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BUREAU CASE HISTORY OF LOESS CUT SLOPES IN NEBRASKA

by

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CONTENTS

FIGURES

INTRODUCTION

Surficial deposits of loess blanket much of eastern and southern Nebraska, see figure 1. These deposits are a western extension of loessial deposits that formed along the Missouri and Mississippi River Valleys. It is in this material that the Bureau of Reclamation has constructed several irrigation projects, whose main features include dams and reservoirs and related distribution systems of concrete-lined canals, earthen canals, and pipelines. During the 1950's and early 1960's, several projects were completed in loessial material in Nebraska. This early work required a considerable amount of field testing and research that resulted in preparation of the Bureau's Engineering Monograph No. 28, *Petrographic and Engineering Properties of Loess* [1][1], which is still the Bureau's guidebook for engineering design in loess.

Evaluation of maintenance problems associated with existing canals constructed in loessial deposits in Nebraska has prompted changes in the Bureau design criteria. These changes are reflected in recent designs for canals in the North Loup Division of Nebraska. Recent problems encountered during construction of these canals have prompted additional changes to canal

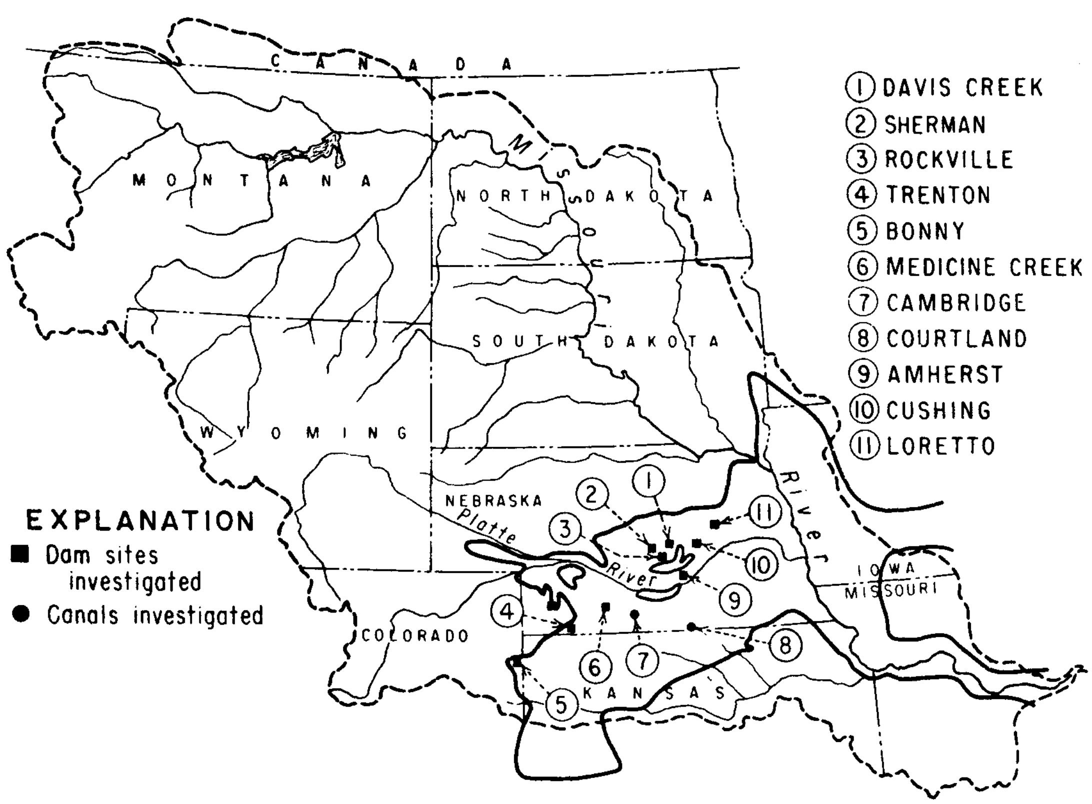


Figure 1. – Location of major loessial deposits in Missouri River Basin.

[1] Numbers in brackets refer to entries in the Bibliography.

design. This report discusses development of current design criteria for Bureau canals constructed in loessial deposits in central Nebraska.

GEOLOGICAL AND ENGINEERING PROPERTIES

The North Loup Division lies in the heart of the Great Plains Region. This area is typified by 10 to several hundred feet of unconsolidated Pleistocene deposits overlying horizontally bedded Tertiary and Cretaceous sediments. Surficial Pleistocene deposits include the silty sands of the Sand Hills in west-central Nebraska, silts and sands of the river valleys, eolian silts of southern and eastern Nebraska, and glacial tills found in portions of eastern Nebraska. Canals and laterals are located within the rolling loessial hills of central Nebraska; however, about 20 miles (32 km) to the northwest, these loessial hills change to the Sand Hills of west-central Nebraska.

Glacial ice sheets are not recognized as having advanced into this area of central Nebraska; however, their influence was recorded by alternating periods of stream downcuttings associated with glacial advances and related lowered ocean levels, by valley fillings during glacial meltbacks, and by sediment-laden streams that moved back and forth across wide expanses of the area during the Pleistocene period. Flood plains of these interglacial streams are considered to be the sediment sources of loessial deposits.

There are several recognized loesses occurring in Nebraska. Peorian Loess has widespread occurrence in the upper stratum and, consequently, was the material most frequently encountered during Bureau construction. Loess was the subject of research and testing in the monograph by Gibbs and Holland [1]. Other loesses are older and have very limited surface exposures in Nebraska; they are generally lean clay and have undergone loading and consolidation, thus having generally more favorable engineering characteristics than Peorian Loess.

Peorian Loess was deposited during the middle Wisconsin period of the Pleistocene epoch. Loess is considered to be the product of glacial-related abrasion, which produced rock-powder silt that was deposited along the flood plains of rivers. This silt was subsequently transported and redeposited by wind action. Peorian Loess is a buff-colored, uniformly sorted mixture comprised predominantly of quartz grains in silt and fine sand sizes. The majority of these grains are coated with very thin films of clay, which is generally montmorillonite and forms intergranular supports or braces within the structure. Calcite, in loess, usually occurs as distinct silt-sized grains in a finely dispersed state rather than as a cementing material. Thin clay coatings and, to a lesser extent, calcite apparently bond the particles together. Upon wetting, this bond weakens and results in a loss of strength.

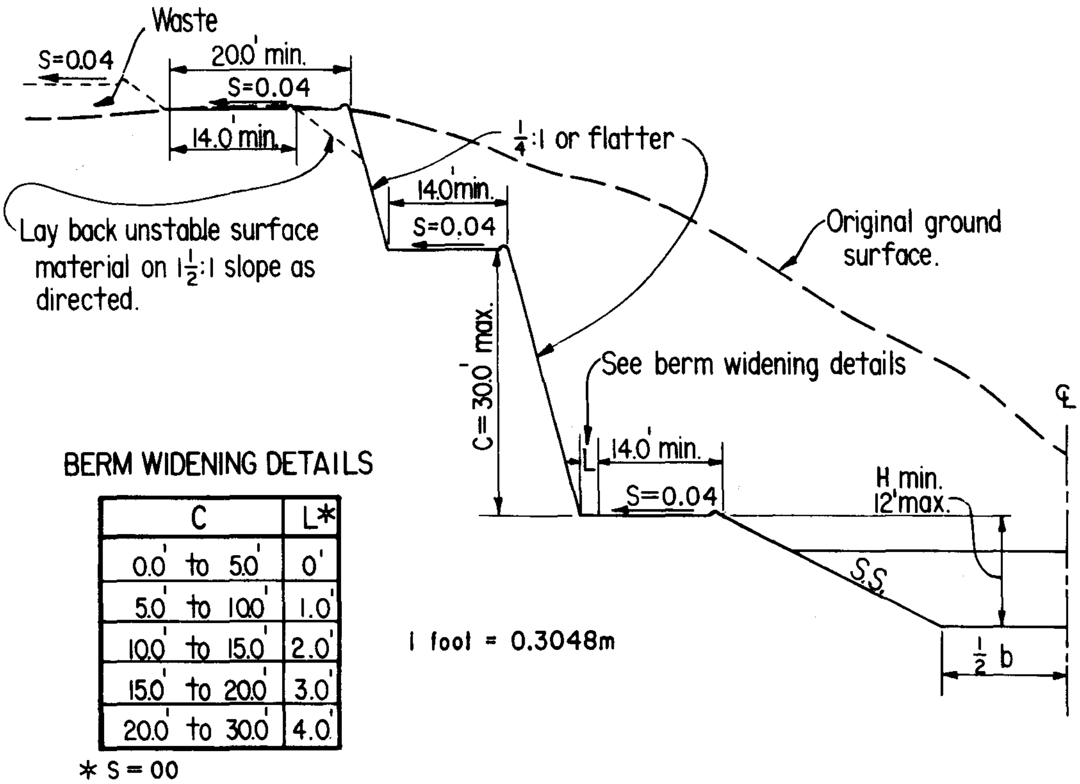
Loess encountered during construction of the North Loup Division was a clayey to silty loess containing less than 5 percent sand (usually 1 to 3 percent) and 18 to 24 percent 0.005 mm or smaller sized material. According to ASTM Designation: D 2487-85 [2], this loess is classified as silt (ML), silty clay (CL-ML), or occasionally lean clay (CL). The loess had a PI (plasticity index) that was usually in the 6- to 11-percent range, with a LL (liquid limit) ranging from 22 to 31 percent; however, along the canal there was a sizable amount of material that had a PI ranging from NP (nonplastic) to 6 percent. Undisturbed dry unit weights of the loess ranged from the low 70's to low 90's lbf/ft^3 (11.0 to 14.1 kN/m^3), but was usually between 77 and 87 lbf/ft^3 (12.1 and 13.7 kN/m^3) [3]. The maximum unit weight of the material normally ranged from 99 to 104 lbf/ft^3 (15.6 to 16.3 kN/m^3), with an optimum moisture content of 19 to 20 percent, as based on cumulative field test data. Field moisture content of the loess was highly variable and dependent on depth of sampling, type of vegetation cover, and climatic conditions.

PERFORMANCE OF EXISTING CANALS

During the 1950's and 1960's, the Bureau used two typical canal sections having cut slopes of 1/4:1 and 1/2:1 in loess. All canal slopes over a maximum height of about 30 feet (9 m) required bench-type construction. Bench widths ranged from 14 to 20 feet (4.3 to 6.1 m) sloping slightly toward the back of the bench. General sketches of the two typical canal sections are shown on figures 2 and 3.

Figure 4 is a current photograph of the Driftwood Canal, located in southwestern Nebraska, as it exists approximately 30 years after construction. Figure 5 is a photograph of Sherman Feeder Canal, located in south-central Nebraska, approximately 25 years after construction. The 1/2:1 cut slope promotes increased vegetation growth, less erosion, and a stable condition.

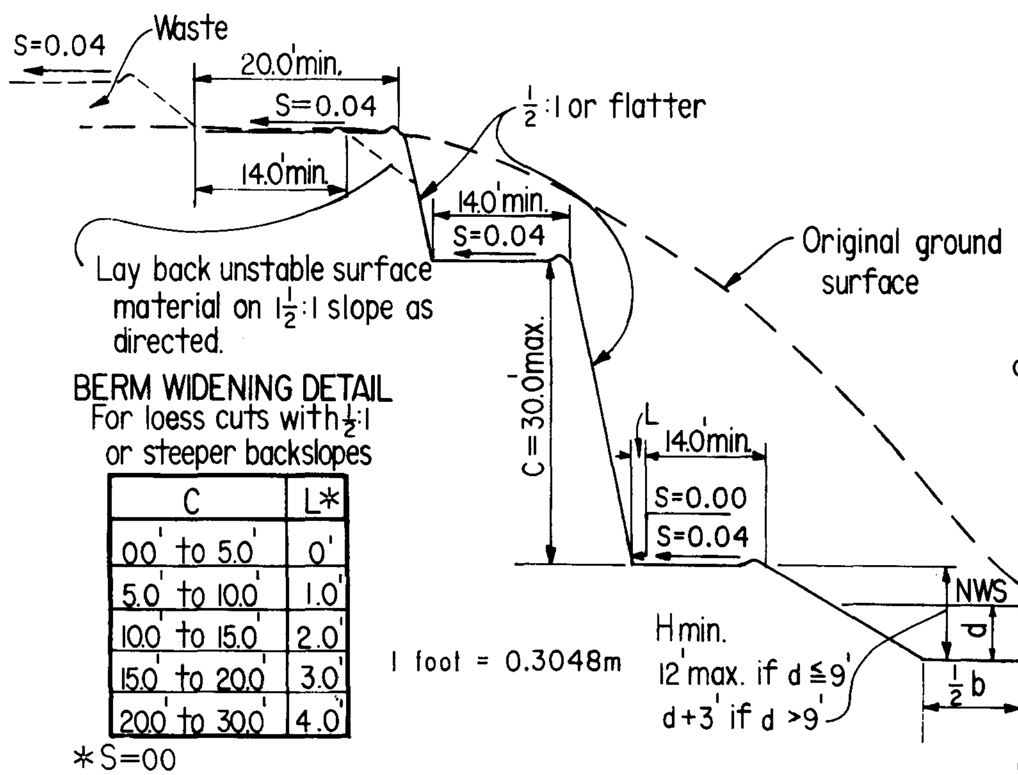
Documentation detailing rationale for past designs and problems encountered during construction is limited; however, recent inspections of these cut slopes indicate all are functioning adequately. Localized slope failures have occurred on several sections of these canals and require continual maintenance. These failures create problems in maintaining O&M (operation and maintenance) roads. In sections of these canals where O&M roads are frequently traveled, fallen material from the steep cut slopes has been spread over the roads causing an increase in the road elevation. A photograph of a raised O&M road is shown on figure 6. In many cases, fallen material from cut slopes has created a toe at the base of the slope having roughly a 1:1 slope, as shown on figure 7. Slopes having an adequate cover of vegetation (slopes of 1/2:1 or less) do not show signs of extensive erosion, as can be seen on figure 5. The presence of a good



C	L*
0.0' to 5.0'	0'
5.0' to 10.0'	1.0'
10.0' to 15.0'	2.0'
15.0' to 20.0'	3.0'
20.0' to 30.0'	4.0'

* S = 00

Figure 2. – Typical 1/4:1 canal cross section constructed during the 1950's and 1960's.



C	L*
0.0' to 5.0'	0'
5.0' to 10.0'	1.0'
10.0' to 15.0'	2.0'
15.0' to 20.0'	3.0'
20.0' to 30.0'	4.0'

* S=00

Figure 3. – Typical 1/2:1 canal cross section constructed during the 1950's and 1960's.

Figure 4. - Driftwood Canal about 30 years after construction. Note that the 1/4:1 slope is relatively stable with only minor sloughing and erosion. Also note the insignificant amount of vegetation growth on slope. P801-D-81420.

Figure 5. - Sherman Feeder Canal about 25 years after construction. Note that minor sliding exists along the hillside of this 1/2:1 cut slope canal causing a stairstep appearance, which is frequently found on steep hillsides in loess. P801-D-81421.

drainage system is the most critical item in controlling erosion. Benches on cut slopes that have accumulated debris often block drainage paths, force water to run down the face of lower cut slopes, and result in severe erosion. Figure 8 is a photograph showing extensive erosion of a cut slope.

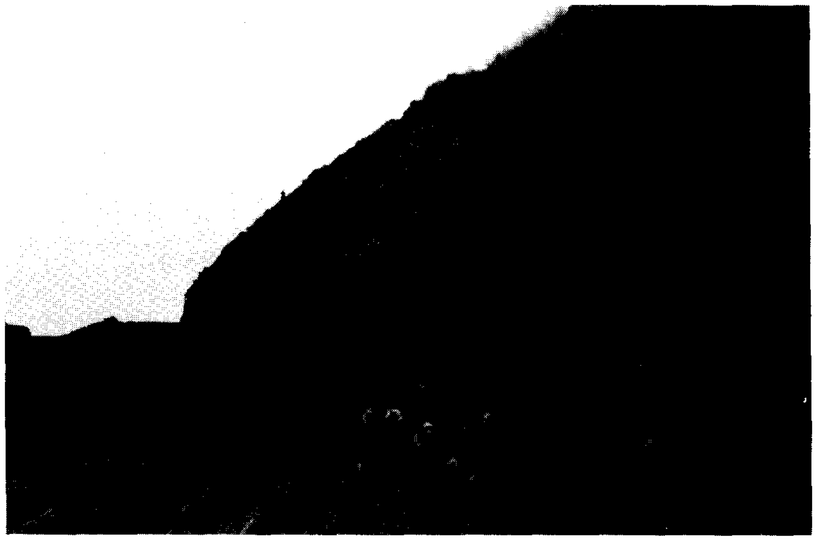


Figure 6. - An O&M road that has been raised with fallen material from a cut slope. P801-D-81422.

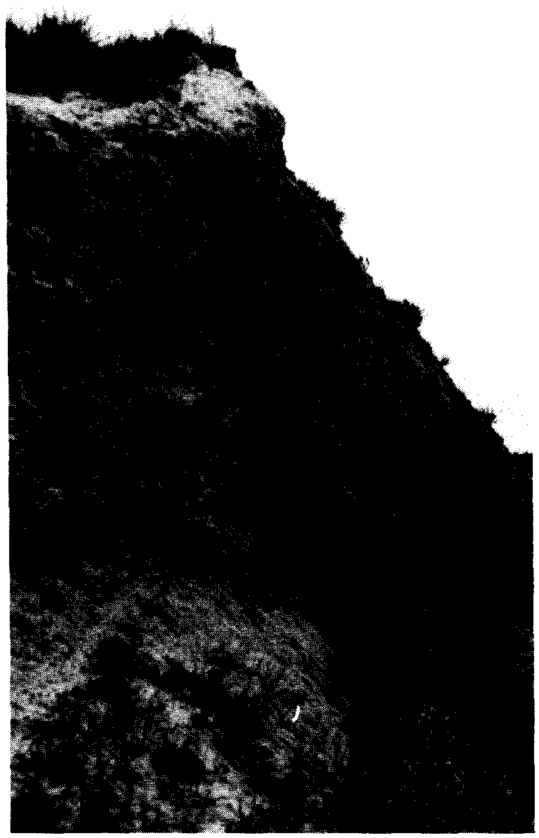


Figure 7. - Natural toe formed by fallen material from a cut slope. P801-D-81423.

Figure 8. - Severe erosion of a cut slope that resulted from a blocked drain. P801-D-81424.

NORTH LOUP DIVISION

Description

The North Loup Division is a Bureau project currently under construction for the Twin Loups Irrigation and Reclamation Districts in central Nebraska (fig. 9). This will be a multipurpose project that derives benefits from irrigation, ground-water recharge, water quality improvement, flood control, and recreation; with the primary purpose being irrigation. Two dams will store 136,000 acre-feet ($168 \times 10^6 m^3$) of water, which will be available to irrigate 53,000 acres (21 000 hectares). For water delivery, there will be 162 miles (261 km) of canals with capacities of 12 to 720 ft^3/s (0.3 to 20.4 m^3/s). Canals having capacities greater than 50 ft^3/s (1.4 m^3/s) will be constructed as open ditches, and those smaller as buried pipelines. A majority of these canals have been or will be constructed in deposits of Peorian Loess. The thickness of the loess ranges from a few feet to more than 100 feet (30.5 m), with an average thickness of 40 to 50 feet (12 to 15 m). Depths of canal excavations range up to 90 feet (27 m) from the O&M road to the original ground surface, with a total canal cut depth of more than 100 feet.

Design Considerations

For economic savings in reducing excavation quantities, the Bureau, State and local road departments, and railroads have used the unique property of loess to stand at near-vertical slopes. State agencies in Nebraska and others involved in road building or repair have, for the most part, abandoned the use of near-vertical slopes because of aesthetics and maintenance

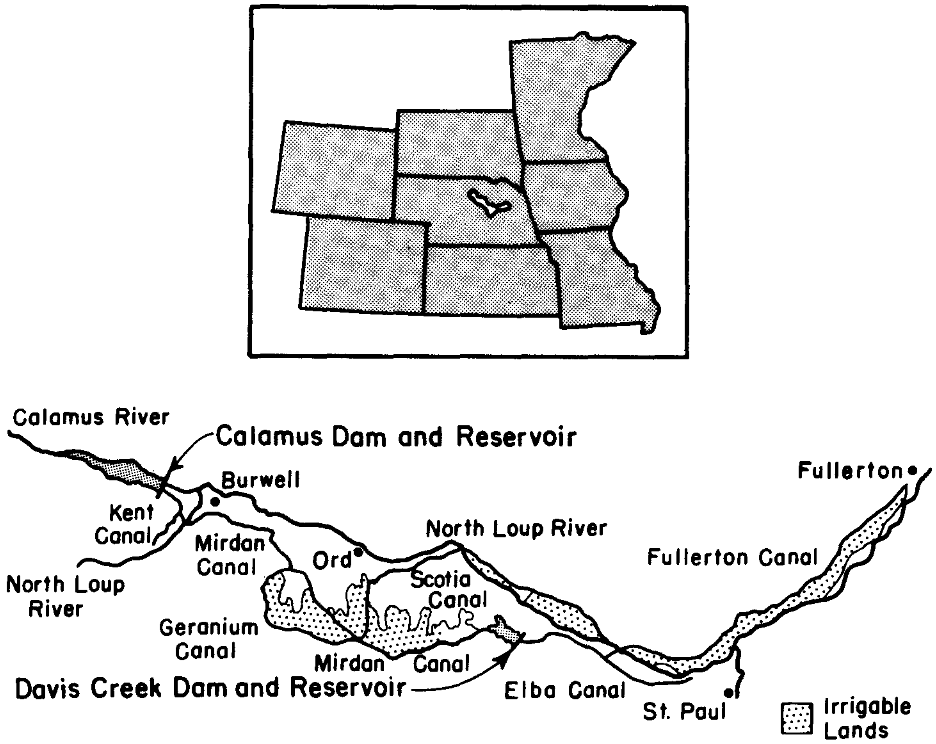


Figure 9. - North Loup Division in central Nebraska.

considerations. These slopes are slow to revegetate, and erosion-damaged faces are very conspicuous. Narrow, deep cuts in loess also serve as snow traps.

The Bureau has utilized steep slopes as an excavation cost-saving measure. Historically, the Bureau has used 1/4:1 and 1/2:1 slopes in loess. When cut depths exceeded 30 feet (9 m), a horizontal bench was included in the slope design. Benches had widths of 14 to 20 feet (4 to 6 m), a slight slope towards the back of the bench to keep concentrated surface runoff from going down the face of the excavation, and a lateral gradient to prevent water from collecting on the bench. This design has worked well during construction, but has proved to be a maintenance problem.

Minor slope failure, slabbing failure, and runoff material accumulate on the bench hampering runoff and causing water to pond. This ponded water then saturates the bench and the base of the slope. Also, concentrated surface runoff runs down the lower slope faces causing severe erosion. Maintenance was not performed on benches; therefore, conditions deteriorated and access to the benches has become impossible or extremely difficult. This has resulted in increased O&M road maintenance.

As a result of the above problems, a design decision was made to eliminate benches and to allow continuous cuts to heights of 90 feet (27 m) with 1/4:1 slopes. This decision was supported by laboratory test data, stability analyses, and the existence of inplace natural comparable slopes that indicated loess had sufficient strength, when dry, to stand at heights in excess of 90 feet.

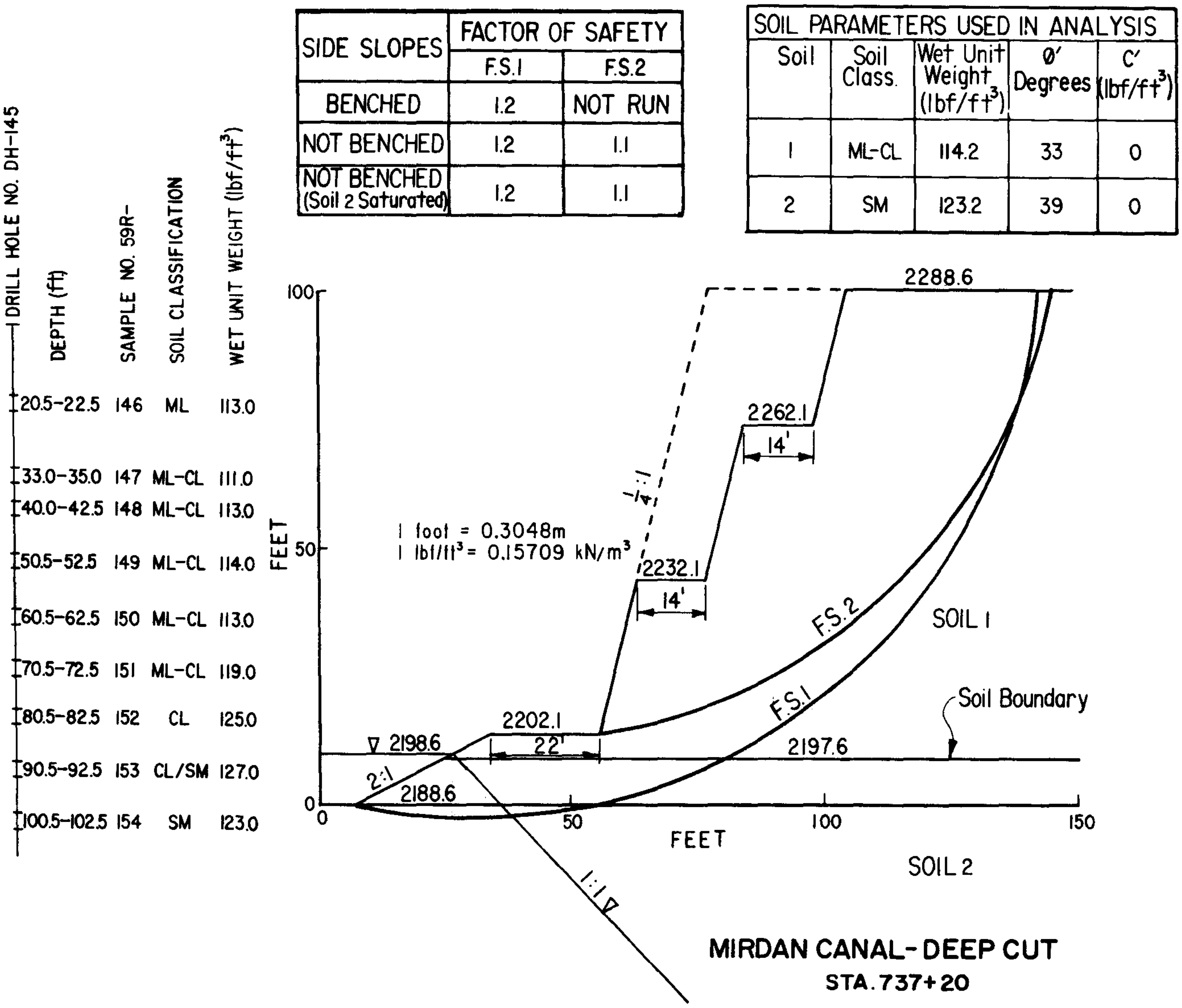
In 1981, during the design phase for Mirdan Canal, slope stability analyses were performed. Based on evaluation of canal cross sections and soil properties along the canal, two stations were selected as representative of the deep cuts along the canal alignment and chosen for slope stability analyses. Station 737+20 feet (STA 224+70 m) was to have a 100-foot (30.5-m) cut (measuring from canal invert up) with silty sand (SM) from 0 to 9 feet (0 to 3 m) and lean clay (CL), clayey silt (ML-CL), and silt (ML) comprising the remainder of the cross section, see figure 10. Station 746+00 feet (STA 227+38 m) was to have a 93-foot (28-m) cut with the cross section consisting primarily of clayey silt (ML-CL). To determine if benching of slopes could be eliminated, slope stability analyses were performed for two different cross sections: (1) with benches, and (2) without benches.

Wright's modification of Spencer's method [4] for SSTAB1 (slope stability analysis) was used to compute the factor of safety against slope failure. Soil parameters used in the analyses were obtained from consolidated-undrained triaxial shear tests performed on Pitcher tube samples obtained from the proposed canal alignment. These parameters were conservative and represented a saturated condition. The Pitcher samples were contaminated with drilling fluid, which most likely resulted in loss of cementation upon wetting. No other sampling or strength testing of materials was performed.

Results of the slope stability analyses for Sta. 737+20 indicated that removing the benches had no effect on the factor of safety against overall failure of the slope. Additional analyses showed that, if the lower sand layer became saturated, the factor of safety against massive overall failure of the slope would not be affected. Figure 10 shows results of the slope stability analyses for this station.

Results of the slope stability analyses for Sta. 746+00 also showed that removing the benches had no effect on the computed factor of safety. In addition, the cohesion varied from 0 to 144 lbf/ft^2 (0 to 6900 N/m^2), which resulted in an increase of 0.1 in the factor of safety. Results of the slope stability analyses for this station are shown on figure 11.

The possibility of localized failures in the 1/4:1 cut slopes existed; however, this type of failure could not be modeled and was expected to constitute only a maintenance problem.



SIDE SLOPES	FACTOR OF SAFETY	
	F.S.1	F.S.2
BENCHED	1.2	NOT RUN
NOT BENCHED	1.2	1.1
NOT BENCHED (Soil 2 Saturated)	1.2	1.1

SOIL PARAMETERS USED IN ANALYSIS				
Soil	Soil Class.	Wet Unit Weight (lbf/ft³)	Ø' Degrees	C' (lbf/ft³)
1	ML-CL	114.2	33	0
2	SM	123.2	39	0

Figure 10. - Slope stability analysis for a 1/4:1 cut slope with a silty sand layer at toe of slope. From [5].

Bureau specifications for section 1 of Mirdan Canal included using unbenched 1/4:1 cut slopes through the hills of Peorian Loess. The maximum height of excavated cuts above O&M roads, which parallel the canal, was to be about 90 feet (27 m).

Canal Excavation

Canal excavation began during the 1982 construction season. During excavation of the first major cut at Sta. 746+00, a failure occurred at a depth of about 60 feet (18 m). This failure had a length of 100 feet (30.5 m), which increased to 150 feet (45.7 m) over a period of several days, see figure 12. The exposed failure plane (head scarp) was near vertical and somewhat irregular. Along failed areas of the slope, spalling occurred at depths of 30 to 35 feet (9.1 to

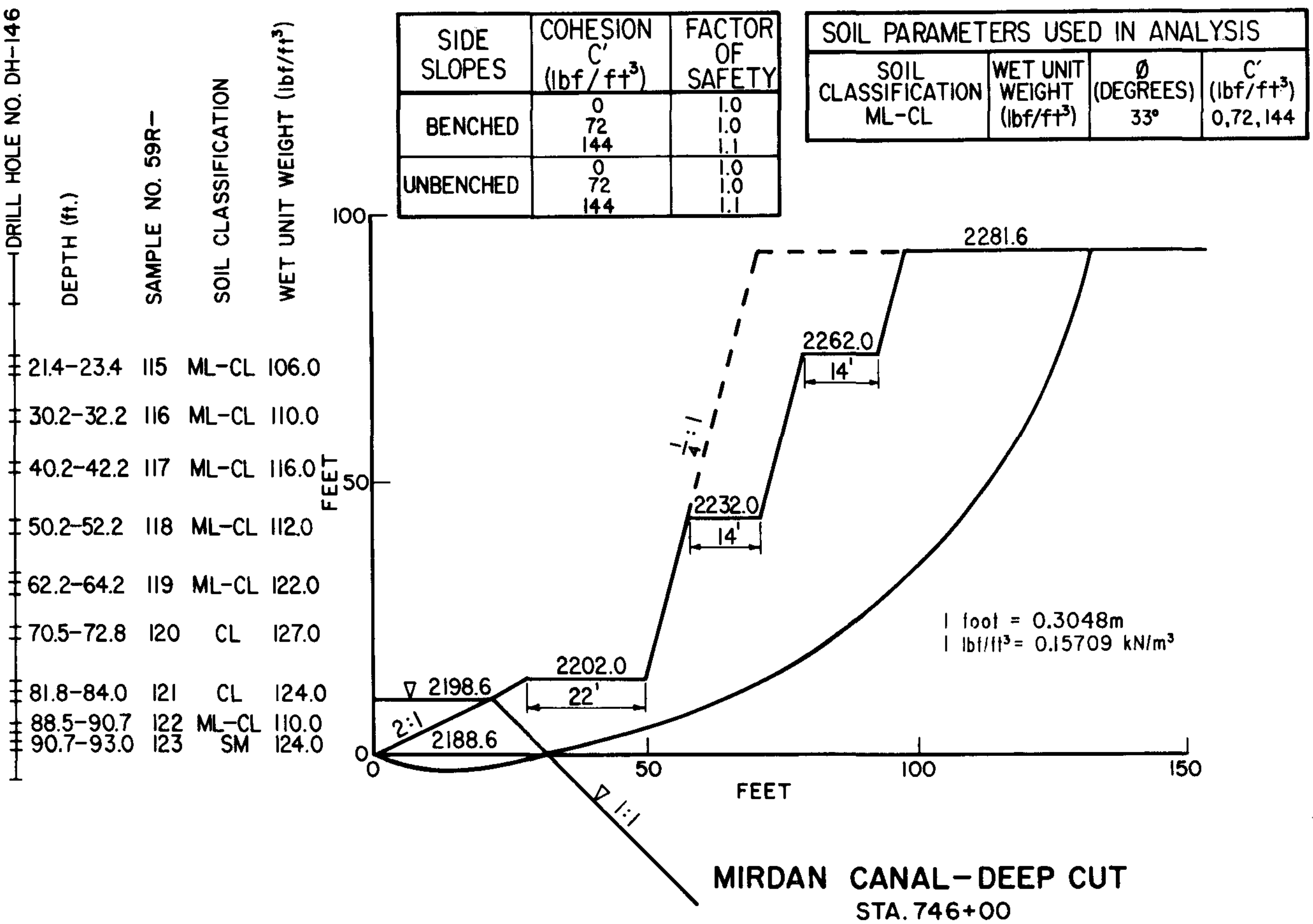


Figure 11. - Slope stability analysis for a 1/4:1 cut slope constructed primarily in clayey silt. From [5].

10.7 m). The spalling (fig. 13) was generally circular in nature, had a thickness normal to the slope of 4 to 5 inches (102 to 127 mm), and may indicate the presence of lateral forces or stresses due to stress relief.

The head scarp exposed numerous vertical joints or cracks that were randomly oriented. The failure is considered to have been a form of slump and toppling [6]. There were existing or incipient vertical joints in the loess that formed vertical discontinuities having little or no strength. It is not known if the vertical joint at the failure surface existed prior to failure. When the vertical load of the wedge formed by the 1/4:1 excavated slope and the vertical joints exceeded the lateral strength of the wedge, failure or movement in a lateral or horizontal direction occurred. The block moved out laterally and then dropped down the steep face.

The remedy was to modify the 1/4:1 slope using 20-foot (6-m) wide benches spaced at about 30-foot (9-m) vertical intervals for cut depths exceeding 35 feet (11 m). These guidelines were

Figure 12. – First major cut failure on Mirdan Canal. Sta. 746+00. P801-D-81425.

Figure 13. – Spalling on cut slope of Mirdan Canal. P801-D-81426.

used for the remainder of the construction season. Freezing, thawing, and desiccation resulted in additional slabbing, as shown on figure 14. A decision was then made to further modify the slope configuration. All slopes were to be excavated at 1/2:1; however, benches at 30-foot (9-m) vertical spacing were retained. These revised slopes have performed noticeably better; minor failures that have occurred were generally associated with lithologic contacts or material changes.

During the following winter and spring, blowing snow formed large drifts at the base of many of the 1/4:1 cut slopes. Subsequent melting of these drifts resulted in moisture contents close to saturation. This wet material in the 1/4:1 slopes failed in thin sheets in the lower 2 to 3 feet (0.6 to 0.9 m) of the slopes, resulting in an undercut condition. A photograph of this condition is shown on figure 15. These slope failures had thicknesses of 5 to 6 inches (127 to 152 mm) normal to the slope and initiated upward progressive failure to the top of the slope. Debris accumulated at the toe of the slope and adversely affected longitudinal drainage along the toe. Ponded drainage further saturated the slope and finally caused transverse drainage to break out over the bench or over the O&M road surface.

In later specifications, the Bureau has added a 5-foot (1.5-m) high, 1:1 slope at the toe of both 1/4:1 and 1/2:1 slopes. Loess is stable in a wet condition on a 1:1 slope, which eliminates undercutting and upward progressive failure of material. The 1:1 slope performed as expected and has now been included in the design of slopes above O&M roads. These 1:1 slopes provide additional benefits in that they help catch debris and assist in establishing vegetation and

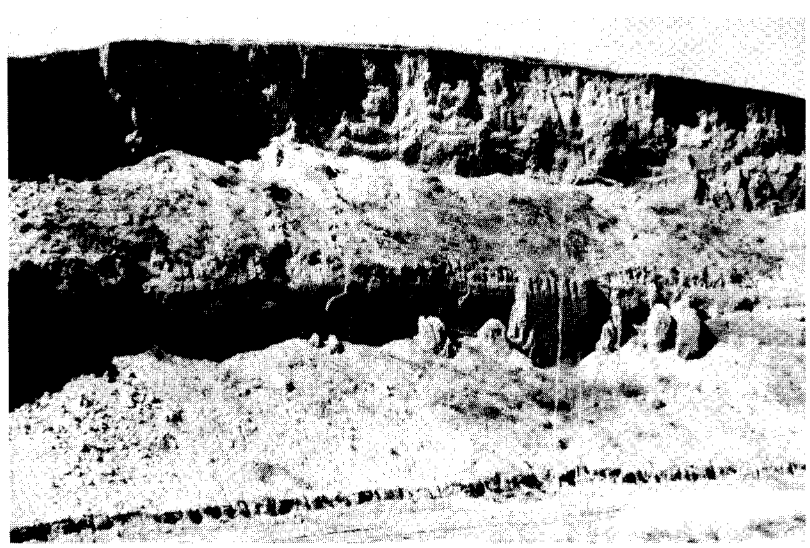


Figure 14. - Mirdan Canal slope failure on benched 1/4:1 cut slopes. P801-D-81427.

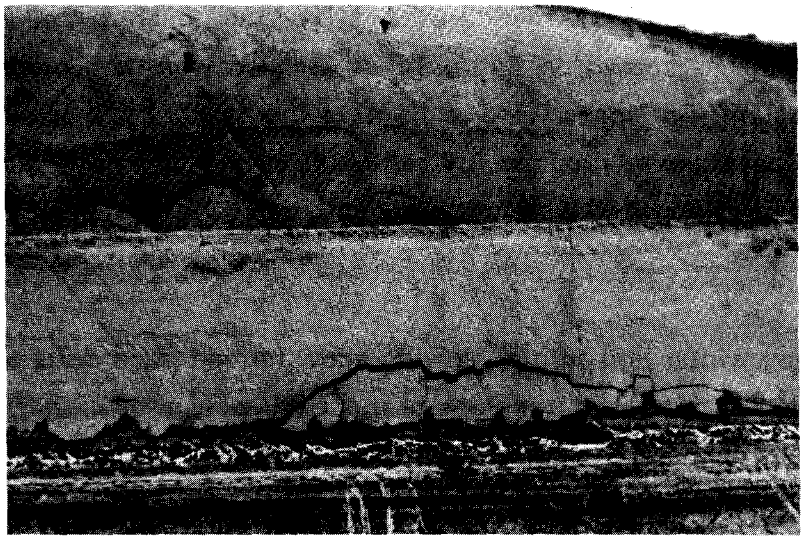


Figure 15. – Failure due to saturation along lower portion of 1/4:1 cut slope. P801-D-81428.

increasing stability. Figure 16 shows the stable condition of a 1/2:1 cut slope with a 5-foot high, 1:1 toe.

Success of the 1:1 slope at the toe and the economic preference of 1/4:1 and 1/2:1 slopes have led to the current Bureau design criteria. Slopes of 1/4:1 are used when the cut above an O&M road is less than 20 feet (6 m), and 1/2:1 slopes without benches are used when the cuts exceed 20 feet. To date, only one unbenched 1/2:1 cut slope having a height of 55 feet (16.8 m) has been constructed. Figure 17 shows the evolution of canal slope geometry that has led to current Bureau design criteria.

CURRENT PERFORMANCE

There has been an apparent increase of localized slope failures on canals in the North Loup Division compared to other canals previously constructed in loessial soil in Nebraska. Random occurrences of limited areas of silty sand (SM) and sandy silt (ML) in the lower portions of Peorian Loess have been identified during the exploration program; slopes of 2:1 were specified for these occurrences. However, all such occurrences were not identified prior to construction, and these unforeseen occurrences have contributed to some failures of the 1/4:1 and 1/2:1 slopes.

There were areas where reworked loess (slope wash) was redeposited in drainage channels. This material did not have the composition and structure of loess and would only stand on

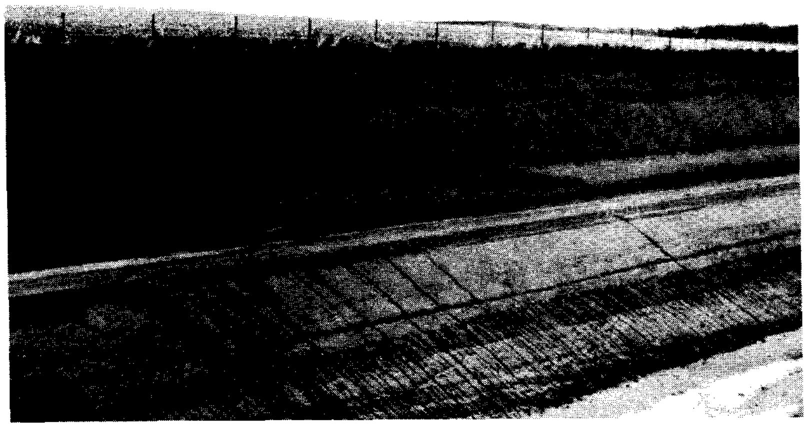


Figure 16. - Stable condition of a 1/2:1 cut slope with a 5-foot-high, 1:1 toe. P801-D-81429.

near-vertical slopes for a short period of time. This generally occurred to shallower depths less than 15 feet (4.6 m).

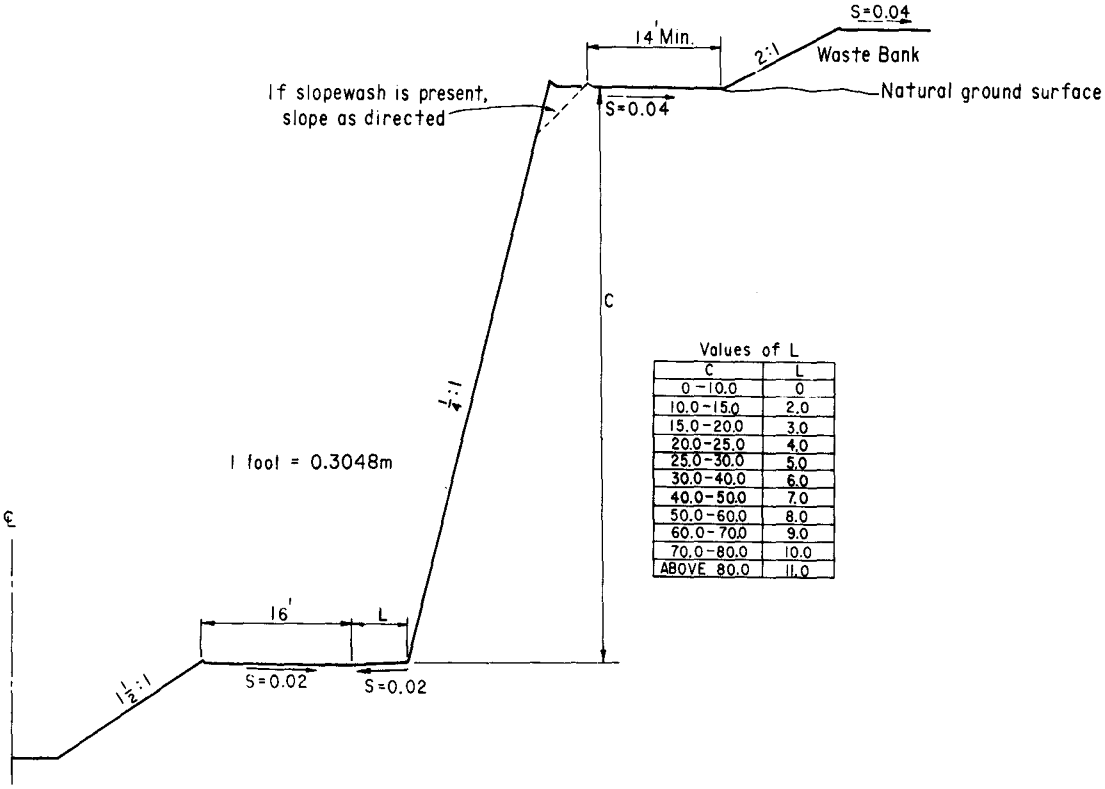
Inspections of recently constructed canal slopes in typical loess indicate that a 1/2:1 cut slope with a 5-foot (1.5-m) high, 1:1 slope at the toe is substantially more stable; and localized failures and spalling are less prevalent. The 1:1 slope at the toe prevents moisture from snow, rain, and construction equipment from ponding and saturating the base of the 1/2:1 cut slope. This toe slope also allows minor amounts of fallen material from the cut slope to accumulate without interference to the O&M road and longitudinal drainage, thus reducing maintenance requirements.

Slopes of 1:1 also make seeding possible and promote vegetation growth on the 1/2:1 slopes. Vegetation is important because it prevents erosion and increases stability.

With the continued construction of North Loup Division canals, it has become evident that diverting drainage above the cut slopes is critical in reducing erosion and preventing slope failures by directing water away from the cut slope face. This drainage should be provided before excavation of the canal cut slopes begins.

SLOPE DIRECTION AND VEGETATION

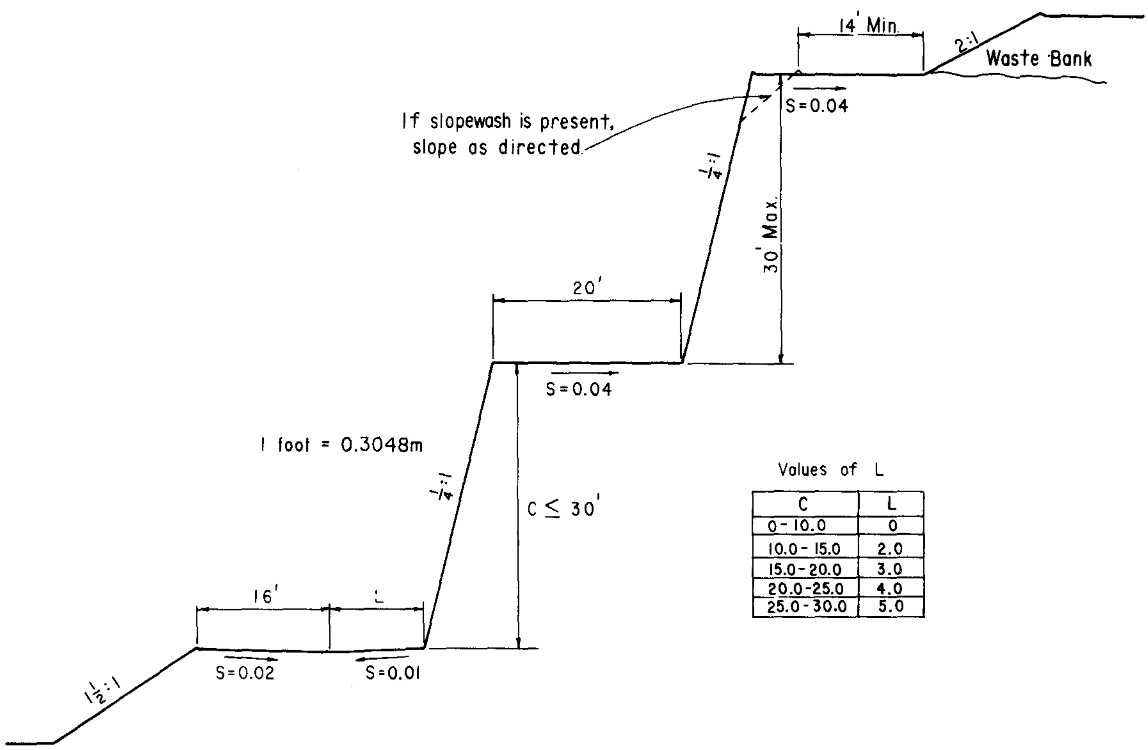
The direction the excavated slope faces makes a noticeable difference in vegetational growth and related slope performance. North-facing slopes of 1/2:1 and 1/4:l had noticeably more vegetation than those facing south, east, or west. North-facing slopes do not receive direct sunlight



Values of L

C	L
0-10.0	0
10.0-15.0	2.0
15.0-20.0	3.0
20.0-25.0	4.0
25.0-30.0	5.0
30.0-40.0	6.0
40.0-50.0	7.0
50.0-60.0	8.0
60.0-70.0	9.0
70.0-80.0	10.0
ABOVE 80.0	11.0

(a) Original design of Mirdan Canal (section 1).

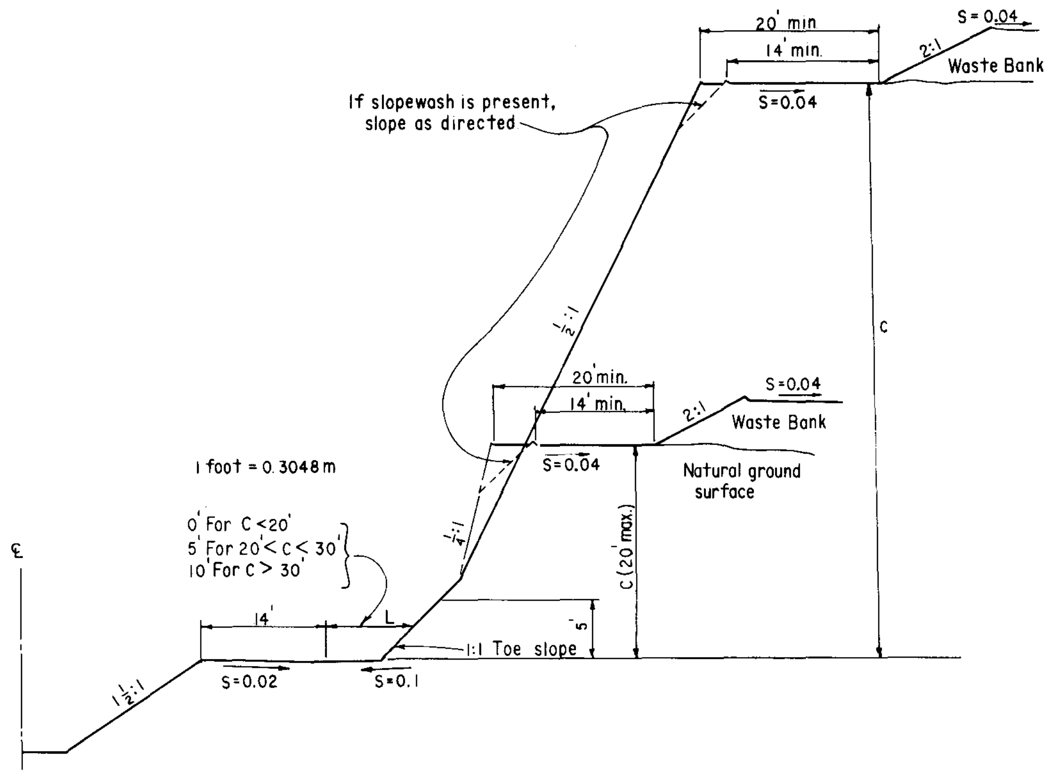


Values of L

C	L
0-10.0	0
10.0-15.0	2.0
15.0-20.0	3.0
20.0-25.0	4.0
25.0-30.0	5.0

(b) Intermediate design during construction of Mirdan Canal (section 1).

Figure 17. – Evolution of canal slope geometry in North Loup Division.



(c) Final design of Mirdan Canal (section 1).

Figure 17. – Evolution of canal slope geometry in North Loup Division.—Continued

and, therefore, have a lower evaporation rate that results in a higher and more uniform moisture content. For these reasons, it appears that vegetation is more readily established on north-facing slopes.

During the winter months, north-facing slopes remain in a stable frozen state for longer periods, while slopes receiving direct sunlight undergo numerous freeze-thaw cycles. These freeze-thaw cycles deplete moisture content and loosen soil. The condition of surface thawing and periodic near-saturation moisture levels, associated with melting snow, places additional load on thawed soil near the surface area. This near-saturated material then fails at the thawed/frozen soil contact creating various degrees of surface failures. These conditions create exposed areas that are more prone to erosion.

The general overall condition observed in the field is that north-facing slopes are the most stable, undergo less erosion of the exposed face, and have the best vegetation coverage.

In the past, brome grass has been the standard grass used to reseed areas along a canal right-of-way. Brome grass has fairly large seed, germinates quickly, is drought tolerant, establishes a thick surface mat of vegetation, has an extremely matted root zone, and spreads quickly through reseeding and rhizome extension. These attributes make brome grass an effective cover along a canal right-of-way by giving the grass the ability to spread and cover 1/2:1 and 1/4:1 slopes that were not originally seeded. On existing canal systems, brome grass seeded along O&M roads has spread and vegetated over a large portion of the 1/4:1 and 1/2:1 slopes.

The ability of brome grass to spread and establish a thick ground cover impedes development of erosion. The thick cover reduces surface runoff by holding or retarding rainfall or snowmelt, and limits the amount of exposed soil; and the associated thick root mat holds soil particles in place. Additional benefits of brome grass are its ability to quickly establish a dense sod on O&M roads and resist traffic wear, which creates desirable road surface conditions when either dry or wet. The dense growth of brome grass is also effective in limiting the growth or spread of weeds.

However, there are several disadvantages in using brome grass. Brome grass has higher nutrient requirements than native grasses and has a tendency to become sod-bound and die out. It is also a cool-season grass that is not popular with farmers.

The thick thatch or ground cover of brome grass is considered to be undesirable for wildlife habitat as the thick cover aids predators by limiting movement of prey. The depth and density of the thatch are also undesirable for ground nesting birds because their nests receive little or no sunshine.

Due to the undesirable habitat conditions of brome grass, native grass is currently being planted along the canal right-of-way of the North Loup Division. These native grasses are slower to germinate and grow than brome grass, often requiring 2 to 3 years to become established. This longer exposure time for the soil allows more erosion to develop, which removes a portion of the tenuous grass cover and results in more erosion and O&M maintenance. The native grass seedings along the North Loup Division are now becoming established; however, it will be several years before their effectiveness on the steeper slopes is known. The seeding subcontractors have generally sown annual seeds such as oats and wheat to promote early ground cover to help establish these native grasses.

Western wheat grass is reported to establish quickly and form a good sod base, but does not develop an extremely thick ground cover like brome grass. It is anticipated that wheat grass will be an important part of the seed mix for portions of the North Loup Division remaining to be constructed.

ACCESS ROADS

The side drainage ditches of access roads constructed in loess generally experience severe erosion. Runoff is concentrated in these ditches of exposed soil, and quickly produces sharp gullies with vertical banks having depths greater than widths. This results from the highly erodible nature of loess. Because of these concentrated flows and the highly erodible nature of loessial soil, vegetation often does not become established; and erosion is a perennial condition. Erosion checks of straw bales, mulching, and fabric are used as a means to control erosion. Elimination of side drainage ditches is another means of minimizing erosion.

The roadway is constructed as a level plane from cut slope to cut slope; the theory is to spread the flow over the entire road surface. This design, combined with a full-width graveled surface, has performed successfully at many other locations. For projects in the North Loup Division, gravel surfacing is not used; instead, grass is grown on the road surfaces.

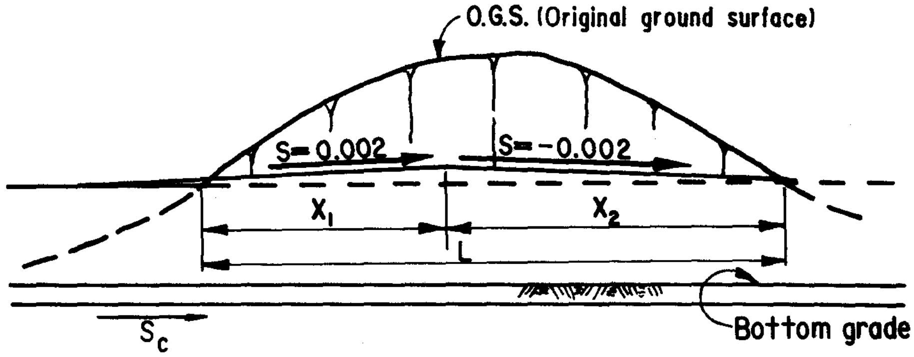
PROPOSED O&M ROAD MODIFICATIONS

To the present, longitudinal ramping of O&M roads has been provided to facilitate drainage in cuts, see figure 18. However, drainage problems continue to occur along these roads. Due to the relatively flat grading, low spots have developed and, along with the sloughing of cut slopes, has caused ponding of water. As a result, the roads become wet and, in many cases, impassable. Also, shallower cuts of less than 20 feet (6 m) in height have had no increase in road width to facilitate vehicle passage and debris cleanup.

Two proposed measures to help alleviate drainage problems along O&M roads for Fullerton Canal are: (1) increase longitudinal slopes to 0.005 percent in the *L* area (fig. 19) where the drainage water will flow while maintaining the 0.002 percent on the actual road surface, and (2) require a minimum widening of 5 feet (1.5 m) on the roads with up to a 25-foot (7.6-m) widening in deep cut sections (fig. 19).

PRACTICAL APPLICATIONS

The elimination of benches on 1/4:1 slopes in the initial designs for North Loup Division canals proved undesirable because of the occurrence of numerous slope failures. The benches catch



Note: To determine X_1 and X_2:

If S_c is slope of canal, then
$a = 0.002 - S_c$ and
$b = 0.002 + S_c$, and

$$X_1 = \frac{aL}{a+b} \quad \text{and} \quad X_2 = \frac{bL}{a+b}$$

$$L = X_1 + X_2$$

Figure 18. – Longitudinal ramping of O&M roads to facilitate drainage in cuts. From [7].

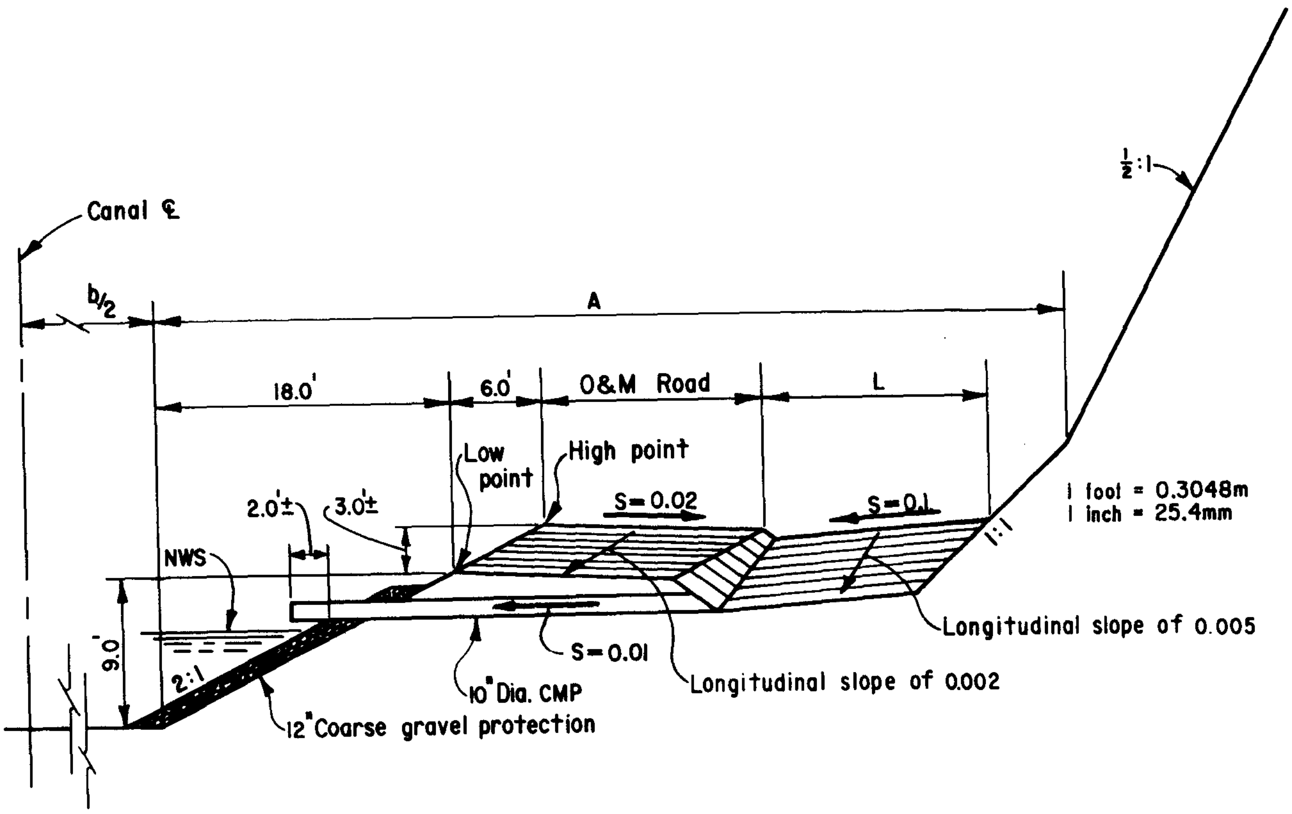


Figure 19. – Proposed measures to alleviate drainage problems along O&M roads.

material from the 1/4:1 slope failures; however, this has resulted in O&M problems because it hampers runoff and causes water to pond, which saturates the bench and the base of the slope. Concentrated surface runoff also runs down the slope face causing severe erosion.

An unbenched 1/2:1 slope with a height of 55 feet (17 m) and a 5-foot (1.5-m) high, 1:1 toe slope was completed during construction of Geranium Canal in October 1986. To date, no slope failures have occurred; and there is no evidence of stress in the cut slope.

The use of 1/4:1 and 1/2:1 slopes provides an excavation cost reduction when compared with the use of flatter slopes. During construction, there is no appreciable difference in excavation savings between benched 1/4:1 and unbenched 1/2:1 slopes. Introduction of the 1:1 toe and an increase in the width of the drainage berm at the base of the slope offsets the excavation savings gained by elimination of benches. The primary benefits derived from elimination of the benches are reduced short-term and long-term maintenance costs. Use of 1/2:1 slopes for heights exceeding 20 feet (6 m) provides an increase in vegetation growth and a decrease in slabbing and minor failures. A 1:1 slope at the toe of all 1/4:1 and 1/2:1 slopes promotes increased vegetation growth and eliminates slope failures associated with temporary saturation of the slope toe. These factors all contribute to reduced O&M costs.

CONCLUSIONS AND RECOMMENDATIONS

1. Historically, the Bureau has used 1/4:1 and 1/2:1 cut slopes for canals in Peorian Loess. When cut depths exceeded 30 feet (9 m), a horizontal bench was included in the slope design. This design worked well during construction; but proved to be an O&M problem in that ponded water saturated benches and bases of slopes, and collected surface runoff ran down the lower slope faces causing severe erosion of the face. Also, temporary saturation at the slope bases contributed to minor failures of slope faces.

2. In the 1970's, design criteria for canals constructed in the North Loup Division allowed continuous cut heights of 90 feet (27 m) with 1/4:1 slopes. Laboratory test data, stability analyses, and the existence of comparable slopes showed loess has sufficient strength, when dry, to stand at heights in excess of 90 feet. Localized failures were possible, but were only expected to create minor maintenance problems.

3. In 1982, localized failures of the recently constructed 1/4:1 slopes resulted in design changes. Benches were added to slopes with cut heights exceeding 35 feet (11 m). The benches were 20 feet (6 m) wide, and spaced at about 30-foot (9-m) vertical intervals. Winter freeze, thaw,

and desiccation resulted in additional slabbing. Many of these failures resulted in failure surfaces having slopes of about 1/2:1.

4. Additional modifications to the 1982 design changes were required. The slopes were excavated at 1/2:1; however, the benches were retained at about 30-foot vertical intervals. These slopes performed better with only minor failures occurring at lithologic contacts or material changes.

5. In subsequent specifications, the Bureau added a 5-foot (1.5-m) high, 1:1 slope at the toe of all 1/4:1 and 1/2:1 cut slopes. This 1:1 toe slope has proven to be a successful addition to the design in that it eliminates undercutting and upward progressive failures associated with temporary saturation of the base of the slope, catches debris from above, and promotes vegetation growth.

6. Success of the 1:1 slope at the toe of the slope and economic preference for 1/4:1 slopes have led to the current Bureau design criteria for loess soil. Slopes of 1/4:1 are used when heights of cuts above an O&M road are less than 20 feet (6 m); 1/2:1 slopes are used when heights exceed 20 feet.

7. During construction of the North Loup Division canals, it became evident that directing water away from the cut slope face before excavation and away from the base after excavation was critical in reducing erosion and preventing slope failures. Diversion drainage is now provided before excavation of cut slopes.

8. Increased localized slope failures of canals in the North Loup Division appear to be the result of more sand lenses and localized higher sand content of the loess.

9. Monitoring ongoing excavation of 1/2:1 slopes having a height greater than 50 feet (15.2 m), with no benches, and a 5-foot (1.5-m) high, 1:1 slope at the toe will continue to provide feedback on the effectiveness of this concept. Economic benefits gained from elimination of the benches will be primarily due to short-term and long-term maintenance costs.

10. Canal design is an ongoing process, and additional changes are continually being made to increase the efficiency and performance of Bureau canals constructed in loessial soil.

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