UNIVERSITI PUTRA MALAYSIA

THERMAL AND STRUCTURAL ANALYSES OF ROLLER COMPACTED CONCRETE DAMS

KHALED HAMOOD BAYAGOOB

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By

KHALED HAMOOD BAYAGOOB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

To all Members of my Family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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By

KHALED HAMOOD BAYAGOOB

December 2007

Chairman: Associate Professor Jamaluddin Noorzaei, PhD

Faculty : Engineering

In the present study, a finite element computer code has been developed and is capable for simulating the sequence of construction of the roller compacted concrete dams taking into account the effects of the reservoir water temperature and climatic changes. The probability of cracking can be determined where the variation of the material mechanical properties with time are incorporated using the newly efficient experimental models found in literature.

The developed code has been validated first for some numerical examples found in literature. Then the code has been verified against the monitoring temperatures measured by the installed thermocouples in a real case study in Malaysia where good agreement has been obtained between the code predicted results and monitoring temperatures. Then the developed code has been applied for the simulation of sequence of construction and operation phase taking into account the reservoir water operation affects on the upstream dam side. Realistic and identical thermal and structural responses from both the two-dimensional and the three-dimensional models have been obtained. Thus the two-dimensional model can be sufficiently

used for the analysis of gravity roller compacted concrete dams without losing or sacrificing the accuracy level.

The capability of the developed code has been demonstrated by analyzing a large roller compacted concrete dam of 169 m in height where the impact of the placement schedule on the thermal and structural response has been investigated. The obtained results show that, the placement schedule has significant effect in reducing the tensile stresses at the critical zones of high foundation restraints.

Moreover, the developed code has been applied for the determination of the thermal and structural response of an unsymmetrical double curvature arch concrete dam as a general case. The roller compacted concrete technology has been tried as an alternative to the proposed conventional method utilizing the special code for the discretization of the arch dam gorges which was modified in the present study for roller compacted concrete arch dam problem. High tensile stresses at the dam bottom and the abutment boundaries in the upstream side have been observed. In addition to small regions of high compressive stresses near the abutment sides in the downstream side. Thus, a special attention should be paid to these regions in the design of roller compacted concrete arch dams.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ANALISIS STRUKTUR DAN TERMA UNTUK EMPANGAN KONKRIT TERMAMPAT GOLEK

Oleh

KHALED HAMOOD BAYAGOOB

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Dalam kajian ini, satu aturcara unsur-terhingga telah dibangunkan yang mampu melakukan simulasi turutan pembinaan empangan konrit termampat golek yang mengambilkira kesan suhu air takungan serta perubahan cuaca. Kemungkinan dimana retakan akan berlaku juga boleh diramal dimana variasi sifat mekanikal terhadap masa telah digunakan dalam aturcara ini mengambil kira model baru berasaskan kajian literatur.

Aturcara yang dibangunkan ini telah dipastikan ketepatannya dengan beberapa contoh numerikal yang terdapat dalam literatur. Kemudian aturcara ini telah disahkan dengan membandingkan suhu yang diambil di sebuah tapak pembinaan empangan di Malaysia. Keputusan yang memberangsangkan telah diperolehi antara nilai yang diambil di tapak serta nilai simulasi aturcara yang dibangunkan. Kemudian, aturcara yang dibagunkan ini telah digunakan untuk mensimulasi turutan pembinaan di tapak yang mengambilkira kesan kerj- operasi air di bahagian atas empangan. Kelakuan struktur yang tepat serta realistik telah diperolehi antara aturcara yang dibangunkan dengan suhu yang diambil melalui jangkasuhu di tapak pembinaan bagi model tiga-

dimensi serta dua-dimensi. Oleh itu, model dua-dimensi boleh digunakan secara efisyen untuk analisis struktur empangan konkrit termampat golek tanpa menjejaskan ketepatan.

Selain itu aturcara yang dibangunkan ini telah digunakan untuk menentukan kelakuan struktur serta terma sebuah empangan dua-lengkungan tidak-simetri sebagai sebuah contoh biasa. Teknologi konkrit termampat golek telah dikaji sebagai alternatif kepada konkrit biasa dengan menggunakan kaedah konvensional untuk diskretasi empangan gerbang dan mengubahsuaikannya untuk analisis empangan jenis konkrit termampat golek. Tegasan tegangan yang tinggi di bahagian bawah empangan serta di bahagian sempadan abutmen telah dikenalpasti.

Julat serta kebolehan aturcara yang dibangunkan ini telah ditunjukkan dengan menganalisis sebuah empangan konkrit termampat golek besar dengan ketinggian 169 meter dimana kesan turutan letakan konkrit di tapak pembinaan terhadap kelakuan struktur serta terma telah dikaji secara mendalam. Keputusan kajian menunjukkan bahawa kesan turutan letakan konkrit di tapak pembinaan memainkan peranan penting dalam menurunkan tegasan tegangan di bahagian-bahagian kritikal seperti di bahagian asas empangan. Juga dilihat bahawa terdapat tegasan mampatan yang tinggi di beberapa kawasan abutmen bahagian bawah empangan. Oleh itu, perhatian yang lebih perlu diberikan oleh para jurutera empangan kepada bagahian-bahagian tersebut dalam rekabentuk empangan konkrit termampat golek.

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Also, I am gratefully acknowledge Hadhramout University for their financial support during the course of this study which gave me the opportunity to pursue my study in Malaysia.

I certify that an Examination Committee has met on 7th December 2007 to conduct the final examination of Khaled Hamood Bayagoob on his Doctor of Philosophy thesis entitled “Thermal and Structural Analyses of Roller Compacted Concrete Dams” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the student be awarded the degree of Doctor of Philosophy.

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Saya mengesahkan bahawa satu Jawatankuasa Pemeriksa telah berjumpa pada 7 Disember 2007 untuk menjalankan peperiksaan akhir bagi Khaled Hamood Bayagoob untuk menilai tesis Doktor Falsafah beliau yang bertajuk "ANALISIS STRUKTUR DAN TERMA UNTUK EMPANGAN KONKRIT TERMAMPAT GOLEK" mengikut Akta Universiti Pertanian Malaysia (Ijazah Lanjutan) 1980 dan Peraturan Universiti Pertanian Malaysia (Ijazah Lanjutan) 1981. Jawatankuasa Pemeriksa tersebut telah memperakukan bahawa calon ini layak dianugerahi ijazah Doktor Falsafah.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

KHALED HAMOOD BAYAGOOB

Date: 1st February 2008

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LIST OF NOTATIONS AND ABBREVIATIONS

Latin Upper Case

A	area
B_w	block width of the dam
$[\bar{B}]$	strain-displacement matrix
$[B]$	strain-displacement matrix
$[C]$	capacitance matrix
C_1, C_2, C_3	elasto-plastic yield surface constants
$[D]$	global element elastic rigidity matrix
$[\bar{D}]$	local elastic rigidity matrix for joint element
D_{ep}	elasto-plastic rigidity matrix
E	material elastic modulus
E_c	concrete elastic modulus
$\{F\}$	vector of equilibrated nodal force
I_1	first stress invariant tensor
$\mathbf{J}$	Jacobian matrix
J_2	second stress invariant tensor
J_3	third stress invariant tensor
K_f	foundation restraint factor
K_R	structure restraint factor
$[K]$	element stiffness matrix
L	loading criterion for a joint element
N_i	shape function at node i
Q	heat transfer rate per unit area

$\dot{Q}$	heat of hydration rate per unit volume
$\{R\}$	nodal point applied external load vector
$\{R\}$	unbalanced (residual) nodal load vector
$\{T\}^e$	vector of element nodal temperatures
T	temperature
T_{ad}	adiabatic temperature rise
T_f	the temperature of the fluid surface
T_{max}	maximum adiabatic temperature rise
T_s	the temperature of the solid surface
$\{\dot{T}\}^e$	vector of element nodal temperatures variation with time
V	wind speed
W_{cr}	permissible dam crack width

Latin Lower Case

a	Plastic flow vector
a_1, a_2, a_3	Plastic flow subvectors
c	specific heat coefficient
c	Cohesion coefficient
$\{d\delta\}$	virtual displacement vector
dV	elemental volume
$f_c^`$	compression strength
$f_t^`$	tensile strength
h	convection heat transfer coefficient
h_c	concrete convection heat transfer coefficient
h_f	wind convection heat transfer coefficient

k_n	normal stiffness of the joint element
k_s	shear stiffness of the joint element
k_x, k_y, k_z	thermal conductivity coefficients in x, y. and z direction
l_x, l_y, l_z	direction cosines of the outward surface normal in x, y, and z respectively
q	heat flux
q_c	convection heat transfer rate
q_r	radiation heat transfer rate
t	time
u	tangential and normal displacements respectively
v	tangential and normal displacements respectively
w	tangential and normal displacements respectively
x,y ,z	cartesian coordinate system
{p}	surface traction forces
{g}	distributed body forces

Greek Upper Case

$\{\Delta F\}$	incremental load vector
$\{\Delta \delta\}$	incremental nodal displacements vector
$\{\Delta \varepsilon\}$	incremental strains vector
$\{\Delta \sigma\}$	incremental stress vector

Greek Lower Case

α	hydration heat rate parameter
β	shear modulus reduction factor