UNIVERSITI PUTRA MALAYSIA

COMBINED THERMAL AND MECHANICAL FINITE ELEMENT MODELING OF ROLLER-COMPACTED CONCRETE DAM

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By

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

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DEDICATION

This work is dedicated to the memory of my supervisor Prof. Jamaluddin Noorzaei.

His invaluable guidance and outstanding knowledge has truly been a great inspiration to me. His numerous suggestions for the improvement of the thesis and his patience and kindness have made this study a memorable experience. Without his professional support and encouragement, this work would never take place.

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

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Chairman: Professor Jamaluddin Noorzaei, PhD

Faculty: Engineering

Roller compacted concrete (RCC) dams are vulnerable to cracking as a result of high tensile stresses due to thermal loads, material properties and mechanical loads. Making reliable prediction of stress fields, and thereby cracking risk, thermal and mechanical properties such as creep form an important part of the material modeling. Recently, many models have been proposed to study the significance of thermal loads and creep on RCC dam. Most of the earlier researchers considered creep very approximately or neglected it altogether. However, due to the significant influence of creep on the stress values, especially in early age concrete, a more accurate creep model is essential. Furthermore, most of the previous researchers who investigated dam concrete mainly focused on the uniaxial compressive and tensile strength, so their studies did not consider safety of the dam concrete under multi-axial stress states.

In this investigation, a system of crack prediction of RCC dam during construction and operation phase has been developed. It takes into account more relevant features

of the behavior of concrete such as ageing, temperature effect, creep and adiabatic temperature. Appropriate boundary conditions in the dam body is used for the water interaction at the upstream face of the dam, taking into account the variation of temperature of the reservoir water with depth. The primary objectives of the present work are:

- To formulate a new viscoelastic model, which includes the ageing and temperature effect on properties of concrete.
- To propose a mathematical crack model for RCC materials, which includes the effect of aging and temporal domain on its formation to reliably establish a precise safety evaluation of the RCC dam behavior.
- To develop a system of crack prediction of RCC dam.

Hence a viscoelastic model, which involves ageing effects and thermal dependent properties, is adopted for the concrete. The maturity concept (degree of hydration) was introduced to describe the development of material properties such as elastic modulus and tensile strength. The influence of different isothermal temperatures on creep is taken into account by the maturity concept and a transient thermal creep term is introduced. In order to assess the occurrence of crack either at short or long term in RCC dams, a mathematical crack model for RCC materials which consider most of the crucial factors such as aging and temperature effect, variation of mechanical properties and current stress state on its formation to establish more reliable safety evaluation of the RCC dam behavior is proposed.

In context of the finite element method, all the above proposed mathematical model were formulated. The existing finite element programs have been extensively

modified to include the above issues (viscoelastic model, aging and temperature effect and mathematical crack model). The validation of the developed finite element programs has been done at two stages, firstly based on experimental evidences and secondly based on analytical evidences. Regarding the experimental evidences, the developed programs were verified against the monitoring temperatures measured by insulating thermocouples in two full real scale tests of RCC dams. The predicted results obtained from the finite element programs were found to be in good agreement with the measured ones. The modified finite element programs were used to solve some numerical examples reported in literature and the predicted results were found to be consistent with the reported ones.

The developed system has been applied to assess the temperature distribution and stress fields of the 65 m height Zirdan RCC dam under hot- dry climate action during the construction and operation phases. In this investigation, alternative studies considering different construction schedules were performed to evaluate their effect on the safety assessment of the dam. The results have shown that, an alternative placing schedule with the stoppage and avoidance of summer work improved the level of safety in the dam.

Furthermore, the developed system has been applied for the determination of the thermal and structural response and evaluates the level of safety of an unsymmetrical double curvature arch concrete dam during the construction stage. The result has shown that, high tensile stresses have been observed at the dam bottom and the abutment boundaries in the upstream side section due to the restriction from the abutment and foundation rock.

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

MODEL UNSUR TERHINGGA KOMBINASI SUHU DAN MEKANIKAL UNTUK EMPANGAN KONKRIT PADAT-TERGELEK

Oleh

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Empangan konkrit padat tergelek (RCC) terdedah kepada keretakan hasil daripada tegasan tegangan yang tinggi disebabkan oleh beban haba, sifat bahan dan beban mekanikal. Bagi membuat ramalan yang boleh dipercayai bagi medan tegasan dan seterusnya risiko keretakan, suhu dan sifat mekanikal seperti rayapan membentuk satu aspek penting dalam pemodelan bahan. Kebelakangan ini, kebanyakan model telah dicadangkan untuk mengkaji kepentingan beban haba dan rayapan dalam empangan konkrit padat tergelek. Kebanyakan penyelidik terdahulu hanya menganggarkan rayapan secara kasar atau hanya diabaikan. Walau bagaimanapun, disebabkan pengaruh penting rayapan dalam nilai tegasan, terutama di usia awal konkrit, model rayapan yang lebih tepat adalah penting**..** Kebanyakan penyelidik terdahulu yang mengkaji empangan konkrit mengutamakan kekuatan mampatan dan tegangan searah, oleh itu kajian mereka tidak mempertimbangkan keselamatan empangan konkrit di bawah keadaan tegasan pelbagai arah.

Dalam kajian ini, satu sistem penaksiran RCC semasa tahap pembinaan dan operasi telah dibangunkan. Ia mengambilkira sifat konkrit yang lebih releven seperti usia,

kesan suhu, rayapan dan suhu adiabatik. Keadaan sempadan yang bersesuaian untuk badan empangan yang digunakan untuk interaksi air pada permukaan hulu empangan dengan mengambilkira kepelbagaian suhu air takungan dengan kedalaman. Objektif utama dalam kajian ini adalah:

- Untuk memformulasikan model viscoelastik baru, termasuk kesan umur dan suhu terhadap sifat konkrit.
- Untuk membangunkan model matematik bagi keretakan untuk bahan empangan RCC termasuk kesan usia dan domain masa dalam pembentukan untuk mengukuhkan penilaian keselamatan yang tepat bagi sifat empangan jenis ini.
- Untuk membangunkan sistem bagi meramalkan kerstakan empangan RCC.

Seterusnya, model viscoelastik yang melibatkan kesan usia dan pengantungan suhu digunapakai dalam konkrit. Konsep kematangan (darjah hidrasi) diperkenalkan untuk mengambarkan pembangunan sifat bahan sepeti modulus elastik dan kekuatan tegangan. Pengaruh suhu isoterma yang berbeza ke atas rayapan diambilkira dalam konsep kematangan, dan terma rayapan suhu transient diperkenalkan. Untuk menilai kekerapan retak samada dalam jangka pendek atau panjang dalam empangan RCC, model matematik untuk keretakan bahan RCC yang mempertimbangkan faktor kritial seperti kesan usia dan suhu, variasi sifat mekanikal dan keadaan tegasan semasa dalam pembentukan untuk mengukuhkan penilaian keselamatan yang lebih dipercayai untuk sifat empangan RCC dicadangkan.

Dalam konteks kaedah unsur terhingga, semua model matematik yang telah dicadangkan di atas telah diformulasikan. Program unsur terhingga yang sedia ada telah diubahsuai secara ekstensif dengan mempertimbangkan semua isu yang telah disebutkan (model viscoelastik, kesan usia dan suhu serta model matematik

keretakan). Validasi untuk program unsur tehingga yang telah dibangunkan dibuat pada dua peringkat, peringkat pertama berdasarkan bukti eksperimen dan peringkat kedua berdasarkan bukti analitikal. Berdasarkan bukti eksperimen, kod yang dibangunkan telah disahkan terhadap suhu kawalan yang diukur menggunakan penebat termogandingan dalam dua ujian berskala penuh empangan konkrit padat tergelek. Hasil ramalan yang diperolehi daripada kod unsur tehingga menunjukkan keputusan yang baik dengan nilai instrumentasi. Kod unsur terhingga yang diubahsuai telah digunakan untuk menyelesaikan beberapa contoh numerikal dalam kajian terdahulu dan keputusan yang diperolehi adalah konsisten dengan hasil yang dilaporkan.

Sistem yang dibangunkan digunakan untuk menilai pengagihan suhu dan medan tegasan bagi empangan RCC Zirdan dengan ketinggian 65m di bawah cuaca panas-kering dalam peringkat pembinaan dan fasa operasi. Dalam penyelidikan ini, kajian alternatif dijalankan dengan mengambilkira jadual pembinaan berbeza untuk menilai kesannya terhadap penilaian keselamatan empangan. Keputusan menunjukkan, satu jadual penempatan alternatif dengan pemberhentian kerja di musim panas meningkatkan tahap keselamatan empangan.

Selain itu, sistem yang dibangunkan telah diaplikasikan untuk menentukan tindakbalas suhu dan struktur serta menilai tahap keselamatan empangan konkrit lengkung ganda tak-simetri semasa peringkat pembinaan. Keputusan menunjukkan bahawa tegasan tegangan yang tinggi telah diperolehi di bawah empangan dan di sempadan tembok di bahagian hulu disebabkan oleh halangan daripada tembok dan batu asas.

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I certify that a Thesis Examination Committee has met on **6th of March 2012** to conduct the final examination of Aeid A. Abdulrazeg on his thesis entitled " **Combined Thermal and Mechanical Finite Element Modeling of Roller-Compacted Concrete Dam**" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the doctor of Philosophy.

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DECLARATION

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

_____

AEID A. ABDULRAZEG

Date: 6 March 2012

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