Antikarst protection for buildings and structures

Protection antikaristique pour les bâtiments et les constructions

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SYNOPSIS The shortage of areas with favorable geological conditions in industrialized countries makes it necessary to develop karstic territories that were considered to be unsuitable for the construction purposes. Operation of large industrial enterprises in service under such difficult geological conditions affects the progress of karst phenomenon by speeding it up considerably. At karstic regions the engineers are facing the problem of protection for projects against karst danger. The main features of the approach undertaken to solve the problem are presented in the paper.

Karst formations and estimation of karst risk

The karst danger consists in karst effect formation either within rock mass or on soil surface (Table I). The karst effects come into interaction with foundations of buildings and structures. The main difficulty of geological engineering exploration of karst results from its considerable depth and impossibility of direct survey of its development. Sinkholes are the most dangerous karst effects for engineering projects. Many factors varying both in time and in space even on limited territories influence on the karst effect development. Generally such changes have a stochastic behavior. Moreover, in process of forthseeing frequently it is hard to locate karst caves and voids - the main origin of sinkholes. Under these conditions the most reliable objective evaluation of karst danger for buildings and structures reflecting the nature of the phenomenon and the knowledge of its features for engineering purposes may be an evaluation based

TABLE I

Classification of karst formations

Karst formations on soil surface	Disturbed continuity of soil surface	Forms of dissolution on soil surface (for uncovered karst)		
		Swallow holes		
		Forms of soil surface	Collapse sinks	Dome-like
				Cylinder-like
			Sinkholes	
	Undisturbed continuity of soil surface	Local subsidence of soil surface		
		Subsidence flexures		
Underground karst formations	No defined boundaries within soil mass	Tenderized zones	Zones of decompaction in overlaying soils	
			Zones of desintegration in soluble rocks	
		Subsidence flexures in soluble rock roofs (for covered karst)		
	Limited boundaries within soil mass	Zones of movements in the overlays		
		Fill within voids and caves in soluble rocks		
		Caves and voids	In the overlays	Unsaturated
				Saturated
			In soluble rocks	

on a probabilistic approach. In result, the evaluation of karst danger for a certain given structure, even if it is based on a deterministic model, has to reflect a stochastic behavior of the phenomenon.
It is known that the frequencies of sinkholes under certain given conditions are close to the Poisson law and that the distribution of their diameters for comparatively large areas approaches to lognormal behavior.
For designing antikarst protection for most of structures it is necessary that the dimensions, primarily the diameters of sinkholes that are expected to be on the site, should be determined. This can be ensured by clearing up and estimating the natural factors influencing the diameters of sinkholes. For areas with determined combinations of those factors the curves of sinkhole diameters distribution can be settled. For instance, it is fixed that the more natural factors are considered, the tighter the analogy to the normal behavior.
Knowing the behavior of sinkhole effect frequencies and their diameters, it is possible to evaluate the safety factor for designed buildings on karstic sites. Under the reliability P of a size A_n structure on a site characterized by the mean $\bar{\lambda}$ for karst effect frequency and by normal sinkhole diameters distribution with expected average value $\bar{d}$ and the standard deviation σ_d^2, one may realize the probability that for the service period t_n a structure should not be affected by a sinkhole of a diameter greater than l_r,

$$P = 1 - P_r ; \qquad (1)$$

where P_r - risk probability, calculated by:

$$P_r = [(1-P_{d_r})\frac{A_n}{A} + \frac{\bar{d}}{d_{max}}(1-P_{l_r})\frac{A_o}{A}]\cdot(1-P_a) ; \qquad (2)$$

$d_{max} = \bar{d} + 3\sigma_d$;

A_o - area of the site with the structure perimeter at a distance of $d_{max}/2$;

$A = A_n + A_o$;

$P_a = \exp(-\bar{\lambda} A t_n)$;

l_r - critical dimension of a sinkhole under a structure foundation, causing unexpected deformations;

P_{l_r} - probability of appearance of a zone of deformation under a foundation that is not more than l_r when happens at the site (fig.1).

It is recomended to settle the curve P_l for certain given conditions by statistic testing method applied to different parts of the structure in plan. The formula (2) can be applied for values $\bar{d}$ and d_{max} defined by deterministic models based on theoretical forcasting methods. Further there will be given a principle of such foreseeing.
Rationing minimum assumed reliability of structures by the formula (2), with taking into account socio-economic consequences of damage, it is not difficult to evaluate P_{l_d} and the related value of the designed span l_d, that is necessary for accounting antikarst foundation constructions (Tolmachyov, Troitzky, 1983).

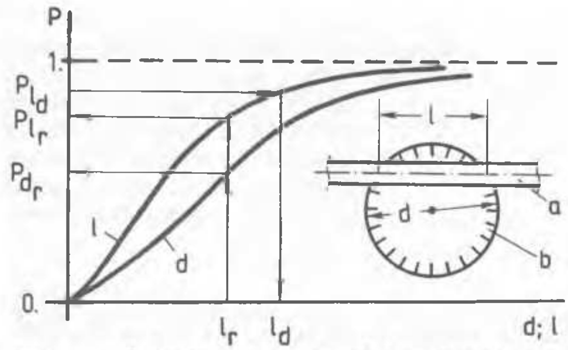

Fig.1 Integral curves of distribution for d and l
a - strip foundation;
b - sinkhole.

Designed locations of sinkholes

Designing unframed buildings on karstic sites and choosing methods of antikarst protection for buildings in service when their soilbase might be influenced by sinkholes, one faces a problem of the most unfavorable location of affected parts. The main schemes of sinkhole dispositions in plan of a building are represented on fig.2.

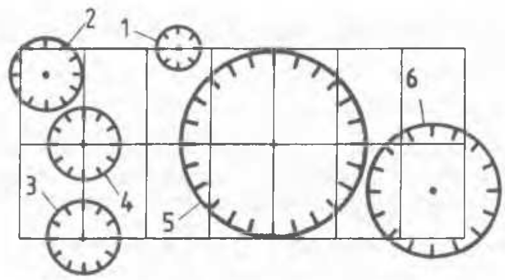

Fig.2 Designed locations of sinkholes

The location of type 1 relates to a rectilinear part of the wall; type 2 - to a corner part; type 3 - to a T-like part; type 4 - to a cross part; types 5 and 6 locating several wall crossings that are common for large sinkholes, comparable to the width of the building.
Determination of designed sinkhole locations under buildings is based on following principles:

1 - designed locations under the parts of supporting walls are those that define the maximum values of acting forces: bending moments M and transversal forces Q;
2 - under the same part of the wall there may be several designed positions of sinkholes, relating to the maximum M and Q for different elements of the construction;
3 - determining the acting forces in constructional elements are taken into account only the parts overhanging the sinkhole, beyond the sinkhole the building is considered to be absolutely rigid and the soilbase undeformable;

4 - the designed scheme of walls is represented by a system of beams charged by uniformly distributed loads.

The use of simplified pre-conditions are fully excused by uncertainty of initial data.

For type 1 - the most unfavorable location of a sinkhole is when it is symmetricaly placed to the axis of a wall with its diameter equal to the free length of a wall between the transversal walls. For type 2 - the largest span of overhanging walls are reached when a corner point is placed on the edge of the sinkhole; the designed scheme is adopted as a V-like beam with tightly pinched supports; in the process of calculation of M and Q for different locations of the sinkhole the extremal values of acting forces for adjoining walls are considered. Type 3 is worked on like type 2. For type 4 two solutions are possible: the wall crossing may be placed either at the axis or the edge of the sinkhole. When sinkhole diameters are large and when several wall crossings overhang a sinkhole (types 5 and 6) a system of cross-beams laying on a undeforbable subsoil beyond the boundaries of a sinkhole is considered as a designed scheme. By means of such designed scheme unfavorable locations of a sinkhole may be defined both for parts adjoining sidewalls and for middle parts of a building as well as for generalized forces acting in walls.

There is no need for constructions of buildings which were not fit for karst damage to be checked for sinkholes of large diameters because their bearing capacity is unsifficiant for sinkholes of lower dimensions.

Evaluation of sinkhole diameters

The investigation of the sinkhole effect behavior makes it clear that the process is developing in two phases: at the first phase a cylinder-like zone of collapse appears on soil surface, its walls are near to a vertical, in some cases they may be dome-like, and, at the second phase sliding brings the walls to a stable condition. If there are loose cohesionless soils in the upper-strata the two phases may develop successively almost simultaneously. Proceeding from these premises formulas enabling forecasting diameters of sinkholes on a soil surface or under foundations were obtained.

The diameter of a collapse sink for the end of the first phase is calculated by:

$$d_p = 4 \cdot \frac{\sum c_j \Delta h_j + \sum \Delta f_j}{q_j} \quad ; \qquad (3)$$

h_j - thickness of a j-layer of the soil with known values of cohesion c_j, angle of internal friction φ_j and unit weight γ_j;

$$\Delta f_j = (\bar{p}_o \alpha_j + \sum \gamma_i \Delta h_i + (\gamma_j \Delta h_j / 2)) k_j \operatorname{tg}\varphi_j \Delta h_j \quad ; \qquad (4)$$

$$q_j = \bar{p}_o \alpha_j + \gamma_j \Delta h_j + \sum \gamma_i \Delta h_i \quad ; \qquad (5)$$

α_j - coefficient of pressure distribution in the soil depth, and α is also a function of dimensions of a charged area of the soil surface and its remoteness;

i= j-1, j-2, etc. - number of soil layers disposed over the j-layer;

$\bar{p}_o$ - average pressure under the foundation base, taking into account hydrostatic subsoil pressure;

k_j - coefficient of lateral pressure in subsoils.

According to the properties of soils laying within the limites of observed subsidence h_o (fig.3), to the charge submited by the foundation of structure, and to its characteristics, the second phase of a sinkhole (funnel-like) is developed by slipping the walls into stable state.

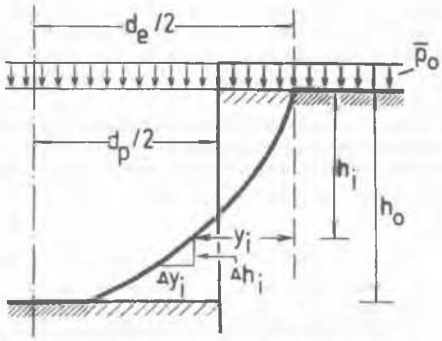

Fig.3 **Design scheme of the sinkhole**

The coordinates of the formed slope are calculated from:

$$y_i = \sum \left(\frac{\Delta h_i}{\operatorname{tg}\varphi_i + \dfrac{c_i}{\bar{p}_o \alpha_i + \sum \gamma_i \Delta h_i}} \right) ; \qquad (6)$$

y_i - ordinate of a stable slope in the depth h_i ;

Δh_i - thickness of an elementary subsoil layer;

The final diameter of a sinkhole (a crater) is calculated by:

$$d_e = 2\left(\frac{\sum y_i^2}{n} + \left(\left(\frac{\sum y_i}{n}\right)^2 - \frac{\sum y_i^2}{n} + d_p^2 \cdot \frac{h_o}{4 \sum \Delta h_i}\right)^{1/2}\right); \qquad (7)$$

where n - number of calculated units of elementary subsoil layers.

The calculation is proceeded unless the values $d_e \leq 2y_i$ or $\sum \Delta h_i = h_i \geq h_o$ are obtained.

The described method of quantitative forecasting presuposes that a foundation subsoil beyond the determined diameter of sinkhole crater retains its full bearing capacity.

A computer program based on the formulas in question enables to take into account multilayered subsoils for foundations of structures and buildings of any design in plan and of any disposition at the site within the influencing zone.

Computation based on the formulas has registered satisfactory likeness between the results obtained and the conclusions of natural observations. Analysis of the obtained data has revealed a regularity resulting in an influence of structures on changing dimensions of karst sinkholes on the soil surface.

Constructional methods of antikarst protection

Antikarst foundations are erected in situ out of reinforced concrete constructions in types of continious strips, cross-strips, boxes and slabs, ensuring interaction between all supporting constructional elements of the structure. Stability for the edge parts of foundations is provided by extension of cantilever beams or cantilever slabs, or other types of foundation constructions beyond the dimensions of the building or structure in plan. Reinforcement of foundations and structures is calculated related to the dimensions of forecasted sinkholes.
As an example an antikarst foundation of a concentrate enterprise is given at fig.4.
For using friction piles the construction of junction to the foundation slab must enable the slip-out of piles (within the boundaries of the sinkhole area).
One of the features of antikarst foundation design is in creating special constructions of foundations for artificial limiting sinkhole (crater) dimensions in plan.

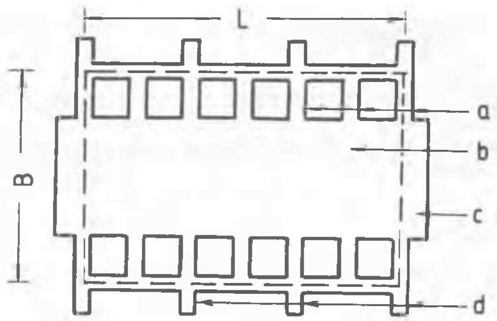

Fig.4 Antikarst foundation
a - cross-strip foundations;
b - foundation slab;
c - cantilever slab;
d - cantilever strips;
L and B - dimensions of the building.

Integrate antikarst protection

The investigations held for last years at the research institutes have enabled to arrange for a number of industrial enterprises, populated areas, and separate structures an effective integrate antikarst protection, including preconstructional and inservice safety measures. It is necessary to note that the most effective solutions both from economic and technicoengineering points of view may be reached if geological exploration and antikarst protection designing would be decided within the framework of a single system (Sorochan et al., 1982).

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