Design of the Trinity Dam, an Earthfill Structure 537 Feet High

Projet du Trinity Dam, barrage en terre d'une hauteur de 537 pieds

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Summary

The requirements for additional water in the Central Valley Project, California, initiated the proposal for the Trinity River Division of which the Trinity Dam is the major feature. The geology of the region and the local damsite geology are described.
The field investigation of the foundation and of available construction material in the vicinity disclosed several interesting and unusual conditions. In addition to routine laboratory testing, special laboratory investigations were made to resolve problems that arose prior to final design.
The foundation treatment and zoning of the embankment of this high structure are discussed.
Special instrumentation to measure pore-water pressure and vertical and horizontal internal strains were installed.
Information on the progress of construction through 1959 is given.

Sommaire

Les besoins d'eau supplémentaire pour l'équipement de la Vallée Centrale de Californie ont donné lieu à un projet établi par la Division de la Rivière de Trinity dont le barrage de Trinity est l'élément principal. La géologie de la région, et celle locale du site du barrage, sont décrites dans ce rapport.
L'étude sur place de la fondation et celle des matériaux de construction disponibles dans le voisinage ont fait apparaître diverses conditions intéressantes et peu habituelles.
Outre les essais courants, des recherches particulières de laboratoire ont été exécutées pour résoudre les problèmes qui sont apparus avant de commencer le projet final.
Le projet de la fondation et des zones du remblai de cet ouvrage élevé a aussi été examiné.
Des dispositifs spéciaux pour la mesure de la pression interstitielle et les déformations internes verticales et horizontales ont été installés.
Un renseignement est donné sur le progrès de la construction durant l'année 1959.

Introduction-Trinity Dam

The Bureau of Reclamation's highest earthfill dam is located in the Klamath Mountains of northern California, about 8 miles north of the town of Lewiston. The damsite vicinity and drainage basin is a sparsely populated region largely supported by mining, lumber, and tourist activities. The altitude ranges from 2,000 to 8,000 feet. The average annual precipitation increases with altitude from 40 inches near the damsite to 80 inches in the high country with 75 per cent in all areas occurring in the months of February through June.

Trinity Dam will store water in a 2,500,000 acre-foot reservoir for release through a 100,000-kilowatt powerplant and subsequent transmoutain diversion to California's Central Valley Project.

The dam fill will be 537 feet high, 2,450 feet long at the crest, and contain 30 million yards. The construction of dam, spillway, and outlet features was begun in March 1957, and is scheduled for completion by March 1962, at a contract price of $48,928,100.50.

Aside from those considerations due to Trinity Dam's unprecedented height, interesting aspects of the design include abutment slope stabilization and foundation treatment procedures required by the geologic situation and utilization of some unusual overburden materials in the construction of the fill.

The purpose of this paper is to provide a general description of foundation and embankment material problems as they were known to the designers. The corresponding solutions adopted for the specifications design are given and construction developments to date (January 1960) are noted.

General Geology

Since the site lies in one of California's gold producing lode and placer mining districts considerable information on the geologic situation was readily available [4]. Bedrocks of the region were known to include seven metamorphic crystalline formations intruded by igneous rock. Most rock of these formations have been deformed several times being, in general, strengthened rather than weakened in the process. Except at higher elevations in glaciated regions and at stream level in the canyons most bedrock types are deeply weathered to depths of several hundred feet. Usually hard non-granitic bedrock types are covered from top to bottom by graduated zones of (1) residual clayey soil, (2) partly decomposed rock preserving structures and textures of parent materials, (3) mingled weathered and hard rock, and (4) fresh rock with weathered joints. Granitic rocks are commonly covered with zones of residual sands having a fairly high water bearing capacity. In addition to these residual soils unconsolidated surficial deposits include a fan and flood plain of eocene age consisting of partly decomposed gravels, sands, shales, and lignite; redeposited soil in the form of accumulated debris on lower canyon slopes; and recent stream and glacial deposits. Landslides on lower canyon slopes are a common feature of the district because the walls along most streams are oversteepened. The landslides are generally shallow and sliding apparently takes place on several spoon shaped surfaces in the upper part of the slide and as a mud flow in the lower part.

Many of the alluvial deposits have been dredged or mined for gold. Streambeds of the area are choked with windrows of dredger tailings which have recently become important sources of construction materials.

Damsite Geology

In the stretch of the Trinity River Canyon selected for the damsite, detailed geologic data were accumulated. By the time specifications for the dam were issued some 130 drill and auger holes, 25 test pits, and resistivity and seismic surveys had been completed in the foundation area.

Two bedrock metamorphic formations were found to underlie the site. The riverbed and the major fraction of the canyon walls are cut in the Copley metaandesite formation. This rock is the greenstone widely exposed in the Klamath Mountains and in the Trinity River Canyon walls. It is a hard crystalline rock resulting from low-grade metamorphism of basaltic and andesitic lavas, tuffs, breccias, and feeder dikes. The rock itself in an unweathered, unaltered form would be highly competent, as a foundation but at the damsite it is extensively fractured, sheared, faulted, and weathered so that its basic characteristics no longer have a bearing on its competence as a foundation. Soundness is quite variable over the foundation depending on the degree of alteration that has taken place.

Minor fractions of the abutments and higher canyon walls are cut through the Bragdon formation. It consists of siliceous and graphitic shales, sandstones, and conglomerates. The shales are brittle, thin bedded and hard when siliceous; and weak, broken, and very fissile when graphitic. The conglomerates and sandstones, roughly 25 percent of the formation, are hard, tough to brittle, and generally thin bedded.

Materials overlying bedrock include (1) dredged and undredged streambed gravels averaging 30 feet in depth and covering narrow waterworn channels or plunge basins that cut into rock to twice that depth, (2) areas of landslide detritus and slope wash resting at stream level and partially overlying the streambed gravels, (3) intermittent areas of landslide detritus and weathered rock blanketing oversteepened canyon walls to depth of several hundred feet and representing active of potential slide areas, and (4) weathered rock in place.

Dam Location

By moving the dam axis, designers could found the structure on Copley or varying combinations of Copley and Bragdon formations. The axis location entirely on Copley was selected because a ridge of relatively competent greenstone was found perpendicular to the river near the proposed centerline; overburden was thicker over the Bragdon; suspected fault zones at the Copley-Bragdon contact could be avoided; and topography favored the outlet and spillway tunnel alinements.

Foundation Treatment

Dredged and undredged stream gravels in the amount of 1,500,000 cubic yards filled a 300-foot channel for the full width of the dam. The third of this deposit which underlies the impervious core had to be removed to permit bonding the water barrier with the rock foundation. Considering the remaining two-thirds, which underlay the outer shells, test pits disclosed appreciable silty gravel deposits intermixed with the pervious gravel. The silty materials were present in both undredged material, possibly due to secondary effects of slope wash and landslide activity, and in dredged material, due to the segregating effect of the dredging operation. Compared with the strength characteristics of the proposed shell fill material and with the values used in the stability analyses, these silty gravel deposits were submarginal. To be assured that all these low-strength areas were eliminated, it was considered necessary to remove all the streambed gravels down to the general rock surface. However, dental cleanup of pockets, plunge basins, and the narrow inner gorge was limited to a band under the core.

Another area requiring extensive excavations is the foundation of the fill on the right abutment upstream (see Fig. 1). This appeared to be a slump or landslide deposit partially displacing and overriding streambed gravels. The base of these debris, at and below stream level, was a soft, silty, gravelly, clayey mass. The top back slope of the slide was backfilled with a loose rubble. About 1,000,000 yards of excavation was required to remove this slump deposit.

A second similar but more extensive landslide area was identified on the left abutment, downstream. Though beyond the limits of the dam, further movement of the mass would endanger the spillway stilling basin. Since the material composing this slide mass was found suitable and economically desirable for use in the embankment, it was decided to unload the slide rather than relocate the spillway. Two million two hundred thousand cubic yards of excavation was estimated to stabilize the area.

The toe of a third potential slump mass is present under the upper half of the left abutment foundation. This bank of debris showed no sign of recent movement and would appear to be buttressed by the dam embankment. Since maximum distress would occur during construction, it was decided to apply remedial measures here if and when they proved necessary as construction progressed.

The remaining fraction of the foundation excavation item, some 1,000,000 yards, consisted of removing the layer of residual clayey soil and decomposed rock covering sound greenstone. The criteria for this stripping was that excavation should reach a material at least as dense as the compacted fill that would replace it. In practice this horizon was found to correspond with the limit of excavation for scraper type equipment.

Construction Foundation Developments

As uncovered during construction, the dam foundation generally conformed with the situation contemplated by the designers. The fractured and sheared condition of the rock was found to be quite variable over the area and with depth. This condition seemed to be divided in broad bands more or less normal to the direction of streamflow and at fairly steep angles, in some places dipping upstream and some places downstream. Superimposed on this condition was a zone of weathering which extends to greater depths the higher one goes up the abutment. The result is a fairly good foundation of hard rock in the valley bottom and over the lower quarter of the abutments. Beyond that level it was not practical to expose rock of equivalent quality for the dam foundation. However, a rather broad band of more competent or less fractured rock that forms a ridge does provide a place to anchor the impervious section of the dam on the right abutment.

A similar mass on the left abutment was found to be traversed diagonally by a gully about 100 feet wide. Judging by exposures in excavations for the spillway and outlet structures this gully is a remnant of some ancient channel that has become backfilled with slumped material, talus, and slides. It would have been desirable to clean out this gully to a condition recognizable as rock in place; however, construction operations and heavy rains during the fall and

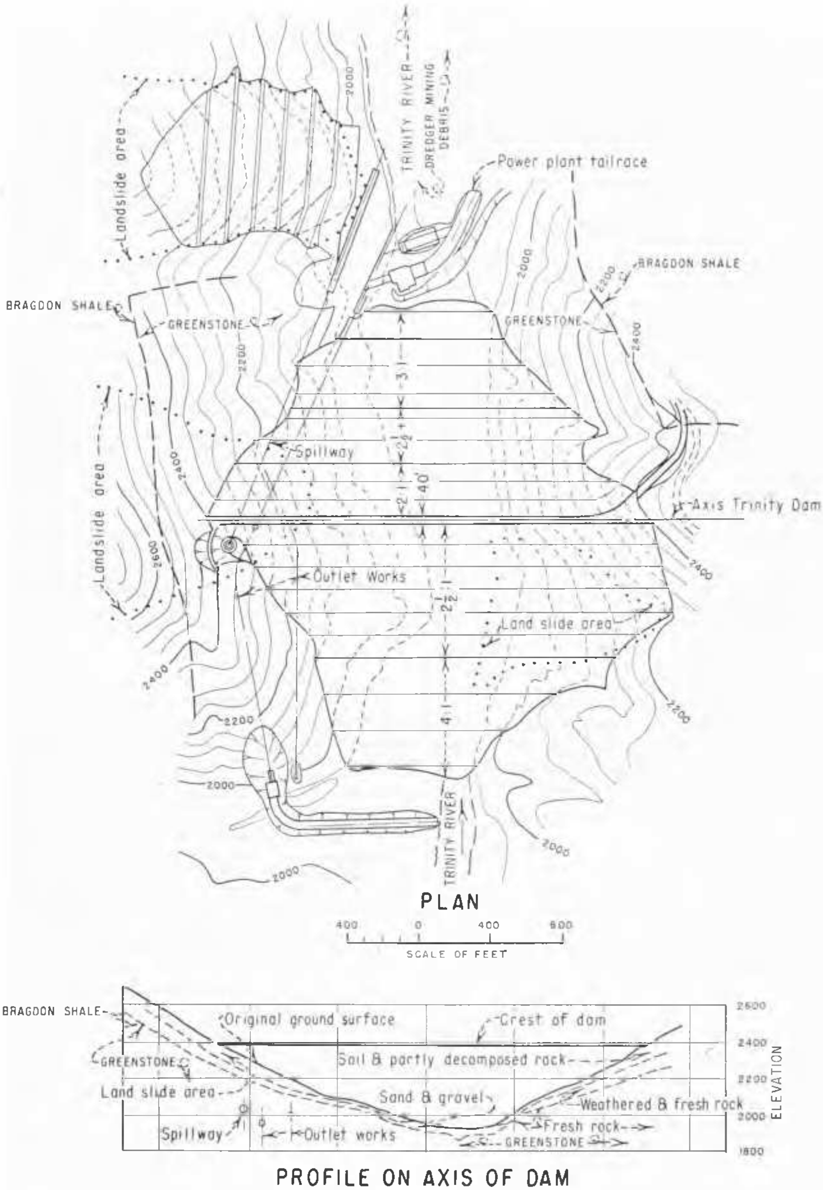
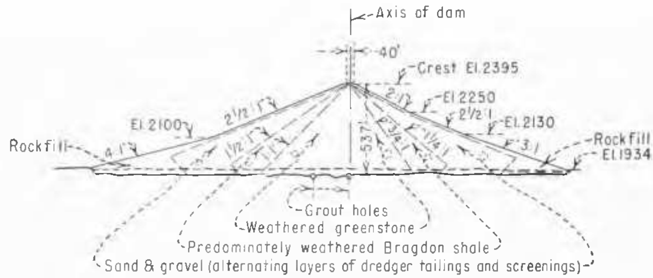


Fig. 1 Plan and Profile on axis of dam.
Plan et coupe suivant l'axe du barrage.



MAXIMUM SECTION

REQUIRED EXCAVATION

PURPOSE	VOLUME IN CUBIC YARDS					
	TOTAL	CLASSIFICATION OF MATERIAL				
		UNCLASSIFIED ②	W. BRAGDON SHALE	SAND & GRAVEL	ROCK	WASTE
Foundation-structures	500,000	170,000		100,000	130,000	100,000
Foundation-Embankment	3,300,000	1,100,000		1,650,000		550,000
Stripping rock quarry	550,000	550,000				
Tailrace channel	7,300,000			7,200,000		100,000
Abutment stabilization ①	2,200,000		1,900,000			300,000
TOTALS	13,850,000	1,820,000	1,900,000	8,950,000	130,000	1,050,000

① Grading landslide area left of spillway stilling basin

② Mixtures of weathered and fresh rock fragments of Bragdon and Copley greenstone formations

PROPERTIES OF AVAILABLE MATERIAL

SOURCE	GRADATION				UNIFIED SOIL CLASSIFICATION	① SPECIFIC GRAVITY	① DRY DENSITY lbs. per cu.ft.	① OPTIMUM WATER CONTENT - percent	NATURAL WATER CONTENT - percent	ANGLE OF INTERNAL FRICTION - TAN φ	COHESION - optimum PSI	① COHESION - saturated PSI	① PERMEABILITY K - ft. per yr	① VOL. CHANGE - CONFINED COMP - % - 300 PSI
	-.005 mm	.005 mm to No.200	No 200 to No 4	No 4 to 3"										
WEAVERVILLE (decomposed gravels of eocene age)	28	33	20	19	MH	2.88	83.7	33.6	40	0.46①	16①	3.5	0.4	12
BRAGDON SHALE (borrow area)	28	47	18	7	ML	2.73	107.2	18	15.2	0.52①	16 ①	0.6	0.4	8.8
BRAGDON SHALE (land slide area)	18	14	18	50	GC	2.72	111.1	16.4		0.64	15	1.6	0.35	5.7
COPLEY (greenstone)	7	18	39	36	SM-SC	2.69	110.8	16.5	12.5	0.54①	13 ①	1.0	0.1	8.3
SAND-GRAVEL (undredged)	4	8	31	57										
SAND-GRAVEL (dredged)	3	6	21	70									138	

① Based on minus No.4 fraction

Fig. 2 Maximum section, Required Excavation, and Properties of Available Material.
Section maximum, excavation nécessaire. Propriétés des matériaux disponibles.

winter of 1958-59 appeared to trigger the slump area lying over and above the gully. Some signs of distress and movement were noted. Movement was arrested during the summer of 1959, but to prevent further slumping during the wet season of 1959-60 it was decided to minimize excavation in the gully area and construct buttress fills in advance of the anticipated rate of fill placement to support the toe of the slump. As a result, foundation treatment in this area is expected to consist of a combination of cutoff trenches and consolidation grouting over a band of rock about 100 feet wide adjacent to the centerline of the dam.

Aside from the gully area a nominal grouting program was sufficient to seal the rock. Special compaction at the rock-impervious fill contact was used in the lower parts of the foundation; however, near the crest of the dam the rock abutments become so soft that an operation consisting of a combination of step cutting and rolling such as is used for earthen abutments may prove more effective.

Construction Materials

A nominal embankment of the specified height at the Trinity site would require 30 to 40 million yards of fill. Of this total quantity, up to 40 per cent or about 14 million yards would be available from required foundation excavations and channel improvements provided the excavations were acceptable as fill materials. A tabulation of classes and quantities of material expected from required excavation is shown on Fig. 2. The difference, a quantity in excess of 18 million yards, must be borrowed.

Embankment construction materials available within a reasonable haul distance were residual soils from Weaverville, Bragdon, and Copley formations; dredged and undredged streambed deposits; and quarried rock. General engineering properties of these materials are listed in Fig. 2. [2].

Embankment Zoning

Owing to the enormous volumes involved, an extensive series of tests and studies were undertaken to determine the most economical combination and arrangement of required excavations and borrowed material that would form a stable water barrier. In addition to the usual soil tests, the unusual nature of the materials [2, 3] and the great height of the dam prompted numerous special investigations. These included detailed petrographic examination, tests to determine change of properties on air drying, large cylinder compaction tests and modifications in triaxial testing. Stability studies and economic analyses were accomplished for numerous zoning schemes. Considering the project as a whole these analyses indicated the cost of a steep sloped, narrow, zoned dam of selected materials to be less than one composed of fills of intermediate quality and with correspondingly extended toes and spillway outlet tunnels. Considering the embankment proper, the tests, studies, and material availability led to utilizing a core of residual soils supported by shells of gravel and rock.

Impervious Core

Of the three soils suitable for the water barrier, soil properties (see Fig. 2) and geographical position established weathered Bragdon or Copley formations as more desirable impervious materials than Weaverville. The soil from potential borrow areas in weathered Bragdon and Copley formations had very similar density, moisture, compressibility, and shear properties on the basis of their minus No. 4 fractions. Practical construction considerations indicated the cost of dam fills from either source would be approximately equal. Of the two, weathered Copley was selected because tests indicated it could be expected to break down into a more desirable coarse grained soil under standard compaction procedures. Bragdon soil available from the left abutment slide area adjacent to the spillway was not strictly comparable with that from the proposed Bragdon borrow area in that it contains numerous irregular deposits of less weathered material and rock fragments. It was rejected as a source of core material because "pit run" excavations to the grade specified to stabilize the area did not seem to permit the degree of selection expected for the core of a 537-foot-high dam. The fact that "pit run" material from this source could still be used in other parts of the dam was a further consideration.

Outer Shells

Selected high-strength pervious materials are placed in the exterior zones to minimize the overall base width of the dam. Rockfills are used in the toes across the valley bottom where sound rock was expected to be exposed by foundation excavation. The remainder of the shell is composed of dredged and undredged streambed gravels from required excavations and borrow areas. The gravel fill is unusual in that, rather than being the normal homogeneous pervious fill, it consists of horizontal 18-inch layers of highly pervious gravels separated by 12-inch layers of semipervious material. This laminated construction is an indirect result of the gold dredging activity which covered the major fraction of the gravel deposits of the region. One effect of the bucket-ladder-type gold dredge used was to partially separate the materials into fine silty sands (screenings), redeposited in the bottom of the dredge cut, and overlain by piles of gravel and cobbles (tailings). Bureau experience has indicated that saturated sand and gravel containing the percent of fines present in the dredger "screenings" might develop soft spots and spongy areas under tractor compaction on the fill. If so, this might require stockpiling and drying, or wasting, about 2,500,000 cubic yards of required "under water" excavation. To avoid this expense or waste, designers decided to try using the high porosity of the tailings to provide the drainage necessary to permit consolidation of saturated screenings by tractor compaction. Alternating 18-inch and 12-inch layers were the dimensions adopted for trial. If successful, this sandwich procedure would also permit use of a substantial volume of saturated undredged material high in silt content that must otherwise be wasted.

Intermediate Zones

Materials produced by required excavation may include 3,720,000 cubic yards of relatively high-strength core-type material containing proportions and sizes of rock incompatible with the impermeability and compaction desired for the water barrier (see Fig. 2). On the other hand, they include excessive fines for sluicing and tractor compaction in the shell.

A final analysis of the proposed section disclosed that this material could be substituted for core and shell materials in a zone at the proposed core and shell boundaries, thereby reducing the proportions of each that must be borrowed. Compaction would be by rollers, but to 12-inch lifts, as a concession to the rock sizes the material contained.

With the addition of the intermediate zones, all required excavation was accommodated in the fill except stripping containing organic matter, saturated impervious material, muck, and low-density deposits.

Instrumentation

Due to the unprecedented size of Trinity Dam and the use of residual soils in the core, a relatively complex system of instrumentation was adopted to gage the performance of the fill. The instruments include: (1) 72 twin-tube piezometers to determine pore-fluid pressures within the embankment; (2) 5 internal vertical movement devices to observe strain in a vertical direction; (3) 9 internal horizontal movement devices to observe strain in a horizontal direction; and (4) 55 surface settlement points to indicate movement of the outer slope.

The horizontal movement devices are the first of their kind installed by the Bureau.

This instrumentation layout will provide a means of obtaining a continuous performance record of the embankment during construction as well as during operation.

Fill Construction Developments

The construction methods and compactive effort proposed for processing impervious core material from residual Copley metaandesite rock were investigated by constructing two 70- by 300-foot by 3-foot-thick test sections. Experience and large scale settlement percolation tests indicated that a fill of suitable imperviousness would be obtained after 12 passes of the specified compaction roller with as much as 50 to 60 percent rock.

The contractor elected to convey the material to the dam by a conveyor belt operation. Material is excavated from various parts of the pit to obtain a blend with the highest practical rock percentage. Oversize is crushed and fed back into the mixture. The soil arrives at the terminal station of the conveyor system 2 to 5 percent dry of optimum moisture. Here, sufficient water is added to insure its arrival on the embankment at about 1 per cent dry of optimum. With the fill procedures employed by the contractor, fill densities are exceeding requirements with a moisture content about 1 per cent below laboratory optimum and with a plus No. 4 rock content of about 40 per cent.

Piezometer readings in the fill to date show materially less pore pressure than values estimated for use in preconstruction stability analyses.

In constructing the outer shell, dredger screenings and some undredged sand and gravel excavated from below the water table was very wet as placed in the 12-inch sandwich layers. Wet sandy silty material worked out into adjoining layers of tailings to the extent that there was some question concerning the perviousness of the entire fill. This situation was investigated by means of a 15-foot-deep test pit excavated in an area of the fill where particularly wet, dirty material had been placed. Both laboratory tests on pit wall samples and the time required for water dumped into the pit to drain away indicated that a fill of satisfactory porosity is being obtained by sandwich-type construction.

Conclusions

(1) Trinity Dam is being constructed on a complex foundation of deeply weathered and altered rock.

(2) Some abutment slope stability problems triggered by required foundation excavations are continuing into the construction phase. Their final solutions may not have yet been found.

(3) Trinity Dam is composed of residual soil, sand, and gravel, and rock zoned to utilize most of the required excavations.

(4) By placing a laminated shell of alternating layers of pervious and semipervious materials, millions of cubic yards of otherwise unusable materials are being incorporated into the dam to form fills of satisfactory overall porosity and strength.

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