

**INFLUENCE OF THICKNESS AND INCLINATION OF CORE  
ON STABILITY OF EARTH AND ROCKFILL DAMS**

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**INFLUENCE OF THICKNESS AND INCLINATION OF CORE  
ON STABILITY OF EARTH AND ROCKFILL DAMS**

*by*

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**JANUARY 2014**

***DEDICATED TO***

***MY WIFE***

***RITU***

## CERTIFICATE

This is to certify that the thesis entitled, “**INFLUENCE OF THICKNESS AND INCLINATION OF CORE ON STABILITY OF EARTH AND ROCKFILL DAMS**” being submitted by **Mr. Rajesh Khanna** to the Indian Institute of Technology Delhi for the award of **Doctor of Philosophy** is a record of bonafide research work carried out by him under our guidance and supervision in conformity with the rules and regulations of the Indian Institute of Technology Delhi. The research report and results presented in this thesis have not been submitted, in part or full, to any other university or Institute for the award of any degree or diploma.

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(Rajesh Khanna)

## **ABSTRACT**

In earth and rockfill dams, the dimensions of the core and shell are usually determined by the types of soils and their quantities available at the dam site. If fine grained soil for the core, as well as coarse grained soil/rock fill for the shell is readily available in abundance, one can design a large variety of dam sections with different thicknesses and inclinations of core. To arrive an economical dam section, it is necessary to choose a core thickness and inclination which results in steepest side slopes and minimum earth work. There are very few studies reported in literature which delineate the zone in which the influence of the core is minimum on slope stability of upstream and downstream slopes of dams.

An analytical study was undertaken to identify the critical core thickness or inclination, in earth and rockfill dams having vertical core and inclined core respectively, within which the position of the core has no influence on the stability of upstream and downstream slopes of the dam. An earth and rockfill dam section, founded on strong base, having section and slopes similar to a high dam in the northern India was used as a base section for analysis. Various sections of the dam with different thicknesses of vertical core and different upstream slope inclinations of inclined core were analysed for slope stability using standard available software to arrive at the factors of safety of the outer slopes of the dam. The critical core thicknesses (for vertical core) and critical core inclinations (for upstream inclined core) were identified, beyond which the factor of safety of outer slopes of the dam was observed to undergo reduction. Stability analysis was carried out for three conditions namely End-of-Construction (EOC), Steady-State-Seepage (SSS) and Rapid-Draw-Down (RDD) with different parameters under static conditions. The following were the parameters that were varied for each of these three conditions:

- i. Core thickness (for vertical core)
- ii. Core inclination (for inclined core)
- iii. Height of dam (in some cases)
- iv. Angle of shearing resistance of shell (to study the effect of relative strength of shell and core)
- v. Effective cohesion intercept of the core material (to study the effect of uncertainty in value of cohesion intercept)
- vi. Flownet for Steady-State-Seepage condition
- vii. Flownet for Rapid-Draw-Down condition
- viii. Pore water pressure ratio,  $r_u$  for End-of-Construction condition

A total of 1644 stability analysis were carried out to arrive at the critical factor of safety for the upstream and downstream slopes of each dam section. On the basis of these stability analyses, the following results are arrived at regarding the influence of thickness and inclination of core on stability of earth and rockfill dams.

Earth and rockfill dam with the vertical core:

- a) The study shows that the stability of downstream slope under Steady-State-Seepage is influenced by thickness of vertical (central) core. The vertical core begins to reduce the factor of safety of the downstream slope when inclination of core slope is beyond 1 V: 0.50 H for base case. Thus, as long as the core thickness is such that the inclination of core slope is lower than 1 V: 0.50 H, there is no influence of core on factor of safety of downstream slope of the dam. The inclination of 1 V: 0.50 H can be referred to as the critical core inclination for vertical central core for the base case and corresponding thickness of the core (i.e. 100 % of dam height (ignoring thickness at crest)) is

referred to as the critical core thickness. The critical core thickness varies with relative strength of core and shell and is observed to lie between 50 % and 150 % dam height. The magnitude of reduction of factor of safety beyond critical inclination is significantly influenced by relative strength of core and shell. However the reduction is not significantly dependent on height of dam and value of effective cohesion intercept i.e.  $c'$ .

- b) The study shows that the stability of upstream stream slope of an earth and rockfill dam under Rapid-Draw-Down is influenced by thickness of vertical core. It is observed that vertical core begins to reduce the factor of safety of the upstream slope when the slope of vertical core is beyond 1 V: 0.75 H. As long as the core thickness is such that the slope of vertical core is steeper than 1 V: 0.75 H, there is no influence of core on stability of upstream slope of dam. This slope of the core 1 V: 0.75 H, is referred to as the critical inclination for vertical (central) core for base case and the corresponding thickness of the core (i.e. 150 % dam height (ignoring thickness at crest)) is referred to as the critical thickness. The critical slope of vertical core varies between 1 V: 0.50 H to 1 V: 1 H depending on the relative strength of the shell and core. The reduction of factor of safety of upstream slope under drawdown is not significantly dependent on height of dam or the magnitude of drawdown.
- c) The study shows that the stability of both downstream and upstream slopes under End-of-Construction is influenced by thickness of the vertical core. The vertical core begins to reduce the factor of safety of the dam slopes when the thickness of the core exceeds the critical thickness which it varies from 50 to 150 % dam height for End-of-Construction condition. The critical core thickness also varies with relative strength of core and shell. The magnitude of

reduction of factor of safety beyond critical inclination is significantly influenced by relative strength of core and shell, the pore water pressure parameters  $r_u$ , the value of effective cohesion intercept as well as height of dam.

Earth and rockfill dam with the upstream inclined core (of fixed thickness):

- a) The study shows that inclined core begins to reduce the factor of safety of the upstream slope under Rapid-Draw-Down when inclination of core slope is beyond 1 V: 0.75 H. As long as the inclination of core is lower than this critical value, there is no influence of core on stability of upstream slope of dam. The critical core inclination varies with relative strength of core and shell and lies in the range of 1 V: 0.25 H to 1 V: 0.75 H. The magnitude of reduction of factor of safety beyond critical inclination is significantly influenced by relative strength of core and shell. However the reduction is not significantly dependent on height of dam and magnitude of drawdown levels.
- b) The study shows that the stability of upstream slope of dam under End-of-construction is influenced by inclination of upstream inclined core. The inclined core begins to reduce the factor of safety of the upstream slope beyond a critical inclination of the core which lies in the range of 1V: 0.5 H to 1 V: 0.75 H. The magnitude of reduction is significantly dependent on the ' $r_u$ ' factor and height of dam. The critical core inclination does not vary with relative strength of core and shell, although magnitude of reduction of factor of safety beyond critical inclination is significantly influenced by relative strength of core and shell.

Critical thickness / inclination of core in earth and rockfill dams:

- a) For stability of downstream slope of dams with vertical core, it is observed that the critical thickness lies in the range of 50 to 150 % dam height for both the Steady-State-Seepage and End-of-Construction. When the relative strength of core is much lower than the shell (on account of large difference in  $\phi'$  or in  $r_u$  values for shell and core), the critical thickness is of the order of 50 % dam height. When the difference in relative strength is not very high, the critical thickness is of the order of 150 % dam height.
- b) For stability of upstream slope of dams with vertical core, it is evident that the critical thickness lies in the range of 100 to 200 % dam height for Rapid-Draw-Down case and in the range of 50 to 150 % dam height for End-of-Construction case. When the relative strength of core is much lower than the shell (on account of large difference in  $\phi'$  or in  $r_u$  values for shell and core), the critical thickness is in the range of 50 to 100 % dam height. When the difference in relative strength is not very high the critical thickness is in the range of 100 to 150 % dam height.
- c) For stability of upstream slope of dams with upstream inclined core (of fixed thickness), it is evident that critical inclination of upstream slope of the core lies in the range of 1 V: 0.25 H to 1 V: 0.75 H for Rapid-Draw-Down case and 1 V: 0.50 to 1 V: 0.75 H for End-of-Construction case. When the relative strength of core is much lower than the shell (on account of large difference in  $\phi'$  or in  $r_u$  values for shell and core), the critical inclination is in the range of 1 V: 0.25 H. When the difference in relative strength is not very high, the critical inclination is in the range of 1 V: 0.75 H.

The present study leads to the major conclusion that a core does not influence the stability of outer slopes of earth and rockfill dams, if it is positioned such that its thickness is less than 50 % of dam height (for vertical core) or its slope inclination is steeper than 1 V: 0.25 H (for inclined core). A core causes a reduction in the stability of outer slopes of earth and rockfill dams if it is positioned such that its thickness is more than 150 % of the dam height (for vertical core) or its slope inclination is flatter than 1 V: 0.75 H (for inclined core). In intermediate cases of cores positions, the influence of core depends on a variety of factors such as relative strength of core and shell, value of pwp ratio  $r_u$ , height of dam, depth of drawdown etc.

Thus, considering the strength properties of available construction materials and other relevant parameters, it is possible to demarcate a safe zone for placing the core within an earth and rockfill dam, such that maximum stability is achieved with minimum earthwork resulting in lowest cost of the project.

# **INFLUENCE OF THICKNESS AND INCLINATION OF CORE ON STABILITY OF EARTH AND ROCKFILL DAMS**

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