NUMERICAL DESIGN ANALYSIS OF FOUNDATION FOR AN RCC DAM ON DEEP HIMALAYAN ALLUVIUMS

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ABSTRACT

Design and construction of dams in the Himalayan regions are faced with the difficult challenges posed by the presence of deep alluviums of over 70 m in addition to handling extreme floods safely and management of sediment inflow for sustainable long-term operation as well as meeting seismic guidelines. Traditionally CFRD or clay-core rockfill dams have been selected where the site is sufficiently wide for providing flood evacuation and sediment handling facilities. Deep cut-off walls were provided in the design and construction of the rockfill dams on deep alluviums. However most sites are narrow with steep abutments and preclude embankment dams. Founding either concrete or RCC dams on competent rock foundation at such sites is not economically feasible. An alternative is to design and construct RCC dams on engineered foundations. This paper presents a numerical analysis procedure for evaluating the feasibility of ground improvement methods along with limited excavation to improve the in-situ foundation and seepage characteristics of alluvial deposits for founding RCC dams. The procedure as applied on a recent project whereby currently available ground improvement methods were evaluated for their acceptability to assess their effectiveness in improving the foundation and seepage characteristics for founding RCC dams.

1. INTRODUCTION

Similar to other high mountain regions, river bed alluviums of varying depths dominate the Himalayan rivers. Depth of these alluviums exceed 50 m at several otherwise potential loca-tions for the construction of large dams which are very essential to sustain economic growth of the regions. Current trend in placing more emphasis on peaking run of river projects in lieu of the run of river projects also has required the construction of large dams in the Himalayan regions particularly bordering India and Nepal. The alluvial materials normally comprise of fine sands to large boulders and are commonly termed 'boulder mixed soils'. To build large dams the alluviums need to be either removed completely to expose rocks or the foundation materials treated using appropriate technology to improve the foundation bearing and compressibility characteristics.

2. DAM ALTERNATIVES

Potential solutions for large dams on alluvial deposits include:

- Large Concrete faced rockfill dams (CFRD) have been built on alluvial deposits over 100 m depth at some locations including in Chile where a CFRD solution was imple-mented. However building CFRD dams in narrow valleys such as those predominant in the Himalayas is not considered a feasible option.
- Composite Dams including central core rockfill dams – These have not been evaluated due to likely space limitations at identified dam locations in the Himalayas. However it should not be ruled out.
- RCC Dams have been built on weak foundations particularly in the middle east and northern Africa.
- Hardfill dams – Normally these are limited 20 to 30 m height and are appropriate for cofferdams.

2.1 CFRD limitation on Valley Shape

Suitability of CFRD at a certain location is limited by the prevailing valley shape if very narrow. If the ratio of dam crest width to dam height is less than 4, it has statistically been documented that the tendency for cracks to appear on the upstream reinforced concrete facing as being extremely high. This observational fact was based on a preliminary 2006 survey of failed CFRD dams around the world. The World Bank Expert Panel overseeing the Khudoni Project Redesign recommended in 2008 that a CFRD option not be considered any further due to the narrow valley limitation. There are also other parameters related to the CFRD design and construction which are not elaborated herein. Some documented CFRD related failures in narrow valleys are depicted on Figure 1 and Figure 2.

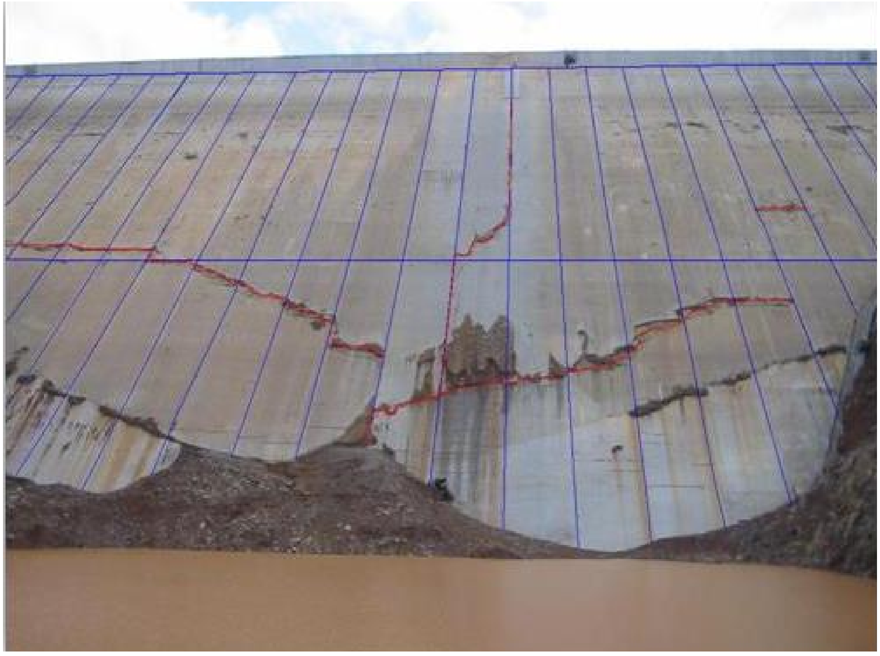

Figure 1 : Severe cracks on the upstream concrete face of a CFRD.

Figure 2 : Pulled reinforcement on the upstream concrete face.

In all the CFRD failures water could not be retained in the reservoirs until emergency rehabili-tations works at great costs were effected. Ma and Cao (2007) have also presented several of such failures as listed on Table 1.

Table 1 : CFRD Dam Failures (Ma and Cao -2007).

Dam	**Height**	**Issue**	**Cause**
Aguamilpa	187m	Concrete facing cracking	Rockfill deformability
Barra Grande	185m	Concrete facing cracking	Joint failures
Campos Novos	202m	Concrete facing cracking	Rockfill deformability
Itá	125m	Slabs cracking	Rockfill deformability
Itapebi	120m	Cracks parallel to the plinth	Foundation geometry
Mohale	145m	Compression joint rupture	Rockfill deformability
Tianshengqiao	178m	Horizontal cracking	Construction sequence
Xingó	150m	Slabs cracking	Sharp geometry of the left abut-ment and material deformability

Himalayan valleys in the upper reaches tend to be very narrow with near vertical rock abut-ments, and finding a feasible location for a CFRD meeting the valley criteria is not always possible.

An alternative to CFRD is the asphalt faced rockfill dams (ASFD). However, the asphalt facing is not as permanent as CFRD and needs to be replaced after 20 to 30 years of operation and is thus not recommended for dams in high mountainous regions such as the Himalayas essentially due to the prohibitive recurring cost and lost revenues during the replacement.

2.2 Clay Core Rockfill Dams

Central core rockfill dams have always fared well under severe earthquake shaking which is to be expected in the seismically prone high mountainous regions. Even if the central core rockfill dam slumps, the surficial repairs could be effected without drawing down the reservoir while continuing full if not partial operations. However, space for flood evacuation spillways, and headworks structures including intakes and sediment flushing bottom outlets works would be required. Since the Himalayan regions comprise of several neighbouring countries close cooperation, understanding and goodwill will be more than essential. This requirement is the same for any dam alternative.

2.3 Composite Dams

Neelum Jhelum dam commissioned an year ago in Pakistan was built over the main boundary thrust fault and has a composite dam design. Headworks hydraulic structures were located and built in concrete on one side of the fault; A central clay core rockfill part spanning over the fault was provided in the 'as constructed' revised design. During large earthquakes the composite part may be displaced in the vertical and horizontal directions by distances estimated in 'metres' accompanied with the slumping of the dam. It was concluded that the rockfill part could be raised and repaired in such an eventuality.

Finding a suitable location for a composite dam which require a wider section along the steep valleys in the Himalayan rivers would be very challenging but not impossible.

2.4 RCC Dams

The majority of large dam construction in the last few decades have incidentally been under-taken in Asia, South America, middle east and north Africa (MENA). Most innovations related to RCC dam construction has rightly come from these regions.

The RCC design and construction technology has matured over the years. Exceptionally good procedures and guidelines from ICOLD are currently available for the design and construction of RCC dam on reasonably sound foundations.

There are also numerous literature available as reference for general guidance when it comes to the detailed analysis of the body of an RCC dam as long the foundation is on good rock. Nevertheless, the design and construction of RCC dams on relatively weak foundation has been on the increase particularly in the middle east and north African (MENA) regions, where water storage is at a premium. Some of these dams have been in operation for over 20 years and have required very minor repairs. Several dams in the region have also been evaluated and earmarked for raising the dam height to obtain additional useable storage volumes to keep up with the increasing demand for potable and industrial needs.

The knowledge gained from the design and construction of RCC dams in the MENA region is a vital source in evaluating RCC dam options for the Himalayan region. For the RCC dams in the MENA region improvised dam geometries and zoning of the dam body was used while ac-counting for the relatively weaker foundations. Further most of these dams use the low paste technology similar to those practiced in Brazil for reasons other than the prevalent high temperatures for most of the year in the MENA region.

On some MENA RCC Dam projects, Designers have had to employ approaches normally con-sidered far too risky for dam foundation at the feasible design stage, when actual construction got underway on the projects. This delayed reaction by the stake holders had led to increased costs along with the longer project schedule. This paper is an initial attempt on how 'difficult design decisions' may be addressed on such projects for constructing large dams on deep alluvial riverbeds by making informed decisions to mitigate the perceived risks.

2.4.1 *RCC Dams on weak foundations*

The foundation requirements for RCC dams are in general as stringent as for concrete dams. However, alternative methods for improving the foundation requirements for RCC dams could be evaluated and implemented. The sections hereunder address the option of treating the foundation in situ which are required for the following reasons particularly specific to the Himalayan regions:

- Concentrating dam construction activities in the Himalayan regions during the non-monsoon months.
- Due to the potential for very high construction floods, significantly large capacity di-version schemes are required, at least until the foundation for the dams are complet-ed.
- An advantage of RCC Dams is overtopping during construction is allowable although not desirable

- Normally the actual construction perior extends from late September to early June in the following year. However religious festivities do impact construction and transpor-tation activities particularly in Nepal, where all construction comes to a standstill in October due to the Dashain and Tihar festivals, which implies the annual construction period is further shortened by a month at least in Nepal. This is a point always over-looked by both local and international dam Contractors in Nepal. In India, the lost productive period in October is normally in weeks.

3. FOUNDATION FOR LARGE RCC DAMS

The question that always arises is how to deal with the foundations for large RCC Dams in the Himalayan alluviums. The normal approach to-date has been to remove the alluvial deposits to expose bedrock. While this is possible, it extends the construction schedule by one or two years for the diversion works and the dam foundation treatment alone to be completed.

An alternative is to evaluate the feasibility of in-situ improvement of the deeper alluviums while limiting removal to the upper strata. This paper proposes the following with this objec-tive:

- Step 1 : decouple the dam analysis from the foundation – use traditional approaches including loading conditions, load factors and minimum factors of safety by assuming target foundation conditions.
- Step 2 : establish minimal foundation requirements for evaluating both bearing capacity and compressibility of the foundation layers
- Step 3 : analyze the foundation for dam imposed loads using assumed representative properties for the alluvial formation
- Step 4 : redo the analysis in Step 3 by using improved representative properties for the alluvial formation. The goal is to evaluate whether jet grouting, bored piling, deep cement mixing and other methods can be used to achieve the target foundation parameters.

ICOLD has published Bulletin 150 on Cutoffs for Dams for using selected methods for providing cut-offs for large dams. These methods do provide adequate seepage control, the effectiveness of which are easily proof tested by water pressure testing and corrective grouting undertaken if required.

However, when any of the methods are used for improving the strength and moduli characteristics for dam foundations quality assurance lacks an acceptable approach.

3.1 Hyperbolic soil model

A hyperbolic model for cohesive soils was first proposed by Kondner in 1963. This model was then improved by Duncan and Chang in 1970, and incorporated to model soils in the first gen-eration FEM analysis programs developed at the University of California, Berkeley, CA, USA. The programs were extensively performed on main frame computers in the 1970s and 1980s.

With the advent of personal computers (PC) in the late 1980s and the availability of specialized versions of FEM software for the PC led to the hyperbolic model based soil-structure analysis being almost forgotten. A few soil mechanics experts always questioned the validity of the hyperbolic soil model in comparison to traditional soil models which were harder to implement in soil-structure interaction analysis.

The theoretical formulation of the hyperbolic model is not elaborated herein and interested readers are encouraged to refer to the publication by Duncan and Chang (1970). The hyperbolic model is routinely referred in the literature as the Duncan-Chang model. Several variations and improvements are now available readily implemented for use on FEM software.

The hyperbolic model began to gain positive acceptance only in the last two decades and is now available on most if not all the civil engineering FEM software.

3.2 Availability of Hyperbolic model for foundation materials in commercial FEM software

Most commercially available FEM 2D and 3D software such as DIANA, Abaqus, Ansys, Plaxis, midas-SoilWorks, Phase2 among others implement the hyperbolic soil model with improve-ments to the original Duncan and Chang hyperbolic model of the 1970s. Some of the software are being used in the design analysis of RCC dams by dam designers around the globe.

3.3 Hyperbolic model parameters for soft clays and silts

Generic hyperbolic model parameters for sands, gravels and clays were published by Duncan et al. (1980). These in general covered most of the soils encountered on typical engineering projects but good results always required equally good judgement and selection of the parameters.

Stark et al. (1994) presented hyperbolic model parameters for silts and Likitlersuang et al. (2013) did similarly for Bangkok soft clays.

3.4 Hyperbolic parameters for rockfill materials

Dong et al. (2013) have made a comparison between Duncan-Chang hyperbolic model and the Generalized Plasticity Model for rockfill in their Analysis of a High Earth-Rockfill Dam. They concluded that in most instances their implementation of the generalized plasticity model yielded lower results in comparison to actual measurements whereas the Duncan-Chang model yielded higher and thus conservative values.

The successful analysis of a rockfill dam using Duncan-Chang hyperbolic parameters for the rockfill in essence forms the basis for assigning similar parameters for the 'boulder mixed' al-luvial formation of the Himalayan region.

3.5 Use of Duncan-Chang model in DIANA software

DIANA software has been extensively used in the 2D and 3D analysis of concrete gravity, gravity-arch and arch dams and lately have also been used in the 2D and 3D analysis of RCC dams. In most analyzed cases the foundations are in exceptionally sound rock and the analysis mainly focused on the dam body.

Analysis have continually shown that the highly stressed rock in the foundations for gravity dams are normally limited to shallow depths only. However, associated deformations are lower because of the higher moduli of the foundation rocks. In weaker rocks, the deformations tend to be much higher putting the RCC dams under distress. Hence it becomes necessary to establish the moduli of the foundation very carefully in addition to bearing capacity and permeability.

Poor foundation for dams are also normally in seismically active zones. Hence the proper evaluation of foundation is of paramount importance in siting RCC dams. This is a very urgent need.

Improved foundation conditions can be effected by appropriately incrementing the initial hy-perbolic parameters.

4. FOUNDATION EVALUATION OF A PROJECT IN THE HIMALAYAS

The longitudinal section along the river and the section at the dam axis on a typical project in the Himalayas are shown on Figure 3 and Figure 4 respectively. The alluvial deposit varies over 50 m to a maximum depth of about 70 m.

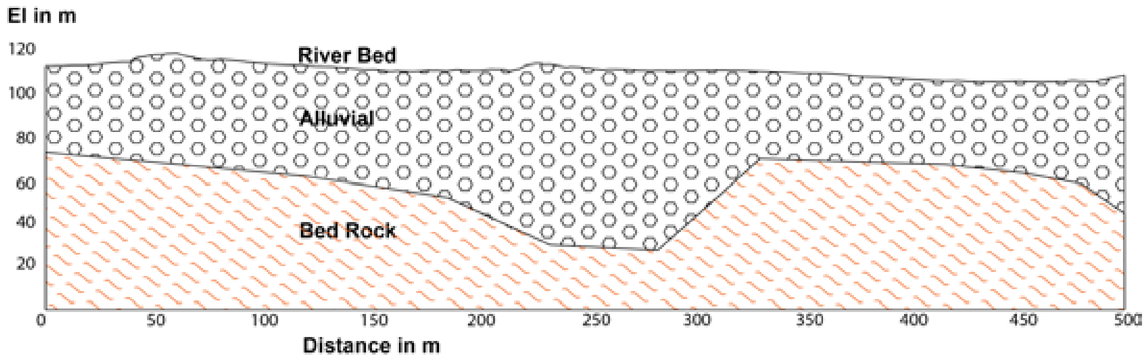

Figure 3 : Longitudinal profiles at the candidate dam site.

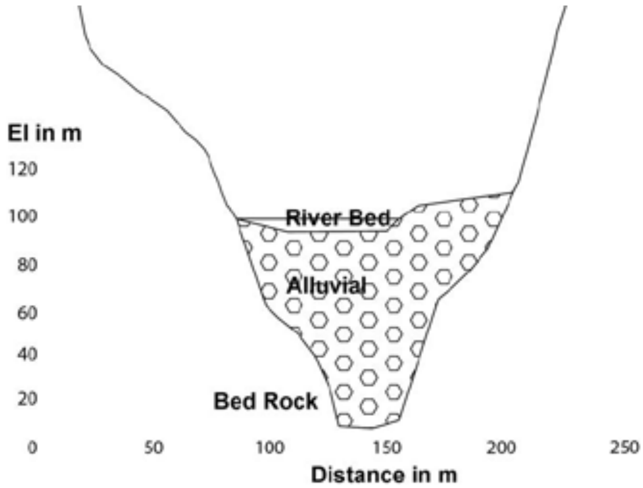

Figure 4 : Cross-section at the candidate dam site.

It is assumed the alluvial deposits at the candidate site are partly from the long-term accumu-lation of upstream erosion transported by the river and partly from slides that may have oc-curred in the past. The material is mixed with boulder, gravels, sand and some fines. The exact depth of the sediments and the composition over the full depth are yet to be confirmed and may exceed the sections as illustrated above.

4.1 Project constraints

In the design, construction and operation of a Himalayan project several prevailing constraints need to be considered and are as listed as follows:

- The projects may be close to the China border. The reservoir extent has to be kept within the host country.
- Sedimentation yield need to be managed to extend the project's useful life. Low level flushing outlets are mandatory.
- Projects are normally located in seismically active zones – preliminary seismic evalua-tion on the candidate project points to a peak acceleration of 0.76g.
- Possibility of very little foundation treatment work during the monsoon months
- Need to have sufficient haul access over 700 m in the river bed to remove the 70 m deep alluvial material from the lowest point; this also impacts where the upstream cofferdam may be located.
- Special intake arrangement for sediment exclusion during operation
- Need to pass very high flood flows

4.2 Preliminary Dam Layout

The initially chosen straight axis was changed to a gravity-arch axis for the RCC option particu-larly to take advantage of the abutment rocks. The gravity-arch arrangement also provides for better energy dissipation of the spillways and hydraulic functionality.

4.3 Foundation Treatment

For constructing the RCC dam ideally the alluvial deposits must be removed to expose bed rock. This although feasible may not be possible during one season using conventional excavation equipment. Advanced and heavier equipment may be mandatory. Extensive dewatering will be necessary if the partial foundation excavations are exposed to the monsoon rains. This will be costly and also time consuming.

As a possible alternative, partially improving the foundation in-situ was evaluated using the following methods:

- Jet grouting
- Bored piles

4.3.1 *Limitations of Jet grouting*

Jet grouting is a specialized technology with higher associated initial mobilization costs. The following aspects limit its use for the over 70 m alluvial deposits at the candidate dam site:

- jet grouting effectiveness decreases with depth
- maximum feasible depth is limited to 30 m even with the most advanced jet grouting technology.

4.3.2 *Limitations of Bored piling*

The following issues limit its use for the over 70 m alluvial deposits at the candidate dam site:

- effectiveness is not depth dependent
- maximum feasible depth can exceed 70 m but may be costly
- equipment and expertise may be locally available.

4.4 Numerical Evaluation of foundation Improvement for RCC dams

Since the focus is on the numerical analysis for the evaluation of the foundation, the worst foundation loads imposed by the dam body need to be taken into account as initial input. For this the dam analysis may assume good foundation conditions and obtained from routine analysis.

The foundation initial material characteristics are normally based on geotechnical investiga-tions. It is very difficult to assess the material characteristics of the alluvial deposits that ex-tend deep. It is always difficult to obtain representative samples for the 'boulder mixed' alluvial deposits even in the best of circumstances.

Road cuts may reveal the composition of the alluvial deposits and should be explored to grasp the typical composition of the alluvial matrix.

For the candidate project geotechnical data gathering is currently ongoing. However, initial material characteristics have been assigned based on visual inspection and gradation of sam-ples collected for the preliminary numerical analysis and an analysis model formulated and al-so simulated.

4.5 Field trials for evaluating pre- and post- foundation treatment

Field trials are to be conducted for obtaining material characteristics under representative in-situ conditions as follows:

1. Geophysical lines will be conducted through the test field.
2. The test field will be instrumented and then pre-loaded in 5m increments up to 25 m height.
3. Deformation will be measured after each pre-load increment to establish the moduli value for the foundation. This information will be used in re-evaluating the Duncan-Chang initial hyperbolic parameters.
4. After the full pre-load geophysical lines along the previous alignments will also made.

The project may be contracted to be constructed as an EPC project. Specifications for the field trial test are being developed and may be left to the EPC Contractor in such an eventuality. Notably similar approach for an RCC dam project was conducted in Jordan. Geophysical data prior to and after consolidation grouting were conducted to assess the achieved improvement of the foundation.

Data from the numerical analysis will be carefully correlated with field measurements. The target characteristics of the foundation to minimize foundation deformation will then be ob-tained from the numerical analysis by simulating the foundation methodology, i.e. jet grouting and bored piling.

The data correlation phase is currently ongoing. The preliminary analysis data has been en-couraging and very useful with the early indication the approach for the evaluation to be effective.

5. CONCLUSIONS

The following conclusions are drawn following the review of the ongoing evaluation and field data gathering:

1. When very deep alluvial deposits are encountered, feasibility of other potential in-situ improvement methods such as jet grouting should be evaluated.
2. Numerical methods using the Duncan-Chang hyperbolic models would yield satisfactory evaluation of target foundation strength characteristics to improve the weaker foundation to be improved for founding RCC dams.
3. Trial field tests using geophysical methods to evaluate and compare pre-treatment and post-treatment of actual deposits is essential prior to accepting the suitability of the in-situ improvement method.

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