The foundations of scientific prognostication of the landslide processes on construction sites

Une base pour la prévision scientifique des processus de glissement sur les sites de construction

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SYNOPSIS: The report deals with theoretical bases for landslides behaviour processes numerical predictions. The rheological properties of clays in slopes are most important in stress-strain conditions for soil mass. In cases, when slopes are used to be bases for buildings and constructions, during the life time of any construction the stress-strain distribution in slope can be estimated by calculations of movement velocities.

The landslide processes are the most wide-spread and active form of manifestation of general exogenous geomechanical processes and most often occur in mountain-fold areas which are now being extensively built up with linear, energetic and hydrotechnical projects.

Therefore, a necessity arises to improve the existing methods and the quantitative estimation of stability and dynamics of the landslide processes to prevent harmful consequences, as well as to work out measures on slope stabilization and to provide favourable conditions for projects utilization.

Now, the problem of scientific forecast of the scarps and slopes stability is solved, mainly, by calculating stability. The results show whether catastrophic shifting (landslide) is possible and they also indicate the volume of landslide body. But in most cases of engineering practice it is necessary to forecast the dynamics of landslide processes with or without a possibility of developing into catastrophic stage for a given period of time. This forecast is conditioned by the utilization of projects interacting directly or indirectly with landslides.

In fact, the division of slopes into stable and unstable is relative, if the time factor and the growing landslide shifting are taken into consideration. A stable slope can develop into unstable state after a long period of time due to spreading deformations of soil along the potentially possible sliding surface. Besides, the growth of considerable shiftings on slopes without developing in catastrophic stage causes irregular deformations of projects interacting with slopes, which, finally, can lead to emergency. Obviously, in the last case the "stable" slope can be characterized as unstable, because the growth of considerable deformations has brought about the failure of projects, i.e. the loss of strength of projects interacting with a landslide body.

As, during the development of landslide territories, a slow growth of landslide shiftings without transforming into catastrophic stage occurs in most cases, it is urgent to improve the existing methods of quantitative forecasting of landslide dynamics. This made it possible to carry out research on designing, to build and to utilize the projects constructed on landslide slopes and scarps on a more substantiated and confident level.

It is evident that the quantitative forecasting of landslide dynamics in general case should include all stages of the development of this process embracing the initial, intermediate and catastrophic phases.

The initial phase is linked with transformation of the initial strain-stressed state (SSS) of the slope, the transformation being conditioned by the construction of projects, the change of slope profile (levelling, embankment, etc.), as well as by the change of hydrorheological conditions (arrangement of reservoirs, drainage, spillway, etc.). On that stage landslide deformations develop, at first, intensively, and, then, gradually stabilize and change into the second stage.

The second stage corresponds to the relatively stabilized SSS of the slope when landslide deformations develop at a constant or (cyclically) variable rate within admissible limits for the project utilization, the project interacting with the landslide. This stage can take a very long period of time and is not likely to develop into catastrophic stage.

This is conditioned, on the one hand, by nonuniformity of the slope's SSS in space and in time, and on the other hand, - by property of the geological structure and hydrorheological conditions of the given slope.

It is obvious that an unambiguous analogy with dynamics of development of creeping deformation of soil specimen tested in laboratory conditions and dynamics of development of landslide process can't be drawn.

Finally, the third catastrophic stage corresponds to the development of landslide shiftings at a progressing rate. This stage takes an end with surface sliding of large masses down to the slope. Therefore, the slopes' failure is the final result of a durable process of a slow soil straining.

The true prognostication of the slope's SSS which includes all these stages, is very difficult to obtain, because one should study landslide process and describe it in mathematical terms.

It is evident that, applicably to the involved areas, the forecasting of landslide shifting should be carried out only for the conditions of damped creeping as uniquely possible for projects built on slopes and which can take place if tensions do not excess over the durable strength limit.

Determination of rheological properties of clay soil forming slope and choice of rheological soil model is an important stage of the landslide process forecasting.

Cyclicity conditioned by the development of creeping deformation in natural slopes under effect of periodically varying head in the slope's water-bearing horizon is one of the characteristic properties of the landslide process dynamics.

The effect of these two factors, in many cases, is determining under development of landslide processes on slopes formed up with water-saturated clay soil.

Landslide processes on slopes formed up with non-water-saturated loessial soil will be conditioned, generally, by the change of the slope's humidity regime.

The present report provides with theoretical foundations of the landslide process forecasting. This process taking plaoe on slopes formed up with water-saturated clay soil and non-water-saturated loessial soil.

1 Forecasting of the landslide process dynamics on slopes formed up with water-saturated clay soil

As it was noted above, the main factors affecting the landslide process of slopes formed up with olay soil are: creeping of skeleton and influence of variable pore pressure on creeping under shifting.

Non-uniformity of SSS and non-stationarity of hydrorheological slope's conditions complicate, to a considerable degree, the task of the landslide process forecasting as a whole. Essentially, the landslide process forecasting comes to determination of deformation and tension components in every point of the massif pore pressure in dependence of geological and geometrical structure of slope, boundary loads and water heads including.

The analysis of the listed by us experimental research of clay soil with intact and deformed texture carried out on instruments of torsion and cylindrical shearing in kinematic and statical loading regimes shows that the process of plastical deformation accumulation occurs at, practically, every values of tangent tensions. But these deformations take shape under excess of tangent tensions over the limit of durable strength or residual strength, i.e. when $\tau > \tau^*_{dl}$ or $\tau > \tau^*_0$. Relation (1) will be valid before the angle deformation of limit which corresponds to peak strength γ^* is obtained:

$$\tau = \sigma \, tg \, \varphi_{dl} + C_{dl} + \dot{\gamma}_{vp} \cdot \eta_{vp} \qquad (1)$$

$$(\gamma \leq \gamma^*)$$

and relation (2) will be valid after the angle deformation exoesses the boundary γ^*

$$\tau = \sigma \, tg \, \varphi_0 + \dot{\gamma}_p \, \eta_p \qquad (2)$$

It results from these equations that depending on the value of the accumulated angle plastic deformation in different points of the landslide massif, the straining rate is different and the degree of resistance to shearing is different, too. So, the transformation of slopes' SSS after variation of its equilibrium state occurs continuously and can end with both damping or progressing course.

Obviously, under cyclical change of pore pressure, temperature under soil humidity, additional irreversible landslide shearings may appear which also can bring the slope into the state of progressing course, as angle deformations are accumulated and soil strength is reduced to the level of residual one.

Theoretical and experimental research carried out in laboratory conditions showed that the periodically changing pore pressure affects considerably the development of shearing deformations. Presently, we have at our disposal the worked out algorithm and the numeric method of the slope's SSS analysis under the effect of its own weight, external loads and heads of water-bearing horizons, and of interaction with engineering projects which make it possible to forecast the components of loading, deformation and displacement in every point of the landslide massif.

2 Foundation of forecasting of the landslide process dynamics on slopes formed up with loessial soil

Engineering-geological conditions in arrangement of the Central Asia mountain reservoirs are rather specific because the slopes of river valleys are covered with thick series of loess which lie on waterproof rocks. Initial filling of the reservoir is followed by elevation of river plane, and the slopes covered with loess become its edges. Loesses get wet. The wetting front starts to transfer from the limits "bank-reservoir" inside of the soil massif. Due to low natural humidity, water movement occurs under effect of the capillary forces, and the wetting front, as show the theoretical and experimental research (1), develops extremely slowly. Water passing through macropores under the effect of the gravity force is an exception to that rule. On this stage it is sufficient to confine oneself to the one-phase model of non-linear infiltration, in which water flow I^w is expressed as the filtration coefficient and the capillary potential gradient:

$$I^w = -K_{ij}(W) \frac{\partial \psi(w)}{\partial ij} \qquad (1)$$

Under complete saturation, the infiltration turns into filtration. The filtration coefficient does not depend on humidity, and the potential is equal to positive head in liquid.

As pores get saturated with liquid, the oharacteristics of loess strength degrade. The friction coefficient and resistance to thorough rupture (MPa):

$$M = 0{,}53 - 1{,}0125\,(W - 0{,}08) \qquad (2)$$

$$H = 0{,}1613 - 1{,}0325\,W^{\dot{}} \qquad (3)$$

are compuded in dependence on gravimetric humidity according to (2) and (3) and are just only over the range from maximum molecular moisture capacity to saturation humidity.

Then, as reservoir banks get wet, two cases are possible:

1) interaction "soil-water" occurs so rapidly that the front "soaking-scouring" moves after the saturation front, and the bank failure happens practically at the same time as wetting occurs, and the separated particles settle down over the slope's surface or are transported by benthic streams;

2) "soaking-scouring" occurs slower than infiltration; the wetting area in series of bank soil takes such considerable dimensions that subsidence starts under effect of its own weight.

In the second case it is necessary to describe in detail subsidental process in time with the account of irreversible skeleton deformations right up to transferring into boundary state, and also with the consideration of retro-ties in interaction of the skeleton with pore liquid. The basic equations on this stage of bank's scouring are:

$$\dot{W} + I^{w}_{k,k} + \left(I^{\text{ск}}_{k} W \right)_{ik} = 0 \qquad (4)$$

$$\sigma^{\text{ск}}_{kl,l} + \delta_{k3} \rho g = \rho \ddot{u}^{\text{ск}}_{k}$$

the former one translates the balance of liquid phase, and the latter one expresses the balance of skeleton pulse, where: W - humidity; I^{w}_{k}, $I^{\text{ск}}_{k}$ - flows of water and skeleton; σ_{kl} - tensor of tensions in skeleton ; ρg - volume weight of three-phase soil. There is a relationship between the skeleton displacement $u^{\text{ск}}_{k}$ and the skeleton flows $I^{\text{ск}}_{k}$:

$$I^{\text{ск}}_{k} = \dot{u}^{\text{ск}}_{k} \qquad (5)$$

To complete equations system (4), besides relationships determining boundary states (2) and (3) and kinetic equation (1), we should involve the law of plastic deforming of soil which is determined in the present work from three main preconditions:

1) the Drukker's postulate (basic inequality of the plastic course theory);

2) dependence of shearing deformation on tangent tension under net shearing;

3) dependence of the dilatant component of volumic deformation on tangent tension under net shearing.

In the plastic course theory the state equation is given in form of loading surface which sets boundary of elastic and plastic strain of material and also determines relationship of volumic and shearing deformations in dependence of the way of loading. The following designations should be used to formulate the loading surface:

σ - normal tension (hydrostatic invariant of tensor of tension);

τ - tangent tension (shearing invariant of tensor of tension);

ε_v - volumic plastic deformation;

ε_i - shearing plastic deformation.

The Drukker's postulate is written as the inequality:

$$\sigma d\varepsilon_v + \tau d\varepsilon_i \geqslant 0. \qquad (6)$$

Deformations under net shearing are expressed through the formulae:

$$\varepsilon_i = \frac{b\tau}{a-\tau}, \quad \varepsilon_v = c\tau \qquad (7)$$

From relationships (7) one can get the expression for the dilatance rate:

$$\Pi = \frac{d\varepsilon_i}{d\varepsilon_v} \qquad (8)$$

In case of net shearing, relation (8) may be simplified:

$$\Pi = \frac{\partial\varepsilon_i/\partial\tau}{\partial\varepsilon_v/\partial\tau} = \frac{ab}{c(a-\tau)^2} \qquad (9)$$

solution (9) and equation (6) give the desired surface in the form of hyperbola:

$$\tau = a + \frac{ab}{c(\sigma-\sigma^*)-b}, \qquad (10)$$

which is assigned by the desired equation of the subsidental soil state.

The law of volumic compression may be represented in traditional logarithmic form:

$$\sigma^* v^{\alpha} = \beta, \qquad (11)$$

where v - soil volume, and all parameters of equations (10) and (11) are determined through experiments as the continuous humidity functions.

Filling of pores with water, loss of structural strength in soil, development of plastical subsidental deformations lead to subsidental process stabilization which coincides with the beginning of the filtration consolidation. In this case the system of basic equations should be written as

$$\left(\frac{k}{\rho_w g} p^{w}_{,i} \right)_{,i} = -\dot{u}^{\text{ск}}_{i} + \frac{1-m_{\text{ск}}}{M^{w}} \dot{p}^{w}; \qquad (12)$$

$$\sigma^{\text{ск}}_{ij} + \delta_{ij} p^{w} + \delta_{i3} \rho g = 0,$$

where p - pressure in liquid; k - the filtration coefficient, ($1 - m_{\text{ск}}$) - porosity, M^{w} - modulus of the liquid volumic compression.

The theory of filtration consolidation in non-linear formulation is used for the analysis of dam stability in works made under supervision of Zaretsky Yu.K. (Zaretsky Yu.K.,).

The draw-down of the reservoir causes water losses on the bank side, and the following fluctuations of the level lead to restraint of considerable air masses and to necessity to take into account its interaction with the skeleton and water not as air-bubbles dissolved in water, but as independent phase. Let's examine a sufficiently large volume of air enclosed in structure-free (after settlement) soil, and encircled by saturated soil. The humidity regime of the bank and the movement of the reservoir headwater level can change in the way, that:

1) restrained air will not change its volume (if the reservoir lowering is accompanied with a fall of free surface of the bank filtration flow); this can take place only under rather slow spillway from the reservoir, which occurs extremely seldom;

2) restrained air expands due to sharp fall

of the level, and soil is submitted to vacuuming;

3) restrained air gets compressed due to sharp rise of the level and seeks to break the incompletely water-saturated soil mass from inside.

As specific character of the mountain reservoirs consists both in a large amount of the level's differential and its quick draw-down-dump, the account of the effect of restrained air becomes an actual task, and the effects due to the change of its stressed state can play a decisive role in bank's slumping. Change of pressures in air results in the first place in change of the water film state, and, as water is present in soil always, in solution of such problems, it is proper to carry out the analysis supposing that air and skeleton interact to a considerable degree through water and to a small degree - immediately.

In case of the balanced air pressure transfer over liquid and solid phase when in every moment of time skeleton and water "instantly" respond to every change of pressure in air, all three phases do not lose the equilibrium state and air in the system is "the slowest link", one can confine oneself to a simple and obvious model of "capillary meniscus". The rise of pressure in air is accompanied by the meniscus' curvature growth and interaction of water films and a part of skeleton weakens. If, on the contrary, air produces vacuuming effect on water menisci, soil gets additional structural strength just as dry sand assumes some connectivity under humidification, and soil, submitted to vacuuming, slowly gets soaked (Talaev M.V., 1961). Change of pressure in air will also bring to a change of the capillary potential in formula (1), which will affect on the water transfer kinetics. For a quantitative study of the "sucking force" of soil depending on pressure in air, special experiments are required.

Supposition on a balanced character of phases' interaction should be considered as the first one and as approximation far from reality. Water and skeleton can not reorganize themselves quicker than air due to their agregate state. Liquid and the system of solids have a higher degree of molecules' interaction, than gases. So, the process of vacuuming and restrained air compression runs in non-equilibrium way and, for its analysis, it is necessary to involve thermodynamics of non-equilibrium processes. One of possible formalizations belongs to Onzager who was the first to introduce it for studies of the chemical reaction kinetics. Flows of some substances I are believed as proportional gradients of the corresponding thermodynamic potentials X. For a three-phase soil in which

$$m_{sk} + m_w + m_a = 1 \tag{13}$$

the skeleton flow equation is represented as

$$I_{sk} = L_{sk,w} X_w + L_{sk,sk} X_{sk} + L_{sk,a} X_a \tag{14}$$

The equations for I^w and I^a look analogous. Coefficient $L_{sk,w}$ means that gradients in water X_w can cause skeleton flows and, vice versa, water flows can arise due to the gradients in skeleton, and so, I^{sk} and I^w are called "conjugated".

Reciprocity conditions (15) are just in linear disbalanced thermodynamics close to the equilibrium state:

$$L_{sk,w} = L_{w,sk} \tag{15}$$

In the present case these conditions are not satisfied. Besides, the very coefficients depend on corresponding concentrations. For example:

$$L_{sk,w} = L\left(m_{sk}, m_w, m_a\right). \tag{16}$$

The analysis of three-phase soil systems in terms of non-equilibrium thermodynamics makes it possible to describe such well-known facts as, for instance, filtration anomalies when liquid moves to humidity rise, but not to its fall, as it is admitted. Filtration flow moves not to heads' loss, but to its gain. Analogous phenomena can take place with both air and description of insufficiently usual quasistatical approximations on which modern analysis models are based.

The presented methods are implemented on electronic computers "ES" with numeric methods on the elaborated complex of programs. Under regular program layout it is convenient to use the finite differences method. In case of complex bank contours or when it is necessary to extend control, the final elements method is used. Obvious schemes should be applied in solution of non-stationary problems, non-linear problems are solved through the initial deformation method. The results of the analysis are represented as series of, consecutively changing in time, reservoir banks profiles which correspond to the cycles of water level's variation.

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