Statistical Analysis of Mechanical Properties of Concrete Cut-Off Wall of Earth-Rock Dam

Guanying Kang, Junrui Chai*, Lifeng Wen, Kaiqiang Geng and Zengguang Xu

State Key Laboratory of Eco-hydraulics in Northwest Arid Region, Xi'an University of Technology, Xi'an 710048, China

*Corresponding author's e-mail: jrchai@xaut.edu.cn

Abstract. With the advantages of superior seepage resistance, geological adaptability, low post-maintenance, and low cost, concrete cut-off walls are used in the foundations of various rockfill dams around the world. This paper discusses the maximum horizontal displacement, top settlement, and stress distortion of ordinary rigid concrete cut-off walls (OC) and plastic concrete cut-off walls (PC) at the late stage of reservoir impoundment. The study then progresses to a comparative analysis of the mechanical properties of concrete cut-off walls by collecting the deformation characteristics and detailed data information of concrete cut-off walls in 31 examples of actual projects in conjuction with numerical simulation calculations. Through the research in this paper, it is hoped that it can provide some references for the design of cut-off walls of earth and rock dams.

Keywords: earth-rock dams; concrete cut-off walls; numerical simulation

1 Introduction

The use of water resources, the protection of the environment, the prevention of flooding, and the promotion of economic growth are all made possible by water conservation projects, which are a crucial component of the economic infrastructure. Dams are an indispensable part of water projects. At present, the total number of dams worldwide is in the tens of thousands, and in China alone, there are 97,036 dams of various types of reservoirs built [1], of which more than 90,000 are earth and rock dams, accounting for 91.8%, which shows that earth and rock dams are currently the most built and most widely used dam type. With superior seepage resistance, geological adaptability, low maintenance, and low cost, concrete cut-off walls are effective in controlling seepage at the base of dams, providing a continuous seepage cut-off point, and are less susceptible to deterioration than other methods [2,3].

The cut-off wall stops seepage water from entering the highly permeable dam unit and the dam's base while the dam is being built and the reservoir is being filled. However, it can also significantly increase the water pressure and hydraulic gradient around the wall, leading to significant plastic deformation and even cracks in the wall. Therefore, understanding wall damage behavior is critical to dam design and construction.

G. Zhao et al. (eds.), *Proceedings of the 2024 7th International Symposium on Traffic Transportation and Civil Architecture (ISTTCA 2024)*, Advances in Engineering Research 241,
https://doi.org/10.2991/978-94-6463-514-0_18

The load characteristics of the cut-off walls are very complex, not only bearing the surrounding water pressure but also bearing a certain amount of dam self-weight and complex interactions with the surrounding soil. Regarding the hydraulic characteristics of the impermeable wall materials, a series of studies have also been conducted by domestic and foreign scholars. Won and Kim [4] monitored and statistically analyzed the leakage of 27 earth dams with rocky foundations over a long period. Rice and Duncan[5] revealed the damage and cracking mechanisms of cut-off walls by studying 30 cases of earth dams, but these studies were only limited to the wall impermeability effect and the material's performance, without considering factors such as long-term loading conditions and potential stress concentrations in cut-off walls. In addition, there were huge differences between different projects in actual projects, so the studies on the performance of cut-off walls are still inadequate, and more extensive and in-depth research is needed.

This research uses a combination of numerical simulation techniques and case statistics from the literature to examine the mechanical properties of concrete impermeable walls. The force characteristics of the concrete impermeable wall are covered first, followed by a discussion of the wall's displacement deformation, settling, and stress based on statistical data. Lastly, the mechanical properties of the concrete impermeable wall are confirmed and methodically investigated using numerical simulation techniques.

2 Load Characteristics, Damage Forms, and Case Statistics of Concrete Cut-off Walls

2.1 Load Characteristics

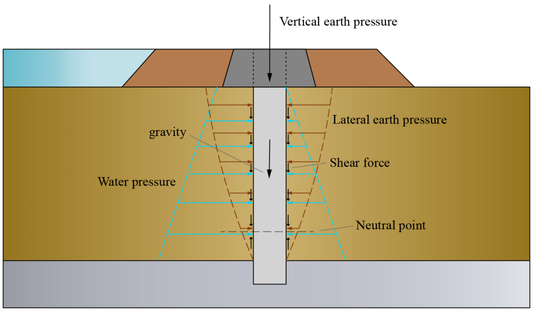

Fig. 1. Schematic diagram of cut-off wall loading located at the bottom of the dam.

The cut-off wall experiences significant complexity during normal load operation, manifesting in both horizontal and vertical loads, which substantially influence its performance. For instance, Figure 1 illustrates a schematic diagram depicting the load on the seepage control wall situated at the center of the dam body. Principal components of the horizontal load include lateral earth pressure and water pressure. The head pressure is associated with the free surface of the seepage, and the foundation's horizontal displacement mainly causes the lateral earth pressure. As the wall moves, the earth pressure increases approximately linearly with increasing depth in the middle and upper regions of the cut-off wall. During the compaction of the fill, the earth pressure rises due to further settlement of the material below the wall, making the wall contact interface friction increase[6], so the layout and compacting of the dam directly affect the lateral earth pressure. There are four main types of vertical loads: vertical earth pressure, vertical water pressure, shear force, and self-weight of the wall.

2.2 Damage Forms

There are four most common types of concrete cut-off walls, as shown in Figure 2.

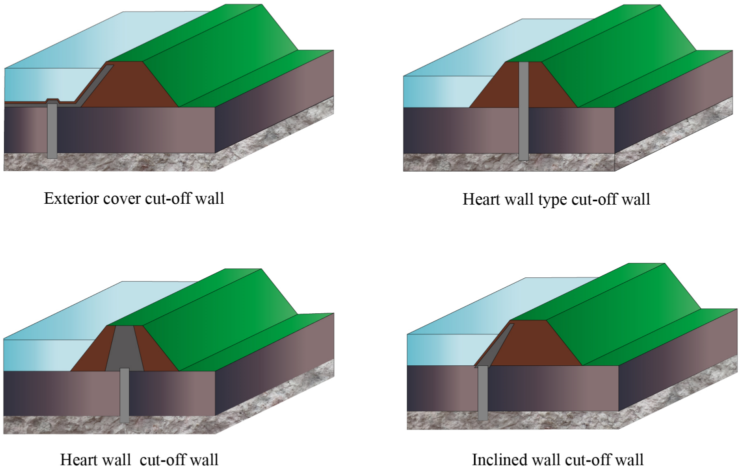

Fig. 2. Types of cut-off walls for earth and rock dams.

Table 1 summarizes the most likely damage behaviors of different types of cut-off walls under the same conditions.

Table 1. The most likely damage behavior that occurs to cut-off walls at different locations.

Types of cut-off walls	Damage behavior of walls
Heart wall-type cut-off wall	Wall stress conditions are complex and subject to large stress and strain. Impermeable walls and the heart of the wall connection are prone to shear damage. The vertical pressure is greater, and the wall may cause extrusion damage,
Heart wall	The interaction between the dam body and the impermeable wall is more significant, and the displacement and settlement of the dam body can easily lead to tensile damage to the wall,
Exterior cover wall Inclined wall cut-off wall	It is mainly subject to bending tensile stress and prone to tensile damage and cracks,

2.3 Case Statistics

In this paper, 31 cases of concrete cut-off wall data were counted from available literature reports, as shown in Table 2 [7-12] of the Appendix, which includes dam foundation data characteristics and containment wall foundation data and deformation behavior information, consisting of 16 cases of OC walls (9 cases located in the upstream dam site section and 7 cases located in the middle of the dam bottom) and 15 cases of PC walls (3 cases located in the upstream dam site section and 12 cases located in the middle of the dam bottom). They came from 9 countries, including 19 cases in China, accounting for 61%. Dam types in the case statistics include homogeneous dams, heart wall dams, inclined wall dams, sloping heart wall dams and panel rockfill dams, and also include cofferdam project seepage control wall data. Among them, 35.5% are core wall dams, 32.3% are panel rockfill dams, and 9.7% are cofferdam projects. The majority of them range in height from 40 to 120 meters, and the overburden is primarily made up of sand and gravel. The dam foundation cover is typically between 30 and 75 meters thick.

The symbols in Table 2 entail the following meanings: H: Dam height; CFRD: Concrete Panel Rockfill Dam; HD: Homogeneous dam; DC: Dams with core walls; CD: Coffer dam; DI: Dams with inclined walls; DM: Dam base materials; SG: Sand, gravel; CG: Crushed gravel; G: Gravel; SP: Sand, pebble; OT: Overlay thickness; WM: Wall materials; WT: Wall thickness; D: Wall depth; A: Wall area; Ec: Modulus of elasticity; Hd: Horizontal displacement; TS: Top Settlement.

3 Mechanical and Hydraulic Properties of Concrete Cut-Off Walls

3.1 Maximum Horizontal Displacement and Settlement of Cut-Off Walls

Based on the case statistics, Figure 3 depicts the relationship between the maximum horizontal displacement and settlement of the impermeable wall and the depth of the wall (D) after the impoundment of the dam. When D < 30m, the impermeable wall displacement is close to 0.35%D; when D is between 30m and 60m, the cut-off wall displacement is 0.1%D ~ 0.35%D; when D is between 60m and 80m, the cut-off wall displacement is mostly 0.05%D ~ 0.35%D, when D > 80m, the cut-off wall displacement is 0.05%D ~ 0.25%D. Most of the PC walls were between 0.05%D and 0.25%D, with an average of 0.13%D, and most of the OC walls were between 0.15%D and 0.35%D, with an average of 0.18%D. The movement between adjacent foundation soils is the key factor contributing to the impermeable wall's horizontal displacement. PC walls have better deformation coordination ability, so their displacement deformation performance is due to OC walls.

Figure 3 shows that when D < 30m, the maximum settlement is 0.6%D and the minimum is 0.02%D; when D is between 30m and 60m, the entire payment is 0.43%D and the minimum is 0.02%D; when D is between 60m and 80m, the maximum settlement is 0.46%D and the minimum is 0.12%D; when D > 80m, the total payment is 0.18%D and the minimum is 0.02%D. The above analysis shows that the settlement in any wall depth interval is distributed within each range, so there is no direct connection between the payment of the impermeable wall and the wall depth. The maximum settlement of PC walls was mainly between 0.04% D and 0.46% D, with an average of 0.22% D. The total payment of OC walls mainly was between 0.02% D and 0.2% D, with an average of 0.08% D. The maximum settlement of PC walls was about twice as much as that of OC walls. The larger payment of PC walls was attributed to the fact that the stiffness of PC materials was much smaller than that of OC materials.

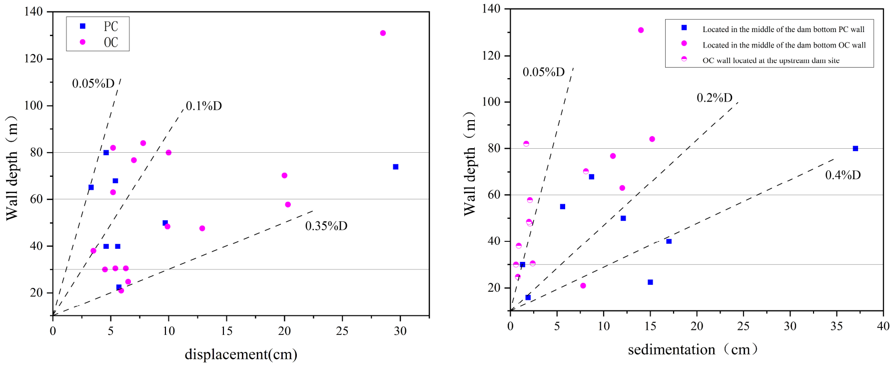

Fig. 3. Maximum horizontal displacement and settlement of PC and OC walls versus wall depth

3.2 Cut-off Wall Stress

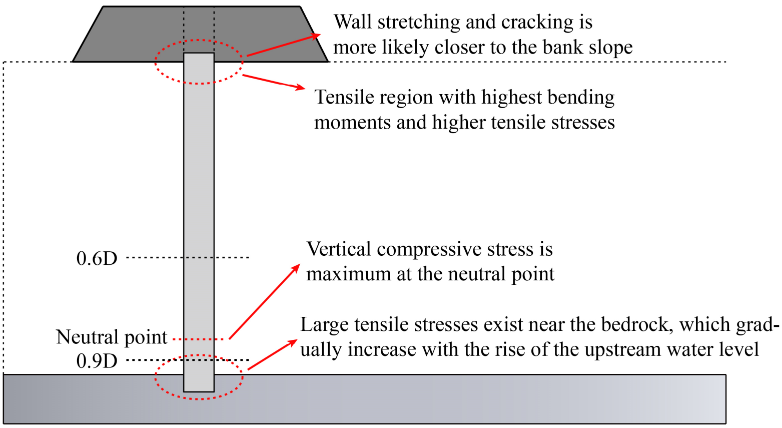

Fig. 4. The location of the maximum stress of the concrete cut-off wall

For a thick, overburdened foundation concrete impermeable wall, the stresses in different areas of the wall are various due to its complex loading conditions and constraints. Tensile stresses are generated in the upper corners of the wall due to end constraints limiting its deformation, and tensile stresses are generated in the expanded end at the top because of uneven deformation at the top of the wall and significant tensile stresses are also developed in the contact end of the wall with the rock wall under composite loads such as overburden friction and river valley constraints. The maximum vertical compressive stress generally occurs near 0.6D ~ 0.9D, indicating that with the maximum at the neutral point and the stress above the neutral point increases from top to bottom, it decreases gradually below the neutral point, as shown in Figure 4.

Based on the aforementioned research, the seepage cut-off wall of the dam experiences highly complicated stress deformation. While the wall in the middle of the dam base is primarily subject to vertical compressive loading and will therefore generate relatively small tensile stresses, there is still a risk of tensile damage at the top of the wall in contact with the bedrock. The cut-off wall located at the upstream dam site section is primarily subject to bending under load and will be subject to significant tensile stresses during both dam construction and impoundment.

4 Numerical Simulation Analysis

4.1 Finite Element Calculation Model

In this paper, a three-dimensional model heart wall dam model is established, and the concrete impermeable wall is a heart wall type cut-off wall. The wall is 82m deep, inserted into the impermeable bedrock 1m, and the top of the base is 1m deep. The dam is divided into the main rock pile area, the secondary rock pile area, the heart wall, the transition layer, drainage prisms, and the base. The height of the dam is 100m, the width of the top of the dam is 10m, and the length of the top of the dam is 300m. The upstream/downstream slope ratio is 1:2, and the slope ratio of the heart wall is 0.25:1. The thickness of the transition layer is 1m, and the width of the bridleway is 2m. The base is 5m long and 2.5m wide, and the thickness of the overburden layer is 80m. Figure 5 shows the model of the dam and the three-dimensional finite element calculation grid of the concrete impermeable wall.

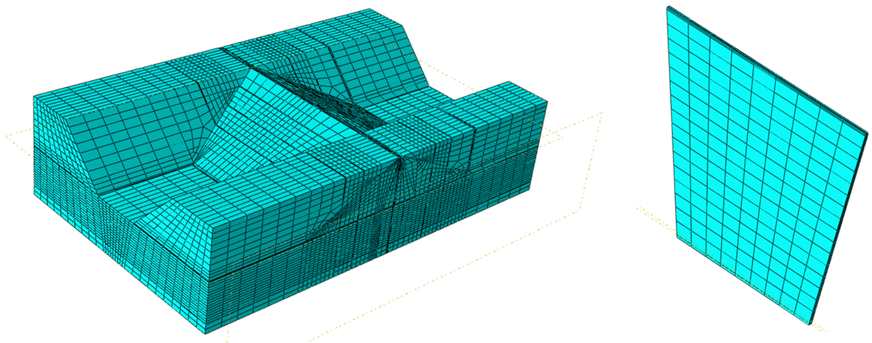

Fig. 5. 3D Finite Element Computational Model Mesh

4.2 Intrinsic Modelling and Material Parameter Selection

In the calculation model, the Duncan-Chang E-B material constitutive model is used for both the dam unit and the deep cover layer; the concrete plastic damage material constitutive model is used for the cut-off wall unit; the linear elasticity model is used for the base, bedrock, and mountain; and Goodman contact simulation is set up between the impermeable wall and the cover layer. The concrete impermeable wall material has tensile strength f_{tk}=2.0MPa, compressive strength f_{ck}=20MPa, and modulus of elasticity is 26GPa. The deep cover layer is divided into two layers: a modern drifting pebble layer with a thickness of 40m and a cobble layer with a thickness of 40m. The material parameters of the Duncan-Chang E-B model are obtained by experiments. 80m head pressure was applied to the upstream surface at the end of the impoundment, and 20m head pressure was applied to the downstream.

4.3 Analysis of Calculation Results

Through the finite element calculation of the concrete impermeable wall upstream and downstream surface large principal stresses, as shown in Figure 6. It can be seen that the stress concentration mainly exists in the middle region of the wall, the maximum stress concentration area in the upstream surface in the middle of the wall in the region of 0.6D ~ 0.9D, the downstream surface of the wall in the upper part of the wall close to the two sides, so the upstream and downstream water pressure difference and the hydraulic gradient will make the wall to produce a concentration of stresses and thus the existence of the potential damage conditions. The displacement and deformation of the concrete cut-off wall are depicted in Figure 7. It is evident that the least displacement, measured at 0.031 meters, happens at the bottom of the wall, and the largest displacement, measured at 0.214 meters, occurs at the top. The statistical analysis and the computed stress concentration displacement and wall deformation are in agreement. One of the primary factors influencing the mechanical properties of the wall is the frictional resistance between the wall and the soil contact surface. When vertical pressure is applied, the difference in stiffness between the cut-off wall and the cover material is very large, resulting in uneven settlement.

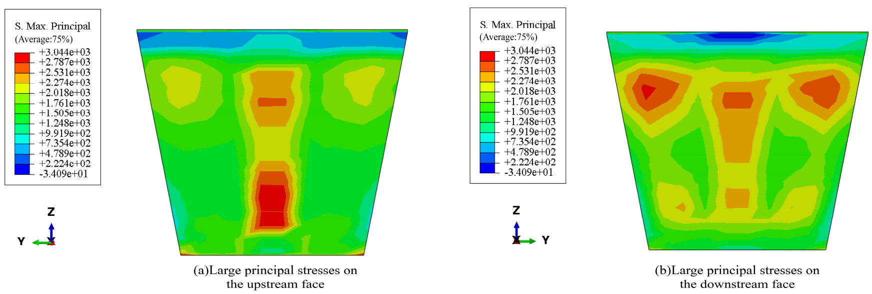

Fig. 6. Large principal stresses on the upstream and downstream surfaces of concrete cut-off walls

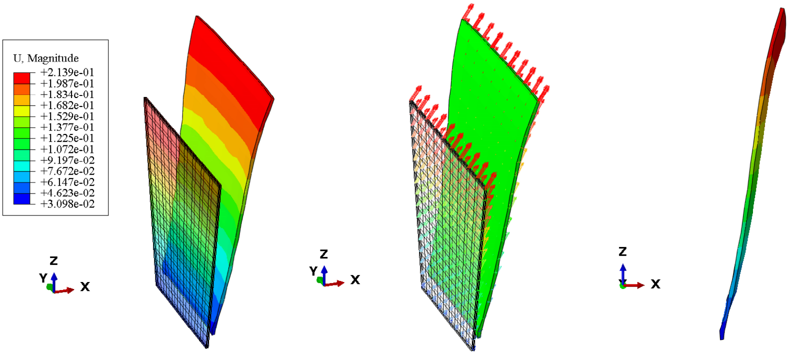

Fig. 7. Concrete cut-off wall displacement - deformation

5 Conclusions

In this paper, the types and mechanical properties of concrete cut-off walls of earth-rock dams are discussed, and the mechanical properties of OC walls and PC walls are based on 31 cases with comparative statistics. We mainly analyze and discuss the stress, top settlement, and maximum horizontal displacement of impermeable walls. Finally, it is verified by numerical simulation calculations. The following conclusions can be drawn based on the above analysis:

During the final stages of dam storage, the concrete impermeable wall experiences horizontal displacement primarily in the downstream direction. When the wall depth is less than 30m, 30m to 60m, 60m to 80m, and more than 80m, the maximum horizontal displacement of the wall is basically within the range of 0~15cm. The horizontal displacement of the wall within all four intervals is between 0.05%D ~ 0.35%D. In general, the greater the depth of the wall, the greater the displacement. The maximum horizontal displacement of the PC wall is 0.13%D on average, and the OC wall is 0.18%D, compared to the PC wall, which has better deformation coordination ability.

There is no direct link between the maximum settlement at the top of a concrete impermeable wall and the wall depth at the end of the dam storage stage. The maximum settlement at the top of the wall located at the upstream dam site is generally within the range of 0.5cm ~ 2.5cm, and the maximum settlement at the top of the wall located in the middle of the dam bottom is within the range of 7.5cm ~ 15cm, so the vertical earth pressure and downward shear force on the wall are the main factors affecting the settlement of the wall. The maximum settlement at the top of the OC wall is 0.08%D on average, and the maximum settlement at the top of the PC wall is 0.22%D on average. PC wall is much larger than OC wall, which shows that when in high earth and rock dam project or under the condition of high vertical pressure, OC wall performs better than PC wall. Although the displacement deformation and stress concentration of regular rigid concrete cut-off walls are computed in this paper using numerical simulation and match the statistical law, further investigation into the mechanical characteristics of plastic impermeable walls is still necessary.

Acknowledgments

This study was financially supported by the National Natural Science Foundation of China (Nos. 51679197), the Natural Science Foundation of Shaanxi Province (Nos. 2017JZ013), the Leadership Talent Project of Shaanxi Province High-Level Talents Special Support Program in Science and Technology Innovation (Nos. 2017-TZ0097), and the Program 2022TD-01 for Shaanxi Provincial Innovative Research Team.

Appendices

Table 2. Concrete cut-off wall case statistics.

	Dam	Year	H:m	Type	DM	OT:m	WM	WT:m	D:m	$A:10^3m^2$	Ec:Mpa	Hd:cm	TS:cm	
1	Santa Juana	1995	113.4	CFRD	SG	30	PC	0.6	30	8.9	/	/	1.3	
2	Brombach	1985	40	HD	G	40	PC	0.6	40	12.5	/	5.6	/	
3	Aromos	1979	42	DC	CG	22	PC	0.8	22.5	/	/	5.7	15	
4	Verney	1982	42	HD	G	75	PC	1.2	50	13	/	9.7	12.1	
5	Arminous	1999	42	DC	SG	15	PC	0.8	16	0.4	/	/	1.9	
6	Penitas	1984	45	DC	SG	55	PC	0.8	55	/	/	/	5.6	
7	Evretou	1988	70	HD	SG	40	PC	0.8	40	2.1	/	4.6	17	
8	Xiabandi	2009	81	DC	G	148	PC	1	80	20.1	/	4.6	37	
9	Colbum	1984	116	DC	G	68	PC	1.2	68	12.8	/	5.4	8.7	
10	MeeksCabin	1995	54	CFRD	SG	/	PC	0.9	47	11.8	/	/	/	
11	Sanxia	1998	/	CD	SG	/	PC	0.8	74	83.5	400~1000	29.6	/	
12	Shawan	2009	86.9	CFRD	SG	69	PC	1	65.1	38.4	3000	3.3	/	
13	xiaolangdi	1994	/	CD	SG	40~70	PC	0.8	61.8	13.9	500	/	/	
14	Shisanling	1990	16.9	CD	SG	21	PC	0.8	31.6	/	800	/	/	
15	Yuecheng	2000	32.5	HD	G	/	PC	0.8	40	49	1200	/	/	
16	Meixi	1998	41	CFRD	SP	30	OC	0.8	30.5	10.5	17000	5.4	/	
17	Dahe	1998	50.8	CFRD	G	37	OC	0.8	38	/	28000	3.5	0.9	
18	Renzonghai	2008	56	DI	G	148	OC	1	82	/	28000	5.2	1.7	
19	Laodukou	2009	96.6	CFRD	SG	29.6	OC	0.8	30	10.7	26000	4.5	0.6	
20	Nalan	2005	109	CFRD	G	24.3	OC	0.8	24.8	/	18000	6.5	0.8	
21	Chahanwushu	2009	110	CFRD	SG	46.7	OC	1.2	47.7	10.2	28000	12.9	2.1	
22	Miaojiaba	2011	110	CFRD	SG	48	OC	1.2	48.5	2.9	26000	9.9	2	
23	Duonuo	2012	112.5	CFRD	CG	35	OC	0.8	30.5	/	26000	6.3	2.4	
24	Jiudianxia	2008	136	CFRD	SG	56	OC	1.2	57.8	8.9	28000	20.3	2.1	
25	Atbara	2013	40	DC	CG	20	OC	0.6	21	11.2	28000	5.9	7.8	
26	Jinping	2010	91.5	DC	SG	85	OC	1.2	80	/	23000	10	/	
27	Manic 3	1976	107	DC	SG	126	OC	0.6	131	20.7	28000	28.5	14	
28	Taleghan	2006	110	DC	SG	60	OC	1.5	63	/	30000	5.2	12	
29	Yele	2005	125	DC	G	420	OC	1	84	22	25000	7.8	15.2	
30	Xiaolangdi	2001	154	DI	SG	73	OC	1.2	70.3	21.2	30000	20	8.1	
31	Pubugou	2010	186	DC	G	75	OC	1.2	76.8	6.2	26000	7	11	/

References

1. Ministry Of Water Resources PROC. 2021 Statistic Bulletin on China Water Activities. China Water & Power Press 2022-12-30; ISBN 978-7-5226-1368-0.
2. Akcakal O, Sutman M, Eser S, Ikiz S, Durgunoglu H. A Case Study - Installation of Cut-Off Wall In Seyrantepe Dam Project. Geotechnical Special Publication 2012; 1287-1293.
3. Moharrami A, Moradi G, Bonab MH, Katebi J, Moharrami G. Performance of Cut-off Walls Under Hydraulic Structures Against Uplift Pressure and Piping Phenomenon. Geotech Geol Eng 2015; 33,95-103.
4. Won M, Kim Y. A case study on the post-construction deformation of concrete face rockfill dams. Can Geotech J 2008; 45,845-852
5. Rice JD, Duncan JM. Findings of Case Histories on the Long-Term Performance of Seepage Barriers in Dams. J Geotech Geoenviron 2010; 136,2-15.
6. Deng B, Yang M, Zhao M. Experimental study on failure mode and lateral earth pressure distribution of unsaturated sand behind retaining walls under active translation mode. Chinese Journal of Geotechnical Engineering 2023; 45,94-102.
7. Rice JD.A Study on the Long-Term Performance of Seepage Barriers in Dams. Virginia Polytechnic Institute and State University 2007.
8. Brown AJ, Bruggemann DA. Arminou Dam, Cyprus, and construction joints in diaphragm cut-off walls. Geotechnique 2002; 52,3-13.
9. Brunner WG FRSE. The Innovative CSM-Cutter Soil Mixing for Constructing Retaining and Cut-Off Walls. Geotechnical Engineering in the Information Technology 2006; 1-6.
10. Gan L, Shen Z, Xu L. Long-Term Deformation Analysis of the Jiudianxia Concrete-Faced Rockfill Dam. Arab J Sci Eng 2014; 39,1589-1598.
11. Rosen JB, M. A. Arnold PD, R. C. Bachus PDD, Schauer, Berrios A. GIS for Geotechnical Decision Making: Visualization of Cut-Off Wall Construction Data. Geo-Frontiers 2011: Advances in Geotechnical Engineering 2010; 2907-2916
12. Yu X, Kong X, Zou D, Zhou Y, Hu Z. Linear elastic and plastic-damage analyses of a concrete cut-off wall constructed in deep overburden. Comput Geotech 2015; 69,462-473.