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SYNOPSIS: Construction of a powerhouse on unconsolidated landslide debris materials at the edge of a stream channel in a narrow, steep-sided canyon in northern California entailed application of an unusual combination of grouting techniques to protect the foundation during peak flows. These techniques included permeation grouting, displacement grouting, compaction grouting, and controlled hydrofracture grouting.

INTRODUCTION

The grouting operations described in this paper were performed in conjunction with construction of the Forks of Butte Hydroelectric Project, an 11.6-MW run-of-the-river hydropower project located in northeastern California. The project was constructed by a private developer under the jurisdiction of the Federal Energy Regulatory Commission. The principal features include an upstream diversion and intake structure, a 600-foot (183 m)-deep shaft, an 11,500-foot (3,505 m)-long power tunnel, a 140-foot (43 m)-long penstock, and a powerhouse with a single generating unit. The approximate plan dimensions of the powerhouse are 43 feet (13.1 m) by 43 feet. The powerhouse is located in a stream channel, on the toe of a landslide. Landslide stabilization activities are discussed in another paper (Klein and Hughes 1992). The subsurface materials are a heterogeneous mixture of cobbles and boulders in a sandy to clayey matrix. Boulders up to 5 to 10 feet (1.5 to 3 m) in diameter are present, and it was believed likely that open voids were present among them. There was a concern that post-construction differential settlement could occur in these deposits, with potentially adverse consequences to the operation of the turbine. Other concerns included a potential for scour by high streamflows, removal of materials beneath the powerhouse by underflow, and loss of bearing capacity due to migration of fines into the interstices between boulders. Construction of a deep foundation system using minipiles to transfer the loads directly to rock was one of two alternatives solutions considered. The second alternative was to improve the underlying materials by grouting so that a mat foundation could be used. The grouting alternative was selected due to its ability to provide scour protection as well as foundation support.

The grouting program included the following elements: (1) construction of a two-line grout curtain to minimize stream underflow and to prevent contamination of the stream by grout; (2) filling of major voids and consolidation of finer-grained materials by displacement and compaction grouting; (3) cementation of sand and gravel deposits by controlled hydrofracture grouting; and (4) consolidation grouting of the landslide materials immediately upslope from the powerhouse. A total of 13,906 cubic feet (394 m^3) of grout was injected into 151 borings drilled to an aggregate depth of 6,067 feet (1,849 m). The grouting program was done in two phases, so as to allow work on stabilization of the adjacent slope to proceed. The grout hole layout is shown on Figure 1.

DRILLING EQUIPMENT

All grout holes were drilled using a Klemm KR 806, track-mounted, hydraulically operated, double-head, overburden drilling unit. The holes were advanced with a down-the-hole (DTH) hammer using a casing crown bit and an inner bit. The inner drill string, which was fitted with the DTH hammer, and the outer casing were advanced simultaneously to completion depth. The 5½-inch (14 cm) crown bit was then popped off and the inner drillstring removed, leaving a cased open hole. All holes extended approximately 10 feet (3 m) into bedrock, with the objective of minimizing the likelihood of ending the hole in stream channel deposits. The casing provided a conduit for compaction grout injection as well as a means to install sleeve tubes for the injection of chemical and cement slurry grouts.

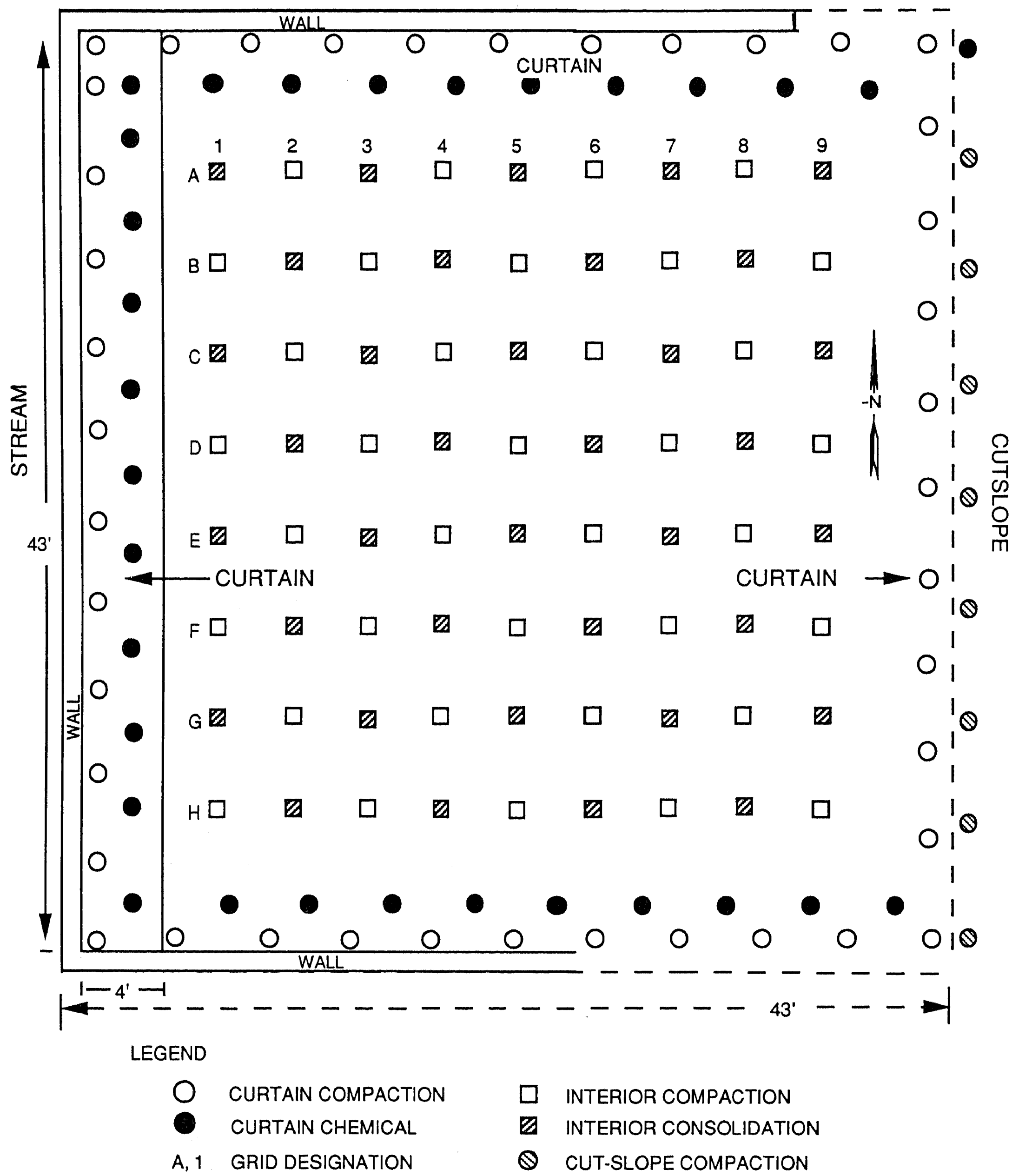

Figure 1. GROUT HOLE LAYOUT

GROUTING EQUIPMENT

The compaction (displacement) grout holes were grouted using a DGS 2015 positive displacement piston pump with a ¼-cubic-foot (7,070 cm^3) capacity per stroke. The grouting material, consisting of silty sand and Type II portland cement, was contained in separate chambers in a hopper truck fitted with a conveyor belt for delivery of the soil and a gravity-feed dispenser for delivery of the cement to an open screw-type mixing auger attached to the rear of the truck. Water sufficient to achieve the desired slump was added to the dry components at the base of the auger. This same system was used to blend and pre-mix the slurry grout components prior to secondary mixing in a high-speed mixer. The chemical/microfine grouts and the slurry grouts were injected using a positive displacement pump that delivered 1 cubic foot (28 l) of grout per 75 pump strokes.

CURTAIN GROUTING

A double-row grout curtain, with holes on 4-foot (1.2 m) centers, was constructed around the perimeter of the powerhouse site. This curtain had two purposes: the immediate purpose of preventing grout injected beneath the foundation from entering the stream, and the long-term objective of minimizing underflow beneath the site. The grouting sequence employed a split-spacing method, whereby primary holes were grouted prior to injecting grout in any secondary hole. The grouted interval included all loose material between bedrock and about 1 meter below the foundation slab. No evidence of underflow or grout loss was observed during subsequent drilling and grouting, when the stream level was substantially higher. The curtain holes included 41 displacement/compaction grout holes, and 29 chemical/microfine grout holes. Twenty-two of the displacement/compaction holes and 21 of the chemical/microfine grout holes were drilled from the top of a concrete construction slab to bedrock, which was encountered at an average depth of about 28.5 feet (8.7 m). The remaining 19 displacement/compaction and 8 curtain chemical/microfine grout curtain holes were drilled through a temporary fill placed to raise the grade above the creek level. This fill added approximately 8 feet (2.4 m) to the average completion and bedrock depths.

Outer Curtain

A No. 10 (32 mm) deformed steel threadbar was socketed approximately 10 feet (3 m) into bedrock in each of the outer curtain holes along three sides of the perimeter, with the objective of securing the grouted alluvial and landslide mass in place. The outer curtain was constructed with a viscous soil-cement mortar mix, with Type II portland cement consisting of at least 12% of the total weight. In general, sufficient water was added to achieve a 0- to 2-inch (0 to 5 cm) slump. However, slumps up to 6 inches (15 cm) were used initially with the intent of permeating the interstices of boulder gravels suspected to be present at the bottom of the channel. The viscous grout was injected as the casing was removed in approximately 1/3-meter "pulls." The minimum injection pressure was approximately 10 psi per foot (226 kPa/m) of casing depth; this minimum was routinely exceeded in order to initiate movement of grout into the ground and to verify refusal. The grout acceptance in each hole typically was less than 100 ft^3 ($2.8 m^3$). However, inferentially as the result of intersecting voids between boulders, six intervals in five holes each accepted more than 100 ft^3 (2.8 m^3) of grout, and one hole accepted more than 800 ft^3 (22.5 m^3) of grout. The aggregate length of displacement-grouted curtain holes was 1,758 feet (535 m^3), and the total volume of soil-cement grout injected in these holes was 5,638 ft^3 (159 m^3).

Inner Curtain

Grout consisting of a sodium silicate/microfine cement mixture was injected into interior perimeter curtain holes on the north, south and west sides only. These holes were offset midway between the compaction grout holes, and about 4 feet (1.2 m) from the exterior row of holes. The two-part grout mix contained a 3-to-1 mixture (by weight) of water and microfine cement combined with sodium silicate solutions, which was no less than 60% of the mix by volume. Dispersant was mixed with the water, at a ratio of 1% by weight of cement, prior to the addition of microfine cement. The microfine slurry and the sodium silicate grout were mixed and pumped separately, and were blended just before entering the ground. The mixture produced a set time of 3 to 5 minutes. This grout was injected through protected ports (one every 1/3 meter) in sleeve pipes that had been grouted in place during casing removal. After the annular grout had set, grout was sequentially injected through each sleeve port, using an interval packer. Following a finding that no grout could be injected at the planned pressure of 30 psi (210 kPa), injection pressures in the range of 180 to 210 psi (1,240 to 1,450 kPa) were used to inject a maximum of 3 cubic feet (0.1 m^3) per 1/3 m stage. The injection rates typically were in the range of 23 to 26 liters per minute. The aggregate total length of inner curtain grout holes was 1,131 feet (345 m), and the total volume of grout injected was 1,883 cubic feet (53 m^3).

INTERIOR CONSOLIDATION GROUTING

Consolidation grouting was done beneath the powerhouse site following completion of the curtain grouting. This included compaction grouting to densify the soils, improving the bearing capacity; and slurry grouting to cement the alluvium together, reducing its permeability and susceptibility to erosion. The consolidation grouting was done in a geometric pattern that included 36 compaction grout holes and 36 slurry grout holes. All injections employed a split-spacing method. All interior compaction drilling and grouting was completed prior to drilling and grouting any slurry grout holes. All drilling and grouting of consolidation holes was accomplished from the cofferdam elevation, 8 feet (2.4 m) above the slab top.

Compaction Grouting

The compaction grouting employed the same materials, methods and pressures that were used in construction of the exterior row of curtain grout holes, maintaining a slump no greater than 2 inches (5 cm). However, no threadbars were installed. The aggregate boring depths and grout takes for the interior compaction holes were 1,455 feet (433 m) and 4,263 cubic feet (121 m^3) respectively. The distribution of compaction grout takes is shown in Figure 2.

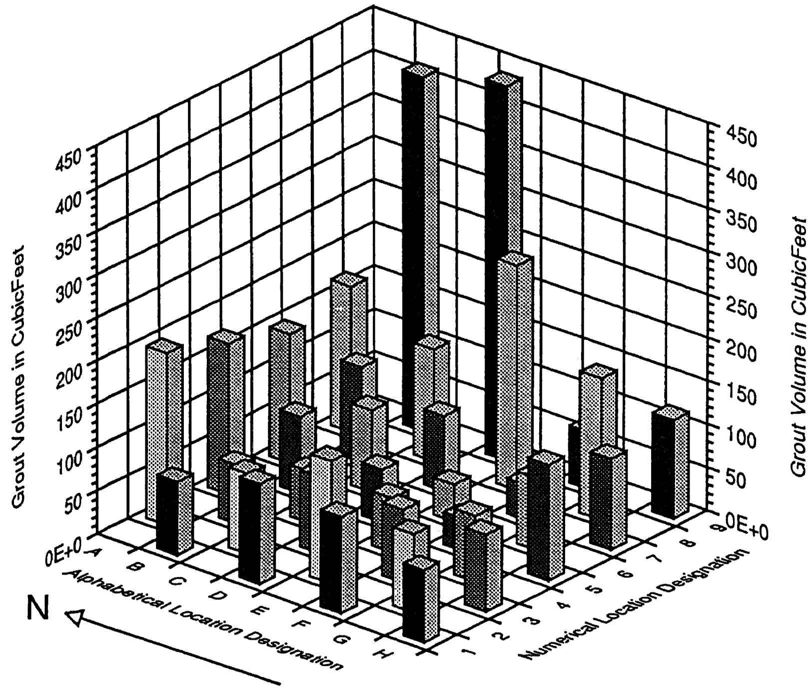

Figure 2. DISTRIBUTION OF COMPACTION GROUT TAKES

Hydrofracture/Permeation Grouting

The compaction grouting was followed by injection of slurry grout at sufficiently high pressures to induce hydrofracture, as was done with the inner curtain grouting. The pressures used for the portland cement slurry typically were in the range of 600 to 650 psi (4,140 to 4,490 kPa); those used for the microfine cement grout were in the range of 200 to 250 psi (1,380 to 1,730 kPa). The objectives of use of hydrofracture procedures were to facilitate movement of the grout to open zones or coarse-grained deposits that could be permeated, to create layers of grout that would prevent vertical movement of fine-grained sediments, and to create a boxwork of grout that would impede underflow. The slurry grout holes were placed at locations intermediate to those of the compaction grout holes. Two types of slurry grout were used in the powerhouse interior consolidation grouting operation, a Type III cement slurry containing silica fume (10 to 15% by weight of cement) and sufficient water and dispersant to achieve an average Marsh viscosity of 38 seconds, and a 3-to-1 (water/microfine by weight) microfine cement slurry. Each slurry hole was injected first with the Type III cement slurry, and next with the microfine cement slurry. The grouting was done by successive, sequential injections through sleeve tubes. The grouted interval included all loose material between bedrock, at an average depth of 9 meters, and about 1/3 meter below the foundation slab. The aggregate boring depth for the interior consolidation grouting was 1,450 feet (442 m). The total Type III cement slurry grout injected was 1,230 ft^3 (34.6 m^3) and the total microfine cement slurry grout injected was 699 ft^3 (19.7 m^3).

CUT SLOPE CONSOLIDATION GROUTING

Consolidation of the lower part of the powerhouse cut slope was accomplished by eight compaction grout holes and one chemical grout hole. All holes were inclined 20 degrees (from vertical) into the slope and were 20 feet (6.1 m) deep. The aggregate boring footage was 180 feet (55 m) for nine holes. The aggregate compaction and chemical grout take was 444 and 23 cubic feet (12.6 and 0.7 m^3), respectively.

VERIFICATION TESTS

Two inclined verification test core borings were drilled following completion of the grouting program. Thirteen water pressure tests were performed in these borings. The average core recovery was approximately 60%. Due to the relatively low-strength nature of soil-cement mortar grout the core consisted principally of boulders of alluvial or colluvial debris origin. Thirteen water pressure tests were run, six in the east-west boring and seven in the north-south boring. Generally, the maximum test pressures were about

75% of the overburden pressure and were carried out in three pressure stages: (1) 50% of the test pressure, (2) the test pressure, and (3) 50% of the test pressure. All of the water takes were less than 3 to 4 gal/min, except for one test in which an excessive pressure was inadvertently used.

CONCLUSIONS

The grout takes, injection pressures, our observations during grouting, the results of foundation core hole water pressure tests, and post-construction performance indicate that the design objectives were successfully achieved.

ACKNOWLEDGEMENTS

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