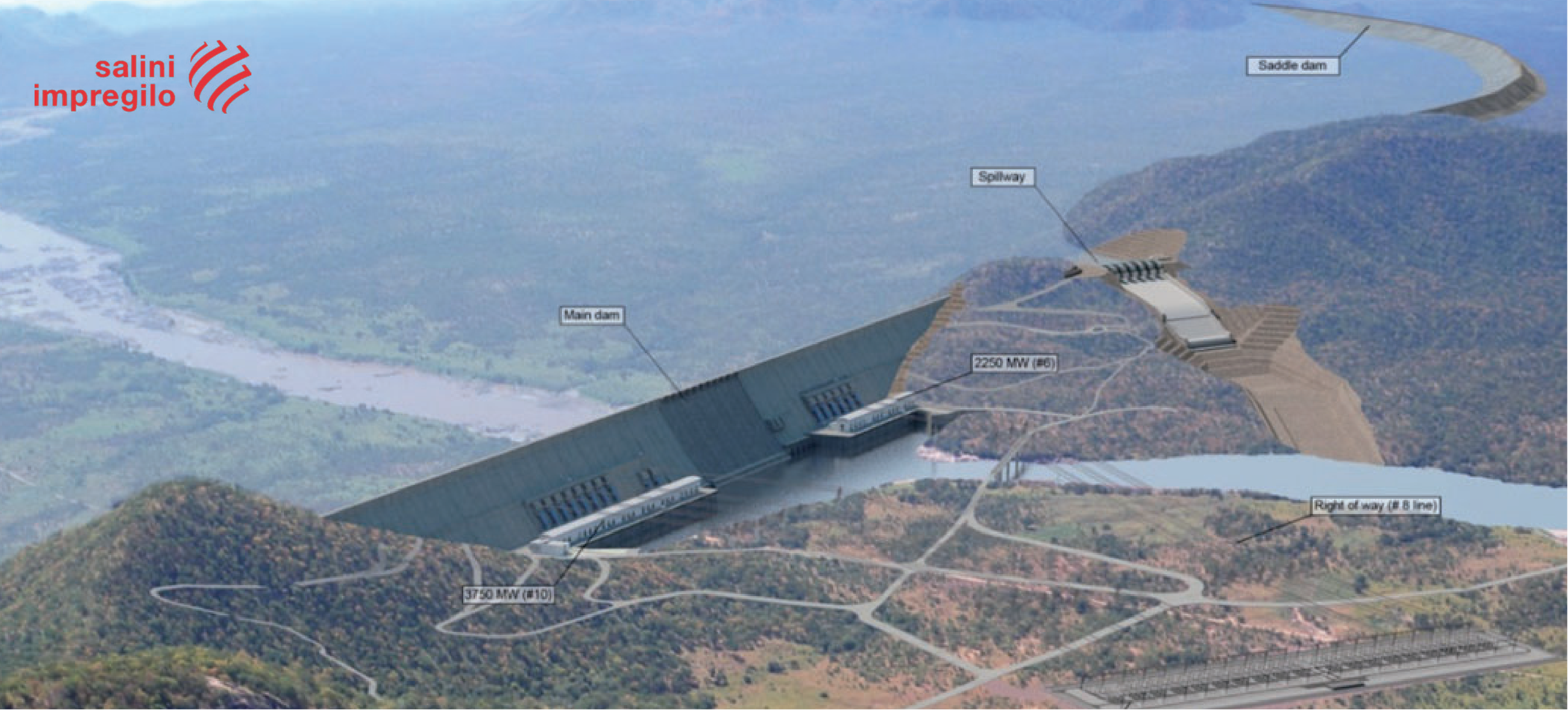

GERDP hydroelectric project, Main Dam general layout

Evaluation of dam performance under seismic loads with DCR time history procedure:
Case study of GERD main dam design

This article presents systematic and rational application of the DCR/CID methodology to estimate the behavior of concrete structures under seismic loads, using time-history analysis. This rational approach, proposed by USACE EM 1110-2-6051, can be used to evaluate the safety of new or existing structures and moreover to optimize the construction costs during the design phase.
Such method has been systematically implemented, through the development of a dedicated calculation code, in order to analyze the behavior under seismic loads of the Grand Ethiopian Renaissance Dam (GERD), along the Nile River. The dam, currently under construction, has a maximum height of 175 m, it's 1780 m long and it has a global RCC volume of 10.2 Mm3. It is designed to store 74 Bm^3 of reservoir serving a 6140 MW Power Plant.

Fig.1 - GERDP Dam under construction

GERD Project
The Grand Ethiopian Renaissance Dam (GERD) Project is located 500 km north west of the Ethiopian capital Addis Abeba, in the Benishangul – Gumaz region, along the Blue Nile River.
The Ethiopian Electric Power company (EEP) is the employer, Salini-Impregilo SpA is the EPC Contractor and Studio Pietrangeli Srl is the designer.
The plant, with its 6'140 MW of installed power and 15.7 TWh of annual energy production, is one the most important projects committed by the Ethiopian Government so to meet the country present and future power requirements. The hydropower plant is currently under construction. Once completed, GERD will be the largest plant in Africa.

Post processor
The rational method, described in the introduction, has been practically applied, thanks to a dedicated computation code that has been developed, tested, validated and systematically adopted by Studio Masciotta engineers.
The computation code consists of a series of Excel Macros and

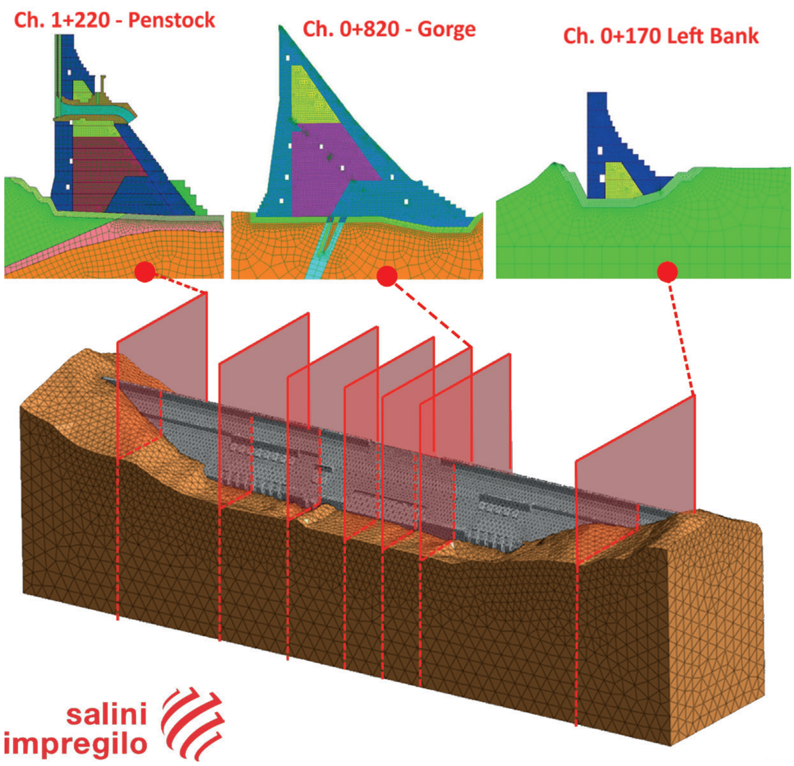

Fig. 2 – Main Dam 3d Model and representative sections

Straus 7 API (Application Programming Interface), aiming at extracting the results out of the FEM model and computing the Demand-Capacity Ratio and the Cumulative Inelastic Duration of selected control points within the dam body.
The dam behavior analysis, considering its relevant length (about 2 kilometers) and with a great variety of geometries and foundation characteristics, required a series of fifteen transversal sections to be analyzed (about a section every 130 meters of length), using a dedicated 2-D FEM models.

Every section has been analyzed considering at least two possible and alternative geometries, in order to identify the optimum one.
Within every transversal section of the dam, an average number of about fifteen control points has been fixed in order to assess the dynamic behavior of the dam under seismic events.
Every transversal section has been analyzed considering six different earthquakes and four possible combinations of horizontal and vertical component signs for every seism.
Each hypnotized earthquake lasts 35 seconds and, assuming that an integration step is set every 0.005 seconds in the linear time history analysis, seven thousand steps of integration characterize each earthquake combination.

The inquired points have been analyzed both in terms of vertical stresses (to be compared with lift joint tensile strength) and maximum principal stresses (to be compared with parent tensile strength), so to have two relevant quantities to be examined at each control point.

It is therefore easy to infer that the quantity of the data to be processed to obtain the graphs of DCR and CID for the inquired sections is the result of: 15 x 2 x 15 x 6 x 4 x 7000 x 2 $\approx$ 151 millions of data.
Assuming that an engineer can process a datum every two seconds, working 8 hours a day, it would take him/her 10500 days, which is more than 28 years, to get the required result, with a clear possibility of introducing widespread human errors in the processed data, whose reliability would be strongly affected. The idea of developing a dedicated software was therefore deemed, not just a reasonable optimization of the work of the engineers, but rather an absolute necessity to comply with the times agreed between the Designer Studio Pietrangeli Srl and the EPC Contractor Salini Impregilo.
The post processing software is articulated in five sub-routines: Init, Eval DCR-CID, Graphs, Synth, Print and it assumes to have correctly performed a linear time history analysis of the dam sections, thus all result files are supposed to be available for this specific purposes.

<u>Init</u> is the interface with the FEM software Straus 7. It contains the calls to Straus 7 API. The user can choose whether the API shall get either the vertical stresses or the maximum principal ones and select which plates to investigate. The engineering assessment is fundamental at this stage in order to limit contain the size of data to be processed by the software. The routine cycles on the FEM model elements and extracts the time history of vertical/maximum principal stresses of the selected ones at saved times.

<u>Eval DCR-CID</u> is the core of the calculation process performed by the software. It considers the time history of stresses extracted during the Initialize (Demand) phase and compares them, step by step, with the Capacity value introduced by the user. It evaluates the Cumulative Inelastic Duration (CID) for DCR values, ranging from 1 to 2 (a DCR higher than 2 is not allowed).

<u>Graphs</u> uses the data computed by the sub-routine Eval DCR-CID to produce the DCR and CID graphs, in order to compare them with the limit line prescribed by USACE code, and to establish whether stability can be assessed by the simplified Linear Analysis (Low to moderate damage) or it's necessary to perform a further Non Linear Analysis (Significant damage).

<u>Synth</u> is a routine responsible only for the chart sorting and formatting. It generates an Excel sheet for every selected element of the FEM model and matching the graphs with the related element in the sheet. The charts are formatted do to make them easy to be read, printed and presented in a calculation Report.

<u>Print</u> gets the graphs produced by the routine Synth and generates a pdf file for every graph, ready to be assembled in the Annex of a Calculation Report of the Dam.

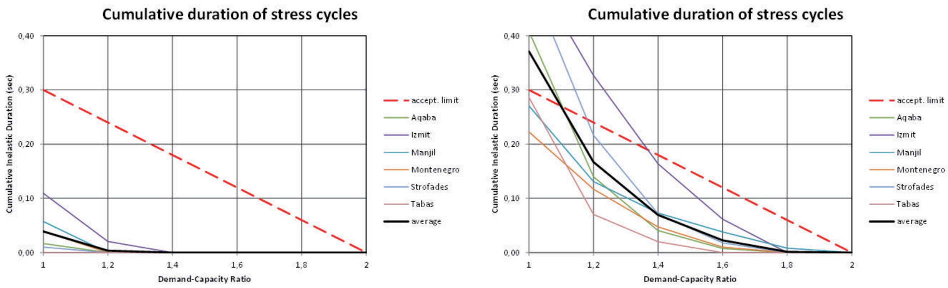

Fig. 3 – Examples of an element fully verified according to DCR method (left) and of an element not verified (right)

Results of DCR/CID analysis

The typical results of an DCR analysis performed by the software are reported in Fig. 3, presenting and element fully verified and another not verified, this exceeding the acceptance limit.

The dam optimization process through the linear time history procedure was carried out essentially during level 2 Design.

The dam was well dimensioned during basic and level 1 Design, using simplified pseudo static methods (Seismic Coefficient Method, Equivalent Lateral Force Method) and modal analyses with Response Spectrum.

The analyzed geometries and sections were generally verified and the linear time history procedure with DCR-CID method was used essentially to optimize the sections. The systematic procedure allowed to achieve the required values, typically 20% lower than the predicted ones during level 1 Design by means of Modal Analysis with Response Spectra

Fifteen sections were systematically analyzed during Level 2 Design, adopting the simplified DCR approach and the relative calculation reports were produced. An approximate number of 9.000 DCR-CID synthesis graphs was generated by the software as described above.

Summarizing, fourteen sections were fully verified and their stability under earthquake SEE was assessed through the linear time history analyses.

Only the stability of the highest section of the dam, in correspondence to the Gorge, proved to have some critical points, since the DCR values were exceeded, adopting the tensile strength values fixed during Level One Design. Further Non Linear Analyses were performed, assuming the potential crack surfaces identified by means of the linear time history analyses. Such activity confirmed the stability of the section and no permanent sliding displacements did occur.

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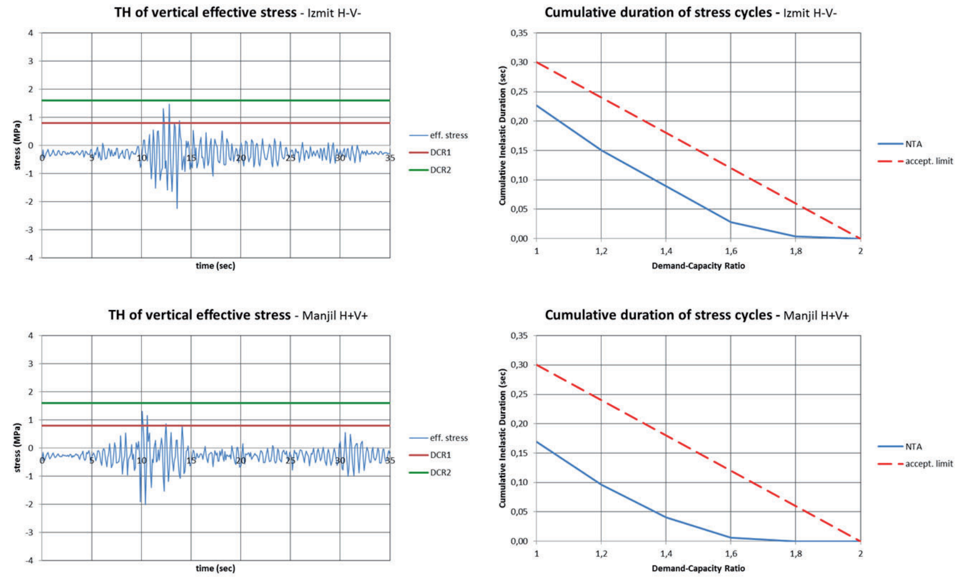

Fig. 4 – Examples of section elements fully verified through DCR method – Time history of stress (left) and DCR-CID graph (right) for two different earthquakes

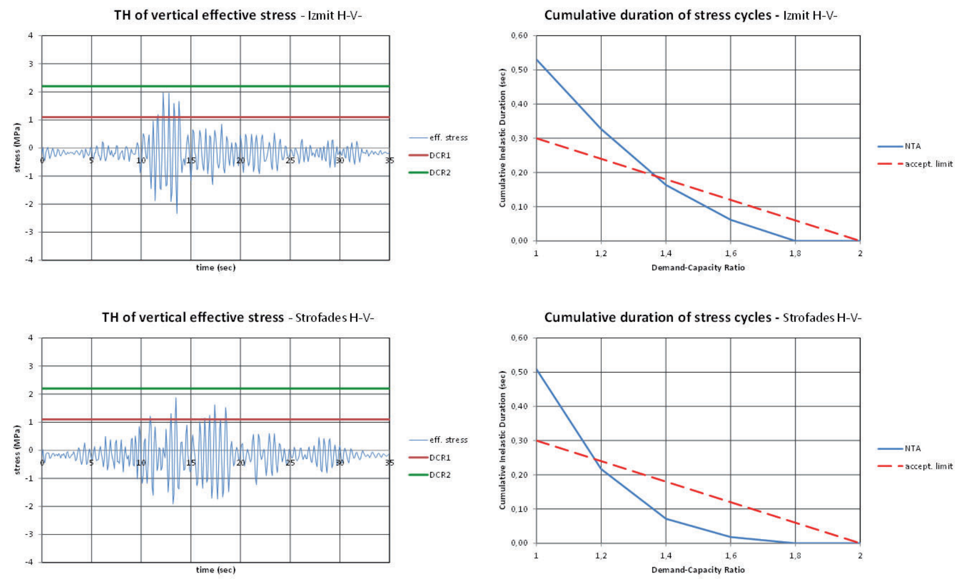

Fig. 5 – Examples of section elements not verified through DCR method – Time history of stress (left) and DCR-CID graph (right) for two different earthquakes