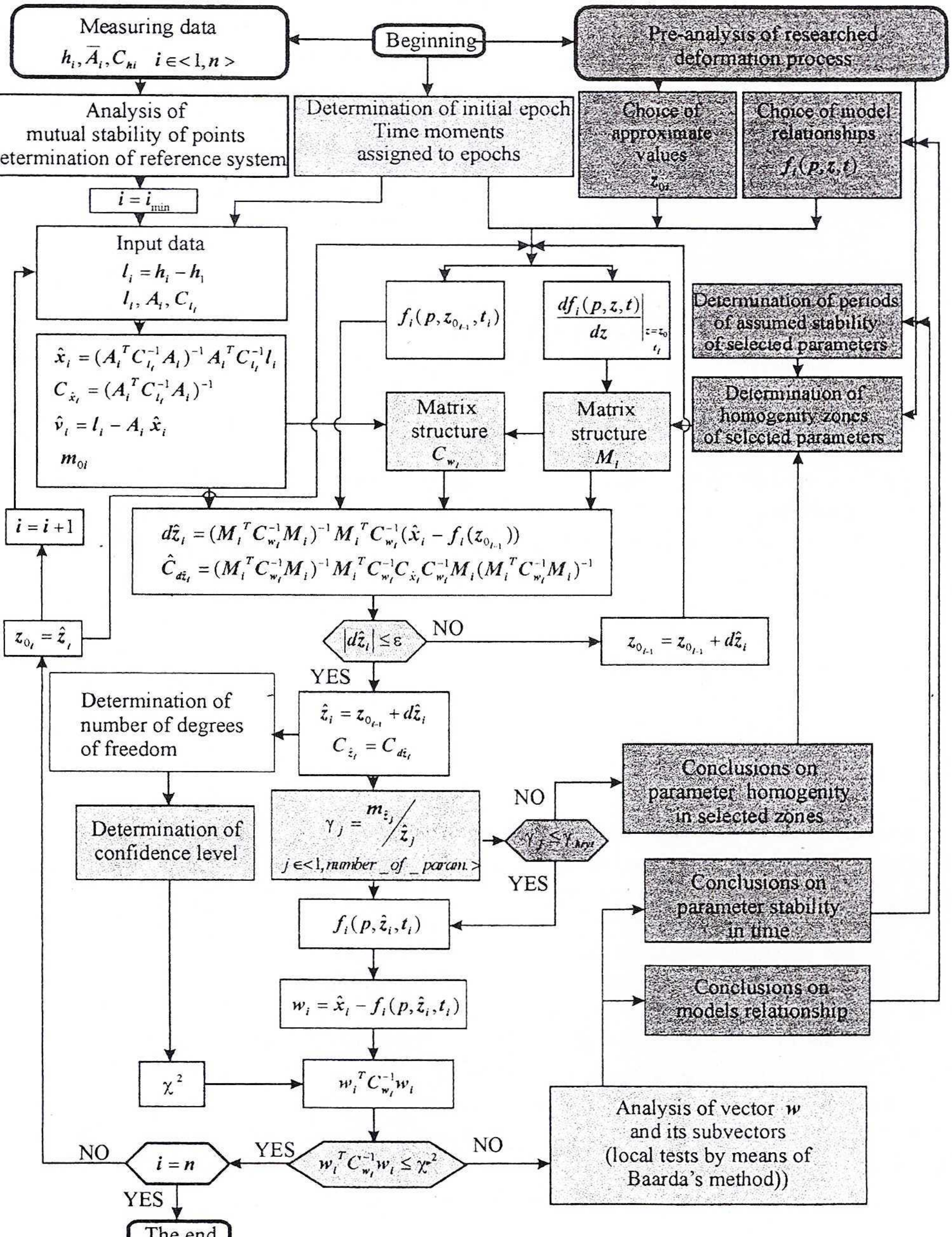
$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_1 \cdot & & & \\ & \mathbf{M}_2 & & \\ & & & \\ & & \dots & \\ & & & \mathbf{M}_k \end{bmatrix} \quad \text{dimensions } (km \times s') \tag{17}$$

According to the degree of complication of the model and the functions of particular unknowns z and their assumed variability in time, tables **M** may assume forms of different levels of complication. However, in each case

$$\mathbf{R}(\mathbf{M}) = s \quad \text{or} \quad \mathbf{R}(\mathbf{M}) = s'$$

is the necessary condition they must satisfy.

During the iterating process it is possible to make changes within matrix **M** (functionally dependent on estimating arguments). A change of values of elements of matrix **M** in the successive epoch may also come about due to determination of new mathematical relationships $f(\mathbf{p}, z, t)$ describing those elements, or another unknown having been added to model equations (if radical changes have come about). The general scheme of the calculating procedure has been presented in Figure 2.



Area of necessary cooperation | Area of recommended cooperation

Preliminary proceedings follow two paths.

In accord with the Papo-Perelmuter postulate [10] of division of geodetical analysis of control network into two stages measuring data gathered throughout successive measuring epochs are subject to analysis and verification (reference system to be determined, gross errors to be eliminated). On the foregoing basis the volume of subsidence of particular controlled points (within the selected, rigid reference system) will be determined alongside the characteristics of the accuracies thereof, calculated as referred to the selected initial epoch.

At the same time preliminary analysis of the researched deformation process will be carried out, due to which a physical model of the phenomenon will be constructed; the observed subsidences will be its visible and measurable symptom. Here are the elementary procedures covered by that formulation:

- site research and analysis of available archival measuring-control documentation, as well as technical documentation of the construction site,
- analysis of influence exerted by the environment upon the object, determination of the most probable causes of the occurrence of the observed changes in the object with possible division of the object into zones of different characteristics of the occurring processes.

Construction of the physical model is a process which forces successive decisive steps to be taken to the end that:

- the essence of the physical process and the factors that affect its course are determined,
- mathematical relationships $x = f(x)$ which make up the formal description of the phenomenon, linking observed displacements (x) with factors (z) determining their volumes, are selected,
- approximate values (z_0) of variables (z) are determined,
- values of derivatives $df(z)/dz$ and displacements (x_0) are determined for approximate values of variables,
- time of assumed stability of selected parameters is determined,
- groups of points are determined whose displacements have been specified by selected factors z (identification of homogeneity zones of ground parameters) ,
- numerical table **M** is displayed.

Estimation of variable z will be carried out in the iterative mode which comes to an end the moment the unknown has accomplished progression smaller than the assumed value ε

On the basis of estimated values of ground parameters (elements of vector $\hat{z}$) and their mean errors, relative estimation errors will be determined, corresponding to the so called parameter homogeneity index (see [9], also called material soil coefficient γ_m (see [14]):

$$\gamma_m = 1 \pm \frac{m_{\hat{z}}}{\hat{z}}$$

The settled critical value not having been exceeded by relative error means that the estimation result of a given parameter alongside identification of its homogeneity zone will be regarded as correct.

Estimated quantity $\hat{z}$ is the basis for determination of quasi-observation corrections and assessment of the compatibility level of the suggested model of a dynamic phenomenon (model mathematical relationships, their variables and the structure of the model's matrix) with reality represented by measuring results. The value of standard $w^T \mathbf{C}_W^{-1} w$ is the exponent of the said level. Quantities smaller than or equal to the critical value of test χ^2 have been regarded as satisfactory. If the required condition has not been satisfied, it is necessary to verify model relationships and/or the structure of model's matrix. Results of local quasi-observation tests carried out by means of the "Baarda's method" may provide a hint in which direction and with reference to which controlled points the model should be changed.

3. *Analysis of the possibilities to apply the suggested concept of the control network model*

The hitherto existing investigations into the possibilities of estimation of ground parameters, carried out in geotechnological milieu, as well as surveyors' experience, acquired upon the examples of large objects, considerably encourage for subject research and attempts to be made to apply the assumed tool (dynamic model of a control network) in smaller scale studies. Unfortunately results of calculating tests upon the example of a real road object [12] do not univocally prove the usability of the tool in question at monitoring the state of earthen structures; they also point out that a large reserve should be maintained towards the concept of the use of the dynamic model as a utility tool while analyzing monitoring results of road engineering objects by means of geodetic control networks.

The following account for that.

- Identification of an object (in the theory of systems sense) and the load complex (forces) in the analyzed dynamic system are much of a problem.
- Solution to the calculating problem calls for well conditioned equations to be constructed, which — in turn — requires the possibly thoroughest analysis of the object's features: its structure, ground and hydrological conditions, and appropriate identification of the physical processes coming about within the object.
- Conditions of numerical nature call for maximum simplification of the mathematical relationships describing the physical aspect of the phenomenon, whereas the nature of those phenomena forces the use of non-linear relationships, hard to be approximated in series expansion.

The answer to the question what should be regarded as a dynamic system object, an earthen structure being a part of it, and what loads (forces) actually affect it, as well as thus implied physical complication degree of the interactive system (such is the object – earthen structure and its constructing base) together with its surroundings, prove that it is the stage of adequate, mathematical description of a physical phenomenon that might be the most difficult one in subject analysis.

However, this does not mean that the question set at the beginning should be answered negatively. The dynamic model of a geodetic control network may be applied in an extended displacement analysis of points of an earthen structure, certain conditions must be satisfied, though.

- The construction of an earthen structure as a physical system must be considerably simple. This means that the mechanism of ground processes is not complicated and the case of mutual overlapping of a few processes does not come about.
- The physical phenomenon that is the cause of the occurrence of detected displacements must be appropriately identified.
- Ground conditions must be determined alongside specification of significant physico-mechanical parameters of ground environment as referred respectively to the structure's body and its base.

- The mathematical description of the deformation process must be considerably simple, which means that the variability of functions should be close to linear one. If possible, the use of exponential functions should be given up.

Calculating tests connected with a real object proved that all the foregoing conditions to be satisfied at the same time, albeit this is not impossible, was extremely difficult to accomplish.

Surely enough the herein analyzed algorithms cannot be applied in already existing objects, especially if alarming changes occur, or — all the more — if an object is in danger. As it is, it is always possible that the object, or the process, have not been properly identified. In such cases it may be either physically impossible to carry out an appropriately extensive geotechnological research, or it may be aimless from economic viewpoint. Then it is necessary to adopt certain assumptions which augment the uncertainty area of the model under construction.

However, it seems proper to mention that the dynamic model of a geodetic control network may be a tool for analysis of the state of newly-built objects for which — in the preliminary investment phase and during the accomplishment thereof — it is possible to collect all information necessary to construct the mathematical models of probable physical phenomena within the ground environment of the structure itself and its base. This has been confirmed by simulation studies: owing to application of appropriately selected approximate data and the so called good conditioning of the system of equations (accomplished by means of correct formulas of the phenomenon's mathematical model), it was possible to determine the final values of the "physical" model's parameters with a satisfactory approximation.

The so specified application range corresponds to the guidelines included in the Order [13]. According to Clause 3 of the said Order "determination of geotechnological conditions of foundation of building objects" covers *inter alia* "determination and verification of the mutual relationships of a building object and ground base at different constructing and exploiting stages" (underlined by the author). Those proceedings should be accomplished with reference to objects of the second and third geotechnological categories, which among other things respectively cover: excavations deeper that 1.2 m., embankments higher that 3 m. (Clause 7.2c), and "building objects founded under complicated ground conditions" (Clause 7.3b).

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Dynamiczny model geodezyjnej sieci kontrolnej jako narzędzie badania stanu budowli ziemnych

S t r e s z c z e n i e

Artykuł porusza kwestię zastosowania dynamicznego modelu geodezyjnej sieci kontrolnej w monitorowaniu osiadań budowli ziemnych. Przedstawiono w nim propozycję modelu sieci kontrolnej zintegrowanego z modelem funkcjonowania ośrodka gruntowego oraz schemat organizacji prac pomiarowo-kontrolnych. Na tym tle przeprowadzono dyskusję zasadności stosowania zaproponowanego algorytmu w monitorowaniu stanu budowli ziemnych oraz określono warunki, jakie wymagają spełnienia by użycie tego algorytmu było możliwe.

Ясек Зыга

Динамическая модель геодезической контрольной сети как орудие исследования состояния земных устройств

Р е з ю м е

Статья касается вопроса применения динамической модели геодезической контрольной сети в мониторинге оседания земных устройств. Представлено предложение модели контрольной сети интегрированной с моделью функционирования почвенной среды, а также схему организации измерительно-контрольных работ. На этом фоне проведено обсуждение обоснованности применения предложенного алгоритма в мониторинге состояния земных устройств, а также определены условия, которые должны быть выполнены для возможности применения этого алгоритма.