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COMPACTED EARTH CANAL LININGS OF LOW-PLASTICITY SOIL

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16. ABSTRACT

In 1983 Reclamation began the final design and construction of the North Loup Division of the Pick-Sloan Missouri Program in Nebraska. The project included several canals (Mirdan, Fullerton, and Elba) which have loessial surface material. The loess is mostly a silt or silty clay which will not only be the foundation for the canals but will also be used for the compacted earth lining and embankment. This material generally has a PI (plasticity index) of less than 10, which is lower than the minimum recommended in figure 108 of Reclamation's *Earth Manual* (Second Edition), and could be highly erodible. To determine the suitability of the material, observations were made of existing canals that had linings with low-plasticity material, and existing literature and past studies were reviewed.

Observations indicated that some canals with low-plasticity lining performed satisfactorily, although all the canals required additional side slope protection (riprap or gravel). The additional protection was placed primarily downstream from in-line structures and on the outside of curves. Additional protection was also placed along some of the straight reaches.

A monitoring program has been established on Mirdan and Geranium Canals in Nebraska and on Dove Creek and South Canals in Colorado to monitor the long-term performance of earth linings.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

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CONTENTS

CONTENTS - continued

Page

TABLES

Table

FIGURES

Figure

CONTENTS - continued

GLOSSARY

A	area of water prism (ft^2)
b	bottom width (ft)
d	normal depth (ft)
G_s	specific gravity
H	canal bank height
LL	liquid limit
n	Manning's coefficient used in design
O.G.S.	original ground surface
PI	plasticity index
Q	design flow (ft^3/s)
r	hydraulic radius
s	longitudinal canal slope
ss	side slope, H (horizontal) to V (vertical)
T	lining thickness (ft)
TF	average tractive force (lb/ft^2) (also called tractive stress) estimated by the following equation: TF = w x d x s
USCS	Unified Soil Classification System
v	velocity (ft/s)
w	unit weight of water (62.4 lb/ft^3)

INTRODUCTION

Earth canal linings are installed primarily to prevent loss of water by seepage. In choosing an earth lining material, an engineer looks for the following features: (1) impermeability, (2) resistance to wave action, (3) resistance to erosion, (4) economical availability, and (5) stability during freezing and thawing.

This investigation was initiated at the start of design of Mirdan Canal in Nebraska to study the suitability of low-plasticity earth material for thick, compacted earth linings. Low-plasticity material is defined as a silt, sand, or clay soil, or any combination thereof, with a PI (plasticity index) less than 12 percent. Designers consider these soils to be of low permeability but subject to erosion unless protected or modified, or unless the maximum water velocity and tractive force (tractive stress) are limited.

The investigation initially consisted of (1) a literature search to review previous studies and articles concerning the erosion or erosion resistance of earth linings, and (2) field investigations to review the performance of several existing low-PI earth canal linings throughout Reclamation. The projects investigated are listed in table 1. The study has been expanded to establish observation reaches in canals currently under construction. Observation reaches were installed in Mirdan and Geranium Canals in Nebraska and in Dove Creek and South Canals in Colorado. The earth lining for Dove Creek and South Canals is more plastic and has properties within current Reclamation guidelines. A full description of the observation reaches in the new canals is given in appendix B. Periodic observation of these reaches over the next 30 to 50 years will increase Reclamation's ability to estimate the durability and lifespan of earth linings.

DISCUSSION

Current Reclamation Criteria and Guidelines

Current Reclamation design criteria for thick, compacted earth linings are given in three publications: (1) *Earth Manual* (Bureau of Reclamation, 1980), (2) *Design Standards No. 3 - Canals and Related Structures* (Bureau of Reclamation, 1967), and (3) *Linings for Irrigation Canals* (Bureau of Reclamation, 1963).

The *Earth Manual* (p. 263) gives plasticity criteria for impervious, erosion-resistant, compacted earth linings: (1) the LL (liquid limit) should be less than 45, (2) the PI should be above 10, (3) a plot of the LL and PI should be above the "A" line, and (4) a PI of 12 or more is preferred. These criteria are shown on figure 1. The *Earth Manual* (p. 189) states that the best material for an earth lining would be a well-graded gravel with plastic fines (GW-GC) and that a clayey gravel (GC) or silty gravel (GM) would also be good. These materials would be impervious and would provide erosion protection when properly compacted.

Figure 8 of the *Earth Manual* gives the important engineering properties and relative desirability for various uses of typical soil groups. According to the *Earth Manual*, erosion is critical in coarser fine-grained material of low plasticity (SM and ML). When satisfactory soils are not available, soil must be manufactured by blending, modified with additives, or the fine-grained soil must be protected with a blanket of sand and gravel (*Earth Manual*, p. 189). Figure 2 shows a typical Reclamation canal section with a thick, compacted earth lining.

According to *Design Standards No. 3* (Bureau of Reclamation, 1967), the velocity in unlined canals ordinarily varies from 1.0 to 3.5 ft/s, and the velocity in an earth-lined canal may be as high as 4.0 ft/s. On a longitudinal canal curve, the minimum radius to canal centerline should be from three to seven times the water surface width if erodible linings are used. The smaller ratio is normally suited for small canals while the larger ratio is needed for large canals. *Design Standards No. 3* give nonsilting, nonscouring velocities for unlined canals, which are based on the Kennedy formula (Lane, 1952) for sediment-laden water flowing in a bed of similar material. These criteria for unlined canals have also been used for earth-lined canals.

Data presented in *Linings for Irrigation Canals* (Bureau of Reclamation, 1963) indicate that water losses in a well-compacted, homogeneous, thick earth lining should be as low as 0.07 ft^3/ft^2 per day. Thick, compacted earth linings are constructed in compacted lifts of no more than 6-inch depth and are compacted to 95 percent of Proctor unit weight. Sheepsfoot rollers are commonly used to compact the material properly and to provide a good bond between soil layers.

Current Study

Past development of Reclamation design criteria for earth canals. - Since the 1930's, Reclamation has been developing procedures for designing unlined and earth-lined canals. Past design guidelines and criteria have been based upon (1) studies of Reclamation canals, (2) studies of channels by others, and (3) laboratory tests using a tractive force machine. Objectives of canal and earth lining design procedures are to provide an impermeable lining with an economical section in which scour and sediment deposits will not occur.

Much of the work up to the early 1950's is presented by Lane (1952). Figure 3 gives Lane's critical tractive force for noncohesive material as determined by several investigators. For allowable velocities and tractive forces in cohesive material, Lane refers to studies done by Etcheverry (table 2), Fortier and Scobey (table 3), and the U.S.S.R. (tables 4 and 5). The tractive forces given in tables 2, 3, and 4 were not provided in the original articles but were estimated by Lane. Figures 4 and 5 aid in calculating the tractive force on a canal invert or on side slopes.

In 1954, Reclamation published an interim report by Holtz (1954) which gave a minimum allowable PI of 7 percent.

Reclamation conducted a field investigation and laboratory test program in the late 1950's, which is documented in a series of three progress reports (Merriman and Enger, 1957, 1958; Bureau of Reclamation, 1960). Based on these progress reports, two procedures were developed for determining the suitability of canal lining material. The procedures were based on erosion tests with the circular tank tractive force machine developed and used in the studies of the 1950's (Merriman and Enger, 1958). The tractive force machine was a 3-foot-diameter tank with a three-bladed impeller rotating inside. An 8-inch-diameter earth sample was placed in the bottom of the tank so that the top of the sample was flush with the bottom of the tank. The tank was then filled with water and the impeller rotated with the speed gradually increasing until erosion of the sample was observed. The tractive force on the sample when erosion was observed was estimated from the rotational speed of the impeller.

The first design procedure was based on general guidelines for the suitability of a material using PI and LL as the significant soil properties. A report titled *A Study of Erosion and Tractive Force Characteristics in Relation to Soil Mechanics Properties* (Gibbs, 1962) is the basis of the *Earth Manual* plasticity criteria for impervious, erosion-resistant, compacted earth linings. Figure 6 shows the trend developed in the report. Gibbs's report also advanced the following conclusions:

1. For the fine-grained cohesive soils analyzed in the current erosion and tractive forces studies, it is concluded that the plasticity characteristic is the principal property for evaluating the erosion resistance.

2. The suggested criteria for the evaluation on the basis of plasticity are given on figure 6. The criteria given in this figure cover only the soil types for which supporting data were available. It is apparent that both the LL and PI should be considered because of the diagonal distribution for the different soils on the plasticity chart which involves both liquid limit and plasticity index.

3. For the fine-grained cohesive soils studied, it was concluded that correlations with gradations would not significantly improve the evaluation criteria because practically all the soils studied had more than 80 percent passing the No. 40 sieve and, therefore, the effects of gradation would be reflected in the plasticity characteristics.

4. It was noted that unit weight had some effect on erosion resistance but not as pronounced an effect as plasticity. For the fine-grained cohesive soils investigated, unit weight values indicated that most of the soils were very loose. A loose condition would be an expected common occurrence for near-surface soils of a canal which are subject to erosion, indicating that little reliance should be placed on this property for near-surface erosion resistance.

5. These results support previous opinions from experience regarding the use of limiting plasticity characteristics as a controlling property for evaluating erosion resistance of fine-grained cohesive soils for earth linings. Holtz (1954) indicated that soils with a PI of less than 7 were not considered entirely suitable for small canals and a limiting value of 10 was sometimes used for larger canals.

The procedure does not correlate the material with an allowable tractive force, velocity, other soil properties, or field conditions.

The second design procedure report, titled *Studies of Tractive Forces of Cohesive Soils in Earth Canals* (Carlson and Enger, 1962), was used to estimate an allowable tractive force, with a mathematical algorithm based on the following soil properties: (1) PI, (2) LL, (3) gradation, (4) unit weight, and (5) vane shear resistance. The correlations showed that the plastic properties, gradation, and unit weight were important in determining the safe tractive force of cohesive soil.

Field investigations of existing canals. -

1. **General.** - Field investigations were limited to canals of 50 ft^3/s or greater since it is current Reclamation practice to use concrete lining for all canals with a capacity less than 50 ft^3/s. The canals investigated are listed in table 1. The investigations consisted of site visits to determine the performance of the earth linings. The canals were inspected visually, excavations were cut into the lining, and cross sections of the canals were taken.

The classification of canal performance relied partially on the amount of gravel or riprap protection observed on the canal side slopes and invert. Gravel or riprap protection, however, was added to the side slopes and invert for the following reasons: (a) to reduce erosion by flow, (b) to reduce erosion by wave action, (c) to stabilize slopes, (d) to control weed growth, and (e) to improve appearance. Maintenance personnel provided guidance on factors leading to the placement of the protection.

Performance of the earth linings observed during the present studies is shown on figure 7. The observations indicate that earth lining materials with PI's from 3 to 12 percent perform satisfactorily (with slight to moderate erosion) if the tractive force is 0.055 lb/ft^2 or less. However, observations of existing canals indicate that a greater length of protection than is currently required should be mandatory downstream of structures and that protection should be required on the outside slopes of canal curves. Many straight reaches of canal also required slope protection. It is current Reclamation practice to estimate the cost of a "beach belt" gravel protection for all earth linings when doing an economic comparison with other lining types. The beach belt protection may be added during construction or at a later date, where required, by maintenance personnel.

2. **Madera Irrigation District.** - The Madera Irrigation District is located approximately 14 miles northwest of Fresno, California. Laterals 6.2 and 32.2 were investigated. The laterals, which turn out water from the Madera Canal, were constructed in the early 1950's and had been in service for approximately 30 years at the time of the observation. The flow was measured at the upstream end of each lateral. Some flow data are presented in appendix A to give an indication of how flow varied throughout the year. Flow at any point downstream of the measurement location was reduced due to turnouts, seepage losses, and evaporation.

The material used for the compacted earth lining was mostly clayey sand (SC) and silty, clayey sand (SC-SM) (table A1 in appendix A). The PI of the lining samples ranged from 3 to 14 percent and the LL ranged from 17 to 28 percent. The minimum recommended PI was 7 at the time of the lining design (Jones, 1953). Based on observations from this study, it appears that lining material with a PI equal to or greater than 11 percent performed satisfactorily.

Damage to the earth lining during cleaning operations was minimal. The lining had a reddish color and was easily distinguishable from the bedload sediment. The lining in the areas sampled was firm and well compacted except for one area that was continually under water. The lining in this area was soft.

Erosion of the lining appeared to be slight to moderate on Laterals 6.2 and 32.2. Areas of the laterals with a noticeable amount of erosion were:

- Upstream of unchecked drop structures where there was a water surface drawdown and the water velocity increased.

- For a distance of 50 to 200 feet downstream from many structures.

- On the outside of many curves but not significantly past the point of tangency.

- On the south side of east-west canals. This side stays wetter than the north side because of shading and is apparently more susceptible to erosion.

Lining protection was added to many of the above areas. Most of the material used for lining protection is called "hardpan," which is a soil of varying hardness. This material has performed well without significant deterioration. The Madera Irrigation District also used broken asphalt pavement, which performed well. A detailed description of the laterals is given in appendix A.

3. **Hammond Project.** - The Hammond Project is located in northwestern New Mexico. The Main Canal carries water from a diversion dam on the San Juan River to about 4,000 acres of irrigated land immediately south of the river between Blanco and Farmington, New Mexico. The canal elevation is about 5500 feet, and the average annual rainfall is below 9 inches. The canal was constructed from 1960 to 1962 and had over 20 years of service at the time of the observation trip.

Much of the lining on the Main Canal of the Hammond Project had been excavated by O&M (operation and maintenance) forces within a few years after construction. The excavation of the lining was unintentional and was due to (a) O&M forces being unaware that the lining existed, and (b) difficulty in distinguishing lining from foundation material when the maintenance forces were cleaning or reshaping the canal. It is therefore impossible to estimate the amount of erosion that occurred in the original lining. A detailed description of the Main Canal is given in appendix A.

4. **Missouri River Basin Project - Frenchman-Cambridge Division.** - Located in the southern part of central Nebraska, the facilities in the division provide a full water supply to 54,680 acres of irrigable land and a supplemental supply to 9,600 acres. The canals were constructed in the late 1950's and had been in service for approximately 25 years at the time of the observation. Lining performance of the Upper Meeker, Driftwood, and Bartley Canals was observed. The soils used in the linings were mostly silts and lean clays of relatively low plasticity. In these canals, it was difficult to distinguish among the lining, foundation material, and sediment. Cattle traffic has been the main problem on the Upper Meeker, Bartley, and Driftwood Canals. Cattle walking across the side slopes loosen the soil, which leads to accelerated erosion. Gravel protection has been placed on the canals to control cattle damage, silt berm growth, and erosion.

A detailed description of the canals is given in appendix A. Several reaches of the lining on the Driftwood Canal were used to test an asphalt emulsion and earth mixture and a portland cement and earth mixture. A description of these reaches is also given in appendix A.

5. **Eden Project.** - The Eden Project is located near the towns of Farson and Eden in southwestern Wyoming. The project, constructed in the 1950's, furnishes irrigation water to approximately 17,000 acres of land. Water deliveries are usually made between May 15 and September 15. Means Canal and Eden Canal (the two main canals on the system) and Farson Lateral were inspected.

Within a few years after construction, the side slopes on the Means and Eden Canals had eroded significantly and the slopes were subsequently protected. This occurred even though the PI's of much of the lining material are above 12 percent. Currently, protection is being added to the canal side slopes to reduce weed growth and to minimize the associated maintenance problems. Three factors that may have contributed to problems with the canal lining are (1) the location of Means Canal immediately downstream of Big Sandy Dam, (2) frost heave, and (3) high winds which would cause sloughing at the waterline due to wave action.

Review of outside literature. - Several articles and textbooks by non-Reclamation authors have been written about the stability of open channels. The criteria described in these publications have been based on field observations and laboratory tests. The authors have attempted to relate the critical tractive force or velocity to shear strength, vane shear strength, dispersion ratio, mean particle size, percent clay, and unconfined compressive strength. Several types of laboratory equipment have been developed to determine the critical tractive force. The more common are submerged jet or flume.

A 1967 report by ASCE (American Society of Civil Engineers) (Masch et al., 1967) contained a review of the literature and current state of knowledge concerning the erosion of cohesive materials. The authors described several procedures to estimate channel stability and to design channels. Conclusions drawn were (1) soil properties, which control erosion resistance, were not conclusively defined; (2) a major research effort must be undertaken to define these properties; (3) design criteria were still lacking, and (4) "simple laboratory devices which permit soil conditions to be easily controlled or undisturbed samples to be used need to be further developed."

Factors affecting performance of earth linings. - It is difficult to estimate the amount of distress that will occur in an earth lining. The durability of the lining depends on not only the material properties but also environmental factors and flow conditions. The following are some of the most significant factors that affect the life of an earth lining:

1. **Canal design.** -

   - Hydraulics - flow, depth, velocity, tractive force
   - Side slopes
   - Longitudinal slope
   - Degree of curvature

2. **Canal construction.** -

   - Unit weight and moisture control
   - Meeting specified dimensions

3. **Canal operation. -**

- Flow over or under design
- Variation of flow throughout operating season
- Seasonal or year-round flows
- Rates of filling and drawdown

4. **Canal maintenance. -**

- Cleaning methods for weeds and sediment
- Degree of care in cleaning (excavation of lining during cleaning operations)
- Reshaping
- Livestock traversing the canal prism

5. **Climatic conditions. -**

- Freezing and thawing
- Wetting and drying
- Precipitation
- Wind

6. **Geologic conditions. -**

- Adjacent water table
- Foundation material and conditions such as gradation, saturation, unit weight, and organic material

7. **Water quality. -**

- Amount of sediment
- Effect of water chemistry on soil properties
- Temperature

8. **Lining material properties. -**

- Atterberg limits (PI, LL)
- Gradation
- Compaction - unit weight and moisture content
- Permeability
- Thixotropy
- Pore-fluid chemistry
- Vane shear strength

Effects of compaction on lining permeability. - Lowitz (1959a) evaluated the earth lining materials of the Courtland Canal in Nebraska, which was a loessial material with a PI ranging from 2 to 18 percent. A reach of the canal from stations 845± to 865± was leaking excessively, which was determined to be caused by the low unit weight of the canal lining. Laboratory tests indicated that the low unit weight probably did not result from frost action. Lowitz did not describe the amount of erosion or identify the cause of the low unit weight soil lining.

According to Jones (1987), it can be expected that unit weights toward the top of the lining decrease more than unit weights toward the bottom of the lining. This is caused by wetting, drying, freezing, thawing, lack of confinement and loading near the top of the lining, and disturbance from canal maintenance operations.

Freeze-thaw effects on earth linings. - In areas where freezing temperatures are common and the lining will be subject to freeze-thaw conditions, the properties of the lining can be expected to change with time. Laboratory testing indicates that the change in unit weight will be minor but the change in permeability may be significant.

Jones and Lowitz (1960) reported on the performance of compacted loessial soil canal linings and studied the effects of freezing and thawing on unit weight and permeability. Field tests indicated that there was some unit weight decrease of the loessial soil linings, the decrease varying inversely with the depth of lining. This was confirmed by a laboratory freeze-thaw test program on specimens subjected to loads from 0 to 2.0 lb/in^2. Laboratory permeability tests conducted on the freeze-thaw specimens indicated that the rate of permeability increases as the unit weight decreases. The increase in permeability was rapid when the soil unit weight was less than 90 percent of the Proctor maximum unit weight, particularly for the less plastic soils. After Franklin Canal's 3 years of service, field ponding tests showed that the lining was still effective in reducing seepage to allowable limits, although there has been some unit weight decrease of the compacted soil lining. The decrease ranged from 3 percent near the bottom to 16 percent near the top of the lining. The seepage losses from the two ponding tests were 0.03 and 0.09 ft^3/ft^2 per day.

Jones (1981a) discussed some effects of closed-system freezing on earth linings. The relevant conclusions of that report were (1) soil moisture migrates to the cold surface, (2) soil unit weight near the surface decreases, (3) soil unit weight in a zone at some depth in the soil increases, (4) thin ice lenses may or may not form, and (5) overall shrinkage of the soil and cracks may occur.

Lowitz (1959b) reported on soil samples tested for frost heave and erosion. The soil was a silt with varying amounts of fine sand. The results indicated (1) the permeability of the specimens in an open system increased significantly after five freeze-thaw cycles, and (2) the erosion resistance of the soil was much less when in clear water than in water with a light sediment load. In an open system, water is available to the sample during the freeze-thaw cycle.

Criteria for Turkey Creek flood channel. - Turkey Creek is a tributary of the Middle Loup River in central Nebraska and flows through loessial material. Strand (1971) analyzed the stability of Turkey Creek. That analysis resulted in figure 8, which relates tractive power to unconfined compressive strength of the soil. Tractive power is the product of the channel slope, the hydraulic radius, the specific weight of water, and the average velocity. For the stability of Turkey Creek, the flow was based on a dominant discharge equal to the 2-year flood peak.

Gravel protection. - A suggested gradation for coarse gravel protection is given by Jones (1981b). This gradation was developed through observation of existing canals, laboratory tests, and observations of test reaches of canals.

CONCLUSIONS

Low-PI (7 to 12 percent) earth linings have performed reasonably well on several of the canals investigated. These materials, if available, should be considered as a lining alternative. The decision to use low-PI material for earth lining should be based on an economic evaluation of this type of lining and other lining alternatives. Construction, lifespan, and maintenance costs should be estimated to make an accurate determination of the best lining alternative. PI alone is not an adequate indicator of the erosiveness of cohesive soils and should not be used as the single criterion for designing an earth lining for canals.

Several of the canals showed erosion of the side slopes downstream of in-line structures. The erosion on Lateral 6.2 of the Madera Irrigation District was typical and extended for 50 to 100 feet. The normal depth in the canal is 5.0 feet. Using 50 feet as a minimum length of bank protection, the riprap should extend 10 x d downstream of siphons. Where turbulent water is expected, 20 x d should be used.

Protection will be required on the outside banks of curves. Some canal side slopes on straight reaches will eventually require protection. It is difficult to determine, during design, which straight reaches of canal will require slope protection. In lieu of providing complete slope protection on the straight reaches during construction, it is often economically justified to have maintenance personnel add protection to those areas where erosion occurs.

Reaches of canals immediately downstream from reservoirs, such as the Means Canal and the first reach of the Upper Meeker Canal, will experience more erosion than canal reaches further downstream where water would be carrying increased amounts of sediment.

In addition to erosion caused by flowing water, deterioration of an earth lining can be caused by wind-generated wave action on the lining.

Domestic livestock (cattle, etc.) should be kept off the lining.

O&M personnel should be careful not to disturb the earth lining when cleaning the canal.

Gravel protection on a canal bank not only protects the bank against erosion and wave action but also reduces maintenance for weed control and improves the appearance of the canal.

The Reclamation publication *Performance of Granular Soil Covers on Canals* (Jones, 1981b) can be used for determining the gradation of gravel covers. However, it should be noted that some naturally occurring materials, such as the "shale" used on the Eden Project, have performed well, may require no processing, and may be economically available.

FUTURE RESEARCH REQUIREMENTS

A laboratory test should be developed to measure the erosion resistance of potential earth-lining materials. Laboratory testing of a variety of soils should be performed to relate erosion resistance to physical and engineering properties of the soil.

Observation reaches should be established on all future earth-lined canals from the beginning of operation, regardless of the type of soil used. Monitoring of the existing observation reaches should be continued throughout the life of the canal.

By combining the two requirements listed above, it may be possible to correlate the erosion rate of a material for a specific flow condition with specific soil properties or mechanical test results. The soil properties could be the PI, LL, shear strength, and grain-size distribution. The mechanical tests could be the compressive strength or vane shear strength. Corrections could then be made for sediment load, freezing conditions, weather, etc.

Ponding tests to rate the seepage performance of the canal lining over time should also be performed. These have been performed in the past and are useful in determining how the lining performs its primary function (preventing seepage) during its lifetime.

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Table 1. - Canal reaches investigated.

Canal or lateral	Project	State
Madera laterals		
Lateral 6.2	Central Valley	California
Lateral 32.2	Central Valley	California
Means Canal	Eden	Wyoming
Eden Canal	Eden	Wyoming
Farson Lateral	Eden	Wyoming
Main Canal	Hammond	Colorado
Upper Meeker	MRBP[1]	Nebraska
Driftwood	MRBP	Nebraska
Bartley	MRBP	Nebraska

[1] Missouri River Basin Project

Table 2. - Comparison of Etcheverry's maximum allowable velocities and tractive forces (from Lane, 1952).

Material	Value of Manning's n used	Velocity (ft/s)	Tractive force (lb/ft^2)[1]
Very light pure sand of quicksand character	0.020	0.75-1.00	0.006-0.011
Very light loose sand	0.020	1.00-1.50	0.011-0.025
Coarse sand or light sandy soil	0.020	1.50-2.00	0.025-0.045
Average sandy soil	0.020	2.00-2.50	0.045-0.070
Sandy loam	0.020	2.50-2.75	0.070-0.084
Average loam, alluvial soil, volcanic ash soil	0.020	2.75-3.00	0.084-0.100
Firm loam, clay loam	0.020	3.00-3.75	0.100-0.157
Stiff clay soil, ordinary gravel soil	0.025	4.00-5.00	0.278-0.434
Coarse gravel, cobbles and shingles	0.030	5.00-6.00	0.627-0.903
Conglomerate, cemented gravel, soft slate, tough hardpan, soft sedimentary rock	0.025	6.00-8.00	0.627-1.114

[1] Tractive forces were estimated by Lane.

Table 3. - Comparison of Fortier and Scobey's limiting velocities with tractive force values (from Lane, 1952).

Straight channels after aging.

Material	n	For clear water		Water transporting colloidal silts	
		Velocity (ft/s)	Tractive force (lb/ft^2)[1]	Velocity (ft/s)	Tractive force (lb/ft^2)[1]
Fine sand colloidal	0.020	1.50	0.027	2.50	0.075
Sandy loam noncolloidal	0.020	1.75	0.037	2.50	0.075
Silt loam noncolloidal	0.020	2.00	0.048	3.00	0.11
Alluvial silts noncolloidal	0.020	2.00	0.048	3.50	0.15
Ordinary firm loam	0.020	2.50	0.075	3.50	0.15
Volcanic ash	0.020	2.50	0.075	3.50	0.15
Stiff clay very colloidal	0.025	3.75	0.26	5.00	0.46
Alluvial silts colloidal	0.025	3.75	0.26	5.00	0.46
Shales and hardpans	0.025	6.00	0.67	6.00	0.67
Fine gravel	0.020	2.50	0.075	5.00	0.32
Graded loam to cobbles when noncolloidal	0.030	3.75	0.38	5.00	0.66
Graded silts to cobbles when colloidal	0.030	4.00	0.43	5.50	0.80
Coarse gravel noncolloidal	0.025	4.00	0.30	6.00	0.67
Cobbles and shingles	0.035	5.00	0.91	5.50	1.10

[1] Tractive forces were estimated by Lane.

Table 4. - U.S.S.R. limiting velocities and tractive forces in cohesive material (from Lane, 1952).

Descriptive term	Compactness of bed: Loose		Fairly compact		Compact		Very compact	
Void ratio	2.0-1.2		1.2-0.6		0.6-0.3		0.3-0.2	
Principal cohesive material of bed	Limiting mean velocity (ft/s) and limiting tractive force (lb/ft^2)[1]							
	ft/s	lb/ft^2	ft/s	lb/ft^2	ft/s	lb/ft^2	ft/s	lb/ft^2
Sandy clays (sand content less than 50 percent)	1.48	0.040	2.95	0.157	4.26	0.327	5.90	0.630
Heavy clayey soils	1.31	0.031	2.79	0.141	4.10	0.305	5.58	0.563
Clays	1.15	0.024	2.62	0.124	3.94	0.281	5.41	0.530
Lean clayey soils	1.05	0.020	2.30	0.096	3.44	0.214	4.43	0.354

[1] Tractive forces were estimated by Lane.

Table 5. - U.S.S.R. corrections of permissible velocity for depth - Cohesive material (from Lane, 1952).

	Average depth							
Meters	0.3	0.5	0.75	1.0	1.5	-2.0	2.5	-3.0
Feet	0.98	1.64	2.46	3.28	4.92	-6.56	8.20	-9.84
Correction factor	0.8	0.9	0.95	1.0	1.1	-1.1	1.2	-1.2

Note: Negative signs were present in original data.

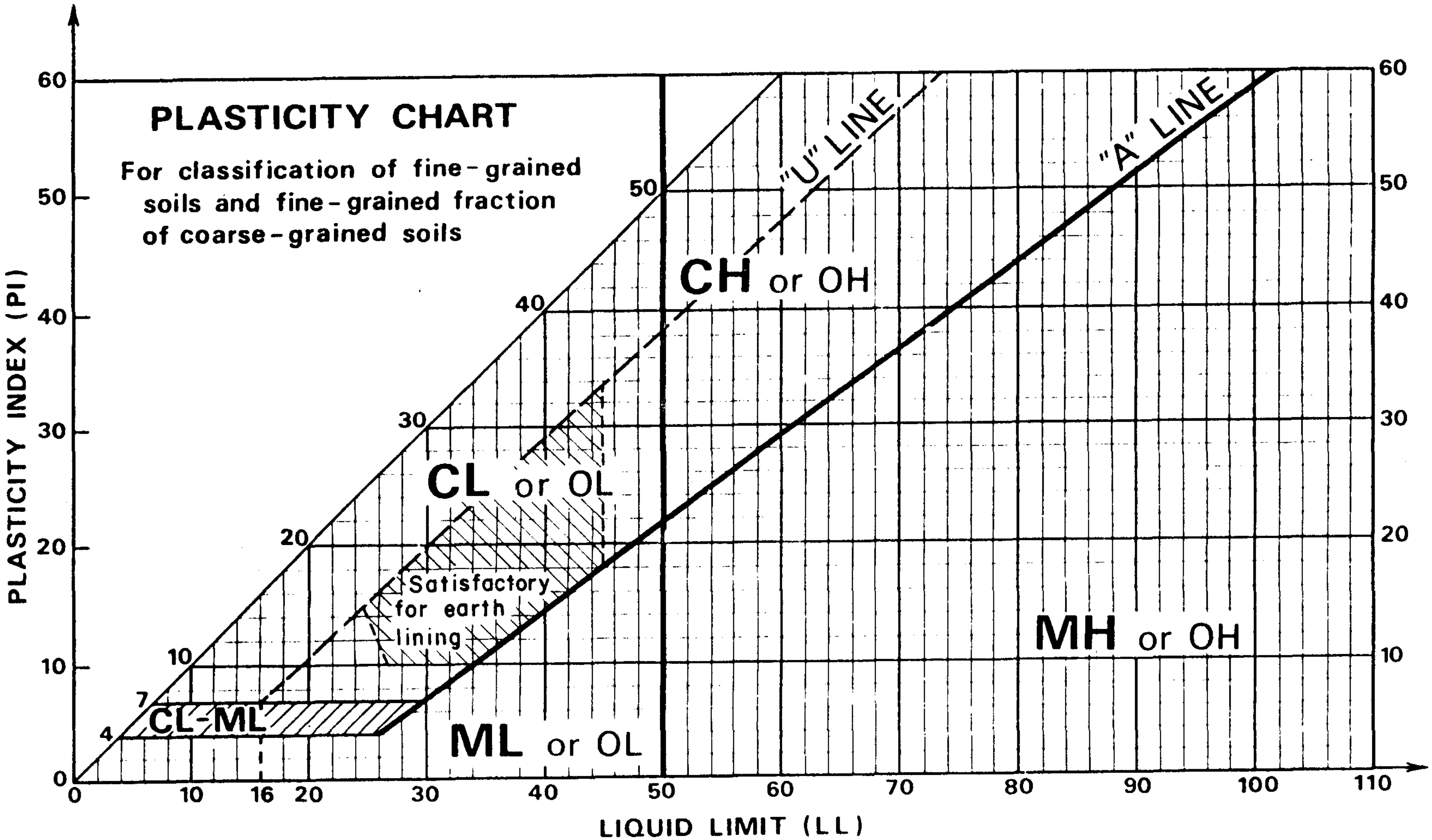
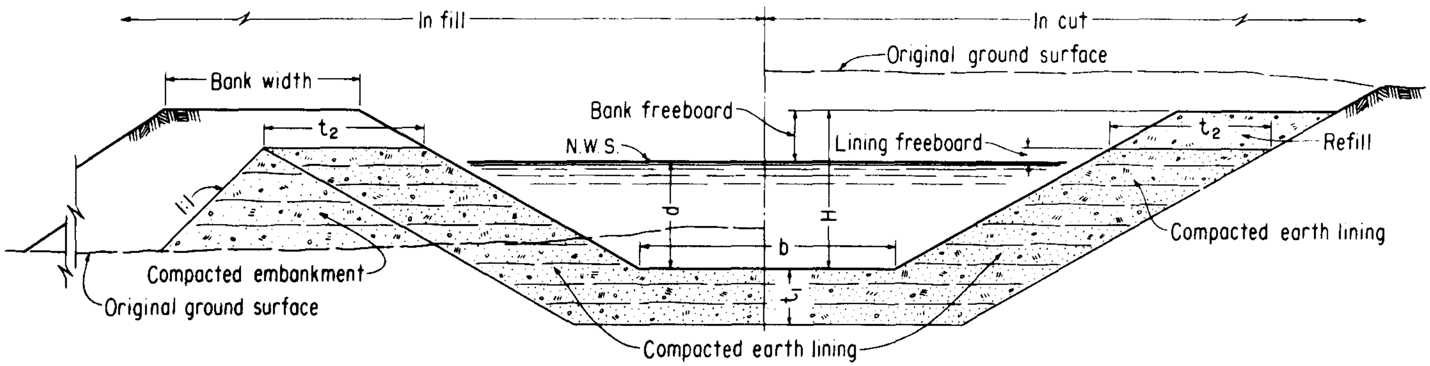


Figure 1. - Plasticity criteria (from Bureau of Reclamation, 1980, p. 263).



TYPICAL EARTH LINED SECTION

TABLE FOR EARTH LINING

d	t_1	t_2
2.0' or less	1.0'	3.0'
>2.0' to 4.0'	1.5'	4.0'
>4.0' to 6.0'	2.0'	6.0'
Over 6.0'	2.0'	8.0'

NOTE

If lining material requires a protective cover of gravel or riprap to prevent scour or erosion, excavation shall be extended to provide for the designated thickness of lining plus the gravel or riprap cover.

Figure 2. - Typical earth-lined section (from Bureau of Reclamation, 1980, p. 264).

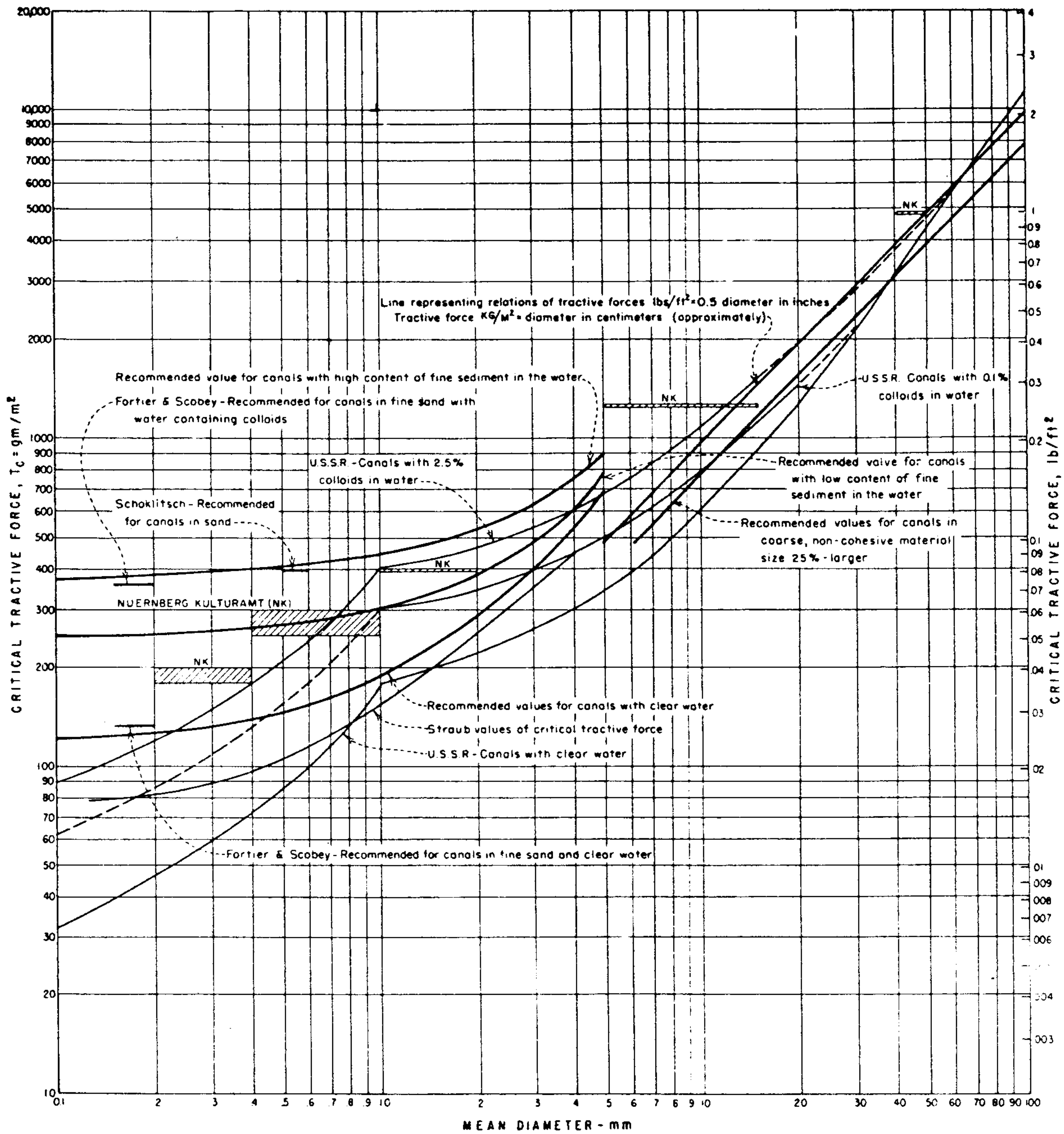


Figure 3. - Limiting tractive forces recommended for canals and observed in rivers (from Lane, 1952).

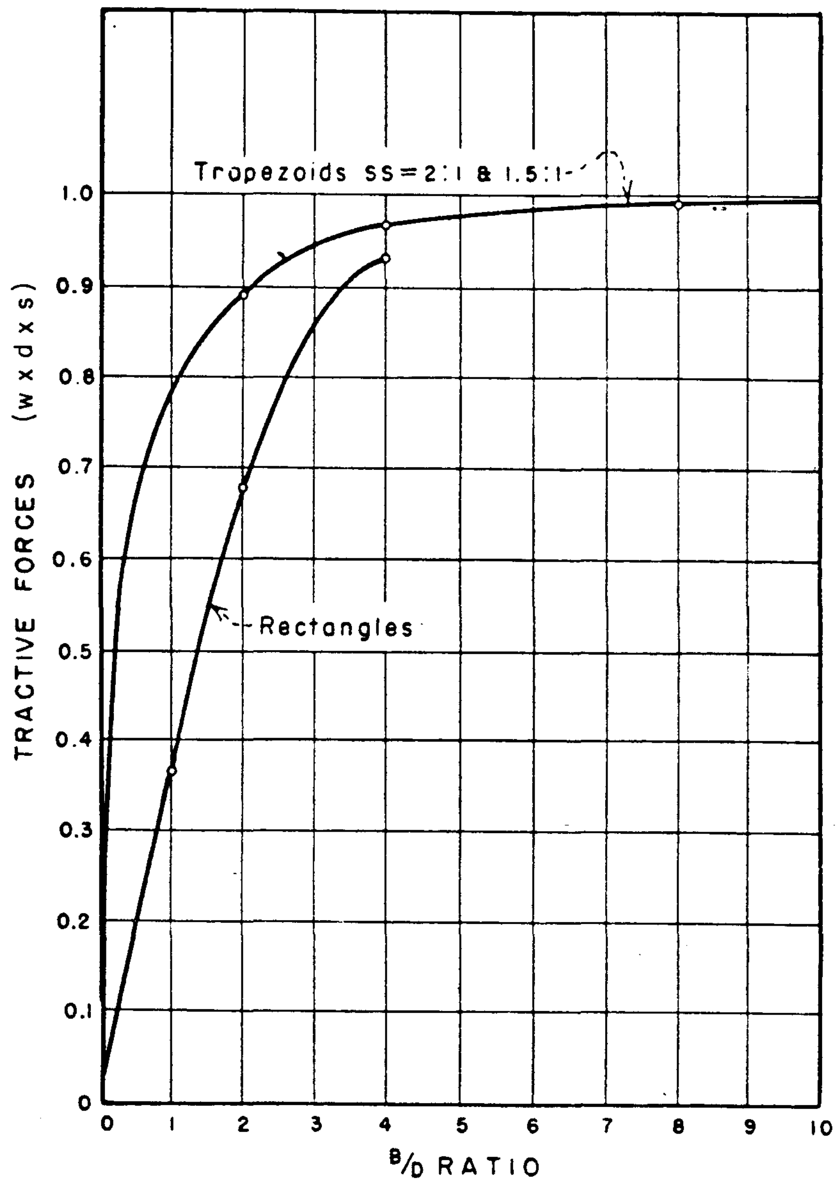


Figure 4. - Maximum tractive forces in terms of 62.4 x depth x slope on bottom of channels (from Lane, 1952).

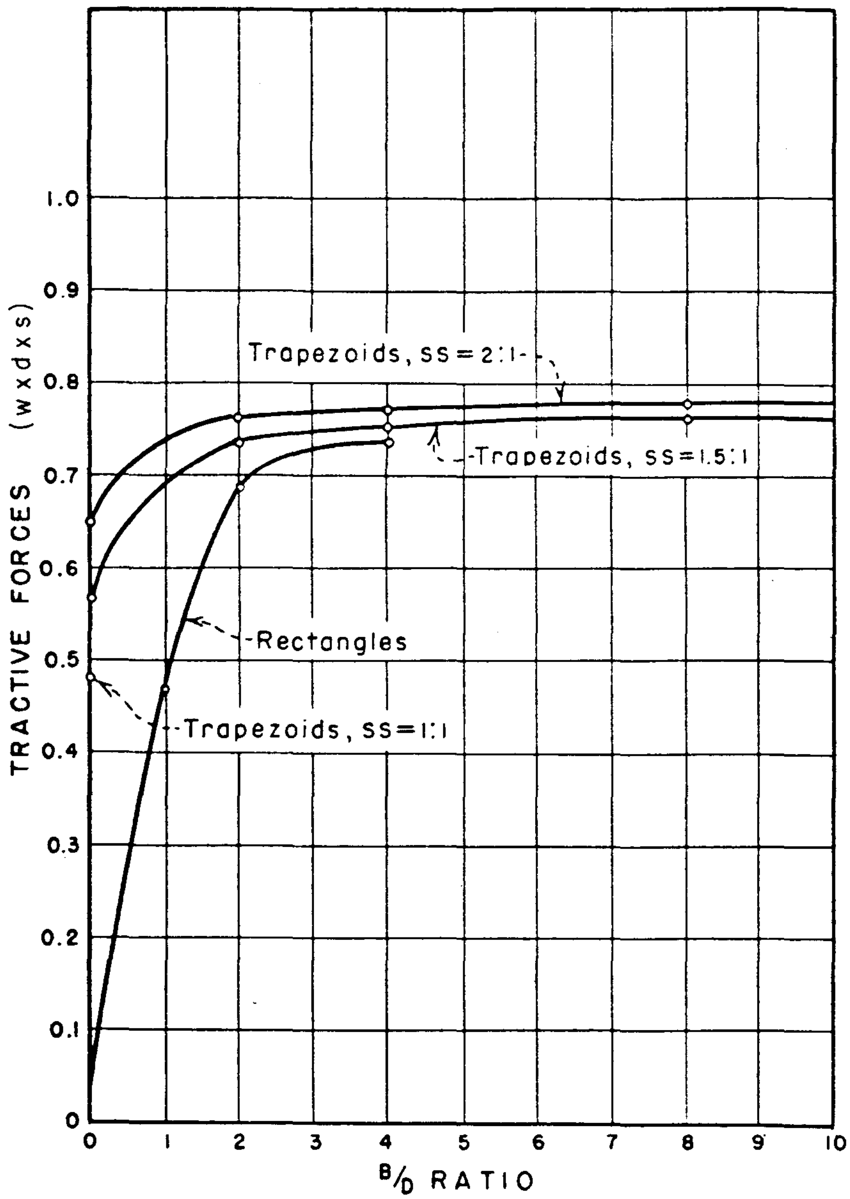


Figure 5. - Maximum tractive forces in terms of 62.4 x depth x slope on sides of channels (from Lane, 1952).

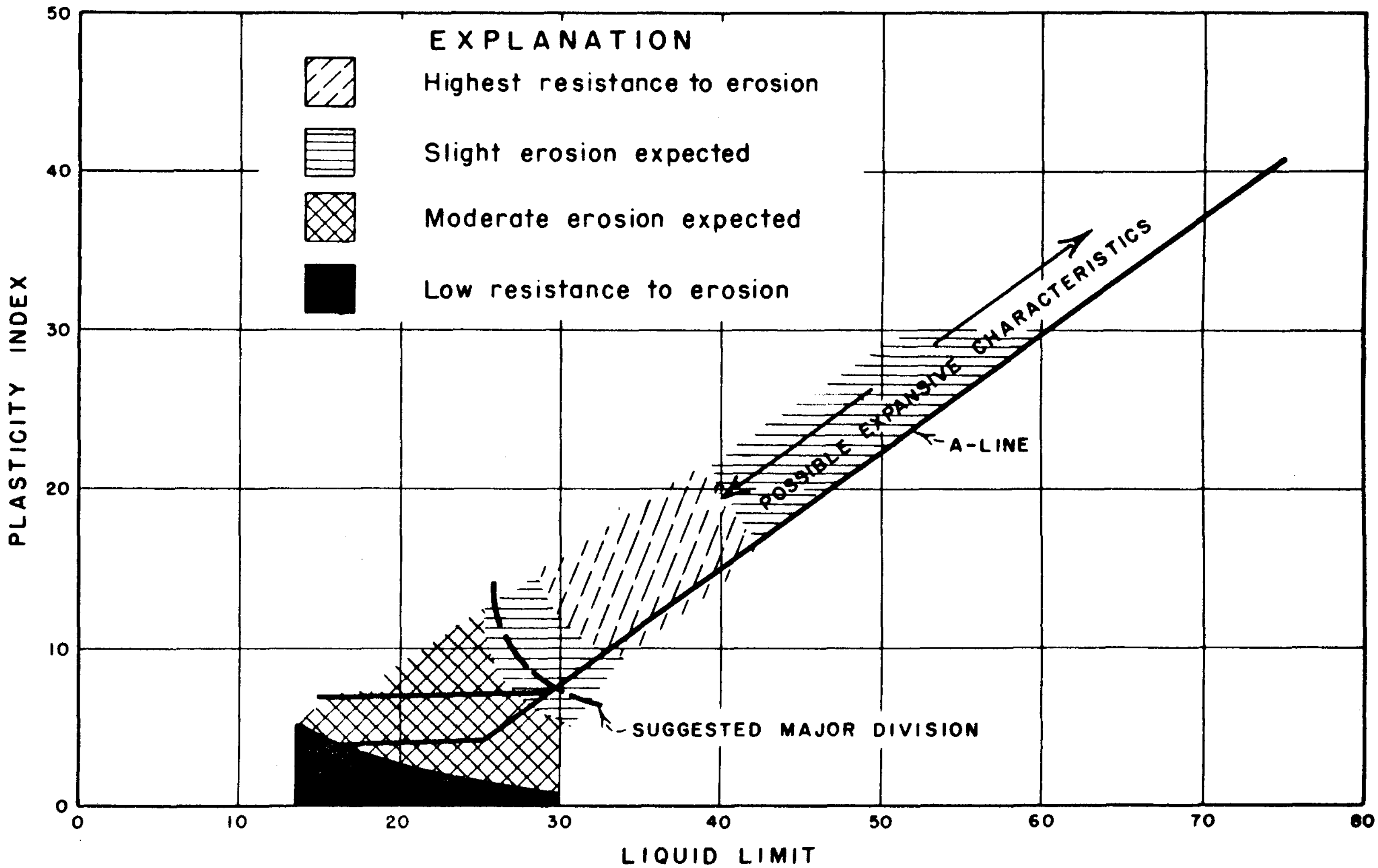


Figure 6. - Suggested trend of erosion characteristics for fine-grained cohesive soils with respect to plasticity (from Gibbs, 1962).

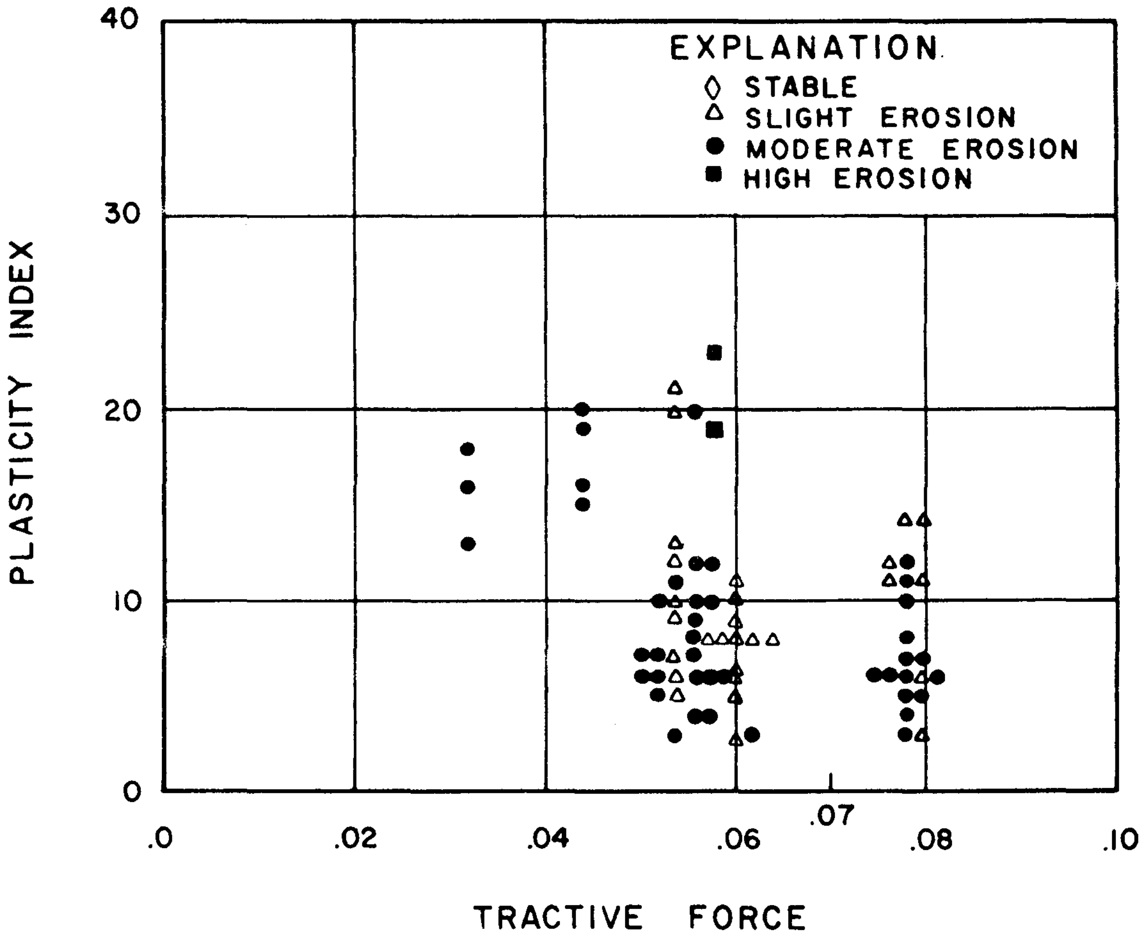


Figure 7. - Performance of existing linings.

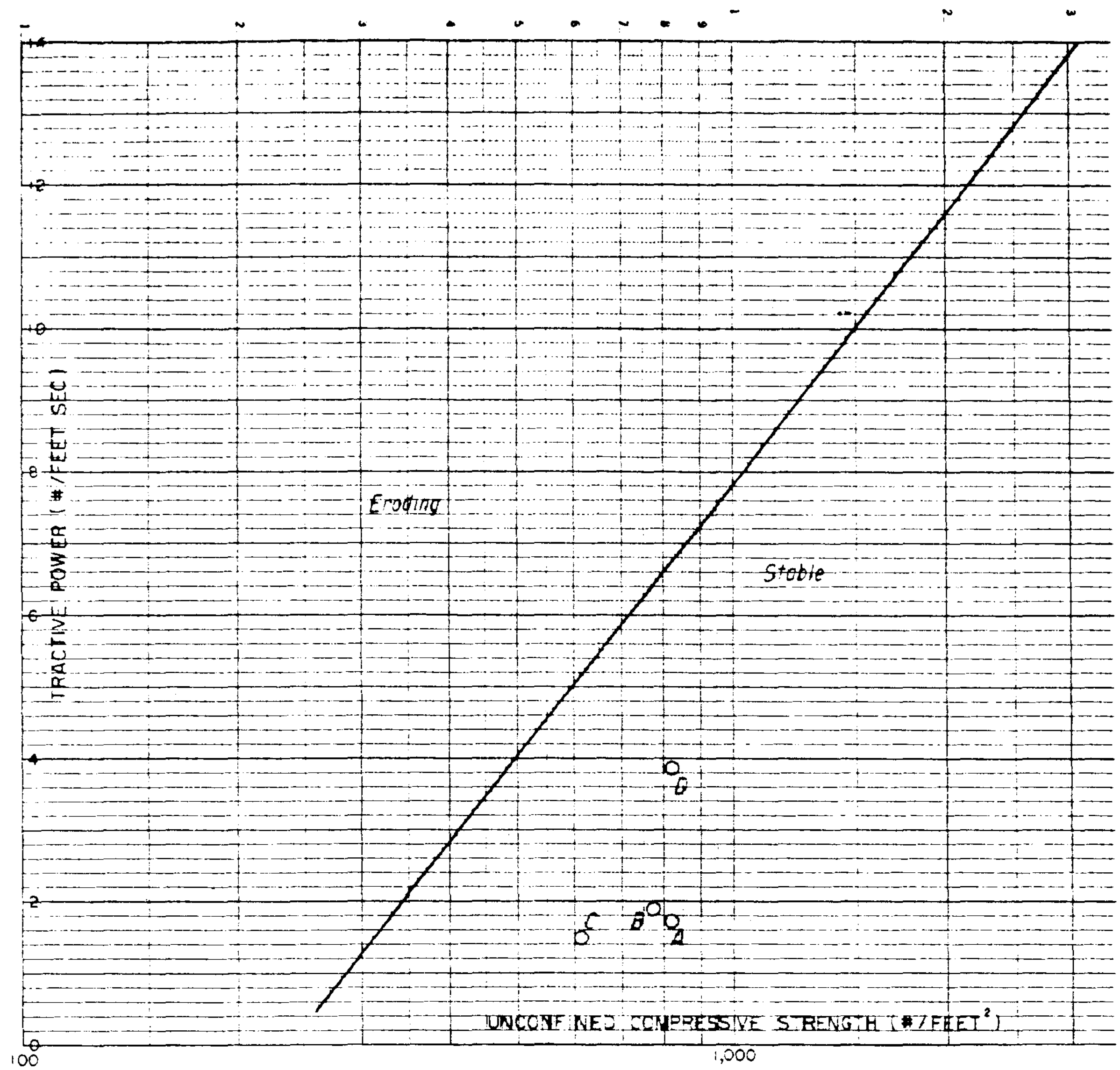


Figure 8. - Tractive power vs. unconfined compressive strength (after Flaxman) (from Strand, 1971).

APPENDIX A

Field Observations of Existing Canals

Central Valley Project - Madera Irrigation District
Hammond Project - Main Canal
Missouri River Basin Project - Frenchman-Cambridge Division
Eden Project

CENTRAL VALLEY PROJECT - MADERA IRRIGATION DISTRICT

Lateral 6.2

Lateral 6.2 is 28.0 miles long. The lateral flow varied from 340 ft^3/s at the upstream end to 15 ft^3/s at the downstream end.

The designed lining was 2.0 feet thick on the bottom and 8.0 feet wide (horizontally) on the sides. The following table gives the hydraulic properties of reaches of Lateral 6.2 from which soil samples were obtained:

Section	Q	A	d	b	ss	v	n	s	TF
2	340	137.5	5.0	20	1-1/2:1	2.47	0.0225	0.00025	0.078
3	278	127.5	5.0	18	1-1/2:1	2.18	0.0225	0.00020	0.062

Approximately 15 to 25 percent of the lateral had riprap protection placed on one or both sides since construction.

Flow in the lateral varied considerably from year to year and also during any 1-year period. Flow records (1972 to 1983) indicated that the high 7-day flow average for any year was 309.7 ft^3/s, and the lowest high 7-day average was 126.9 ft^3/s. The peak recorded flow for this time period (1972 to 1983) was 331 ft^3/s.

Cross sections were taken at stations 212+35 and 483+95 and are shown on figure A1. Soil samples for this study were taken at stations 211+00, 433+00, 480+00, and 665+00. Properties of soil samples are shown in table A1. The lining performance at these locations is plotted on a plasticity chart (fig. A2).

The lateral lining at station 211+00 had a PI of approximately 11 to 14 based on soil samples. This reach has had a small amount of bank protection placed and is performing well.

The lateral lining at station 433+00 had intermittent riprap cover on the canal side slopes. The lining had a PI of approximately 4 to 6 based on the soil samples; this is lower than the acceptable range of the PI used in the original design.

The lateral at station 480+00 had a noticeable amount of erosion of the earth lining. The lining had a PI of approximately 7 to 8 based on soil samples. The LL was approximately 21 to 22. Riprap protection on the side slopes in this area is intermittent.

The lateral lining at station 665+00 had received riprap protection on the side slopes. The one soil sample taken at this location had a PI of 3 and an LL of 17. The PI was lower than required by the project design criteria.

Two samples were taken for petrographic study. Results of the studies are as follows:

1. **Sample No. 48Y-X127.** - Air-dry; tan to reddish brown; coarse grained to silt and clay sized; ferruginous; very slightly effervescent in cold dilute hydrochloric acid; loose and

unconsolidated with a few soft, highly friable peds; minor to trace amounts of organic material; no detectable amounts of water-soluble chloride or sulfate ions.

2. **Sample No. 48Y-X126.** - Air-dry; gray to reddish brown; coarse grained to silt and clay sized; ferruginous; noneffervescent in cold dilute hydrochloric acid; loose and unconsolidated with a few soft, highly friable peds; minor to trace amounts of organic material; no detectable amounts of water-soluble chloride or sulfate ions.

The mineralogical composition and estimated volume percentages of the samples are as follows:

Mineralogy	Sample No. 48Y-X126 (%)	Sample No. 48Y-X127 (%)
Clay minerals:		
Smectites[1]	5	5
Illite/mica[2]	5	5
Kaolinite	5	5
Quartz	50	50
Feldspars	20	20
Iron oxides[3]	5	5
Calcite	-	Trace
Dolomite	Trace	Trace
Minor[4]	10	10

[1] Chiefly calcium-rich montmorillonite, includes trace amounts of mixed and interlayered varieties.
[2] About equal amounts of illite and micas (muscovite and biotite).
[3] Includes hematite, dust-size magnetite, ilmenite, and unidentified amorphous types.
[4] Includes trace amounts listed above, hornblende, epidote, chlorite, garnet, zircon, tourmaline, apatite, organic material (plant roots and stems), and trace amounts of unidentified clay-size minerals.

Lateral 32.2

Lateral 32.2 is 15 miles long. The lateral flow varied from 182 ft^3/s at the upstream end to 30 ft^3/s at the downstream end. The designed earth lining was 2.0 feet thick on the bottom and 8.0 feet wide (horizontally) on the sides. The following table gives the hydraulic properties of two earth-lined sections of Lateral 32.2:

Section	Q	A	d	b	ss	v	n	s	TF
13	182	79.34	4.30	12	1-1/2:1	2.30	0.0225	0.0003	0.080
4	85	56.69	3.66	10	1-1/2:1	1.50	0.0250	0.0002	0.046

Flow in the lateral varied considerably from year to year and also during any 1-year period. Flow records (1972 to 1983) showed that the high 7-day average for a year has varied from 75.1 to 169.9 ft^3/s. The peak flow measured during this 12-year period was 180 ft^3/s.

Eight lining samples for this study were taken from approximate stations 137+50 and 355+00. The soil properties are shown in table A1. The lining performance at these locations is plotted on a plasticity chart (fig. A3).

The lining at station 137+50 has performed well and has not required gravel protection. The PI varied from 3 to 14 percent, and the LL varied from 18 to 28 percent.

At station 355+00, the left bank had gravel protection placed on top of the earth lining. The PI varied from 5 to 6 percent, which is lower than the original design criteria.

HAMMOND PROJECT - MAIN CANAL

Canal section properties are shown in the following table:

Section	Q	A	d	b	ss	v	n	s	TF
2	90	52.48	3.2	10	2:1	1.72	0.025	0.0003	0.060
5	45	29.84	2.7	7	1.5:1	1.51	0.025	0.0003	0.051

Canal flows varied from year to year and also during any 1-year period. The average flow in July has been as high as 92 ft^3/s (1968). The canal usually operates from April through November.

Maintenance personnel had excavated through the earth lining at many locations during canal cleaning operations. Subsequently, several of these reaches required concrete lining to reduce seepage.

The cross section at station 152+74 (fig. A4) and five soil samples for this study were taken in an embankment section constructed with 6 inches of gravel protection on the side slopes and invert. Most of the original gravel protection was still in place on the bottom; however, the gravel protection was almost entirely missing on the right and left banks. The gravel protection had most likely been excavated during canal cleaning operations. Gravel mixed with soil appeared in cleaning piles on the outer roadway edge. The lining on the side slopes where the gravel cover (GP-GM) had been removed appeared to be stable. The lining was classified as silty clay (CL-ML) and silt (ML). The PI of the soil samples was between 3 and 7 percent, and the LL was between 23 and 26 percent. The embankment soil properties are given in table A2. The lining performance is plotted on a plasticity chart (fig. A5).

The results of a petrographic study of one material sample of the Main Canal embankment are as follows: air-dry; light grayish brown or tan; fine grained to silt and clay sized; slightly ferruginous; slightly effervescent in cold dilute hydrochloric acid; loose and unconsolidated with a few soft, highly friable peds; minor to trace amounts of organic material; trace amounts of water-soluble sulfate ions.

The mineralogical composition and estimated volume percentages of the samples are as follows:

Mineralogy	Sample No. 48Y-X125 (%)
Clay minerals:	
Smectites[1]	5-10
Illite/mica[2]	5
Kaolinite	5
Quartz	50-55
Feldspars	15-20
Iron oxides[3]	2-3
Calcite	Trace
Dolomite	Trace
Minor[4]	10

[1] Chiefly calcium-rich montmorillonite, includes trace amounts of mixed and interlayered varieties.
[2] About equal amounts of illite and micas (muscovite and biotite).
[3] Includes hematite, dust-size magnetite, ilmenite, and unidentified amorphous types.
[4] Includes trace amounts listed above, hornblende, epidote, chlorite, garnet, zircon, tourmaline, apatite, organic material (plant roots and stems), and trace amounts of unidentified clay-size minerals and trace amounts of water-soluble chloride ions.

MISSOURI RIVER BASIN PROJECT - FRENCHMAN-CAMBRIDGE DIVISION

Upper Meeker Canal

The Upper Meeker Canal is 15.4 miles long; the design flow varied from 284 ft^3/s at the upstream end to 250 ft^3/s at the downstream end. The designed canal lining was 2.0 feet thick on the bottom and 6.0 feet wide (horizontally) on the side slopes. The canal section properties are as follows:

Section	Q	A	d	b	ss	v	n	s	TF
1	284	118.43	5.03	16.0	1.5:1	2.40	0.0225	0.00025	0.078
3	250	123.76	5.20	16.0	1.5:1	2.02	0.0225	0.00017	0.056

Most of the earth-lined reaches and some of the unlined reaches have been covered with gravel protection on the side slopes to protect against erosion and disturbance by cattle. Laboratory tests for this study were performed on 15 lining soil samples from various locations along the canal. These tests consisted of Atterberg limits, gradation, and specific gravity. The results are shown in table A3. The material was classified mostly as lean clay (CL) and silty clay (CL-ML). Most of the PI's varied from 4 to 12 percent with one sample as high as 20 percent. The LL varied from 24 to 34 percent. The lining appeared to have undergone moderate erosion. The performance of the lining at the locations sampled is shown on a plasticity chart (fig. A6). Gradation and Atterberg limits tests were performed on one sediment sample (No. 48Y-155), and a gradation analysis was performed on sample No. 48Y-149. A gradation analysis was performed on one sample of the gravel cover (No. 48Y-165). The gravel cover was not eroding and was performing satisfactorily.

A cross section was taken at station 790+50 (fig. A7). The canal section at this location had a U-shape; the side slopes were covered with a gravel protection.

Driftwood Canal

The Driftwood Canal is 14.2 miles long; the design flow varied from 225 ft^3/s at the upstream end to 90 ft^3/s at the downstream end.

The designed lining was 2.0 feet thick on the bottom and 6 feet wide (horizontally) on the side slopes. The canal section observed is as follows:

Section	Q	A	d	b	ss	v	n	s	TF
4	225	115.58	4.59	16	2:1	1.95	0.0225	0.00019	0.054

The canal was approximately 30 percent lined and appeared to be in generally good condition. However, cattle traversing the canal section has been a serious problem that has contributed to the instability of lined and unlined side slopes. Scour was apparent downstream of the siphon outlets at stations 860+35 and 917+20. Both of these reaches were earth lined during original construction. Riprap has been added downstream of these outlets since construction. The outsides of curves on many lined or compacted embankment reaches of this canal were covered with gravel protection. Laboratory tests for this study were performed on 12 lining soil samples from various locations along the canal. The tests consisted of Atterberg limits, gradation, and specific gravity. The results are shown in table A3. The material was classified as silty clay (CL-ML) and lean clay (CL). The PI varied from 7 to 21 percent; the LL varied from 26 to 37 percent. The performance of the lining at the sampled locations is shown on a plasticity chart (fig. A8).

A cross section was taken at station 849+40 (fig. A7). The erosion at this location was moderate to heavy.

Several reaches of the Driftwood Canal were used as lining test reaches. During initial construction, small amounts of asphalt emulsion or portland cement were mixed with the lining soil to increase the erosion resistance of the lining. The asphalt was mixed in the full 6-foot horizontal width of the lining. The portland cement was mixed only in the middle 2 feet of the 6-foot horizontal width. The 2 feet of untreated soil on the inner slope were trimmed off to expose the treated soil to water. Jones (1982) presented results of tests made on samples from the cement-treated test sections. Observations from the current study are described below.

The left side of the canal from station 980+25 to station 990+25 was lined with soil-cement placed at a rate of 4-1/2 percent cement (by dry weight of soil) mixed with the soil. The lining appeared to be slightly cemented but highly fractured, particularly between lifts. The material was apparently durable with possible high permeability. Due to the method of lining construction, the treated soil was backed by 2 feet of untreated compacted soil to help control canal seepage.

The left side of the canal from station 1024+70 to station 1033+70 was lined with 2-1/2 percent cement-soil mixture. The soil in the lined area showed no indication of being cemented.

The right side of the canal from station 1050+00 to station 1055+00 was lined with 2 percent asphalt emulsion mixed with soil. The lining appeared to be durable and impervious; the lining was performing satisfactorily.

The right side of the canal from station 1055+90 to station 1065+75 was lined with 1 percent asphalt emulsion mixed with soil. Visual examination indicated that the asphalt emulsion had no lasting effect on the soil properties.

The right side of the canal from station 1092+00 to station 1097+00 was lined with 2 percent asphalt emulsion mixed with soil. The asphalt-treated side had good appearance; the untreated lining on the opposite side showed the effects of cattle traffic.

Bartley Canal

The Bartley Canal is approximately 19.3 miles long. The canal flow varied from 130 ft^3/s at the upstream end to 42 ft^3/s at the downstream end.

The designed canal lining was 2.0 feet thick on the bottom and 8 feet wide (horizontally) on the sides. Hydraulic properties of canal section 1 were as follows:

Lined section	Q	A	d	b	ss	v	n	s	TF
1	130	66.09	3.75	12	1.5:1	1.97	0.0225	0.00026	0.060

Approximately 5 percent of the canal is lined. Several earth-lined reaches of the Bartley Canal were inspected and appeared to be in good condition. Laboratory tests for this study were performed on 10 lining soil samples from various locations along the canal. The results are shown in table A3. The material was classified as lean clay (CL), silty clay (CL-ML), and silty clayey sand (SC-SM). The PI varied from 5 to 11 percent, and the LL varied from 19 to 27 percent. The performance of the lining is shown on a plasticity chart (fig. A9). The invert lining near station 260+85 was thin (about 8 in); however, the elevation of the present canal bottom was at design grade. The lining on the sides appeared to be satisfactory. The right side of the canal had a silt and sediment buildup.

There was noticeable erosion and cattle damage in an earth-lined reach just downstream of the siphon outlet at station 236+33.

EDEN PROJECT

Means Canal

The Means Canal is 6.0 miles long. The designed lining in the canal sections had a bottom thickness of 2.0 feet and a side width (horizontally) of 8.0 feet. The following table lists the hydraulic properties of the original lined canal sections:

Section	Q	A	d	b	ss	v	n	s	TF
C	475	196.86	6.11	20	2:1	2.41	0.020	0.00016	0.060
F	475	197.15	5.85	22	2:1	2.41	0.020	0.00016	0.058

Approximately 20 percent of the canal was lined during construction. Since that time, all but 1 mile has been lined and the side slopes have been covered with "shale" protection. The earth linings on this canal appear to have performed poorly even though the material was installed within current lining guidelines. Laboratory tests for this study were performed on three lining soil samples at station 138+80 of the canal. The tests consisted of Atterberg limits, gradation, and specific gravity. The results are shown in table A4. The lining material was classified as lean clay (CL). The PI varied from 19 to 23 percent, the LL varied from 37 to 41 percent, and one sample was nonplastic. The lining performance at station 138+80 is plotted on a plasticity chart (fig. A10). Tests were performed to determine the dispersive characteristics of the lining. The tests indicated the lining was nondispersive.

Water to a depth of approximately 2 feet was left in the canal during the winters and may have contributed to erosion of the side slopes. Freezing of the water has subjected the side slopes to mechanical abrasion from the ice and to open-system frost heave.

Eden Canal

The Eden Canal is 10.8 miles long. Approximately 6.2 miles of the canal were earth lined. The design flow of the canal was 300 ft^3/s at the upstream end and 150 ft^3/s at the downstream end. The designed lining thickness was 1.5 to 2.0 feet on the bottom and 8 feet (horizontally) at the sides. The following table gives the hydraulic properties for the original lined canal sections:

Section	Q	A	d	b	ss	v	n	s	TF
C	300	147.68	5.20	18	2:1	2.03	0.0225	0.00017	0.056
D	300	147.68	5.20	18	2:1	2.03	0.020	0.00014	0.044
F	190	99.06	4.36	14	2:1	1.92	0.0225	0.00020	0.054
G	150	82.08	3.80	14	2:1	1.83	0.0225	0.00021	0.050
F-1	190	102.90	4.20	14	2:1	1.85	0.0225	0.00020	0.052

Laboratory tests for this study were performed on 13 lining soil samples at various locations along the canal. The tests consisted of Atterberg limits, gradation, and specific gravity. The results of the tests are shown in table A4. The lining material at station 405+00 was classified as lean clay (CL) and silt (SM). The lining material between stations 677+00 and 684+00 was classified as clayey sand (SC); silty sand, (SM); and silty, clayey sand (SC-SM). The PI of the tests on the lining varied from 3 to 20 percent, the liquid limit varied from 21 to 37 percent, and two samples were nonplastic. The performance of the lining at stations 405+00 and 684+00 is plotted on plasticity charts (figs. A11 and A12, respectively). Tests were performed to determine the dispersive characteristics of the lining. The tests indicate the lining was intermediate to dispersive.

Figure A13 shows canal cross sections taken at stations 683+69 and 686+27. At station 683+69, shale protection had been added to both side slopes. At station 686+27, shale protection had been added to the right side slope only.

Farson Lateral

Farson Lateral is 8.9 miles long. The design flow varies from 150 ft^3/s at the upstream end to 6 ft^3/s at the downstream end.

The designed lining was 1.5 feet thick on the bottom and 8.0 feet wide (horizontally) on the sides. The following table gives the hydraulic properties of the earth-lined sections:

Q	A	d	b	ss	v	n	s	TF
150	83.25	3.84	14	2:1	1.80	0.0225	0.00020	0.048
140	79.47	3.71	14	2:1	1.76	0.0225	0.00020	0.046
120	73.78	3.51	14	2:1	1.63	0.0225	0.00018	0.039
90	64.67	3.18	14	2:1	1.39	0.025	0.00018	0.036
80	56.66	3.11	12	2:1	1.41	0.025	0.00020	0.039
70	54.48	3.02	12	2:1	1.28	0.025	0.00017	0.032
50	41.16	2.68	10	2:1	1.22	0.025	0.00018	0.030

Approximately 4.6 miles were lined during original construction. The lining has experienced slight to moderate erosion.

Three soil test samples (table A4) for this study were taken between stations 246+11 and 255+31. The material was classified as a lean clay (CL) with PI between 13 and 18 percent and LL between 31 and 36 percent. The performance of the lining at the locations sampled is shown on a plasticity chart (fig. A14).

This reach of canal was the site of a ponding test in September 1985, which indicated an average seepage rate of 0.19 ft^3/ft^2 per day. A maximum seepage rate of 0.10 ft^3/ft^2 per day is expected from a well-designed and constructed lining. A seepage rate of 0.19 ft^3/ft^2 per day was high but still acceptable.

One test was performed to determine the dispersive characteristics of the lining. The test indicated the lining was nondispersive.

Table A1. - Soil lining properties - Madera Irrigation District.

Lateral	Sta. (ft)	Lateral section	Sample No. 48Y-	PI (%)	LL (%)	Gravel (%)	Sand (%)	Fines (%)	G_s	USCS
6.2	211+00	2	X98[1]	11	25	0	58	42	2.59	SC
6.2	211+00	2	X99[1]	14	27	0	64	36	2.59	SC
6.2	211+00	2	X100[1]	12	27	0	67	33	2.58	SC
6.2	433+00	2	84	4	17	0	67	33	2.64	SC-SM
6.2	433+00	2	85	6	19	0	75	25	2.63	SC-SM
6.2	480+00	2	X101[1]	7	21	0	64	36	2.60	SC-SM
6.2	480+00	2	X102[1]	7	21	0	56	44	2.64	SC-SM
6.2	480+00	2	X103[1]	8	22	0	67	33	2.61	SC
6.2	665+00	3	92	3	17	0	56	44	2.67	SM
32.2	137+50	13	94	3	18	0	70	30	2.66	SM
32.2	137+51.5	13	104	14	28	0	56	44	2.71	SC
32.2	137+51.5	13	105	11	27	0	49	51	2.72	CL-SC
32.2	137+51.5	13	107	6	18	0	71	29	2.70	SC-SM
32.2	355+00	13	95	6	18	0	58	42	2.69	SC-SM
32.2	354+82	13	106	6	19	0	60	40	2.71	SC-SM
32.2	354+82	13	108	5	22	0	74	26	2.74	SC-SM
32.2	354+82	13	109	6	18	0	58	42	2.71	SC-SM

[1] Composite samples

Table A2. - Soil lining properties - Hammond Project, Main Canal.

Sta. (ft)	Canal section	Sample No. 48Y-	PI (%)	LL (%)	Gravel (%)	Sand (%)	Fines (%)	G_s	USCS
152+60	2	X122[1]	6	26	0	13	87	2.69	CL-ML
152+60	2	X123[1]	7	25	0	17	83	2.69	CL-ML
152+60	2	X124[1]	3	24	0	13	87	2.68	ML
152+00	2	121[2]			52	40	8		GP-GM
154+70	2	117	4	23	0	19	81	2.68	CL-ML

[1] Composite sample
[2] Gravel blanket

Table A3. - Soil lining properties - Missouri River Basin Project, Frenchman-Cambridge Division.

Canal	Sta. (ft)	Canal section	Sample No. 48Y-	PI (%)	LL (%)	Gravel (%)	Sand (%)	Fines (%)	G_s	USCS
Upper	2+75	1 (lined)	147	12	30		17	83	2.59	CL
Meeker	2+75	1 (lined)	148	10	28		23	77	2.59	CL
	2+75	1 (lined)	149[1]				22	78		
	2+75	1 (lined)	150	11	29		21	79	2.59	CL
	578+00	3	151	8	28		3	97	2.59	CL
	706+85	3	152	4	25		9	91	2.60	CL-ML
	722+40	3	153	6	26		12	88	2.60	CL-ML
	722+40	3	154	9	26		10	90	2.59	CL
	722+40	3	155[1]	9	29		13	87	2.63	CL
	727+20	3	x197[2]	6	26		8	92	2.62	CL-ML
	727+20	3	157	20	34		8	92	2.58	CL
	738+60	3	159	12	30		5	95	2.63	CL
	738+60	3	160	12	30		6	94	2.62	CL
	738+60	3	161	10	29		7	93	2.59	CL
	790+50	3	162[3]	4	24		7	93	2.58	CL-ML
	790+50	3	163[3]	6	26		9	91	2.64	CL-ML
	790+50	3	164[3]	10	29		15	85	2.64	CL
	790+50	3	165[4]			63	19	18		
Driftwood	849+40	4	167	7	27		4	96	2.59	CL-ML
	849+40	4	x198[2]	7	28		8	92	2.59	CL-ML
	943+75	4	169[3]	7	26		8	92	2.59	CL-ML
	1070+00	4	174	5	26		10	90	2.59	CL-ML
	1070+00	4	x199[2]	6	27		5	95	2.58	CL-ML
	1098+00	4	175	21	37		2	98	2.56	CL
	1098+00	4	176[3]	7	27		9	91	2.58	CL-ML
	1098+00	4	177	20	36		3	97	2.58	CL
	1098+00	4	178	13	33		2	98	2.57	CL
	1148+00	4	179	9	29		2	98	2.59	CL
	1148+00	4	180	12	30		3	97	2.59	CL
	1149+00	4	181	10	30		4	96	2.57	CL
Bartley	239+00	1 (lined)	182	10	27		21	79	2.59	CL
	239+00	1 (lined)	183	6	24		16	84	2.58	CL-ML
	239+00	1 (lined)	184	8	25		16	84	2.58	CL
	260+85	1 (lined)	185	9	26		16	84	2.61	CL
	260+85	1 (lined)	186	5	19		61	39	2.61	SC-SM
	260+85	1 (lined)	187	8	25		24	76	2.60	CL
	266+35	1 (lined)	188	8	25		24	76	2.63	CL
	266+35	1 (lined)	189	8	26		15	85	2.64	CL
	266+35	1 (lined)	190	8	24		31	69	2.59	CL
	266+35	1 (lined)	191	11	27		21	79	2.59	CL

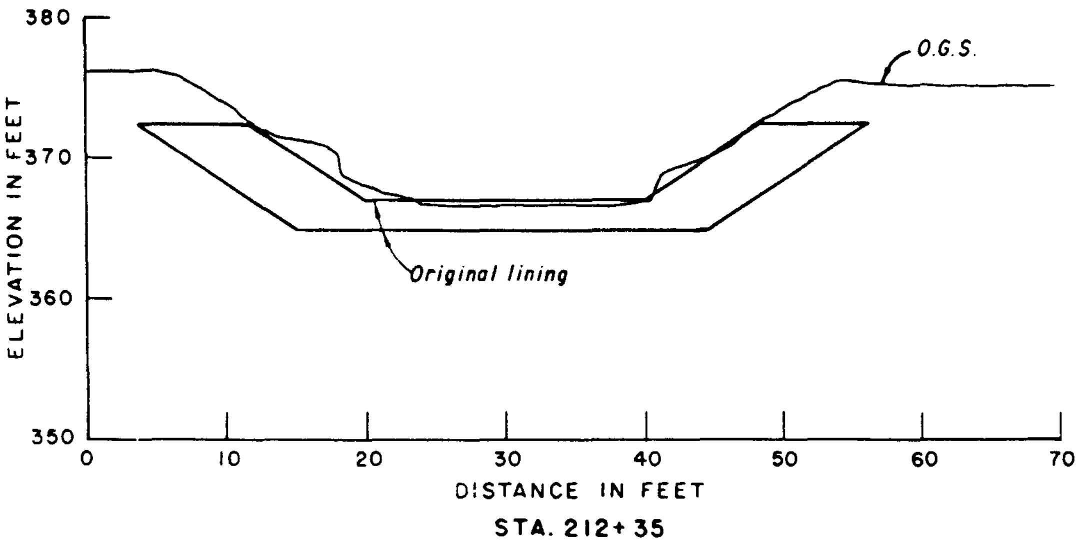
[1] Sediment over lining
[2] Composite sample
[3] Unsure if lining material
[4] Sample of gravel cover

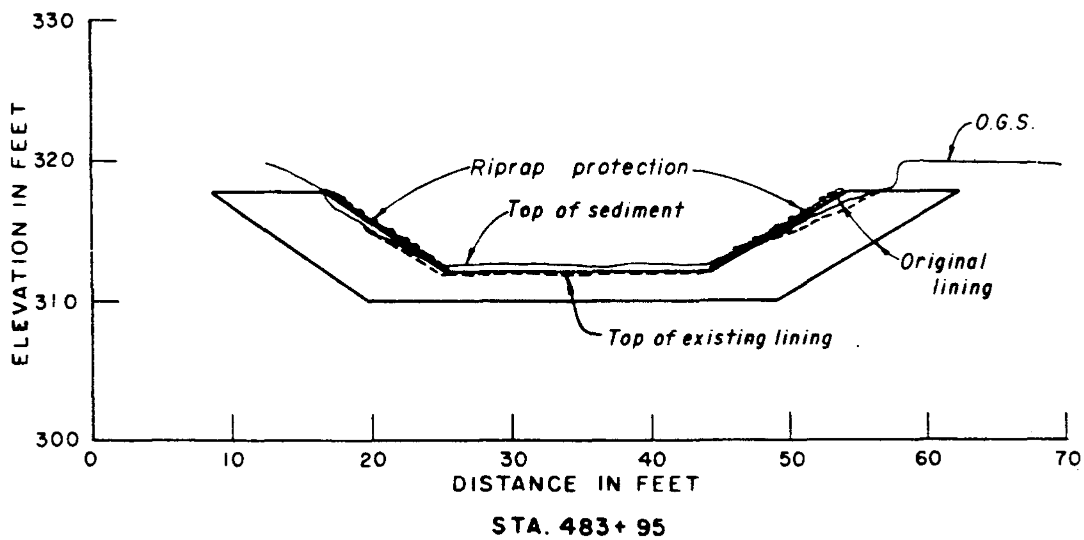
Table A4. - Soil lining properties - Eden Project.

Canal	Sta. (ft)	Canal section	Sample No. 48Y-	PI (%)	LL (%)	Gravel (%)	Sand (%)	Fines (%)	G_s	USCS
Eden	405+00	D (lined)	203	19	37		15	85	2.62	CL
	405+00	D (lined)	206[1]				83	17		
	405+00	D (lined)	208	NP			57	43		SM
	405+00±	D (lined)	x229[2]	20	36		33	67		CL
	405+00±	D (lined)	x230[2]	15	33		32	68		CL
	405+00	D (lined)	x231[2]	16	34		48	52		CL
	677+70	F (lined)	128	10	26		63	37	2.61	SC
	681+33	F (lined)	131[3]	5	24		68	32		SC-SM
	683+69	F (lined)	135[3]	11	31		57	43		SC
	683+69	F (lined)	136[4]	NP			78	22		SM
	684+00±	F (lined)	x194[2]	6	25		59	41	2.64	SC-SM
	684+00±	F (lined)	x195[2]	6	27		60	40	2.63	SC-SM
	684+00±	F (lined)	x196[2]	3	21		73	27	2.64	SM
Means	138+80	F (lined)	224[5]	NP		38	47	15		GM
	138+80±	F (lined)	x232	23	41		30	70		CL
	138+80±	F (lined)	x233	19	37		33	67		CL
Farson	246+11	70 ft^3/s[6]	219	18	36		35	65		CL
	256+63	70 ft^3/s[6]	220	16	32		26	74		CL
	255+31±	70 ft^3/s[6]	221	13	31		34	66		CL

[1] Sediment
[2] Composite sample
[3] Lining mixed with subgrade
[4] Subgrade
[5] Granular cover
[6] Section identified by discharge

MADERA IRRIGATION DISTRICT





LATERAL 6.2

Figure A1. - Madera Irrigation District - Cross sections, Lateral 6.2.

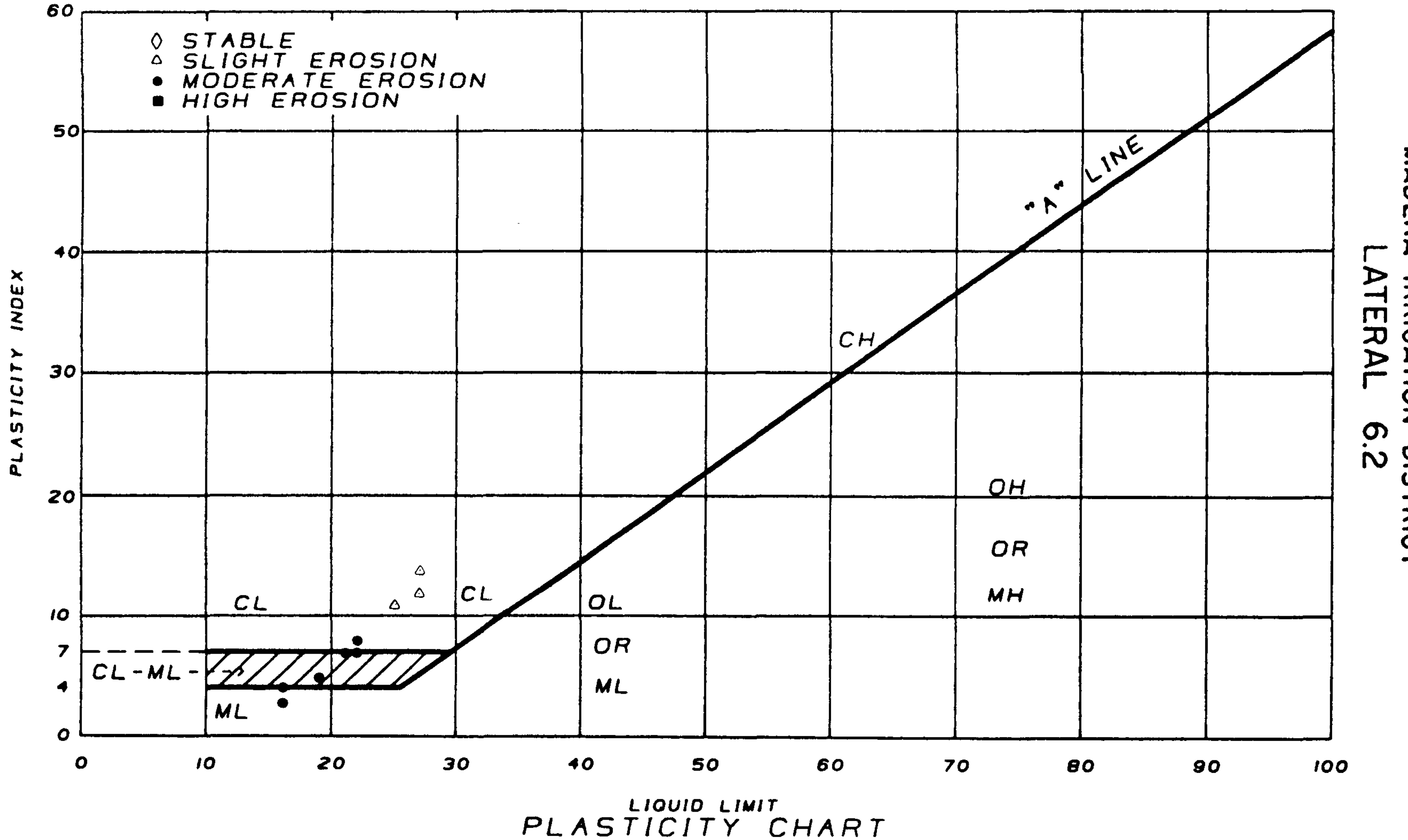


Figure A2. - Madera Irrigation District - Performance of Lateral 6.2 lining.

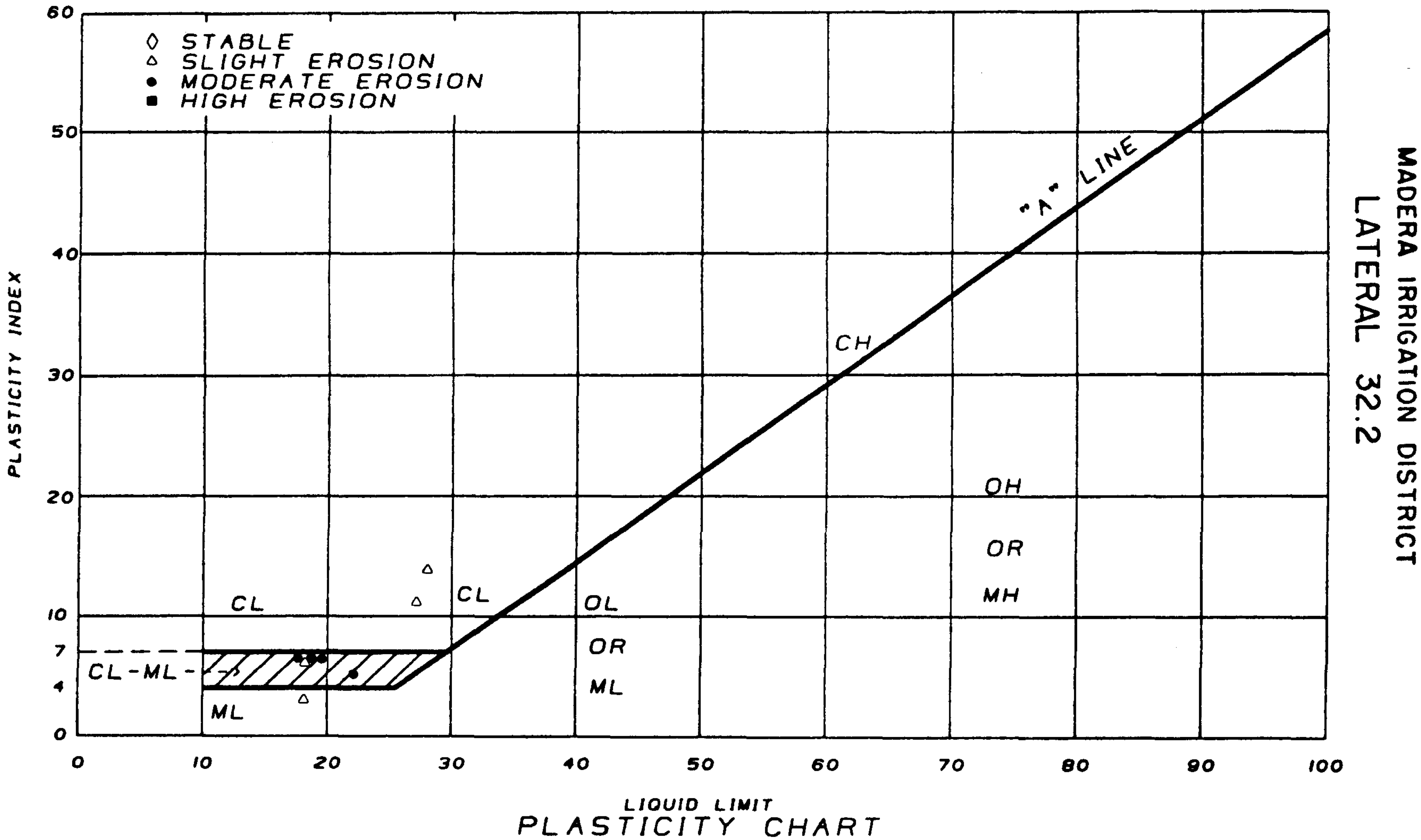


Figure A3. - Madera Irrigation District - Performance of Lateral 32.2 lining.

Note: Much of the gravel protection on the sideslopes has been inadvertenty removed by maintenance personnel.

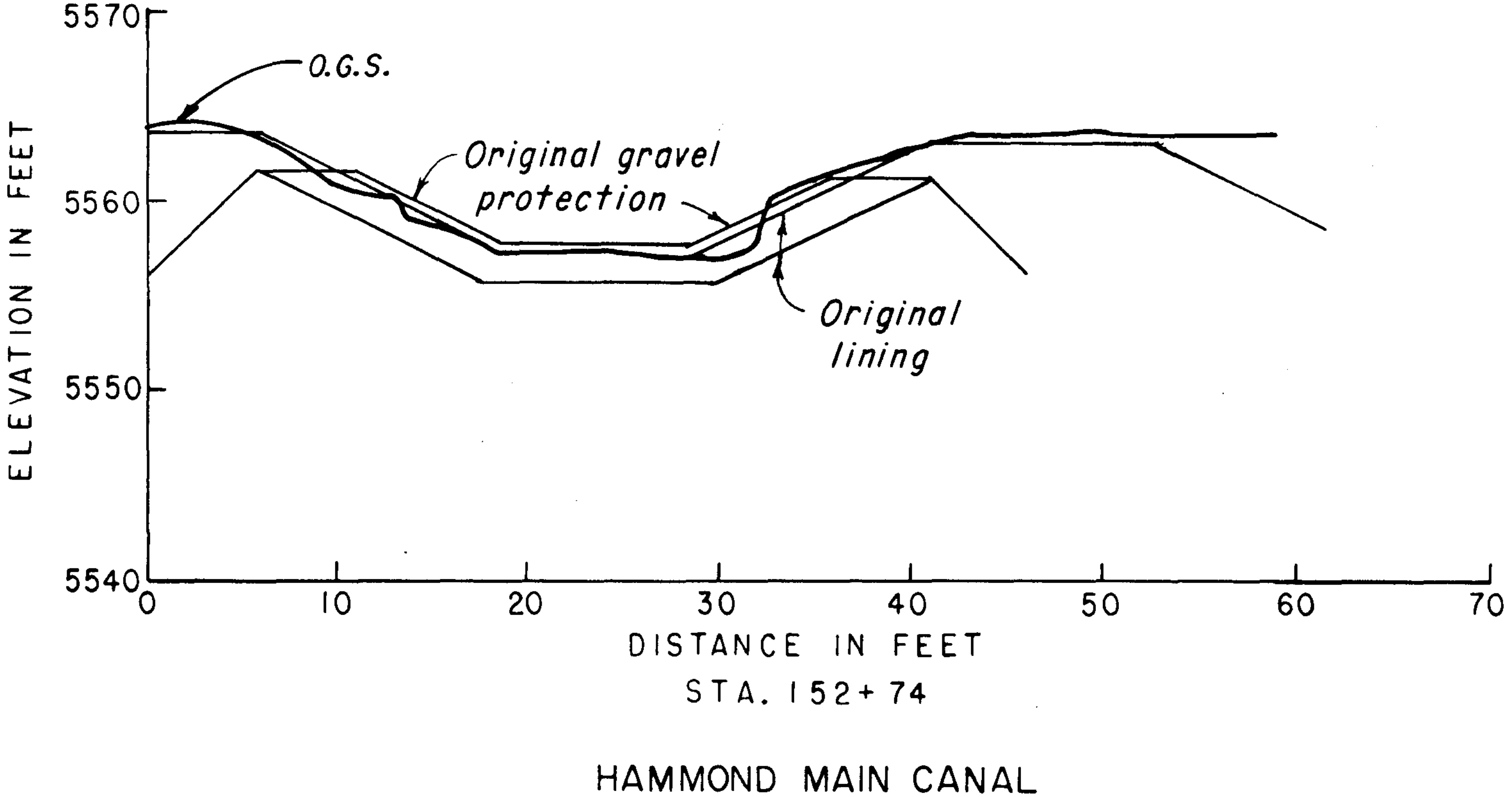


Figure A4. - Hammond Project - Main Canal (cross section Sta. 152+74).

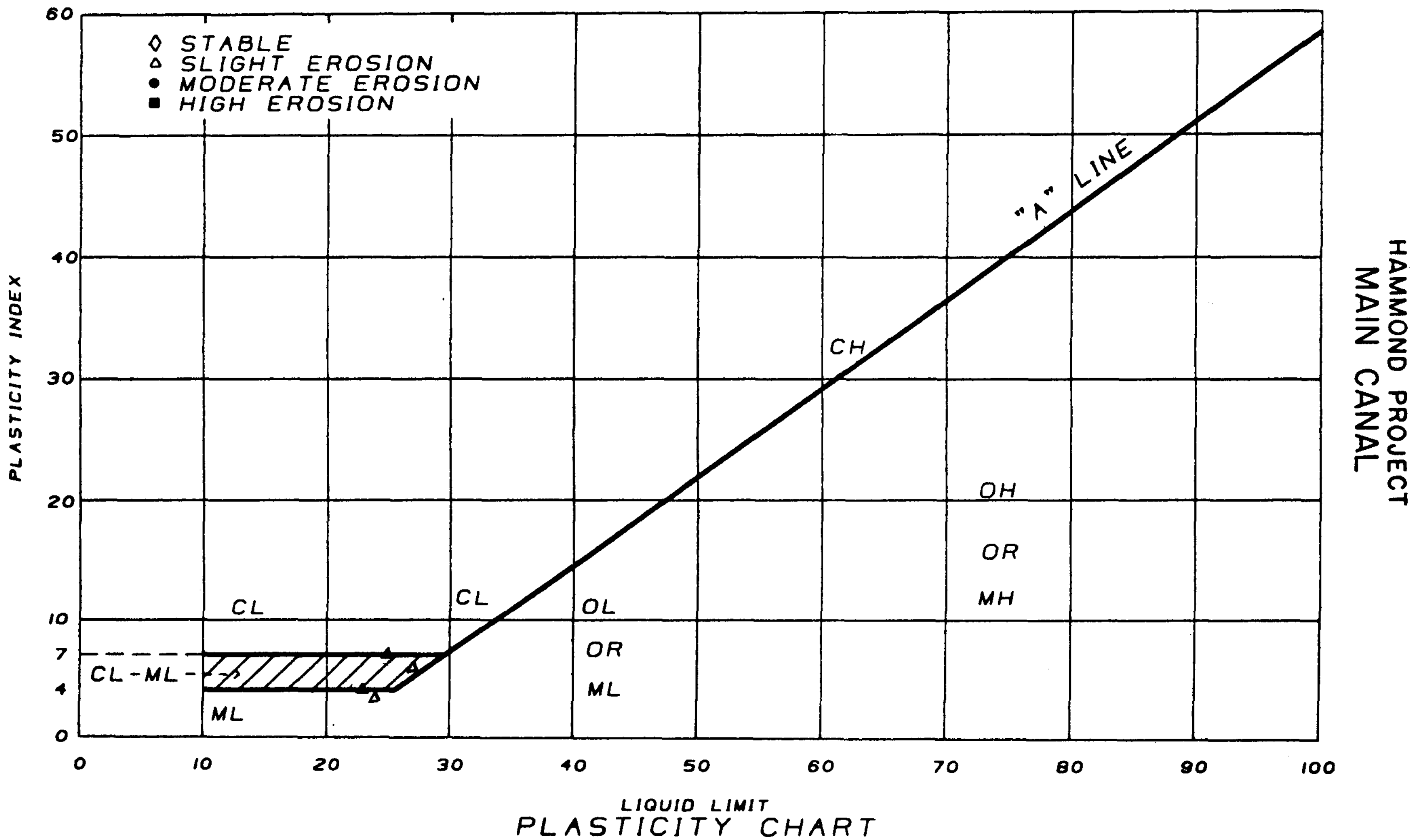


Figure A5. - Hammond Project - Performance of Main Canal lining.

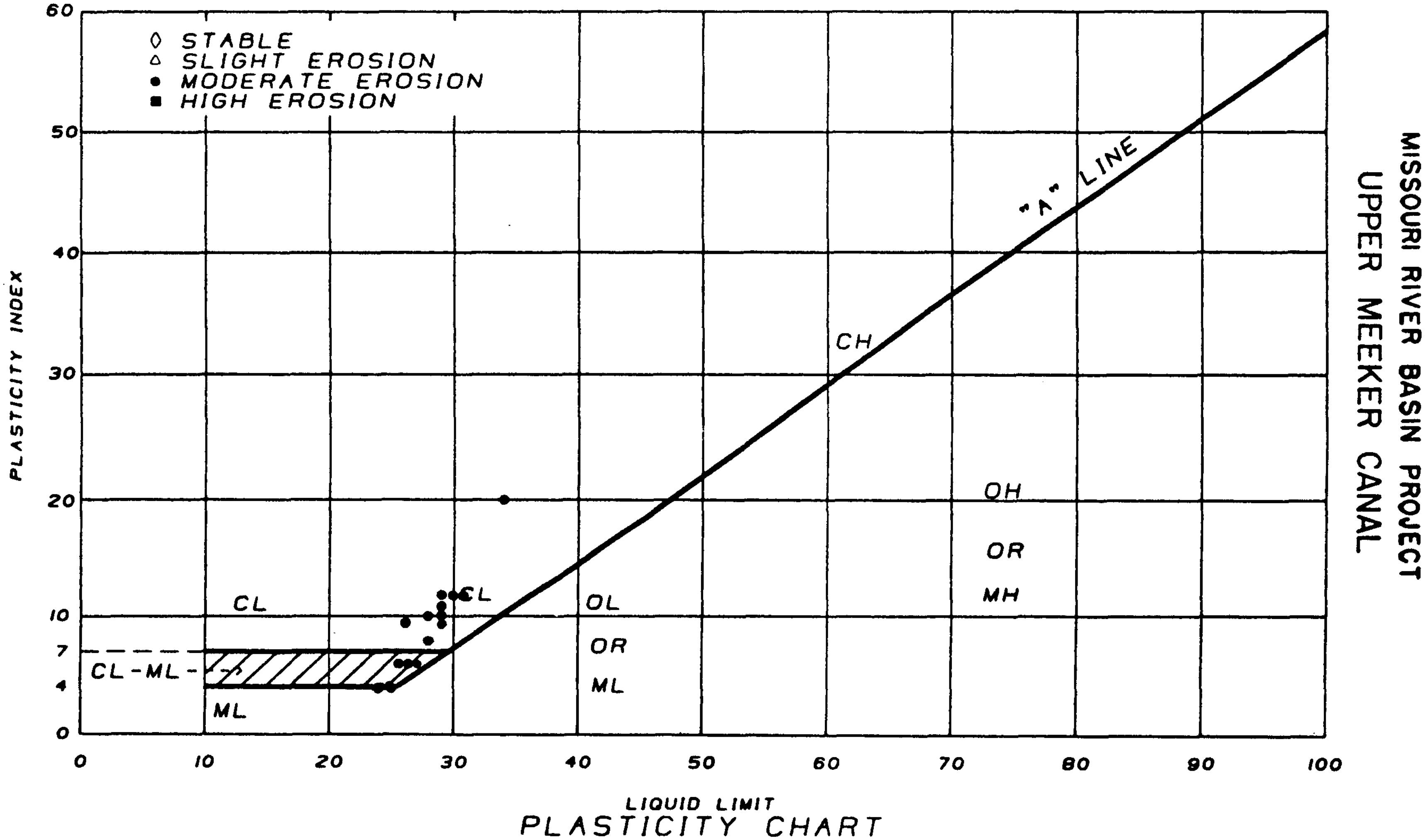
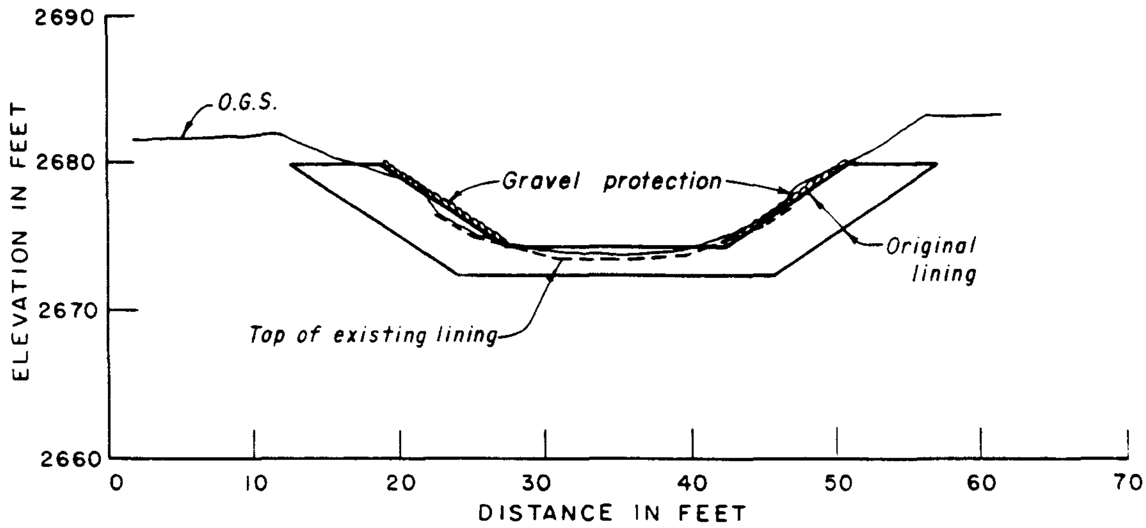
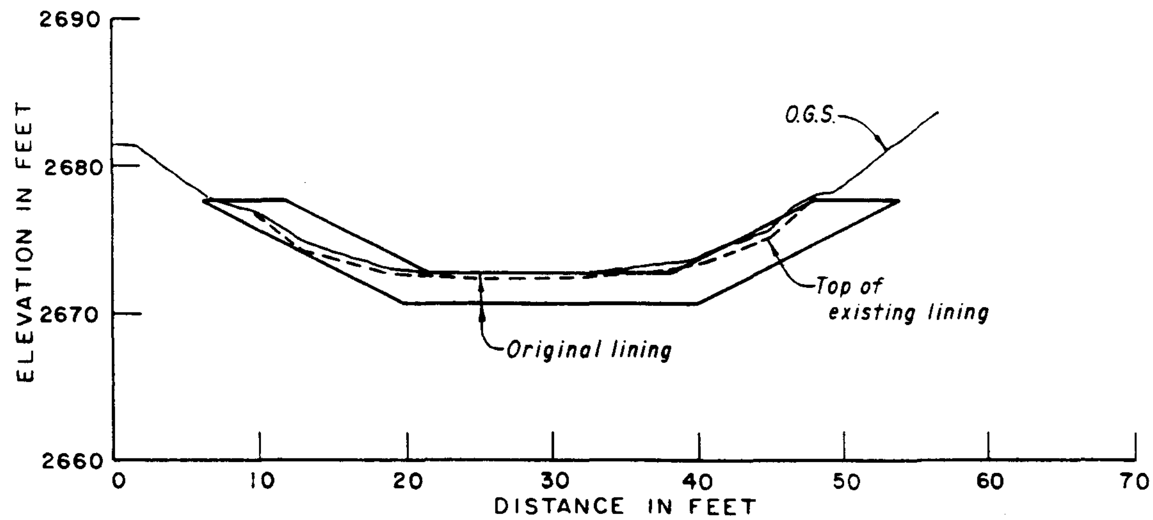


Figure A6. - Missouri River Basin Project - Performance of Upper Meeker Canal lining.



STA. 790+50

UPPER MEEKER CANAL



STA. 849+40

DRIFTWOOD CANAL

Figure A7. - Missouri River Basin Project - Cross sections
(Upper Meeker Canal - Sta. 790+50; Driftwood Canal - Sta. 849+40).

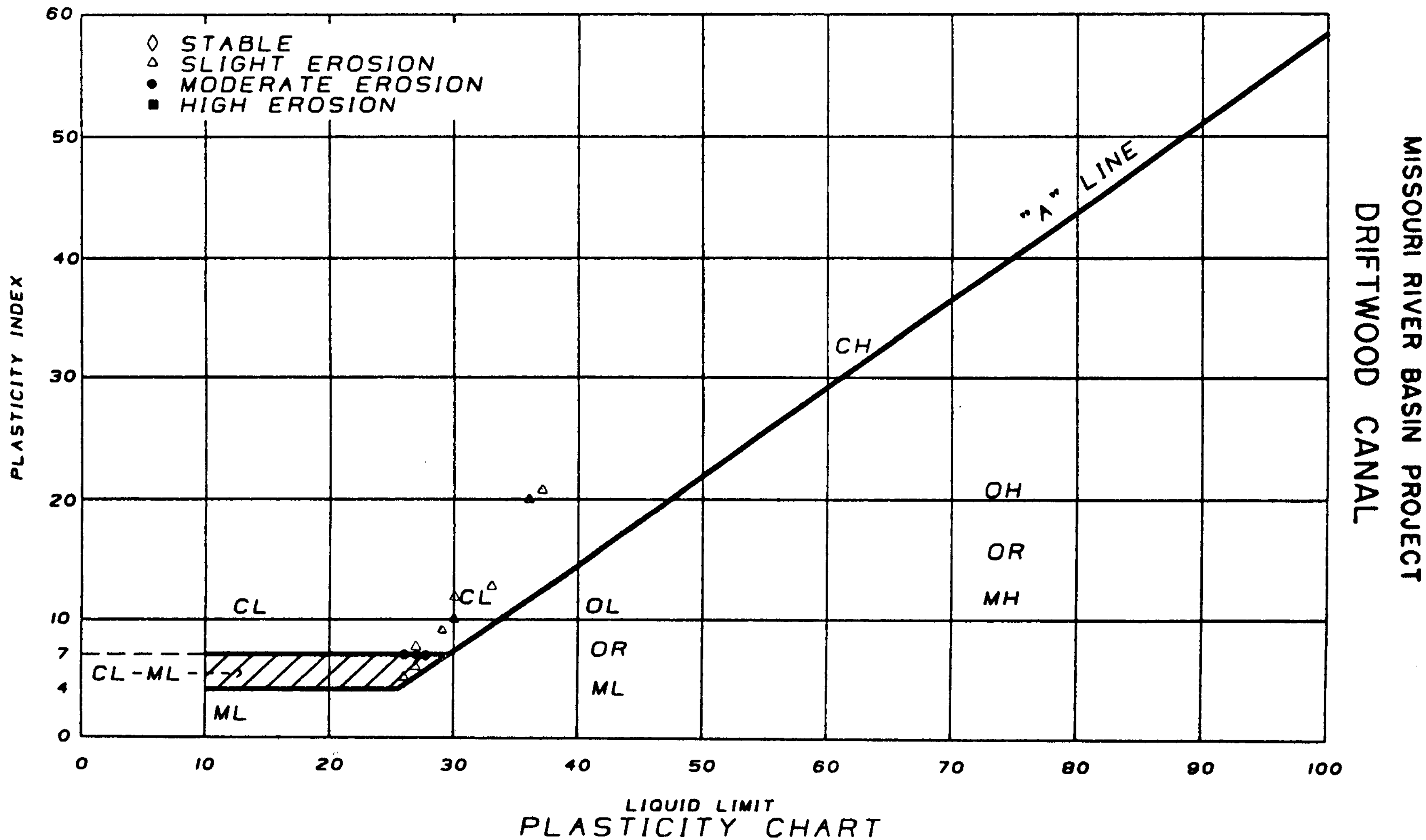


Figure A8. - Missouri River Basin Project - Performance of Driftwood Canal lining.

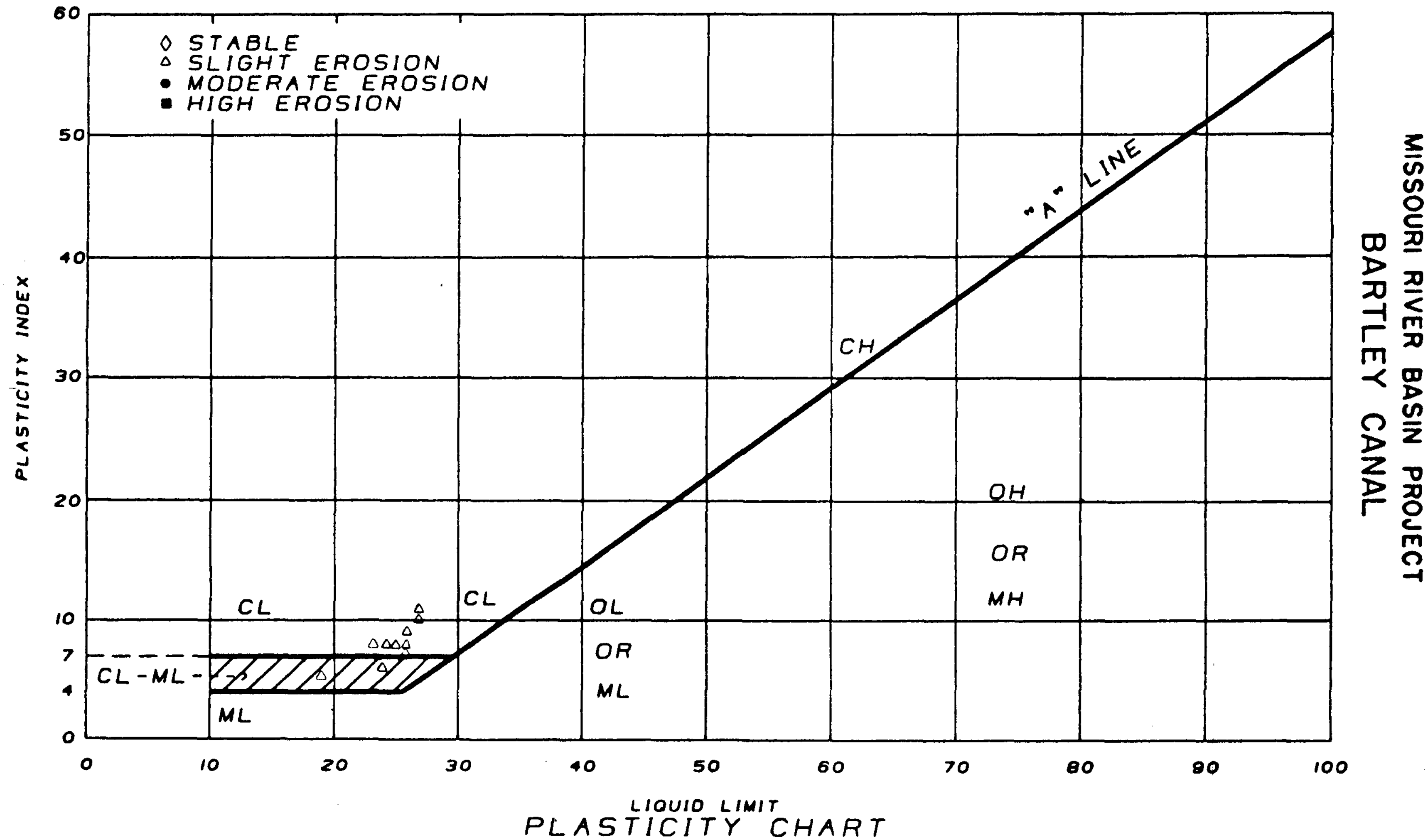


Figure A9. - Missouri River Basin Project - Performance of Bartley Canal lining.

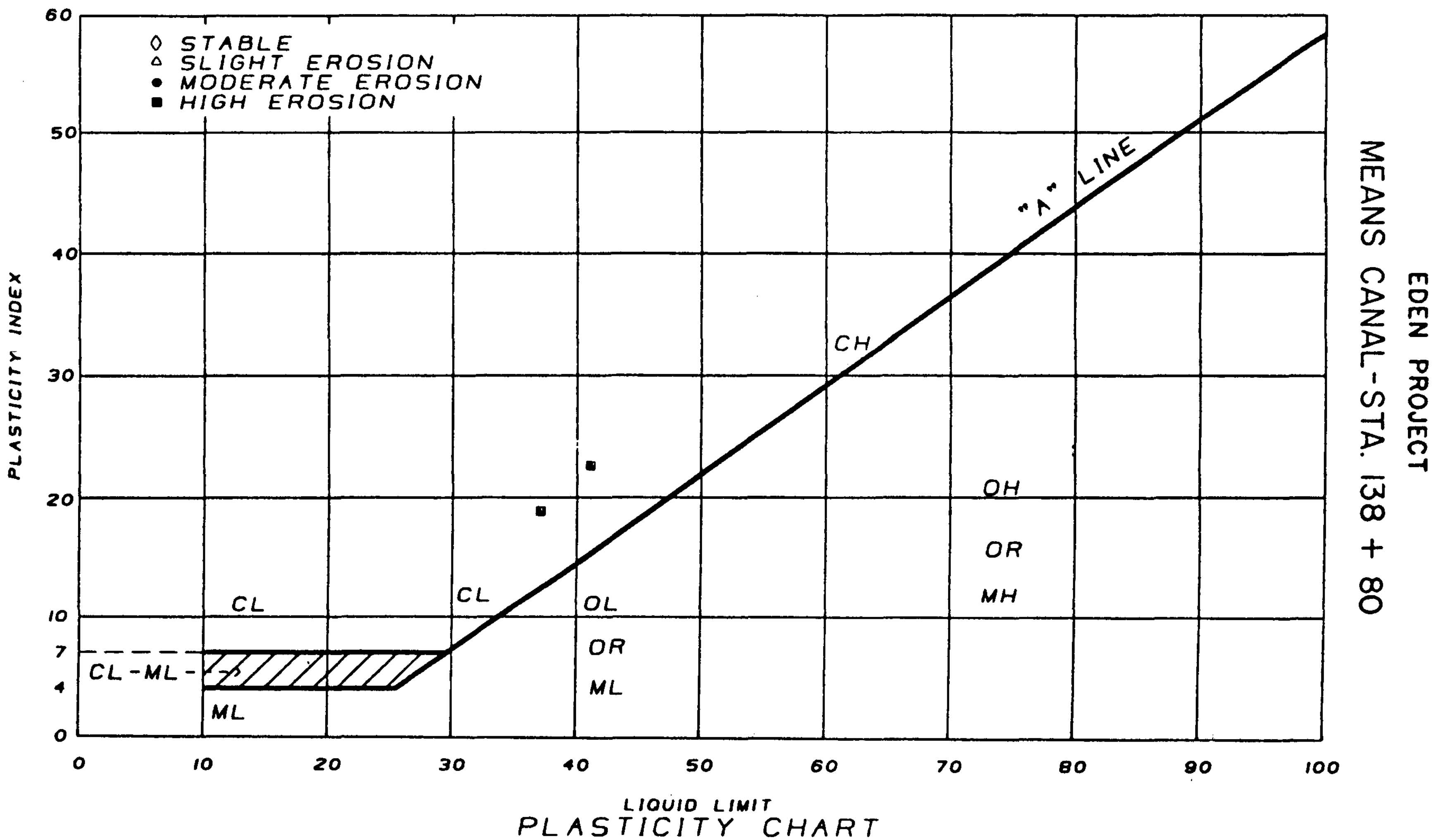
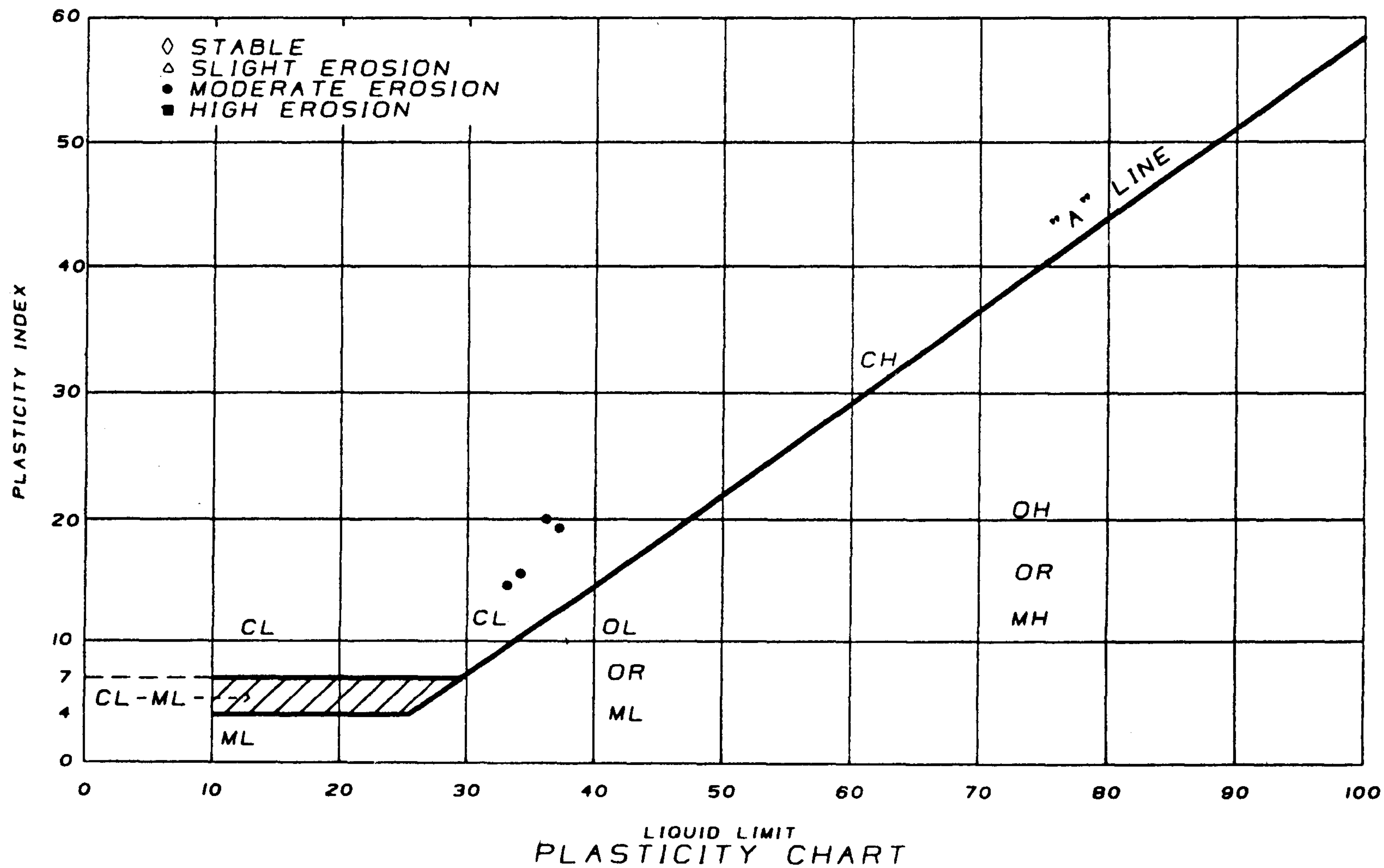


Figure A10. - Eden Project - Performance of Means Canal lining (cross section - Sta. 138+80).



EDEN PROJECT

EDEN CANAL - STA. 405+00

Figure A11. - Eden Project - Performance of Eden Canal lining (Sta. 405+00).

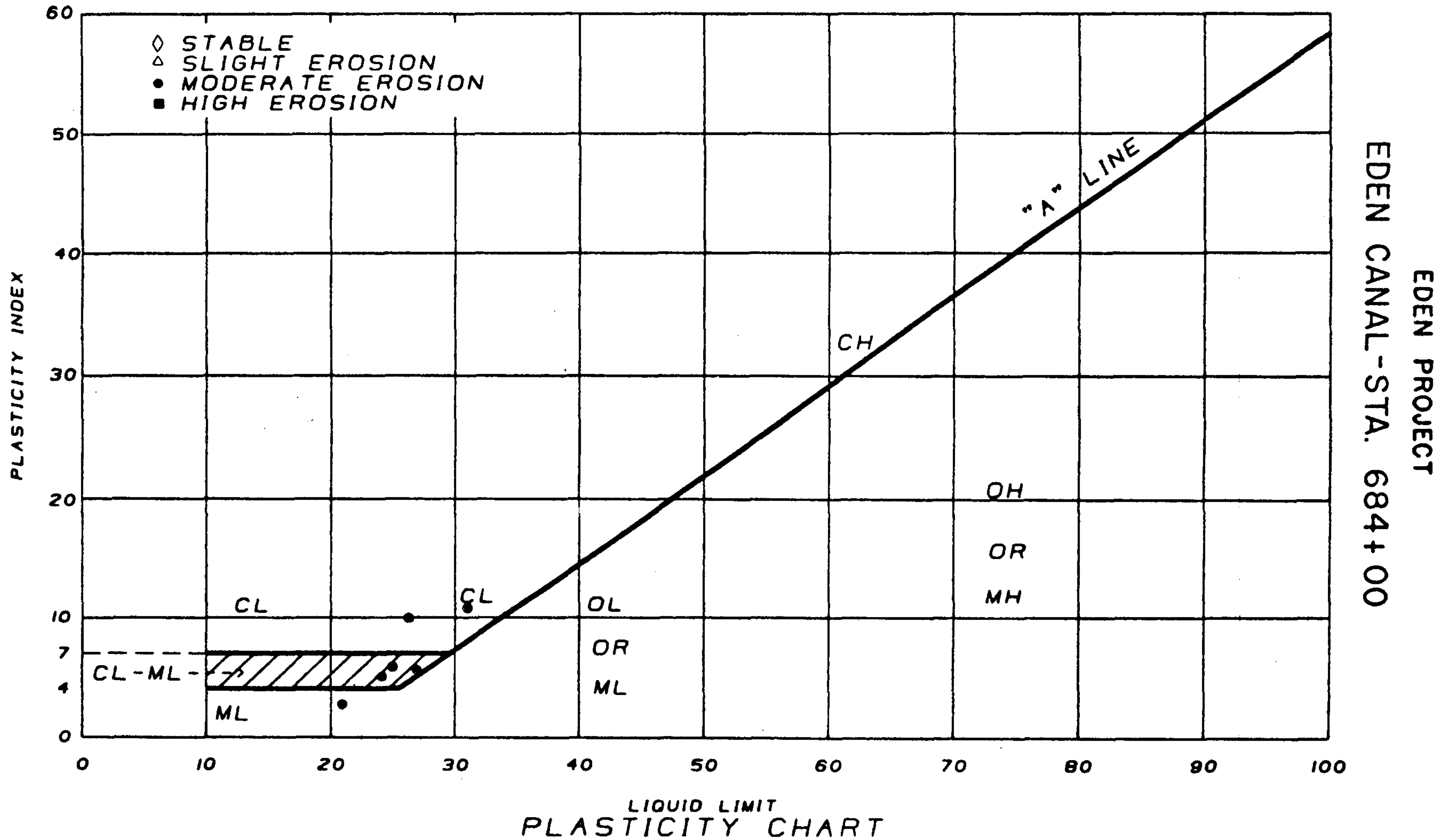


Figure A12. - Eden Project - Performance of Eden Canal lining (Sta. 684+00).

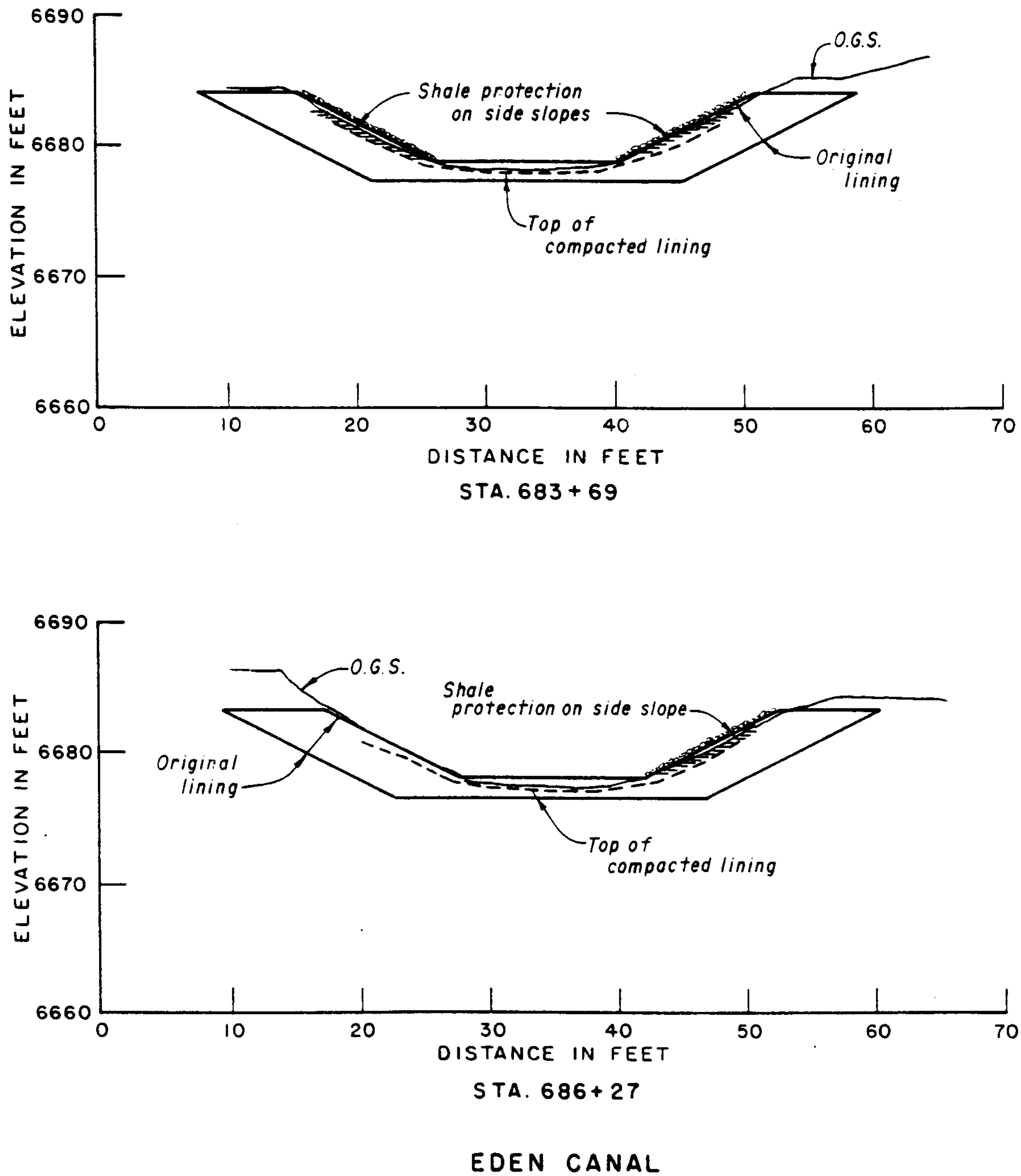
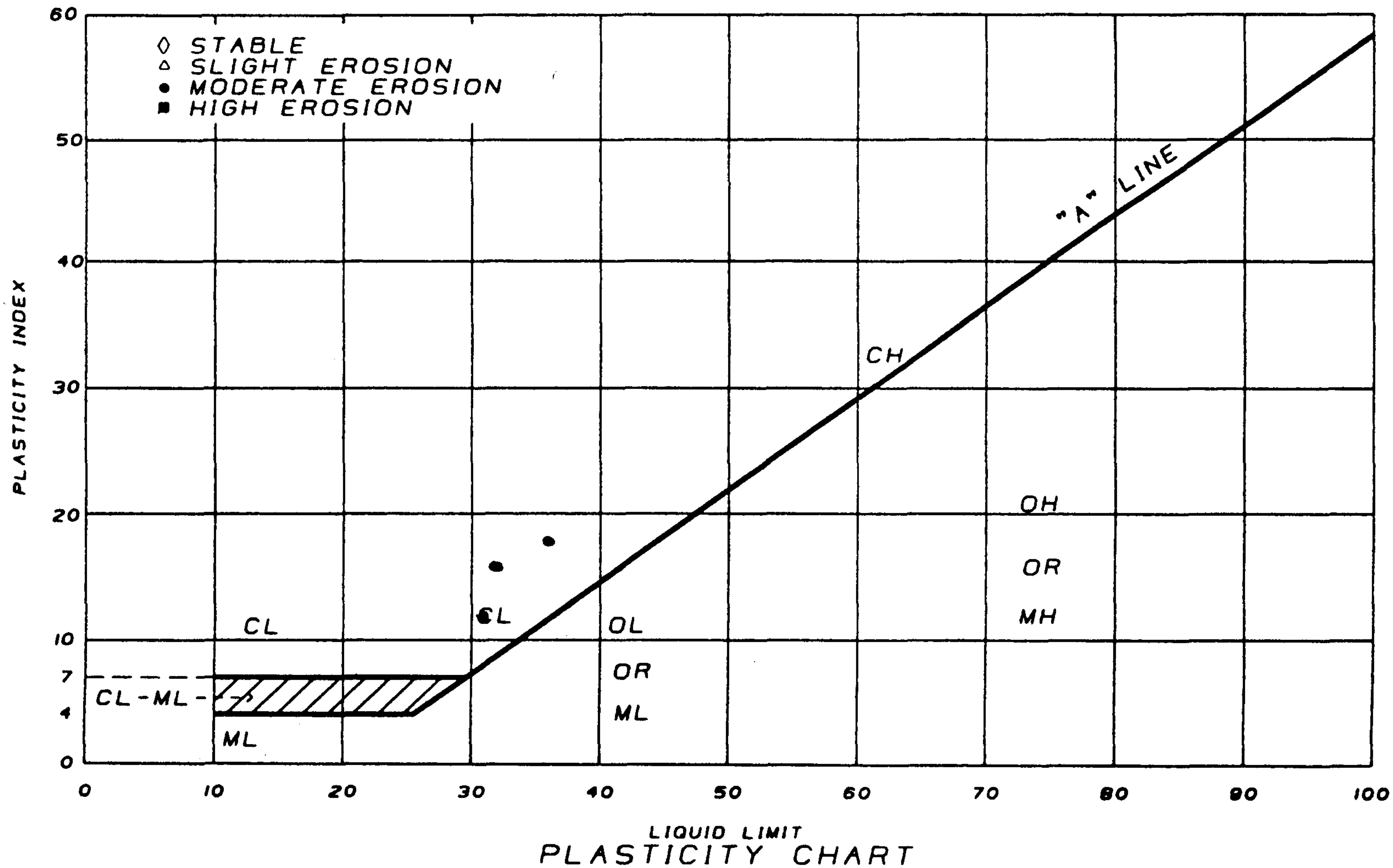


Figure A13. - Eden Project - Eden Canal
(cross sections, Sta. 683+69 and 686+27).



EDEN PROJECT
FARSON LATERAL

Figure A14. - Eden Project - Performance of Farson Lateral lining.

APPENDIX B

Field Observation Reaches

General Description
Projects and Canals

GENERAL DESCRIPTION

The observation reaches were established to monitor the performance of the canal linings over an extended period of time. The observation reaches were 200 to 400 feet long and were established in straight lengths of the canals in which the flow and erosion were not affected by curves in the alignment or by structures. The observation reaches were located at least 500 feet downstream from curves and 250 feet downstream from existing structures.

Each observation reach consisted of two or three surveyed cross sections. Two concrete markers and two to four erosion monitoring plugs were installed at each cross section (fig. B1).

A 6-inch-diameter by 48-inch-long concrete marker was located on each side of the cross section. The markers were placed within the canal prism and 1 to 4 feet horizontally outside the water surface. The tops are set within ±0.1 foot vertically of each other. To install the concrete markers, a 6-inch-diameter by 2.5-foot-long PVC (polyvinyl chloride) (or metal) tube was set in an augered hole at the appropriate height. Concrete was then mixed and placed into the tube. A forming nail was placed in the center of the marker. The nail protruded from the top of the concrete to allow for the attachment of a measuring tape.

The erosion monitoring plugs were installed on the canal side slopes and in the invert when possible. The details of an erosion monitoring plug are shown on figure B1. Four aluminum disks and a 2-foot nylon tape were installed in each plug. To install an erosion plug, a 3-inch-diameter hole was augered into the canal lining (embankment) to a depth of 2 feet. Then a disk (marked 24) was placed into the bottom of the hole with a 2-foot section of nylon tape running the length of the hole. Using the original soil removed from the hole, the lining was recompacted to a depth of 18 inches. A disk (marked 18) was then placed into the bottom of the hole and recompacted using the original soil to a depth of 12 inches. This process was continued (with disks marked 12 and 6), placing disks at appropriate depths and recompacting the lining until the hole was compacted to the original ground surface.

PROJECTS AND CANALS

Pick-Sloan Missouri Basin Program

Mirdan Canal. - Mirdan Canal is located in Nebraska and is approximately 49 miles long. Figure B2 shows the typical earth-lined sections of the canal. This canal was constructed from 1984 to 1988 and had not been placed into operation.

Material encountered during construction of the canal was a clayey to silty loess containing less than 5 percent sand (usually 1 to 3 percent) and 18 to 24 percent 0.005-mm or smaller sized material. According to ASTM Designation: D 3487-85 (ASTM, 1986), the loess in this area is classified as silt (ML), silty clay (CL-ML), or occasionally lean clay (CL). The loess had a PI that normally fell in the 6 to 11 percent range with an LL range from 22 to 31 percent. Undisturbed dry unit weights of the loess ranged in the low 70's to low 90's lbf/ft^3, normally ranging between 77 and 87 lbf/ft^3. Maximum unit weight of the material normally ranged from 99 to 104 lbf/ft^3 with an optimum moisture content of 19 to 20 percent. Field moisture content of the loess was highly variable and dependent on depth of sampling, type of vegetation cover, and climatic conditions.

Results of soil tests taken at the locations of the observation reaches are shown on table B1. The PI in these reaches varied from 7 to 14 percent, and the LL varied from 30 to 35 percent.

The earth lining for the Mirdan Canal was designed differently than for most other Reclamation canals. The canal lining was placed in two thicknesses (2.5 and 3.0 ft) and only in the invert. Lining was not placed on the side slopes. This design was based on an estimate of the cost of placing lining compared to the benefits of the lining. It was assumed that the foundation material (loess) would have a much greater permeability in the vertical direction than in the horizontal direction. Based on this assumption, it was concluded that lining only the invert would be economically beneficial in reducing the seepage losses.

Canal reaches in fill were selected for the study to validate the performance of both the invert and side slopes. The material used in the embankment and the compaction requirements for the compacted embankment were the same as for the earth lining. Thus, an embankment section simulated an earth-lined section and allowed observation of the performance of an entire cross section. The locations of the observation reaches are as follows:

Observation reach	Canal section	Cross section station (ft)
1	2A	1067+00
1	2A	1069+00
1	2A	1071+00
2	3A	1712+42
2	3A	1715+72
3	3A	2092+23
3	3A	2095+39
3	2A	1345+00
4	2A	1349+00

Geranium Canal. - The Geranium Canal is approximately 12 miles long and takes water from the Mirdan Canal. One observation site was established on the Geranium Canal. Typical sections of the canal are shown on figure B3. Results of the soils tests are shown on table B1.

The locations of the observation reach and cross sections are as follows:

Observation reach	Canal section	Cross section station (ft)
5	4	417+72
5	4	421+22

Dolores Project

Dove Creek Canal. - Dove Creek Canal is part of the Dolores Project located in southwestern Colorado near Cortez. The canal is approximately 20 miles long; the design capacity varies from 380 ft^3/s at the upstream end to 120 ft^3/s at the downstream end.

Reclamation laboratory tests showed that existing materials on Dove Creek Canal, Reach 2, were predominantly classified as lean clay (CL). Physical properties tests were as follows: LL varied from 27 to 34 percent, PI varied from 11 to 17 percent, sand ranged from 10 to 15 percent, and the specific gravity ranged from 2.62 to 2.64. The properties are listed in table B2.

The cross section of the canal is shown in figure B4.

The locations of the observation reaches are listed below:

Observation reach	Canal section	Cross section station (ft)
6	1	170+00
6	1	172+00
7	4	322+50
7	4	324+50
8	1	372+00
8	1	374+00
9	1	629+00
9	1	631+00
10	1	797+00
10	1	799+00
11	2	1025+00
11	2	1028+00

South Canal. - The South Canal is part of the Dolores Project located in southwestern Colorado near Cortez. The canal is approximately 6.9 miles long; the design capacity varies from 150 ft^3/s at the upstream end to 106 ft^3/s at the downstream end.

A cross section of the canal is shown in figure B5.

The locations of the observation reaches are listed below:

Observation reach	Canal section	Cross section station
12	2	152+00
12	2	153+50
13	2	353+00
13	2	355+00

Two soil samples were taken for testing. Reclamation laboratory tests were used for classification. The existing materials on South Canal were lean clay (CL). Tests are shown on table B2.

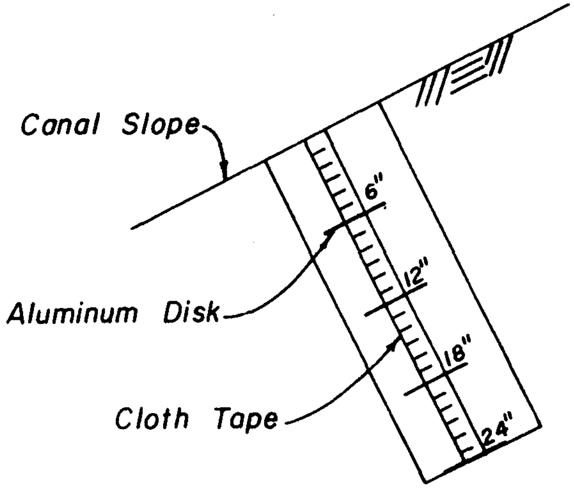
Table B1. - Soil lining properties - Mirdan and Geranium Canals.

Canal	Sta. (ft)	Sample No.	PI (%)	LL (%)	Gravel (%)	Sand (%)	Fines (%)	G_s	USCS
Mirdan	1069+00	59R-550	7	31	0	2	98	2.58	ML
Mirdan	1342+00	59R-551	10	34	0	1	99	2.60	ML
Mirdan	1742+50	59R-552	8	31	0	0	100	2.56	ML
Mirdan	2097+00	59R-553	14	35	0	2	98	2.56	CL
Geranium	421+50	61G-23	7	30	0	3	97	2.58	ML

Note: All the above are composite samples.

Table B2. - Soil lining properties - Dove Creek and South Canals.

Canal	Sta. (ft)	Sample No.	PI (%)	LL (%)	Gravel (%)	Sand (%)	Fines (%)	G_s	USCS
Dove Creek	170+00	61J-64	17	34	0	12	88	2.63	CL
Dove Creek	322+60	61J-65	16	32	0	13	87	2.63	CL
Dove Creek	374+00	61J-66	14	30	0	15	85	2.63	CL
Dove Creek	631+00	61J-67	16	32	0	11	89	2.62	CL
Dove Creek	796+95	61J-68	12	28	0	10	90	2.63	CL
Dove Creek	1028+00	61J-69	11	27	0	11	89	2.64	CL
South	153+50	61J-70	13	29	0	12	88	2.62	CL
South	355+00	61J-71	13	29	0	13	87	2.62	CL



DETAIL FOR EROSION
MONITORING PLUG

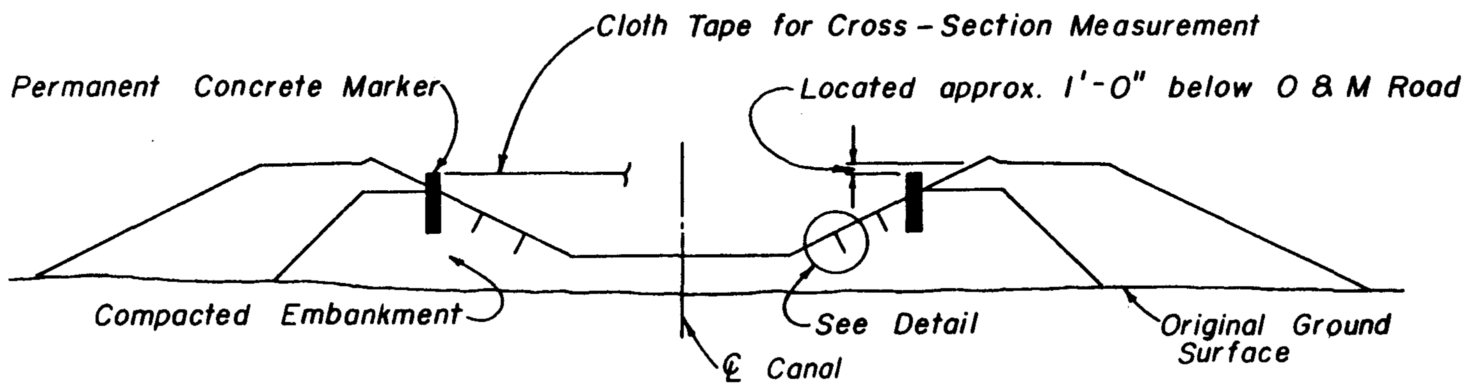
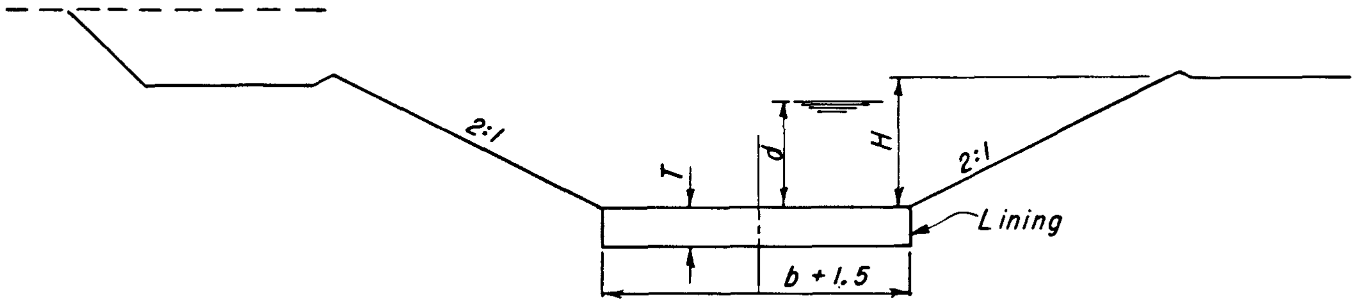
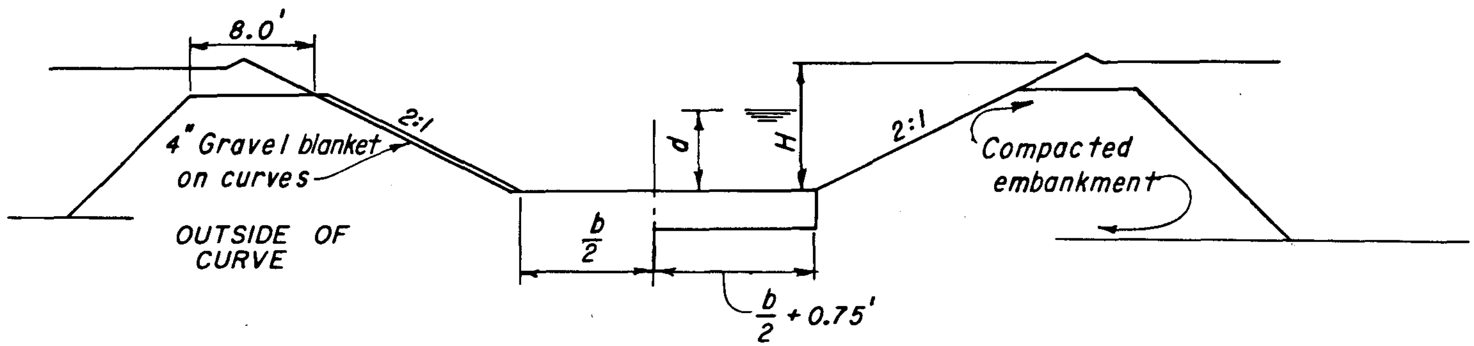


Figure B1. - Typical observation section in fill.



TYPICAL SECTION IN CUT



TYPICAL SECTION IN FILL

MIRDAN CANAL

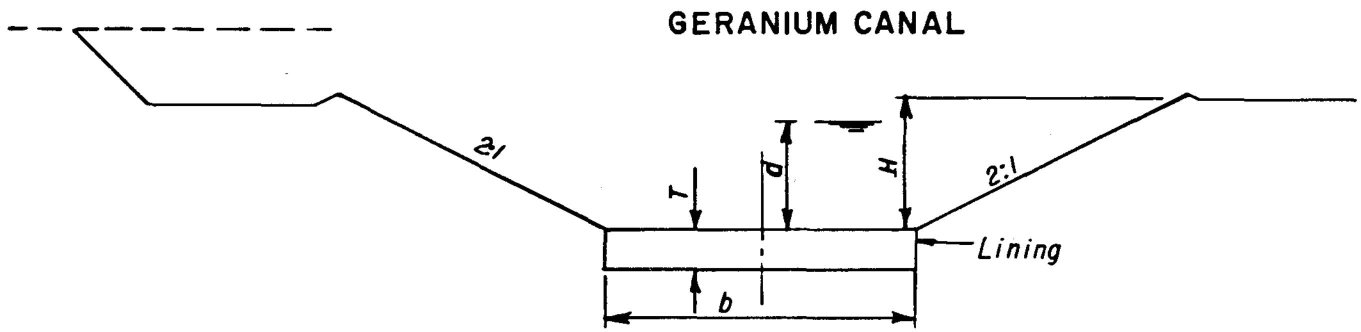
SECTIONS 2 AND 3

HYDRAULIC PROPERTIES

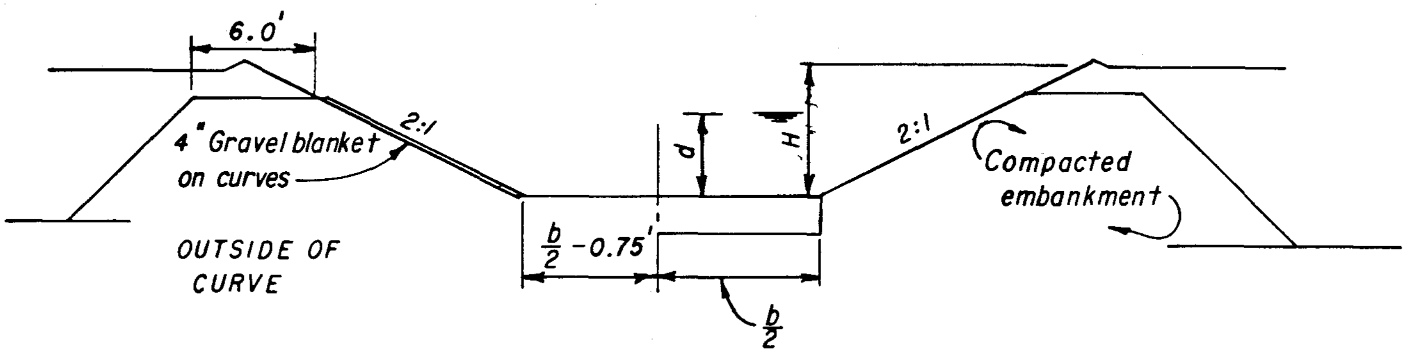
SECTION	A	V	Q	r	n	s	b	d	H	T.F.	T
2A	262.08	1.91	500	4.84	0.0225	0.000102	22.0	7.20	10.23	0.046	3.0
3A	163.52	1.71	280	3.80	0.0225	0.000113	18.0	5.60	8.21	0.039	2.5

Figure B2. - Mirdan Canal - Sections 2 and 3 (typical sections).

GERANIUM CANAL



TYPICAL SECTION IN CUT



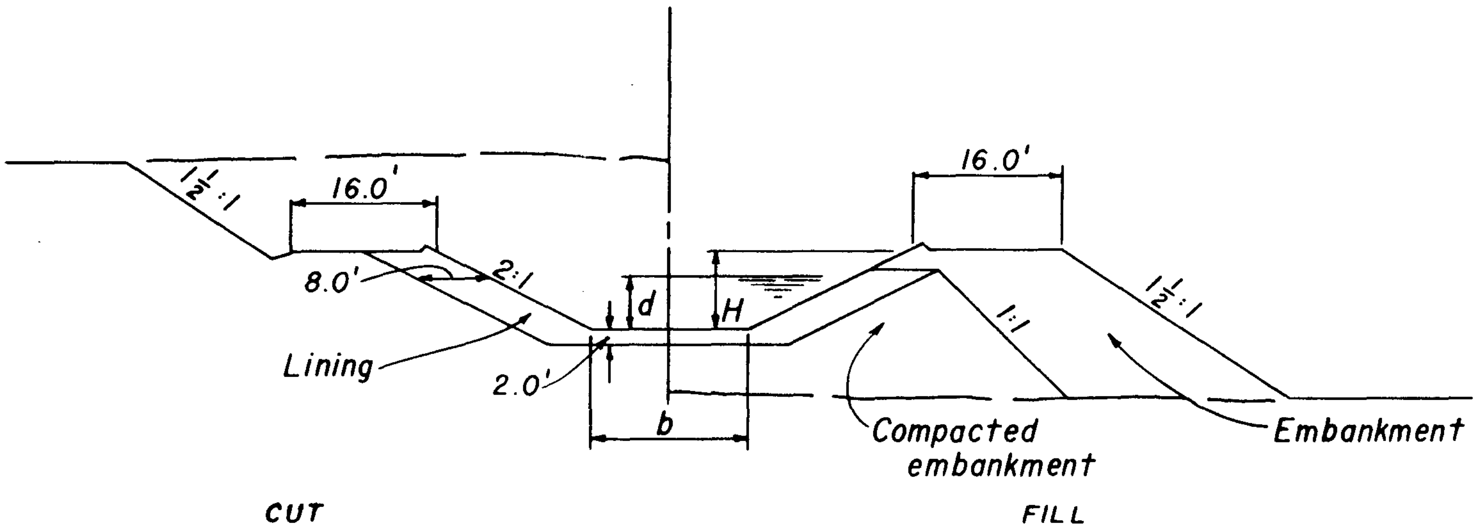
TYPICAL SECTION IN FILL

HYDRAULIC PROPERTIES

SECTION	A	V	Q	r	n	s	b	d	H	T.F.	T
4	88.67	1.75	155	2.79	0.0225	0.000178	15	4.09	6.3	0.045	2.5

Figure B3. - Geranium Canal (typical sections).

DOVE CREEK CANAL



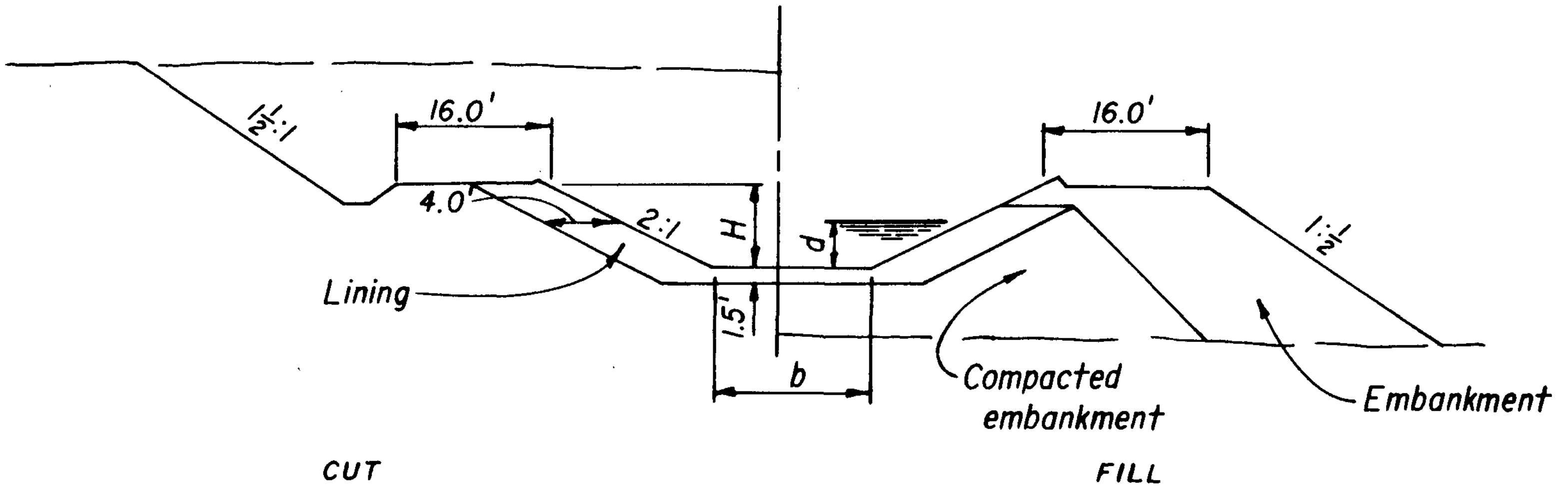
TYPICAL CANAL SECTION

HYDRAULIC PROPERTIES

SECTION	A	V	Q	r	n	s	b	d	H	T.F.
1	172.50	2.2	380	3.92	0.0225	0.00018	18.0	5.82	9.32	0.065
2	172.50	2.2	380	3.92	0.0225	0.00018	18.0	5.82	9.32	0.065
4	172.50	2.2	380	3.92	0.0225	0.00018	18.0	5.82	9.32	0.065

Figure B4. - Dove Creek Canal (typical canal section).

SOUTH CANAL



TYPICAL CANAL SECTION

HYDRAULIC PROPERTIES

SECTION	A	V	Q	r	n	s	b	d	H	T. F.
2	57.64	1.84	106	2.34	0.0225	0.00025	8.0	3.73	5.75	0.058

Figure B5. - South Canal (typical canal section).

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-7923A, PO Box 25007, Denver Federal Center, Denver CO 80225-0007.