International Conference on Case Histories in Geotechnical Engineering
(1988) - Second International Conference on Case Histories in Geotechnical Engineering

01 Jun 1988, 1:00 pm - 5:30 pm

Stress Field under a Reservoir and Its Induced Earthquake

Tao Zhen-yu
Wuhan Institute of Hydraulic and Electric Engineering, Wuhan, China

Tang Fang-fu
Wuhan Institute of Hydraulic and Electric Engineering, Wuhan, China

Proceedings: Second International Conference on Case Histories in Geotechnical Engineering, June 1-5, 1988, St. Louis, Mo., Paper No. 4.06

Stress Field under a Reservoir and Its Induced Earthquake

Tao Zhen-yu
Professor of Rock Mechanics, Wuhan Institute of Hydraulic and Electric Engineering, Wuhan, China

Tang Fang-fu
Engineer, Wuhan Institute of Hydraulic and Electric Engineering, Wuhan, China

SYNOPSIS: This paper provides a conceptual model for the study of water-induced earthquake, from which a coupled analysis program of two-dimensional elasto-plastic media has been made. It analyzes the characteristics of the change of stress field and infiltration field under reservoir and studies the relationship between these characteristics and those of water-induced earthquake. At last, it gives out prediction results to a water-induced sequence.

INTRODUCTION

Whether the water-induced earthquake takes place is mainly connected with the four factors of tectonics, rock properties, condition of geostress and the reservoir etc. That water induces the change of stress field, and then the breaking of rockmass and the sending out of energy is the mechanical explanation of water-induced earthquake. For the change of stress field of rockmass under reservoir, some scholars such as Gough (1969), Gough et al (1970) and Withers et al (1978) have done stimulating calculations in their own consideration. Each of them argues with the importance of water in water-induced earthquake. But all of them do not take into the main aspects connected with water-induced earthquake. how ever, Tao et al (1987) have made up for this shortcoming and have done some coupled analysis to this problem.

The final purpose of the studies to water-induced earthquake is to know whether a reservoir will induce earthquake or not, if it will, how about the three principal factors (time, position and earthquake magnitude), so as to provide data for dam design. General engineering geology method can not reach the quota accuracy, and only after the dam has been built, can the induced earthquake wave be got, so we try to use the conception of coupled analysis to set up a new conceptual model, calculating the stress field under reservoir and predicting the three principal factors of water-induced earthquake.

THE PRINCIPAL ASSUMPTIONS OF THE CONCEPTUAL MODEL

Water-induced earthquake is in connection with many factors. Different consideration to these factors makes models differ from each other. Almost all models presented are to special reservoirs and do not have widely fitation. Therefore we provide a new conceptual model, the principal assumptions of which are as follows:

a) Neglecting secondary fracture, only taking into account big fault. The total area considered is devided into several parts, each of which is equal to a homogeneous and identical medium and has different mechanical data and porous ratio. The infiltration property of medium may be identical or unidentical in all directions.

b) Rockmass are ideal elastic-plastic medium, the yielding function of which abides by Drucker prager rule or Mohr-Coulomb rule.

c) The rockmass below certain depth under reservoir is unsaturated. The infiltration of underground water is saturated-unsaturated infiltrating fluid.

d) Taking into account the dynamic and static force produced by infiltrating fluid and the softening effects of saturated rockmass.

e) Taking into account the coupled actions between rockmass and underground water.

f) As the depth increasing, the porosity of rockmass reduces down and the temperature rises up, so the porous pressure factor η becomes lower and lower. Assump that η is a linear function of depth h.

g) With the depth increasing, the infiltrating ability of rockmass becomes lower, which can be neglected below certain depth.

SEVERAL PROBLEMS IN COUPLED ANALYSIS

1. The action of stress to fluid

The pumping test which has been done in fissured layer at different depth reveals that the formula

$$K = K_0 \exp(-\alpha \sigma_e) \quad (1)$$
$$\sigma_e = \gamma_t h - p \quad (2)$$

can express the change of infiltrating coefficient. In the formula:

- K_0: the infiltrating coefficient of top layer
- γ_t: the specific gravity of rockmass;
- h: the thickness of top layer;
- p: the compression force of water;
- α: a coefficient

If layer contain no water, then:

$$K = K_0 \exp(-\alpha \gamma_t h) \quad (3)$$

When tectonic stress is considered, formula (3) can be revised as:

$$K = K_0 \beta(h, \sigma_x) \exp(-\alpha \gamma_t h) \quad (4)$$

$\beta(h, \sigma_x)$: affecting coefficient of horizpntal tectonic stress σ_x.

Therefore, the initial infiltrating coefficient K_{h0} at any depth can be given. K_{h0} has already take into account the influence of natural stress field. When the actions of water is considered, the stress field of rockmass will change, which will make the infiltrating coefficient change. But this change is too small to be neglected. However, if an element of rockmass breaks, the change of infiltrating coefficient of it has to be considered. We revise it as follows:

1) Broken by tension in one direction. Assump that φ is the angle between the direction of principal stress and X-anxil, then:

$$K_\varphi = K_{h0} \quad (5)$$
$$K_{\varphi+90} = K_{h0\,\varphi+90^\circ} \quad (6)$$

2) Broken by tension in two directions:

$$K_\varphi = \xi K_{h0\varphi} \quad (7)$$
$$K_{\varphi+90} = \xi K_{h0\,\varphi+90^\circ} \quad (8)$$

3)Broken by yielding

$$K_\varphi = K_{h0\varphi} \exp(-\alpha \sigma_1) \quad (9)$$
$$K_{\varphi+90^\circ} = K_{h0\,\varphi+90^\circ} \exp(-\alpha \sigma_2) \quad (10)$$

The value of ξ may be gained through experiments. α is a coefficient, the value of which may be a small number that get the infiltrating coefficient of that element approach to that of zones of fault.

2. The influence of fluid to stress field

The fluid in condinuous media has force acting on media, the magnitude of which is:

$$F = -\mathrm{grd}\,p \quad (11)$$
$$p = \gamma_w (\varphi - y) \quad (12)$$

That is, $$F = -\gamma_w \mathrm{grad}\,\varphi + \gamma_w \mathrm{grad}\,y \quad (13)$$

$A = \gamma_w \mathrm{grad}\,y$ is static pressure, the effect of which is considered by means of effective stress.

$S = -\gamma_w \mathrm{grad}\,\varphi = \gamma_w J$ is the dynamic force of water which is considered as external force at calculation.

3. The softening effects of saturated rockmass

Using saturated-unsaturated infiltration method, we may affirm the forward surface of underground water at any time. Because the rockmass above the forward surface is saturated, the softening, is considered in this area (P.A. Witherspoon et al, 1977). Assump the initial parameter matrix of rockmass as follows:

$$AMT(I,8) = \begin{bmatrix} E_1 & \mu_1 & C_1 & \varphi_1 & C_1 f & \varphi_1 f & \gamma_1 & \sigma_{t1} \\ E_i & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ E_I & \mu_I & C_I & \varphi_I & C_I f & \varphi_I f & \gamma_I & \sigma_{tI} \end{bmatrix} \quad (14)$$

The softening matrix is as follows:

$$\text{RAMT}(I,8)=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} \\ a_{I1} & a_{I2} & a_{I3} & a_{I4} & a_{I5} & a_{I6} & a_{I7} & a_{I8} \end{bmatrix} \quad (15)$$

E_i : elastic modula of rockmass in i^{th} area;
μ_i : Poisson ratio of rockmass in i^{th} area;
C_i : cohesion of rockmass in i^{th} area;
φ_i: internal frictional angle of rockmass in i^{th} area;
C_{if}: residual cohesion of rockmass in i^{th} area;
φ_{if}: residual internal frictional angle of rockmass in i^{th} area;
γ_i : the specific gravity of rockmass in i^{th} area;
σ_{ti}: the tension strength of rockmass in i^{th} area.

Each element in matrix RAMT(I,8) is the softening coefficient of the element in the same place of matrix AMT(I,8). Through maltiplying the elements of matrix AMT(I,8) by that at the same place of matrix RAMT(I,8). We may obtain the usable parameter matrix.

4. The fitation of Green-Ampt model to infiltrating fluids in rockmass.

Green-Ampt model is a infiltration model which depends on the theory of capillary. The principal assumptions may be described as: medium is formed by many capillaries which have different diameter; The forward surface of infiltration is almost horizontal; The negative water heads at every points of forward surface are the same., so, according to Darcy's law and balance principal of water, one may get the formula:

$$t = \frac{\theta_s - \theta_o}{K(\theta_s)}\left[Z-(H+S_m)\ln\frac{H+S_m+Z}{H+S_m}\right] \quad (16)$$

H: the thickness of water layer above ground;
S_m: the negative water head of medium at forward surface;
Z : the distance forward surface moves;
θ_s: saturated water ratio;
θ_0: unsaturated water ratio;
$K(\theta_s)$: saturated infiltration coefficient;
t: time

according to formula (16), one may get the place forward surface may arrive at any time.

For the homogeneous medium which the fissured rockmass is equal to, its negative water head is generally smaller than that of clay, which does not surpass 2 or 3 metre. On the other hand, for the infiltration under reservoir in which we are interested, H is generally one hundred metres and more, and Z is still counted by thousand metres. The comparison of pratical calculation shows that the two values of Z obtained from neglecting and considering the negative water head is nearly the same for the same t and H. Therefore, we neglect S_m and formula (16) change to:

$$t = \frac{\theta_s - \theta_o}{K(\theta_s)}\left(Z - H\ln\frac{H+Z}{H}\right) \quad (17)$$

Using formula (17), one may estimate the lowest place of forward surface at any time after the reservoir has been filled up.

PREDICTION TO THE WATER-INDUCED EARTHQUAKE

Using the program TNCAPE we have made from the conceptual model, we have done some predicting work for the water-induced earthquake around a reservoir. The results obtained are as follows:

a) This reservoir will induce earthquake after it is filled up.

b) The earthquake will take place at about 660 days after the reservoir is filled up. The earthquake magnitude is 5:1 and the earthquake epicentre is in the zone of fault which is about 8000 metres below reservoir.

c) The mainearthquake will take place at about 1300^{th} day after the reservoir is filled up. The earthquake magnitude is 5.1 and the earthquake epicentre is about 8500 meters below the reservoir.

d) The aftershock comes to stop slowly and it will endure a rather long time, the maximum earthquake magnitude of which will reach 4.5.

e) The characteristics of earthquake sequence this reservoir will induce are as follows: When the forward surface reaches the depth of 3000 metres in 290^{th} day, no rockmass element breaks;

When the forward surface reaches the depth of 6000 metres in 623^{th} day, several rockmass elements in zone of fault begins to break, which se sends out the energy of 0.3186×10^8 t.m that equals to the earthquake magnitude of 4.1; With the underground water infiltrating furtherly, great readjustation of stress field takes place and the energy of 0.6109×10^8 t.m. will be send out, which is equivalent to the earthquake magnitude of 4.2; When the forward surface reaches the depth of 9600 meters, the minor mainearthquake takes place., which sends out the energy of 2.0868×10^8 t.m that is equicalent to the earthquake magnitude of 5; From this time, the stress field and infiltration field readjusts continuously and small earthquakes takes place frequently; The mainearthquake will take place in about 1300^{th} day, the magnitude of which is 5.1. Fig.1 express the relationship between the energy and the time, the controlling point of which means the total energy sented out by all broken element in a period of time. Fig.2 shows the relationship between the earthquake magnitude and the time, which is corresponding to Fig.1. Because of the disconcentration of broken elements, the line connected through the controlling points may be regard as the maximum value line of earthquake sequence the energy sent out in any time will not surpass.

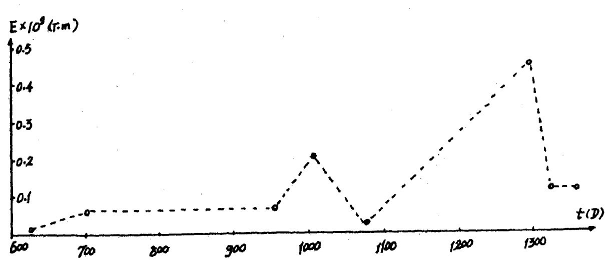

Fig.1 Energy-Time Relationship

From the change process of stress field and infiltration fluid field. We discover that water-induced earthquaek is generally of the characteristics as follows: water-induced earthquake generally belongs to the type of preearthquake-mainearthquake-aftershock or earthquake clusters.

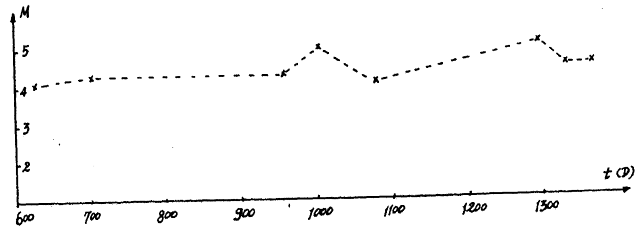

Fig.2 Earthquake Magnitude-Time Ralationship

If the static water load can induce earthquake, the type of it will belong to that of mainearthquake-aftershock. In the long run, it will not belong to the type of isolated-earthquake. The broken rockmass elements appear firstly in the zone of fault and the area where rockmass property changes. The complication of the distribution of zone of fault and the constitution of the types of rockmass and the readjustation of coupled stress field have the earthquake epicentre of it be of the characteristics of disconcentration and jumption.

CONCLUSION

The coupled action of rockmass and underground water reflects the mechanism of water-induced earthquake. Whether a reservoir induces earthquake or not is determined by the contradiction between the stress field and the strength of rockmass. The results from the analysis to infiltration fluid field principally reflcects the general characteristics of water-induced earthquake, which shows the fitation of the conceptual model. The reliability of prediction results depends directly on the parameters used. Some of the parameters we used are obtained from experiments, but the others are obtained from comparison, so, the prediction results should be regard as reference.

REFERENCE

Gough, D.I. (1969), "Incremental Stress under a Two-dimensional Artificial Lake", Can.J. Earth Sci., 6: 1067-1075

Gough, D.I. and Gough, W.I. (1970) "Stress and Deflection in the Lithosphere near Lake Kariba",1, Geophys.J.21:65-78.

Withers, R.J. and Nyland, E. (1978), "Time Evalution of Stress under an Artificial Lake and its Implication for Induced Seismicity," Can. J. Earth Sci, 15, No.9.

Tao Zhen-yu and Shen Xiao-ying, (1987),"The Analysis of Coupled Stress of Reservoir-Induced Earthquake", Proc. of Intern. Symposium on Engineering Geological Environment in Montainous Areas", Beijing, CHINA.

Witherspoon, P.A. and Gale, J.E. (1977), Mechanical and Hydraulic Properties of Rocks Related to Induced Seismicity", Engineering Geology, 11, No.1, 23-25