American Journal of Engineering Research (AJER) 2015

American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-4, Issue-6, pp-31-35
www.ajer.org
Research Paper Open Access

Research on the Application of Fluid-Structure Interaction in Soil Rock Mixture Slope

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ABSTRACT : *traditional seepage theory has defects, and the fluid-structure interaction research has developed. Through the analysis of the fluid-structure interaction problems in engineering, this paper expounds the characteristics of fluid-structure interaction, research methods and research status quo, mathematical model of the slope is put forward.*

Keywords -*Earth-rock mixture slope; Fluid-structure interaction; The research status; Mathematical model*

I. INTRODUCTION

In 1856, through many experiments Darcy's law was concluded by Darcy, which laid the foundation for the development of the theory of seepage and also provided the theoretical support for researching on rock slope stability under the effect of water. Some experts and scholars at home and abroad also improved the seepage theory, and studied instability mechanism earth-rock mixture slope from the angle of seepage. However, the traditional percolation theory has its limitations [1]. In traditional theory, porous skeleton is perfectly rigid, that is to say, in the process of pore fluid pressure change, deformation of solid skeleton will not produce (elastic or plastic), and the seepage problem can be treated as a coupling problem.

This simplification can get an approximate solution to the problem, but there are many shortage, and it is not conform to the actual production. As long as there is water, stress field and seepage field will occur mutual influence. Both are in a complex dynamic process, which is called Fluid-Structure Interaction (FSI). This paper focuses on the principle, characteristic and research status of Fluid-Structure Interaction, and mathematical model of the Fluid-Structure Interaction in the earth-rock mixture slope.

II. THE FLUID-STRUCTURE INTERACTION IN ENGINEERING

The instability of the slope is a complex dynamic process, and the influence factors can be divided into internal factors and external factors. Internal factors mainly refers to the joint of side slope and lithology etc. and external factors mainly refers to a variety of external force acting on the slope. Among them, the effect of water is the key factor affecting the stability of slope. In general, water inside the slope is influenced by external factors, inducing the deformation and failure of slope. Its induced ways mainly include rainfall and melting snow causing the dynamic change of water, the dynamic change of water caused by river water level change and human engineering activities causing the softening effect of rock and soil strength and pore water pressure changing, etc. The relationship between the seepage field and stress field in landslide mainly embodies in two aspects: one is that the change of pore fluid pressure can cause the change of effective stress of porous skeleton, which leads to soil properties such as porosity, permeability coefficient change. On the other hand, the change of the properties such as porosity and permeability will influence the distribution of pore fluid flow and pressure. The interaction and mutual influence of seepage field and stress field finally makes the seepage field and stress field coupling to achieve a state of equilibrium, which respectively form the stability of the seepage field under the influence of the stable stress field and stable seepage field under the influence of the stress field. For earth-rock mixture slope, seepage field and stress field coupling is mainly reflected in two ways. For the rock mass, by applying tangential lift force and normal penetration on the fracture surface, seepage field affects the stress distribution of rock mass, and stress change permeability coefficient by changing the width of the crack, thus affecting the permeability and seepage field of rock mass. For soil, by applying distribution of seepage body force in the area of the seepage and seepage pressure in a certain surface, the seepage change stress distribution, and stress affect the permeability coefficient by changing the soil porosity and soil volume strain, which changes the seepage field.

III. THE FEATURES, RESEARCH METHODS AND RESEARCH STATUS OF FLUID-STRUCTURE INTERACTION

In mesoscopic level, fluid and solid respectively have their own area. Because of the complexity of pore structure, size, geometry, the order and the extension direction have no certain rules to follow, so it has no any precise mathematical method that is used to describe complicated geometry of pore inner surface. Moreover, under the influence of fluid-structure interaction, pore channel is constantly changing. Therefore, it is difficult to accurately determine the boundary conditions. In order to overcome these difficulties, as well as classic seepage mechanics, we should study it from a macro point of view, that is to say, the macroscopic continuum method should be used. In this way, a significant feature of fluid-structure interaction is that fluid and solid should be considered to be an interacting unit, and it is difficult to be clearly separated.

Fluid-structure interaction research methods includes analytical method and numerical method.

The natural state of geological body make fluid-structure interaction problems difficult to obtain analytical solution. Definitely, based upon a large number of simplification and assumption, the analytical solution can be gotten. Especially for nonlinear problems, heterogeneous materials, the discontinuity problem and arbitrary geometry problems, the analytical method is difficult to calculate the real solution [2]. Therefore, fluid-structure interaction problem commonly uses numerical method.

Numerical methods includes finite element method and finite difference method. The basic idea of the finite element is to use the approximate solution to approach precise solution of differential equation, which is a regional discrete method. Its characteristic is that there is no limit to the shape of solution domain, and boundary conditions are easy to handle. And finite difference method is a classical method for numerical solution of partial differential equation. In solution domain, continuous domain with be divided into a finite discrete point set by finite difference grid or difference node, and then derivative terms of partial differential equations will be replaced by difference quotient, deducing the algebraic equations that contains discrete point and a finite number of unknowns. The solution of algebraic equation is a solution of partial differential equations. From mathematical perspective, approximate degree of finite difference method is higher than finite element method, but in practice, the finite element method is far better than finite difference method, because the finite element method is simple and flexible. The finite element method not only can adapt to the complex geometric shapes and various types of boundary conditions, but also can deal with all kinds of complex material nature problem. At the same time, the finite element method can also solve the problem of heterogeneous continuum.

A large number of scholars at home and abroad studied earth-rock mixture slope failure mechanism from the point of view of seepage. From the point of water Seepage in rock-soil mass, the deformation and damage of rock-soil mass because of the changes of pore-pressure and osmotic-pressure were summarized, and kinds of harmful effects because of the underwater were concluded by Hu yuanxin[3].Based on an indoor physical simulation test and FLAC numerical simulation method, changing regulations of pore water stress and total stress of roadbed along reservoir or river are studied in the dynamic fluctuation of river or reservoir water level by Zhang Lijuan[4].

Chen Ping think that the hydraulic and deformation characteristics of jointed rock are mainly determined by the distribution, density and dimension of its joints. A coupled seepage/stress analysis procedure is proposed based on hydraulics and deformation constitutive law of fractures in rock. Numerical analysis of a gravity dam/foundation is given as an example [5].The mechanism of the action and reaction between the seepage and stress field in the single-zone embankment dam is analyzed according to the seepage characteristic of the single-zone embankment dam. The continuum mathematical model for coupled stress and seepage field in the single-zone embankment dam is presented, and the finite element numerical solution method of the mathematical model is discussed. Based on the principle of virtual displacements, the direct coupling formulae of FEM in the anisotropic saturated soils with the assumptions of homogeneous and continuous elastic-plastic porous media are derived by Yang Linde[6].Taking into account the behavior that the permeability of deformable porous media varies with their porosity, the liquid-solid problem of liquid f lowing through porous media under general plain stress condition is discussed. First the governing equations are published, then a decoupled method is proposed, and the fields of pore pressure, the stresses, strains and displacement of media are derived analytically by Xu Cenghe [7]. The analysis software CFX and ANSYS were adopted to analyze the two-way fluid-solid coupling of the debris flow blocking dam with small- and medium-scale landslide silting up by Zhu Yanpeng [8]. The fluid movement of debris flow and the stress-strain and displacement of the dam were obtained.

IV. A MATHEMATICAL MODEL OF THE FLUID-STRUCTURE INTERACTION

Mathematical model of Earth-rock mixture slope of the Fluid-Structure Interaction should meet the following several aspects [9]:

(1) soil-rock-mixture is completely saturated isotropic body line elastomer;
(2) The solid particle and pore water can be compressed;
(3) The deformation of solid skeleton follows Terzaghi effective stress principle;
(4) The seepage of pore water obeys the Darcy's law;
(5) The displacement of rock and soil particle will happen in the process of seepage;
(6) The porosity and permeability coefficient is dynamic change.

On the basis of satisfy the basic assumption, from two aspects: under the influence of seepage field on stress field and under the influence of stress field on the seepage field, partial differential equation is established.

4.1 Stress field under the influence of seepage field

The influence of seepage field on stress field is summarized as water load, which is shown by penetration volume force and penetration pressure. So the effect of seepage field on stress field is through the change of stress field load (water load) to change the distribution of stress field [10]. Thus there is

$$p = r_w (\mathrm{H} - \mathrm{z})$$

Among: z is potential head.

Infiltration volume force can also be calculated:

$$\begin{Bmatrix} f_x \\ f_y \\ f_z \end{Bmatrix} = \begin{Bmatrix} \dfrac{-\partial p}{\partial x} \\ \dfrac{-\partial p}{\partial y} \\ \dfrac{-\partial p}{\partial z} \end{Bmatrix} = \begin{Bmatrix} r\dfrac{\partial H}{\partial x} \\ r\dfrac{\partial H}{\partial y} \\ r(\dfrac{\partial H}{\partial z} - 1) \end{Bmatrix}$$

So the constitutive relation can be gotten:

$$\sigma_{ij}^{'} = D_{ijkl}\varepsilon_{kl} = \lambda\varepsilon_v\delta_{ij} + 2\mu\varepsilon_{ij} \quad (1)$$

Geometric relationships is

$$\varepsilon_{ij} = \frac{1}{2}(\mathrm{W}_{j,i} + \mathrm{W}_{i,j}) \quad (2)$$

Stress equilibrium equations is

$$\begin{cases} (\lambda+\mu)\dfrac{\partial\varepsilon_V}{\partial x} + \mu\nabla^2 W_x + \dfrac{\partial p}{\partial x} + \dfrac{\partial f_x}{\partial x} = 0 \\ (\lambda+\mu)\dfrac{\partial\varepsilon_V}{\partial y} + \mu\nabla^2 W_y + \dfrac{\partial p}{\partial y} + \dfrac{\partial f_y}{\partial y} = 0 \\ (\lambda+\mu)\dfrac{\partial\varepsilon_V}{\partial z} + \mu\nabla^2 W_z + \dfrac{\partial p}{\partial z} + \dfrac{\partial f_z}{\partial z} = 0 \end{cases} \quad (3)$$

From equations (1) (2) (3), stress field equation can be gotten under the influence of seepage field：

$$\begin{cases} \dfrac{G}{(1-2\nu)}\dfrac{\partial\varepsilon_V}{\partial x} + G\nabla^2 W_x + \dfrac{\partial p}{\partial x} + \dfrac{\partial f_x}{\partial x} = 0 \\ \dfrac{G}{(1-2\nu)}\dfrac{\partial\varepsilon_V}{\partial y} + G\nabla^2 W_y + \dfrac{\partial p}{\partial y} + \dfrac{\partial f_y}{\partial y} = 0 \\ \dfrac{G}{(1-2\nu)}\dfrac{\partial\varepsilon_V}{\partial z} + G\nabla^2 W_z + \dfrac{\partial p}{\partial z} + \dfrac{\partial f_z}{\partial z} + F_z^{'} = 0 \end{cases}$$

Among : G is the elastic constants， ε_{ij} is strain tensor field， υ is Poisson's ratio， ∇^2 is Lame equation: $\nabla^2 = \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + \dfrac{\partial^2}{\partial z^2}$ ， ε_v is volume strain。

4.2 Seepage field under the influence of stress field,

In general, the greater the porosity or void ratio of soil, the greater permeability coefficient. Soil coefficient of permeability and porosity or void ratio has the following relationship[18]:

$$K = K(\mathrm{n})$$

Setting the initial porosity for one unit is n_0. Under the effect of the stress field, volume strain is

$\varepsilon_v = \Delta V / V$ (compressive strain is negative). V is as the total volume of soil, ΔV is the change of pore volume. Assuming that all the volume strain is caused by pore volume change, the porosity is

$$n = n_0 \cdot \exp(-\alpha\sigma + aP) = n_0 + \varepsilon_V$$

Because the volume strain ε_v is determined by the stress field σ_{ij} , so the permeability of soil mass can be expressed as a function of stress field, namely $k = k(\sigma_{ij})$. Thus it can be seen that the stress field affects the soil permeability by influencing the volumetric strain and porosity of the soil to, thereby affecting the seepage field.

Considering fluid and the effective stress principle of solid, the speed of the fluid particle is

$$\vec{V_f} = \vec{V_r} + \vec{V_s} \quad (4)$$

The earth-rock aggregate skeleton continuity equation is shown:

$$\nabla \cdot \left[\rho_s (1-n)\vec{V_s}\right] + \frac{\partial[\rho_s(1-\text{n})]}{\partial t} = 0 \quad (5)$$

The continuity equation of pore fluid is shown:

$$\nabla \cdot (\rho_f n \vec{V_f}) + \frac{\partial(\rho_f n)}{\partial t} = 0 \quad (6)$$

Based on equations (4) (5) (6), soil-rock-mixture continuity equation of fluid-solid coupling can be gotten:

$$-\nabla \cdot \left[\frac{K}{\mu}\left(\nabla p - \rho_f g \nabla H\right)\right] + \frac{\partial \varepsilon_V}{\partial t} + \left(\frac{1-n}{E_s} + \frac{n}{E_f}\right)\frac{\partial p}{\partial t} = 0$$

4.3 Definite condition

4.3.1 Seepage definite condition

Soil-rock-mixture boundary conditions can be divided into three categories, respectively

(1) The first category: head known boundary conditions

$$H|\Gamma_1 = H_1(x,y,z,t) \; (x,y,z) \in \Gamma_1$$

(2) The second category: flow boundary conditions

$$\frac{\partial h}{\partial n}\Big|_{\Gamma_2} = -v_n / k = f_2(x,y,z,t)$$

(3) The third class: mixed boundary conditions

$$h + a\frac{\partial h}{\partial n} = \beta$$

Initial conditions is the function of coordinates and the time for the head, namely

$$H(x,y,z,t_0) = H_0(x,y,z,t_0)$$

4.3.2 The stress field in definite condition

（1）The displacement boundary conditions

$$\vec{W}|_{边界} = \vec{W_t}$$

（2）The stress boundary condition

$$\cdot\sigma'_{ij} \cdot \vec{n_j}|_{边界} = T_i$$

V. CONCLUSION

For fluid-structure interaction of earth-rock mixture slope, this paper mainly introduces the characteristics of the fluid-structure interaction and its research progress. Mathematical model of the Fluid-Structure Interaction in the earth-rock mixture slope is given. It provides a theoretical basis for the further theoretical research and numerical simulation.

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