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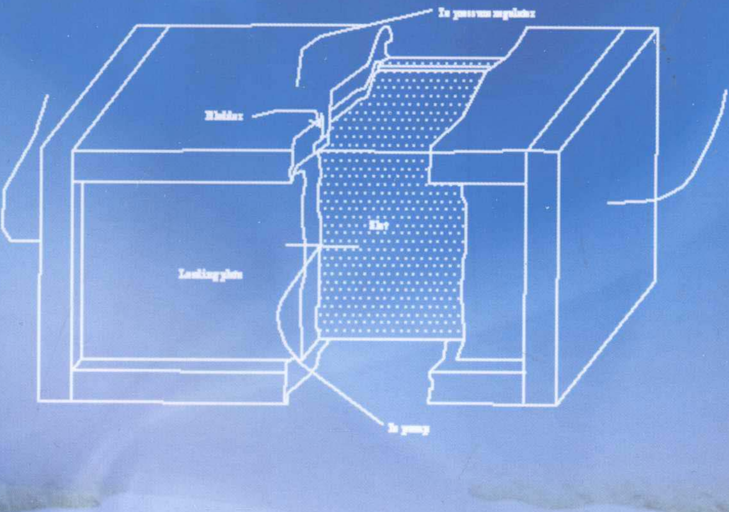

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Hydraulic Fracturing in Earth-Rock Fill Dam
（土石坝水力劈裂）

Jun-Jie Wang
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内 容 提 要

水力劈裂是一种在岩石或土体中由于水位上升引起裂缝产生或扩展的物理现象。土石坝水力劈裂是一个关系大坝安全的复杂问题。本书从水力劈裂的发生条件和机理、判定准则和数值模拟方法三方面研究土石坝水力劈裂问题，并研究了糯扎渡土石坝的抗水力劈裂性能。

本书内容包括：文献综述，水力劈裂发生条件和机理，心墙土体的断裂韧度和抗拉强度、Ⅰ-Ⅱ复合型断裂破坏判定准则，水力劈裂判定准则、数值模拟方法和影响因素。

本书读者包括水利工程的研究者、设计者和建设者，以及对水利工程研究感兴趣的人士。

Hydraulic fracturing is a physical phenomenon in which the crack in rock or soil is induced or expanded by water pressure due to the rising of the elevation of water level. The occurrence of hydraulic fracturing in soil core of earth-rock fill dam is a very troublesome geotechnical technique related to the safety of the dam. This book has focused on the investigation on the problem of hydraulic fracturing in earth-rock fill dams from the three aspects, i. e. conditions and mechanisms of hydraulic fracturing, criterion of hydraulic fracturing, and numerical method on hydraulic fracturing. As an example to analyze the ability of earth-rock fill dam to resist hydraulic fracturing, the Nuozhadu Dam located in Western China is analyzed.

The main content of this book includes review of literature, conditions and mechanisms of hydraulic fracturing, fracture toughness and tensile strength of core soil, fracture failure criterion for core soil under Ⅰ-Ⅱ mixed mode, hydraulic fracturing criterion, numerical method for hydraulic fracturing and factors affecting hydraulic fracturing.

The book's main audiences are the researchers, designers and constructers engaged in water conservancy project, as well as readers interested in the study of water conservancy.

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ABSTRACT

Hydraulic fracturing is a physical phenomenon in which the crack in rock or soil is induced or expanded by water pressure due to the rising of the elevation of water level. Hydraulic fracturing is also defined as a weak link phenomenon, in which fracturing will occur in the least resistant soil subjected to increased water pressure. Hydraulic fracturing can occur even in a theoretically homogeneous embankment, but the probability of its occurrence is much higher if the material is not homogeneous with respect to deformability and permeability. The occurrence of hydraulic fracturing in soil core of earth-rock fill dam is a very troublesome geotechnical technique related to the safety of the dam. At one extreme, hydraulic fracturing is believed to have caused the complete failure of the Teton Dam, the important erosion damage of Balderhead Dam or the leakage after several years of satisfactory performance of Hyttejuvet Dam. In China, 17 earth-rock fill dams higher than 100 m have been or are constructed, and more than 24 will be constructed. The investigation on the problem of hydraulic fracturing in earth-rock fill dam is very useful and important to the safety of the dams.

This book has focused on the investigation on the problem of hydraulic fracturing in earth-rock fill dams from three aspects, i. e. ①conditions and mechanisms of hydraulic fracturing; ② criterion of hydraulic fracturing; ③numerical method on hydraulic fracturing.

The occurrence of hydraulic fracturing in the soil core of the earth-rock fill dam depends on some material and mechanic conditions. The material conditions are the cracks located at the upstream surface of the core and the low permeability of the core soil. The crack located at the upstream face of the core allows water to enter the core along the crack rapidly, but the low permeability of the core soil keeps the water from seeping into the soil

around the crack rapidly. The mechanic condition is the intensity “water wedging” action induced by the water pressure acting on the inner surfaces of the crack. In order to induce the “water wedging” action in the crack，two conditions are necessary. One is the rapid filling， and the other is the unsaturated soil core. The occurrence of hydraulic fracturing can be regarded as the propagation of the crack under water pressure. The mechanical mechanism of hydraulic fracturing should therefore be explained according to the theories in Fracture Mechanics. The water entering the core along the crack may not only induce the water pressure applied on the inner surfaces of the crack， but also soften the soil around the crack. The nominal stress state near the tip of the crack may change due to the “water wedging” action. In terms of the theory in Fracture Mechanics， if only the intensity of the nominal stress near the tip reaches its critical value， the crack will spread. Therefore， the mechanical mechanism of hydraulic fracturing is that the “water wedging” action changes the intensity of nominal stress near the tip of the crack. If there is no “water wedging” action， there will be no hydraulic fracturing.

The criterion of hydraulic fracturing is very important to investigate the problem of hydraulic fracturing. In order to establish a criterion of hydraulic fracturing based on the theories in Fracture Mechanics， the fracture behavior of the core soil should be investigated firstly. The silty clay used to construct the core of the Nuozhadu Dam located in western China is used as the testing soil. In order to study the fracture behavior of the core soil by experimental methods under modes Ⅰ， Ⅱ and Ⅰ-Ⅱ loading conditions， two improved testing methods are suggested. One is based on the conventional three-point bending beam and loading assembly. The other is based on the conventional four-point unsymmetrical bending beam and loading assembly. The fracture behaviors of the silty clay under the loading conditions of modes Ⅰ， Ⅱ and Ⅰ-Ⅱ are investigated by experiments. The influences of water content， dry density and preconsolidation pressure on the fracture behaviors of the tested soil are analyzed. The relationship between the fracture toughness and the tensile strength of the tested soil is established. Based on the testing results and the theories in Lineal Elastic Fracture Mechanics, a new criterion (called as the circular fracture failure criterion in this book) is suggested to determine the fracture failure of the soil under any loading condition of the mode Ⅰ, Ⅱ or Ⅰ-Ⅱ. The new criterion then is used to establish the criterion of hydraulic fracturing. The criterion of hydraulic fracturing can used to determine the occurrence of hydraulic fracturing if the fracture toughness K_{IC} of the core soil is obtained from experiments and the stress intensity factors K_{I} and K_{II} in the core are determined from calculations.

In order to investigate the problem of hydraulic fracturing, a new numerical simulate method is suggested. The method is based on the conventional two-dimensional finite element technique, and the theoretical formulations to calculate energy release rate using virtual crack extension method. The main differences of the new method from the published studies exist in the finite element model of crack and element mesh besides and ahead of the crack. Present technique can simulate the same structure with different crack depths using only one element mesh. The recreation of mesh is not necessary. This can conveniently simulate the propagation of crack if hydraulic fracturing occurs. The influence factors on convergence of calculated J integral are investigated. The accuracy of the calculated J integral is verified by analyzing the three typical problems in Fracture Mechanics, in which propagation of crack may follow mode Ⅰ, mode Ⅱ and mixed mode Ⅰ-Ⅱ respectively. Using the new numerical method, the factors affecting the occurrence of hydraulic fracturing in the earth-rock fill dam are investigated. The investigating results indicate that increasing any of the Young's modulus, the Poisson's ratio and the density of the core soil is helpful to reduce the likelihood of the occurrence of hydraulic fracturing. The likelihood of the occurrence of hydraulic fracturing increases with increasing the water level or the crack depth. The lower part of the dam core is the zone in which the phenomenon of hydraulic fracturing may be induced easily. As an example to analyze the ability of earth-rock fill dam to resist hydraulic fracturing, the Nuozhadu Dam located in Western China is analyzed.

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NOMENCLATURE

a	crack depth
	crack half-length
	inner radius of circular or spherical cavity
a'	inner radius of circular or spherical cavity after expansion
A	cross sectional area of specimen
	effective area of conductor
A'	cross section of two-dimensional elastic body
b	external radius of circular or spherical cavity
	distance from reservoir water level to dam crest
b'	radius of interface between elastic and plastic zones
B	thickness of specimen
	base reaction
	volume deformation modulus
c	cohesion force of soil
	horizontal distance from crack to loading point
c_1	cohesion of crack before water entering
c_2	cohesion of crack after water entering
C	gravity force of core
d	depth of crack plane
$\mathrm{d}a$	increment of crack depth
$\mathrm{d}L$	change of conductance
$\mathrm{d}s$	unit of length along arc
D	pore water pressure coefficient
E	Young's modulus of material
E_c	Young's modulus of core soil
E_s	Young's modulus of shell rock-fill
E_t	tangent Young's modulus
E_{ur}	tangent Young's modulus under unloading conditions
f_1	function of ratio of crack depth to specimen width used to calculate K_{I}
f_2	function of ratio of crack depth to specimen width used to calculate K_{II}
F	shear force applied on core by shell
F_1	oefficient of correction for stress intensity factor of mode Ⅰ crack
F_2	coefficient of correction for stress intensity factor of mode Ⅱ crack
F_{down}	shear force acting on downstream face of core induced by downstream shell rock-fill
$F_{\max}$	maximum tensile force
F_{up}	shear force acting on upstream face over crack of core induced by upstream shell rock-fill
G	total strain energy release rate
	total weight of loading pole, upper grip and upper part of the specimen from fault face
	water pressure acting on inner faces of crack
G_S	specific gravity
G_w	gradient water pressure
H	water head in crack
	dam height
	hydrostatic pressure in horizontal direction
H_0	water head at which value of K_{I} equals to zero

water head at which the values of $(K_{\mathrm{I}}^2 + K_{\mathrm{II}}^2)^{0.5}$ for different cracks are equal to each other

H_{h0} water head at which value of K_{I} equals to zero for horizontal crack

H_{v0} water head at which value of K_{I} equals to zero for vertical crack

I_P plasticity index

J J integral

k conductance ratio

k_0 static lateral pressure coefficient

K stress intensity factor

a parameter in Duncan-Chang E-B model

K_b a parameter in Duncan-Chang E-B model

K_{I} stress intensity factor of mode I crack

K_{IC} fracture toughness of material

K_{II} stress intensity factors of mode II crack

K_{IIC} fracture toughness parameter of mode II

K_{ur} a parameter in Duncan-Chang E-B model

l effective length of conductor

L conductance of conductor

L_1 horizontal distance from fulcrum A (or D) to loading point

L_2 horizontal distance from fulcrum B (or C) to loading point

m slope coefficient of curve $P_f \sim \sigma_h$

a parameter in Duncan-Chang E-B model

M bending moment acting on crack plane

n proportionality coefficient

a parameter in Duncan-Chang E-B model

p water pressure

p_a atmospheric pressure

p_0' increment of effective stress

P load applied on the specimen

total concentrated load applied on soil beam

P_d driving pressure of injected fluid

P_{dip} driving pressure of infiltrated pore fluid

P_f water pressure applying on internal surface of circular or spherical cavity

q_u unconfined compression strength of soil

Q shearing force acting on crack plane

r radial distance from center of circular or spherical cavity

coefficient of determination

R resistance to propagate crack

ratio of average vertical stress to water pressure

R_f a parameter in Duncan-Chang E-B model

R_L average load transfer ratio

R_w ratio of water pressure to overburden pressure

S coefficient related to diameter of needle inserted into specimen

effective length of specimen

gravity force of shell rock-fill

T traction vector defined according to the outward normal along Γ

u excess pore water pressure in soil element

pore water pressure in soil

displacement vector

u_0 initial pore pressure

V_{frx} volume of crack itself

V_{leak} volume leaked out through crack walls

w crack width

W width of specimen

strain energy density

hydrostatic pressure in vertical direction

W_L liquid limit

W_P plastic limit

x direction pointing at left abutment along a horizontal line parallel to dam axis
coordinate axis x

y direction pointing at downward stream perpendicular to dam axis
coordinate axis y

z direction pointing at upward vertical
coordinate axis z
distance in vertical direction

α coefficient related to compression of soil
proportionality coefficient

α_m Henkel pore water pressure coefficient

β slope angle of crack face
coefficient related to compression of soil

γ unit weight of soil
coefficient of determination

γ_w unit weight of water

Γ curve surrounding notch tip starting from lower flat notch surface and ending to upper flat surface

Γ_0 initial curve surrounding notch tip

Γ_1 curve surrounding notch tip after small distance Δa outward along crack

Γ' bounding curve of two-dimensional elastic body

Γ'' portion of Γ' on which tractions T are prescribed

Δa virtual increase in crack depth

Δp_m increment of water pressure in circular cavity while hydraulic fracturing is induced

Δu increment of pore pressure

$\Delta\sigma_{oct}$ increment of octahedral normal stress

$\Delta\sigma_z$ increment of vertical normal stress σ_z

$\Delta\tau_{oct}$ increment of octahedral shear stress

$\Delta\tau_r$ increment of shear stress τ_r

$\Delta\tau_{yz}$ increments of shear stress τ_{yz}

$\Delta\tau_\theta$ increment of shear stress τ_θ

$\Delta\varphi$ increment of internal friction angle of material

θ propagation angle of crack

Π total potential energy

$\Pi(a)$ potential energy of body with notch tip at $x=a$

$\Pi(a+\Delta a)$ potential energy of body with notch tip at $x=(a+\Delta a)$

ρ density of material

σ load applying on soil element
effective normal stress developed on crack face

σ_1 major principal stress

σ_2 middle principal stress

σ_3 minor principal stress

σ_h radial normal stress acting on exterior surface of circular or spherical cavity
confining pressure perpendicular to central axis of circular cavity in sample

σ_n normal stress applying on crack face

σ_r radial stress in soil mass of circular or spherical cavity

σ_t shear stresses applying on crack face
tensile strength of soil

σ_{ta} apparent tensile strength of soil

σ_x normal stress applying at vertical planes perpendicular to upstream surface of core
normal stress applying on the element in x direction

σ_y normal stress applying on vertical planes parallel to upstream surface of core
normal stress applying on the element in y direction

σ_{ys} yield stress of material

σ_z normal stress applying on horizontal plane

normal stress applying on the element in z direction

σ_θ circumference stress in soil mass of circular or spherical cavity

σ' effective stress in soil element

σ'_t effective shear stress applying on crack

σ'_{v0} effective stress in vertical direction

$\bar{\sigma}_z$ average of vertical stresses

τ effective shear stress applying on crack face

τ_f shear strength of crack

$\tau_{r\theta}$ shear stress in polar coordinates

τ_{yz} shear stress applying on vertical planes parallel to upstream surface of core

τ_{zy} shear stress applying on horizontal plane

τ^* reverse shear stress

ν Poisson's ratio of material

ν_c Poisson's ratio of core soil

ν_s Poisson's ratio of shell rock-fill

φ internal friction angle of material

φ_0 initial internal friction angle of material

φ_1 internal friction angle of crack before water entering

φ_2 internal friction angle of crack after water entering

∂a spreading depth of crack

$[K]$ structural stiffness matrix

$[K]_a$ overall stiffness matrix with crack depth (a)

$[K]_{a+\Delta a}$ overall stiffness matrix with crack depth $(a+\Delta a)$

$\{P\}$ vector of corresponding nodal loads

$\{u\}$ vector of displacements corresponding to every degree-of-freedom in structure

$-\partial \Pi$ reduced energy of elastic system

-Notional meaning of mathematical sign

displacement towards upstream

displacement towards right bank

displacement downward, i. e. settlement

decrease of conductance

CONTENTS

Chapter 1

Introduction

1.1 Types of Embankment Dam

In dam engineering, many dam types, such as arch dam, gravity dam, arch-gravity dam, barrage, and embankment dam, were/are used, but the embankment dam is the most important type. This is because majority of dams worldwide are embankment dams.

Embankment dams are made from compacted earth, and have two main types, rock-fill and earth-fill dams. Embankment dams rely on their weight to hold back the force of water, like the gravity dams made from concrete.

Rock-fill dams are embankments of compacted free-draining granular earth with an impervious zone. The earth utilized often contains a large percentage of large particles, such that the term rock-fill is called. The impervious zone may be on the upstream face and made of masonry, concrete, plastic membrane, steel sheet piles, timber or other material. The impervious zone may also be within the embankment, in which case it is referred to as a core. In the instances where clay is utilized as the impervious material, the dam is referred to as a composite dam. To prevent internal erosion of clay into the rock-fill due to seepage forces, the core is separated using a filter. Filters are specifically graded soil designed to prevent the migration of fine grain soil particles. When suitable material is at hand, transportation is minimized leading to cost savings during construction. Rock-fill dams are resistant to damage from earthquakes. However, inadequate quality control during construction can lead to poor compaction and sand in the embankment which can lead to liquefaction of the rock-fill during an earthquake. Liquefaction potential can be reduced by keeping susceptible material from being saturated, and by providing adequate compaction during construction.

A concrete-face rock-fill dam is a rock-fill dam with concrete slabs on its upstream face. This design offers the concrete slab as an impervious wall to prevent leakage and also a structure without concern for uplift pressure. In addition, the concrete-face rock-fill dam design is flexible for topography, faster to construct and less costly than earth-fill dams. The concrete-face rock-fill dam originated during the California Gold Rush in the 1860s when miners constructed