Prestressed Concrete Dams 1934 – 1964

by A. C. Roemermann*

Two methods of prestressing dams have been in use since their inception in the early 1930's:

1. The Coyne method of prestressing with tendons.
2. The Freyssinet method of prestressing without tendons, but with inflated flat-jacks.

The purpose of this report is to describe the Coyne method, and only brief mention will be made of the Freyssinet method.

Prior to the turn of the century, it was common practice to design gravity dams without any allowance for uplift pressures, such dams depending solely upon their weight for stability against sliding and overturning. Uplift pressures, when permitted to build up, have in time resulted in increasing a dam's buoyancy, thus decreasing its effective weight. Disregard for uplift has contributed, in large part, to the failure of some old dams, and to the threatened failure of other dams.

It was not until about 1910 that uplift in dams began to receive merited recognition. Since 1910, serious attention has been directed toward corrective measures for keeping uplift within allowable limits. Such measures include grouting and drainage of dam foundations. Furthermore, considerably more attention has been devoted to the selection of suitable dam sites. In such selections, geologic investigations and rock mechanics now play more important roles than in the past.

The importance of uplift in hydraulic structures was fully recognized by the United States Bureau of Reclamation at an early date. At the conclusion of an extensive research program undertaken in 1915, the Bureau reported that: "Water under pressure was found at every point under all U.S.B.R. dams".

In 1935, foundation uplift pressures were first recorded in the 726 ft. high Hoover Dam, which was the world's highest concrete gravity dam until 1960. These tests showed increases in uplift until 1939, when further corrective measures were carried out by additional foundation grouting. Through World War II and into the 1950's the grouting was continued. Final foundation treatment on the Hoover Dam was completed in 1953.

While uplift in the design and construction of dams had been entirely neglected in the past, it is now fully provided for in all dams. The assumed allowance for uplift in the design of new dams, as adopted by the United States Government agencies, is usually about two-thirds of

**Structural Engineer*
Formerly associated with
Abbott, Merkt & Company, Inc.
New York, New York

the upstream hydrostatic pressure, decreasing uniformly to zero at downstream tailwater. Such uplift is usually assumed to be effective on 100% of the base area. However, should special conditions warrant, those assumptions must of course be varied.

In the early 1930's, French engineers, confronted with failures and potential failures of gravity dams, chiefly in North Africa, undertook to make studies and tests for strengthening dams. These dams had been constructed in the 1880's, without allowance for uplift. The late Andre Coyne, noted French consulting engineer, and former President of the International Commission on Large Dams, met this challenge by devising an ingenious method for stabilizing weak gravity dams by anchoring them to foundation rock with post-tensioned vertical tendons. This method likewise permitted increasing their height without the customary addition of new masonry on the downstream face.

Among various methods for heightening of gravity dams, the one most frequently adopted has been to add and bond new masonry on the existing downstream face, to increase the base width—usually a difficult and costly procedure. The Coyne method has made it practical and economical to heighten dams without adding downstream masonry. It is necessary only to add a small volume of masonry atop the dam's crest, and to depend upon post-tensioned cables to restabilize the dam for the additional height.

In the early 1930's the late Eugene Freyssinet, noted French consulting engineer and pioneer in the prestressing of concrete, invented a method of prestressing dams by inflation of flat-jacks without utilizing post-tensioned tendons. The Freyssinet method, owing chiefly to its rather complicated character, has not been too frequently utilized in dam construction. However, the Coyne method, since its inception in 1934, has been quite frequently utilized in both new and old dams in various countries for strengthening and heightening. The Freyssinet method has usually been applied to new dams of the multiple arch and buttress types, constructed, for the most part, in Algeria.

Since the purpose of this report, as noted above, is to describe the Coyne method, only brief mention will here be made of the Freyssinet method. In both methods, artificial forces are created; the Coyne forces being applied in the upstream portion of a dam, while the Freyssinet forces are applied in the downstream buttresses, as follows:

In the Freyssinet method, thrusts usually of 10,000 to 20,000 tons per buttress, but exceeding 30,000 tons on occasion, are produced by inflating, under pressures up to 2,000 psi, flat steel pouches or flat-jacks. When the desired runout (maximum = 1 in. per jack) is attained, thus inducing precompression in the buttresses, the jacks are usually grouted in to remain permanently in the structure. These thrusts serve to counterbalance large predetermined portions of the active water pressure, usually about one-third. Many adjustments of the flat-jacks are made at regular intervals normally over periods of several years to compensate for creep, shrinkage and temperature changes in the concrete and rock, and also to compensate for changes in reservoir water level.

In 1934-1940, the Beni-Bahdel multiple arch dam was constructed in Algeria for irrigation and power purposes. Construction was nearing completion in 1937 when it was decided to supply the City of Oran with drinking water. To meet this increased demand, it was necessary to heighten the dam by 24 ft. to 188 ft., thereby increasing the overturning moment by 50%. Thanks to Freyssinet's ingenious invention, major revisions in the plans were not required. The solution adopted was to assume a design load per buttress of 22,000 tons for reservoir full and 11,000 tons for reservoir empty for inducing thrusts. The number of flat-jacks required per buttress ranged from 14 for the lowest to 40 for the highest buttresses.

The following recent examples of the Freyssinet method are cited:

Erraguene (Djen-Djen) Dam: Multiple-arch, 256 ft. high, constructed in Algeria 1955-60. In addition to thrusts of 8,800 to 37,400 tons induced by flat-jacks at the base of the 11 buttresses, the arch-barrels were post-tensioned by means of 36 Freyssinet cables per barrel, each cable having 36-wires 0.276″ in diameter. This dam is claimed to be one of the world's largest multiple-arch dams.

Menjil Dam in Iran: Buttress type, 350 ft. high, bolstered by 23 self-supporting buttresses. Thrusts of 30,000 tons were induced in each of the 13 highest buttresses. Prestressing with tendons is also utilized in this dam. Each sector-gate is designed to sustain 1870 tons maximum water pressure. Prestressed concrete girders, post-tensioned with Freyssinet cables, are used to support these gates. Menjil Dam, claimed to be the world's highest buttress type, was completed in 1962.

COYNE METHOD

In 1934-1935, the first practical applications of the Coyne method were carried out in the rehabilitation of the stone masonry Cheurpas and Fergoug (El Habra) Dams, constructed in Algeria in the 1880's. At this time almost all installations were dependent for continuous operation upon a single source of water supply. The Coyne method made it possible to strengthen and restore such dams without accompanying drawdown of reservoirs, and without interruptions in service for irrigation, power and water supply.

The Coyne method consists of placing steel cables, consisting of many small high tensile wires usually 0.2″ in diameter, in vertical holes drilled through the dam and into rock near the upstream face. The lower ends of the wires are left exposed and loosened, and are securely anchored into foundation rock by grouting. The upper wire-ends are spread out in bouquet fashion, and well embedded into heavily reinforced concrete headblocks which are approximately cylindrical in shape. Tensioning of the cables, including 10% initial overloading, is done with hydraulic jacks, mounted on the crest, beginning at least three weeks after homing in. The larger cables are tensioned in stages, while the smaller ones require only a single stressing operation. On completion of the tensioning, the cable elongation is usually held by wedging steel cylinders filled with concrete between crest and headblock. Finally, the cables receive a protective coating of grout, injected under pressure. Following is listed the range of cable sizes and spacing, that have been used to date:

	Minimum	Maximum
Cable O.D. (in.)	1⅜	Unknown
No. of wires	37-0.2″ dia.	400-0.276″ dia.
Capacity (tons)	78	1570
Spacing (ft.)	3-6	13-21
Vert. hole (in.)	2½	14
Drill method	Percussion	Rotary

In dams where excessive uplift pressures have developed, as in India's Tansa Dam, a minimum cable spacing of 18″ was required and, in addition, the cables were placed in two rows.

The following briefly describes the restoration in 1934-1935 of two Algerian gravity dams constructed of stone masonry in the 1880's:

Cheurfas Dam: Rehabilitation after failure was carried out by placing 37 Coyne cables 6″ in dia. x 1,100 tons, spaced 13 ft. cc., and located about 7.5 ft from the upstream face. Each cable was assembled on the crest from 630 galvanized, parallel wires (0.2″ dia.) wrapped in sailcloth and bitumen and placed in 10″ dia. drill holes, enlarged to 15″ dia. to form an anchorage for the grout plug. At least three weeks after homing in, each cable was tensioned to 1100 tons in 3-stages (to 330, 770 and 1100 tons) by 3-440 ton hydraulic jacks mounted on the crest. Tensioning time required per cable was one week. Maximum length of cable was 164 ft., and penetration into limestone foundation rock was 32 ft. The combined force, 40,700 tons, of the 37-cables was equivalent to increasing the dam's weight by about one-third, thereby making it possible to increase the operating head by 10 ft. Tests made on some of the cables in 1944 after 9 years of service showed an average loss of prestress of only 4.5%. This loss was restored by re-jacking.

Fergoug (El Habra) Dam: In flash floods of 1927, Fergoug Dam's weak crest section was torn away to depths of 13 to 33 ft. below the crest. Restoration was carried out in 1934 by capping the remaining stone masonry with concrete anchored thereto by means of Coyne cables similar to but smaller than the above-mentioned Cheurfas Dam cables. The new concrete was placed in 13 to 17.5 ft. sections separated by copper sheets. Each new block was anchored into place by one cable placed at its midpoint. Cable lengths varied from 29 to 59 ft., and capacities from 138 to 315 tons. The cables, in this case, served only to tie the new concrete to the existing masonry without penetrating foundation rock. The maximum penetration into stone masonry was about 40 ft., and the grouting length of the anchorage was about 16 ft.

Plant, equipment and site-labor required to carry out the early applications of the Coyne method were quite extensive. Since about 1953, the Coyne method has been materially streamlined to reduce the costs of such items. Prefabrication techniques have been used, and there has been a trend toward using smaller cables. For example, the cables required to stabilize India's Tansa Dam, and to heighten South Africa's Steenbras Dam were only 1⅜″ diameter, shop-fabricated from 37 wires 0.2″ in diameter, transported to the job site in reels, and placed in 2½″ dia. drill holes.

Implementation of the Coyne or similar methods is generally carried out by specialist firms, such as The Cementation Company Limited in Great Britain, Soletanche and Sondages, Etanchements & Consolidations in France. In the past ten years, the British firm's activity has been devoted, in large measure, to the prestressing of both existing and new dams, especially in South Africa and Australia.

In designing gravity dams, one of the usual criteria specified is to have the resultant of forces acting on the dam intersect its base within the middle third. When post-tensioned vertical cables are placed near the upstream face of a weak dam, its resultant line of pressure is shifted upstream to a position more favorable than that of a conventional dam without cables. Such addition of cables is equivalent to increasing the dam's weight, and, thereby, its stability against sliding and overturning. In the case of new prestressed concrete dams, the addition of upstream cables is effective in reducing the weight of masonry required in the downstream face. Savings in costs of 15 to 20% have been realized in the recent construction of such new dams.

Since 1951, new gravity dams have been designed and constructed as all prestressed concrete structures in various countries. In the United States, prestressing in connection with dams has recently taken a different pattern. Since about 1960, our Government agencies and others have applied prestressing to new construction of the appurtenant works of dams and power plants. As anticipated, such prestressing has taken a form in which prefabrication and precasting have played an important role in achieving substantial reductions in site-labor and equipment costs over conventional methods. Some recent examples are cited below:

Markland Locks and Dams: The Corps of Engineers, U.S. Army have, since the late 1950's, frequently utilized prestressing techniques in the construction of concrete piers for spillways, chiefly to reinforce the trunnion anchorages for tainter (radial) gates. Subject to the continuous pressure of flowing water, such anchorages are now usually post-tensioned to induce sufficient precompression in the concrete to prevent the formation of cracks. The trunnion anchorages for tainter gates 100 ft. wide by 42 ft. high, placed in the Markland Dam, are the largest utilized to date by the Corps of Engineers. Details of this work are shown in Figs. 1-3. The anchorages were assembled by shop-fabrication in eleven units, each 83 ft. long, made up of 56-1¼"

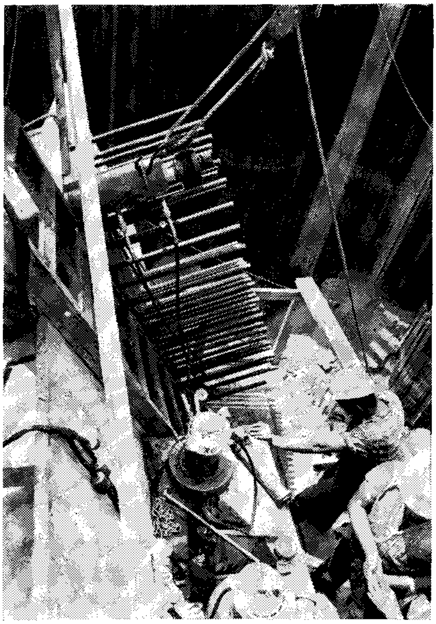

Fig. 1—Markland Dam—Post-tensioning

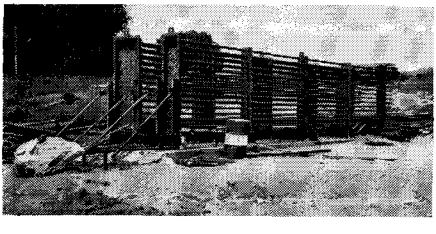

Fig. 2—Markland Dam—83 Ft. Fabricated Bar Assemblies

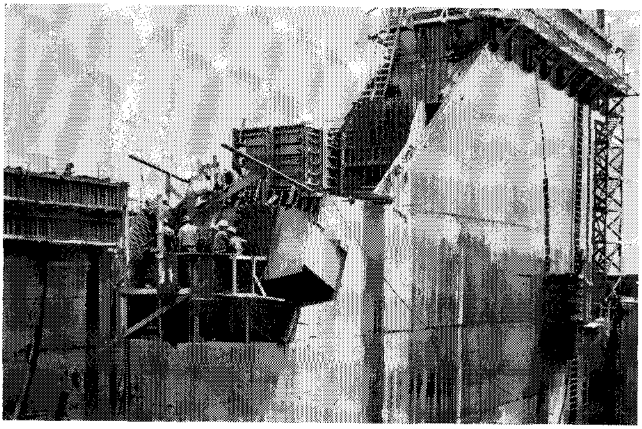

Fig. 3—Markland Dam—Spillway Pier

dia. high-tensile Stressteel bars, spaced at 6″ vertically and at 7″ horizontally. The assemblies were placed in the piers by crane. The bars were post-tensioned to 100,000 psi simultaneously in symmetrical pairs by separate hydraulic jacks. Each assembly was designed to develop a prestress force of 3425 tons to resist the maximum water pressure.

Wanapum Dam: This dam was recently constructed on the Columbia River for Grant County (Washington) Public Utility District. In its spillway, 11 concrete piers support trunnion anchorages for gates 50 ft. wide x 65 ft. high. Each pier is reinforced with a 12-ton assembly, prefabricated in a jig 5 ft. wide x 10 ft. high x 75 ft. long. Each assembly consists of 14-90 wire tendons (with ¼″ dia. wires) sheathed in undulating ducts, and post-tensioned to 4,400 tons by the Swiss BBRV prestressing system. The wires have cold-formed buttonhead ends. The 11 assemblies were prefabricated in Seattle, complete and ready for installation, trucked to the site and placed by crane. Each 12-ton assembly is designed to resist water pressures up to 3,750 tons. Dense, almost impervious and crackless concrete obtained through post-tensioning is now frequently utilized to withstand these high pressures and vibrations. It is claimed the 65 ft. high tainter gates, each weighing 224 tons, are the worlds' highest. Some details are shown in Figs. 4-6. In 1961-1962, prestressing was also utilized in Wanapum Dam's intake works where 78 large vertical tendons, about 74 ft. long, were placed in 16″ dia. holes drilled into foundation rock. Each tendon is made up of 4 groups of 90 wires ¼″ in diameter. Four 500 ton hydraulic jacks were required to post-tension each group of 360 wires to 1270 tons after grout anchorages were permitted to harden for two or three weeks. In pull-out tests with a maximum force of 1950 tons per group, about 1.5 times the design load, neither the wires nor the bond of the grout could be broken.

In recent applications, the Tennessee Valley Authority has utilized prestressing for stabilizing the walls of cofferdams during construction, and in other minor construction applications.

Listed below in 4-groups are some

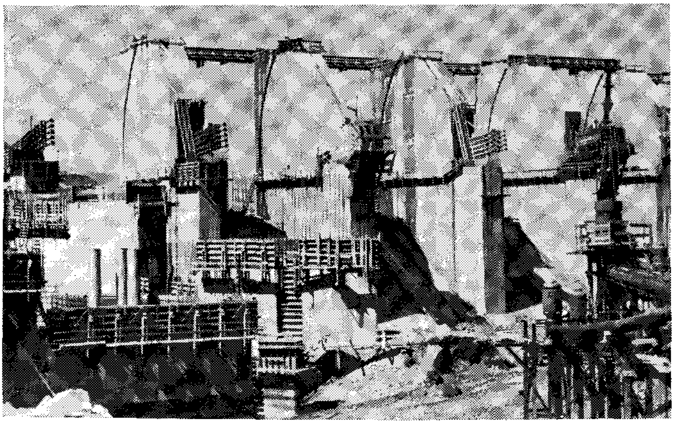

Fig. 4—Wanapum Dam—Downstream Face

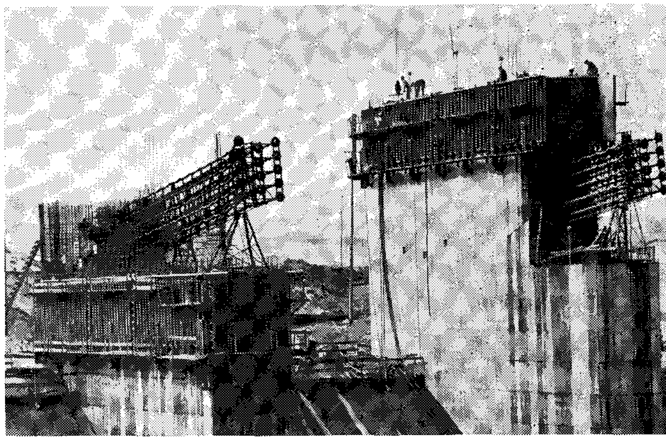

Fig. 5—Wanapum Dam—Downstream Face of Two Spillway Piers

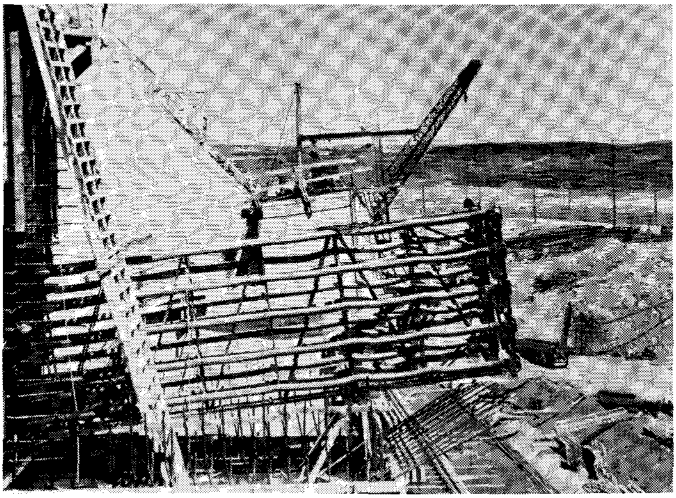

Fig. 6—Wanapum Dam—Assembly Being Lifted into Place

of the dams that have been strengthened, heightened or constructed as new prestressed concrete structures since about 1948. Those dams indicated by an asterisk will be briefly described:

Group 1 includes some of the new prestressed concrete dams constructed from 1951 to date:

Ernestina Dam, Brazil Freyssinet	(1951-54)
*Allt-Na-Lairige, Scotland Lee-McCall	(1954-56)
*Tourtemagne, Switzerland Freyssinet	(1957-58)
Swallow Falls, So. Africa Coyne	(1956-58)
*Catagunya, Tasmania Coyne	(1959-61)
*Meadowbanks, Tasmania Coyne	(1964-)

Group 2 includes some new dams designed for future heightening, with cables omitted in the present construction. However, ducts or shafts have been left in the original construction to sheath the future cables when increased water demand must be met. For example:

*Girotte Dam, So. France Multiple-arch, to be raised 36 ft.	(1946-48)
*Avon Dam, Great Britain To be raised 13 ft.	(1954-58)
Erfenis Dam, So. Africa To be raised 30 ft. in three stages.	(1959-61)

Group 3 covers the strengthening of existing gravity dams without increase in height:

*Tansa Dam, India 2399 cables @78 tons	(1953-55)
Walwhan Dam, India 292 cables @224 tons	(1960-61)
*Mahinerangi, New Zealand 20 cables @300 tons	(1960)
Waitaki Dam, New Zealand 46 cables @300 tons 45 cables @179 to 224 tons	(1960-61)

Group 4 includes existing gravity dams that have been heightened and restabilized by means of Coyne cables:

*Steenbras Dam, So. Africa Raised 6.5 ft. plus 5.5 ft. flood surcharge	(1953-54)
Witbank Dam, So. Africa Raised 18.5 ft.	(1957-59)
Compies Dam, So. Africa Raised 23 ft.	(1958-59)
Hume Dam, Australia Raised 6 ft. and 24 ft. gated spillway added	(1959-60)
Mazoe Dam, So. Rhodesia Raised 10 ft.	(1960-61)
*Argal Dam, Great Britain Raised 10 ft.	(1960-61)

GROUP 1

Tourtemagne Dam

The Tourtemagne Dam, located in south Switzerland, is 108.3 ft. high, and is claimed to be the first new arch dam to be prestressed. It was constructed to impound Alpine glacial waters in a reservoir that can be entirely emptied in winter seasons, and alternately filled and emptied several times in summer seasons. In the upper three-fifths of its height this dam is only 3.9 ft. thick. This slenderness and fluctuating reservoir levels combine to subject it constantly to temperature stresses. Its stability is assured without recourse to tensioned cables by sharp horizontal curvature with radii only 66 ft. and 98 ft. long, and crest length of only 377 ft.

Both vertical and horizontal prestressing by Freyssinet cables of 12 wires 0.276″ in diameter, and Freyssinet flat-jacks was utilized to neutralize temperature stresses, and to eliminate all tensile stresses with the reservoir either full or empty. Sixty vertical cables, spaced 3.3 ft. in the center section and 4.9 ft. at the ends, were placed in a 230 ft.

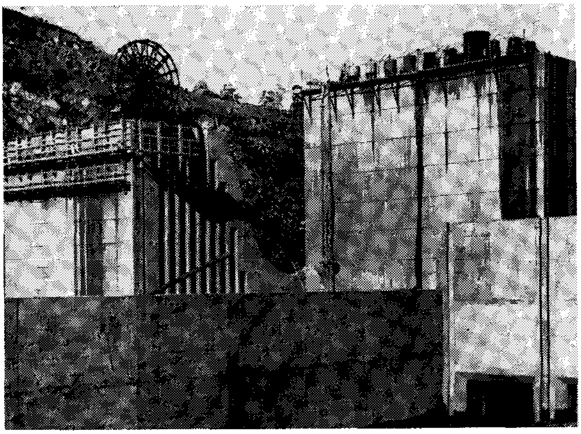

Fig. 7—Catagunya Dam—Cable Heads and Homing Wheel

section of the 377 ft. crest length.

Prestressing without tendons was carried out by inflating Freyssinet flat-jacks 16½" in diameter. In each of the vertical expansion joints separating the concrete monoliths, 12 Freyssinet flat-jacks, spaced 3.3 ft. vertically on the dam's center line, were placed and inflated. On completion of adjustments, the jacks were grouted in place.

Allt-Na-Lairige Dam

The Allt-Na-Lairige Dam, located in Scotland, is 83 ft. high x 1360 ft. long, and is claimed to be the first dam in which high tensile bars instead of wire cables were utilized as tendons. The tendons consist of 28 vertical Macalloy bars 1⅛" in diameter x 109 ft. long placed in 47 shafts 4'-0" in diameter and spaced 21'-0" on centers. The prestressed section extends over 987 ft. of the dam's 1360 ft. crest length. The bars were spliced at two points by threaded couplers and post-tensioned individually to 47 tons using the Lee-McCall system after anchorage by grouting into 26 ft. of granite rock. The estimated saving in the concrete placed over that of a conventional gravity dam was about 40%, and the saving in cost was 15%.

Catagunya Dam

The Catagunya Dam (Figs. 7 and 8), located in Tasmania, is 150 ft. high. This newest and highest of the new prestressed concrete dams, completed in 1961, is provided with an over-hanging spillway section 425 ft. long designed for 18 ft. of surcharge. The spillway cantilevers 24 ft. upstream from the vertical upstream face, and discharges into a high-level bucket dissipator. It was stabilized with 412-3 in. dia. Coyne cables, each of 224 ton capacity. The cables were assembled from 102-wires 0.2" in diameter and placed in two rows. Holes for the cables were 4" in diameter, and were percussion-drilled into dolerite rock. Transite pipe sheaths 4⅝" in diameter were used in passing through concrete. Maximum length of cable was 170 ft., and grout anchorage in dolerite was 13 ft. The estimated saving in cost over a conventional gravity dam was about 20%.

Meadowbanks Dam

In January 1964, construction of a

new prestressed concrete dam of the buttress type, 130 ft. high x 830 ft. crest length, with a 250 ft. spillway, was begun by the Cementation Company Limited in Tasmania. Prestressing with tendons will be carried out later when 14,000 lin. ft. of cable will be placed in the dam at 35° to the vertical. Each of the 140 Coyne cables will consist of 72 galvanized wires, 0.276″ in diameter and will have a capacity of 300 tons. Heretofore, post-tensioned cables placed in dams have, in most cases, been vertical or nearly vertical. In this case, the cables will be sloped to provide both vertical and horizontal stabilizing forces. The spillway will be provided with two sector gates 119 ft. wide x 15 ft. high. The Cementation Company's contracts for preloading and grouting of foundations, and of placing the post-tensioned cables will total about $560,000.

GROUP 2

Avon (Dartmoor) Dam

The Avon Dam in Great Britain is presently 108.5 ft. high. The proposed future increase in height

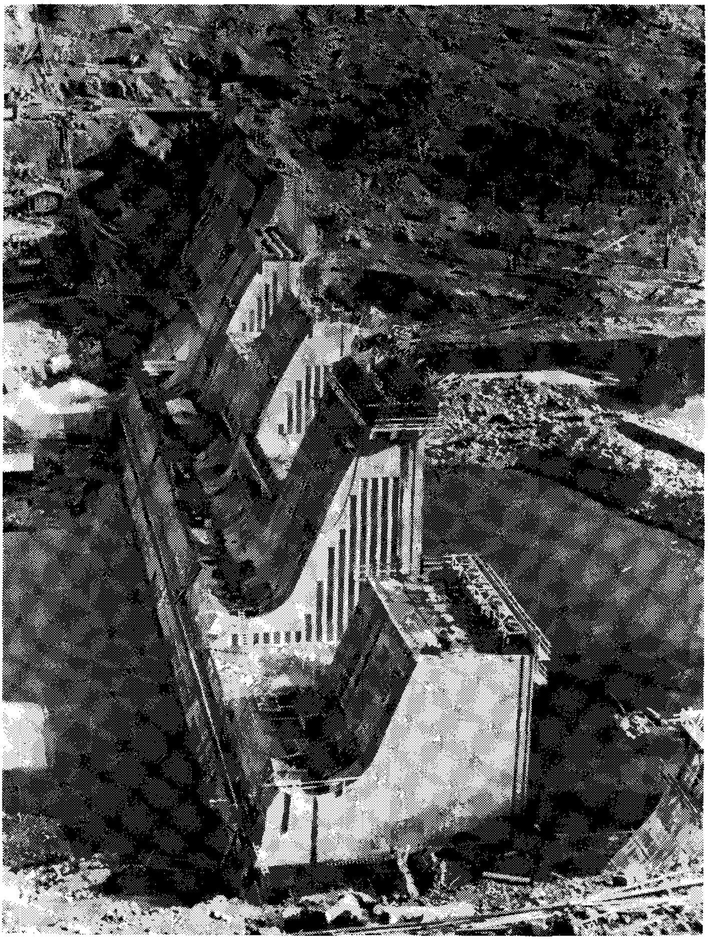

Fig. 8—Catagunya Dam—Partially Complete Showing Line of Cable Heads

of 13 ft. was not known at the time the design plans were completed and the contract awarded in 1954. However, provision for 34 future cables was made at small additional cost in the present construction. As concreting proceeded in 6 ft. lifts, ducts required to sheath future cables were formed by means of 21" dia. concrete pipe in 6 ft. sections. In foundation rock, 24" dia. x 15 ft. holes, temporarily capped with 2 ft. of concrete, were provided for future anchorage. Had Avon Dam been originally designed in prestressed concrete, a considerable saving in volume of concrete on the downstream slope could have been realized.

Girotte Dam

This multiple-arch dam, 114 ft. high with 18 inclined arch-barrels supported by buttresses spaced 78.7 ft. on centers, was designed for 36 ft. future heightening. When the increased water demand must be met, this dam will be restabilized by means of post-tensioned vertical cables placed at buttress centers in shafts provided in the original construction (one shaft per buttress). In the future addition, the 18-barrels will be extended up 36 ft. vertically, and securely anchored to the original inclined barrels.

GROUP 3

Tansa Dam

The stone masonry Tansa Dam in India now 133 ft. high was constructed from 1886 to 1891 to a height of 118 ft. of greenstone (basalt) masonry laid up in surkhi (lime mortar). It was designed, without uplift allowance, for 17 ft. higher head, and was heightened to 133 ft. in 3-stages—in 1914, 1925 and 1946. For years the City of Bombay had depended solely upon this unstable dam for its water supply. It was kept under close observation, and was investigated at various times by such prominent hydraulic engineers as the late Andre Coyne and the late Louis F. Harza, former President of the Harza Engineering Company of Chicago. By the early 1950's, measures for stabilizing it, complicated by a post-war population explosion, had become extremely urgent.

In 1953-55, under Andre Coyne's supervision, the stabilizing was carried out by the Cementation Company Limited. In this project more than 240,000 lin. ft. of 1⅛" dia. cables were placed in 2399 holes 2½" in diameter drilled through the dam 5 ft. from the upstream face. Penetration into basalt rock was 25 ft. The cables were shop-fabricated from 37 wires, 0.2" in diameter, placed in coils 1200 to 1400 ft. long, transported to the site, passed into the holes, and anchored into grout plugs 12 ft. long. Maximum cable length was 180 ft. The upper ends of the cables were anchored into Meehanite cast iron headblocks, and post-tensioned by means of hydraulic jacks mounted on the crest. At least 3 weeks after homing in and grouting in, each cable was tensioned above its working load to 90 tons. After a lapse of an additional 4 weeks, each cable was finally tensioned so that a minimum design load of 78.4 tons was permanently held. In sections where uplift was excessive, the cables were placed 18" apart in two rows.

Rehabilitation of Tansa Dam, carried out over a 28 month period terminating in March 1955, was by far the largest project of its kind ever undertaken. This work was done with the reservoir full, and without interruptions in water supply.

Mahinerangi Dam

The 140 ft. Mahinerangi Dam in New Zealand was strengthened in 1960 by means of 20-300 ton vertical cables of 72-parallel stranded wires, 0.276″ in diameter, placed in 4″ dia. drill holes 3′-3″ from the upstream face. Anchorage length of the cables in rock was 25 ft., and maximum length was 160 ft. The wires were arranged in three concentric circles around 1⅛″ I.D. x 6″ central ferrules spaced 6′-0″ on centers. The cable headblocks, conical in shape, were poured in place and embedded in the dam just below the crest.

GROUP 4

Steenbras Dam

The 80 ft. Steenbras Dam in South Africa was heightened by 6.5 ft. and, in addition, designed to sustain 5.5 ft. flood surcharge as follows: Concrete in the existing curved crest section was first cut down about 3′-6″, and a 21″ reinforced-concrete cantilever wall 9′-3″ high having the same upstream face was superimposed on the lowered crest. The new wall was securely anchored to the existing dam by steel dowels. Required for stabilizing were 163-1⅜″ dia. semi-endless cables, each of 37 wires, 0.2″ in diameter, placed in 326 drill holes 2½″ in diameter, and anchored by grouting. The cables were bent over precast semicircular saddles mounted on the crest and post-tensioned to 154 tons (77 tons per leg) by 224 ton jacks. The design was based on the following assumptions:

1. Uplift pressure = 0.67 of full static head at the upstream face, decreasing uniformly to zero at the downstream toe.
2. Effective area of uplift—100% of base.
3. Coefficient of friction for balancing the horizontal forces = 0.75, assuming shear in concrete = 0.

Interesting to note in connection with the rehabilitation of Steenbras Dam was the fact that the proceeds from the sale of water obtained from the enlarged reservoir during the first summer of 1955 more than paid for the entire cost of the project. Provision for further heightening was made in the present construction by so arranging the currently placed cables to allow sufficient space for future cables.

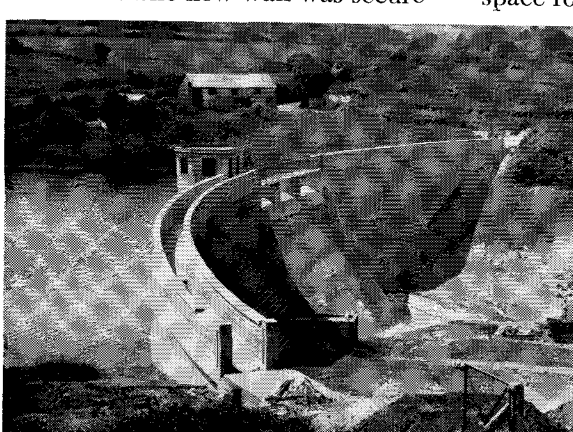

Fig. 9—Argal Dam

Fig. 10—Argal Dam—Cables Bent Over Steel Cages

Argal Dam

The Argal Dam (Figs. 9-10) in Great Britain was constructed in 1939-40 and heightened by 10 ft. in 1960-61 to meet an increased demand for water. This marks the first application of the Coyne method in Great Britain. After the existing curved crest section was cut down by three feet, the new concrete was placed in two lifts of 7 and 6 feet. In the first lift, the crest was heightened by 7 ft. to form the base and face for placing 47 vertical cables spaced 5′-6″ on centers in 4″ dia. holes percussion-drilled to 27 ft. minimum below the foundation. Each cable is about 3″ in diameter and is fabricated on the site of 102 wires, 0.2″ in diameter, arranged in circular cross-section around a central ½″ dia. grout pipe. Cables were anchored by grouting 13 ft. into foundation rock, and in reinforced-concrete cylindrical head-blocks on the crest. At least 3 weeks after homing in, each cable was post-tensioned to 224 tons, after initial overloading by 10%, by means of 3-112 ton hydraulic jacks mounted on the crest. Cable elongation was maintained by means of steel tubes filled with concrete. On completion of the post-tensioning, the second lift, 6 ft. of new concrete, was placed to form the new crest section and encase the cable head-blocks.

I.C.O.L.D.

At the 6th Congress of the International Commission of Large Dams in New York in 1958, under Question No. 20, various ways of heightening dams, including prestressing, were fully considered. Of 29 papers presented with discussion, 6 papers were on prestressing of dams.

It is deemed impractical and uneconomical to construct new prestressed concrete dams higher than 200 ft. This has generally been accepted as the ceiling, and has been confirmed in a discussion at the 7th Congress of ICOLD in Rome in 1961.

ACKNOWLEDGEMENT

The writer is indebted to the Cementation Company Limited of London, Stressteel Corporation and Joseph T. Ryerson & Sons, Inc. for much of the information contained in this report.