Smart Dams and Reservoirs

Pepper
ISBN 978-0-7277-6411-9
https://doi.org/10.1680/sdar.64119.381

Palo Redondo: smart CFRD design and construction

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SYNOPSIS The Palo Redondo CFRD (Concrete Face Rockfill Dam) and associated works form part of the Chavimochic Irrigation Project in Peru that will provide irrigation of about 50,000Ha of new lands and improve the irrigation system of another 20,000Ha. The 97m high dam will create storage for approximately 400Mm³ of water within a normally dry valley and regulate water transferred to the reservoir by canal.

The dam is founded on sedimentary rocks on the right abutment and igneous rocks on the left abutment, and is founded on alluvium across the valley centre. The dam crest length is 840m and the embankment body contains over 9 Mm³ of alluvial gravel materials.

This paper explains how modern design techniques were employed to appraise the design challenges. It will also explain how instrumentation deployed during construction was used to inform the final design of the dam and the construction methodology. New construction techniques were used which reduced the health and safety risks to the workforce and improved fill placement productivity.

INTRODUCTION

The Chavimochic Irrigation Project in Peru transfers water from the Santa River to the Valleys of Chao, Virú and Chicama and will be able to supply irrigation of approximately 145,000Ha of land when fully completed. The first and second stages of this project were concluded between 1986 and 2012 with approximately US$960 million of investment. The third stage, with US$715 million investment is a public private concession currently under construction. The development consists of 128km canal, three syphons and the Palo Redondo reservoir which will provide irrigation water for about 50,000Ha of new lands and improve the irrigation system of another 20,000Ha. The project is located in the municipality of La Libertad, in northern Peru, depicted in Figure 1.

Figure 1: Chavimochic Irrigation Project – 3rd Stage

This paper presents how modern design techniques were employed to appraise Palo Redondo Concrete Faced Rockfill Dam (CFRD) design and construction challenges. It will also explain how instrumentation deployed during construction was used to inform the final design of the dam and the construction methodology. New construction techniques were used which reduced the health and safety risks to the workforce and improved fill placement productivity.

PALO REDONDO AND ASSOCIATED WORKS

Project Layout and Main Features

Palo Redondo CFRD and associated works will regularise the Santa River flows, increasing the supply capacity to the current irrigation system. Figure 2 shows the project general layout and the existing irrigation structures.

The dry Palo Redondo valley, shown in Figure 3 will be fed by an existing feeder canal, and the CFRD will create a reservoir storage capacity of approximately 400Mm³. A drawoff structure located at the right abutment and 2.6km long free flow transfer tunnel sized to discharge 78m³/s will connect the existing inter-basin tunnel and irrigation system, as shown in Figure 2. The discontinued segment of the current inter-basin tunnel will be sealed by a concrete plug.

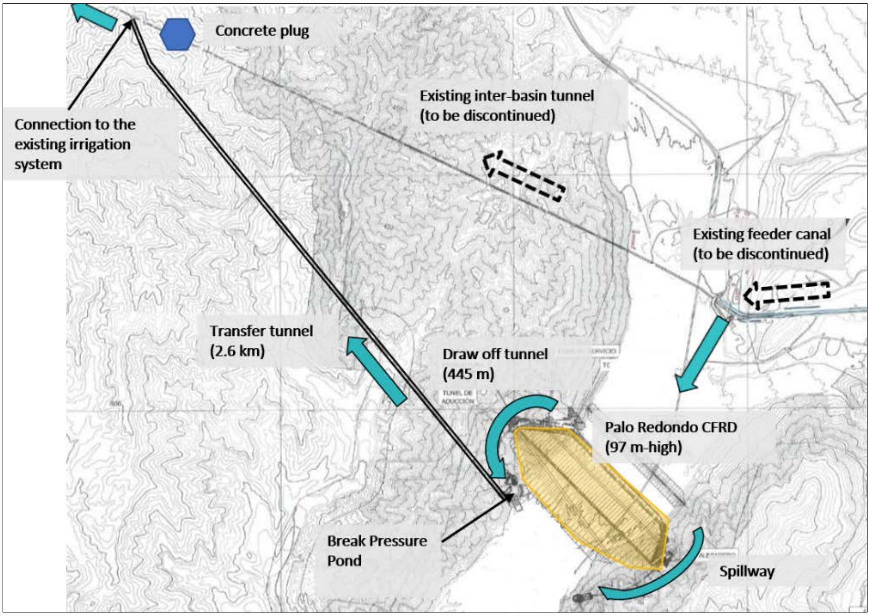

Figure 2: Palo Redondo CFRD and Associated Works General Layout

Figure 3: Palo Redondo Valley, showing the CFRD downstream face

The reservoir head will be dissipated by Howell Bunger valves located at the outlet structure, just downstream of the 445m long concrete lined drawoff tunnel.

Floodwater will be controlled by a free overflow weir and spillway tunnel located at the left abutment, sized to discharge 193m^3/s (the Probable Maximum Flood) without overtopping of the dam crest.

Palo Redondo CFRD

A concrete face rockfill dam type was selected mainly due to the large availability of gravel materials from the natural riverbed. Other factors such as wide experience in CFRD design and construction in Latin America and historically adequate performance under seismic loading led to the selection of a CFRD as the most suitable dam type for Palo Redondo site. Another advantage of the selected dam type is that the foundation cutoff works could be carried out independently of the rockfill placing, which enabled a reduction of 12 months in the construction programme.

Palo Redondo CFRD consists of a 97m high dam with an upstream slope of 1.5H:1V and downstream slope of 1.6H:1V, 840m long, 7m wide crest and a total fill volume of approximately 9Mm^3. The typical cross-section and fill displacement monitoring instruments are indicated in Figure 4. The material description is given in Table 1, and the applied rockfill characterised in Table 2.

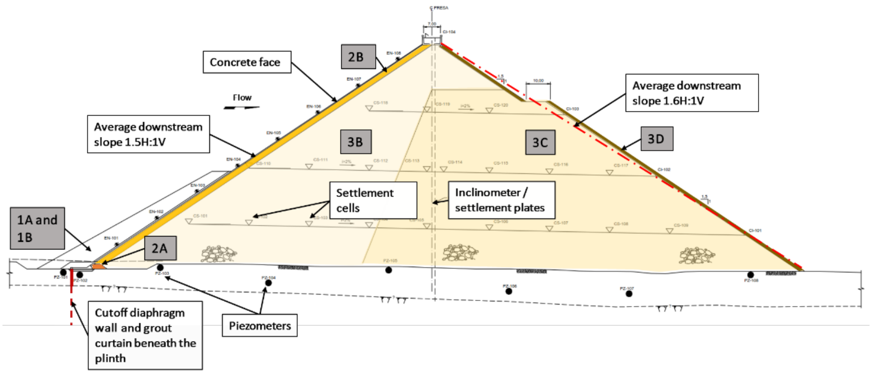

Figure 4: Palo Redondo CFRD Typical Cross Section

The dam is founded on both volcanic and sedimentary rocks: shale, siltstones and sandstones at the right abutment and andesite on the left abutment. At the riverbed, the dam is founded on approximately 20m depth granular alluvial soils overlying rockhead.

The alluvial gravel material from the natural riverbed was used as rockfill source for the dam body. The material was obtained by excavating a large quarry a short distance upstream of the dam site within the valley floor, providing an increase in the dead storage available for sedimentation.

Table 1: Palo Redondo CFRD Material

Material	Description
1A / 1B	Cohesionless fine-grained soil / Random Fill
2A	Perimeter zone filter
2B	Processed filter
3B/3C	Quarry run rockfill, characterised in Table 2 below
3D	Placed large rocks

The Palo Redondo valley, approximately 510m wide at the base and 35°–40° at the right and left abutments has a favourable geometry, in which cross-valley arching is insignificant. Based on this valley shape, high compressive stresses are not expected. However, following the incidents registered in other CFRDs such as Campos Novos and Mohale, compression joints and anti-spalling reinforcement were adopted in Palo Redondo CFRD design.

Due to the high groundwater table and to avoid dewatering or pumping works at the riverbed and potentially increasing construction programme, a cutoff diaphragm wall of plastic concrete to seal the permeable alluvial soils was preferred to the alternative of an open cut excavation and founding the facing plinth on weathered rock. A grout curtain was formed directly beneath the cutoff wall, connected to the plinth and concrete face slabs by a joint system sealed by a combination of waterstops (see Figure 4).

Palo Redondo CFRD is located within a highly seismic region with an Operating Basis Earthquake (OBE) peak ground acceleration (PGA) of 0.35g.

OPPORTUNITY FOR INNOVATION

The design evolution of CFRDs has been based mainly on precedent and experience and there has been continuous progress in design and construction technology, proving to be satisfactory for dam heights up to approximately 200m. The change from dumped to compacted rockfill in the 1950s and project requirements to build higher dams, and thus higher consequences of failure, have been crucial to improve the design and construction of CFRDs.

The rockfill compressibility and material zoning are key elements for successful dam behaviour and performance in terms of settlements, horizontal displacements, and concrete face deflection, during construction, post construction and under a seismic event (Cruz, 2009).

Opportunities to optimize the placement of the over 9Mm³ of rockfill on the Palo Redondo CFRD were studied in the early construction stage. The close cooperation between the designer and contractor enabled the compaction criteria to be developed resulting in an increase in the maximum layer thickness required to maintain the design requirements of the low compressibility materials. The design criteria, material settlement monitoring and the construction methodology gave confidence in the design and material performance, as well as cost savings and health and safety risk mitigation in the completed works, as detailed in the following sections.

ROCKFILL PLACEMENT

Roller equipment

The rockfill material was initially costed to be compacted with 10T–19T roller with layer thickness of 600mm–800mm for material 3B and 3C, based on extensive experience of this type of material applied in other dams. Considering the nearly 9Mm³ of fill to be placed, a heavier roller was selected in order to optimise the compaction criteria as described in the section below. The polygonal vibratory roller with an operating weight of approximately 26T was used in the compaction works.

Rockfill Properties

To estimate the dam behaviour in terms of settlement and deformation during construction and operation, numerical analysis was undertaken using the alluvial gravel parameters at each design and construction stage as detailed in Figure 5 below.

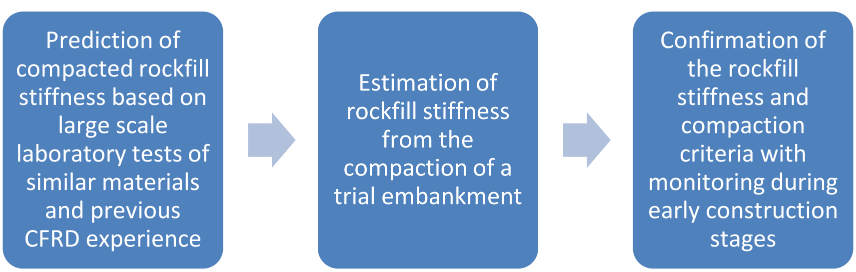

Figure 5: Rockfill Compressibility Calibration

Based on the alluvial gravel material characteristics given in Table 2 below, with a high uniformity coefficient of the order of 150 and less than 5% passing on sieve 200, it was expected that the material would result in a permeable rockfill, and in a very low void ratio after compaction, and thus a high modulus of compressibility.

Since compressibility parameters obtained from laboratory tests are strongly dependent on the grain size and as the sample particle sizes are significantly smaller than the placed rockfill material, trial embankments and monitoring data are paramount to calibrate and confirm the expected material parameters.

The material compressibility is also dependent on the compaction criteria and therefore 0.80m–1.40m thick layers were tested in trial embankments using a 26T vibratory roller, shown respectively in figures 6 and 7.

Figure 6: Dry density and void ratio tests (from trial embankment)

Figure 7: Polygonal vibratory roller (26T)

The trial embankments were evaluated based on the dry density and void ratios taken from the top and bottom layers shown respectively in figures 8 and 9. In terms of dry density, all layer thicknesses presented a satisfactory result. However, if analysed by the void ratios, the 1.20m and 1.40m layers thickness proved poor in comparison to the thinner layers, particularly at the bottom of the layer, as the energy of the roller would not be transmitted. It can also be noted that for 0.80m and 1.20m thick layers the surface the material presents a higher density and lower void ratio than compared with the results taken from the bottom of the layer.

Based on the trial embankments results, a layer thickness of 1.0m and nine passes was defined. The use of water was tested, however as the material retained some moisture from the riverbed source location, and considering the well-graded characteristic and no breakage of the gravels particles, water was not added during compaction.

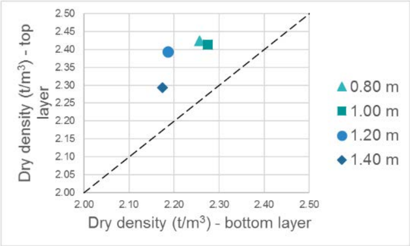

Figure 8: Average dry density by layer thickness (from trial embankment)

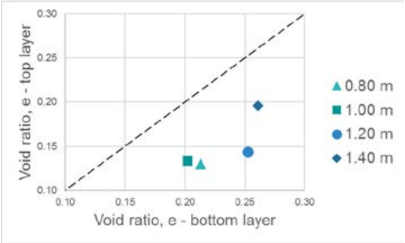

Figure 9: Average void ratio by layer thickness (from trial embankment)

During construction the rockfill performance was monitored using settlement plates installed in the inclinometers, and from settlement hydraulic cells installed along the embankment indicated in Figure 4. The average modulus of compressibility obtained during construction was 210MPa, considering the settlement results from the settlement plates and hydraulic settlement cells. This is consistent with the expected design parameters for satisfactory behaviour of the dam during operation and in line with the registered parameters of similar materials as shown in Figure 10.

Table 2: Materials 3B/3C characteristics

Material Features	**Description**
Uniformity of grading	Well-graded gravel, uniformity coefficient Cu (D_{60}/D_{10}) around 150
Average maximum particle size	d_{max}= 500 mm
% finer 0.075 mm	Less than 5%
Dry density (average) (*)	2.3 t/m^3
Void ratio	0.19
Placement	9 passes, 26 t vibratory roller, no water
E_{rc} (average)(*)	210 MPa
Permeability	2x10^{-4} m/s

(*)E_{rc}, Secant vertical modulus during construction, and dry density values considering 80% of the completed fill. As materials 3B and 3C are from the same quarry and have similar compaction criteria the moduli results were averaged.

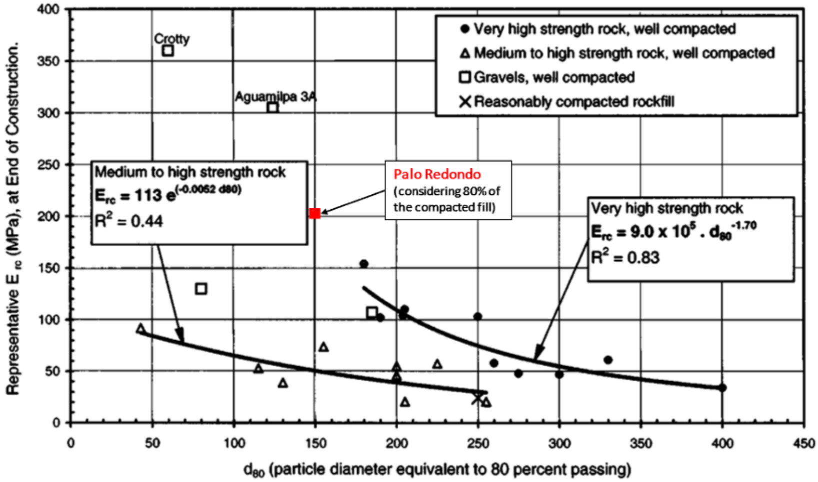

Figure 10: E_{rc}, Secant vertical modulus during construction versus rockfill particle size, adapted from Hunter and Fell (2003).

Construction Technique

The dam construction sequence and the fill placement topography was modelled in 3D and the model was paired with the sensors installed at the dozers and rollers. This technology enabled the control of the number of passes, checked the level and maintained the compacted surface layer mapped in real time. This provided a gain of equipment and machinery efficiency in approximately 30% by increasing the hourly volumetric rate of fill.

This technology provided the project with environmental benefits such as reduction of fuel and contamination. As the system employed for the rollers had sensors that allowed the correct the fill layer level to be achieved, a limited number of staff were required for the fill topography check, and hence the number of safety incidents in the dam fill placement was significantly reduced.

Figure 11 shows the dam fill compaction works, with the reduced number of staff concentrated only in the zone indicated in the dotted line for the settlement cells installation across the section and the fill monitoring tests (dry density and void ratio).

The favourable rockfill availability within a short distance upstream of the dam site within the valley floor in addition to the construction technique employed enabled a high fill placement productivity. With a double shift, and a working week from Monday to Saturday, the fill volume reached a placement peak of 235,400m³/week and an average volume of 99,375m³/week, when 80% of the fill had been completed.

Figure 11: Palo Redondo CFRD compaction works (from downstream face)

CONCLUSIONS

The close cooperation between the designer and contractor and the previous experience in concrete face rockfill dam (CFRDs) enabled the design and construction methodology to be optimised. The design criteria, material settlement monitoring and the construction methodology gave confidence in the design and material performance, as well as cost savings and health and safety risk mitigation in the completed works.

The average modulus of compressibility obtained during construction for the rockfill materials was 190MPa, which is consistent with the expected design parameters for satisfactory behaviour of the dam during operation and in line with the registered parameters of similar materials.

The favourable rockfill availability within a short distance upstream of the dam site within the valley floor in addition to the employed construction technique enabled a high fill placement productivity reaching an average fill placement volume of 99,375m³/week.

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