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Strengthening of Gravity Dams Using Post-Tensioned Anchors

Renforcement des barrages poids à l'aide d'ancrages précontraints

Verstärkung der Schwergewichts-Dämme mit Hilfe von nachgespannten Ankern

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SUMMARY

Many old gravity dams are in need of rehabilitation as a result of ageing, deterioration, deficiencies in design and construction, and more stringent safety standards. Post-tensioned anchors are the most practical and cost-effective method for strengthening concrete gravity dams subjected to direct tension, sliding, overturning, and seismic loading. This paper reviews 27 case histories of concrete gravity dams strengthened by cement grouted multi-strand post-tensioned anchors. The general design of post-tensioned anchors for strengthening gravity dams is outlined.

RÉSUMÉ

De nombreux barrages poids doivent être consolidés suite au vieillissement, à la détérioration, aux déficiences dans la conception et la construction, et aux normes de sécurité plus sévères. La post-tension par ancrages est la méthode de renforcement la plus pratique et la moins onéreuse pour les barrages poids en béton soumis à une tension directe, glissement, renversement ou à un séisme. Cet article décrit 27 cas de barrages poids en béton renforcés à l'aide d'ancrages précontraints composés de câbles injectés au coulis de ciment. La conception générale des ancrages précontraints pour le renforcement des barrages est présentée.

ZUSAMMENFASSUNG

Viele der alten Schwergewichtsdämme sind renovationsbedürftig aufgrund der Alterung, Abnutzung, Mangel in Plan und Konstruktion, sowie strenger werdender Sicherheitsnormen. Benutzung von nachgespannten Ankern ist die praktischste und kostengünstigste Methode für die Verstärkung von Beton-Schwergewichts-Dämmen, welche der direkten Spannung, Rutsch- und Umkippgefahr, und Erdbebenlasten ausgesetzt sind. In diesem Artikel werden 27 Fälle dargelegt, in denen Beton-Schwergewichts-Dämme mit vorgespannten Ankern verstärkt worden sind. Allgemeine Entwürfe und Bauarten vorgespannter Anker für die Verstärkung von Schwergewichtsdämmen werden beschrieben.

1. INTRODUCTION

Many old gravity dams are in need of rehabilitation as a result of aging, deterioration, deficiencies in design and construction, and more stringent safety standards. Post-tensioned anchors are the most practical and cost effective method for strengthening gravity dams. The application of the post-tensioning force increases the frictional resistance at the concrete/rock interface and the moment against overturning, and reduces uplift pressures underneath the dam and tensile stresses on the upstream face. Post-tensioning a gravity dam can be an especially suitable remedial under the following conditions: 1) where the lift joins were inadequately treated during construction and so were weak in tension and shear; 2) when drawing down reservoir level is restricted due to the intolerable economic loss; 3) preservation of historical structures is required; 4) the space on the downstream face is limited for adding concrete mass; and 5) adding concrete is objectionable as in seismically active areas. The post-tensioning technique requires minimum demolition, has only minor impact on the structure, and is relatively inexpensive by using a small number of anchors.

Table 1 shows some gravity dams strengthened using cement grouted post-tensioned anchors in the last 20 years for the various reasons: 1) upgrading to the Probable Maximum Flood (PMF) (11 dams); 2) raising dam height (5 dams); 3) upgrading to the Maximum Credit Earthquake (MCE) (4 dams); 4) deficiencies in design (2 dams); 5) stabilizing concrete cracks (2 dams); and 6) others (4 dams). A dam may have more than one reason for rehabilitation. Post-tensioned anchors are most commonly used to meet the new design criteria relating to the updated PMF and MCE that expect much greater loads acting on a dam.

Steel strands are widely used for post-tensioned anchors due to their high strength, ease of tendon transport and storage, and considerable length. Recently, a comprehensive research program is being conducted on the strengthening and rehabilitation of gravity dams using post-tensioning techniques at the Université de Sherbrooke. This includes: 1) using various types of tendon strands such as conventional strands, epoxy-coated strands, and fibre reinforced plastic (FRP) strands; 2) developing instrumentation systems such as using vibrating wire gauges and optical fibre sensors; 3) investigating the performance of post-tensioned anchors in dam rehabilitation. On reviewing 27 case histories, anchor dimensions used in dam rehabilitation are summarized. The general design of cement grouted multi-strand post-tensioned anchors for strengthening gravity dams is highlighted.

2. DESIGN METHODS

Each anchor installed in a dam should be regarded as permanent. Therefore, corrosion protection is a vital and integrated part of anchor design and construction. The anchor design consists of mainly the overall stability of the strengthened dam, fixed anchor dimensions, and anchor embedment depth.

2.1 Overall Stability of a Strengthened Gravity Dam

The stability analysis of an old gravity dam strengthened with post-tensioned anchors can be accessed in the manner as for a normal gravity dam, with the addition of an extra stabilizing force from the anchors. Post-tensioned anchors for dam rehabilitation should be installed as near as practicable to the upstream face of the dam to provide the greatest stabilizing moment. Basically, a gravity dam should be safe against overturning at its toe and against sliding along the concrete-rock interface or at any weak plane within the foundation. The loads acting on a dam consist of the hydrostatic loads (H_1, H_5), uplift load (V_2), inertia loads of water (H_6) and concrete (H_7, V_3) due to seismic activity, and excess loads due to silt (H_2), ice (H_3), and impact of waves (H_4), as shown in Fig. 1. The post-tensioned anchor (F) will counteract, together with the dead concrete weight (V_1), against overturning and sliding of the gravity dam. Stability against sliding along the concrete-rock interface and overturning about its toe is expressed as:

Sliding: $$SF = \frac{Ac+(V_t+F)f}{H_t} \quad [1]$$

Overturning: $$\frac{\sum MW + MF}{\sum MV} \geq F_s \quad [2]$$

where SF = shear friction factor; A = contact area of the base; c = unit shear resistance at the base; H_t = total horizontal load; V_t = total vertical load; f = coefficient of internal friction at the base; F_s = designated factor of safety; $\sum MW$ = summation of anti-clockwise moments of forces V_1, H_5 about point O; $\sum MV$ = summation of clockwise moments of forces H_1, H_2, H_3, H_4, H_6, H_7, V_2, V_3, about point O; MF = moment of force F about point O.

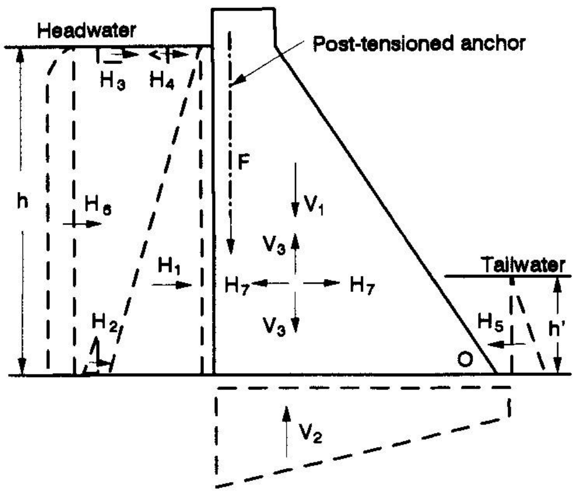

Fig. 1 Loads acting on the section of a gravity dam

The loads acting on a dam are generally categorized as usual, unusual and extreme. Post-tensioned anchors are usually used for the unusual and extreme loading situations that are based on the usual load combination with the PMF level, instead of the normal design reservoir level, and the usual load combination acting together with the MCE, respectively. The recommended factor of safety should be 2.0 and 1.3 for the unusual and extreme load combinations [18]. The force for individual anchor can be obtained from the above equations and is based on the dimension of dam crest, anchor spacing requirement and availability of anchor capacity. Most codes require a design working load of $0.5f_{pu}$ (ultimate load of anchor tendon) with a factor of safety of 2 for permanent anchors. However, an analysis of anchors in Table 1 shows that a higher design working load of $0.6f_{pu}$ is commonly used for permanent anchors. An even higher working load of $0.65f_{pu}$ has been used for several dams in Australia where the anchors are monitorable at any time. Currently, the anchors installed at Burrinjuck Dam in Australia are the largest ones in the world, which consist of 63 No. 15.2 mm strands with a maximum capacity of 16500 kN and an overall length of 128 m [9].

2.2 Fixed Anchor Dimensions

The design approach to calculate the fixed anchor dimensions has been based on an assumed uniform bond stress between the grout and the rock [19]. Generally, the ultimate bond stress depends on the shear strength of the rock, the grout strength, and the method of construction. In UK practice [21], it is required that the ultimate bond strength used in the design should not exceed the minimum shear strength for rock with uniaxial compressive strength (UCS) less than 7 N/mm^2, and can be taken as 10% of the UCS of the rock for strong rock but should not exceed 4.0 N/mm^2 for UCS value exceeding 40 N/mm^2. Cement grouts with water-cement rations of 0.40 to 0.45 are commonly used in practice and the rock/grout bond values recommended for design can be found elsewhere [18, 19, 21].

The fixed anchor length should be neither less than 3 m nor greater than 10 m [20]. For a short bond length (less than 3 m), sudden changes in rock quality along the fixed anchor zone as well as any constructional errors may induce a significant decrease in pull-out capacity. On the other hand, fixed anchor lengths of 10 to 12 m are considered useful only in particularly weak rocks such as mudstones and shales [21]. An analysis of anchor bond length in Table 1 shows that the bond lengths are generally in the range of 5.5 to 10 m. Anchors with a longer bond length up to 16 m have also been seen in practice. One of the extreme example is at Lake Lynn Dam, where a bond length of 18 to 40 m was used in clayey siltstone [6].

Fixed anchor diameters depend mainly on the size of tendon, corrosion protection requirements, size of drilling bit, and ground conditions. The practical hole sizes adopted in dam rehabilitation generally range from 114 to 330 mm (4.5 to 13 inch). Anchor spacing affects the behaviour of individual anchors. In dam rehabilitation, the minimum spacing is governed by practical requirements such as hole tolerances to avoid deep anchor crossing in the drilling line, anchor capacity, applied load per meter length of the dam, and rock mass discontinuity spacing. An analysis of anchor spacing in Table 1 shows that anchor spacing is generally in the range of 0.9 to 5.5 m with a more common range of 1.5 to 2.5 m.

2.3 Anchor Embedment Depth

The load of an anchor is resisted by the weight of a mobilized rock mass beneath the dam. Two alternative methods are used to determine the size of the mobilized rock mass. The pull-out cone method assumes that an inverted cone of rock is pulled out of the rock mass for a single anchor at failure. The weight of rock mass mobilized is calculated using the volume of the cone and the submerged weight of rock situated below water table. The wedge method assumes that the foundation rock is tied to the dam to against overturning with the dam. Case study has shown that the assumed cone method is more common than the wedge method in practice.

Current design approaches ensure that anchors are embedded deep enough so that failure of the tendon or at the grout-rock interface occurs before the rock mass being pulled-out. Over the years, the choice of apex cone position has been varied from the base of the anchor, the middle of the fixed anchor to the top of the fixed anchor. In dam rehabilitation, apex cone positions are usually chosen at the top or at the middle of the fixed anchor, and are often dictated by the surrounding ground conditions. It suggests that the apex cone position be taken at the middle of the fixed anchor when considering load transfer by bond [19, 20].

Generally, the included angle of inverted cone is assumed to be 90° in sound homogeneous rock with the apex at the bottom of the fixed anchor, and 60° in weak or highly jointed rock masses with the apex at the middle or at the top of the fixed anchor. When groups of closely spaced anchors have their fixed anchor zones located in the same rock horizon and the rock mass is horizontally bedded, a laminated failure could occur. As a result, it is necessary to incline the fixed anchor further apart or stagger the fixed anchors at different depths in order to reduce the intensity of stress on any plane.

3. SUMMARY

Based on reviewing 27 case histories, anchor dimensions used in dam rehabilitation are summarized. The general design of post-tensioned anchors for strengthening gravity dams is briefly described.

Country-Dame	Dam height (m)	Anchor no.	Strand tendon (mm)	Design capacity T_c (kN)	Design load (%T_c)	Bond length (m)	Anchor spacing (m)	Hole size (mm)	Anchor length (m)	Ref.
USA-Minidoka	*	7	44/15.2	11458	60	7.6	5.5	254	35	[1]
USA-Morgan Falls	16.8	100	31/12.7	6461	55	9.0	*	165	*	[2]
USA-Rainbow	8	6	Strand	4447	60	*	4.5	152	22	[3]
USA-Ryan	27	31	45/12.7	9576	60	16.2	0.9	203	49	[3]
USA-Crescent	12.2	151	12/15.2	3600	52	*	*	*	31	[4]
USA-Conowingo	30.4	537	20/15.2	5300	60	8.4	2.8	190	61	[5]
USA-Lake Lynn	38.1	75	58/15.2	15118	60	39.9	2.0	280	92	[6]
USA-Shepaug	40	97	53/15.2	13789	59	14.9	1.8	254	59	[7]
USA-Libby	128	100	16/12.7	2936	60	6.1	*	127	46	[8]
Australia-Cataract	54	*	55/15.2	13750	60	*	2.5	310	84	[9]
Australia-Burrinjuck	79	161	63/15.2	16500	65	*	1.5	310	128	[9]
Australia-Nepean	76	*	63/15.2	16500	57	*	2.0	314	119	[9]
Australia-Goulburnweir	15	*	27/15.2	6750	*	*	1.8	200	*	[9]
Australia-Hume	51	*	55/15.2	13750	65	*	*	312	85	[9]
Australia-Warragamba	137	*	63/15.2	16500	60	*	2.5	310	112	[9]
Australia-Maroondah	47	*	52/15.2	13670	*	*	3.6	305	*	[9]
Australia-Bickley	13	*	12/15.2	3150	*	*	1.2	165	*	[9]
Australia-Manly	19	46	24/15.2	6000	60	*	5.0	215	43	[9]
Iran-Sefid Rud	106	*	54/15.2	14000	54	*	*	*	40	[10]
Morroco-L. Taberkoust	57	54	49/15.2	12625	53	*	*	*	115	[10]
Australia-Tenterfield	15	>44	12/12.5	2508	62	5.5	1.8	114	24	[11]
Germany-Eder	47	104	34/15.2	8800	52	10.0	2.3	273	75	[12]
UK-Mullardoch	50	26	37/15.2	11100	42	5.4	1.5	330	55	[13]
Brazil-Rasgao	22	80	12/12.7	2232	45	*	1.0	*	*	[14]
Parkistan-Tarbela	148	576	16/15.2	4170	60	6.0	*	165	38	[15]
Uganda-Owen Falls	*	115	12/15.2	3180	62	8.0	*	131	36	[16]
Zimbabwe-Sebakwe	38.8	80	38/15.2	9905	60	8.0	*	175	70	[17]

Note: * = data not available

Table 1 Concrete gravity dams strengthened using multi-strand post-tensioned anchors

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