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Hydraulic and structural evaluation of rockfill dam behavior when exposed to throughflow and overtopping scenarios

PhD Thesis summary

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Abstract

Dams are vulnerable to extreme flood events in turn leading to accidental overtopping. This in particular applies to rockfill dams comprised of pervious and erodible material. Obtaining better understanding of behavior of rockfill dam components under extreme loading conditions is of significance from stability and economic standpoints. The aim of the research work forming the basis for the thesis has been to present descriptions of hydraulic and structural behaviors of rockfill dams under throughflow and or overtopping scenarios. Research findings outlining failure mechanisms and stability aspects of ripraps under overtopping scenarios are presented. Results from field surveys conducted to investigate construction aspects of placed ripraps constructed on rockfill dams are described. Further, experimental results demonstrating the hydraulic response of rockfill dam structures exposed to overtopping conditions are provided. Furthermore, behavior of rockfill dam structures coupled with disparate toe configurations subjected to throughflows are described based on experimental model studies. The overarching focus of the research has been to obtain a holistic evaluation of rockfill dam behavior when subjected to extreme loading conditions. This in turn is intended at improving the state of the art in design and construction of these structures.

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1. Scope and objectives

The overarching theme of the research project is to contribute to the field of rockfill dam engineering through generation of new knowledge aimed at improving dam safety. The investigations are in particular, focused on achieving better understanding of hydraulic and structural response of rockfill dams or dam components under extreme loading circumstances. The research efforts under this theme are directed at conduction of experimental studies aimed at achieving the following research objectives: ***Objective 1:*** Analyzing failure mechanisms and key factors affecting stability of ripraps constructed on the downstream slopes of rockfill dams under overtopping conditions. ***Objective 2:*** Evaluating the hydraulic response of rockfill dams exposed to throughflow scenarios and studying the effects of rockfill toes on throughflow hydraulic properties of rockfill dams]

2. Methods and findings

Assessment of rockfill dam stability under extreme loading scenarios is an intricate task influenced by significant number of parameters. Ripraps comprising of large natural rock elements are constructed on the downstream slopes of rockfill dams to protect against surface erosion due to overflow. Under throughflow scenarios, rockfill dam stability is primarily influenced by the interaction between the flow and the rockfill material. Further, rockfill dam toes are commonly coupled with the downstream rockfill dam structure to counter the destabilizing effects of throughflow.

The downstream slopes of Norwegian rockfill dams are protected with single layer placed ripraps, comprising of stones placed in an interlocking pattern. Available international literature describing stability aspects of placed ripraps under overtopping conditions is limited. Furthermore, past studies have been limited to describing 1D failure mechanisms in placed ripraps. With an aim of further extending past findings describing unidimensional failure mechanisms in placed ripraps to 2D, experimental data sets accumulated by a past investigation conducted at NTNU, Trondheim through physical modelling investigation conducted on 1:10 scaled model ripraps constructed with angular stones on a steep slope ($S = 0.67$) were further analyzed with additional tests. Results from the study provide qualitative and quantitative descriptions of a unique failure mechanism in placed ripraps interrelating the disciplines of hydraulic and structural research.

Toe sections of rockfill dams and ripraps are considered critical locations for initiation of progressive dam failure under overtopping conditions. With an objective of investigating construction aspects of rockfill dam toe structures and toe support conditions for placed ripraps, a field survey of nine Norwegian rockfill dams was carried out as part of this doctoral study. As part of the survey, key parameters describing quality of placed riprap construction such as stone sizing, angularity and placement inclination were analyzed. Conformity of placed riprap construction practices with official dam safety guidelines were evaluated. Further, details concerning existing state of toe conditions for the surveyed riprap structures were outlined. Study findings suggest that construction practices adopted for placed ripraps meet the requirements of official dam safety regulations with respect to sizing of the stones. However, additional recommendations put forward by the dam safety authorities with regards to placement inclination, material uniformity and angularity are not prioritized. Furthermore, detailed survey of riprap toe sections revealed that well-defined toe support measures stabilizing riprap toes are currently not implemented at any of the surveyed rockfill dams.

All past experimental model studies investigating placed riprap stability under overtopping conditions have been conducted with ripraps constrained at the toe section. However, as demonstrated by findings from the field survey, ripraps constructed on the downstream slopes of rockfill dams are generally not provided with any form of toe support. Hence, it is of importance from stability and economical standpoints to understand the failure mechanism in placed ripraps with realistic toe support conditions. Experimental overtopping tests on 1:10 scaled model placed ripraps constructed on a steep slope ($S = 0.67$) unsupported at the toe section were conducted as part of this study. Employing Smartstone probes, a new technology in stone movement monitoring, laser measurement techniques and Particle Image Velocimetry (PIV) techniques, detailed description of the underlying failure mechanism in placed riprap with unconstrained toe under overtopping conditions is presented. Study findings demonstrate sliding as the underlying failure mechanism in placed ripraps with unsupported toes. Further, placed ripraps with unrestrained toes on an average experience a fivefold reduction in stability, characterized by the critical overtopping magnitude as compared with placed ripraps provided with fixed toe supports. Furthermore, toe support conditions were found to have no effects on either the failure mechanism or the overall stability of dumped ripraps.

Comprehending response of rockfill dam structures when subjected to throughflow facilitates effective design and safety assessment. It is also of relevance for development of numerical models predicting rockfill dam breach process. To obtain a better understanding of non-linear flow through rockfill dams, experimental data sets obtained from model studies conducted as part of the IMPACT (Investigation of Extreme Flood Processes and Uncertainties) project were further analyzed as part of this study. The research project was undertaken during the period 2001-2004 by researchers from a consortium of 11 institutions across Europe, including NTNU, Trondheim. Experimental overtopping investigations were conducted on homogenous rockfill embankments of sizes 0.6 m, 1.2 m and 6 m. Based on statistical analysis conducted on the experimental data sets, a general non-Darcy type power-law describing non-linear flow through homogenous rockfill dams is proposed. Also, performance of the proposed power-law is subjected to a comparative evaluation with some of the well-known power-law relationships from the available literature employing the experimental data sets. Analysis results demonstrate better correlation between empirical predictions and experimental observations for the proposed non-linear flow law as compared with existing criteria.

A key component of the rockfill dam overtopping system is the rockfill dam toe, constructed in tandem with the downstream rockfill shoulder. Quantitative description of throughflow development in rockfill dams basing on experimental data is seldom found in international literature. Further, experimental corroboration of differences in hydraulic performance of disparate rockfill toe configurations has been rare. Findings from the present study add valuable knowledge to the state of the art on behavior of rockfill dam structures exposed to throughflow. Experimental throughflow tests were conducted on 1 m high rockfill dam models coupled with different toe configurations as part of this study. Investigation outcomes provide qualitative and quantitative descriptions of effects of internal, external and combined toe configurations on throughflow hydraulic properties. Key features describing the hydraulic effects of disparate toe configurations on flow through rockfill dams such as phreatic surface development and internal pore-pressure buildup are evaluated.

3. Discussion and conclusion

Obtaining a better understanding of stability aspects of these rockfill dam components under extreme loading conditions is vital for the rockfill dam construction industry. From dam safety and economical standpoints, accumulating technical knowledge on the hydraulic and structural behavior of these structures can lead to safe and economical design, construction and rehabilitation of rockfill dams. With an objective of adding to the international technical expertise on rockfill dam stability, this study was conducted as part of the research project titled 'Embankment dam safety under extreme loading conditions'. The research was initiated by a consortium between the Norwegian Research Centre for Hydropower Technology (HydroCen) and the Norwegian University of Science and Technology (NTNU).

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