SUSITNA HYDROELECTRIC PROJECT

TASK 6 - DESIGN DEVELOPMENT

SUBTASK 6.04

CLOSEOUT REPORT

EVALUATION OF ARCH DAM

AT DEVIL CANYON SITE

MARCH 1982

Prepared by:

ACRES

ALASKA POWER AUTHORITY

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1 - INTRODUCTION

Subtask 6.04 of Task 6 Design Development studies for the Susitna Hydroelectric Project is entitled "Evaluation of Arch Dam at Devil Canyon Site." The purpose of this subtask is to carry out a preliminary review of the technical feasibility of constructing a concrete arch dam at the site as a basis for continuation of design studies as part of the Susitna Project feasibility assessment.

1.1 - Background

Devil Canyon is located on the Susitna River approximately 100 miles upstream of Cook Inlet (see Figure 1.1). It was first identified as a potential hydroelectric development site by the U.S. Department of the Interior, Bureau of Reclamation (USBR) in the early 1950s. The site is situated within and close to the entrance of the canyon where the walls of the V-shaped gorge rise 500 feet above the river at which point they are approximately 900 feet apart.

The USBR proposed a 635 feet high single curvature thin arch dam at the site in 1961. As work proceeded on the project the Alaska Power Administration in their Devil Canyon Project status report of 1974 proposed a double curvature thin arch design and the Corps of Engineers proceeded with this design in their 1975 Interim Feasibility Study. In a review of the 1975 Interim Feasibility Study the U.S. Government Office of Management and Budget questioned the technical feasibility of an arch dam at the site and the economic feasibility of the project which had been based on the assumption that such a dam could be designed and constructed to meet acceptable criteria. In response, the Corps developed designs and estimates for a more conservative and costly gravity dam.

The scope of work under this subtask is essentially to review the designs previously undertaken not only for the Devil Canyon site but for comparable sites elsewhere in the world, and to consider the application of current state of the art design techniques for a dam at this site.

1.2 - Report Contents

Section 2 of this report is a summary of the studies performed and the conclusions reached. The scope of work is outlined in more detail in Section 3 and the results of a review of worldwide arch dam designs are presented in Section 4. Geotechnical and seismic design considerations are reviewed in Sections 5 and 6, respectively, and an evaluation of earlier Devil Canyon Dam designs is presented in Section 7. Preliminary design concepts and results are presented in Sections 8 and 9, and the conclusions arrived at from the study are given in Section 10.

2 - SUMMARY

2.1 - General

Under Subtask 6.04 a preliminary assessment was made of the feasibility of an arch dam at Devil Canyon and whether further study of this type of dam should be continued. The findings are summarized in the following subsections.

2.2 - Review of Arch Dam Precedents

A review of arch dams throughout the world, either constructed or in the process of construction, indicated that the proposed dam at Devil Canyon was within precedent in the aspects of physical size, anticipated foundation conditions and the seismicity of the region.

Several dams are higher than Devil Canyon and the crest length/height ratio is not exceptional.

Arch dams such as Pacoima in California and Vidraru-Arges in Rumania have undergone severe seismic shaking with minimal damage and an extreme example of the inherent stability of an arch dam is the Vaiont dam in northern Italy which suffered only minor damage to the crest when it was overtopped by a 400 foot high wave.

2.3 - Geotechnical Considerations

The determination of site suitability is based on existing surface mapping and subsurface investigations. The USBR initiated these investigations at Devil Canyon in 1957 with diamond core drilling and test pits. Further sampling has been done under the current program.

Previous studies suggested the existence of a shear zone in the left abutment. The 1980 drilling program has not proven the existence or non-existence of this feature. Although further investigation will be necessary to determine if a potential problem area exists, there are presently no data that make an arch dam infeasible at Devil Canyon.

2.4 - Seismic Considerations

Current studies are underway by Woodward-Clyde Consultants as part of Task 4 to assess the seismic design parameters for the Devil Canyon site. One lineament which will require further study has been identified approximately 10,000 feet upstream of the site. To date, ground motions and acceleration have not been determined for the Devil Canyon site. For preliminary design an earthquake acceleration of 0.5g has been assumed as corresponding to the maximum credible earthquake.

2.5 - Evaluation of Previous Designs

The first dam considered for the Devil Canyon site was a single curvature arch dam proposed by the USBR which was later modified to a double curvature thin arch dam. Subsequently, a concrete gravity dam was proposed to ascertain economic feasibility based on a conservative cost estimate for the Devil Canyon development. This does not imply that the arch dam was not technically feasible but rather that the arch dam's feasibility was not adequately proven.

A double curvature thin arch dam appears suitable for the valley section at the Devil Canyon site. The primary advantage of a thin arch is the efficiency of this type of design which requires a relatively small volume of concrete resulting in a consequent cost saving. Problems which may exist in a thin arch dam design include the following:

- The valley section at this site is not symmetrical which may lead to torsional stresses in the dam.

- Thin arch dams can transmit high stresses to the abutments; however, this can be moderated by abutment pads.

- Temperature extremes may reach as low as -50°F at the site, leading to high temperature stresses.

- Locating an adequate spillway for a thin arch dam may be difficult.

These factors may result in increased costs but are not foreseen as insurmountable.

The concrete gravity dam has certain advantages, as follows:

- An overflow spillway can be incorporated into the center section of the dam.

- Lower stress levels occur in the structure and at the abutments under non-seismic loading conditions.

Problems associated with the concrete gravity dam are as follows:

- The large mass of concrete will be considerably more expensive than for an arch dam, but this may be partly offset by savings in spillway costs.

- The shape of the gorge will result in a straight gravity dam behaving not as a gravity dam but rather as a three-dimensional structure supported at the abutments and base.

- The response due to earthquake motion in an upstream direction parallel to the river is generally much worse than for an arch dam.

2.6 - Draft Designs

Draft designs were laid out for two dams, a thin double curvature arch as proposed by the USBR and a thick or gravity arch developed for comparison.

2.7 - Stress Analysis

In order to make a preliminary assessment of dam stresses, a finite element analysis was carried out on the two dam types for selfweight, hydrostatic, temperature, and seismic load combinations. The mesh involved in establishing the stress modes is too coarse and does not give representative stresses at the abutments. Although a more detailed finite element analysis would be appropriate for final design, such an approach would not be cost-effective during design development and feasibility assessment. More appropriate models based on the trial load method of analysis should be used for these types of analyses.

2.8 - Conclusions

In general, a thin arch dam will be subject to greater internal stresses than a gravity arch indicating a degree of redundancy within the latter structure should the thin arch prove to be an acceptable design.

Within the limitations of the scope of this report both types of concrete arch dam appear feasible and should be studied further under Subtask 6.07. This conclusion is based on the following:

- The proposed arch dam is well within the bounds of previous experience relating to height, crest, length, and height to length ratio.

- Large seismic loadings have been experienced by arch dams with minimal damage.

- To date no information has been obtained from the subsurface investigations that would indicate that an arch dam is technically or economically infeasible at Devil Canyon.

3 - SCOPE OF WORK

3.1 - Objective

The objective of Subtask 6.04 is to make a preliminary assessment of the technical feasibility of an arch dam at the Devil Canyon site and to determine whether further study of this type of dam is warranted at this time.

3.2 - Approach

The technical and economic feasibility of constructing an arch dam at Devil Canyon will ultimately depend on a number of factors, many of which are not addressed under Subtask 6.04. Further studies under Subtask 6.08, Preliminary Devil Canyon Dam Alternatives, and Subtask 6.12, Preliminary Design Devil Canyon Dam, will address these factors in more detail and the alternatives to an arch dam, such as a rockfill dam. To meet the objective of Subtask 6.04, the work was organized to include:

- A review of arch dams throughout the world, either constructed or under construction, that are comparable in size and/or in site conditions to the proposed dam at Devil Canyon.

- An examination of all available geology and geotechnical data relating to the site including that available from previous investigations and from the present study.

- A review of known seismic conditions at the site.

- An evaluation of previous designs as proposed in the USBR and COE reports of 1961, 1974, 1975 and 1979.

- The development of preliminary designs for a gravity arch and a thin arch dam at the site.

- An initial determination of stress conditions for a preliminary dam design under gravity, hydrostatic and extreme temperature conditions and of dynamic stresses due to seismic shaking under initial conservative assumptions for the possible maximum credible earthquake event.

From the above reviews and studies an evaluation of the potential for construction of an arch dam was made.

4 - REVIEW OF ARCH DAM PRECEDENTS

4.1 - General

This review serves to place in context an arch dam design for Devil Canyon relative to other concrete dams around the world. Table 4.1 gives a list of several high arch dams with some of their key parameters readily available from a literature search. A graph showing the height of these dams plotted versus crest length is given in Figure 4.1. The following sections give general descriptions and highlights of special conditions at several of the world's highest arch dams.

4.2 - Inguri

The Inguri Dam located on the Inguri River in the USSR will have a height of 890 feet when completed in 1985. This will be the world's fourth highest dam and the highest arch dam. This double curvature arch dam will have a base thickness of 282 feet, a crest thickness of 33 feet and a crest length of over 2500 feet. A total of approximately 5,000,000 cubic yards of concrete will be used in the construction.

4.3 - Vaiont

The Vaiont Dam located in Italy has a height of 858 feet and a crest length of 624 feet. This is a double curvature arch and is one of the few dams that, due to the valley shape, has a crest length/height ratio of less than unity. In 1963, two years after completion of the dam, the face of a mountain (350 million cubic yards) slid into the reservoir resulting in a 400 foot-high wave overtopping the dam. The only structural damage was chipped concrete along the top three feet of the crest due to boulders carried by the wave over the dam.

4.4 - Chirkei

This Russian dam was completed in 1975 with a height of 764 feet and a crest length of 1109 feet. The thickness varies from 98 feet at the base to 21 feet at the crest. This is the fifth highest arch dam in the world.

4.5 - Hoover

Hoover Dam is a concrete gravity arch dam completed in 1936 and is still the highest concrete dam in the United States. It has a structural height of 726 feet, a length of 1244 feet, a base thickness of 660 feet and a crest thickness of 45 feet. The dam contains close to 4.5 million cubic yards of concrete. It is located between two faults 900 feet apart.

In the design development for Hoover Dam on the Arizona/Nevada border, the USBR did considerable research to clarify the structural behavior of the thin arch. In spite of this research the USBR chose a gravity dam. What would now be considered a conservative approach was justifiable at that time as the height of the dam was over twice as high as any previously constructed and therefore there was no experience of arch dams of a comparable size. Experience has been gained on arch dams constructed subsequently with greater heights and crest lengths than those of the Hoover Dam.

4.6 - Vidraru-Argues

Vidraru-Arges is a double curvature arch dam located in Rumania. The dam height is 548 feet, length is 958 feet, base thickness is 82 feet and crest thickness is 20 feet. In 1977 the Vrancea earthquake occurred in Rumania with a resulting earthquake intensity of 7-8 MSK (approximately 7.2 Richter) at the site. Design had been based on an earthquake with an intensity equal to 8 MSK. There was no damage suffered by the structure due to the earthquake.

A dynamic analysis was performed on the dam. The following periods corresponding to the first mode of vibration were determined:

Full Reservoir	- Along Valley Axis	- 0.51 sec.
	- Normal to Valley Axis	- 0.31 sec.
Reservoir 1/2 full		- 0.38 sec.

Tensile stresses were computed to be up to 1000 psi in the dam during the earthquake.

4.7 - Pacoima

The Pacoima Dam is a double curvature arch dam located in the San Fernando Valley of southern California with a height of 372 feet and a crest length of 589 feet.(4) The dam was built around 1930 without consideration of earthquake loads. In 1967-68 an investigation was carried out to determine the condition of the dam. Findings included the following:

- Compressive strength of the concrete was 4900 psi.

- No significant deterioration of the dam had occurred.

- Extensive jointing was found in the left abutment as well as shear zones along which instability could occur.

- Analysis showed the dam to be stable for an earthquake of 0.15 g.

The San Fernando earthquake with a magnitude of 6.6 on the Richter scale occurred in 1971. The epicenter was located approximately four miles from the dam and the focal depth was eight miles. The surface fault trace was five miles from the dam.

At the time of the earthquake, the Pacoima Dam was drawn down 145 feet to allow storage during the winter rainfall season. An accelerograph at the site measured horizontal accelerations of 1.25 g and vertical accelerations of 0.7 g. It was considered that the location of the accelerograph contributed to the abnormally high acceleration measurements and a more realistic figure would be 0.6 to 0.8 g for the base ground acceleration. Due to regional movements during the earthquake, the following permanent relative movements of the abutments were measured:

- The distance between abutments was shortened by 0.9 inches;
- The north end of the dam dropped 0.68 inches relative to the south end; and
- The dam axis was rotated 30 seconds relative to the base line.

Despite this severe earthquake, the only visible damage to the dam itself was the opening of the vertical radial contraction joint between the arch and the left abutment thrust block. The opening was between 0.25 and 0.38 inches wide and extended along the contraction joint and into the thrust block down to the abutment. Intersection with the abutment rock was approximately 50 feet below the crest.

Other damage consisted mainly of rock slides and minor rock falls on the abutments. One large area (approximately two acres) on the left abutment slumped approximately 13 inches. In several areas the gunite covering of the abutment rock was cracked.

Remedial work was performed to allow safe operation of the dam during the impending storm seasons. This consisted mainly of removal of or stabilization of rock crevasses loosened during the earthquake, repair to a portion of the grout curtain around the spillway, and temporarily patching the upstream opening of the crack in the dam itself. Permanent repairs were initiated after detailed investigation and analysis of the dam was complete, almost three years after the earthquake. They consisted of grouting the joint in the dam, further stabilizing the rock mass that had slumped, and foundation and abutment grouting which had been considered before the earthquake.

It should be noted that two hydraulic fill dams located in the San Fernando Valley suffered major slides, one on the upstream and one on the downstream slopes.

4.8 - El Cajon

The El Cajon dam presently being constructed in Honduras will be a double-curved thin concrete arch structure. Its height will be 741 feet and it will have a crest length of 1246 feet. The dam is founded in limestone and 3 known faults pass beneath the foundation area. The damsite is located in a seismically active area and the maximum credible earthquake is set at 7.5 on the Richter scale. The design-baseground acceleration for the dam is 0.32g.

4.9 - Auburn

The Auburn Dam was designed in the late 1960s and early 1970s by the USBR as a double curvature arch dam. It was to be the world's largest with a crest length of 4150 feet. The height was to be 685 feet with a base thickness of 200 feet and a crown thickness of 40 feet. Extensive foundation investigations were carried out during the design phase.

These investigations included several adits and shafts with large scale in-situ rock strength and deformation tests. The foundation is characterized by rock-type anomalies, numerous joints, shears and faults. A major fault system strikes approximately cross river with a dip of 50°.

Construction began on Auburn Dam in the early 1970's, but was halted after approximately $100 million had been spent on the foundations. This was primarily due to concern raised by the Association of Engineering Geologists over possible fault displacement. In the ensuing controversy over the seismic design criteria, opinions on possible fault displacement ranged from one inch as originally proposed by the USBR to over nine inches recommended by California's consultants.

The thin arch design was subsequently dropped from further consideration. In 1979 an extremely severe design criteria allowing five inches of fault displacement was adopted.

Currently, a curved gravity section is being considered which utilizes a portion of the existing foundations.

4.10 - Comparison with Devil Canyon

The approximate principal dimensions of a Devil Canyon arch dam, with a 635 foot height, 1,400 feet crest length and crest/height ratio of 2.2, (see Section 7), place the dam well within the field of experience established by other projects in relation to the physical size of the dam.

Large arch dams have been built in areas with apparently poorer foundations and in areas of high seismicity.

When compared with dams mentioned in this section and those itemized in Table 4.1, there appears no area in which a concrete arch dam at Devil Canyon would be establishing a precedent.

TABLE 4.1: LARGE CONCRETE DAMS

DAM	LOCATION	HEIGHT ft(m)	CREST LENGTH ft(m)	BASE THICK. ft(m)	MINIMUM THICK. ft(m)	VOLUME $yd^3(m^3)$	SEISMIC PARAMETERS	FOUNDATION	ABUTMENTS	REMARKS	CENT. ANGLE
Inguri (1985)	Georgia, USSR	892 (272)	2513 (766)	282 (85)	33 (10 m)	4,967,000 (3,800,000)				ENR Dec. 14, 1978 + Dave Shandalov Info Thin Arch	
Vaiont (1961)	Veneto, Italy	858 (262)	624 (190)			460,000 (352,000)				Overtopped by 400 ft high wave on Oct. 9, 1963. Minor chipping of the top 3 ft due to boulders was the only damage.	
Sayan-Shusen (1980)	Krasnoyarsk, USSR	794 (242)	3504 (1068)			11,916,000 (9,117,000)					
Mauvoisin (1957)	Valais, Switzerland	777 (237)	1706 (520)			2,655 (2,030)					
Chirkei (1975)	North Caucusas, USSR	764 (233)	1109 (338)	98 (30 m)	21 (6.5 m)	1,602,000 (1,226,000)					
El Cajon (1984)	Yoro/Cortes, Honduras	741 (226)	1246 (382)	157 (48)		1,924,000 (1,472,000)					
Hoover (1936)	Nevada, Arizona, U.S.A.	726 (221)	1244 (379)	660	45	4,400,000 (3,364,000)	Spaced between two faults about 900 ft apart			Gravity Arch	
Contra (1965)	Ticino, Switzerland	722 (220)	1246 (380)			861,000 (658,000)					
Mratinje (1976)	Montenegro, Yugoslavia	722 (220)	879 (268)			971,000 (742,000)					

TABLE 4.1 (Cont'd)

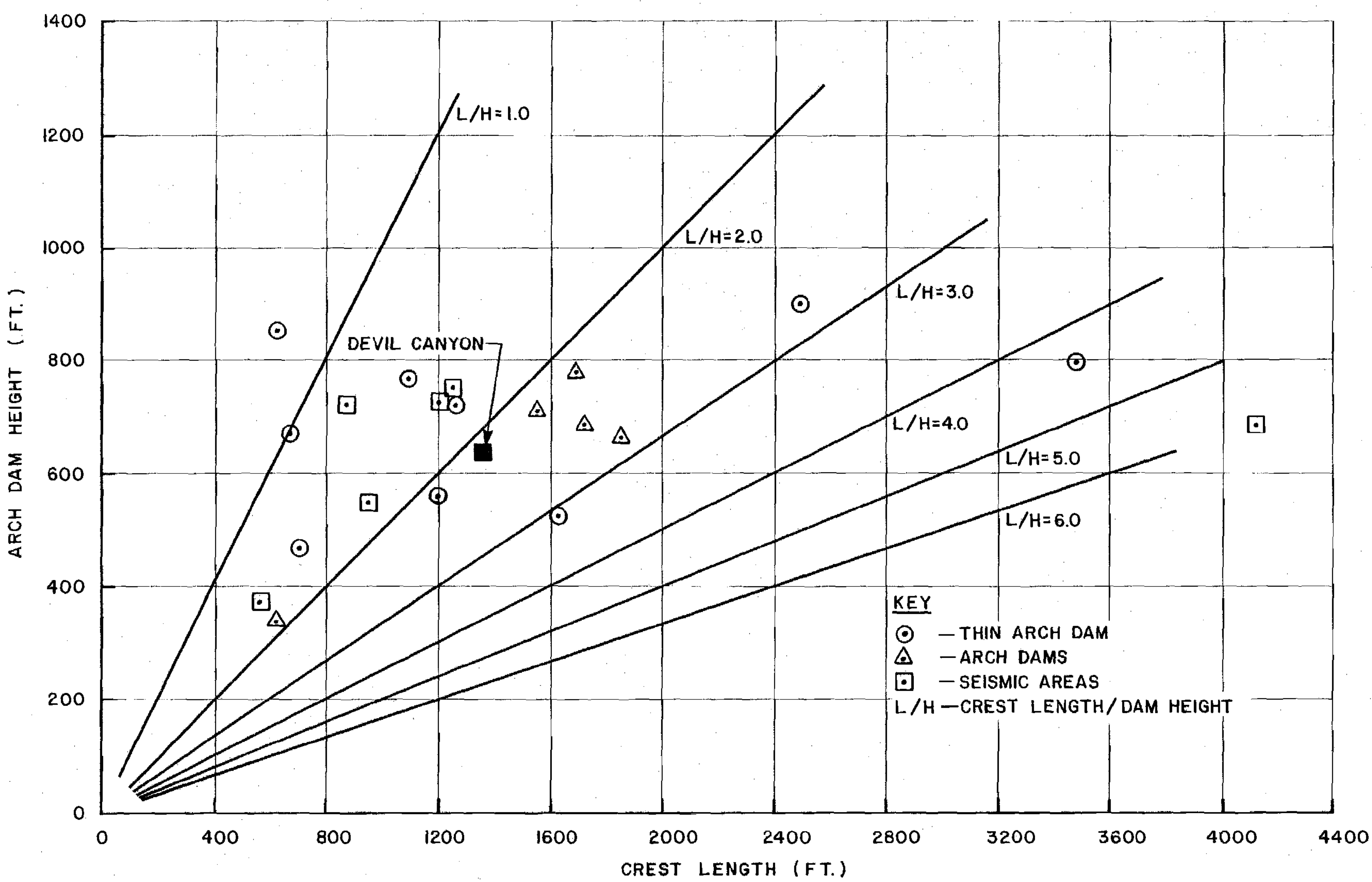
DAM	LOCATION	HEIGHT ft(m)	CREST LENGTH ft(m)	BASE THICK. ft(m)	MINIMUM THICK. ft(m)	VOLUME $yd^3(m^3)$	SEISMIC PARAMETERS	FOUNDATION	ABUTMENTS	REMARKS	CENT. ANGLE
Glen Canyon (1964)	Arizona, USA	710 (216)	1560 (475)			4,901,000 (3,747,000)					
Luzzone (1963)	Ticino, Switzerland	682 (208)	1738 (530)			1,739,000 (1,330,000)					
Mohamed Reza Shah Pahlavi (1963)	Khouzestan, Iran	666 (203)	696 (212)			647,000 (497,000)					
Almendra (1970)	Salmanca, Spain	662 (202)	1860 (567)			2,188,000 (1,673,000)					
Idikka	India	555	1220	80	25	613,000					
Vidraru-Arges	Rumania	548 (167)	588 (292)	82 (25.0)	20 (6.0)		Earthquake in 1977 with an intensity of 7-8 on the MSk scale at the site. 7 = 2.5% g 8 = 5% g. 9 = 10% g.			Measurements after the earthquake showed no odifications to normal behavior	
Gocekaya	Turkey	521 (159)	1620 (494)	74 (27.5)	20 (6)	933,000 (714,000)				Designed by EBASCO	107.4
Morrow Point	Colorado	465	720	51.65'	12.0	360,000	In design it is wood up a point				
Pacoima	California	372 (113)	589 (180)	99 (30.2)	10.4 (3.2)	220,000 (168,000)	Seven significant faults within 3.8 miles (6 kM) radias of the site.	Gneissic Quartz Joint sets divide rock into angular blocks of approximately 4'6"		- Built around 1930 - Constant angle arch - Earthquake loads not considered in design	

Table 4.1 (Cont'd)

DAM	LOCATION	HEIGHT ft(m)	CREST LENGTH ft(m)	BASE THICK. ft(m)	MINIMUM THICK. ft(m)	VOLUME $yd^3 (m^3)$	SEISMIC PARAMETERS	FOUNDATION	ABUTMENTS	REMARKS	CENT. ANGLE
							1952 - Earth-quake of 5.0 Rickter @ 15 mi. 1971 - San Fernando earthquake 6.6 Rickter @ 4 mi. (Horizontal Acc. 1.25 g, measured on abutment), Vertical Acc. 0.70 g base acceleration estimated at 0.6 to 0.8 g				
Crystal Dam	Nestren Colorado	340	620			145,000					
Green Lake Dam	Sitka, Alaska	210	460	16 ft.		26,000	Miximum Cred-ible earthquake Magnitude = 8 Richter @ 16 mi. Acceleration = 0.40 g. Duration = 45 sec. Design Earth-quake Magnitude = 8 Richter @ 33 mi. Acceleration = 0.23 g. Duration = 40 sec.	Competent massive graywacke			

TABLE 4.1 (Cont'd)

DAM	LOCATION	HEIGHT	CREST LENGTH	BASE THICK.	MINIMUM THICK.	VOLUME	SEISMIC PARAMETERS	FOUNDATION	ABUTMENTS	REMARKS	CENT. ANGLE
		ft(m)	ft(m)	ft(m)	ft(m)	$yd^3(m^3)$					
Auburn (Abaondoned Design	California	685	4150	200	40	6,300,000				3 circular acres	
										left 4000 ft rod	580' arc
										center 1400 ft rod	1810' arc
										right 4000 ft rod	1275' arc



ARCH DAM HEIGHT vs. CREST LENGTH

ACRES

FIGURE 4.1

5 - GEOTECHNICAL CONSIDERATIONS

5.1 - General

Evaluation of the feasibility of an arch dam is contingent upon the following considerations:

- Stability of the dam against sliding.

- Adequate abutment and foundation load bearing capacity with acceptable deformation.

- Stability of foundation and abutments under seismic loads.

- Potential leakage problems and extent of treatment required for foundation and abutments.

The implications of these factors on the feasibility of an arch dam at Devil Canyon are discussed in the following paragraphs.

5.2 - Site Geology

The Devil Canyon site is located in a broad U-shaped glacial valley, with an incised V-shaped gorge approximately 500 feet deep. The width-to-height ratio of the "V" section is approximately 2:1, presenting a favorable configuration for an arch dam central section, which would be flanked by a saddle dam on the left abutment. The bedrock is graywacke and argillite, with bedding striking E-W (oriented subparallel to the river). The dip of the beds is 50 to 70° to the south (left abutment), with three distinct joint sets. One set of joints is well developed and widely spaced. This set strikes approximately N25°W and dips 80 to 90°E. The other two sets are tight and less well developed. Drilling indicates that rock quality improves with depth.

Shear zones have been mapped both parallel and perpendicular to the river, and a major lineament has been mapped on the left abutment. This lineament could be a buried stream channel or a joint or shear zone. The 1981 program will be planned to confirm or negate the existence of this geologic feature.

5.3 - Geotechnical Considerations

(a) Sliding Stability

For an arch dam, a major portion of the thrust will be carried by the abutments. The stability of the abutments is controlled by the geologic features such as bedding planes and joints, their orientation and density, the shear resistance of the rock along these features, and the slope of the valley. Certain geological features (potential shear zones parallel to the valley and the major joint set in the right abutment) require special considerations. The information available to date is not sufficient to perform these analyses. Therefore, using available data, a sensitivity analysis will be performed to identify potential problem areas and possible means of stabilization as required. The rock quality, in general however, looks adequate for an arch dam. Additional investigations are necessary to define these features.

(b) Foundation and Abutment Rock Strength and Deformations

For the intact rock in the foundation and the abutments, the overall bearing capacity and the associated deformation modulus (E) depends to a large degree on the nature and density of the geologic discontinuities such as shear zone and joints. The modulus of elasticity used in preliminary analyses ($E = 1.8 \times 10^6$ psi) was based on tests performed by the USBR. The state of the knowledge is such that a sensitivity analysis will be undertaken to evaluate the impact of changes in E. However, it is not anticipated that stresses in the dam will be greatly affected by changes in the modulus of elasticity. The foundation excavations will be excavated to find the concrete structure in competent, unweathered rock.

(c) Potential for Leakage and Treatment

The cost of treatment of the foundation will be increased by extensive joints and cracks in the rock. Information available so far indicates that substantial treatment will be required in all areas and extensive treatment may be required in local areas. The treatment is expected to include excavation of weathered rock, consolidation and curtain grouting, and possibly a drainage curtain. The investigations conducted to date have not revealed any features that would make the Devil Canyon site infeasible for an arch dam. The only exception to this statement would occur if further investigation indicated the potential for fault displacement under the dam or severe abutment stability problems that could not be economically treated.

6 - SEISMIC CONSIDERATIONS

The Devil Canyon site as well as the entire Susitna River is in a seismically active region. The Bureau of Reclamation considered a maximum earthquake with a magnitude of 8.5 Richter at 40 miles or one with a magnitude of 7.0 Richter at a distance of 10 miles. The 8.5 magnitude earthquake at 40 miles was determined to be the maximum credible earthquake.

Currently, seismic studies are being conducted by Woodward-Clyde Consultants as part of Task 4. From these studies, one lineament which will require further investigation has been identified approximately 1,000 feet upstream from the Devil Canyon site. This lineament crosses the Susitna River roughly at right angles at the horseshoe shaped bend upstream from the site. Continuing investigations will determine whether this will have an impact on design.

In general, a concrete dam can be designed against ground motions and accelerations up to reasonable limits (0.5 g). However, if surface rupture (or differential movements between two parts of the dam foundation) of significant magnitudes (greater than approximately two to three inches) is determined to be likely, a concrete dam would probably be ruled out. This is, in fact, the reason a thin arch dam was ruled out at Auburn (geologists indicated at Auburn that relative movements of up to nine inches could be expected).

No indication of potential for such differential movement is in evidence.

7 - EVALUATION OF PREVIOUS STUDIES

7.1 - Thin Arch Dam

The first report on the Devil Canyon Project, issued by the U.S. Department of the Interior in 1961, proposed a single curvature arch dam as shown in Figures 7.1 and 7.2. As studies progressed, this was modified to a double curvature thin arch dam as described in the Devil Canyon Status Report by the Alaska Power Administration in 1974 (Figures 7.3 and 7.4). This was further modified by the Corps of Engineers before issuing their Interim Feasibility Report in 1975 (see Figures 7.5 and 7.6).

The design consisted of a double curvature thin arch dam in the steep-walled canyon with an impervious core rockfill saddle dam over the buried valley on the left abutment. The rockfill/earthfill section had a maximum height of approximately 200 feet. The concrete section had a maximum height of approximately 635 feet above the base or 550 feet above normal river level, and a crest length of approximately 1,400 feet. A concrete thrust block was located on the left abutment between the concrete and the earthfill section.

The double curvature thin arch design had a base thickness of 85.6 feet and a crest thickness of 20 feet at the crown section. The slenderness ratio was 0.135. The Corps of Engineers performed a stress analysis on the dam using a maximum credible earthquake of 8.5 Richter at a distance of 40 miles. In order to compensate for high tensile stresses in the upper third of the central portion of the dam, high strength steel strands were to be incorporated into the upstream face.

Although rock conditions are not ideal at Devil Canyon, they appear adequate for the dam foundations. If rock quality proves to be poorer than anticipated, there are methods in which the abutments of an arch dam can be adapted to weakness of the rock. The bearing pressures at the concrete/rock interface may be reduced by increasing the abutment thickness of the arch or by using abutment pads. These abutment pads would be analogous to the use of spread footings for a wall foundation. They also provide an efficient means of bridging small zones of poor rock. Abutment pads have been used in Inguri (the world's largest arch dam) and were also proposed at Auburn.

At the dam location the river valley is not symmetrical and this may lead to excessive torsional stresses in the dam. The symmetry could be improved by the use of abutment pads, or a two-centered configuration could be adopted with two separate pairs of lines of centers, one for each side of the dam, defining the horizontal arches. On the right side of the dam the arches would have larger radii corresponding to the longer arch circumferences and the flatter slope of the abutment. This would direct the thrust from the dam more directly into the rock rather than along the face as would be the case with geometry based on smaller radii.

Temperature extremes may reach as low as approximately -50°F at the site with prolonged temperatures of -30°F to -40°F for several weeks at a time. These temperatures will induce stresses within the dam and cause surface cracking of the concrete. Often dams in Russia have been insulated to overcome these problems. A thicker dam would be less likely to develop temperature problems as the cracks would penetrate for a relatively shorter distance.

In the 1974 design the double curvature arch dam incorporated a spillway consisting of six gated orifices below the dam crest which discharged water with a free fall of 450 feet into a 150 foot (maximum) deep plunge pool just downstream of the dam. In the 1975 Corps' version of the thin arch design, the spillway was changed to a chute-type flip bucket on the left abutment. This was primarily due to the plunge pool's proximity to the dam and the very great depths to which this type of pool could erode. The gated control structure was located between the earth section and the arch dam. The concrete-lined chute was founded on sound rock downstream of the left abutment with a flip bucket discharging flows in a jet into the river. This could lead to erosion of the river valley, but it would not be close to the dam foundation or other major structures. The stability of the left bank for a spillway has been questioned, however, as the rock is more highly fractured and generally of poorer quality.

7.2 - Concrete Gravity Design

A concrete gravity dam was proposed by the Corps of Engineers in 1979 for the purposes of determining economic feasibility of the project based on a conservative estimate of cost. This was in response to the Office of Management and Budget's statement that the feasibility of the thin arch dam was not adequately proven.

Problems can exist with a concrete gravity section. The Devil Canyon gorge is V-shaped with a ratio of length at the dam crest level to the dam height of about 1.9 to 2.0. A straight masssive concrete dam would not behave as a gravity structure in such a gorge. Because of the narrowness of the gorge it would perform as a three-dimensional structure under hydrostatic and seismic loadings, supported at the abutments as well as at the base. This form of beam action between the abutments does not accord with an efficient design of an arch configuration.

The location of a gravity cross section in narrow gorges is generally difficult to justify technically or economically. An arch dam gives a more efficient resistance to upstream loadings than a straight gravity dam because the arch transfers the thrust deep into the abutments rather than along the face. Under seismic loadings the increased mass, and hence inertia, of a gravity dam will produce a greater overall stress in the foundation and abutments.

Straight gravity dams have two advantages over arch dams. The first advantage is the improved response to earthquake loading parallel to the crest, particularly when the reservoir is drawn down. A straight dam across a canyon is much stiffer in the transverse direction than an arched dam. The second advantage of a gravity dam is its suitability for the use of an overflow type spillway. An overflow spillway terminating in a stilling basin will provide a minimum of scouring of the riverbed and drifting of spray over the surrounding area.

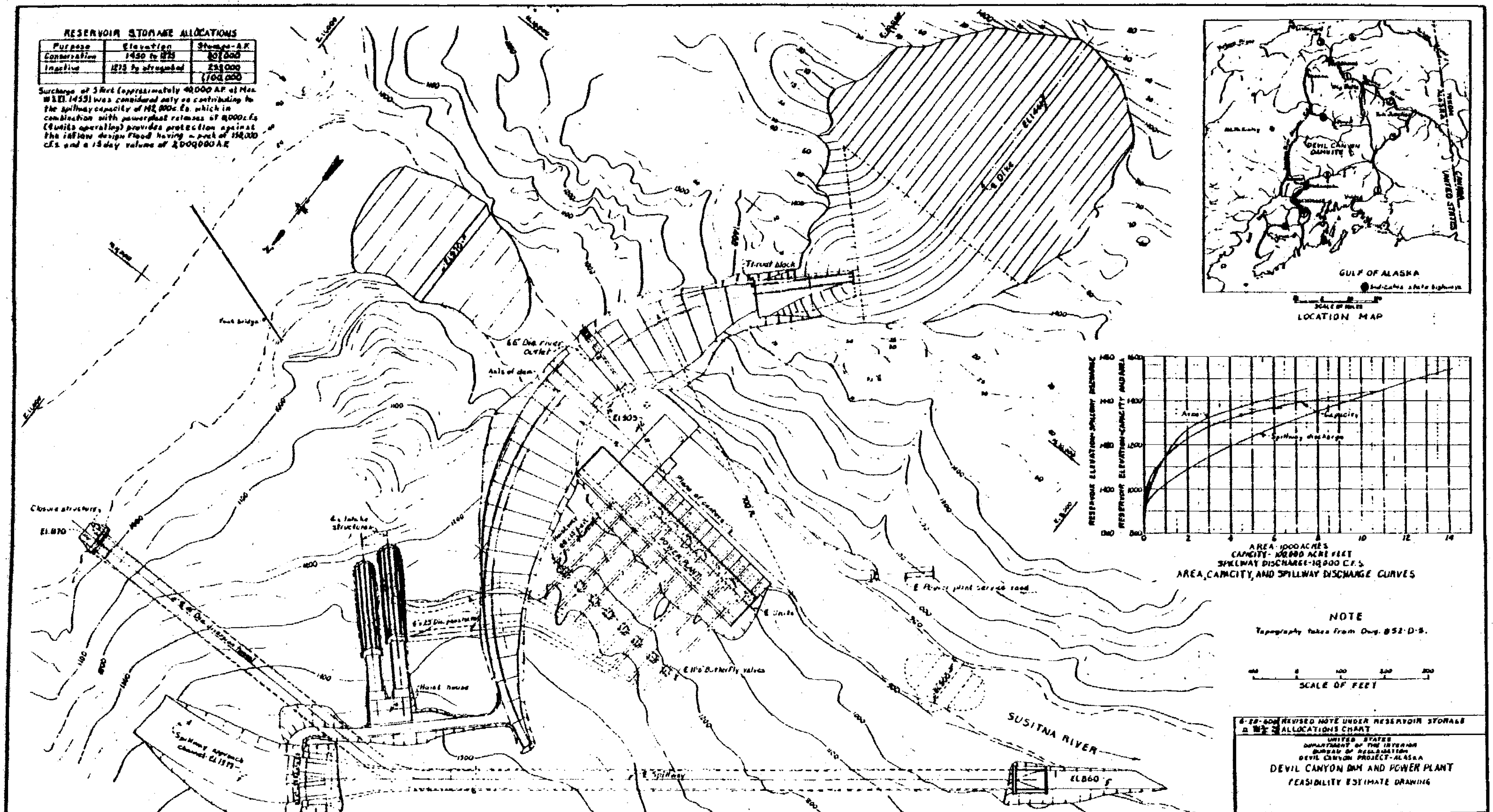


FIGURE 7.1 (REFERENCE 16)

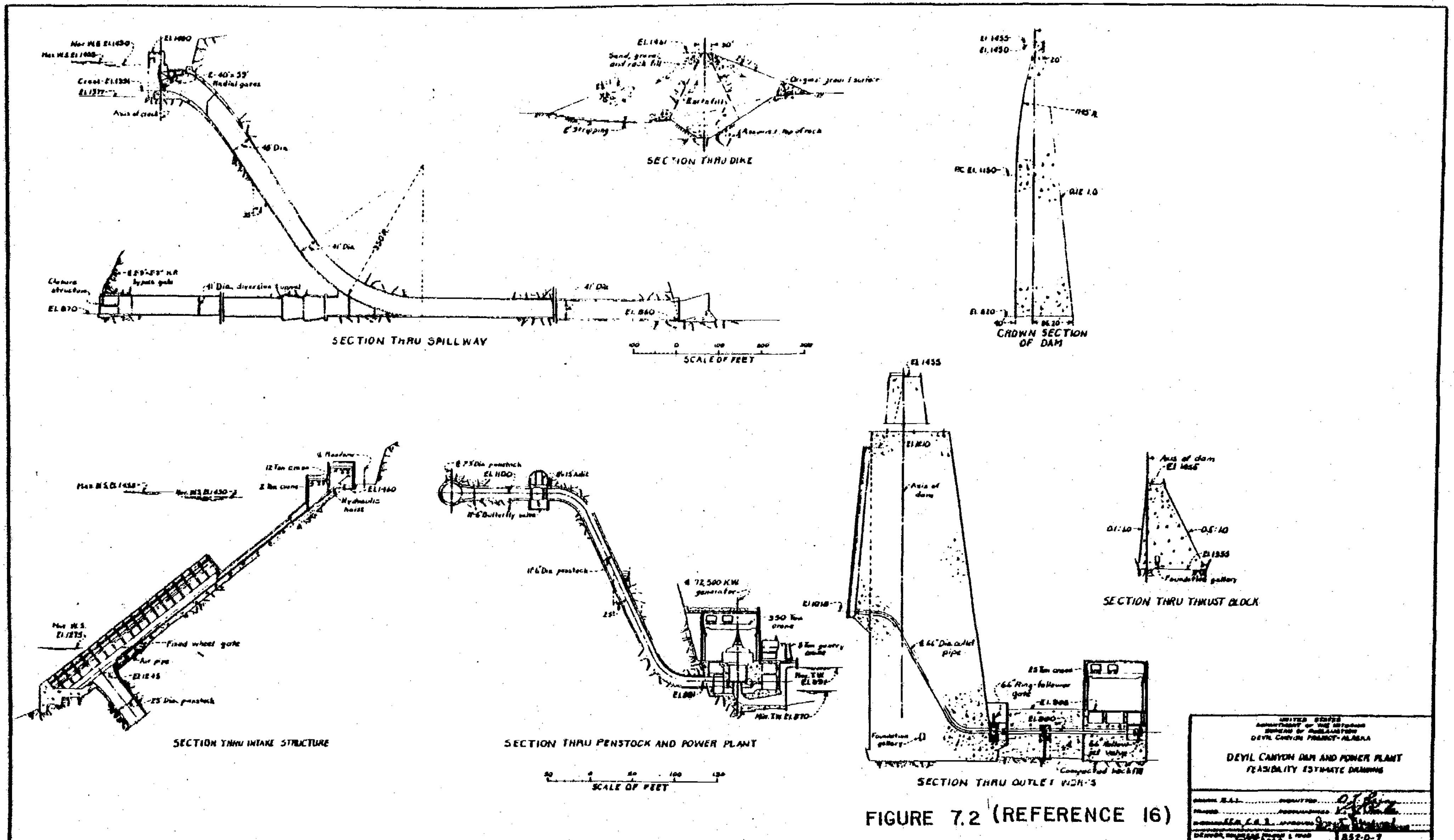
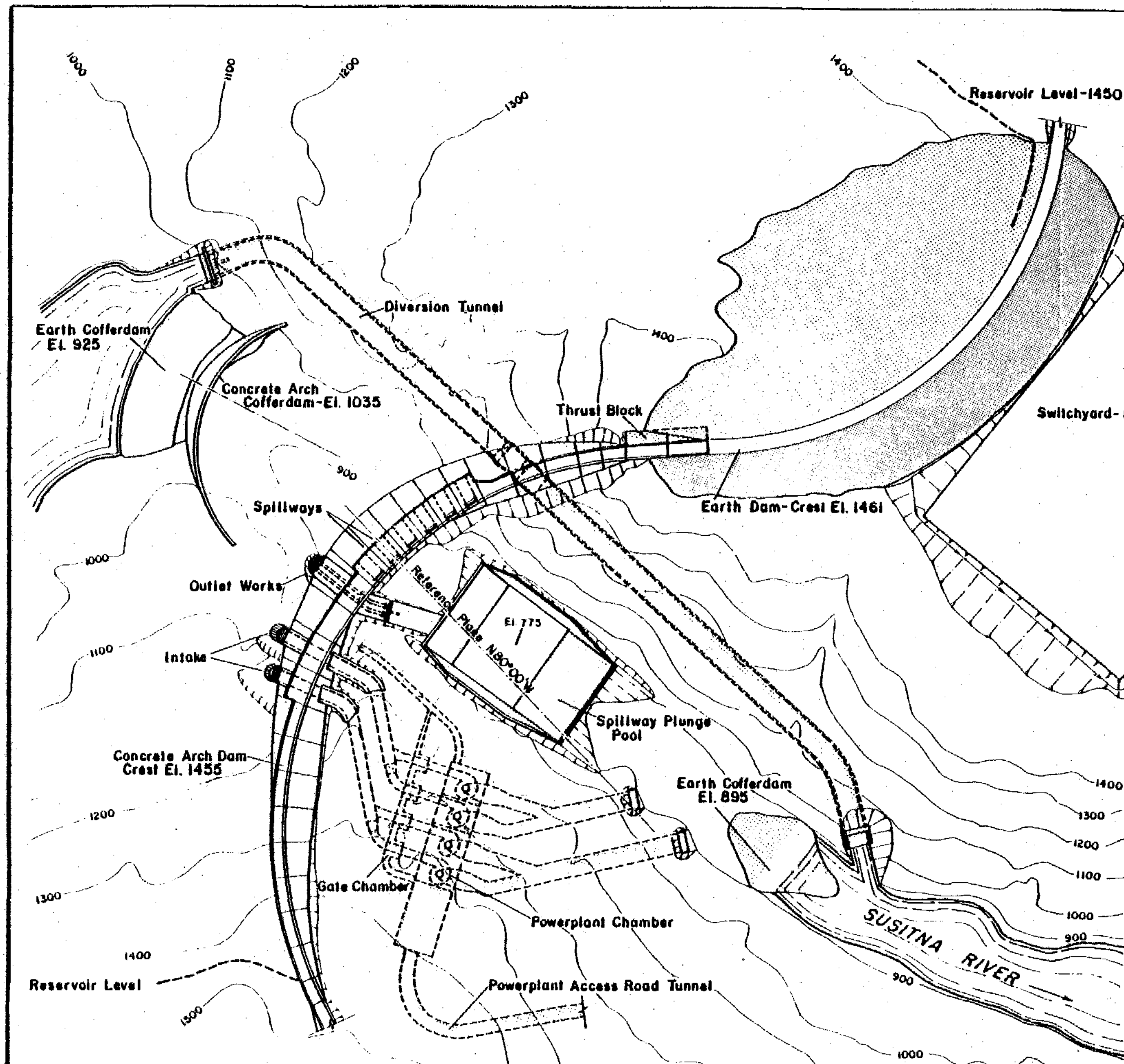


FIGURE 7.2 (REFERENCE 16)



U.S. DEPARTMENT OF THE INTERIOR
ALASKA POWER ADMINISTRATION

DEVIL CANYON DAM AND POWERPLANT

GENERAL DAMSITE LAYOUT

SCALE
0 100 200 400 600 Ft.

FIGURE 7.3 (REFERENCE 17)

APA 2-74

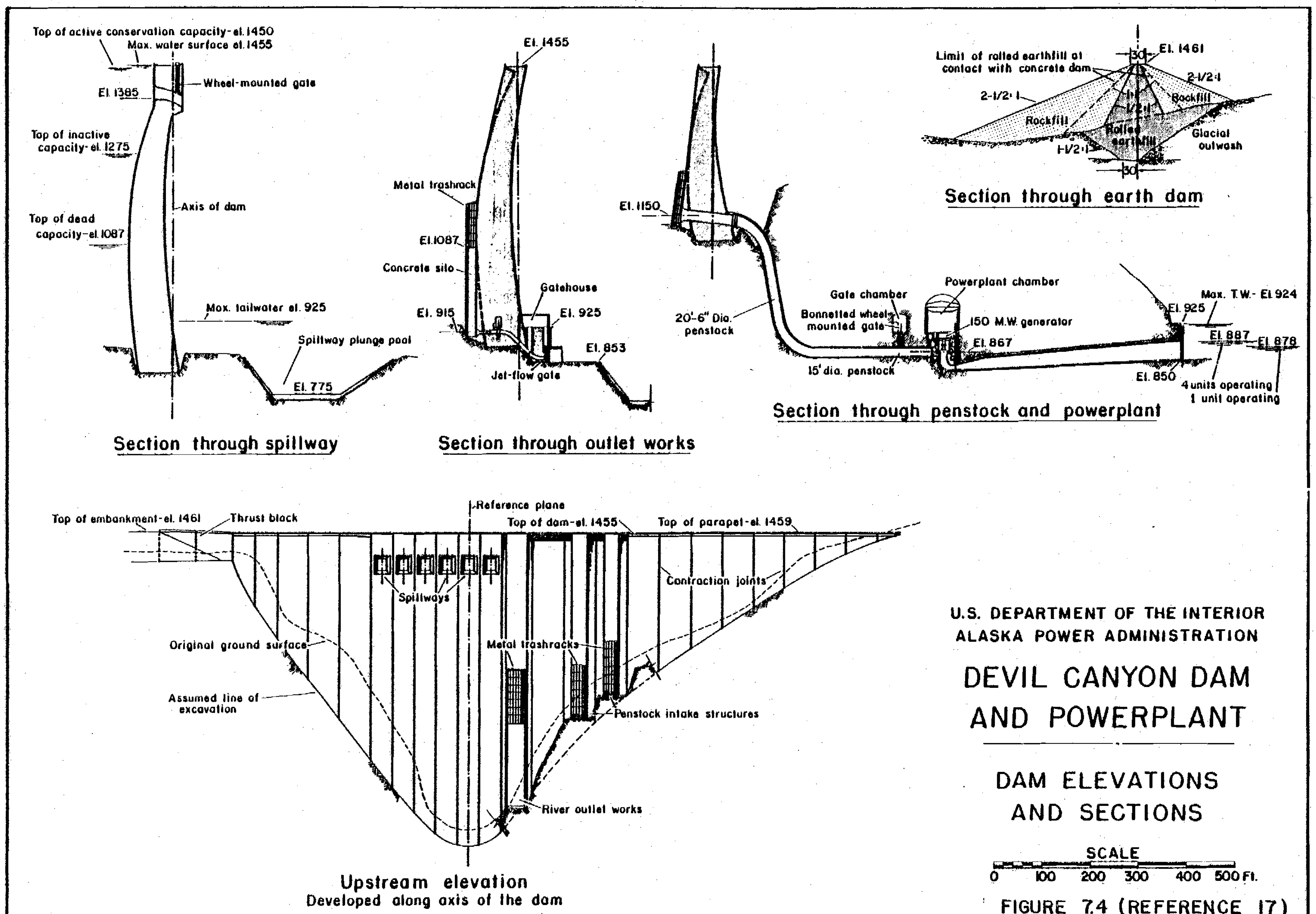


FIGURE 7.4 (REFERENCE 17)

APA 2-74

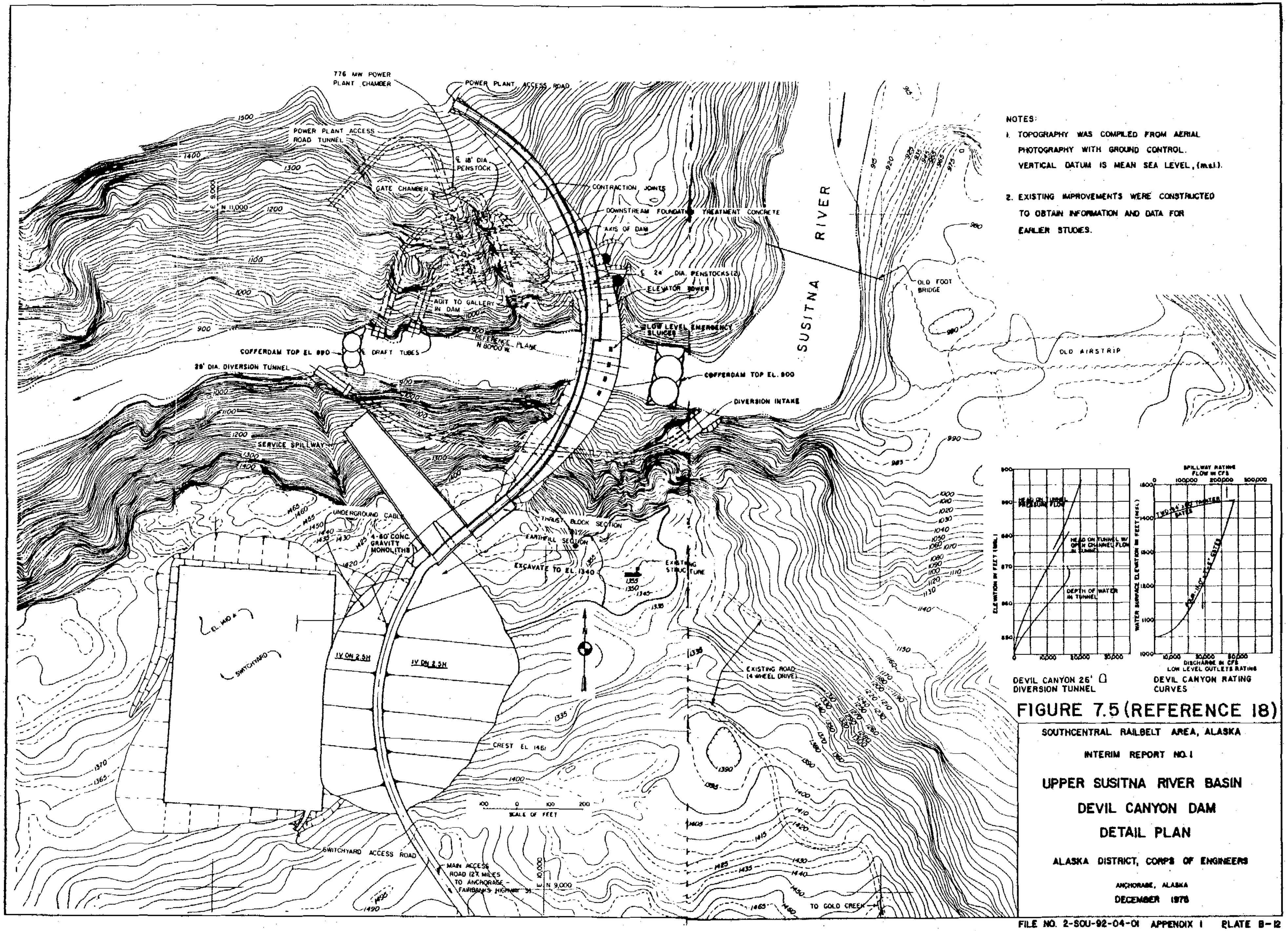


FIGURE 7.5 (REFERENCE 18)

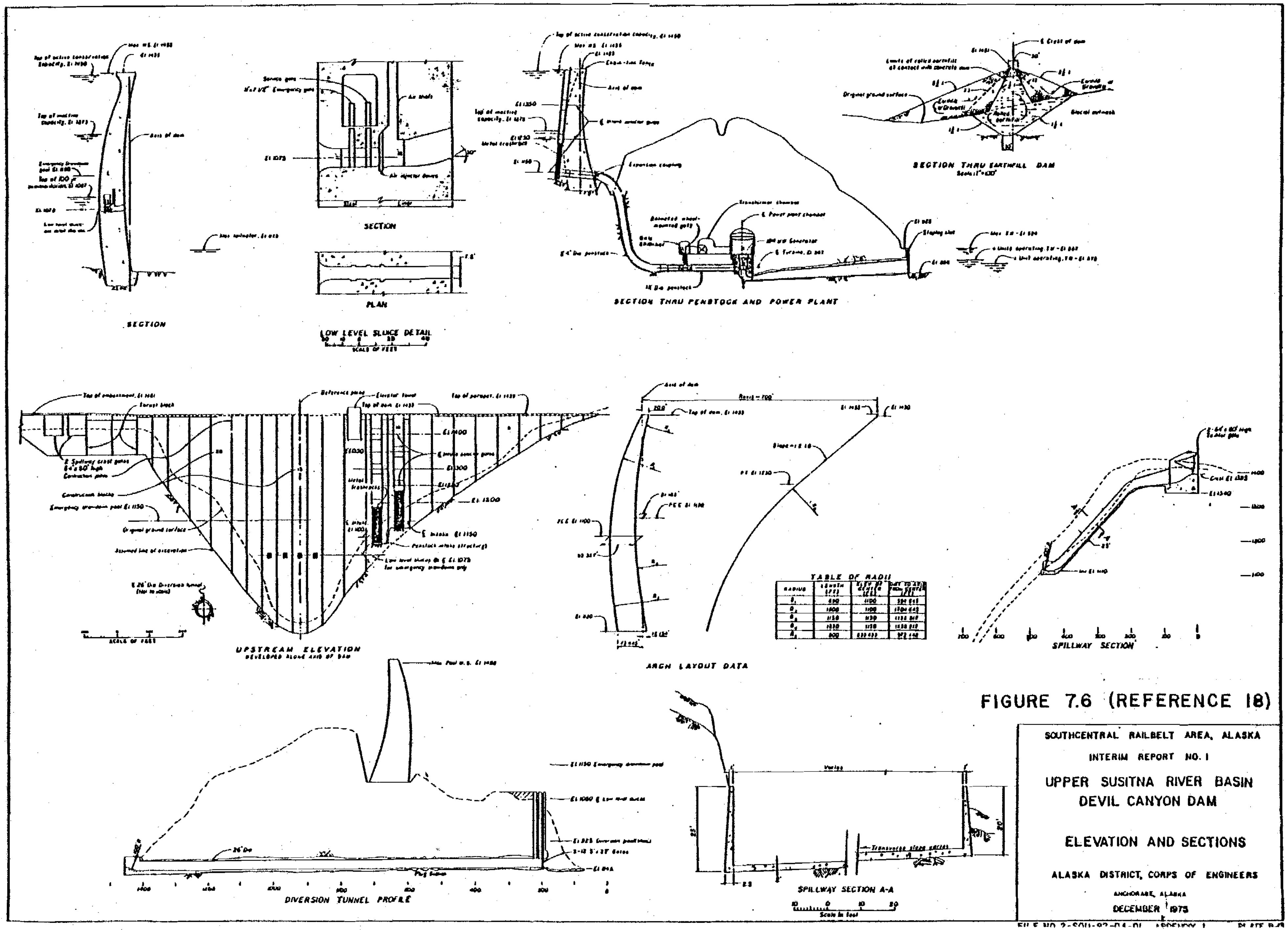


FIGURE 7.6 (REFERENCE 18)

8 - DRAFT DESIGN

8.1 - General

An initial assessment of feasibility of a concrete arch dam has been based on two dam designs, a thin arch dam and a gravity arch type. It was anticipated that the substantially thicker section of the latter would result in lower stresses in the arch direction with a greater portion of the loads being taken in the cantilevers.

8.2 - Thin Arch Dam

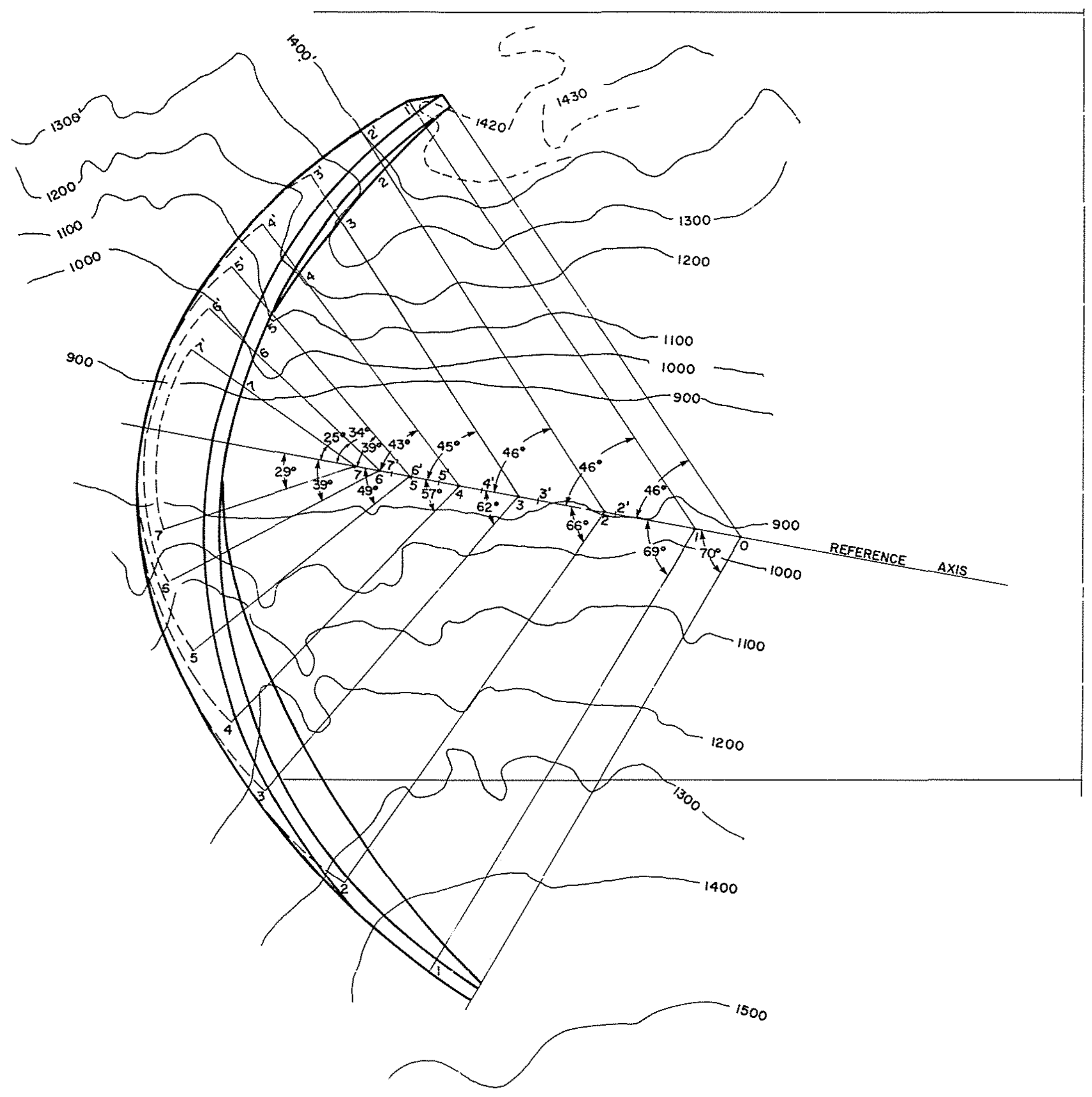
The thin arch dam geometry assumed for initial preliminary design is similar to the double curvature single center design established by the USBR as shown in Figures 7.3 and 7.4 and defined in Plate 8.1. The principal dimensions are as stated in Section 7.

8.3 - Gravity Arch Dam

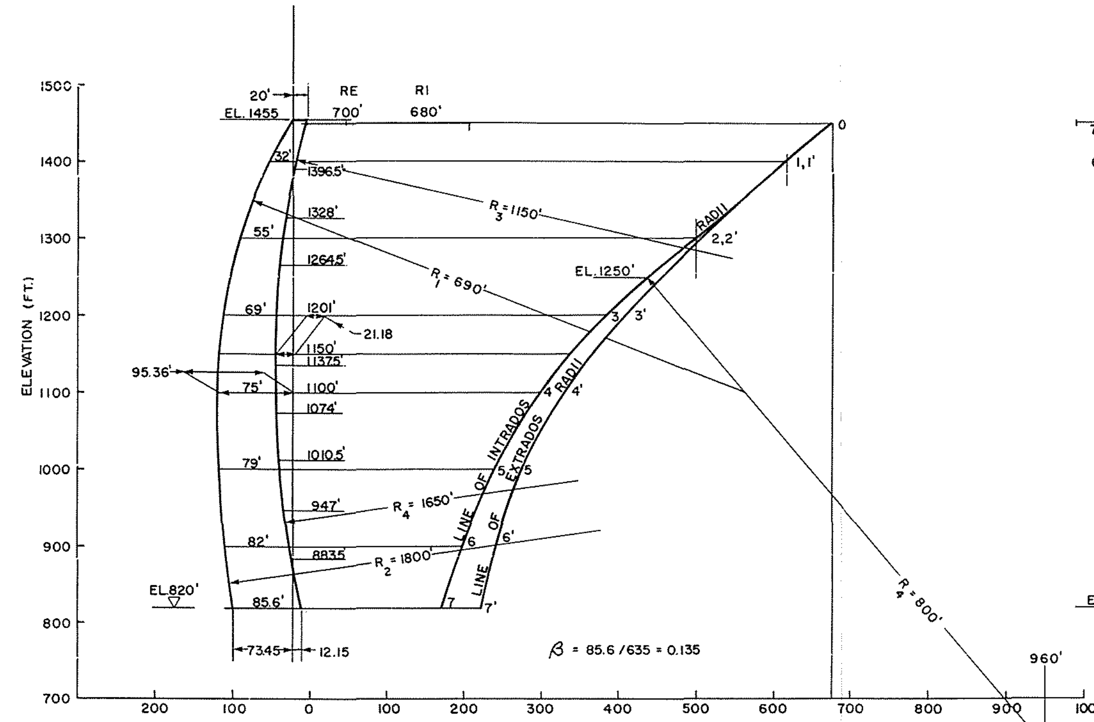
The general layout and geometry for a gravity arch dam is as shown in Plates 8.2 and 8.3.

The dam has a single center configuration with arch centers located on the same vertical axis. The cantilever sections have a vertical upstream face and a straight downstream face inclined 1(V) to 0.4(H). The upstream face is undercut at the bottom in order to reduce the tension stresses in the cantilever. The height of the dam is 635 feet and the thickness at the base is 225 feet, giving a slenderness ratio of 0.35. The thickness of the crest is 30 feet. The reference plane of the arch gravity dam has been reoriented from the location of the reference plane of the double curved arch dam in order to increase the symmetry. The arches are symmetrical at mid-height, but the symmetry decreases toward both the top and the bottom by up to 6°. The central angles of the arches vary from 112° at the crest to 28° at the base. Relatively small central angles of the arches are chosen in order to increase the resistance of the structure to cross-canyon seismic motions and to ensure the sliding stability of the abutments.

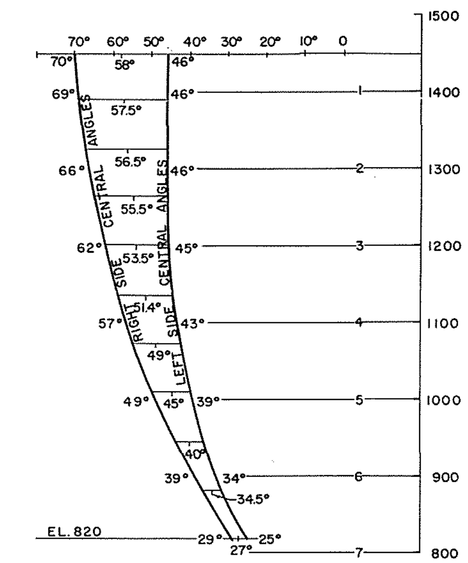
A massive concrete thrust block 75 feet high rises above the rock on the left abutment. The arches have a uniform thickness (parallel faces). The depth of excavation of the downstream edge of abutments below the natural rock surface varies from 25 feet to 50 feet. Half-radial arch abutments are used instead of full-radial types to reduce the amount of excavation.



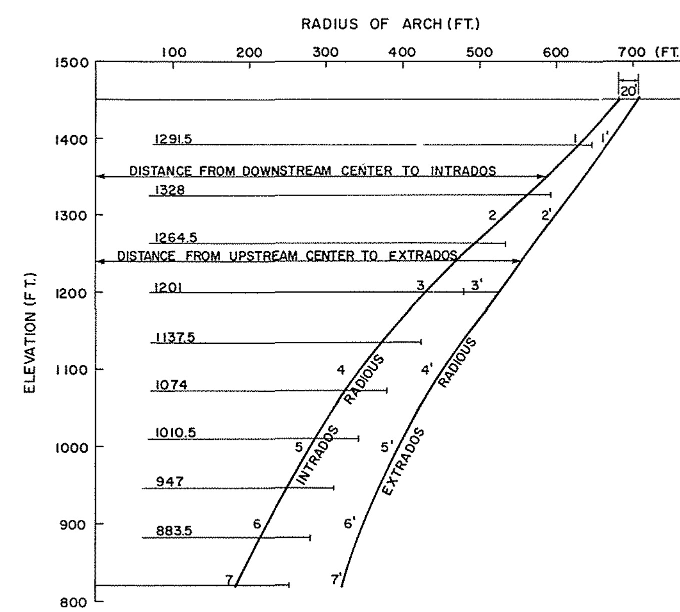
PLAN OF ARCH



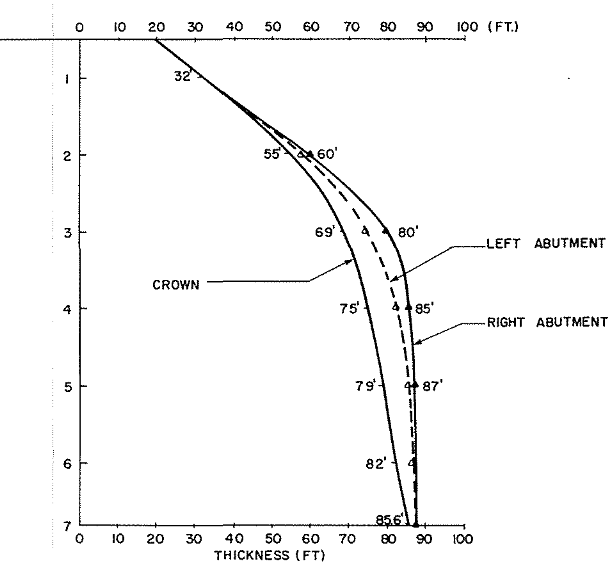
ARCH CROWN SECTION



ANGLES OF HORIZONTAL ARCH TO REFERENCE AXIS



HORIZONTAL ARCH RADII



ARCH THICKNESS

NOTE:
GEOMETRY DERIVED FROM U.S. DEPT. OF INTERIOR LAYOUT

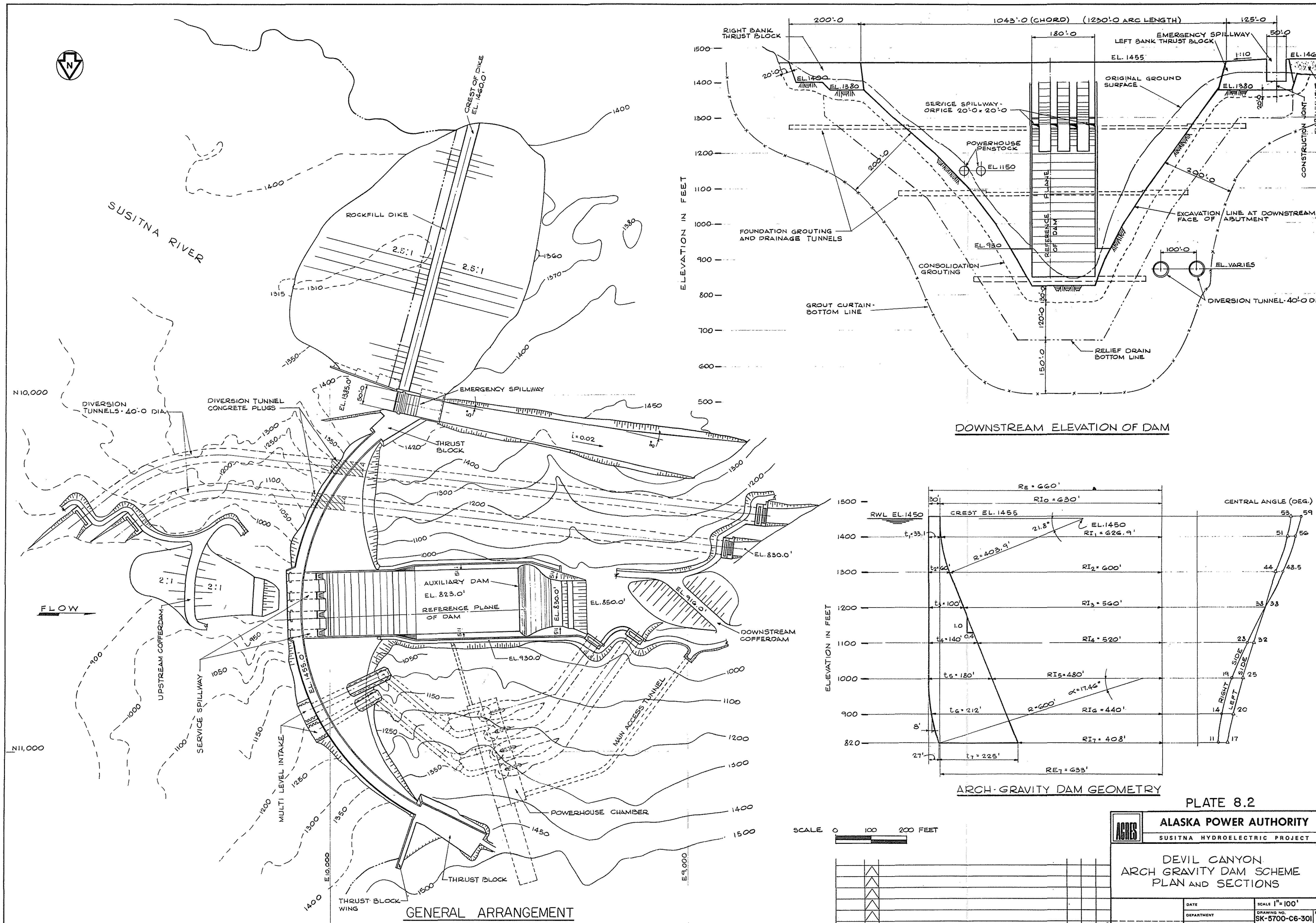
PLATE 8.1

ALASKA POWER AUTHORITY
SUSITNA HYDROELECTRIC PROJECT

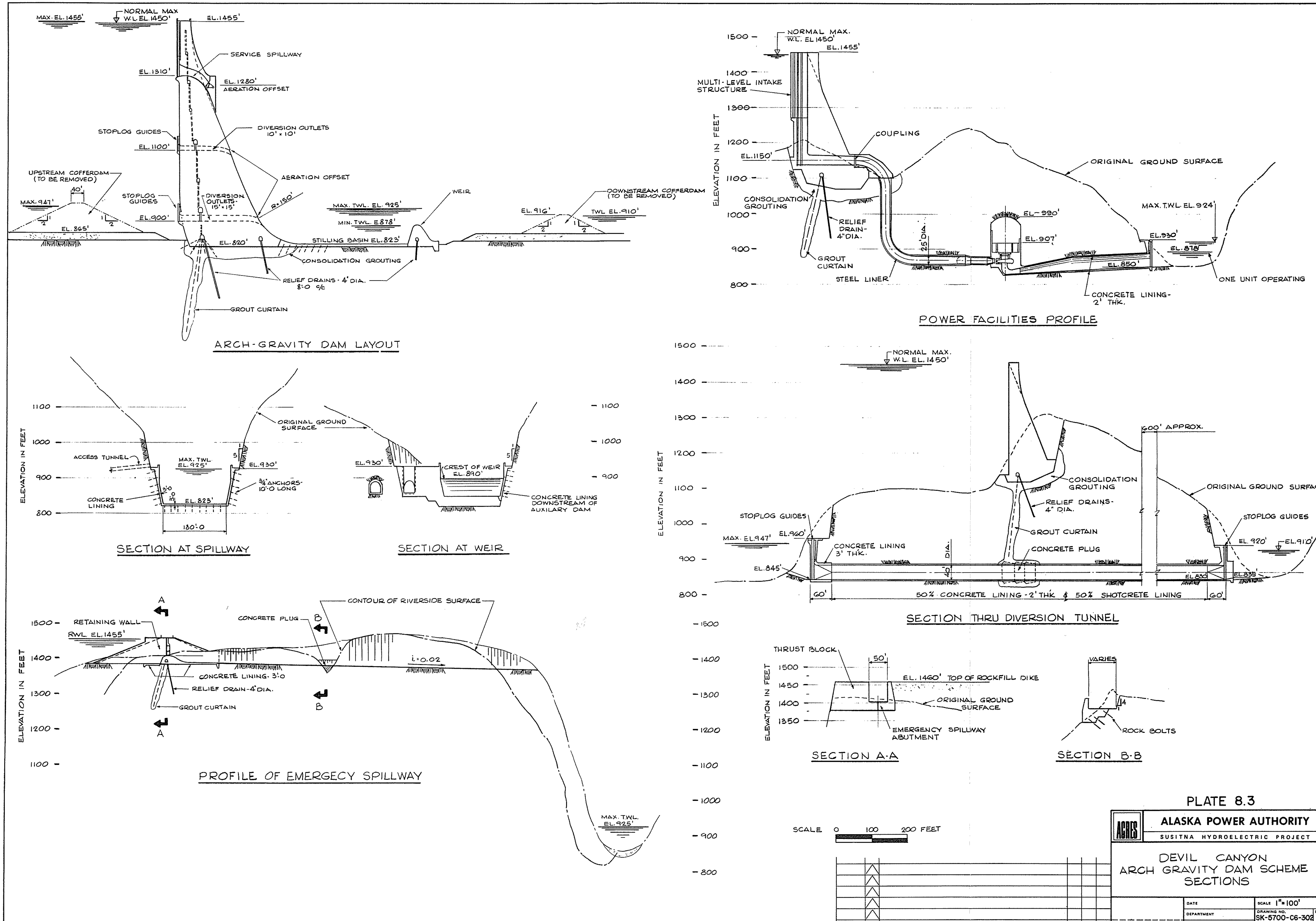
DEVIL CANYON
THIN ARCH DAM GEOMETRY

DATE	NO.	REVISIONS	CH.	APP.	APP.

ACRES AMERICAN INCORPORATED | PROJECT | DATE | DEPARTMENT | SCALE | DRAWING NO. SK-5700-C6-303 | SHEET OF | REV.



SUSITNA RIVER
CREST OF DIKE EL. 1460.0'
ROCKFILL DIKE
2.5:1
EMERGENCY SPILLWAY
DIVERSION TUNNELS 40'-0 DIA.
DIVERSION TUNNEL CONCRETE PLUGS
THRUST BLOCK
i=0.02
N10,000
N11,000
FLOW
UPSTREAM COFFERDAM
SERVICE SPILLWAY
2:1
AUXILIARY DAM EL. 823.0'
REFERENCE PLANE OF DAM
EL. 850.0'
EL. 830.0'
EL. 930.0'
EL. 916.0'
DOWNSTREAM COFFERDAM
EL. 1455.0'
MULTI LEVEL INTAKE
MAIN ACCESS TUNNEL
POWERHOUSE CHAMBER
THRUST BLOCK
THRUST BLOCK WING
E10,000
E9,000
GENERAL ARRANGEMENT
200'-0
1043'-0 (CHORD) (1230'-0 ARC LENGTH)
125'-0
180'-0
50'-0
RIGHT BANK THRUST BLOCK
EMERGENCY SPILLWAY
LEFT BANK THRUST BLOCK
EL. 1455'
EL. 1460
EL. 1400
EL. 1380
ORIGINAL GROUND SURFACE
SERVICE SPILLWAY ORFICE 20'-0 x 20'-0
POWERHOUSE PENSTOCK
EL. 1150
CONSTRUCTION JOINT
EMBANKMENT
FOUNDATION GROUTING AND DRAINAGE TUNNELS
EXCAVATION LINE AT DOWNSTREAM FACE OF ABUTMENT
EL. 930
CONSOLIDATION GROUTING
100'-0
EL. VARIES
DIVERSION TUNNEL 40'-0 DIA.
GROUT CURTAIN BOTTOM LINE
RELIEF DRAIN BOTTOM LINE
120'-0
150'-0
ELEVATION IN FEET
DOWNSTREAM ELEVATION OF DAM
RE = 660'
RI0 = 630'
RWL EL. 1450
CREST EL. 1455
EL. 1450
RI1 = 626.9'
R = 403.9'
21.8°
t1 = 33.1'
t2 = 60'
RI2 = 600'
t3 = 100'
RI3 = 560'
t4 = 140'
RI4 = 520'
t5 = 180'
RI5 = 480'
α = 17.46°
t6 = 212'
R = 600'
RI6 = 440'
RI7 = 408'
t7 = 225'
RE7 = 633'
CENTRAL ANGLE (DEG.)
RIGHT SIDE
LEFT SIDE
ARCH-GRAVITY DAM GEOMETRY
SCALE 0 100 200 FEET
PLATE 8.2
ACRES
ALASKA POWER AUTHORITY
SUSITNA HYDROELECTRIC PROJECT
DEVIL CANYON ARCH GRAVITY DAM SCHEME PLAN AND SECTIONS
SCALE 1" = 100'
DRAWING NO. SK-8700-C6-301
DATE NO. REVISIONS CH. APP. APP.
ACRES AMERICAN INCORPORATED


ARCH-GRAVITY DAM LAYOUT
MAX. EL. 1455'
NORMAL MAX W.L. EL. 1450'
EL. 1455'
SERVICE SPILLWAY
EL. 1310'
EL. 1280' AERATION OFFSET
STOPLOG GUIDES
DIVERSION OUTLETS 10' x 10'
EL. 1100'
AERATION OFFSET
UPSTREAM COFFERDAM (TO BE REMOVED)
40'
MAX. 947'
STOPLOG GUIDES
DIVERSION OUTLETS 15' x 15'
R=150'
EL. 900'
EL. 865'
MAX. TWL. EL. 925'
MIN. TWL. E. 878'
WEIR
DOWNSTREAM COFFERDAM (TO BE REMOVED)
EL. 916'
TWL EL. 910'
EL. 820'
STILLING BASIN EL. 823'
CONSOLIDATION GROUTING
RELIEF DRAINS - 4' DIA. 8'-0 c/c
GROUT CURTAIN
SECTION AT SPILLWAY
ELEVATION IN FEET
1100
1000
900
800
ACCESS TUNNEL
MAX. TWL EL. 925'
EL. 930'
ORIGINAL GROUND SURFACE
CONCRETE LINING
EL. 823'
3/4" ANCHORS 10'-0 LONG
180'-0
SECTION AT WEIR
EL. 930'
CREST OF WEIR EL. 890'
CONCRETE LINING DOWNSTREAM OF AUXILARY DAM
PROFILE OF EMERGECY SPILLWAY
RETAINING WALL
RWL EL. 1455'
CONCRETE PLUG
CONTOUR OF RIVERSIDE SURFACE
CONCRETE LINING 3'-0
RELIEF DRAIN-4' DIA.
GROUT CURTAIN
i=0.02
A
B
MAX. TWL. EL. 925'
1500
1400
1300
1200
1100
1000
900
800
POWER FACILITIES PROFILE
NORMAL MAX. W.L. EL 1450'
EL. 1455'
MULTI-LEVEL INTAKE STRUCTURE
COUPLING
ORIGINAL GROUND SURFACE
EL. 1150'
CONSOLIDATION GROUTING
RELIEF DRAIN-4' DIA.
GROUT CURTAIN
STEEL LINER
25' DIA.
EL. 990'
EL. 907'
EL. 850'
EL. 930'
EL. 878'
MAX. T.W.L. EL. 924'
ONE UNIT OPERATING
CONCRETE LINING-2' THK.
SECTION THRU DIVERSION TUNNEL
NORMAL MAX. W.L. EL. 1450'
600' APPROX.
CONSOLIDATION GROUTING
ORIGINAL GROUND SURFACE
RELIEF DRAINS-4' DIA.
GROUT CURTAIN
CONCRETE PLUG
STOPLOG GUIDES
MAX. EL. 947'
EL. 960'
CONCRETE LINING 3' THK.
40' DIA.
EL. 845'
EL. 830'
EL. 835'
EL. 920'
EL. 910'
60'
50% CONCRETE LINING - 2' THK & 50% SHOTCRETE LINING
SECTION A-A
THRUST BLOCK
50'
EL. 1460' TOP OF ROCKFILL DIKE
ORIGINAL GROUND SURFACE
EMERGENCY SPILLWAY ABUTMENT
1500
1450
1400
1350
SECTION B-B
VARIES
ROCK BOLTS
SCALE 0 100 200 FEET
PLATE 8.3
ACRES
ALASKA POWER AUTHORITY
SUSITNA HYDROELECTRIC PROJECT
DEVIL CANYON
ARCH GRAVITY DAM SCHEME
SECTIONS
DATE
DEPARTMENT
PROJECT
SCALE 1"=100'
DRAWING NO. SK-5700-C6-302
SHEET OF
REV.
DATE NO. REVISIONS CH. APP. APP.
ACRES AMERICAN INCORPORATED

9 - STRESS ANALYSIS

9.1 - General

Preliminary analyses were carried out on the thin arch and gravity arch designs. The analyses were based on a finite element analysis as incorporated into the Arch Dam Analysis Program (ADAP) developed at Berkeley from the widely used SAP finite element analysis program. The program divides the dam into five shells, the two external faces and three internal shells, and stresses are calculated at points on a grid system running parallel to the shells. For the purpose of this initial phase of the study a coarse grid was used in order to reduce the cost of computer time. The degree of accuracy of the output suffices for a preliminary determination of stresses, but for a more detailed analysis, particularly of stresses close to the dam foundations and abutments where use of a coarse grid induces large distortions in the results, a much finer mesh will be necessary.

Stresses caused by the following combinations of loads were examined:

(1) Hydrostatic loads + self weight of the dam
(2) Hydrostatic + self weight + temperature
(3) Hydrostatic + self weight + earthquake parallel to dam axis
(4) Relative displacement of the dam abutments caused by earthquake

Temperatures within the concrete mass were based on a consideration of the dam as a semi-infinite solid subject to harmonically varying temperatures at the surface.

9.2 - Design Criteria

Dam crest elevation	- 1455 ft MSL
Water surface elevation	- 1450 ft MSL
Deformation modulus of rock	- 1.8×10^6 psi
Elasticity modulus of concrete	- 3.6×10^6 psi
Poisson's ratio for rock	- 0.25
Concrete density	- 155 lbs/ft^2
Concrete compressive strength at 365 days	- 4,500 psi
Allowable concrete compressive stress	- 1,500 psi
Allowable concrete tensile stress	- 150 psi
Allowable concrete tensile stress (extreme loadings)	- 500 psi
Minimum ambient temperature during grouting	- +37°F
Mean annual ambient temperature	- +28.9°F
Mean January ambient temperature	- +44°F
Mean January reservoir temperature	- +32°F over upper 50 ft, +39°F below 70 ft

Earthquake induced stress based on response spectrum for the 1952 Hast earthquake in California. Maximum ground motion acceleration	- 0.5g
Relative movement of abutments in lateral direction base assumed hinged (x - displacement)	- 1-1/2 in.

Relative movement of abutments in longitudinal direction (z - displacement) - 1-1/2 in.

9.3 - Stresses

Stresses and displacements for the thin arch dam under loading conditions (1) and (2) are given on Plates A.1 and A.2 in Appendix A. Stress distributions across the face of the dam and within four typical cantilever and arch sections are illustrated. Figure A.1 to Figure A.4 in Appendix A illustrates stresses along the faces of the upstream crown cantilever and crown arch sections under loading condition (3).

Stresses and displacements for loading conditions similar to the thin arch are given for the gravity arch dam in Appendix B on Plates B.1 and B.2 together with crown stresses for differential movement of the abutments.

Crown cantilever stresses under loading condition 4 for a relative 1-1/2 inch lateral displacement of the abutments and for a relative 1-1/2 inch longitudinal displacement are given for an arch gravity dam in Appendix B, Figures B.1 to B.6.

Maximum stresses for the various loading conditions are given in Table 9.1.

9.4 - Conclusions

Under hydrostatic and gravity loadings stresses are generally within acceptable limits for both dams, the only exception being a 156 psi tensile arch stress in the thin arch dam.

Under temperature loadings combined with hydrostatic and gravity loadings, compressive stress is acceptable but high tensile stress (up to 615 psi in the case of the thin arch) exists on the downstream face. Both tensile and compressive stresses are higher for the thin arch dam.

In both the above loading cases, distributions of the arch stresses between the left and right sides of the dams are uneven. Tension predominates over the downstream face of the lower arches and, in the case of the thin arch, is evident in the downstream face of the crown cantilever.

Displacements of the gravity arch and thin arch dams are up to 3 inches and 4 inches respectively under temperature loadings.

Seismic loadings cause tensile stresses of up to 1,230 psi in the downstream face of the gravity arch crown cantilever. In the case of the thin arch dam the arch tension rises to 850 psi on the downstream face.

TABLE 9.1: MAXIMUM STRESSES IN PROPOSED CONCRETE DAM TYPES AT DEVIL CANYON

	Gravity Arch				Thin Arch			
Loading Conditions	Cantilever	Face	Arch	Face	Cantilever	Face	Arch	Face
a) Hydrostatic + gravity	+590 psi -8 psi	intrados extrados	+504 psi -102 psi	extrados intrados	+500 psi - 60 psi	extrados extrados	+969 psi -156 psi	extrados intrados
b) Hydrostatic + gravity + temp.	+372 psi -180 psi	intrados intrados	+625 psi -436 psi	extrados intrados	+607 psi -465 psi	extrados intrados	+1188 psi -615 psi	extrados intrados
*c_1) Hydrostatic + gravity + earthquake (earthquake acting d/s)	+1100 psi -1150 psi	intrados extrados	+622 psi -740 psi	intrados extrados	+1020 psi -820 psi	intrados extrados	+1472 psi -740 psi	intrados extrados
*c_2) Hydrostatic + gravity + earthquake (earthquake acting u/s)	+1620 psi -1230 psi	extrados intrados	+1780 psi -148 psi	extrados intrados	+1210 psi -820 psi	extrados intrados	+2428 psi -850 psi	extrados intrados
d_1) 1.5 inch relative lateral movement of abutments	+750 psi -400 psi	intrados extrados	+60 psi -45 psi	extrados intrados				
d_2) 1.5 inch relative downstream of abutments			+3600 psi	intrados				

Note: Stresses shown are at predetermined nodes on grid which does not extend to dam crest or abutments. Finer mesh would be required to obtain stress values in these areas.

\- denotes tension
\+ denotes compression

* Crown section only.

10 - CONCLUSIONS

10.1 - Considerations

From a review of existing dams throughout the world and the analyses carried out on the preliminary geometry developed for the thin arch and arch gravity dams a number of significant factors emerge which influence the decision of whether to continue with analysis of an arch dam at Devil Canyon.

- The physical dimensions of an arch dam at Devil Canyon are well within world experience in terms of height, width and height/width ratio.

- Stresses within the dam caused by a full reservoir and the dam self weight are acceptable for both dams.

- Under low temperature conditions tensile stresses exist on the downstream side of the dam. These stresses can be reduced in the lower arches by increasing the rise or overall angle of the arches, and in the cantilever by inclining the cantilever further downstream.

  The uneven distribution of stresses between the left and right sides of the dam can be improved by adopting a two center configuration resulting in different arch radii on each side of the dam axis.

- The major causes of concern are stresses under earthquake loading, particularly for ground motion downstream, with resultant stresses acting in an upstream direction. Under this latter condition the dams are subjected to loading in the opposite direction from that of the normal load condition of full reservoir for which they are primarily designed. Whereas loads in a downstream direction can be accommodated by adjusting the dam geometry, it is more difficult to design for upstream loadings where an overall tensile effect is produced within the dam. It is to be noted, however, that the vertical construction joints within the dam will open under tension, causing a relaxation of the arches and redistribution of stress to the cantilevers. Adjustments in the geometry can be made to reduce these cantilever stresses. The analysis which has been undertaken does not cater for this cracking and redistribution of load, and a different approach will have to be taken in future calculations. High seismic loadings have been experienced by the Pacoima and Vidraru - Arges dams with minimal damage to the structures. Although the Pacoima dam is 372 feet high, as opposed to 635 feet for Devil Canyon, it is interesting to note that the dam was not severely damaged after earthquake loading resulting from a ground acceleration of probably 0.6 - 0.8g at the site.

- It is significant that stresses under seismic loads are greater in the gravity arch than in the thin arch dam. This enhanced effect of the ground acceleration is caused by the greater inertia of the more massive dam.

- From the information available to date from field investigations, the rock at the site is adequate for the foundation of a concrete arch dam. No discontinuties are apparent at the site that would preclude such a dam on the basis of either stability or water-tightness within the foundation and abutments.

10.2 - Conclusion

It is anticipated that additional study of the arch dam under seismic loading will dispel any reservations relating to its behavior as discussed above. Subject to much more intensive investigation of the local geology and the confirmation of sound abutment and foundation conditions, it is apparent that an acceptable design for either a thin arch or arch gravity dam can be derived capable of withstanding hydrostatic, self weight and temperature-induced stresses. Improvements can be made in the dam geometries such as aligning it more perpendicular to the canyon, increasing the rise of the lower arches, inclining the cantilever sections more steeply downstream, and adopting a two center configuration. With these adjustments and the correspondingly improved behavior of the structure it is concluded that either a thin arch or an arch gravity dam will be feasible at Devil Canyon. These two dam types will be studied under Subtask 6.07 - Preliminary Watana Dam Alternatives.

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(19) U.S. Department of the Army, Corps of Engineers (Alaska District), Hydroelectric Power and Related Purposes: Southcentral Railbelt Area, Alaska Upper Susitna River Basin - Supplemental Feasibility Report, Anchorage, Alaska, 1979.

APPENDIX A

STRESSES IN THIN ARCH DAM

ADAP RESULTS: SUSITNA THIN ARCH DAM

CROWN CANTILEVER STRESSES

INTRADOS

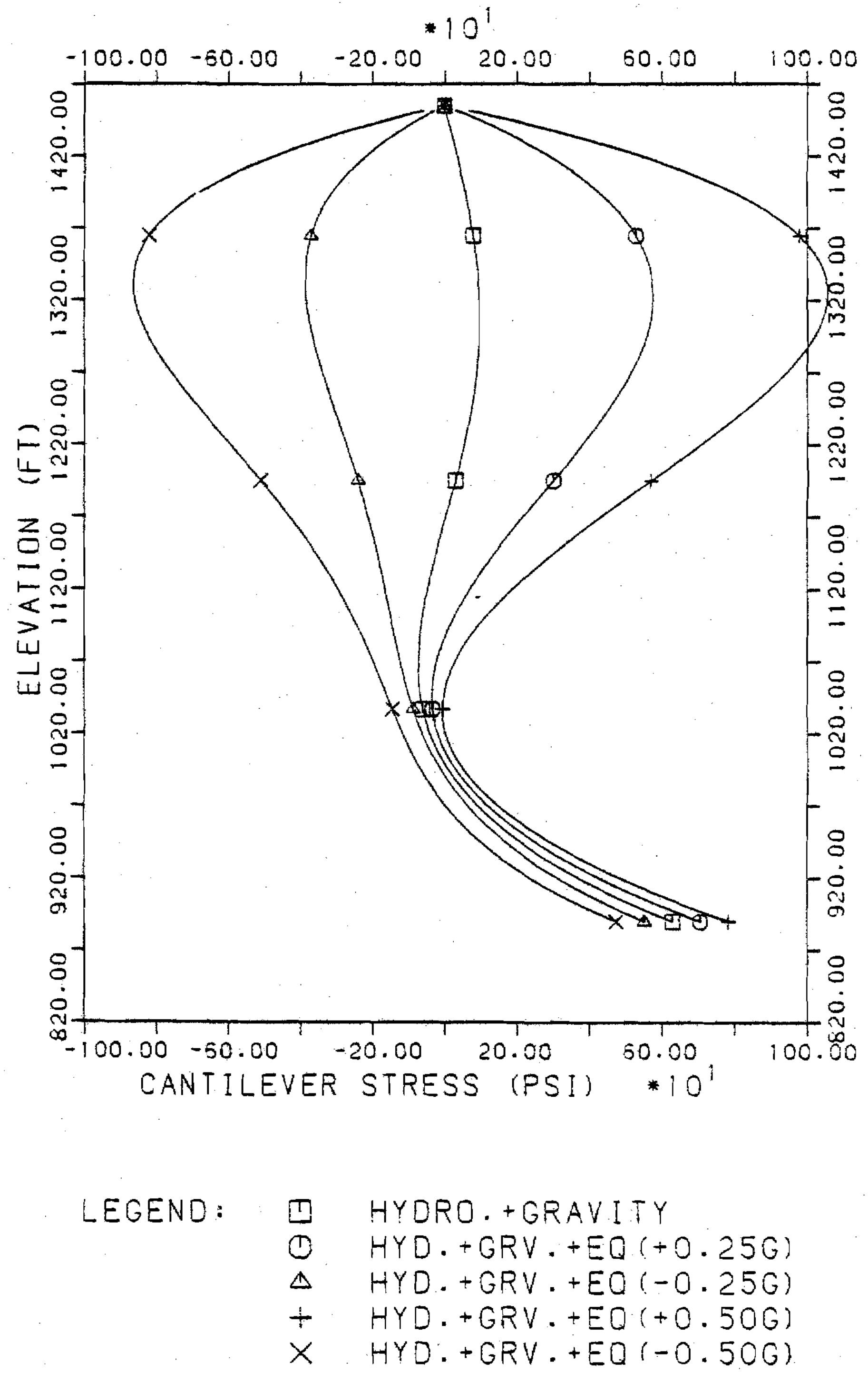


FIGURE A1

ACRES

ADAP RESULTS: SUSITNA THIN ARCH DAM

CROWN CANTILEVER STRESSES

EXTRADOS

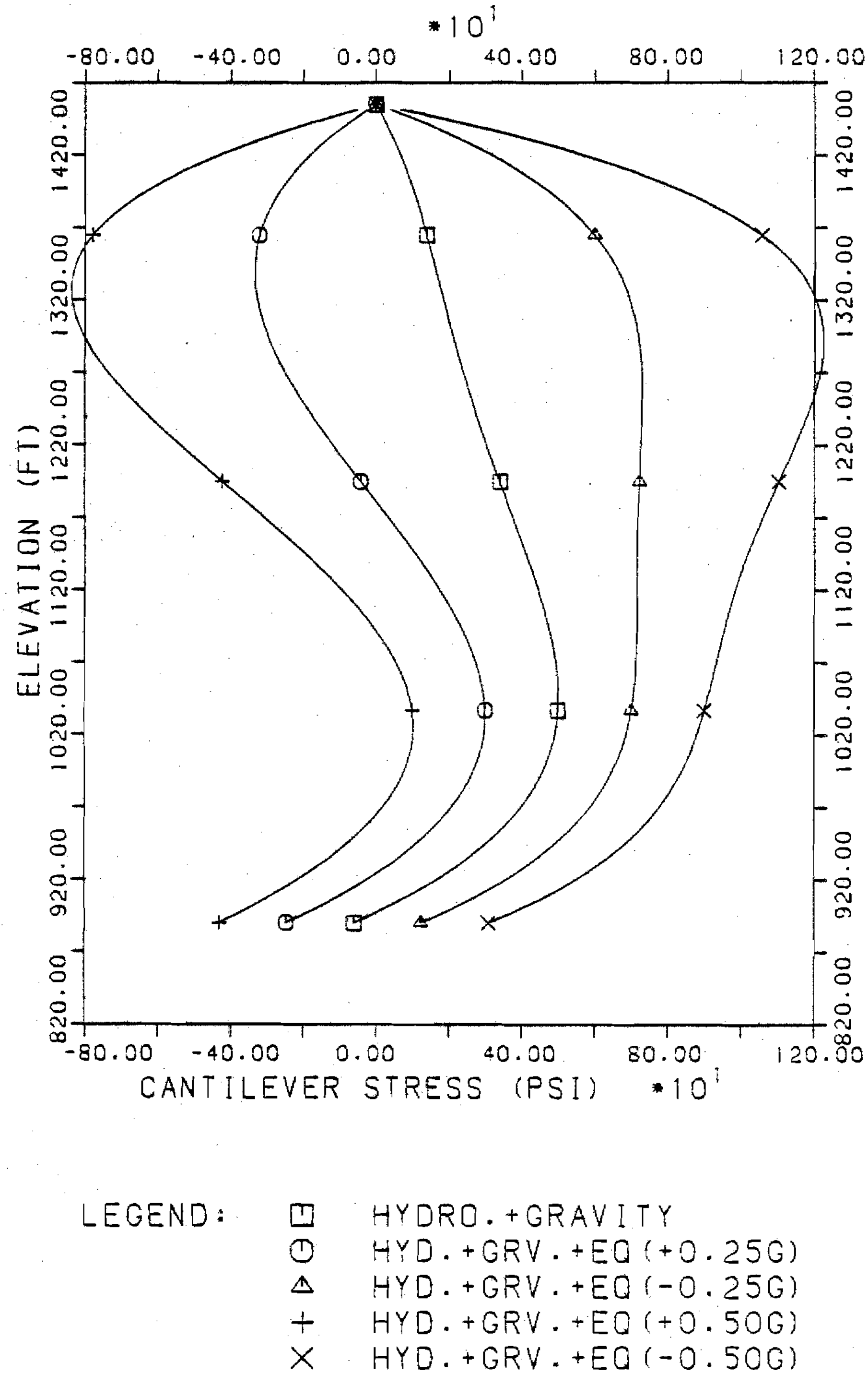


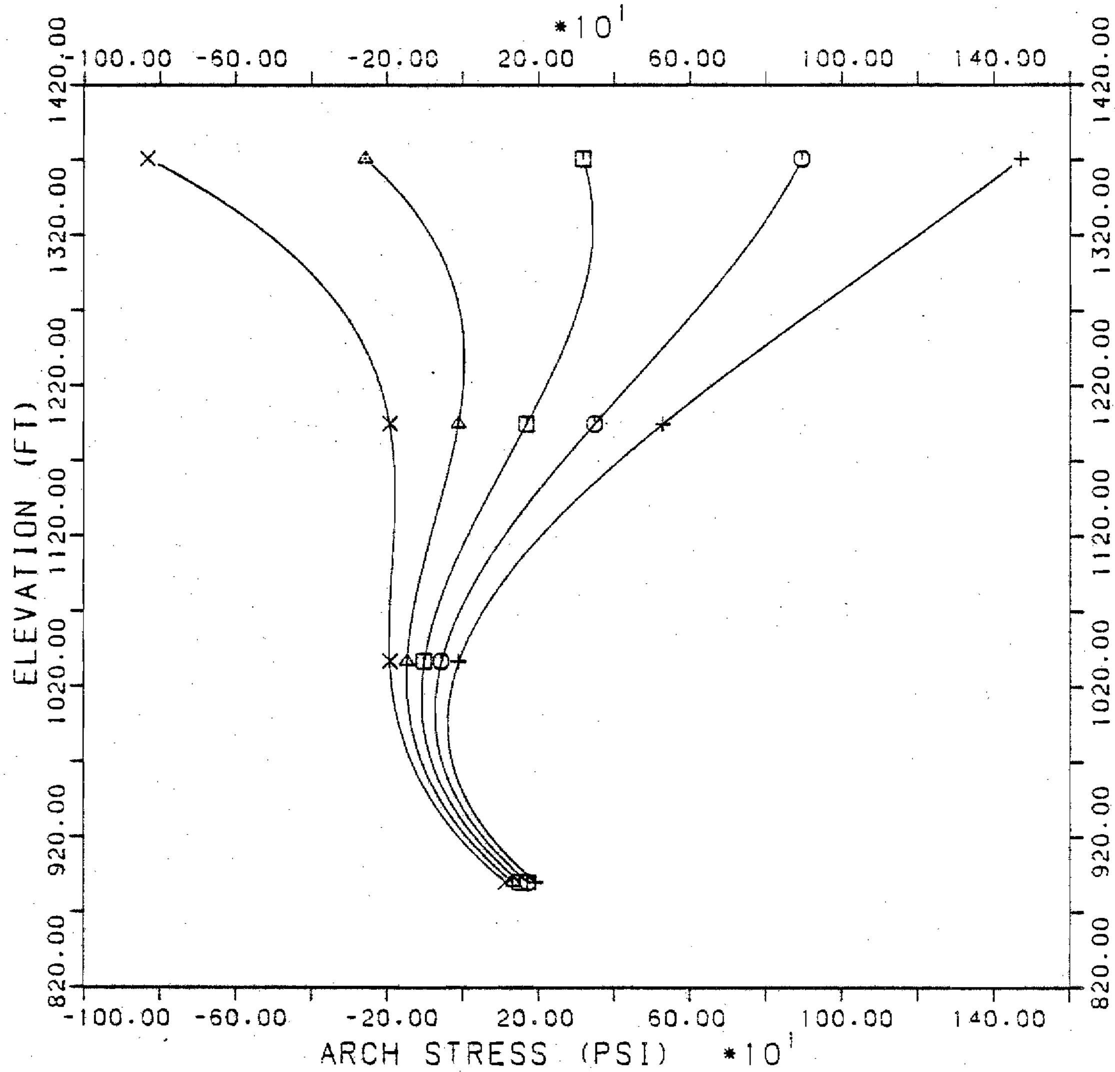
FIGURE A2

ACRES

ADAP RESULTS: SUSITNA THIN ARCH DAM

CROWN ARCH STRESSES

INTRADOS



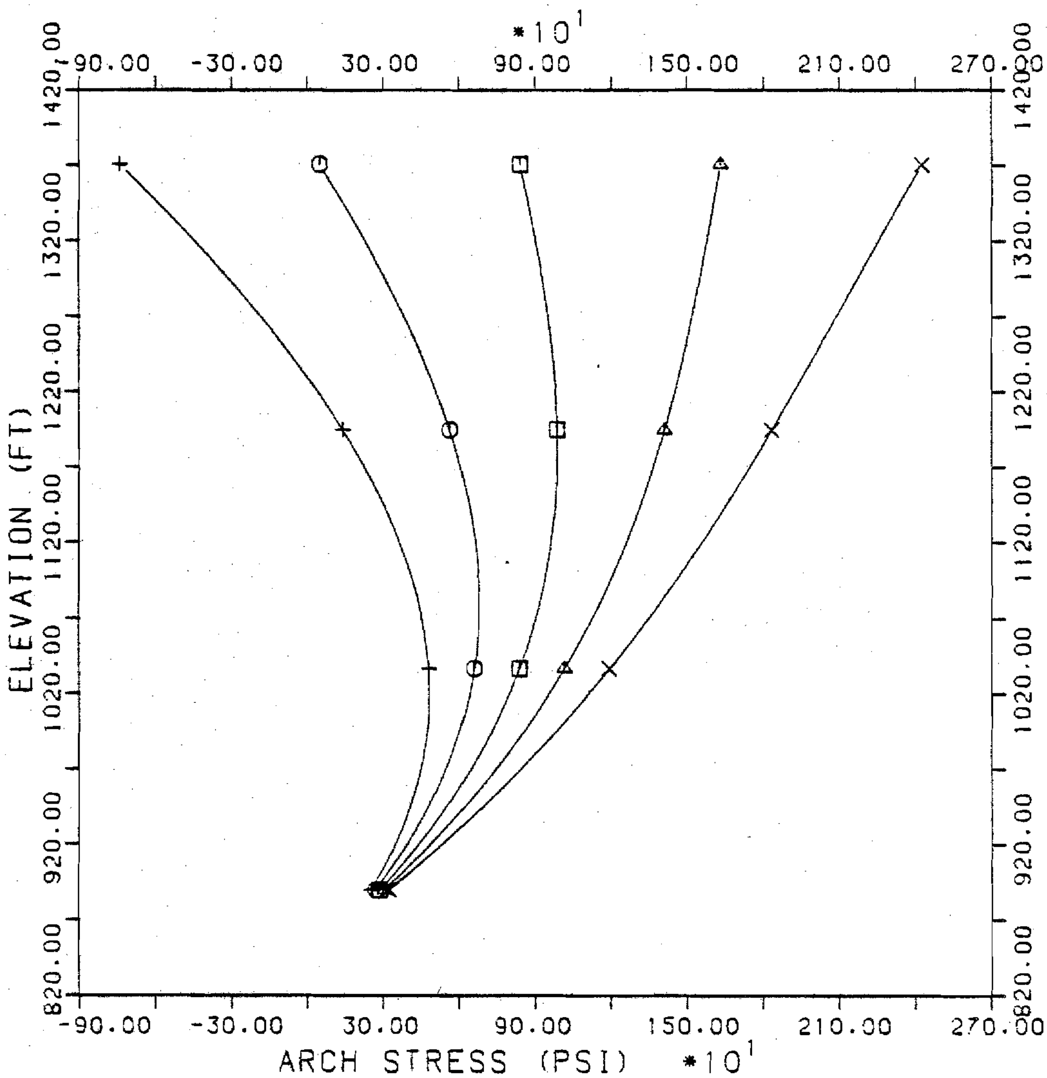
LEGEND:
- □ HYDRO.+GRAVITY
- ○ HYD.+GRV.+EQ(+0.25G)
- △ HYD.+GRV.+EQ(-0.25G)
- + HYD.+GRV.+EQ(+0.50G)
- × HYD.+GRV.+EQ(-0.50G)

FIGURE A3

ADAP RESULTS: SUSITNA THIN ARCH DAM

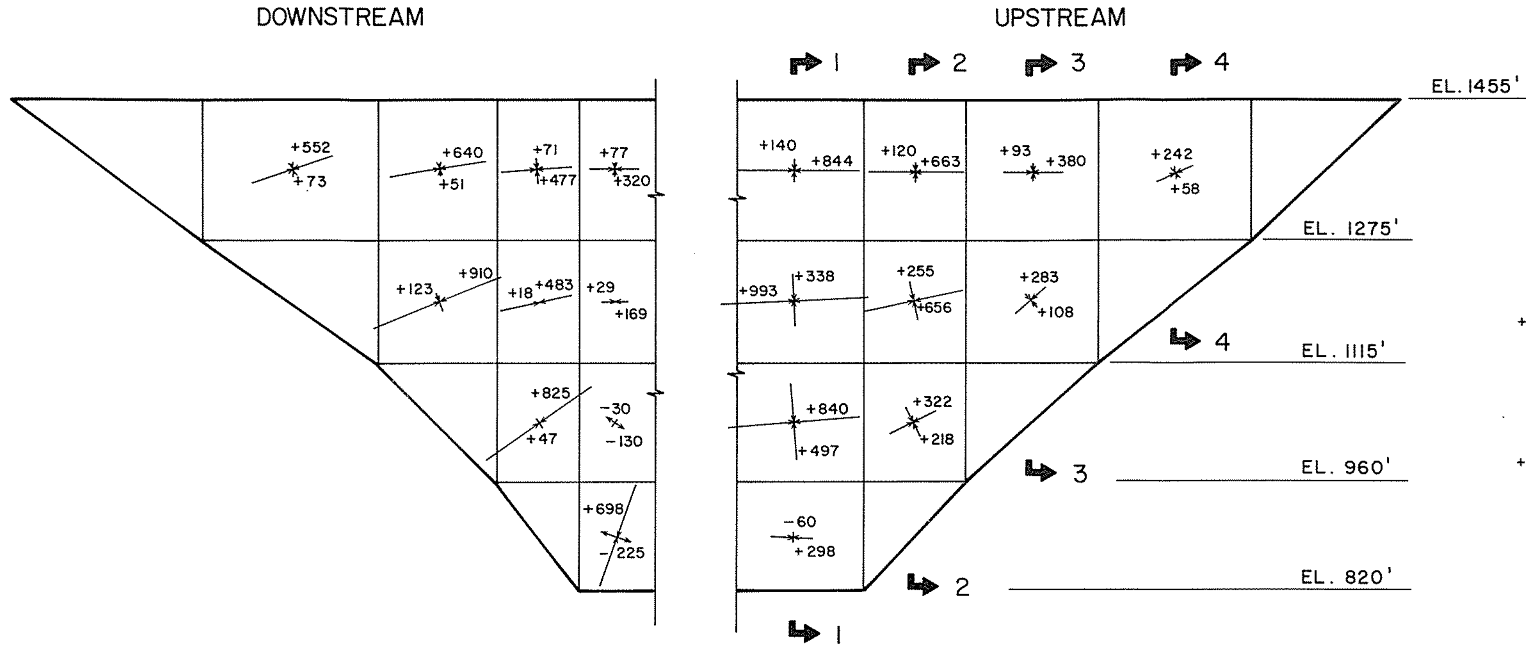
CROWN ARCH STRESSES

EXTRADOS

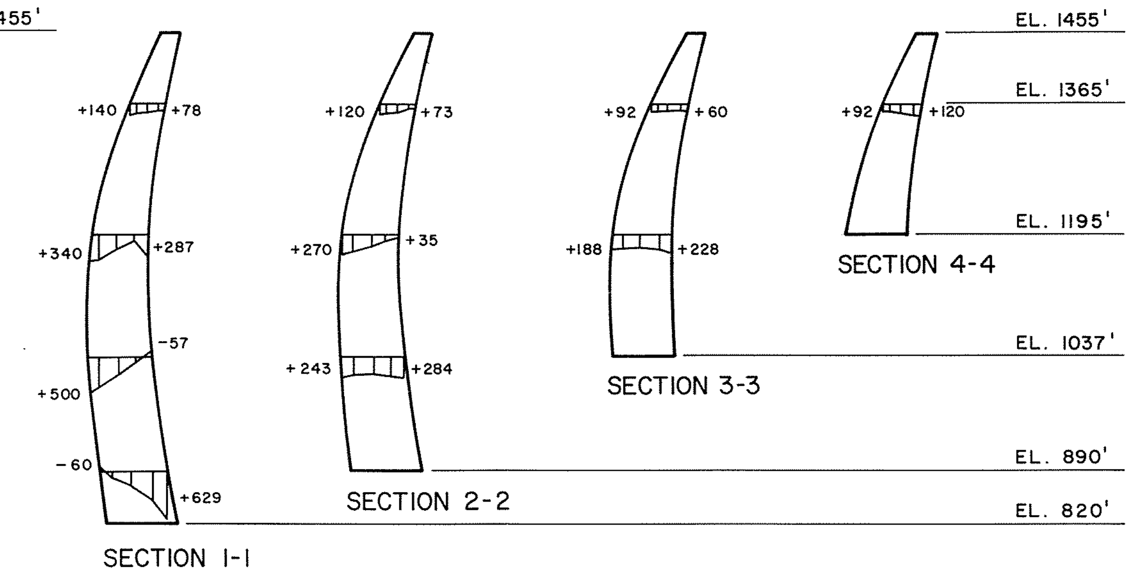


LEGEND:
- □ HYDRO.+GRAVITY
- ○ HYD.+GRV.+EQ(+0.25G)
- △ HYD.+GRV.+EQ(-0.25G)
- + HYD.+GRV.+EQ(+0.50G)
- × HYD.+GRV.+EQ(-0.50G)

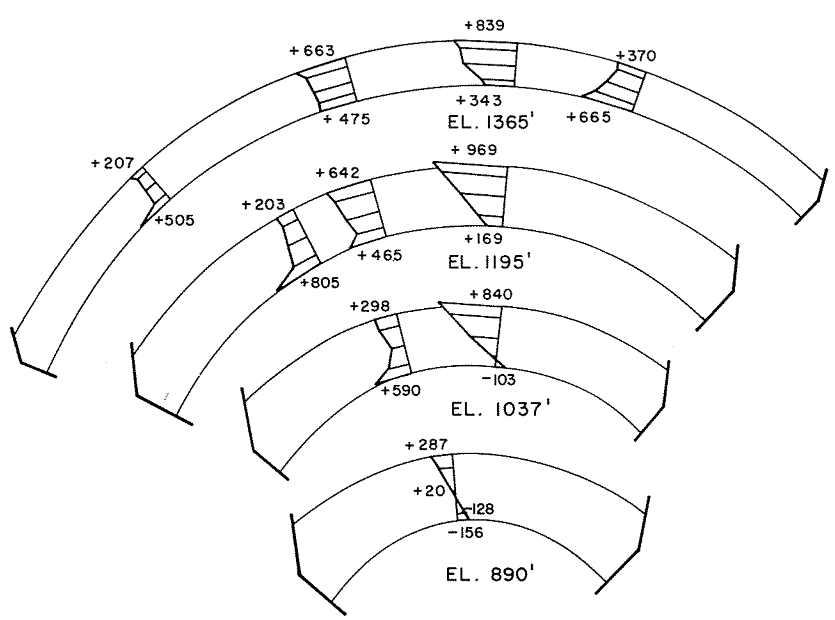
FIGURE A4



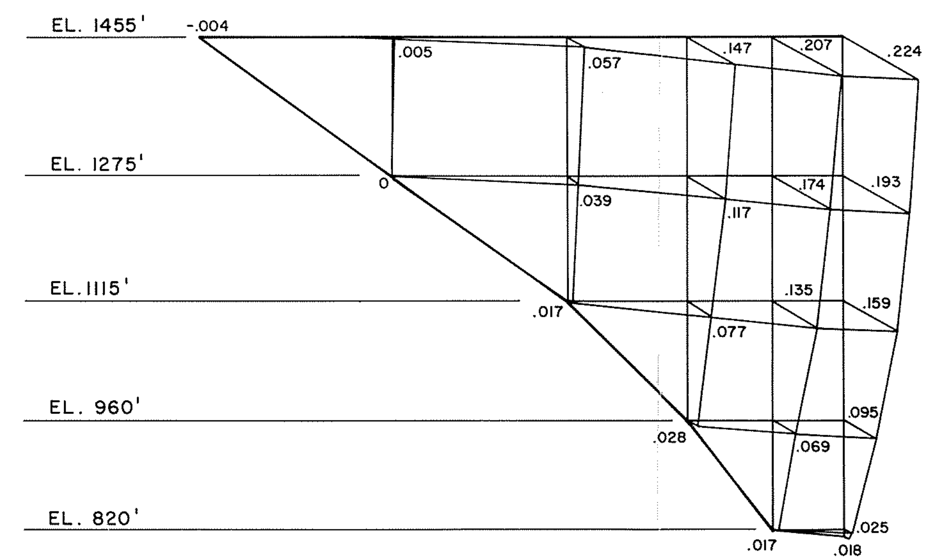
PRINCIPAL STRESSES



CANTILEVER STRESSES



ARCH STRESSES



DISPLACEMENTS (FT.)

STRESS UNITS: P.S.I.

LOADING CONDITION

- DEAD LOAD OF CONCRETE (UNJOINTED DAM)
- WATER PRESSURE WITH RESERVOIR LEVEL AT EL. 1450 FT.

PROPERTIES	CONCRETE	ROCK
UNIT WEIGHT	150 lb / ft.^{3}	
MODULUS OF ELASTICITY	5.22×10^8 psf	2.61×10^8 psf
POISSON'S RATIO	0.15	0.25

DATE	NO.	REVISIONS	CH.	APP.	APP.

PLATE A-1

ACRES

ALASKA POWER AUTHORITY

SUSITNA HYDROELECTRIC PROJECT

DEVIL CANYON
THIN ARCH DAM
STRESSES AND DISPLACEMENTS

ACRES AMERICAN INCORPORATED

DATE DEC. ,1980

SCALE

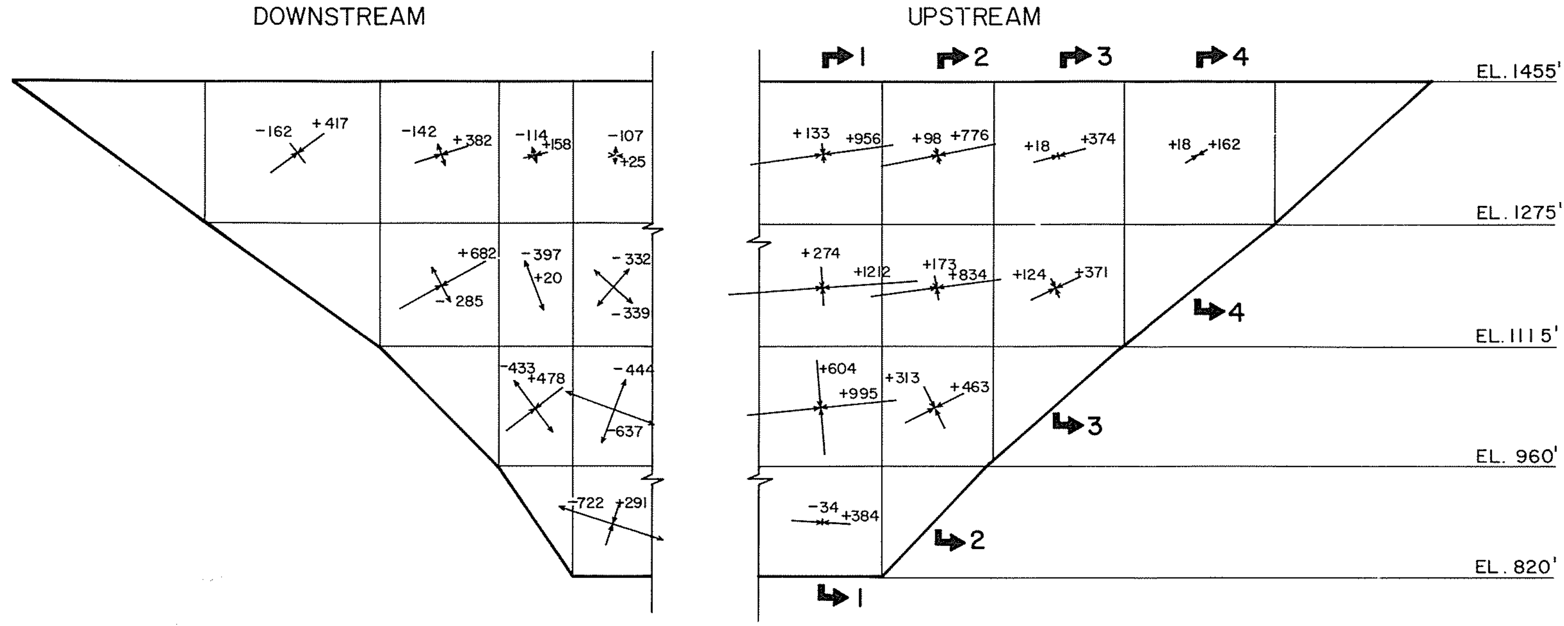
DEPARTMENT

DRAWING NO.

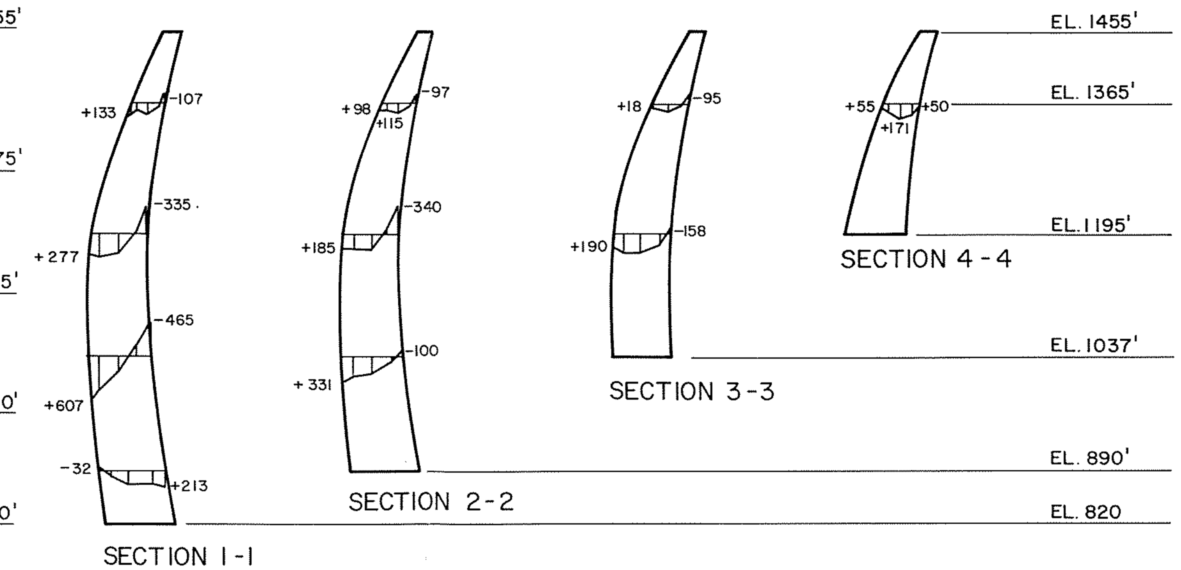
REV.

PROJECT

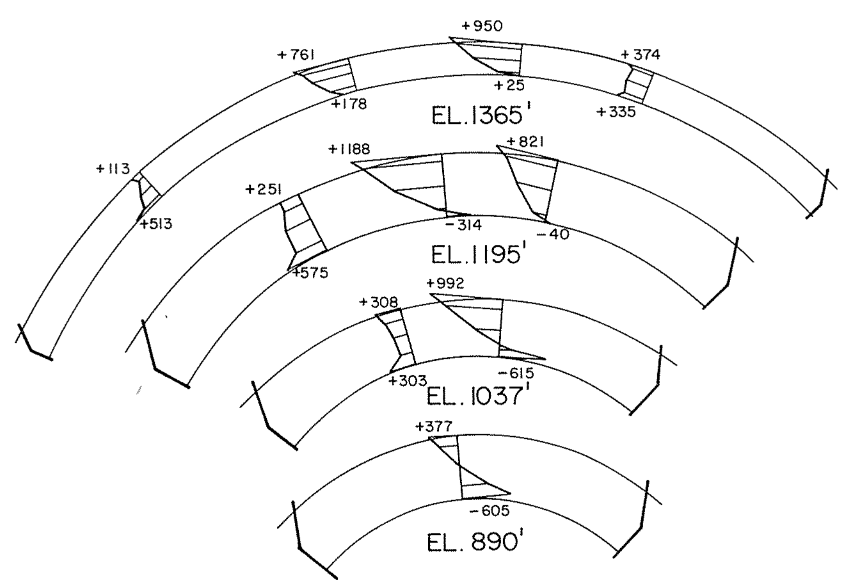
SHEET OF



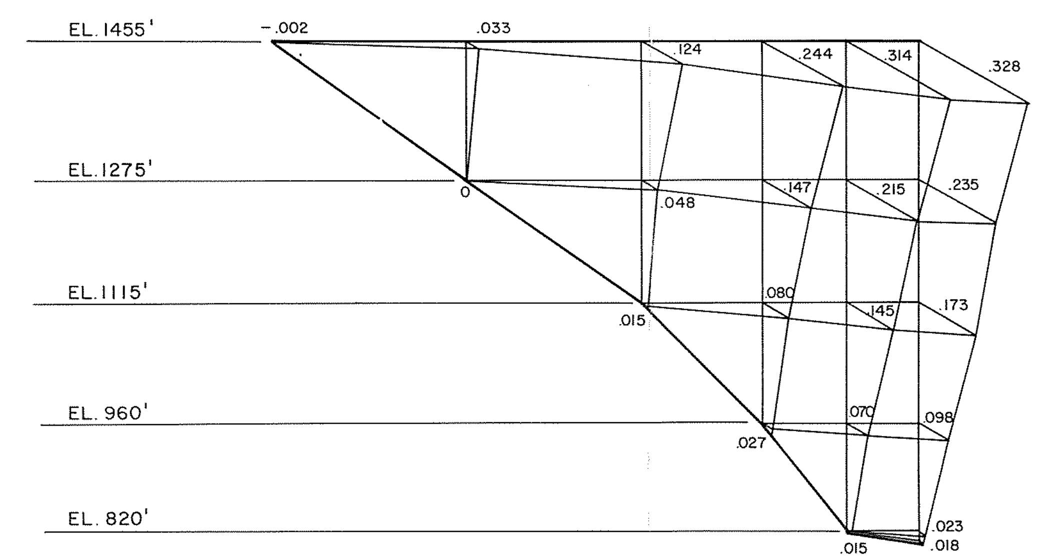
PRINCIPAL STRESSES



CANTILEVER STRESSES



ARCH STRESSES



DISPLACEMENTS (FT.)

STRESS UNITS: P. S. I.
LOADING CONDITION

- DEAD LOAD OF CONCRETE (UNJOINTED DAM)
- WATER PRESSURE WITH RESERVOIR LEVEL AT EL. 1450 FT.
- TEMPERATURES - JANUARY MEAN 4.4°F
  YEARLY MEAN 28.9°F
  GROUT TEMP. 37° F

PROPERTIES	CONCRETE	ROCK
UNIT WEIGHT	150 lb / ft.^{3}	
MODULUS OF ELASTICITY	5.22 x 10^8 psf	2.61 x 10^8 psf
POISSON'S RATIO	0.15	0.25

DATE | NO. | REVISIONS | CH. | APP. | APP.

PLATE A-2

ACRES

ALASKA POWER AUTHORITY

SUSITNA HYDROELECTRIC PROJECT

DEVIL CANYON
THIN ARCH DAM
STRESSES AND DISPLACEMENTS

ACRES AMERICAN INCORPORATED

DATE DEC. ,1980

DEPARTMENT

PROJECT

SCALE

DRAWING NO.

SHEET OF

REV.

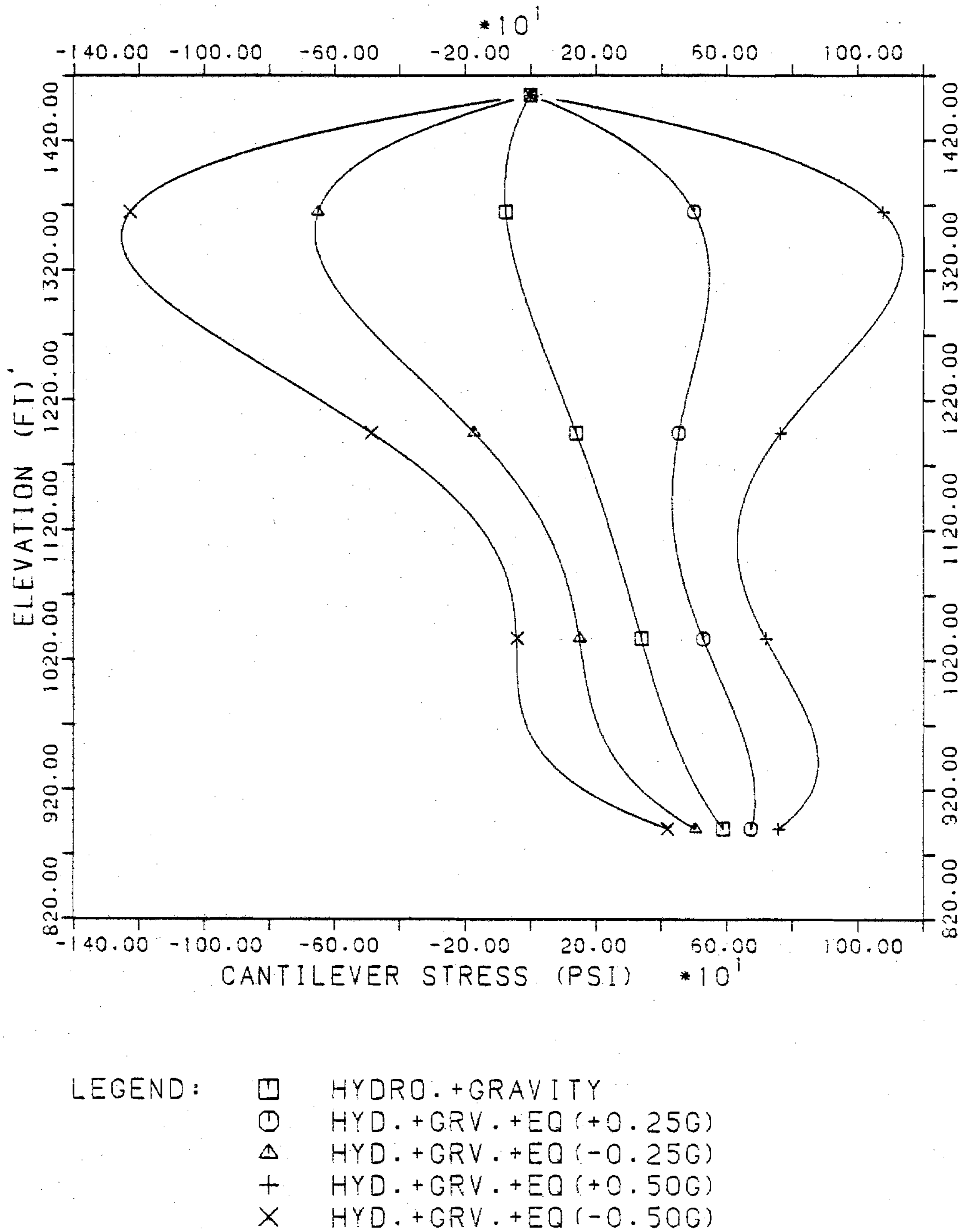
APPENDIX B

STRESSES IN GRAVITY ARCH DAM

ADAP RESULTS: SUSITNA ARCH-GRAVITY DAM

CROWN CANTILEVER STRESSES

INTRADOS



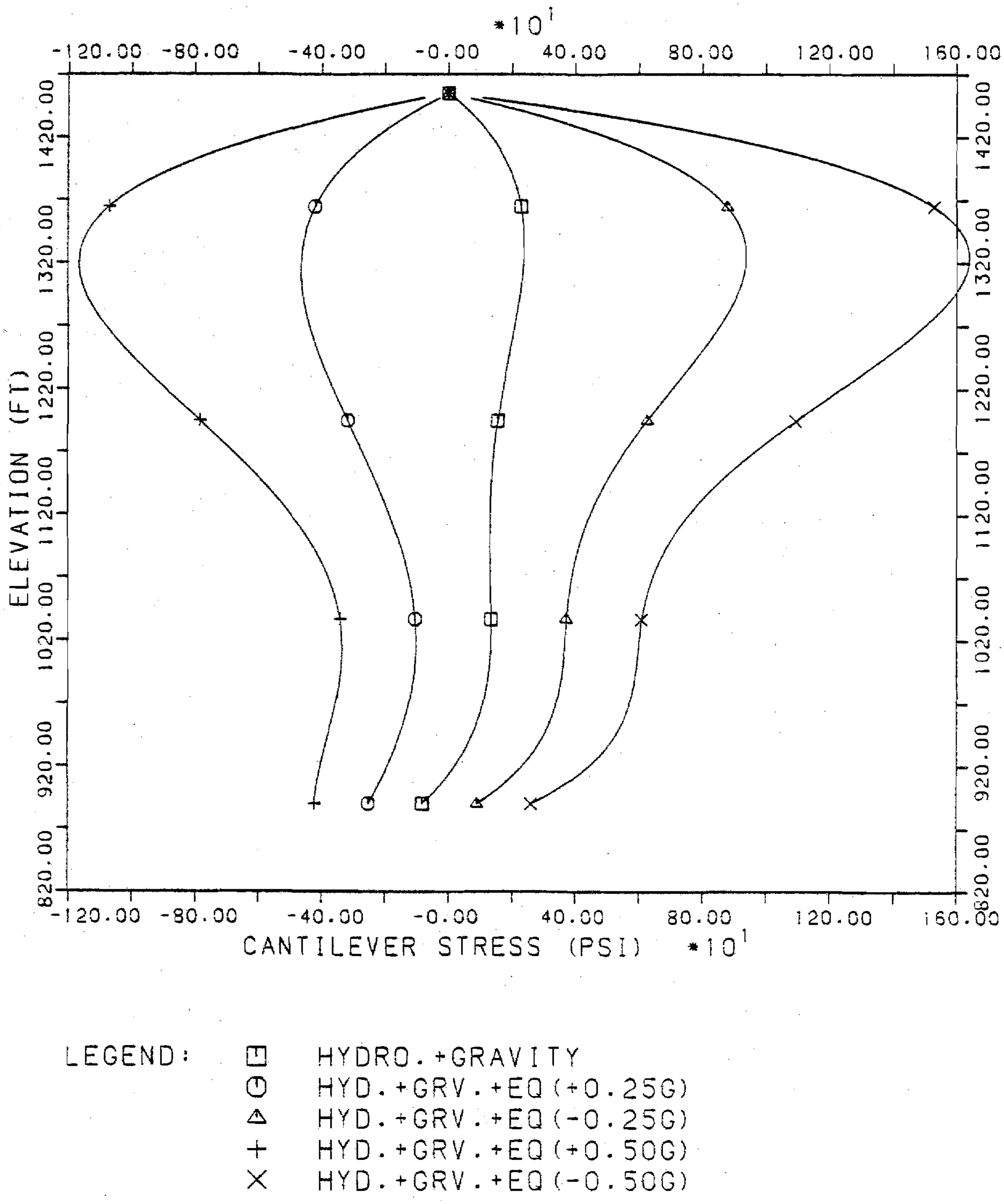
ACRES

FIGURE B1

ADAP RESULTS: SUSITNA ARCH-GRAVITY DAM

CROWN CANTILEVER STRESSES

EXTRADOS



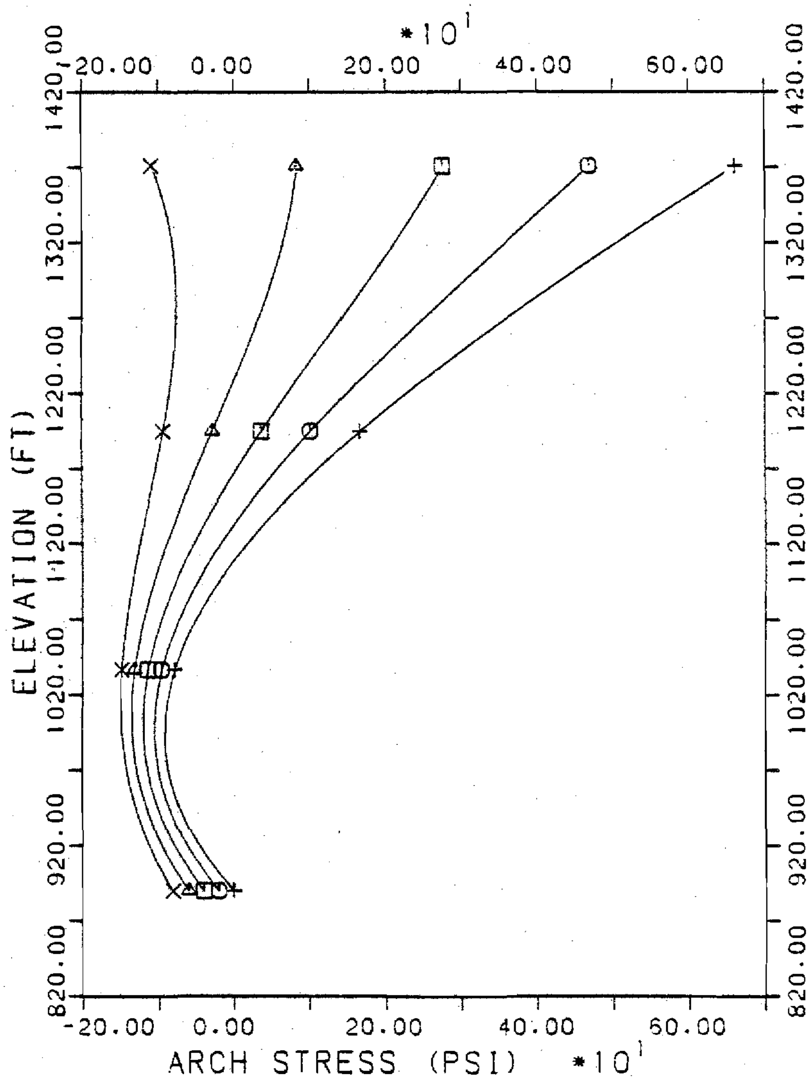
ACRES

FIGURE B2

ADAP RESULTS: SUSITNA ARCH-GRAVITY DAM

CROWN ARCH STRESSES

INTRADOS



LEGEND:
- □ HYDRO.+GRAVITY
- ○ HYD.+GRV.+EQ(+0.25G)
- △ HYD.+GRV.+EQ(-0.25G)
- + HYD.+GRV.+EQ(+0.50G)
- × HYD.+GRV.+EQ(-0.50G)

ACRES

FIGURE B3

ADAP RESULTS: SUSITNA ARCH-GRAVITY DAM

CROWN ARCH STRESSES

EXTRADOS

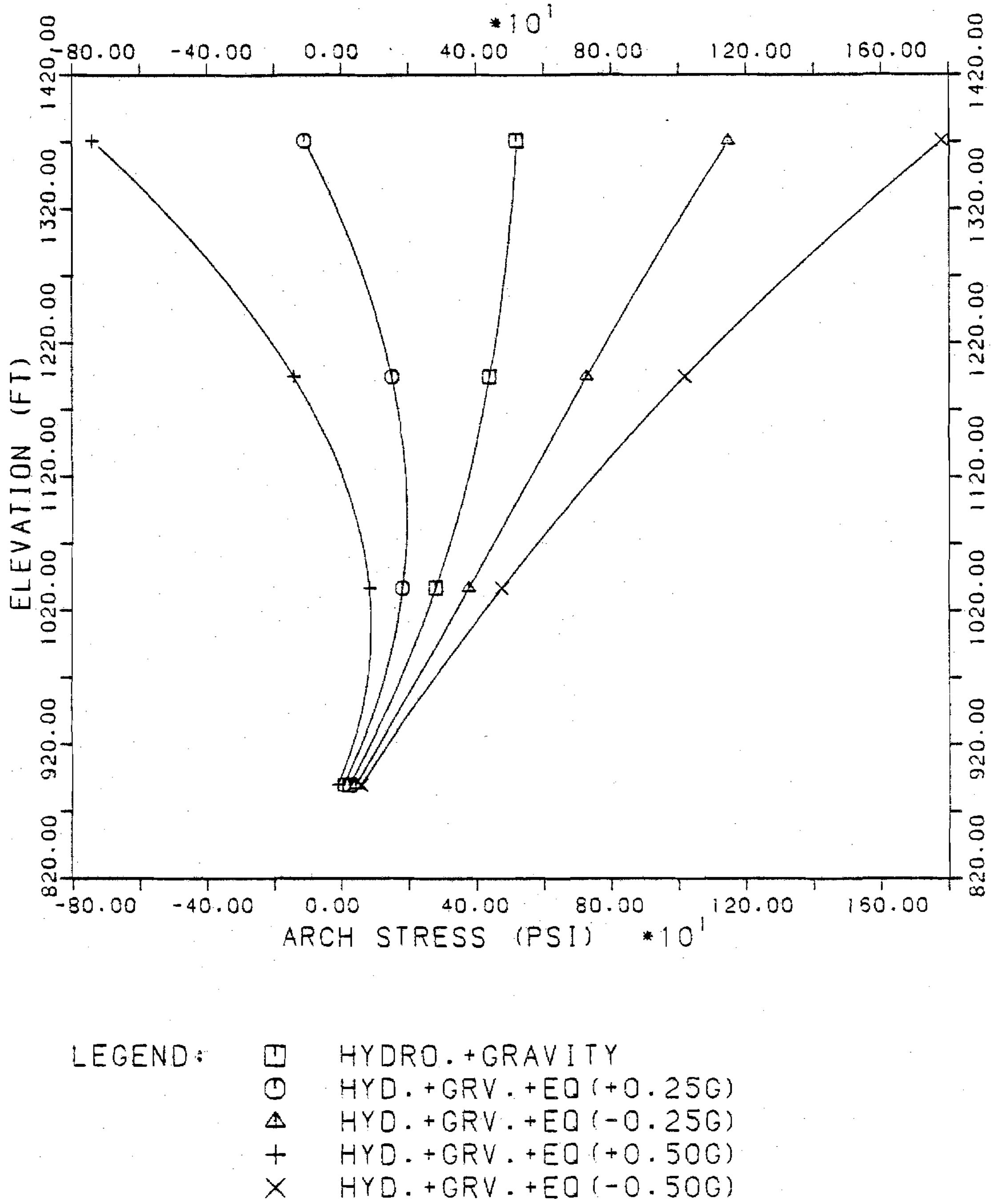


FIGURE B4

ACRES

ADAP RESULTS: SUSITNA ARCH-GRAVITY DAM

MAX. STRESSES

INTRADOS CROWN SECTION

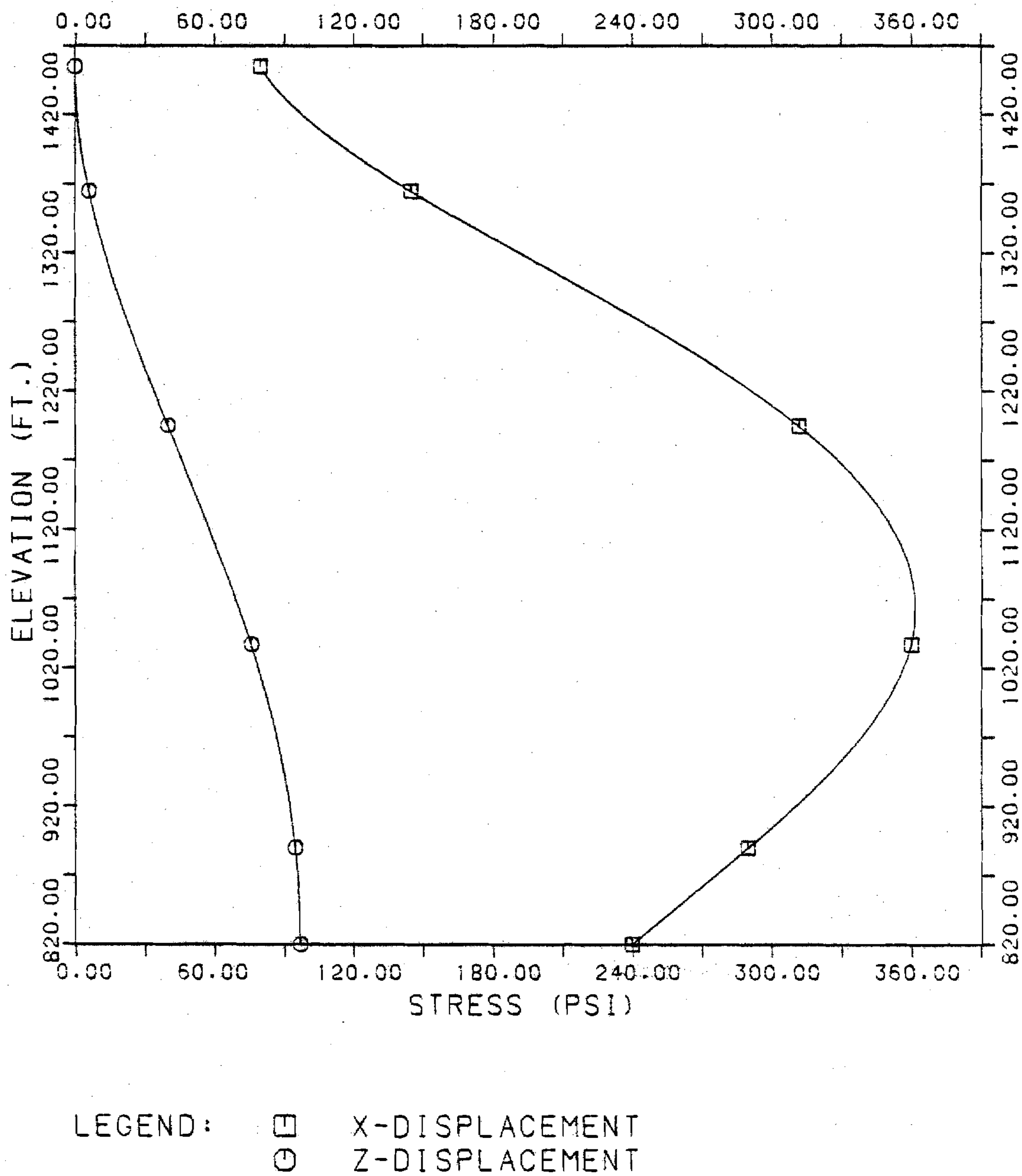


FIGURE B5

ACRES

ADAP RESULTS: SUSITNA ARCH-GRAVITY DAM

MAX. STRESSES

EXTRADOS CROWN SECTION

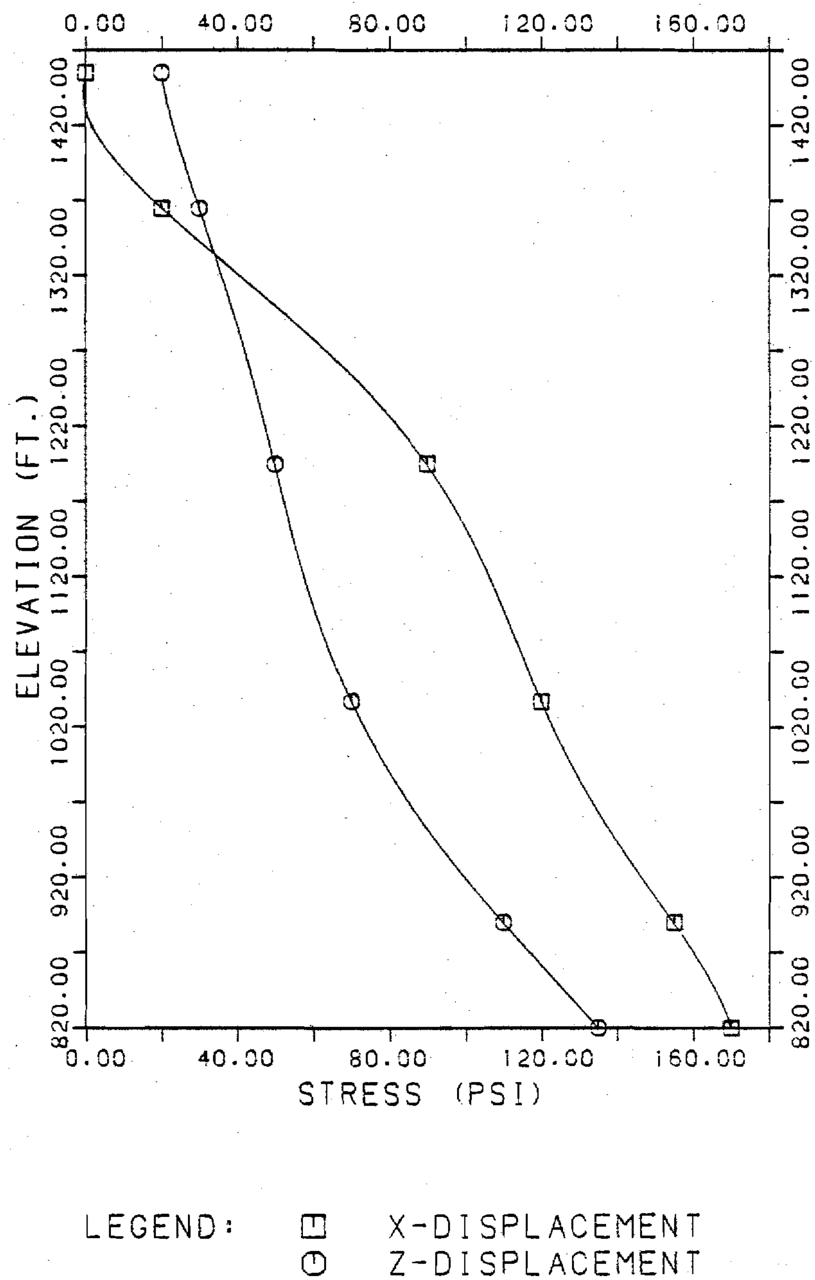
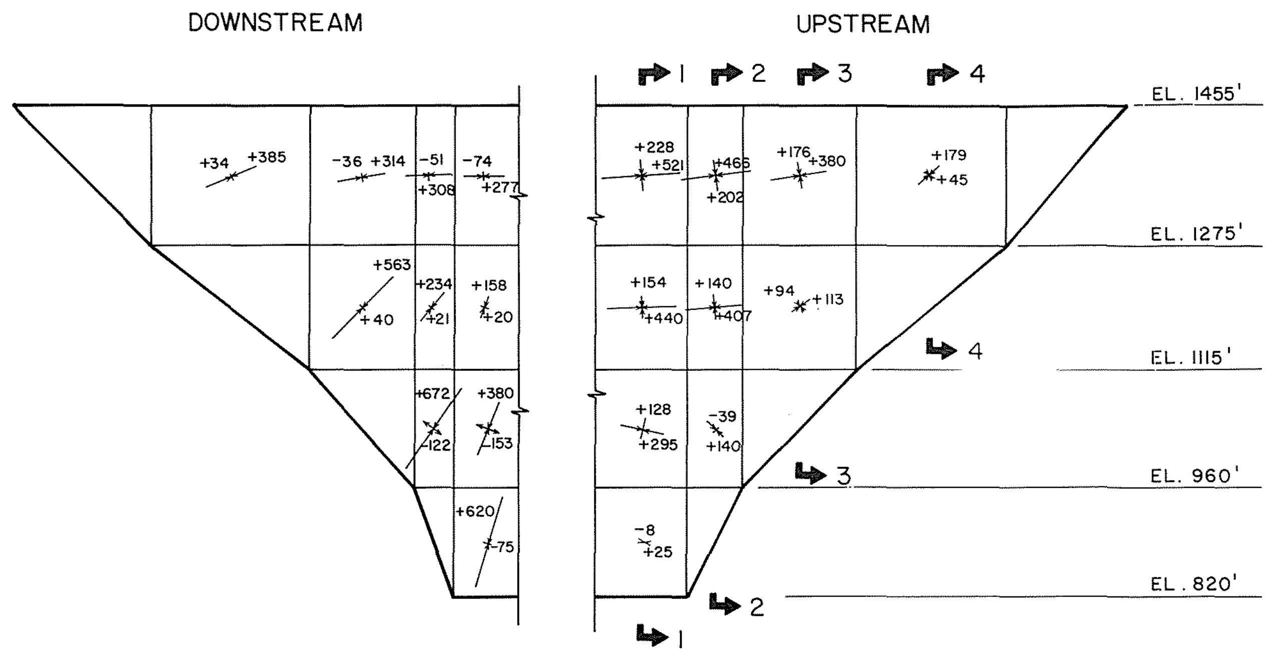
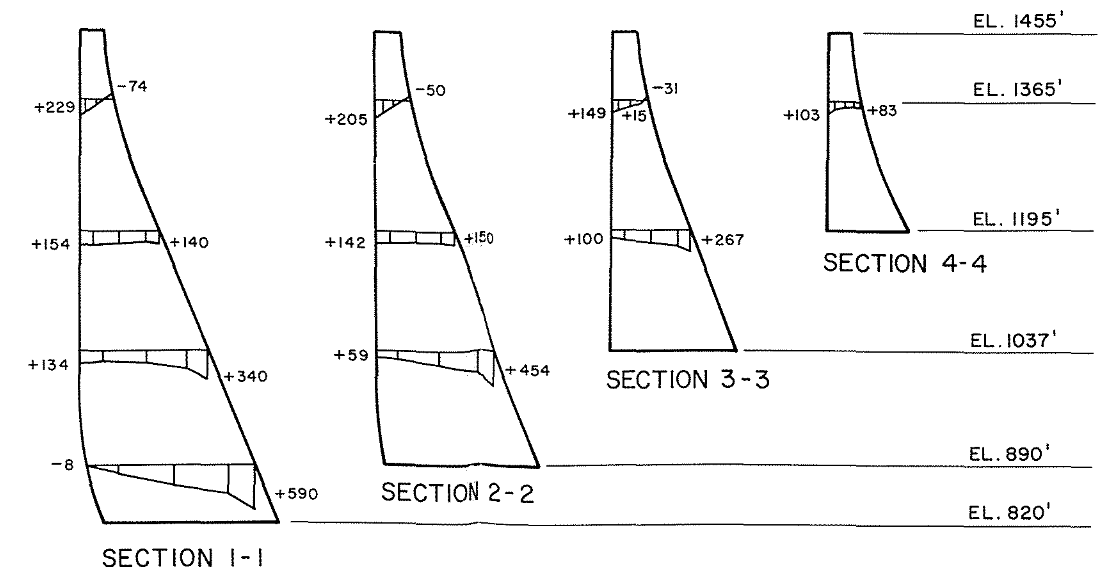


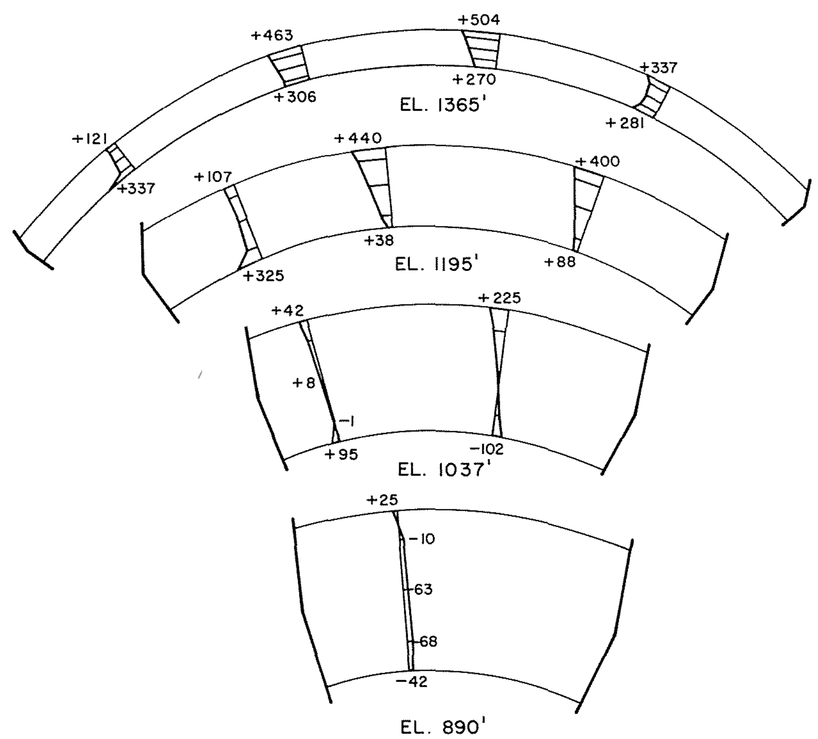
FIGURE B6



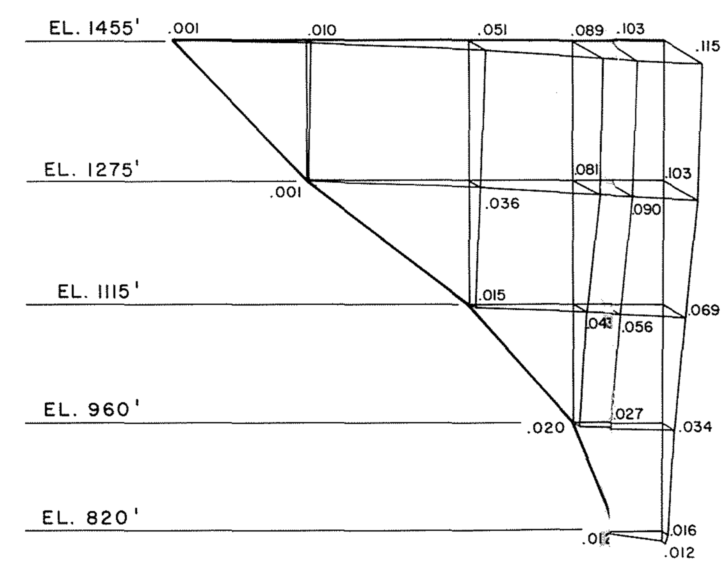
PRINCIPAL STRESSES



CANTILEVER STRESSES



ARCH STRESSES



DISPLACEMENTS (F^T)

STRESS UNITS: P.S.I.

LOADING CONDITION

- DEAD LOAD OF CONCRETE (UNJOINTED DAM)
- WATER PRESSURE WITH RESERVOIR LEVEL AT EL. 1450 FT.

PROPERTIES	CONCRETE	ROCK
UNIT WEIGHT	150 lb / ft.^{3}	
MODULUS OF ELASTICITY	5.22×10^8 psf	2.61×10^8 psf
POISSON'S RATIO	0.15	0.25

PLATE B-1

ACRES

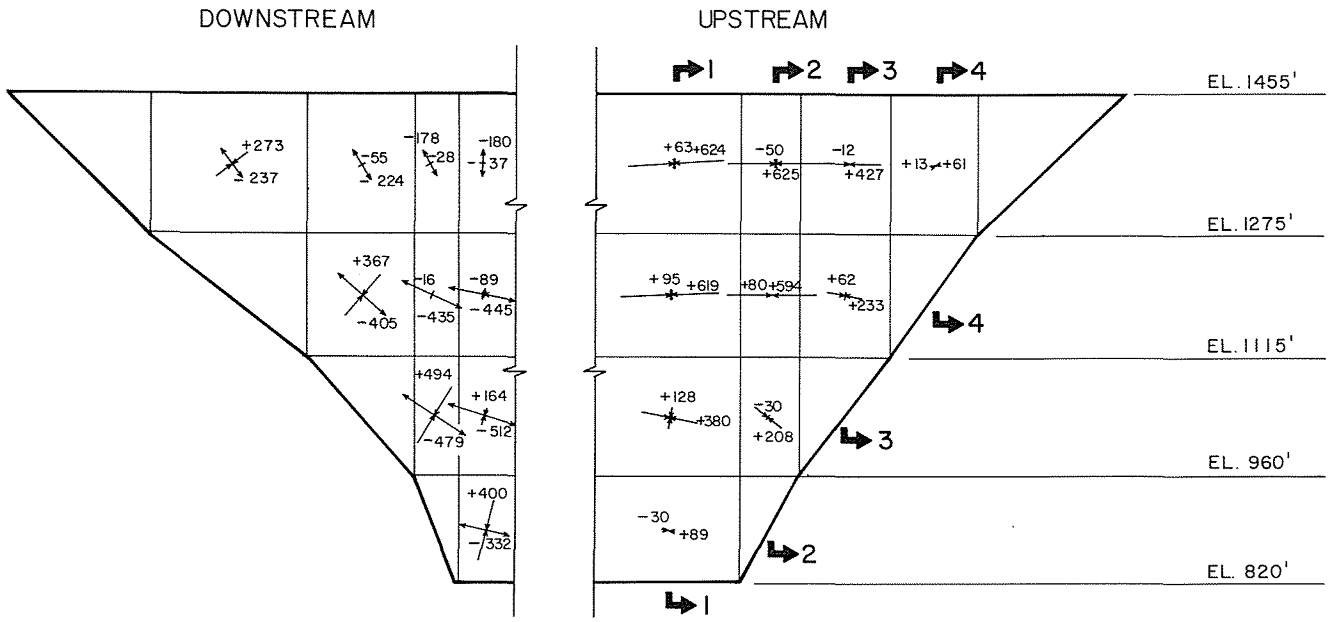
ALASKA POWER AUTHORITY

SUSITNA HYDROELECTRIC PROJECT

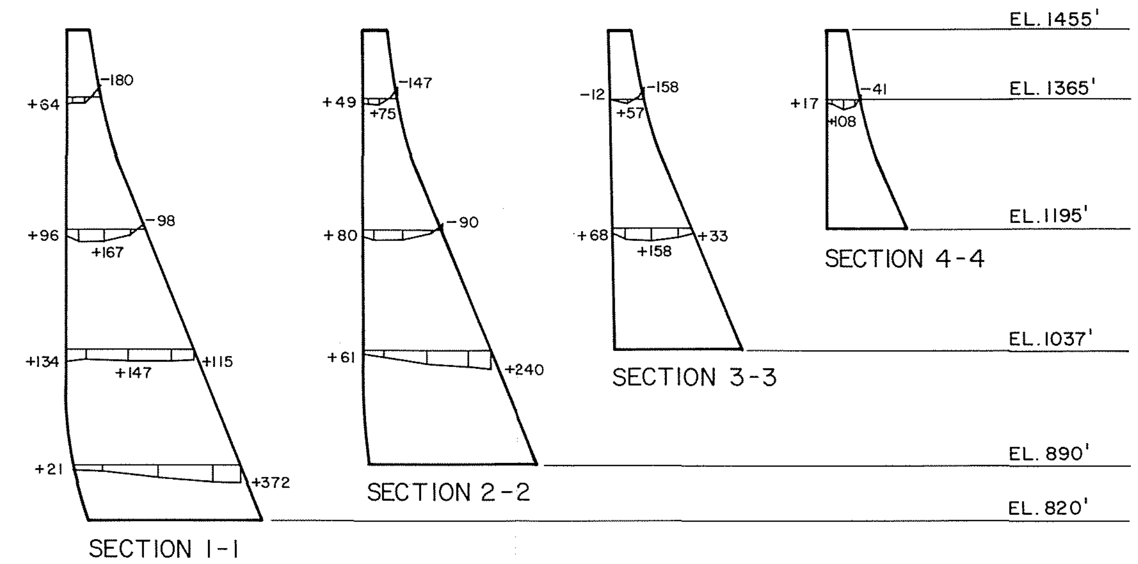
DEVIL CANYON
ARCH GRAVITY DAM
STRESSES AND DISPLACEMENTS

DATE DEC. 1980

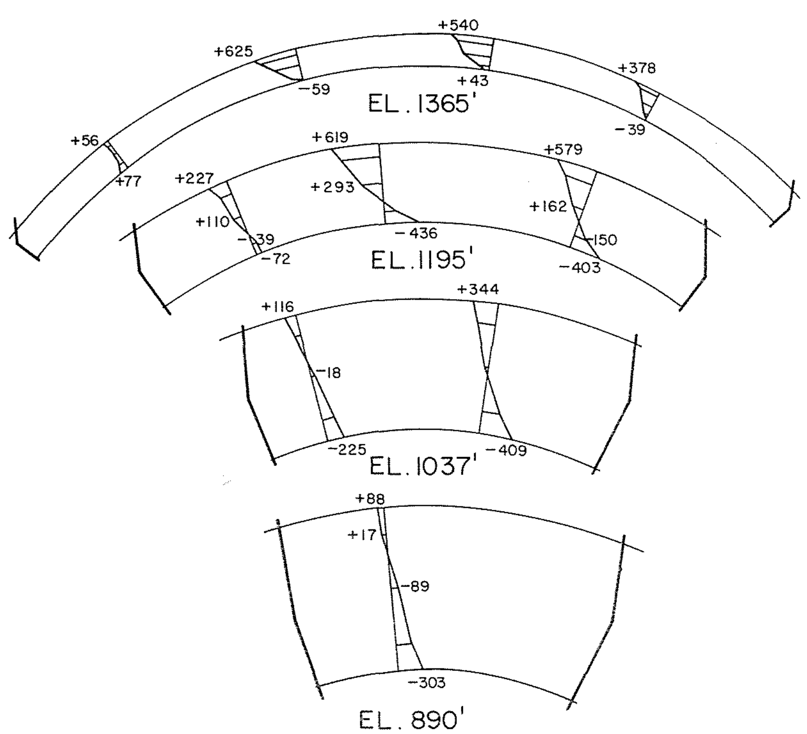
ACRES AMERICAN INCORPORATED



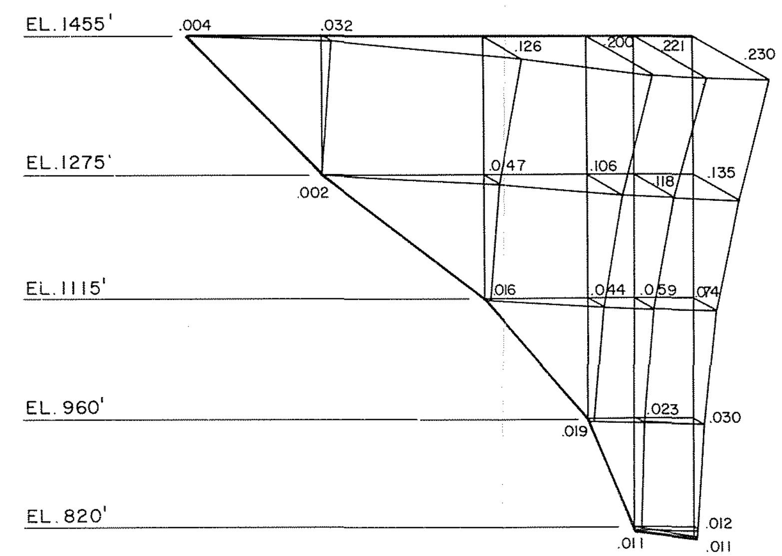
PRINCIPAL STRESSES



CANTILEVER STRESSES



ARCH STRESSES



DISPLACEMENTS (FT.)

STRESS UNITS: P.S.I.
LOADING CONDITION

- DEAD LOAD OF CONCRETE (UNJOINTED DAM)
- WATER PRESSURE WITH RESERVOIR LEVEL AT EL. 1450 FT.
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  YEARLY MEAN 28.9°F
  GROUT TEMP. 37° F

PROPERTIES	CONCRETE	ROCK
UNIT WEIGHT	150 lb / ft.^{3}	
MODULUS OF ELASTICITY	5.22×10^8 psf	2.61×10^8 psf
POISSON'S RATIO	0.15	0.25

DATE	NO.	REVISIONS	CH.	APP.	APP.

PLATE B-2

ACRES

ALASKA POWER AUTHORITY

SUSITNA HYDROELECTRIC PROJECT

DEVIL CANYON
ARCH GRAVITY DAM
STRESSES AND DISPLACEMENTS

ACRES AMERICAN INCORPORATED

DATE DEC. 1980 | SCALE | DEPARTMENT | DRAWING NO. | PROJECT | SHEET OF | REV.