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CRACKING, PIPING AND REMEDIAL MEASURES

FISSURATION, RENARD ET MESURES CORRECTIVES

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SYNOPSIS: Comments on some selected points of the above, rather complex topic are given in the paper. The fundamental terms are defined and distinction between the differential settlement pattern and stress redistribution relevant to cracking of the crest (mainly due to post-constructional deformations with maximum on the surface) and those relevant to hydraulic fracturing of the clay core (mainly due to constructional differential movements with maximum at the mid-height) is made. Conditions under surface and internal cracks occur are listed and the corresponding criteria selected. The role of upstream fill structural collapse due to wetting in development of cracks is highlighted and the numerical procedures for estimating cracking and hydraulic fracturing potential of dams commented. Concerning the safe design of embankment dams the necessity of a complex approach accounting for all possible failure modes and considering both the static and hydraulic function of particular zones of the dam is emphasized. According to field evidence accidents are often brought about by "trendy design" focusing on one failure mode and disregarding the others. It should be recognized that the most measures increasing the shear resistance of the clay core is contradictious to the measures improving its cracking and hydraulic fracturing resistance. To obtain well balanced design and give valuable recommendations for dam construction and reservoir operation, among others a numerical model capable of realistic prediction of the dam performance is necessary. The efficiency of preventive and remedial measures against different failure modes can be evaluated by such a model.

INTRODUCTION

The mechanical behaviour of embankment dams is governed by interaction of dissimilar materials forming the dam, its reservoir and foundation. Different response of these materials to loading by self-weight and water pressure produces differential settlements causing shear stresses to develop along the zonal interfaces. Global stress transfer and arching occur in transversal (core/ transitions/ shoulders) and longitudinal directions (core/ abutment), as well as local ones at narrow trenches, bedrock irregularities and along the embedded structures. Distressed and tensile zones arise and if the material cannot accommodate these conditions, local destruction of its fabric, i.e. cracking occurs.

The most severe conditions are met at reservoir/impervious core interface, where cracks can be initiated and jacked open by the water pressure (hydraulic fracturing). These conditions allow for leakage and internal erosion - a process depending on flow velocity and material erodibility. Piping is an accelerated process of internal erosion through a leakage channel which can result in damage or failure of the dam. According to the statistics more than 40% of unsatisfactory embankment dam performance can be attributed to this phenomenon.

Over the last three decades a considerable effort of the profession has been devoted to these questions and many excellent publications appeared treating almost all significant aspects of the problem. Along with the fundamental works (Sherard et al., 1963, 1984a,b; Sherard, 1973,1986; Leonards and Narain,1963; Vaughan et al., 1970, 1982; Penman and Charles, 1979; Penman, 1985 and others) many valuable contributions have been published in special sections of ICOLD Proceedings dealing with cracking (10th ICOLD,Q.36,1970),leakage (12th ICOLD,Q.45,1976), interface problems (13th ICOLD, 1979,Q.48) and failure of dams (13th ICOLD, 1979, Q.49). Even the writer made attempts to contribute to the problem by prediction of cracking and hydraulic fracturing potential of dams using numerical models consistent with field measurement and bending test results (Doležalová, 1970, 1976, 1983; Doležalová et al., 1988; Doležalová and Zemanová, 1993).

Keeping the writer's experience these comments are focused on conditions of cracking, its prediction and prevention. The mechanism of catastrophic failure by piping as well as the design of filters to prevent erosion are beyond the scope of the paper. Although large zoned dams on incompressible foundation are mainly considered, most of the conclusions are valid for small, homogeneous dams, too.

CONDITIONS OF CRACKING

Conditions under which cracking occurs are due to two groups of factors. The factors controlling the stress state and those determining the material properties, i.e. their ability accommodate differential settlements.

Cracks on the Crest

Any cracks on the dam crest occur due to development of tensile zones caused by post-constructional differential settlements. Any structural change of the fill due to consolidation and creep after construction or due to collapse settlement on reservoir filling produces displacements displaying maximum on the dam surface.

Typical displacement patterns producing tensile zone in longitudinal direction are characterized by movements directed at the center of the valley (Fig1). It reflects the influence of the valley shape and the shear stresses developing along the core/bedrock contact. The corresponding horizontal displacements induce extension near abutments and compression in the central part of the valley.

While volume changes at slow rate (consolidation, creep) allow for material self-adjustment, sudden structural collapse of the upstream fill due to wetting often causes transversal and longitudinal cracks on the crest.

A typical example is shown in Fig.6 of the companion paper (Doležalová, Zemanová, 1993), where exceptionally large differential settlements and several longitudinal cracks occurred during construction, reservoir filling and dam operation . All troubles were caused by extremely weak structure of the upstream rockfill from weathered gneiss placed without compaction (Doležalová, 1983).

Internal Cracks

Internal cracks occur due to differential settlements, arching effects and distress zones developed during construction. As the multilift construction procedure produces maximum displacements in the middle part of the dam the maximum stress transfer also takes place at this level. As approaching the crest the differential settlements decrease, there are right conditions for the silo effect producing hanging, arching and distressed zones. The combination of transversal and longitudinal or global and local stress transfer is particularly dangerous

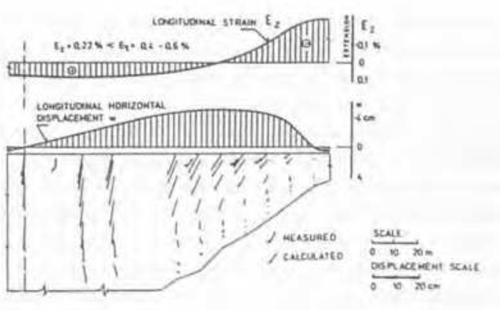

Fig.1. Post-construction displacements due to creep and wetting by 3D FEM (Doležalova, Leitner, 1980)

in this part of the dam.

This is the reason why hydraulic fracturing and leakage channels mostly occur near abutments at the mid-height of the dam. It develops without notable settlements or any other indication on the dam surface. So internal cracks caused by constructional differential settlements and surface cracks brought about by post-constructional differential settlements do not appear,as a rule,together. The only exception to this rule is the above mentioned sudden settlement of the upstream shoulder due to first reservoir filling. This collapse makes the adjoining core move causing not only cracks on the crest but also additional differential settlements and stress transfer in the longitudinal direction. There are a number of dams, where this process triggered hydraulic fracturing.

Material Properties

Field evidence of embankment dam performance shows that unsaturated, stiff cores of low plasticity (silty clays, coarse, broadly graded soils from glacial moraines, etc.) compacted on the dry side of Standard Proctor Optimum were mostly damaged by cracking and piping, while flexible, saturated, soft cores compacted on the wet side and exerting high pore pressures during construction behaved well. This is despite the fact that stiffer materials with higher moduli are more compatible with the transitions and shoulders.The high unconfined strength of these materials, however, allows for development of high shear stresses and almost zero minor and intermediate principal stresses along the core/bedrock and core/concrete contacts, i.e. creates conditions of hydraulic fracturing. The unsaturated, stiff materials are also susceptible to both, the cracking by tension and the sudden structural collapse due to wetting. So flexible, saturated, soft cores are preferable for preventing cracking and hydraulic fracturing. On the other hand their low shear strength reduces the safety of the dams against shear failure.

PREDICTION OF CRACKING

The above complex picture can be only predicted by a numerical model. Some comments on numerical models allowing estimation of cracking risk are given below.

1) The end of construction is a decesive loading stage and maximum rate of consolidation of the core should be assumed for hydraulic fracturing prediction, while minimum one for surface cracking assessment. A correct simulation of the construction sequence including the stress state of the crest is of particular importance.
2) The rapid first filling of the reservoir causing settlements due to wetting should be modelled with account for 3D effects, using either 3D model or two interacting 2D models in cross and longitudinal directions (Fig.2).
3) Loading stage corresponding to the maximum post - constructional settlements of the dam due to reservoir operation and creep should be taken into account for predicting cracking potential of the crest.
4) The constitutive model with its parameters should be capable of realistic displacement prediction in both, the zones of compression and tension. Bending test results can be used for tensile zones.
5) The adverse case of cracking under undrained conditions should be used as a criterion for estimating safety against cracking. Cracks on the crest occur if the calculated tensile strains exceed the maximum elongation of compacted clay according to bending tests.
6) Hydraulic fracturing under undrained conditions occurs if the reservoir pressure exceeds the minimum total earth pressure and the undrained tensile strength of compacted clay on any plane normal to the reservoir/core interface. Checks of this kind always show critical conditions at the mid-height of the dam (Doležalová et al., 1988; Beier et al., 1979).

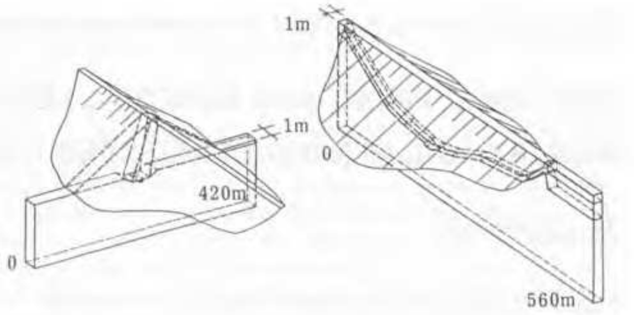

Fig.2. 2D FEM analyses of Slezská Harta Dam in transversal and longitudinal directions (Dolezalova et al., 1988)

Analysis of multilift construction, constitutive models for zoned dams, as well as empirical relations for collapse settlements are given in the companion paper.

PREVENTION OF CRACKING

The best remedy is prevention and hence, this type of measures is focused. Some of effective measures preventing cracking, however, besides their main purpose reveal side effects worsening the safety against other failure modes. These measures deserve particular attention and some of them are listed below.

1) According to field evidence flexible, wet clay core of medium to high plasticity exerting high pore pressures before the first reservoir filling is the best remedy against any cracking. The large lateral thrust of such a core, however, requires well compacted, pervious shoulders, otherwise slope failure occurs (see Carsington Dam, Potts et al., 1990).
2) Global and local widening of the core (boots,etc.) and placement of flexible core material compacted on the wet side along the core/bedrock contact and in tensile zones have the same impact. These measures improve the cracking resistance,but reduce the shearing resistance.
3) Well compacted, sluiced rockfill of good quality prevents the collapse of the upstream shell due to wetting and so cracking of the crest. Using weathered rocks, however, smooth, impervious contact planes, dangerous for shear failure can be created by these measures.

These few examples prove the necessity of well balanced design accounting for all possible failure modes and evaluating the benefits and shortcomings of the measures applied. In any case the complexity of cracking phenomenon requires a multiple line of defence. Filters capable of controlling internal erosion and sealing the cracks are the most important permanent elements of such a defence.

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