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GOVERNMENT OF PAKISTAN
UNITED STATES AGENCY FOR INTERNATIONAL DEVELOPMENT
IRRIGATION SYSTEM MANAGEMENT PROJECT

VOLUME 3
GENERAL OPERATION AND MAINTENANCE PROCEDURES FOR CANAL EMBANKMENTS

PRC ENGINEERING/CHECCHI
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FOREWORD

Section 1 : Purpose

The purpose of this manual is to provide only the technical information and guidelines that are required to maintain the canal prism and embankments in an irrigation system. No manual can cover solutions to all the potential combinations of problems that could someday occur from operating a system. The guidelines presented herein cover the normal conditions involved in maintaining the canal and its embankments.

This manual was prepared with the intent of introducing modern technology into the operation and maintenance of an irrigation system under the current organization of the Irrigation Circle and Provincial Irrigation Department policies and guidelines. Particular emphasis was placed on the maintenance procedures and requirements. It breaks with some of the traditional procedures currently in effect.

Section 2 : Authorization

This manual has been prepared to partially meet the requirements of task V.d of the PRC Engineering/Checchi Work Plan, 1986-87. Task V.d requires "Editing and Publishing of New General O & M Manual".

CHAPTER I

INTRODUCTION

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INTRODUCTION

A. Overview

The Indus Basin Irrigation System was designed to carry large volumes of water long distances to serve a very large number of farmers. The canal embankments are the most important feature of the system as they confine the water supply. The canal banks have been constructed from locally available soil and the water level is often well above the surrounding land. A failure of an embankment causes considerable economic damage to the surrounding areas; not only the covering of farm land with a layer of sandy bed material but also the lost crops and the time and money spent to grow them. A failure also interrupts the supply of water to downstream users who may also suffer considerable damage if the availability of water is not quickly returned.

Canal failures are usually due to inadequate operation or maintenance procedures. Major drainage flows are normally not allowed to enter the canal system, therefore, inflows are usually controlled by Irrigation Department personnel. Even in those instances where drainage flows enter a system, wasteways located at strategic locations can protect the system from overtopping. The principle causes of failure are:

* Inadequate freeboard
* Improper operation of water control facilities
* Farmers tampering with outlets (unauthorized closures)
* Failure to maintain canal capacity
* Rodent Holes
* Freeboard deterioration due to animal trespass
* Inadequate inspection and follow up supervision
* Lack of timely repairs and preventive maintenance

B. Maintenance Objectives

The objectives of embankment maintenance should be to:

* Keep the system in top operating condition at all times through proper maintenance.
* Obtain the longest life and greatest use of the systems facilities by providing good maintenance and timely replacement.
* Achieve the foregoing objectives at lowest possible cost.

Maintenance begins before the rehabilitation of a system is completed and the system or sub-system is placed back in operation. Keeping maintenance work current on all facilities in a system is the keystone of any successful irrigation project. Preventive maintenance not only pays dividend in economical operation, a smooth working system, but also means an uninterrupted delivery.

C. Maintenance Program

All canals and facilities are subject to deterioration in varying degrees. Constant vigilance is necessary to identify and correct potential unsafe or unsatisfactory conditions as they develop. Cracks in lining, general erosion, settlement of embankment or structure, scour, seepage etc. can result in major failures if not corrected or repaired without delay. Breaches are expensive failures, not only due to the cost of repair but for the loss or damage to crops of the farmers directly affected as well as those downstream who are deprived of water.

Many problems that develop may not be of such a serious nature as to cause failure. The control of weeds, storm erosion of banks, seepage of water through banks, aggradation, degradation, loss of freeboard and animal damage may be less serious, but they are problems that must also be given attention. Frequently these problems are more time consuming and costly over the years.

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The development of a comprehensive maintenance program is a management function. Therefore, it is not covered in this manual. The manual's emphasis is on the technical methods and techniques of maintaining canals and embankments and the necessary repairs. The technical aspects of inspections, performance standards, records and monitoring are also included. When to inspect and who will perform the inspection is a management decision.

The five general measures that must be considered in canal and embankment maintenance are:

* Trash removal and weed control
* Inspection and monitoring
* Canal Safety (freeboard and embankment section)
* Hydraulic characteristics (capacity and water surface elevation)
* Inspection road and miscellaneous items

Canal safety involves the continuous maintenance of freeboard above the design freeboard level. Raincuts, rodent holes and rainholes (gharas) must be repaired as soon as practical. Compacted earth must be placed on the top or dry side of the embankment to replace material that has been worn and washed off before the minimum allowable section is reached.

The lack of compaction of soil in the canal embankments during the initial construction of the canals years ago and during more recent rehabilitations has been the cause of some embankment failures. Poorly compacted soil leads to increased maintenance costs due to a more rapid erosion of soil off the surface, rainholes, piping as well as higher seepage rates. Silty sands do not consolidate over time as do clayey soils so that if loosely placed during construction they still remain the same today. To emphasize the soil problems and provide the PID staffs with information, considerable material on soils has been included that might otherwise be referred to.

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CHAPTER II

MAINTENANCE STANDARDS

CHAPTER II

MAINTENANCE STANDARDS

A. Overview

The rehabilitation of an irrigation system or a canal restores the canal embankment and hydraulic section to a design standard. It then becomes the responsibility of maintenance to keep the canal and embankments in a good state of repair and not let it deteriorate.

There have to be defined limits between which various maintenance functions can be carried out and those which are inviolate. For example, it is economically impractical to replace one inch of freeboard worn off a canal embankment in a year. Therefore, restoration of freeboard is carried out at an interval based on practical and cost effective earthwork methodologies. In other words, limits are established wherein the freeboard can be at any given time, but below which it can never be. The established limits are defined as performance standards.

Performance standards differ somewhat from maintenance standards. Maintenance standards are based on performance standards but are prepared to indicate the amount of maintenance work that is estimated to be required in a year. It is a management tool for budgeting and scheduling work to keep the canal within performance standards.

Other items to be considered would include freeboard, inspection road condition, raincuts, rainholes, vegetation control, structural conditions, gate and mechanical equipment condition, condition of lined sections, local drainage problems, location of desilted material and numerous other items. It is possible to develop a rating score that would assist in the evaluation of all these conditions over time.

As indicated above, the criteria that rates the performance standards must be sufficiently detailed so that most monitoring/inspectors will arrive at the same rating.

B. **Future Efforts**

In the future, the methodologies and technologies that have been used in the past will slowly change. The use of mechanical equipment in the performance of maintenance will continue to increase with time. How fast the change will come is anyone's guess. Motorcycles have replaced the horse to improve inspection, supervision and communication along the conveyance system. Tractors with trollies replace man and donkeys in some situations. Short closure times require a massive effort to accomplish major desiltings and equipment is often more productive than massive musterings of men and animals. Timely availability of manpower and economics will determine how work objectives will be accomplished. Some operations such as soil compaction can only be effectively accomplished by using mechanical equipment.

It is difficult to prepare a manual that covers both manpower and mechanized maintenance systems when the later is not well defined nor a implementation program established. Much depends on the Governments and the PID's efforts to improve maintenance programs at the field level. Without a full commitment, changes will be slow and embankment conditions will continue to deteriorate towards the tail ends. Because of the general reluctance of the PID's to change, this manual will concentrate more on current technology and procedures rather than emphasize an unknown future.

Not all changes need to be tied to equipment and modern technology. All the main methodologies to keep an irrigation system in top operating condition have been detailed in previous manuals and statement of orders. Equipment and other modern conveniences only offer faster and possibly more economical ways of performing the work items. It is a lack of commitment and discipline that allows conditions to deteriorate, not a lack of knowledge.

Inspection and constant field supervision is a basic requirement to obtain the results desired. It is not enough to issue an order. It is absolutely necessary to follow up to see that it is carried out correctly and the work is accomplished according to specification.

C. Inspection

1. Periodic Inspection

Inspections are made to ensure that the irrigation system is operating correctly and all features are maintained correctly. Inspections are also made in order to properly supervise the beldars in doing their work, re-group to overcome a problem or to request additional help when they are unable to keep up. Inspection trips allow the supervising officers to see what is happening and to take corrective action as required.

The spreading out of the beldars to cover several miles of canal minimizes what he can do if he is expected to visually cover the zone of responsibility daily. Where problems become acute, the Sub-division Officer (SDO) will have to provide additional help by assigning a work gang to make the necessary repairs.

The sight and knowledge that superiors will visit a beldar zone of responsibility at frequent intervals will tend to make him more responsible and keep his work up to normal levels.

2. Closure Period Inspections

Detailed inspections of all structures and canals must be made during the closure period to determine what deterioration, if any, has taken place during the past operating period. For minor structural defects and prism conditions preventive maintenance procedures can be immediately taken to prevent further deterioration. More extensive repairs would be programmed for the coming fiscal year to be accomplished during the next closure period. It is absolutely necessary that good records be kept and the results of each annual inspection be recorded in detail and kept on file. The major closure period inspections are made by the SDO and his staff. The SE and XENs will conduct sufficient inspections in each division and sub-division to check that the condition of structures and canal prisms meet performance standards and ensure that the records on each are up todate.

Inspections should cover the following:

1. Conditions of gates. Each gate should be opened and closed to check the ease of operation. Gates requiring painting and repair should be noted. Replacement of rusted metal work should be scheduled as soon as practical.
2. Condition of the masonry. Damaged, cracked or loose masonry should be noted. Repairs should be scheduled to be completed prior to re-opening of the canal.
3. Condition of upstream and downstream structural backfill. Leakages and piping should be noted. Piping conditions must be repaired as soon as possible after being observed; repair must not be deferred.
4. Quantity of sediment upstream of the structure and in the canal sections upstream or in measuring structures.
5. Condition of measuring structures and gauges. Verify occurrence of last rating check of the stage-discharge curve.
6. Check freeboard available at each structure.
7. Scour and other damage downstream of structures.
8. Safety features.
9. Rain gauge sites.

Upon completion of the annual inspection, a written report should be prepared and submitted by the SDO. This report should incorporate the results of inspections made by the Sub-engineers or others and a description of all actions taken to make immediate repairs during the closure period.

Typical formats for canal inspection forms have been included as Exhibit II-1.

D. Performance Standards

Performance standards refer to the thresholds of performance considered acceptable, tolerable or unacceptable. In canal maintenance, visual

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observations are often used to evaluate performance. Unfortunately, individuals will not evaluate a reach of canal the same unless a comprehensive rating criteria is used. In other words, a well maintained system is in the eye of the viewer; manicured banks are impressive and look good but it is the wetted section and overall bank condition that tell the real story. Standards are necessary to evaluate the true condition of the system, and determine if conditions are getting better or worse with time.

The performance standards for maintaining canals are shown in Table II-1 and Figure II-1. These define the minimum conditions that can be tolerated. The performance standards are based on the canal design standards shown in Table II-2.

For example, standard for freeboard is that up to 5 inches of soil can be worn off the top of any canal embankment from the rehabilitated freeboard F_b without requiring restoration that as soon as any point along the canal has the freeboard worn off 5 inches, immediate restoration is required, it can not be delayed for any reason. This is a critical problem at unauthorized canal crossings and animal bathing facilities (ghats). Sufficient freeboard could be lost at these locations within weeks of rehabilitation in some instances. Section IV.5 discusses this problem in more detail. Under more normal conditions, the freeboard is eroded off at a much slower rate but over the entire length of the canal.

E. Maintenance Standards

Maintenance standards carry the performance standard one step further by estimating the quantity of work required to maintain the canal in the condition defined by the performance standard. The maintenance standard is an estimate of the average amount of work that must be preformed each year, see Table II-3 for example.

Canal yardsticks are determined from canal maintenance standards developed for various canal size categories combined with the actual cost of doing the work. Canal yardsticks are used as a method of determining the annual budget requirements for maintenance.

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The maintenance standards for each canal should be determined each year based on actual work preformed to keep the canal in compliance with the performance standards.

F. Maintenance Categories

Maintenance work is divided into four categories to facilitate the work effort including; funding and accountability, responsibility, scale of work, who does what, equipment management contract work and administration and other management related reasons. The regular routine maintenance efforts are done on a daily or weekly basis and must be performed by permanent staff. Seasonal or periodic maintenance or repairs are accomplished either on a fixed schedule or on a "as required" basis. Annual programs are those that are accomplished by outside contractors because they are performed in only a part of a division; for example, the replacement of freeboard on 20% of the canals each year.

1. Emergency Repairs

Emergency repair refers to the repair of serious damages or failures which unless prompt action is taken, may entail even more catastrophic problems concerning canals and farm land. Damages are not always predictable either with respect to the time of occurrence or to their scale; therefore, the Sub-engineer incharge should always be ready to face the occurrence of an embankment failure or other major problems, preferably before they occur.

Catastrophic damages of irrigation facilities may result from any or combination of the two or more of the following causes:

* Flood or heavy rainfall.
* Embankment failure due to sliding (shear) or piping.
* Careless operation of irrigation facilities.
* Human actions like stealing water through embankment, blocking canals, destroying gates etc.
* Destruction by animals like rodents, buffalos, etc.

Action needed to cope with emergency situations should be taken as soon as possible, and it is advisable to follow the procedures defined by the appropriate authorities.

2. Routine Maintenance

Routine maintenance refers to the day to day work items that must be accomplished to keep a system operating well. They are basically preventive maintenance functions that if done on a continuous basis prevent the problem from becoming larger and more expensive later on. It is the first line of defence and is extremely cost effective if carried out in a competent and professional manner.

Many of the routine maintenance functions that Sub-engineers will have to supervise on a continuous basis are:

* Filling raincuts, rainholes and rat holes when observed.
* Promptly removing trees that have fallen into canal.
* Stop piping and replace backfill material where water flows around a outlet structure.
* Clean weeds and other floating trash from in front of structures.
* Fill pot holes and ruts in patrol road.
* Cutting-off new tree and brush sprouts.

3. Seasonal Maintenance

The difference between seasonal and annual maintenance refers primarily who is responsible. Seasonal maintenance is light maintenance work part of which has to be accomplished during closure. It is work that is often classified as force account work meaning it is done by using permanent employees or casual labor hires. It may also be contracted out depending on the local situation. Annual work is heavy maintenance work that must be contracted out to private contractors or the Mechanical Circle.

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Seasonal work is limited in extent because of the short time period available during closure and the availability of staff and casual laborers. It includes:

* Repair and resetting of outlets.
* Berm Trimming.
* Repair lining.
* Repair structures.
* Complete temporary repairs.
* Riprap scour holes.
* Fill in low spots in freeboard.

Some of the seasonal repairs can be carried out throughout the year and are not dependant on closure; such as berm trimming, ripraping scour holes and filling in low spots in the freeboard.

4. Annual Maintenance

The annual maintenance program is beyond the capability of the Sub-Division. The annual maintenance program involves the extraordinary or extensive program of replacing the eroded freeboard and embankment slope. It also includes the grading of the patrol road 6 times a year and a comprehensive raincut repair program when required.

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TABLE II - 1

PERFORMANCE STANDARDS FOR CANAL MAINTENANCE

1. Freeboard

The freeboard (Fb) is never allowed to erode or be worn off more than 5 inches. The freeboard must be replaced as soon as the minimum freeboard is reached at any point on the canal embankment.

2. Capacity

The canal capacity must never be allowed to become less than the design capacity.

3. Maximum Discharge

The maximum discharge allowed in the canal is 1.2 times the design discharge at full supply level (FSL). The duration of a discharge greater than the design discharge cannot exceed two weeks under any circumstances.

4. Maximum Water Level

The maximum water level can never to allowed to exceed one half the design freeboard (1/2 fb) under any circumstances. This standard fixes the siltation standard.

5. Siltation

Silt accumulation in a distributary or minor is not allowed to exceed 9 inches. When 6 inches of sediment is observed or measured above the design bed level of the canal desilting must be programmed for the next closure period.

6. Canal Width

The average width of a canal will be allowed to vary between the design width (b) and 1.1 times the design width (1.1 b) without concern. No canal will be allowed to become narrower than the design width. A canal will not be allowed to widen beyond 1.2 times the design width without corrective action being taken.

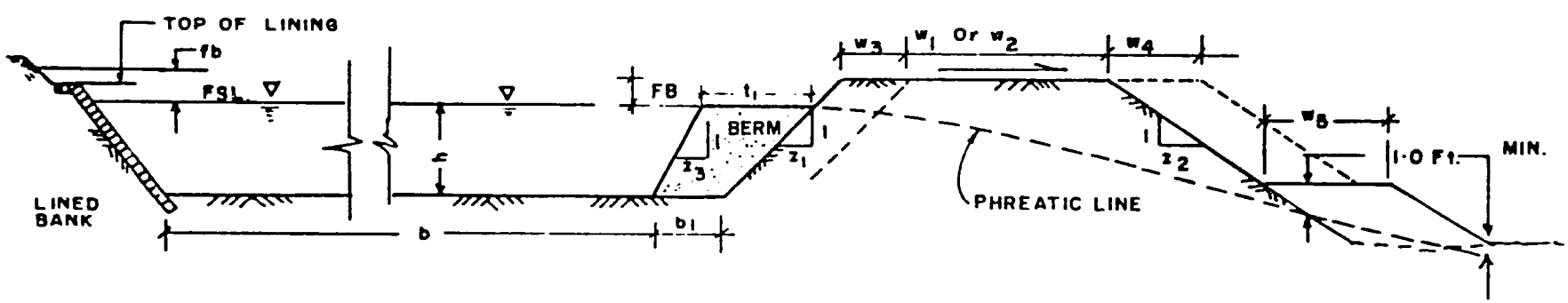
The bottom width is the critical dimension. The average top width is used to judge the condition of the canal. Minor scalloping due to animal ingress and egress, is not considered in evaluating the canal width as it does not effect hydraulic performance.

TABLE II-2

REHABILITATED CANAL EMBANKMENT DESIGN STANDARDS

Depth of flow h	Freeboard				Min. top Width W_1	Road Width - W_2				Berm Width b_1	Slopes		
	Rigid Lining 1/	Design fb	Rehab. - FB			Equip Maint.	Patrol	Village	Highway		Inside	Outside	Berm
			Earth	Metalled									
(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(z_1)	(z_2)	(z_3)
< 2.50	0.5	1.0	1.5	1.0	4	5	0	18	30	0	1.5	1.5	1.5
2.5 - 3.99	0.5	1.5	2.0	1.5	5	7	12	18	30	2	1.5	1.5	0.5
4.0 - 4.99	0.6	1.5	2.0	1.5	6	7	12	18	30	3	1.5	1.5	0.5
5.0 - 5.99	0.75	2.0	2.5	2.0	8	9	15	18	30	4	1.5	1.5	0.5
6.0 - 7.99	1.0	2.5	3.0	2.5	10	9	15	18	35	5	1.5	1.5	0.5
8.0 - 9.99	1.5	2.5	3.0	2.5	12	12	20	20	40	6	1.5	2.0	0.5
10.0 -11.99	1.6	3.0	3.5	3.0	15	12	20	20	40	7	1.5	2.0	0.5
>12.0	Site Specific Study Required												

Notes:
1. Distance from FSL to top of lining (earth freeboard also required)
2. W_3 = Dowel and W_4 = Avenue; W_3 = W_4 = 5 foot; neither are required but may be retained if already on existing embankment.
3. W_1 = Minimum top width where maintenance road is not required.
4. W_5 = Outside berm required to cover existing seepage surface if necessary.
5. b_1 = Designed to protect toe; maintained using top width (t_1).
6. FB = f_b + 5 inches = Freed board established during rehabilitation.



SCHEMATIC DESIGN SECTION

TABLE II-3

CANAL MAINTENANCE STANDARDS

Definition

The canal system facilities requiring annual maintenance are the channel embankments, bed levels and structures. The work items required are repair of the inside and outside slopes of the embankment and repair of the inspection road on the embankment crest. Maintenance of channel bed levels requires removal of deposited sediment and maintenance of structures requires painting of metal surfaces and repair of upstream banks and downstream stilling basins.

Maintenance Standards

Facility	Maintenance Standard
Embankment Inspection Road	1. Replace 5 inches of material along 20% of total length each year. 2. Grade road surface 6 times per year. 3. Prohibit public access to non paved inspection roads (the Highway Department must provide alternate roads or take over maintenance).
Embankment Slope, Outside (includes 4 feet of road shoulder)	1. Replace 10 inches of material along 20% of total length. 2. Repair 250 rain cuts per mile on main canals and 450 per mile on distributaries and minors. 3. Remove all trees and brush, establish turfing where feasible and control weed growth to facilitate inspection of seepage on outside slopes.

TABLE II-3
CANAL MAINTENANCE STANDARDS
(Continued)

Embankment Slope, inside	1. Provide 50 feet of killa bushing per mile to correct and prevent erosion as necessary. 2. Maintain existing turf on inside slopes above water surface. 3. Cut weeds as necessary to allow visual inspection of canal prism. 4. Remove all trees and brush.
Bed Level Control	1. Remove an average of 15,000 ft^3 of material per mile of canal at selected locations. 2. Establish monitoring stations at downstream locations to ensure cross-sections and sediment concentrations remain within design limits. 3. Initially the sediment removed directly from the canal will be placed along the toe of the canal. An evaluation of the potential problem of purchasing sediment storage areas will be made when more exact amounts and locations are determined.
Structures	1. Inspect all gates, gate hoists and steel accessories annually and repaint, repair or replace as needed during the canal closure period. A miscellaneous cost is included for this work. 2. Provide 50 feet of killa bushing and 25 feet of brick pitching in stilling basins downstream of each structure. 3. For lined sections, replace 1% of total area each year.

ANNUAL CANAL INSPECTION

1. Canal Name:_____ Sub Division:_____

2. Date:_____ Time;Start:_____Finish:_____

3. Inspector:_____ Signed:_____

CONDITION OF CANAL

RD	Embankments	Prism	Partrol Road	Bank Seep

Remarks:_____

_____

_____

_____

OUTLET INSPECTION CHECK LIST

1. Canal Name:_____ Sub Division:_____

2. Date:_____ Time, Start:_____ Finish:_____

3. Inspector:_____ Signed:_____

RD	Outlet Designation	Side	Condition

Remarks:_____

_____

_____

_____

REGULATOR INSPECTION AND MAINTENANCE RECORD

FILE NO._____

EQUIPMENT_____ _____

FACILITY_____ LOCATION_____ INSPECTIONS FREQUENCY_____

EQUIPMENT DATA

Specification/Solicitation_____ Date Furnished_____

Supplier_____ Type_____

MFR_____ Size_____

Model or Style No._____

INSPECTION AND MAINTENANCE RECORD

DATE	INSPECTED BY	CONDITION FOUND OR DESCRIPTION OF WORK DONE

REPORT OF DAMAGE TO DISTRIBUTION SYSTEM FACILITY

Canal Name:_____

1. Date:_____ Time:_____

2. Facility:_____

3. Location:_____

4. Description of Damage:_____

_____

_____

_____

_____

5. Damage caused by:_____

_____

_____

6. Proposed Method of Repair:_____

_____

_____

_____

7. Are Emergency repairs required:_____

8. Action taken on role violation(s) if any:_____

_____

_____

9. Remarks:_____

_____

_____

_____

10. Inspector/Reporting Officer:_____ Signed:_____

MAINTENANCE WORK REQUEST

Work Action No._____ Priority Code:_____

(1) Emergency:

(2) Urgent; within one week:_____

(3) Normal; Date required:_____

(4) Next Closure Period:_____

Work Name and Location

Describe Work Requested, Recommended and Justification

_____

_____

_____

_____

_____

_____

Work Authorized by_____ Date:_____

Maintenance action taken, recommendation, Problems encountered

(include people, hours works, craft used etc.)

_____

_____

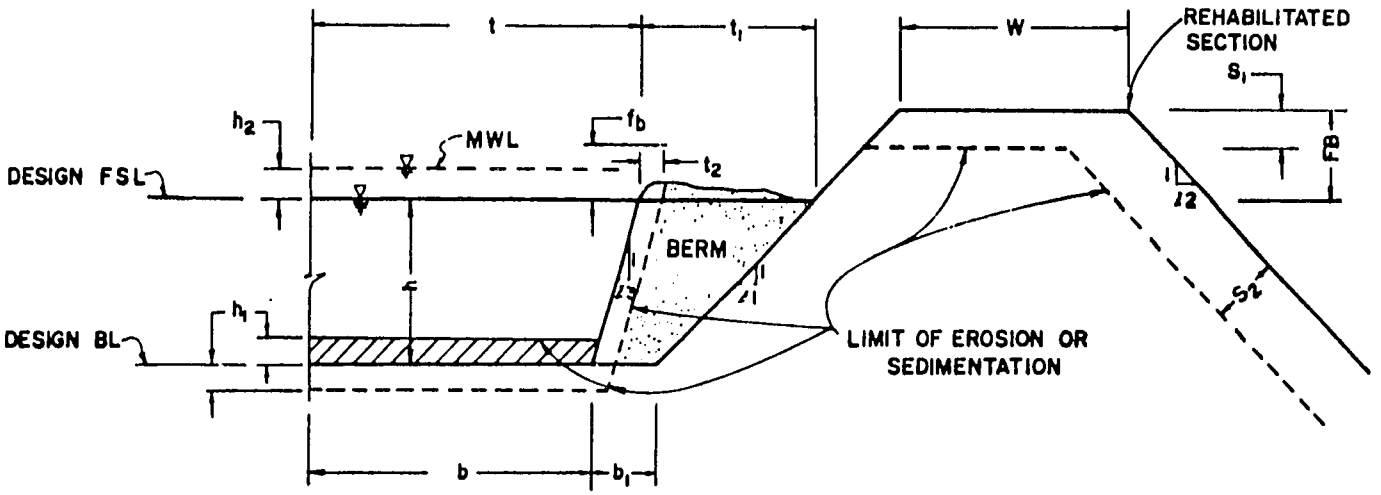
_____

_____

_____

_____

Completed by:_____ Date Completed_____



CANAL SECTION

Legend

b	=	Design width.
b_1	=	Design berm width.
h	=	Design depth.
h_1	=	Maximum allowable depth of sediment accumulation/bed erosion.
h_2	=	Maximum water level encroachment on design freeboard = 0.5 fb.
FB	=	Constructed freeboard = fb + 5 inches.
S_1	=	Maximum allowable freeboard erosion = 5 inches.
S_2	=	Maximum allowable embankment erosion = 10 inches.
W	=	Top width of embankment.
fb	=	Minimum allowable freeboard = design of freeboard.
t	=	Top width.
t_1	=	Berm top width corresponding to b_1.
t_2	=	Maximum allowable bank erosion = 0.1 b_1.
FSL	=	Full supply level.
BL	=	Bed level.
MWL	=	Maximum allowable water surface.

PERFORMANCE STANDARDS
CANAL MAINTENANCE

CHAPTER III

GENERAL EARTHWORK CONSIDERATIONS

CHAPTER III

GENERAL EARTHWORK CONSIDERATIONS

SECTION 1 : FOUNDATION AND EMBANKMENT PROBLEMS

A. General

Many canals will exhibit soil related problems of one kind or another. Hydrostatic forces and low permeability are the major cause of canal lining failures although expansive clays, unconsolidated low density soils, salt heave or removal and freezing can also cause problems under certain conditions. Settlement, particularly differential settlement is a major problem affecting structures particularly those with gates. Unconsolidated or uncompacted soils are a major cause of settlement. The lack of sufficient bearing strength under small canal structures, in most cases, could have been overcome by proper foundation preparation and spread footing designs. Piling often is a solution to increasing load carrying capacity so long as the adjacent soils do not consolidate or shrink, leaving an opening that could initiate piping.

Foundation conditions are investigated prior to design and construction so that the engineer can design embankments and structure to overcome potential problems. A short discussion of foundation problems and soils is provided to background the maintenance staff in this subject and to recognize problems in the field. A major maintenance item will be the replacement of worn and eroded embankment material which requires a working knowledge of soil properties so as to ensure proper compaction and supervision of placement.

Although only indirectly related to foundations, the lack of compacted backfill and the use of cutoff walls is the major cause of piping and subsequent structural failure. Differential settlement and piping are two major causes of canal bank failure involving structures in Pakistan. It is important that maintenance personnel recognize this. Early recognition in the field may prevent a later breach.

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B. **Bearing Capacity**

The foundation must be safe against punching into the ground. This may involve both shearing properties and consolidation properties. A saturated weak clay can be visualized as resulting in settlement of the soil under the foundation accompanied by bulging of the soil out from around the foundation. A large, rigid structure sometimes causes catastrophic failures because of this shearing weakness; however, when a soil is found to be firm, it can resist this weakness. Improving the foundation with regard to bearing capacity problems can be accomplished by (1) deeper foundations, (2) over excavation and refill, (3) pile driven to firm material, and (4) larger foundation areas to reduce load.

C. **Stability**

Stability of cuts and slopes is dependent largely upon the shearing characteristic. For example, a sand without cohesion will not stand in a vertical trench, yet a clay stands in a vertical trench up to a certain height depending on its cohesion. This is called the critical vertical height and it would certainly be dangerous to dig a trench to depths near that of critical height. Permanent slopes are commonly excavated at 1-1/2:1 and 2:1 and temporary slopes at 1:1. However, slopes in dry loessial soil where the binding strength is high are sometimes excavated at 1/4:1 or 1/2:1. If these slopes become wetted and the binding strength decreases, it is obvious that the critical height will be reduced and failure will result. Some clay soils soften and swell when wetted, and weaken to the extent that relatively flat slopes fail. Canal side slopes of marginal stability should never be subjected to rapid drawdown during unwatering operations as side slope slougning is likely. A rule-of-thumb procedure when unwatering canals is to lower the water level not more than one foot a day to permit the soil-water pressures within the soil to dissipate. This criteria would include non-perennial canals.

An important and simple rule to follow is to observe the success of slopes already existing in the area for an indication of expected stability.

Generally, slopes can be stabilized by (1) flattening the slopes (2) weighing the toe of the slope, (3) unloading the top of the slope, (4) dewatering the zone of slippage by draining, or (5) stabilization of clay by the addition of lime.

D. **Settlement and Uplift**

Some settlement can always be expected for foundations resting on soil. However, it is important to keep these settlements within tolerable limits. When no settlement is permitted, the foundation needs to be placed on solid rock or on piers, piles, or caissons to solid rock. Some settlement is not objectionable if it is not of appreciable differential amounts beneath the structure. In hydraulic structures, it may be better to have the structure settle with the foundation to prevent underseepage than to have it supported on piles or piers. The principal ways to control settlement are (1) increase footing size, (2) compact earth pads, (3) do the construction in stages, or (4) use piles.

Opposite to settlement, uplift and soil expansion may occur. For example, water under head behind a foundation would have an uplifting effect. Some clays develop enormous expansion forces due to their ability to pull water into their mineral complex. For this reason, these clays are particularly objectionable in hydraulic structures. Heave of the subgrade can also be caused by an excessive amount of sodium sulfate salt in the pore water that crystallizes due to temperature changes.

E. **Deterioration**

Some shales and dense clays lose their strength by drying and cracking and subsequent wetting. Therefore, it is desirable that such materials be protected from drying and deterioration before the overlying part of a structure is built.

There are soils high in salt content that dissolve when in contact with water and if permeable the dissolved salt will leave a void.Occasionally in permeable soils, dissolved salts will recrystallize with a lowering of

temperature sufficiently to cause an expansion or expansive force if contained.

Organic soils should not be used as a construction material because they decompose, compress, and will allow water to pass readily through them where this is not desired.

F. Erosion

Canal side slopes can be protected by using a gravel beach belt or a moderate plastic, compacted clay lining which falls within thelimits shown in Figure III-I. Plasticity index (PI) greater than 10 and liquid limit (LL) greater than 25 but less than 45.

G. Permeability

Permeability is important in hydraulic structures such as those used in canals because they are intended to provide a water barrier of some kind. In granular soils, it is surprising, that it takes only small amounts of silt or clay to reduce permeability. Soils such as clean gravel, sands, and some uncompacted silts have high permeability, although many, such as gravelly soils, may be very desirable regarding stability and low settlement. When permeability becomes excessive, water movement can remove particles and this piping action will undermine structures. In canals, piping may cause sinkholes in addition to the objectionable loss of water. There are ways of correcting the problem of high permeability and piping by blocking the movement of fine soil with layers of selected soils in a filter. However, from a soil mechanics standpoint, some clay content is the most desireable natural means of keeping permeability under control.

SECTION 2 : CONSIDERATION OF SOILS TYPES

The above section presented the general problems and requirements associated with foundations. The corrective measures can be taken once the problem is defined. This will be done by examining the various soil types, going from fine clays to coarse gravels. Table III-1 presents the Unified Soil Classification which has been accepted internationally. Table III-2

presents a summary of foundation problems and remedial measures.

A. Firm, Consolidated Clays

As a foundation material, firm, consolidated clays are generally desirable. They are frequently called formation material and in geologic terms may even be called bedrock. These clays have been consolidated by large, past overlying soil or glacial ice pressures and, as a result, are preconsolidated to pressures greater than those placed on them by new structures. Also, such materials located below the ground surface are desireable for supporting piles and caissons. As mentioned previously, they may be subject to deterioration upon disturbance. However, as long as they are not disturbed, the preconsolidation pressures have given them strengths that are capable of sustaining appreciable loads. These soils may swell when the excavation process removes the overburden loads. Also, if they contain expansive clay minerals, the influx of water may make them objectionable. Nevertheless, for moderate-sized structures, the supporting capacity of such clays is usually not a problem. The location and general firmness of such clays can be determined by the penetration resistance tests.

B. Compressible Clays

Compressible clays are critical materials regarding foundation settlement and bearing capacity. These are the materials that require soil mechanics analyses and decisions of whether settlement can be tolerated or whether they should be improved by excavating and placing the foundation at greater depth or by the use of piles or caissons, or use of a compacted earth pad. These clays generally have not been preconsolidated by past heavy loads. Instead, they are geologically recent deposits and, commonly, new water-deposited sediments.

Compressible clays are not restricted from being satisfactory foundations but are the clays which usually require tests and soil mechanics interpretation for the evaluation of their supporting capacity. They may be critical in both settlement and the problem of punching into the ground, accompanied with lateral bulging.

C. Expansive Clays

The expansion of some clays when additional water is made available to them is a characteristic that is related to the type of minerals composing the clays. This can be a problem with either compressible or consolidated clays. It is, of course, far more critical when the clays are initially dense as in consolidated clays, because they then have much more possibility of expansive volume change.

These clays have mineral constituents which have a particular affinity to pull water molecules into their structure. The water effect on these clays causes them to shrink and crack when they are dried, and swell with sometimes appreciable force when they become wetted. A method of identifying these clays is as follows:

(1) A high plasticity index means that the soil can have a large change in moisture and still be in a plastic condition. Since moisture is the principal cause of volume swell, it is logical that a high plasticity index is a contributing indicator of expansion.

(2) A low shrinkage limit value means that it is possible that the soil can shrink to small volumes by drying. Therefore, this characteristic would be a contributing indicator of possible shrinkage volume change.

(3) Soils with a high content of colloidal clay, which is the most active ingredient, means that there is a large amount of material which has the possibility of causing expansion.

Data from laboratory index tests on many samples serves as a guide to estimating the percentage and degree of expansion. In the use of these index values, all three of the above-mentioned properties should be considered together to arrive at the expansion estimate.

Data from index tests			Probable expansion* % total volume change(dry to saturated condition)	Degree of expansion
Colloid content	Plasticity index	Shrinkage limit (%)		
> 28	> 35	< 11	> 30	Very high
20-31	25-41	7-12	20-30	High
13-23	15-28	10-16	10-20	Medium
< 15	< 18	> 15	< 10	Low

*Based on a vertical loadings of 1.0 lb/in .

During construction the in-place moisture density condition is most important. The USBR found that if the natural moisture of a soil was sufficiently high, it would not expand thereafter if the moisture were retained above the line shown in Figure III-2. If the natural clays dried during construction, they were moistened by sprinkling for 30 days before embankments were built on them. Expansive clays can be controlled from a structure foundation stand point by (1) placing the structure on caissons to increase foundation loadings and to anchor it in nonchanging material, (2) controlling subsoil moisture changes, and (3) mixing lime with the clay to change the chemical structure and form a stronger product.

D. Silts and Intermediate Soils

Silts and low plasticity clays are soils with moderate characteristics. They generally are not considered a problem in a recompacted condition, except they may need to be checked for settlement and shear resistance by laboratory tests. Natural deposits, however, are frequently a problem because they are sometimes very loose or of low density.

Silty sands that are dumped into canal banks without adequate compaction, which is the general condition of most canal banks in Pakistan, are subject to settlement piping. This is leading cause of canal breaches.

Silt and low plasticity clays can be very stable under dry conditions where small amounts of binder hold them together. As these soils become saturated, however, the binding effect deteriorates and the soils become unstable and frequently subside appreciably. It is important that the

looseness of these soils be recognised.

Soils of different plasticity or water-holding capacity will collapse at different densities. The liquid limit is a moisture content, determined by standard laboratory tests, which represents the weakest plastic condition of the soil or the approaching a liquid condition. When the soil has a low density, such that its void space is sufficiently large to hold the liquid-limit moisture content, saturation can easily cause a liquid-limit consistency and the soil is able to collapse. When a soil has a void space too small to hold the liquid-limit moisture, it cannot reach this consistency when it ecomes saturated. It will not collapse but will retain a plastic condition and only settle as a normal result of loading. Figure III-3 presents a guideline.

When the natural density is evaluated at frequent locations and depths and compared to the limiting density based on the liquid-limit moisture content, the criterion discussed above becomes a useful aid in showing when in-place densities are either adequate or lower than limiting density and trend toward probable near-surface subsidence.

E. Sands and Coarse-grained Soils

Granular and gravelly soils are generally more desireable for foundations. About the only major bad feature of these soils is their occasional occurrence at low density. A test called relative density is used to determine how dense these soils are. This test shows the natural density in terms of the minimum and maximum density that can be obtained by a standard method in the laboratory. Normally the soil density is acceptable if it is above 70% relative density. If granular soils are very loose and saturated, they may liquify under earthquake shocks.

Gravelly soils are considered particularly desireable as a construction material; they are the select materials used for roadways. The gravel has advantages in having low settlement and high shear resistance. About the only objectionable feature of gravelly soils is that of possibly high permeability. The all-around properties of gravelly soils become improved

with small amounts of clay binder. Reduction of seepage in gravels is best accomplished by adding clay as a binder. However, excess clay makes the soil revert to a less stable condition. If piping is found to be a problem (fine soil carried by water through a coarse soil), a filter or zone of intermediate size soil is necessary to prevent the movement of soil particles.

F. Solid Rock Foundation

Solid rock is only mentioned here to complete the circle of earth types. It is usually considered to be the best type of foundation and has little reason to be questioned. However, rock varies in strength and sometimes is reported as bedrock when it is only a formation of consolidated clay. Also, there can be problems with some solid rocks, such as limestone which, under certain ground-water conditions, may dissolve and form potholes.

G. Soil Classification

To select soils, it is first necessary to identify and classify them according to a system which is related to their physical or engineering properties. The Unified Soil Classification System presented in Appendix B is a universally recognized system. The system provides for both a visual method and a method based on laboratory tests. The proportions of the soil components (gravel, sand, silt, or clay) and the plasticity (the stickiness or cohesiveness) of the silt and clay fraction are defined. The visual method uses hand tests and visual observations and is not expected to be as precise as the laboratory method. With a limited amount of training and an interest in soil classification, one can identify soils with sufficient accuracy to classify them according to the 15 basic soil groups, which is considered to be adequate for most O&M work (see Table III-I).

The next step in the selection of soil for the use in construction is to relate the group or type of soil and its engineering properties. This has been done on a broad basis by the Engineering use chart in Table III-1. This chart may be used as a guide for evaluating the relative desirability

of soil types for various uses and estimating their important properties. A chart listing average numerical values based on laboratory tests in shown in Table III-3.

SECTION 3 : FIELD PROCEDURES

A. General

Personnel engaged in the operation of an irrigation system are required to maintain, repair, and occasionally engage in relocation of existing structures. The majority of this work involves the use of soil as a construction material. Therefore, they should have a working knowledge of the properties of soils which will aid in the proper selection for a specific purpose. Of equal importance to proper selection is to realize and understand that the successful use of a soil depends upon proper processing, that is, to increase or decrease the moisture content as required and thoroughly mix to form a uniform homogeneous mixture, and finally, proper placement and compaction.

Maintenance work in irrigation systems is concerned with the repair or replacement of completed structures. Failures are usually due to the action of water. Insofar as earthwork is concerned, an entire structure such as a canal bank may wash out or slide, or the soil backfill around a buried structure may erode or pipe, causing partial failure. A knowledge of soils and their physical properties, particularly as influenced by water, will aid in quickly determining the cause of failure and selecting the most suitable soils for repair and the proper method of processing and replacement.

B. Planning Earthwork Repairs or Construction

The first step in planning the repair of an earth structure or the earthwork portion of a structure is to determine or decide the basic cause of failure. The second step is to decide the best or most practical way to make the repair.

The type of soil, its properties, and if it has been appropriately used, should be considered when determining the cause of failure. If the type and use of the soil are satisfactory, then the placement conditions such as density, moisture, uniformity of material, and bond to the structure should be considered.

After inspecting the site, a decision must be made as to the best or most practical method of repair. Changes in the structure, alinement, installation of drains or drainage ditches, increase in the size or change in the type of structure, and the natural foundation or topographic features should be considered. The reuse or selection of another soil depends upon the type of soil, its properties, its present condition, intended use, and precautions required in replacement.

Basically, three classes of embankments are used in construction. **Dumped fill**, as the name implies, is a soil fill placed by dumping. There are no compaction or moisture requirements; hence, there are no structural requirements other than to complete the shape of an embankment or fill a hole or depression. Equipment-compacted embankments use selected material, and routing of hauling equipment provides some compaction. Moisture control may or may not be required. This type of construction is used for some minor canal embankments and road construction. The best class of embankment is rolled earthfill which requires selection of material and specific requirements as to placement density and moisture. Continuous inspection of materials and placement methods and procedures, as well as field and laboratory tests, are required to ensure that specification's requirements are met. Tractor compaction is used for granular, free-draining soils in which crawler-type tractors consolidate the soil to a specified density. Rolled earthfill or tractor-compacted embankments are required when specific engineering properties are needed to ensure that stability, erosion protection, permeability or impermeability, and minimum settlement requirements are obtained.

C. Embankment Repairs or Construction Procedures

The first step in soil embankment repairs is to locate the material to be used and initiate moisture conditioning. Dry soils, particularly fine-grained soils, require time to absorb and attain a uniform moisture content. Wet, clayey soils should be worked, that is, scarified and mixed to prevent formation of hard-surfaced, dried chunks. Occasionally, blending of plastic and non plastic soils may be required. It is preferable to mix the soils and then add moisture to ensure that the final mixture is homogeneous and the moisture uniform. Proper preconditioning will overcome most of the deficiencies noted in earthwork construction.

The question is asked, how can the desireable moisture content be estimated without the use of field and laboratory tests? This is not particularly easy and requires a knowledge of the compaction characteristics of soils.

One way to judge if the moisture content of a clayey soils is near that desired for maximum compaction (optimum moisture) is to take a handful of the minus 3/16-inch fraction of the soil and squeeze it into a ball. If a firm ball with a relatively smooth surface can be formed, the soil will be near, probably slightly more than, the optimum required for standard compaction. The relatively smooth surface indicates that sufficient moisture has penetrated the clay chunks to permit them to deform. Before working on large replacement projects employees should compare visual samples with laboratory tests.

Another method of judging the moisture content of a fine-grained silty or clayey soil or the fine-grained fraction of a coarse soil is to perform the "toughness test", one of the manual tests used in the visual method for classifying soils, see Table III-4.

For silty soils, the optimum moisture for compaction is somewhat less (from 2 to about 5 percent less) than the moisture content needed for the toughness test. For lean clays, the optimum moisture and moisture for the toughness test are about the same (plus or minus about 2%). For flat clays, the optimum moisture is more than the toughness test, an amount

ranging from 2 to 10 percent depending upon the plasticity of the clay.

It is difficult to overcome insufficient or nonuniform moisture conditions by any means other than adding moisture and thoroughly mixing prior to compaction. Occasionally, additional compaction is suggested as a substitute for moisture, that is, by increasing the number of roller passes or decreasing the thickness of lifts and obtaining the maximum or specified density at a moisture content less than the optimum desired for compaction. Insofar as permeability is concerned, laboratory tests have shown that to attain the same low permeability, the density of the soil must be greater than the maximum, when placed dry of the optimum moisture. A rule-of-thumb would be an increase of one pound in dry density for each percentage point the moisture is dry of optimum.

For coarse-grained, gravelly, sandy, or silty soils, the time element for moisture conditioning or moisture control is not critical for compaction. The moisture content should be more than the bulking moisture, which is about 5%, and sufficient to lubricate the particles. Dry loose soil of a fixed volume will bulk (increase in volume) if the moisture content increases above 5%. Therefore, extra material may be required to meet a compacted inplace volume. The adequacy of moisture can be judged by observing the material during compaction. If the fill is soft, the moisture is too great; if it is fluffy, there is insufficient moisture. If free moisture appears in the tracks immediately following passage of compaction equipment and then disappears, the moisture is adequate. Another suggestion is to observe if the soil is picked up by the tracks of the tractor and forms cakes. If the soil is too wet or too dry, cakes will not form.

The second step is to prepare the foundation, abutments, and surfaces of structures. All objectionable materials such as trash, organic material, and oversized particles should be removed. Low-density, sloughed, or washed soils should be removed, or stockpiled if the moisture is to be reused. During the latter operation, moisture conditioning should be initiated, adding moisture or drying as required. The purpose of the clean

up is to remove undesirable natural foundation or uncompacted materials and expose competent surfaces on and against which to place compacted soil. The lowest part of the foundation should be leveled. If the foundation is rock or surfaces of concrete structures are exposed, they should be clean (free or loose or chunks of natural material) and moistened by spraying before placing soil on or against them. If the exposed foundation is clayey soil, the natural moisture should be maintained by spraying. If this is not practicable, the dried surface material should be removed or scarified, moistened, thoroughly mixed, and compacted. If the foundation is sandy or granular silty soils, the foundation should be thoroughly moistened before placing the first layer of soil. Soil should not be placed on any foundation having standing or flowing water on the surface. Soils should not be placed when either the soil or the surface on which the soil to be placed is frozen.

As construction proceeds, weathered or dried material on the exposed abutments or side slopes should be removed and the surfaces moistened. Structure or rock surfaces should be moistened.

The third step is to construct the embankment. The preconditioned soil should be placed, thoroughly mixed, and spread to the desired thickness to form a homogeneous mass free from lenses, pockets, streaks, or layers of material differing substantially in texture or gradation or moisture from the surrounding material and, when compacted, free of potential paths for percolation.

If necessary, moisture should be added to the material that has dried during the final mixing. In embankment construction, the coarser particles should be placed toward the outer slopes. An effort should be made to maintain the surface of each compacted layer level and horizontal. The surface of the preceding layer must be scarified and correctly moistened before placing the next layer.

The next step in construction is to compact or densify the loose layer of soil as required to obtain stability against sliding, to reduce the

permeability through the soil mass, to obtain and maintain good bond between the compacted soil and surfaces of structures, and to minimize settlement.

The sheepsfoot tamping roller is the most desireable method for compacting clayey or silty soils. Experience has shown that about 12 passes will produce a density equivalent to the maximum obtained by the standard USBR laboratory compaction test, designation E-11, providing the soil is near (plus or minus 2 percentage points) the optimum moisture, and the thickness of the layer after compaction is 6 inches (8 to 9 inches thick before compaction). The maximum size of particles in the soil to be compacted is limited to about 4 inches.

Therefore, if the standard roller is available and the other items of moisture and thickness of lift are controlled, 12 passes will produce within tolerable limits the desired density.

It should be noted that for equivalent compaction the weight of the roller, number of passes, and thickness of layer are interrelated. However, 24 passes of a roller weighing 2,000 pounds-per-linear-foot will not produce the same degree of compaction as 12 passes of a 4,000 pound-per-linear-foot roller on the same thickness of lift. Sheepfoot usually "walk out" after the density they are capable of producing is attained and further rolling produces little or no additional increase in density. Walking out is where the feet no longer penetrate the fill material but ride on top of the compacted soil.

If a tamping roller weighing less than 4,000 pounds-per-liner-foot is the only roller available, the thickness of lift should be reduced proportionally; 3-inch compacted lift or 4-inch loose lift would be required for 12 passes of a roller weighing 2,000 pounds-per-liner-foot to maintain equivalent compactive effort and, hence, attain approximately equivalent density. The number of passes may be reduced if the roller has definitely walked out. Reducing the thickness of lift also reduces the maximum size of particle (stone) permitted in the soil to be compacted.

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In case of a 3-inch compacted lift, the maximum stone size should be about 2-1/2 inches.

Sometimes "hardness" and "density" are confused when evaluating the results of compaction. The expression that the soil is "packed hard" does not always indicate that it is dense. If the moisture of a clayey or silty soil is less than the optimum required for compaction, the surface may become very hard during compaction and yet the density could be low. Clayey soils are usually plastic and give the impression of being soft, at least not hard, when compacted at the optimum moisture content; however, depending upon the amount of coarse grains in the soil, they may become firm when compacted.

To consolidate most granular, free-draining soils, experience has shown that four passes of a crawler-type tractor weighing about 40,000 pounds will produce a density equivalent to about 70% relative density provided the soil is thoroughly wetted and the thickness of layer after compaction is no more than 12 inches, the maximum size of particle in the soil to be compacted being limited to about 12 inches.

The area of the treads and weight of the tractor influence the pressure imposed on the soil. A review of manufacturers' data indicated that heavy tractors weighing from 40,000 to 58,000 pounds exerted a soil pressure of about 0.6 ton per square foot, those weighing from 10,000 to 26,000 pounds have soil pressure of about 0.5 ton per square foot, and the light-weight tractors weighing about 7,000 pounds have soil pressures of about 0.4 ton per square foot.

To obtain densities comparable to those obtained with four passes of a heavy tractor, the thickness of lift and maximum size of particle should be limited to about 8 inches for the medium tractor and 6 inches for the smaller size tractor.

Vibrating tamping rollers and vibratory compactors are being used to compact silty and clayey soils as well as coarse-to-fine-grained, free-

draining soils. Manufacturers claim that these rollers are more efficient than the conventional methods for compaction or consolidating soils. There are no established guidelines based on weight, number of passes, or thickness of lift for the use of vibrating rollers. These rollers are permitted on construction job but their performance is closely checked by field and laboratory tests. Moisture control and preconditioning of the soil are just as important when using vibrating rollers as conventional tamping rollers.

D. Backfill for Repairs or Construction

Backfill is a term used to define earth placement in confined spaces or specified within certain boundaries. There are two classes: (1) loose backfill in which there are no compaction requirements and (2) compacted backfill.

If working space is limited, compaction of backfill can be accomplished by hand-operated compactors (self-propelled, air operated tampers, gasoline operated). The maximum size of stones permitted is usually limited to 3 inches. Conventional methods and equipment for compacting and consolidating backfill are discussed in the following paragraphs.

Backfill compaction of silty and clayey soils is usually done by hand-operated power tampers. Tests conducted using different types of tampers showed that the total weight and area of tamping foot influenced the number of passes required to compact a 6-inch thick layer (8-inch loose thickness) to the maximum standard laboratory density. For example, a tamper weighing 220 pounds with a tamping foot 75 square inches required about 150% coverage (1-1/2 minutes per square yard of surface for most commercial tampers) to produce the maximum density; whereas, a tamper weighing 31 pounds with a tamping foot of 25 square inches required about 450% coverage (4-1/2 minutes per square yard of surface). The time required is dependent upon the frequency of impact, which in turn depends upon the equipment being in good operating condition and the air pressure of pneumatic equipment is as specified by the manufacturer. This study led to performance specifications for backfill tampers comparable to the 12 roller

passes for the standard tamping roller, providing, of course, all other requirements for preconditioning materials, thickness of lift, and operating conditions of the equipment are met. The specifications are as follows:

> The degree of compaction shall be equivalent to that obtained in a layer of material 6 inches thick, after compaction, by using a pneumatic tamper operating on an air pressure of not less than 100 pounds per square inch; having a total weight in pounds, including the weight of the tamping foot, of not less than 2-1/2 times the area, in square inches, of the tamping foot; and operating uniformly over an area of 1 square yard for a period of not less than 1-1/2 minutes. Provided, that the area of the tamping foot shall not be less than 40 square inches. A reduction in size of the tamper can be compensated for by a reduction in thickness of the compacted layer.

It is suggested that compaction be done in terms of passes; the tamper should be moved continuously to cover the area (one pass) and then the procedure should be repeated for a second pass. This will require about 2-1/2 minutes per square yard. Note that a reduction in size of tamper can be compensated for by a reduction in thickness of the compacted layer. This provision is comparable to that suggested for rollers with less weight than the standard.

Backfill consolidation of granular free-draining soils is usually done by hand-operated, surface and internal vibrators. A cursory study of the performance characteristics of surface vibrators, have been used as a guide for determining the adequacy of compaction in lieu of tests. The guide specifications are as follows:

> When compacting cohesionless materials, the distribution of the materials shall be such that the compacted material will be homogeneous and free from lenses, pockets, streaks, or other imperfections. During compaction operations, the materials shall

be wetted thoroughly, as determined by the contracting officer, so as to produce the maximum density that can be obtained by the method of compaction specified.

The degree of compaction shall be equivalent to that obtained in a layer of material, 6 inches thick after compaction, by using a flat plate-type surface vibrator with a baseplate area of not less than 300 square inches, having a total weight in pounds not less than half the vibrator baseplate area in square inches and a centrifugal (vertical impact) force of at least 4 pounds per square inch delivered at a rate of 5,000 vibrations per minute (r/min) at the baseplate, and operated uniformly over an area of 1 square yard for a period of not less than 1 minute. The thickness of the compacted layer may be increased at the discretion of the contracting officer provided a larger and more efficient compactor is used.

E. Repair or Construction of Other Earthwork

Other earthwork repair or construction involves the same basic considerations discussed for embankment and backfill. Many of these special purpose uses involve restrictions on the type of soil used. Some of the uses encountered in O&M work will be discussed briefly.

1. Compacted Earth Lining

Compacted earth lining may be constructed of selected coarse-or fine-grained impervious soils, such as GC (clayey gravel), SC (clayed sand), CL (lean clay), CH (fat clay),or GM (silty gravel). Soils of these types often do not require erosion protection. The coarse-grained soils are erosion resistant because of the large particles, and the fine-grained clayey soils because of plasticity. Fine-grained clayey soils must have a plasticity index of at least 10 to provide adequate resistance to erosion. SM (silty sand) and ML (silt) may be sufficiently impervious for lining material but cover must be provided for erosion protection. Uniformity of material and moisture is particularly important when materials are blended to construct a lining. Maintaining the moisture near or just wet of

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optimum and obtaining good bond between layers are required to insure a satisfactory lining.

Filters are used to carry away seepage water without erosion or displacement of the soil. They are constructed of specially selected pervious soils, process, if necessary, to meet rigid gradation requirements. These requirements and precautions in construction are discussed in standard soils tests.

2. Riprap

Protective covers are layers of selected pervious material for preventing the displacement of soil particles by water flowing through or past the soil surface. The maximum size of particle and grading depend upon the purpose. Riprap is a form of protective blanket where the particles range in size up to 1 cubic foot. The maximum size depends upon the expected maximum velocity and depth of moving water in the case of canals. Bedding for riprap is another type of protective blanket which is equally important in providing protection. For canals, the bedding generally consists of selected sand and gravel reasonably well graded, having a maximum size of about 1-1/2 inches and less than 5% fines. Failures may be the displacement of the riprap particles down the slope or along the canal and displacement of the soil beneath the blanket. The first is generally due to improper size and grading of riprap particles. The second is generally due to improper grading of the bedding, permitting the foundation to erode, and the riprap particles to settle. When a failure has occurred, the cause should be determined before repairs are initiated.

A cover layer used for erosion protection of unlined or earth-lined canals is a form of protective blanket, consisting of pit-run sand and gravel up to 3 inches in size and preferably with a maximum of 5% fines. Table III-5 provides guidelines for erosion protection of earth-surfaced canals.

The primary consideration in placing protective blankets is to minimize segregation and loose pockets. Adding moisture to sand and gravel mixtures will minimize segregation. Although riprap is usually placed by dumping,

an effort should be made to see that the individual loads contain a good representation of all particle size. Broken burnt brick with a good mix of all sizes may be utilized for riprap. Maximum size should be increased because specific weight is much less than stone. Longevity of burnt brick riprap is unknown.

TABLE III-1

UNIFIED CLASSIFICATION AND PROPERTIES OF SOILS

TYPICAL NAMES	IMPORTANT PROPERTIES						UNIFIED SOIL CLASSES
	SHEAR STRENGTH	COMPRESS-IBILITY	WORKABILITY AS CONSTRUCTION MATERIAL	WHEN COMPACTED	K CM. PER. SEC.	K FT. PER DAY	
Well graded gravels, gravel-sand mixtures, little or no fines.	Excellent	Negligible	Excellent	Pervious	$K > 10^{-2}$	$K > 30$	GW
Poorly graded gravels, gravel-sand mixtures, little or no fines.	Good	Negligible	Good	Very Pervious	$K > 10^{-2}$	$K > 30$	GP
Silty gravels, gravel-sand-silt mixtures.	Good to Fair	Negligible	Good	Semi-Pervious to Impervious	$K = 10^{-3}$ to 10^{-6}	$K = 3$ to 3×10^{-3}	GM
Clayey gravels, gravel-sand- clay mixtures.	Good	Very Low	Good	Impervious	$K = 10^{-6}$ to 10^{-8}	$K = 3 \times 10^{-3}$ to 3×10^{-5}	GC
Well graded sands, gravelly sands, little or no fines.	Excellent	Negligible	Excellent	Pervious	$K > 10^{-3}$	$K > 3$	SW
Poorly graded sands, gravelly sands, little or no fines.	Good	Very Low	Fair	Pervious	$K > 10^{-3}$	$K > 3$	SP
Silty sands, sand-silt mixtures.	Good to Fair	Low	Fair	Semi-Pervious to Impervious	$K = 10^{-3}$ to 10^{-6}	$K = 3$ to 3×10^{-3}	SM
Clayey sands, sand-clay mixtures.	Good to Fair	Low	Good	Impervious	$K = 10^{-6}$ to 10^{-8}	$K = 3 \times 10^{-3}$ to 3×10^{-5}	SC
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	Fair	Medium to High	Fair	Semi-Pervious to Impervious	$K = 10^{-3}$ to 10^{-6}	$K = 3$ to 3×10^{-3}	ML
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.	Fair	Medium	Good to Fair	Impervious	$K = 10^{-6}$ to 10^{-8}	$K = 3 \times 10^{-3}$ to 3×10^{-5}	CL
Organic silts and organic silty clays of low plasticity.	Poor	Medium	Fair	Semi-Pervious to Impervious	$K = 10^{-4}$ to 10^{-6}	$K = 3 \times 10^{-1}$ to 3×10^{-3}	OL
Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.	Fair to Poor	High	Poor	Semi-Pervious to Impervious	$K = 10^{-4}$ to 10^{-6}	$K = 3 \times 10^{-1}$ to 3×10^{-3}	MH
Inorganic clays of high plasticity, fat clays.	Poor	High to Very High	Poor	Impervious	$K = 10^{-6}$ to 10^{-8}	$K = 3 \times 10^{-3}$ to 3×10^{-5}	CH
Organic clays of medium to high plasticity, organic silts.	Poor	High	Poor	Impervious	$K = 10^{-6}$ to 10^{-8}	$K = 3 \times 10^{-3}$ to 3×10^{-5}	OH
Peat and other highly organic soils	NOT SUITABLE FOR CONSTRUCTION						Pt

TABLE III-1

UNIFIED CLASSIFICATION AND PROPERTIES OF SOILS

EMBANKMENTS

COMPACTION CHARACTER-ISTICS	STANDARD PROCTER UNIT DENSITY LBS. PER CU. FT.	TYPE OF ROLLER DESIRABLE	RELATIVE CHARACTERISTICS: PERME-ABILITY	RELATIVE CHARACTERISTICS: COMPRESS-IBILITY	RESISTANCE TO PIPING	ABILITY TO TAKE PLASTIC DEFORMATION UNDER LOAD WITHOUT SHEARING	GENERAL DESCRIPTION & USE	UNIFIED SOIL CLASSES
Good	125 - 135	crawler tractor or steel wheeled & vibratory	High	Very slight	Good	None	Very stable, pervious shells of dikes and dams.	GW
Good	115 - 125	crawler tractor or steel wheeled & vibratory	High	Very slight	Good	None	Reasonably stable, pervious shells of dikes and dams.	GP
Good with close control	120 - 135	rubber-tired or sheepsfoot	Medium	Slight	Poor	Poor	Reasonably stable, not well suited to shells but may be used for impervious cores or blankets.	GM
Good	115 - 130	sheepsfoot or rubber-tired	Low	Slight	Good	Fair	Fairly stable, may be used for impervious core.	GC
Good	110 - 130	crawler tractor & vibratory or steel wheeled	High	Very Slight	Fair	None	Very stable, pervious sections, slope protection required.	SW
Good	100 - 120	crawler tractor & vibratory or steel wheeled	High	Very Slight	Fair to Poor	None	Reasonably stable, may be used in dike with flat slopes.	SP
Good with close control	110 - 125	rubber-tired or sheepsfoot	Medium	Slight	Poor to Very Poor	Poor	Fairly stable, not well suited to shells, but may be used for impervious cores or dikes.	SM
Good	105 - 125	Sheepsfoot or rubber-tired	Low	Slight	Good	Fair	Fairly stable, use for impervious core for flood control structures.	SC
Good to Poor close control essential	95 - 120	Sheepsfoot	Medium	Medium	Poor to Very Poor	* Very Poor	Poor stability, may be used for embankments with proper control. * Varies with water content.	ML
Fair to Good	95 - 120	Sheepsfoot	Low	Medium	Good to Fair	Good to Poor	Stable, impervious cores and blankets.	CL
Fair to Poor	80 - 100	Sheepsfoot	Medium to Low	Medium to High	Good to Poor	Fair	Not suitable for embankments.	OL
Poor to very Poor	70 95	Sheepsfoot	Medium to Low	Very High	Good to Poor	Good	Poor stability, core of hydraulic fill dam, not desirable in rolled fill construction.	MH
Fair to Poor	70 - 105	Sheepsfoot	Low	High	Excellent	Excellent	Fair stability with flat slopes, thin cores, blanket & dike sections	CH
Poor to very Poor	65 - 100	Sheepsfoot	Medium to Low	Very High	Good to Poor	Good	Not suitable for embankments.	OH
DO NOT USE FOR EMBANKMENT CONSTRUCTION								Pt

TABLE III-1

UNIFIED CLASSIFICATION AND PROPERTIES OF SOILS

CHANNELS		FOUNDATION				TENTATIVE FOR TRIAL USE ONLY	UNIFIED SOIL CLASSES
LONG DURATION TO CONSTANT FLOW.		FOUNDATION SOILS, BEING UNDISTRUBED, ARE INFLUENCED TO A GREAT DEGREE BY THEIR GEOLOGIC ORIGIN. JUDGEMENT AND TESTING MUST BE USED IN ADDITION TO THESE GENERALIZATION.					
RELATIVE DESIRABILITY		RELATIVE DESIRABILITY			REQUIREMENTS FOR SEEPAGE CONTROL		
EROSION RESISTANCE	COMPACTED EARTH LINING	BEARING VALUE	SEEPAGE IMPORTANT	SEEPAGE NOT IMPORTANT	PERMANENT RESERVIOR	FLOODWATER RETARDING	
1	-	Good	-	1	Positive cutoff or blanket	Control only within volume acceptable plus pressure relief if required.	GW
1	-	Good	-	3	Positive cutoff or blanket	Control only within volume acceptable plus pressure relief if required.	GP
4	4	Good	2	4	Core trench to none	None	GM
3	1	Good	1	6	None	None	GC
6	-	Good	-	2	Positive cutoff upstream blanket & toe drains or wells	Control only within volume acceptable plus pressure relief if required.	SW
7 if gravelly	-	Good to Poor depending Upon Density	-	5	Positive cutoff or upstream blanket & toe drains or wells	Control only within volume acceptable plus pressure relief if required.	SP
8 if gravelly	5 erosion critical	Good to Poor depending upon density	4	7	Upstream blanket & toe drains or wells	Sufficient control to prevent dangerous seepage piping.	SM
5	2	Good to Poor	3	8	None	None	SC
-	6 erosion critical	Very poor susceptible to liquafication	6, if saturated or pre-wetted	9	Positive cutoff or upstream blanket & toe drains or wells.	Sufficient control to prevent dangerous seepage piping.	ML
9	3	Good to Poor	5	10	None	None	CL
-	7 erosion critical	Fair to Poor, may have excessive settlement	7	11	None	None	OL
-	-	Poor	8	12	None	None	MH
10	8 volume change critical	Fair to Poor	9	13	None	None	CH
-	-	Very Poor	10	14	None	None	OH
-	-			REMOVE FROM FOUNDATION			Pt

No. 1 is best numerical rating.

TABLE III-1

UNIFIED CLASSIFICATION AND PROPERTIES OF SOILS

			LABORATORY CRITERIA			UNIFIED SOIL CLASSES
COARSE-GRAINED SOILS Less than half of material passes the No. 200 sieve size.	GRAVELS Less than half of the coarse fraction passes the No. 4 sieve size.	CLEAN GRAVELS Less than 5% passing the No. 200 sieve size.	Borderline cases require the use of dual symbols.	WELL GRADED Meets gradation requirements	GRADATION REQUIREMENTS ARE: $C_u = \frac{D_{60}}{D_{10}} > 4$ and	GW
				POORLY GRADED Does not meet gradation requirements.	$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} <$ between 1 & 3	GP
		GRAVELS WITH FINES More than 12% passing the No. 200 sieve size.		Plasticity limits of material passing No. 40 sieve size plots below "A" line and P.I. less than 4.	Plasticity limits above "A" line with P.I. between 4 and 7 are border-line cases and require use of dual symbols	GM
				Plasticity limits of material passing No. 40 sieve size plots above "A" line of P.I. more than 7		GC
	SANDS More than half of the coarse fraction passes the No. 4 sieve size.	CLEAN SANDS Less than 5% passing the No. 200 sieve size.	Borderline cases require the use of dual symbols.	WELL GRADED Meets gradation requirements	GRADATION REQUIREMENTS ARE: $C_u = \frac{D_{60}}{D_{10}} > 6$ and	SW
				POORLY GRADED Does not meet gradation requirements.	$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} <$ between 1 & 3	SP
		SANDS WITH FINES More than 12% passing the No. 200 sieve size.		Plasticity limits of material passing No. 40 sieve size plots below "A" line and P.I. less than 4.	Plasticity limits above "A" between 4 and 7 are border-line cases and require use of dual symbols.	SM
				Plasticity limits of material passing No. 40 sieve size plots above "A" line or P.I. more than 7.		SC
FINE-GRAINED SOILS More than half of material passes the No. 200 sieve size.	SILTS AND CLAYS Liquid limit less than 50	Below "A" line and P.I. less than 4		Above "A" line with P.I. between 4 and 7 are border-line cases requiring use of dual symbols		ML
		Above "A" line or P.I. more than 7				CL
		Below "A" line and P.I. less than 4 and $\frac{\text{L.L. (oven dry soil)}}{\text{L.L. (air dry soil)}} > 0.7$				OL
	SILTS AND CLAYS Liquid limit greater than 50	Below "A" Line				MH
		Above "A" Line				CH
		Below "A" line and $\frac{\text{L.L. (oven dry soil)}}{\text{L.L. (air dry soil)}} < 0.7$				OH
	HIGHLY ORGANIC SOILS				$\frac{\text{L.L. (oven dry soil)}}{\text{L.L. (air dry soil)}} < 0.7$	Pt

TABLE III-2

FOUNDATION PROBLEMS AND REMEDIAL MEASURES

Foundation problem	Possible remedial measures*
CLAYS - SOFT (COMPRESSIBLE)	
Settlement	1. Reduce unit design load by increasing the footing size 2. Stage construction - gradual loading of subsoil 3. Compacted earth pad (over excavation and refill) 4. Use piles to transfer loads to deeper soils
Slope stability	1. Flatten slope 2. Prevent saturation - install drains 3. Weight the toe of the slope 4. Unload the top of the slope 5. Strengthen soils with lime or cement additives
Erosion	1. Cover surface with erosion-resistant material 2. Densify existing soils 3. Use medium plasticity clay lining or soil-cement
CLAYS - FIRM (CONSOLIDATED)	
Expansion	1. Increase foundation loadings by using caissons embedded in nonchanging soil 2. Prevent future subsoil moisture changes - use membrane 3. Prewet foundations and retain their moisture 4. Stabilize by mixing with lime
Deterioration	1. Protect foundation surfaces from drying and cracking
SILTS AND INTERMEDIATE SOILS	
Soil collapse	1. Saturate subsoils before construction 2. Compacted earth pads
Settlement	1. Same considerations as for compressible clays
Frost action	1. Place footings below frostline 2. Restrict supply of water 3. Compact earth pad (use sand or gravel) 4. Apply thermal insulation 5. Use soil additives
SANDS AND GRAVELS	
Settlement	1. Densify subsoils using vibratory methods
Permeability	1. Mix clay with sand or gravel 2. Grout
Piping	1. Use filter zone or a clay binder
Liquefaction	1. Densify subsoild

* Selection of most economical remedial measure depends on the structure

TABLE III - 3
AVERAGE PROPERTIES OF SOILS

Soil classification group	Proctor Max dry density in lbs./cu ft	compaction optimum water content percent	Void ratio e_o	Permeability K feet per year	Compressibility @ 20 psi percent	Compressibility @ 50 psi percent	Shearing strength C_o psi	Shearing strength C_{sat} psi	tan ϕ
G W	>119	<13.3	*	27000± 13000	<1.4	*	*	*	>0.79
G P	>110	<12.4	*	64000± 34000	<0.8	*	*	*	>0.74
G M	>114	<14.5	*	>0.3	<1.2	<3.0	*	*	>0.67
G C	>115	<14.7	*	>0.3	<1.2	<2.4	*	*	>0.60
S W	119 ± 5	13.3 ± 2.5	0.37 ± *	*	1.4 ± *	*	5.7 ± 0.6	*	0.79 ± 0.02
S P	110 ± 2	12.4 ± 1.0	0.50 ± 0.03	>150	0.8 ± 0.3	*	3.3 ± 0.9	*	0.74 ± 0.02
S M	114 ± 1	14.5 ± 0.4	0.48 ± 0.02	7.5 ± 4.8	1.2 ± 0.1	3.0 ± 0.4	7.4 ± 0.9	2.9 ± 0.9	0.67 ± 0.02
SM-SC	119 ± 1	12.8 ± 0.5	0.41 ± 0.02	0.8 ± 0.6	1.4 ± 0.3	2.9 ± 1.0	7.3 ± 3.1	2.1 ± 0.8	0.66 ± 0.07
S C	115 ± 1	14.7 ± 0.4	0.48 ± 0.0±	0.3 ± 0.2	1.2 ± 0.2	2.4 ± 0.5	10.9 ± 2.2	1.6 ± 0.9	0.60 ± 0.07
M L	103 ± 1	19.2 ± 0.7	0.63 ± 0.02	0.59 ± 0.23	1.5 ± 0.2	2.6 ± 0.3	9.7 ± 1.5	1.3 ± *	0.62 ± 0.04
ML-CL	109 ± 2	16.8 ± 0.7	0.54 ± 0.03	0.13 ± 0.07	1.0 ± 0.2	2.2 ± 0.0	9.2 ± 2.4	3.2 ± *	0.62 ± 0.06
C L	108 ± 1	17.3 ± 0.3	0.56 ± 0.01	0.08 ± 0.03	1.4 ± 0.2	2.6 ± 0.4	12.6 ± 1.5	1.9 ± 0.3	0.54 ± 0.04
O L	*	*	*	*	*	*	*	*	*
M H	82 ± 4	36.3 ± 3.2	1.15 ± 0.12	0.16 ± 0.10	2.0 ± 1.2	3.8 ± 0.8	10.5 ± 4.3	2.9 ± 1.3	0.47 ± 0.05
C H	92 ± 2	25.5 ± 1.2	0.80 ± 0.04	0.05 ± 0.05	2.6 ± 1.3	3.9 ± 1.5	14.9 ± 4.9	1.6 ± 0.86	0.35 ± 0.09
O M	*	*	*	*	*	*	*	*	*

The ± entry indicates 90 percent confidence limits of the average value
* denotes insufficient data, > is greater than, < is less than
Source: USBR

TABLE III-4

FIELD IDENTIFICATION PROCEDURES FOR FINE GRAINED SOILS OR FRACTIONS

These procedures are to be performed on the minus No. 40 sieve size particles, approximately 1/64 inches. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

DILATANCY (Reaction to shaking)

After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

DRY STRENGTH (Crushing characteristics)

After removing particles larger than No. 40 sieve size, mold a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely be over, sun, or air drying, and then test its strength by breaking and crumbing between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

TABLE III-4
FIELD IDENTIFICATION FOR THE GROUND SOILS OR FRACTIONS
(Continued)

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

TOUGHNESS (Consistency near plastic limit)

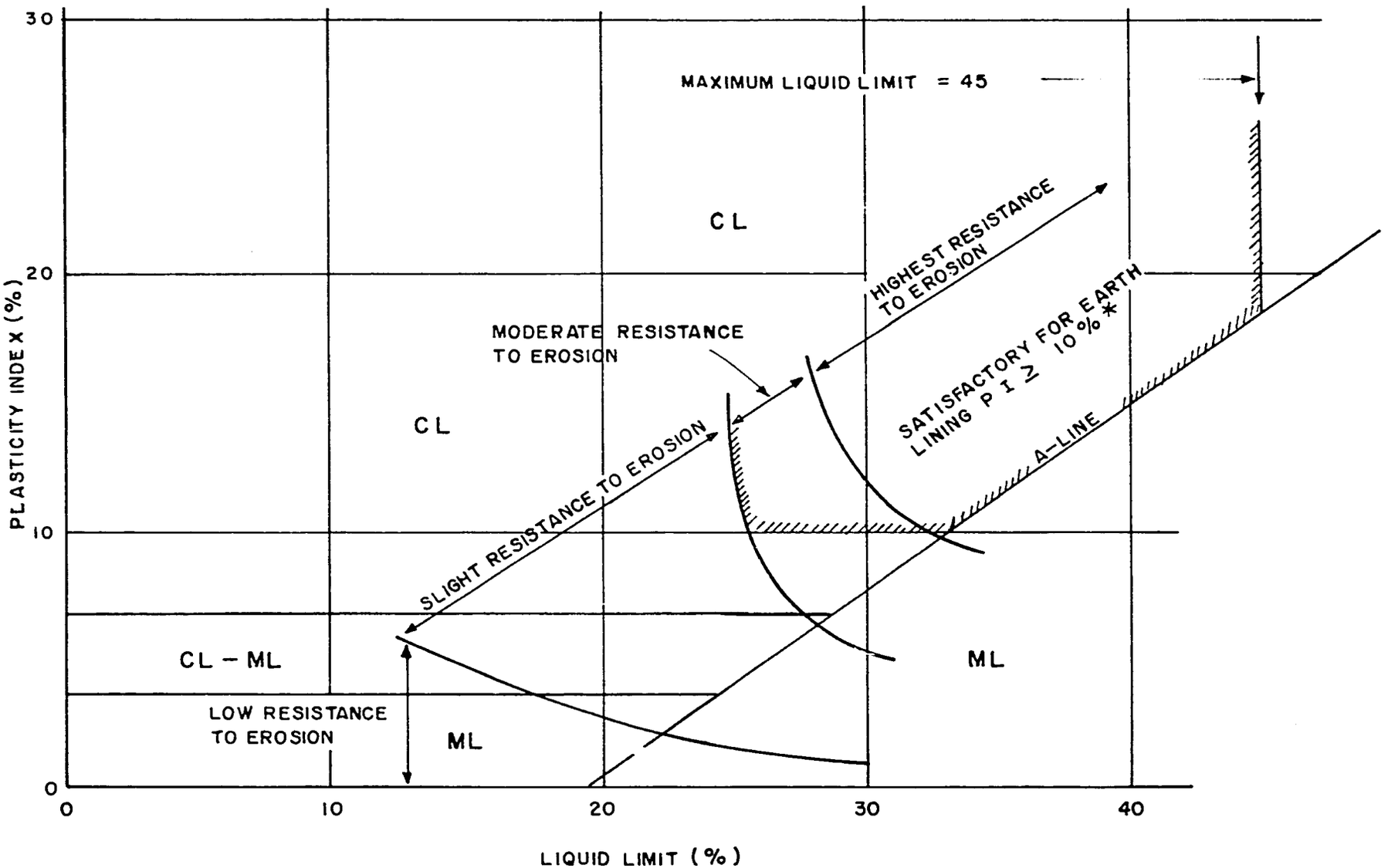
After removing particles larger than the No. 40 sieve size, a specimen of soil about one-half inch cube in size is molded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one-eighth inch in diameter. The threads is then folded and rerolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as Kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

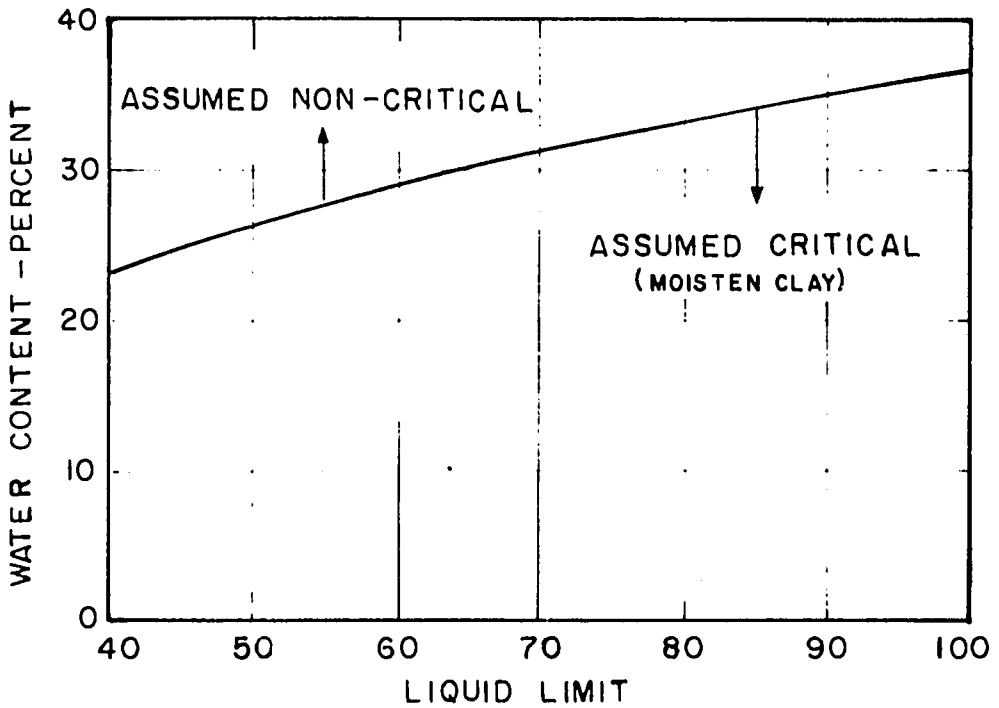
Source: USBR Soil Manual



* ALTHOUGH A P I OF 10 % IS ACCEPTABLE A VALUE OF 12 % IS PREFERRED

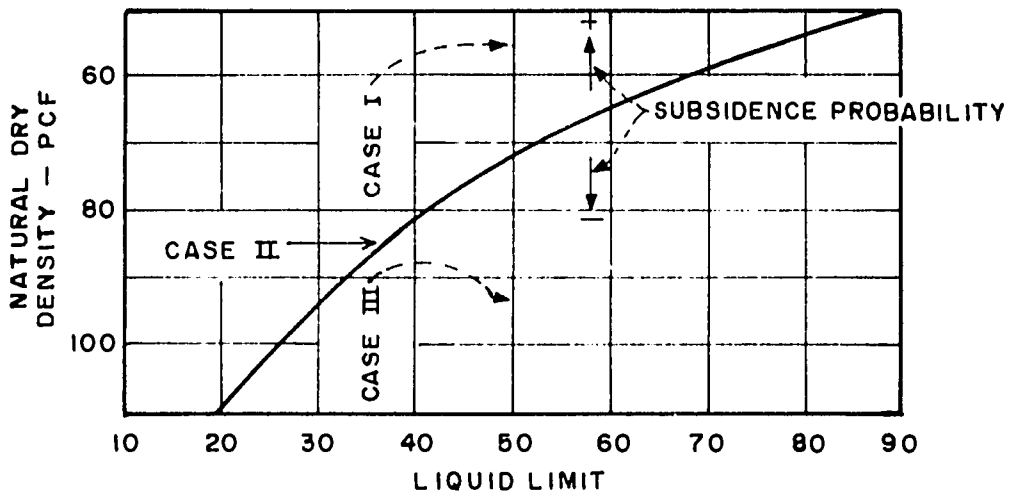
EROSION RESISTANCE WITH RESPECT TO PLASTICITY

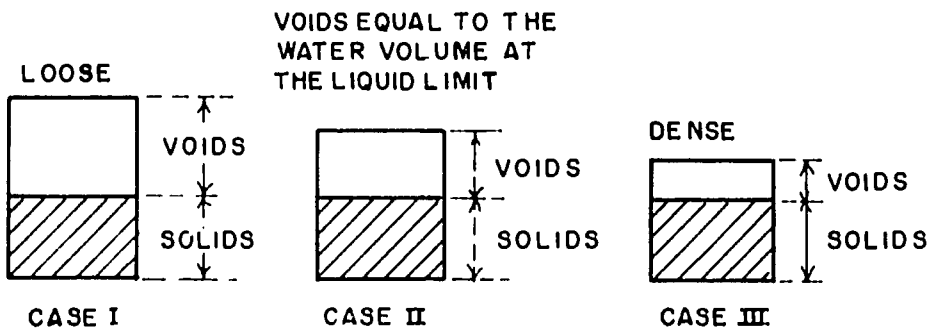
FIGURE III-1



SOURCE: U.S. BUREAU OF RECLAMATION

MINIMUM WATER CONTENT REQUIRED TO STABILIZE CLAYS FOR HYDRAULIC STRUCTURE FOUNDATIONS





SOURCE: U.S. BUREAU OF RECLAMATION

GUIDELINE FOR EVALUATING LOOSENESS AND PROBABILITY OF SUBSIDENCE

CHAPTER IV

EMBANKMENT MAINTENANCE

CHAPTER IV

EMBANKMENT MAINTENANCE

SECTION 1 : MAIN EMBANKMENT

A. General

The embankment is considered to be that portion that was constructed by placing earth in a prescribed manner to fit a designed section with fixed slopes. Berms are considered separately since the majority of them were formed hydraulically. Road surfaces, spoil banks and vegetative control are considered separately. In the majority of cases, the embankments are considered stable and not subject to failure so long as the original design is maintained. Erosion will reduce the safety factor. In a few instances, seep areas may be observed on canal banks, particularly those in elevated situations. Those exhibiting seepage should be considered as marginally safe and will require berms to strengthen. This work should not be delayed.

B. Routine Maintenance

Routine maintenance refers to those work items performed by the beldars while patrolling his zone of responsibility that help keep the canal in good operating condition. In essence they are preventive maintenance, i.e., the first line of defence against deterioration. Routine maintenance procedures are defined in Table III-1. Items 1,5 and 8 may exceed the capabilities of individual beldars to perform adequately. Therefore, outside assistance should be provided before conditions deteriorate beyond the performance standard. Filling raincuts should have priority over cattle cuts because it fits the beldars work pattern better than that of a work gang.

Rain-holes, sink-holes, rat-holes and rotted out roots may lead to piping failure. Most canal embankments were not constructed with compacted embankments. Staunching was limited more to the large canals than the smaller ones. Fine sandy silts and similar materials tend to bulk when

placed by basket work leaving considerable voids in the completed embankments. Upon wetting of these unconsolidated areas, water may cause soil particles to move and open up voids. As the void areas tie together to form longer channels, water movement may take place along the channel which can cause additional soil particles to move. If the channel opens up to the outside, a piping failure can occur.

Rat-holes start above the water line or on the back slope of the embankment. When these connect up with voids, rotted tree or other decayed root channels, rain-holes or what have you; a rise in water surface could cause a piping failure. Seepage of water into such a subsurface channel system may continue a process that was started by other means.

There have been instances where insects have burrowed through the embankment and caused considerable seepage which could lead to a slide failure if not corrected immediately. The mole cricket is the most common insect. A giant grasshopper has also been observed which can burrow for distances up to 200 feet. The best control is obtained using an appropriate insecticide. Success has also been achieved by placing a compacted backfill in a trench excavated parallel to the canal down the center of the embankment.

The maintenance strategy must concentrate on preventive maintenance practices that will repair or fix a small problem before it becomes a major one. This is a very cost effective way to reduce maintenance costs.

The performance standards that govern maintenance work are defined in Chapter II. These must be strictly adhered to. Existing design configuration may be maintained if they conform.

C. Freeboard Restoration

Table II-1 provides the freeboard standards for various size canals. The design freeboard should never be violated (i.e. allowed to erode). Therefore a 5 inches of additional freeboard was added to the minimum freeboard during rehabilitation. When this extra freeboard is worn or

washed off, it must be replaced. Freeboards should be restored as soon as the performance standard is exceeded.

Bed sediments should not be used to repair/replace freeboard material. Materials to be used on the top of the embankment should be a fine sandy silt or similar soil material that meets an engineering classification of ML or CL. The criteria are further defined in Paragraph 5.D below.

The anticipated steps to replace embankment material used to restore the freeboard are as follows:

(1) Borrowed from authorized borrow areas.
(2) The depth of loose material will depend on compaction equipment to be used to meet the specification of 85% Standard Proctor dry density or as specified by contracting officer.
(3) Add water to increase moisture content to about 10%.
(4) Disk the material using a tractor to break up lumps and incorporate the moisture uniformly into the soil.
(5) Compact material using a tractor towing a heavy roller.

The above operations can be mechanized to various degrees depending on the local labor situation and the source of borrow material. Basket work is generally limited to 100 feet from the canal. Haul or lead distances above 100 feet usually require donkey labor or tractor-trolley combination.

Placement of material would tend to be by hand but it can be improved/ accomplished with equipment of various types. Water can be added by hand pumping with a hose or a water tank fitted on a trolley. Mixing the soil with a tractor equipped with a farm disk improves the quality of the work as well as breaking up lumps. It also adds a levelling component.

Compaction can be accomplished by a number of different means. The hand operated equipment will work but is very time consuming and not cost effective. Contractors would have to be monitored very closely or the

compacting would not get done properly. A tractor drawn roller means a relatively large area can be compacted quickly. The major power unit is the 40 hp farm tractor that is used in combination with the trolley. Its use with a roller does not introduce a major new technology as it is already being used in highway work. It would not be difficult to enforce compaction specifications.

Non-patrol road embankment tops should be sprigged with the local bermuda grass or another drought resistant grass that will provide complete cover.

D. Embankment Slopes

The outside embankment slope is subject to considerable erosion due to heavy rainfall. A sodded embankment is much less subject to erosion than a non-grassed one. Compacted embankments also exhibit less erosion potential. It is estimated that embankment slopes will loose about 2 inches of soil each year which should be replaced every five years. The inside slope is protected by the berm and is nearly always protected by a grass cover down to the waterline.

Raincuts and rain-holes are the major mechanism of soil removal from the outside slope. One single heavy raintall after material is dumped and spread uncompacted on a slope can remove a large percentage of the material near the top of the slope.

Restoration of embankment material would be similar to that for freeboard in many respects. The following general procedures should be followed to place when restoring a canal embankment to design specification with compacted soil material:

(1) Clear and grub the slope.
(2) Borrow from authorized borrow areas.
(3) Haul and dump on top of embankment.
(4) Add water to increase moisture content to roughly 10%.
(5) Disk with tractor to thoroughly incorporate the water and break up clods.

(6) Push soil over side and rake to correct depth and slope.

(7) Repeat steps 1 to 6 as required to obtain necessary volume and depth.

(8) Rewet material on slope if it has dried out.

(9) Compact slope.

(10) Sprig with appropriate grass.

Most of the procedures for restoring a canal embankment are similar to those used to replace freeboard. All grass, bushed and vegetative material shall be removed and the earth loosened to provide or bond with the new fill material. As many trees as possible should be removed from the bank. It will not be possible to achieve a uniform compaction if trees are left on the slope.

The most difficult problem will be to achieve adequate soil moisture for placing and compacting. This can best be achieved by dumping the material top of the embankment, adding water, mixing the material with a disk (which also breaks up the clods) and then pushing it over the side. It can be hand raked to a loose depth of 7 to 8 inches to provide a 5-inch compacted layer. The process would have to be repeated twice before sufficient material is placed to restore the slope to specification, nominally the addition of 10 inches of compacted material perpendicular to the slope.

The most cost effective form of compaction appears to be the use of a special purpose crawler tractor using a side mounted winch to pull a vibrating sheepsfoot roller up and down the slope. Four passes per layer are expected to provide sufficient compaction to meet the 85% Standard Proctor specification. This piece of equipment will cover about 500 lineal feet per hour.

As discussed in Section 4 there are other ways to compact embankments Figure IV-1 list the equipment and working requirements of some of the other equipment. All of these methods require working on narrow lifts in stairstep fashion. Supervision of any contractor using these methods will

be difficult because it is expensive, time consuming and tempting to skip over doing it properly.

The restored embankment slope should be sodded (sprigged) to protect it from erosion. A low grow grass with a stoloniferous (spreading) root system that is drought resistant should be used. The newly planted/ sprigged slopes should be watered long enough to get the grass well established. This may not be a practical solution in areas of very low rainfall. Cattle must be kept off the embankments.

E. Restricted Use of Bed Sediment

The bed sediments deposited in the canals or located along watercourses are cohesionless materials devoid of fine silt and clay particles. This material should not used in freeboard restoration unless specially handled. Cohesionless material will not remain compacted if subject to vehicular and other traffic. It is also highly erosive under heavy rainfall conditions. Therefore, it must be confined and protected. Figure IV-2 shows one method of accomplishing this. The small compacted embankment constructed on the wet side of the embankment is to prevent a direct seepage path in case the water level exceeds the full supply level in the canal. It also protects against burrowing animals, fish or insects. Both the bed sediment and cover layer must be compacted to 85% of Standard Proctor dry density, or as directed by the contracting officer.

Figure IV-3 presents a method of utilizing bed-sediments on the dry side of the embankment to restore eroded material or to be used as a berm to protect/strengthen a seep area. Both the sediment and the covering or protective layer must be compacted to prevent erosion of material, particularly near the intersection of the top and slope. It may be desireable to increase the amount of cover material in this location.

Figure IV-4 is another alternative when the spoil area is used as a road and right-of-way is available. If the area is not to be used as a road, then the blanket material may not be required.

F. Top Width Cross-Slope

The cross-slope on the top of the embankment must be maintained between S = 0.017 and 0.020 to prevent water from ponding on the surface. The slope must be steep enough to carry the water off yet flat enough to prevent soil erosion. A dowel located on the canal side of the embankment top does not affect drainage. Water must flow off as sheet flow. Any curbing caused by improper blading when grading the road will cause the water to pond initially. This temporary curbing will fail at a weak point and the existing water will cause a large raincut or erosion rivulet. This is why the grade of the road parallel to the center line be maintained, without dips because they would cause surface flow to concentrate. Where such flow concentrations cannot be avoided, a porous or French drain, as presented in Figure IV-5, can be used to prevent erosion.

G. Bridge Access

In older canal systems, access to bridges by maintenance vehicles is limited by the turning radius of the vehicle(s). This causes the bridge railings to be broken and knocked off. To prevent damaged the embankment should be widened out to allow the complete turning radius of a 5-ton truck. The wider outside radius is required because the trucks rear wheels do not follow the front wheels in a turn but cut a shorter radius. The same is true for a tractor-trolley combination. Figure IV-6 presents a sketch showing the canal embankment widening requirements depending on the local conditions.

H. Ramps

A ramp or runup is required during rehabilitation or restoration of freeboard and embankments by mechanized equipment for animals. They allow vehicles and equipment to reach the top of the embankment and reduce haul distances. Slopes on ramps are limited to 10% (10 feet horizontal to 1-foot vertical). The ramp must be wide enough to safely handle the equipment; 10 feet would be a nominal dimension.

Ramps are not allowed to cut the embankment below the full supply level of the canal. A ramp cutting into an embankment effectively narrows it, thus

weakening it. On the dry side, the ramps can be left in place after construction. On the wet side, they will have to be removed.

SECTION 2 : INSIDE BERMS

A. General

A major problem in maintaining berms is the damage caused by water buffalo. Once the canals adapt to regime conditions, both sediment load and flow, the berms should remain relatively stable. Obviously, when discharges are increased for long periods of time (sanctioned or otherwise) the canal will re-adjust to the new flow conditions which could often include the erosion of berms.

Table II-2 presents recommended berm standards for various size canals. The recommended berm standards recognize the problems of maintenance of canals that are operated eleven or more months a year. It is anticipated that Killa-bushing will still be the main method of berm repair and maintenance.

B. Failure Modes

Mass failure is not a widespread problem in alluvial canals in Pakistan. Some slope failures have occurred, but many of them are explained by subsurface piping often due to inadequate surface and subsurface drainage. Erosion of sand layers unfortunately incorporated into berms or embankments (possibly during cleaning) have resulted in some wedge failures after sections have been undercut by erosion, see Figure IV-7. Erosion and retreat of berms is due not only to excessive increases in discharge but is often more attributed to wave action and disturbance of the berms by animals. Animals are thought to be the single greatest excuse of berm disturbance and erosion on all sizes of canals. As the berms retreat the original toe of the embankments can be exposed, whereupon erosion can accelerate dramatically with some embankment materials. This is particularly true with unconsolidated clayey-silty soils, see Figure IV-8.

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Soils typically used in canal embankment construction and in silt berm formation are at best moderately resistant to fluvial erosion. Most soils exhibit some cohesion and are resistant to normal canal design velocities. The root structure of plants growing on the silt berms contribute to the resistance of the berms to erosion.

Wave wash in irrigation canals does not have the same connotation as it does in rivers as the scale (size) of the waves is usually much smaller. Waves in canals are only a few inches high and are not necessarily continuous. Where bank material is stable these waves have little affect on particle movement but when the banks have poorly consolidated material or very sandy materials they have sufficient energy to move the soil particles. This becomes important when there are lenses of fine sandy materials in the canal berms or banks because with time some of this material will be displaced. When sufficient underlying material is displaced, the overlying soils become weaker and fail. The embankment materials exhibit very little cohesive strength, particularly in an unconsolidated condition. The sandy silts that compose much of the original embankment material do not consolidate very much with time as most clay soils will. Therefore, the voids and pore space left at the time the materials were dumped into the embankment still remain today. This is one reason seepage, raincuts, rat-holes, root channels, etc. lead to piping and failure.

The erosion problem may not occur unless the zone or layer of sandy material is exposed to erosive forces. Often this may only occur during filling and dewatering operations so that it can go on for long periods of time before sufficient material is removed that will cause a slip failure.

C. **Repair of Berms**

The repair of a canal berms in sediment laden water is usually accomplished using killa-bushing. The brush is placed in the eroded zone which causes a decrease in water velocity so that sediment accumulates behind and downstream of the eroded zone. Different patterns are used; 1)

longitudinal revetments, 2) cross spurs, 3) hanging spurs and 4) any combination of the first three. Longitudinal staking and bushing to construct a revetment is limited to depths up to about 4 feet. Above this, the cost increases rapidly. Figure IV-9 shows revetment type construction. Cross spurs are usually employed in channels of more than 4-foot depth and usually spaced about 10-12 feet apart. Hanging spurs are used in very large canals. Hanging spurs are usually trees to which more branches may be added plus weights to keep the trees from floating out of the eroded zone.

Berms should not be rebuilt on top of pervious bed sediments. Bed sediments should be removed from the toe of the embankment and replaced with other berm material. Figure IV-10 shows details of the correct procedure for rebuilding a berm overlying bed sediment.

In some cases, it would be possible to repair a berm during closure using the stair step method shown in Figure IV-1. This would work well for short reaches requiring considerable material replacement.

D. <u>Trimming Berms</u>

As berms are formed, they have a natural tendency to grow higher at the lip. When the lip appears to be too high it should be cut off and the material placed against the bank. The process is repeated over a period of years. Upon completion, the berm should be higher at the bank side by about 6 inches. This ensures that small changes in water level do not reach the bank. The raised bank of the berm tends to lessen the area where rats can burrow as well as keep water out of the rat holes thus, lessening the potential of a piping failure. The tendency for lips to build up is more prevalent in smaller than larger canals.

Berms will seldom have to be trimmed to widen a reach. Normally, reaches tend to widen and these may require killa-bushing. In reaches where berms are quickly replaced, the berm material could be excavated and used for freeboard restoration. Care must be taken not to endanger the embankment toe. Material is usually excavated by lowering the berm rather than

removing the face. When this is done, bars of earth should be left every 10 feet to facilitate new deposition. Depth of cut should be limited to about 1-foot.

E. Scour Control

Scour will generally occur downstream of structures where the velocity has increased. Eddy currents are formed with higher velocities acting against the bank material causing scour or erosion of the bank material. Lining the downstream reach for a distance up to 10 times the depth of flow is one solution. Riprap is another solution. Scour will also occur in curved reaches of a canal, particularly where the minimum radius of curvature has not been adhered to. Bank scour may still occur in very flat curves where the material is susceptible to erosion. Lining the bank is the recommended solution. Table III-5 contains guidelines for using riprap (also see Section 3.E.2, Chapter III).

SECTION 3 : PATROL ROADS

A. Introduction

The patrol road wearing surface is, in a sense, a drainage system. The wearing surface collects, transports, and disposes of surface water. Ideally, most of the rainfall water runs off a semi-permeable surface to a ditch or edge drainage system.

Patrol road, all weather wearing surfaces are not impermeable and water may enter by infiltration or through cracks. Surface water may infiltrate and saturate the subbase and subgrade. Other sources of moisture include canal seepage, high water table, capillary water, and flow from cut slopes.

Water within the subgrade may significantly reduce its supporting strength. Partial loss of subgrade support reduces the load-bearing capacity of the roadway, eventually leading to failure. Extensive rutting and pot holes are telltale signs of serious problems.

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Drainage cannot be overemphasized in road construction and maintenance. Water affects the entire serviceability of the road. Too much water in the base materials weakens the road. Water allowed to remain on top of a gravel or blacktopped road weakens the surface and, when combined with traffic, causes potholes, cracking and rutting. If improperly channeled, water causes soil erosion and breakdown of roadway edges. The heavier the vehicle load the bigger the problem, that is why commercial trucks must be kept off the patrol roads unless these roads are designed for heavy loads. Canal bank patrol roads are normally not designed for heavy roads; i.e., base and subbase courses and interval drainage are not included.

A good start is to become more aware of the importance of good drainage practices and the adverse effects of poor drainage, and to initiate positive actions to correct situations where inadequate drainage is evident.

B. Inspection

The first step in establishing a good drainage maintenance program is planning. Inspect all facilities and note ditches and drainage structures in need of maintenance. The best time to make inspections is during or soon after a heavy rain. Look for ditches that have silted, or filled up with other debris, have low spots and pond water, or that have severely eroded.

Check for damaged culverts that may have restrictions at or near the inlet or outlet. You may find silted flow lines and erosion problems in the cross drains, both upstream and downstream. Also check any other drainage structures.

After inspection, pinpoint problem areas on the project map, schematic diagrams of profile sheets by stationing and designate maintenance required. Work then should be scheduled in a manner to obtain the maximum use of personnel and equipment.

Building a good surface drainage system and maintaining it is the best way to lessen water's damaging influence on a road. A proper surface drainage system prevents water from infiltrating the wearing surface, and removes water in a constant thin sheet to the side or ditches which carry the water away from the roadway.

A surface drainage system has four basis components:

* The road crown or cross slope of the road surface allows water to run off to the side.
* Shoulders are an extension of the road surface for the continued flow of water to the side or ditches.
* Ditches are used to carry water away from the roadway. They need to be kept clean and protected from erosion. Water left in the ditch may leak back into the pavement foundation materials. Water collected and carried in the ditch has to be directed away from the roadway at frequent intervals, sometimes using culvert pipe.
* Culverts usually channel water from one side of the road and canal to the other, helping to control the flow of water.

C. Cross Slope Maintenance

Patrol roads are usually designed to have a single cross slope from one side to the other to minimize water from causing raincuts on the prism side. Non-patrol road bank tops are also sloped to the dry side but at a reduced slope. Where rainfall is not a major factor, roads could be crowned.

Maintaining a cross slope is very important for proper road drainage. Most gravel roads should have at least a 6-inch difference in elevation (slope = 0.04 ft/ft), but no general rule can be applied. The actual height of the cross slope is dependent upon local conditions, including frequency and severity of rain, quality (drainage) of gravel on the surface, and frequency of vehicle travel.

The best time to grade a road is right after a heavy rain. The water helps to loosen the gravel and make it easier to reshape.

The amount and kind of use a road receives will determine the frequency of grading required. For example, trucks carrying heavy loads flatten the slope and create ruts in which water ponds or travels parallel to canal before running off and causing a raincut. Vehicles which travel too fast blow away the light particles from the road surface and cause wash boarding. These roads require grading more often than roads receiving light traffic.

Roads should be graded to allow all surface water to drain perpendicular to the canal on to the grassed bank or into a roadside ditch. When grading care should be taken not to leave a ridge berm at the edge of the grader blade. This berm acts as a barrier, stopping water from flowing over the slopes. It may be the cause of serious damage in the future by concentrating water into raincuts.

D. Shoulders Maintenance

The shoulders are the additional width along the outside edge of the wearing surface. These will be grass-covered. The width will depend on canal size, expected traffic volume and passing requirements. The slope of the shoulder from the road edge to embankment foreslope must be equal or slightly greater than the road surface cross slope. This will allow for good drainage of surface water from the roadway. When reshaping the roadway, the shoulders should also be worked in the same manner.

E. Ditches Maintenance

Drain ditches are required in cut section to move excess rainfall to the end of the cut. They are normally sloped from the center towards each end. At the end of the cut section, the drainage ditch must be directed away from the toe of the canal embankment. This may require a lined section or drainage structures.

Under normal conditions the excess rainfall coming from the canal bank is allowed to enter the fields adjacent to the canal. Where this causes a drainage problem or where canal seepage causes water logging, a drainage ditch is constructed parallel to the canal to a natural drain or low area where the water can be wasted.

Roadside ditches should be built as an extension of the shoulder. A smooth transition gives a better appearance, a less steep slope, and is easier to clean with a grader. Ditches that can be cleaned with a grader are more economical to maintain.

Silted or clogged ditches cause the subgrade to retain water and lead to roadway distress. Severely eroded ditches should be corrected and lining such as sod, rock riprap, concrete or masonry should be used to minimize future erosion.

If eroded ditches remained uncorrected, the roadway might eventually be undermined. In places where ditches continually erode, ditch checks should be used. Ditch checks are small dams of wood, stone or concrete.

Three goals of ditching are cleaning, reshaping, and restoring the flowline of the ditch to the design grade (slope). Cleaning involves removal of all dirt, debris and unwanted vegetation to the original flowline. In reshaping, the ditch is shaped to its original cross-section. The cross-section should be shaped as uniformly as possible. If the ditch widens, the water velocity will decrease and deposit sediment and debris. If the ditch narrows, the velocity will increase and may cause erosion.

When scraping or cleaning ditches, attempt to leave some of the roots of vegetation for stability so that the plants can become re-established quickly.

In the event of erosion, such areas should be restored to original grade with large aggregate or other such materials that will not erode again. Sodding, seeding, or use of jute matting should be considered for some

areas. It is important to keep vegetation short so that it will not obstruct the flow of water.

Cleaning and reshaping ditches to their original flowline elevation usually requires removal of 6 to 10 in. of material. It may vary appreciably and will depend upon many factors. never excavate too deeply; as that could create problems rather than correct them.

F. **Culvert Maintenance**

A culvert should be strong enough to support the weight of the fill material above it as well as the other loads placed on it. It must be durable and have the hydraulic capacity to carry away a set amount of water in a given time. If the culvert is too small, flooding upstream of the culvert will result. If the culvert is too large, it may be unnecessarily expensive. Generally, however, a little insurance against the heavy storms can be obtained by installing oversized culvert pipe.

Culvert are normally designed to carry maximum anticipated quantities of water for areas in which they are constructed and are placed to take advantage of existing contours by placing the culvert in the existing channel. The gradients should provide a velocity of approximately 2½ ft per second to prevent the accumulation of sediments in pipes. Pipe culverts should have at least 12 in. of cover for sizes smaller than 24 in. in diameter and not less than one-half the diameter for larger sizes. Culverts other than pipe should have a minimum of 12 in. and preferably 18 in. of cover.

The capacity of culverts can often be improved by altering the entrance configuration. By simply beveling the edge of the inlet, capacity can be increased significantly. Additional increases in capacity can be obtained by having side-tapered inlets, and further improvement can be accomplished with slope-tapered inlets.

One of the major maintenance problems will be the clearance of sediment and trash from in front of the entrance. Trash guards may be required in

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locations where floating debris is a major problem. These will prevent material from clogging a culvert.

G. Rut and Pot Hole Maintenance

Most patrol roads on canal banks are not constructed with adequate base or subbase courses to support daily traffic of any kind. They are there to allow the canal to be inspected and provide access for maintenance equipment at least cost. Therefore, excessive use during wet weather or use by heavy load vehicles may cause rutting of creation of pot holes in soft spots.

Ruts and pot holes should be dewatered and back filled with compacted material. It may be necessary to excavate some of the loose wet material to allow a good bond with the new fill material. Soil placed in pot holes or ruts that have not been dewatered cannot be adequately compacted and will remain soft and unable to carry a load. The compacted backfill can be left slightly higher to allow for additional consolidation due to vehicle traffic.

Blading with a grader when conditions are wet as described above, will not solve the problem.

SECTION 4 : TREE AND BRUSH CONTROL

A. Background

The establishment of trees on canal embankments is an old custom that should be revised. Until the tree falls into the canal it does not affect the hydraulic performance and may strengthen the bank. Once the tree falls into the canal it causes siltation and scour in the canal prism. It also causes weakness and a shortened seepage path in the canal bank when the root mass rotates and carries soil in the resulting ball.

When trees die or are removed the decaying roots create a hazard and potential embankment failure. The rotted roots create potential seepage paths for water which combined with other voids and seepage paths could

result in piping. Piping is the movement of water through a void in the embankment such that it can carry soil particles and thus erode soil material.

On the other hand, trees provide the material for killa bushing and considerable shade for animals and people. There is no existing management policy governing silviculture rail tree and the economics of agro-forestry. The use of mechanical equipment can be severely curtailed by trees. This includes the equipment used in desilting the canal as well as that used to compact the canal's outside bank slope when canal banks are strengthened.

B. Guidelines for the Control

A discriminate tree control program should be implemented on reasonable judgement and practicality. The following guidelines should be considered in developing a tree and vegetative management control program.

(1) A program should be initiated to remove all large trees and old stumps. All tree stumps should be excavated and main roots grubbed out and the embankment replaced and compacted to prevent piping action and retard erosion. Trees over hanging the canal would be removed first.

(2) Trees and brush should be prevented from growing on the inside canal bank.

(3) Trees up to 4 inches in diameter would be allowed to grow on the outside canal bank only so long as compaction equipment is not used in restoring canal banks. Trees so located can not be used as an excuse not to compact soil on the embankment and would be removed for restoration.

(4) Trees could be grown as an agro-industry in the canal right-of-way to within 5 feet of the toe of the embankment. Size would be determined by economics and a harvesting-replanting cycle would be established.

(5) Killa-bushing requirements would be met by allowing the appropriate species to grow near the toe of the embankments as brush but under no circumstances would they be allowed to exceed

2 inches in diameter.

(6) All noxious weeds should be removed.

(7) Water buffalo should be kept off of canal banks except at regulated facilities.

(8) Oxen, goats and sheeps may be allowed to graze the banks but care must be exercised to prevent over grazing and loss of grass turf. Although these animals will drink from a canal they do not have a natural tendency to enter them. If grazing appears to increase the frequency of freeboard restoration etc, it should be curtailed.

SECTION 5 : ANIMAL CONTROL FACILITIES

A. Background

There is some question whether an illegal "ghat" is a structure or a destroyed canal bank. In this section a semi-permanent ghat will be discussed as an alternative method of reducing canal maintenance costs. It acknowledges that water buffalo can not be kept out of the canals and that the canals will continue to be used by farmers for various non-conforming practices including animal bathing.

The performance standards for canal maintenance on rehabilitated canals are much more stringent than those used in the past and their enforcement may be monitored to a much greater degree than in the past. Animal trespass has been a major cause of canal embankment deterioration when it has been confined to short reaches of a canal. This usually occurs near settlements and where local roads/trails intersect the canal and where no bridge has been located. The problem is expected to continue after rehabilitation as few improvements to the described conditions will be incorporated.

The performance standards state that freeboard must be restored as soon as 5 inches of material are eroded off the embankment crest. Under concentrations of animals with access being made several times a day, it may only require a few months to wear of freeboard to endanger the safety of the embankment. The process is illustrated in Figure IV-11.

B. Installing a Semi-permanent Ghat

A semi-permanent ghat is a widening of the canal embankment by flattening the slopes. Inspection of canal banks used by animals for access to canals indicates that they wear the slope back to 3H:1V or 4:1. It appears that most animals can negotiate an earth slope of 3:1 without excessive displacement of soil. Therefore, to reduce maintenance all that is required is to simply widen the embankments in the critical areas to accommodate these slopes and the top width.

A typical cross-section is shown in Figure IV-12. The top width has not been fixed.The minimum would be 5 feet based on Table II-2. It appears reasonable to expect that if it was widened to 10-12 feet, the wear and tear on the freeboard would be less and/or material would be available to be pulled up to keep the crest elevation seasonally. Obviously, the wider the section the more right-of-way or land area required to accommodate it. This can be a problem where farmers have encroached on the canal right-of-way.

Widening the canal embankment will require adjustments be made in embankment configuration both upstream and downstream of the selected location as shown in Figure IV-12 . The facility does not have to be constructed all at once but can be allowed to evolve as material is transported to the site to maintain the performance standards for rehabilitated canals. This would slowly push the location of the canal top away from the canal center line. Eventually things should stabilize so that a cross-section similar to that shown in Figure IV-12 will be obtained. It is doubtful that it would stabilize so that the erosion rate is only in inch per year but it may last 2 or 3 years and the amount of replacement material would only amount to a few trollies full. The best part would be a safe canal.

This solution would not be adaptable inside a built up area because encroachments of buildings would not allow the slopes to be developed and still maintain the canal top width. In this case, a permanent structure would be required or the location shifted.

To control access to the semi-permanent ghat it would be necessary to construct pucca brick walls 2½ to 3 feet high to guide the animals and to keep them off the normal canal embankment sections.

TABLE IV-1

ROUTINE MAINTENANCE PROCEDURES

Item	Procedure
1. Remove Fallen Trees from Canal.	The tree must be removed as soon as possible to limit scour damage to berm/bank. As many limbs as possible should be cutoff and removed to lighten the tree. A tractor with a chain a steel cable can be used to pull the tree up. Start near the top with the cable as the load will be lighter. As the tree comes out of the water, additional branch can be removed. Once the trunk is out and on the berm it can be cut up and removed.
2. Killa-bush Berm Repair	Killa-bush spurs can be placed 10 to 12 feet apart along reaches that require additional berm. In severe cases parallel revetment with branch laid behind it can be constructed.
3. Raincut Repair	Raincuts must be dug out and then the replacement material compacted in place. A hand tamper can be used. Soil material must be moistened before it is placed to obtain good compaction.
4. Rain-hole Filling and Repair	The rain hole must be fully opened up, cleaned and back filled with compacted material. A hand tamper can be used. The soil must be moistened as it is mixed and placed.
5. Freeboard/Cattle Cut Repair	Same procedures as for raincuts or rain hole repair.
6. Vegetation Control	Oxen and goats will keep grass cut. New brush or tree growth must be cut off at ground level with a machete or other implement.
7. Sodding Bare Spots	At the beginning of the monsoon season large bare spots on the embankment should sprigged or sodded with a drought resistant spreading type grass.

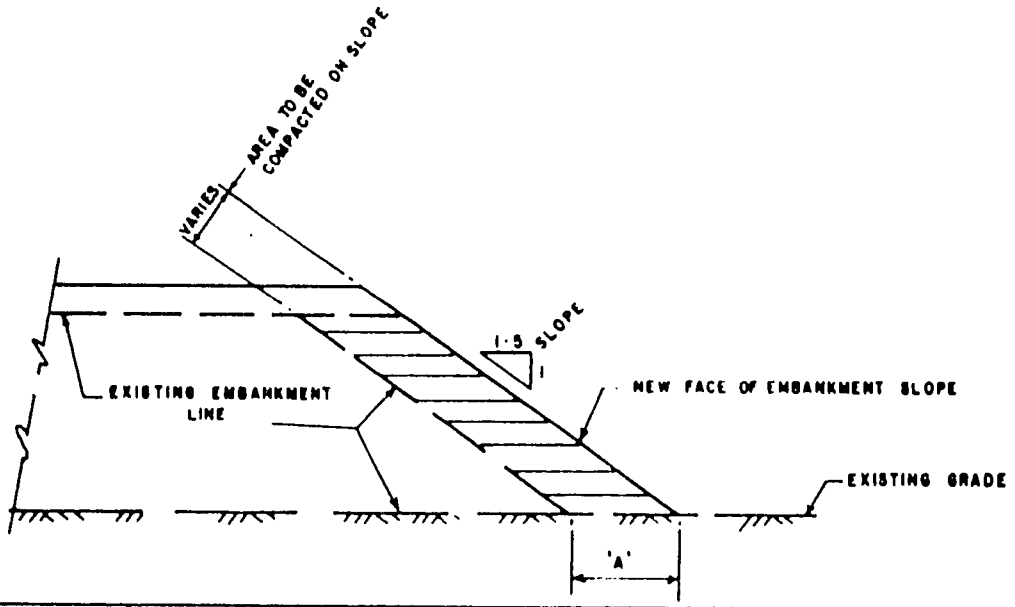
TABLE IV-1
ROUTINE MAINTENANCE PROCEDURES
(Continued)

8.	Blow Sand Control	Fencing made of small vertical bamboo or reeds woven together and stood vertically will retard drifting sand. Post spaced about 12-feet apart buried 3-feet in the ground with a wire strung near the top of the post to hold up the woven fencing. The fence should be located about 100 feet on windward side of canal.
9.	Temporary Repair of Piping Around Structures	Piping around an outlet can be temporarily stopped by rodding or tamping material along the edge of the structure to reduce or close the opening through which water is moving. Additional earth may be required to help fill the void. Complete repair must be made during closure.
10.	Pothole Repair	Pothole and ruts can form in the patrol road in wet weather. These must be filled with compacted soil or base course material. Hand tampers will work.
11.	Remove Floating Trash From Infront of Structure	A long handled rake can be used to help pull trash out of the canal.

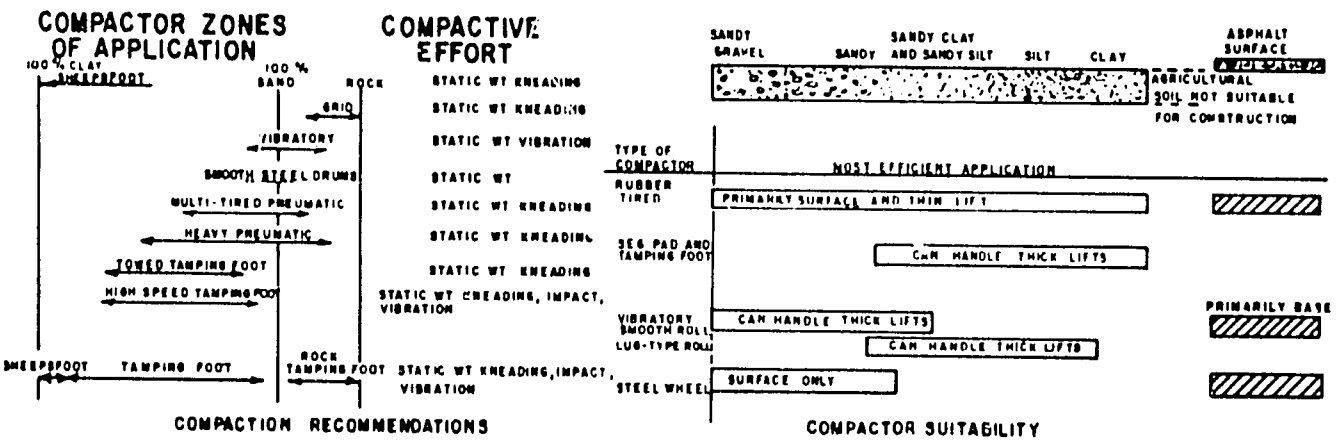
TABLE IV-2

TIPS ON MAINTAINING GRAVEL ROADS

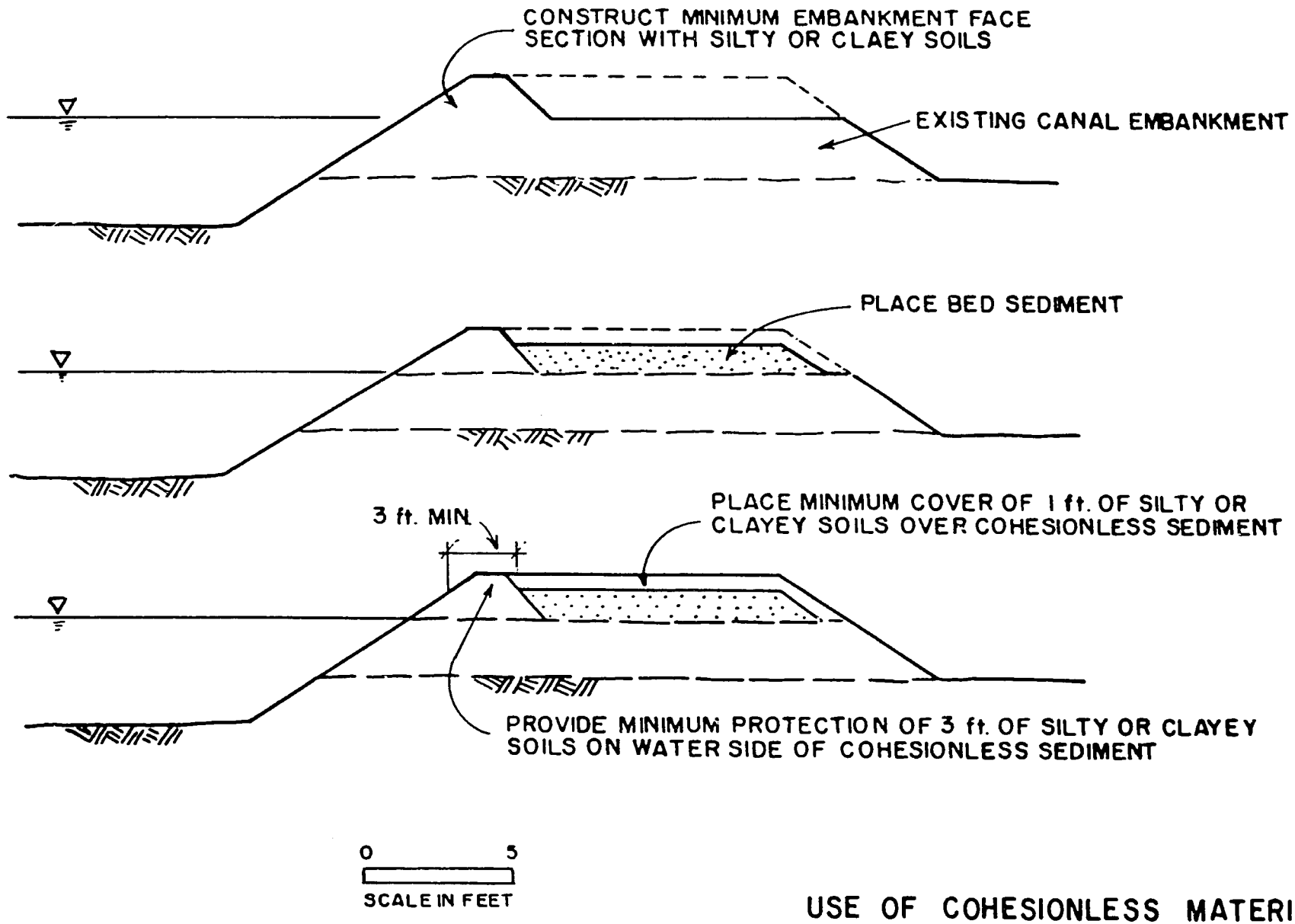
* Work gravel surfaces when moist or after a rain.
* Most washouts occur because of improper drainage.
* Avoid a double ditch. Leaving a furrow in the travelled way will keep water on the road. Smooth the surface to the embankment line. Grade from the outside to the center when forming or crown.
* Layers of gravel should be at least twice the thickness of the largest stone size. If you put on a 6-in. gravel course, the largest stone should be 3 inches.
* A key to maintaining problem wash-board areas and achieving a tight, strong surface is to use high-quality crushed gravel. Also check soil quality in the base as well as the need for under drainage.
* In wet season use quality gravel instead of sand to correct problem wet areas.
* Rather than disturb the entire road-way to correct occasional potholes on an otherwise sound gravel surface, patch them with a 50/50 mixture of crushed gravel and calcium chloride, sprinkle with water and tamp.
* Establish a schedule for periodic inspection and resurfacing of all gravel roads.



DIMENSION 'A'	TYPE OF EQUIPMENT TO BE USED	REMARKS
0 — 2'-0"	WINCH ON DOZER PULLING VIBRATING TAMPING ROLLER	OPERATES ⊥ TO SLOPE OR CAN USE VIB. TAMPER HAND HELD OR BOTH
2'-0" — 3'-0"	HAND HELD IMPACT TYPE COMPACTOR	OPERATES IN LIFTS 6" TO 8" ± (LIGHT WEIGHT)
3'-0" — 4'-0"	SELF PROPELLED TAMPING ROLLER	MAXIMUM WIDTH ROLLER 2'-9" PAD TYPE - IN 8" LIFTS
ABOVE 4'-0"	VIBRATORY TAMPING ROLLER SELF PROPELLED	MAXIMUM WIDTH ROLLER 3'-9" ± COMPACT IN 8" TO 10" LIFTS



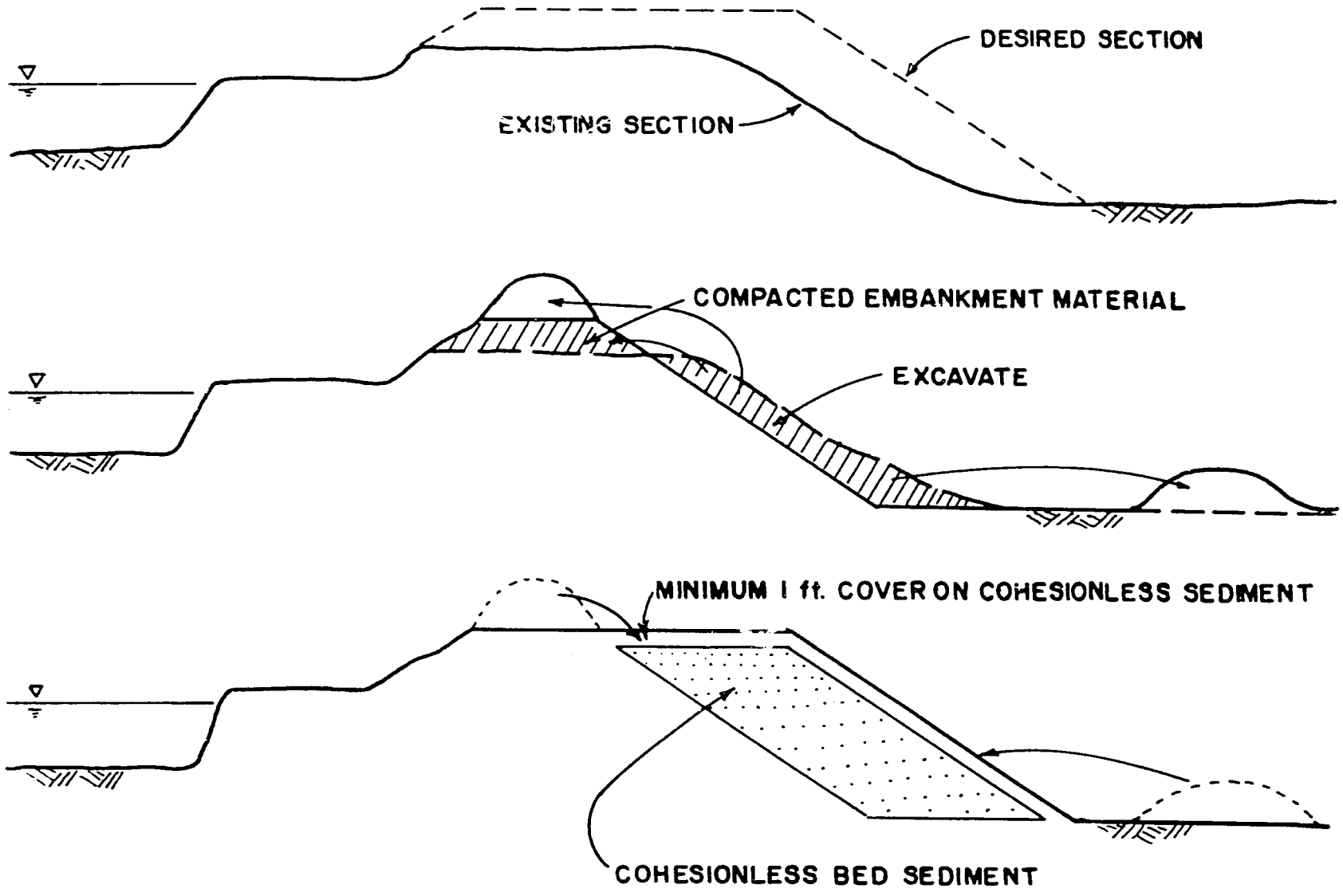
COMPACTION EQUIPMENT & WORKING REQUIREMENTS ON STEEP SLOPES



USE OF COHESIONLESS MATERIAL ON TOP OF CANAL EMBANKMENT

PRC ENGINEERING/CHECCHI

FIGURE IV-2

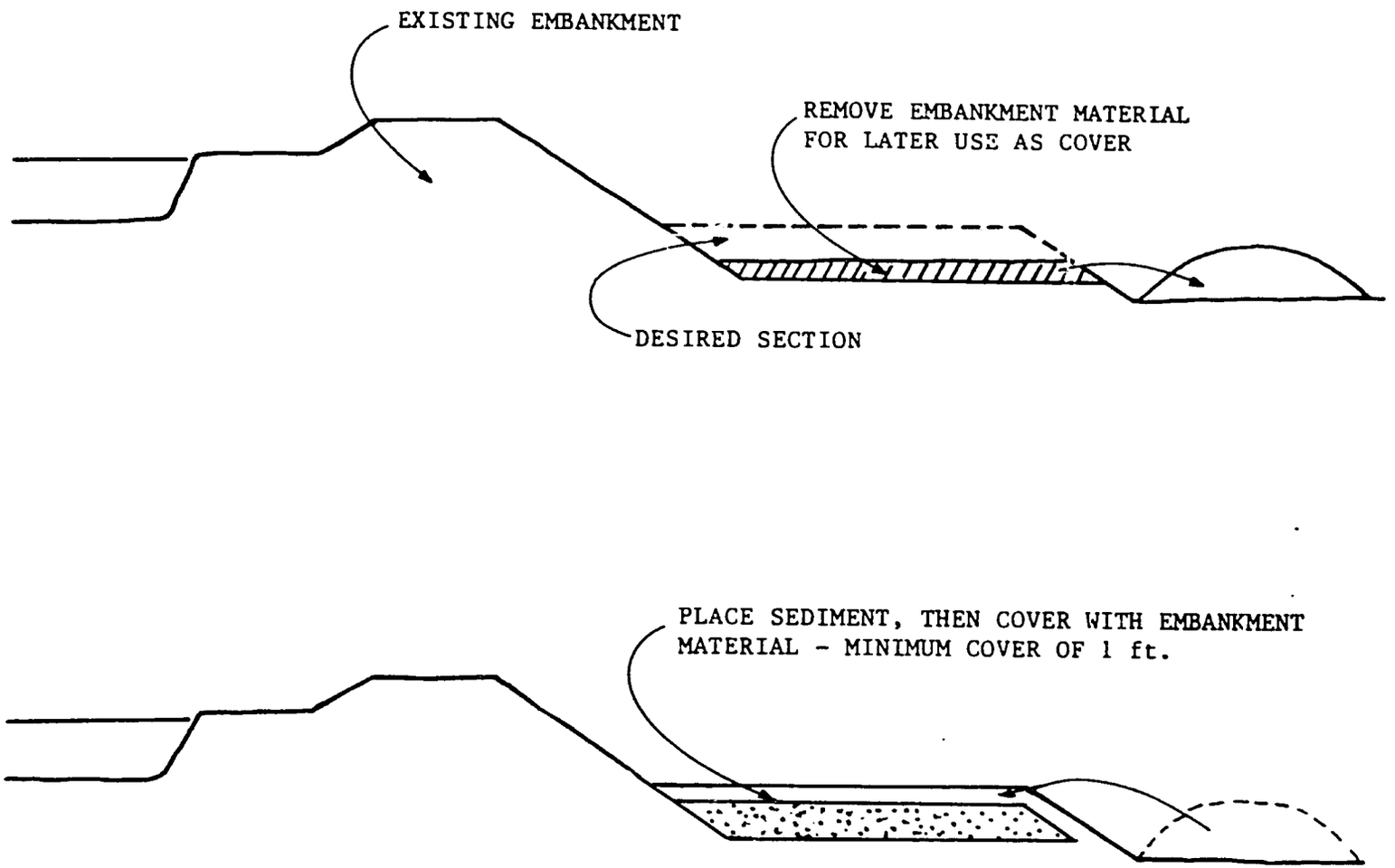


0 5
SCALE IN FEET

WIDENING CANAL EMBANKMENT
WITH BED SEDIMENT

PRC ENGINEERING/CHECCHI

FIGURE IV-3

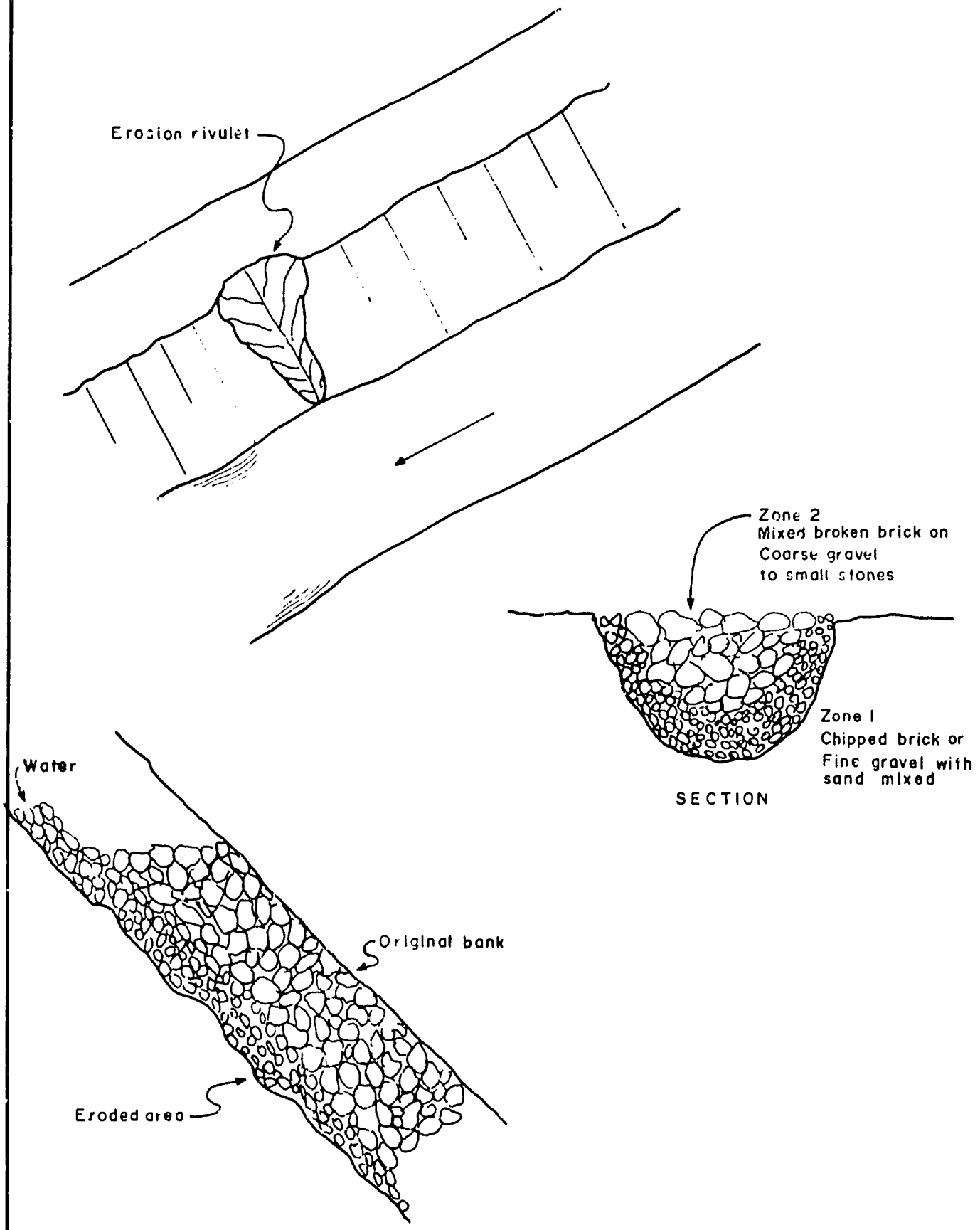


0 5
SCALE IN FEET

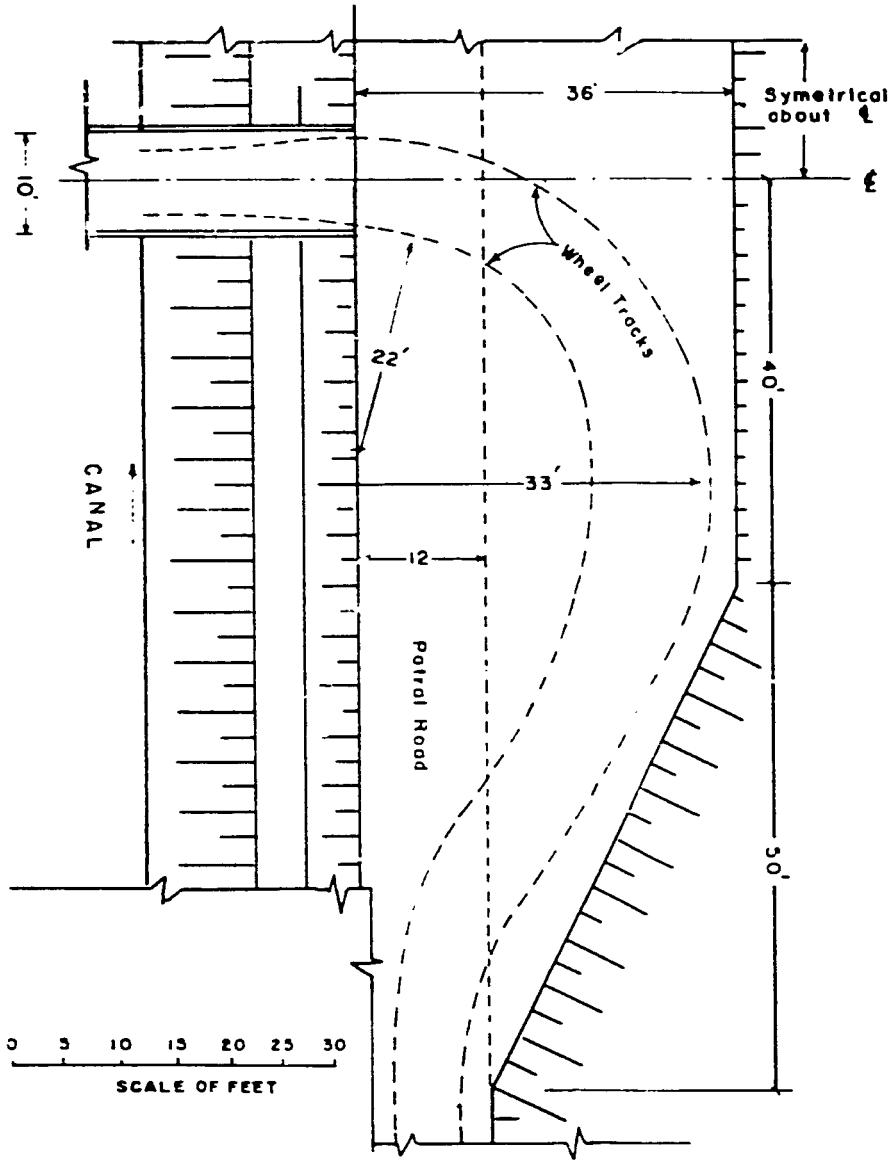
UTILIZING BED SEDIMENT
TO RAISE INSPECTION ROAD

PRC ENGINEERING/CHECCHI

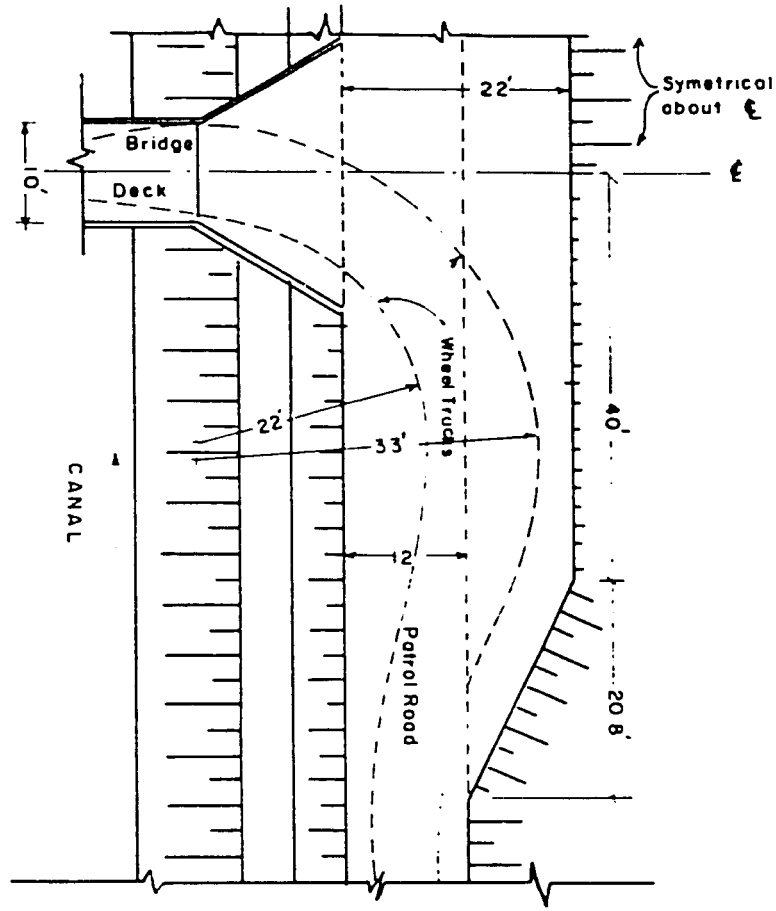
FIGURE IV - 4



REPAIR OF EROSION RIVULETS
ON CANAL BANKS USING
FRENCH DRAIN



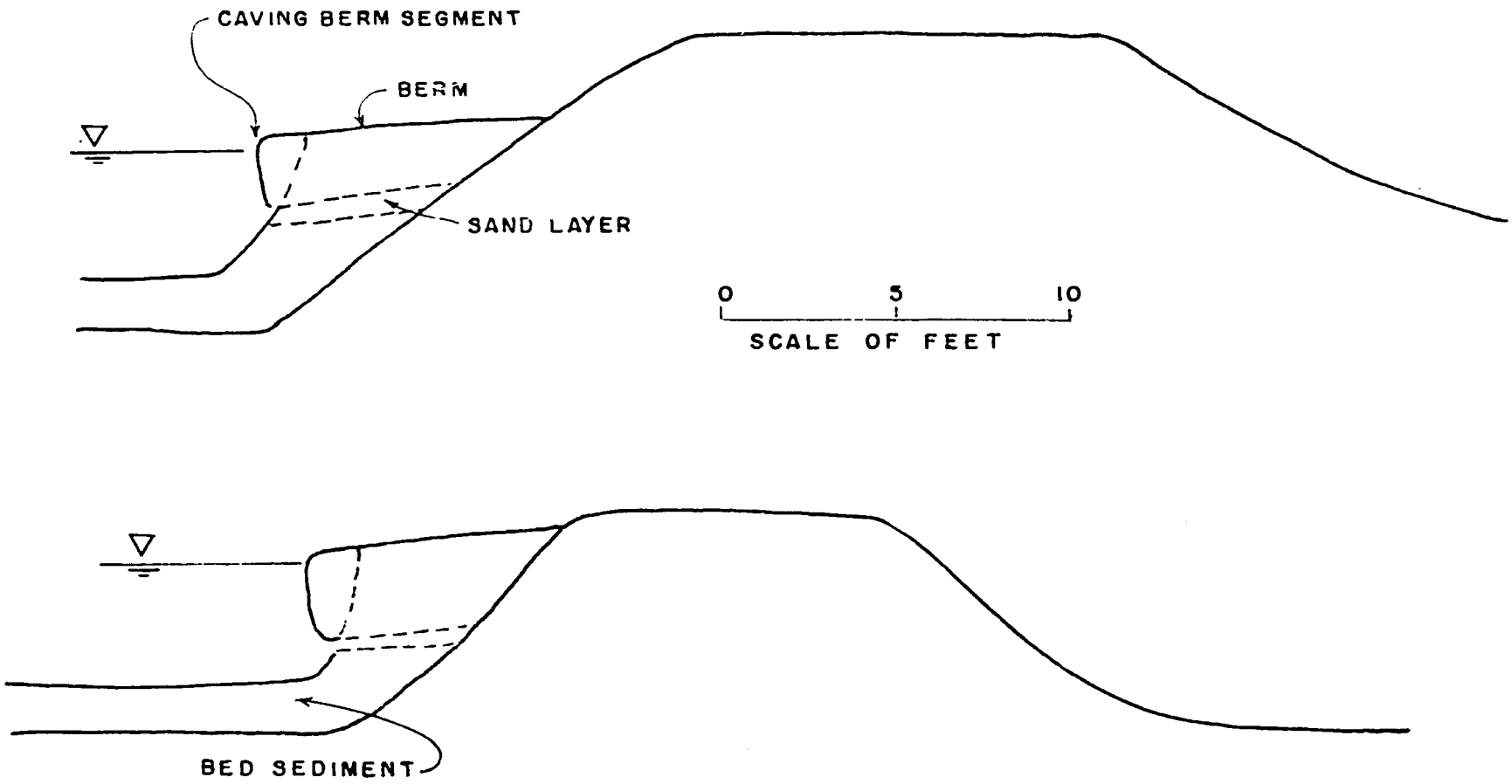
CASE A



CASE B

WIDENING EMBANKMENT
FOR BRIDGE ACCESS

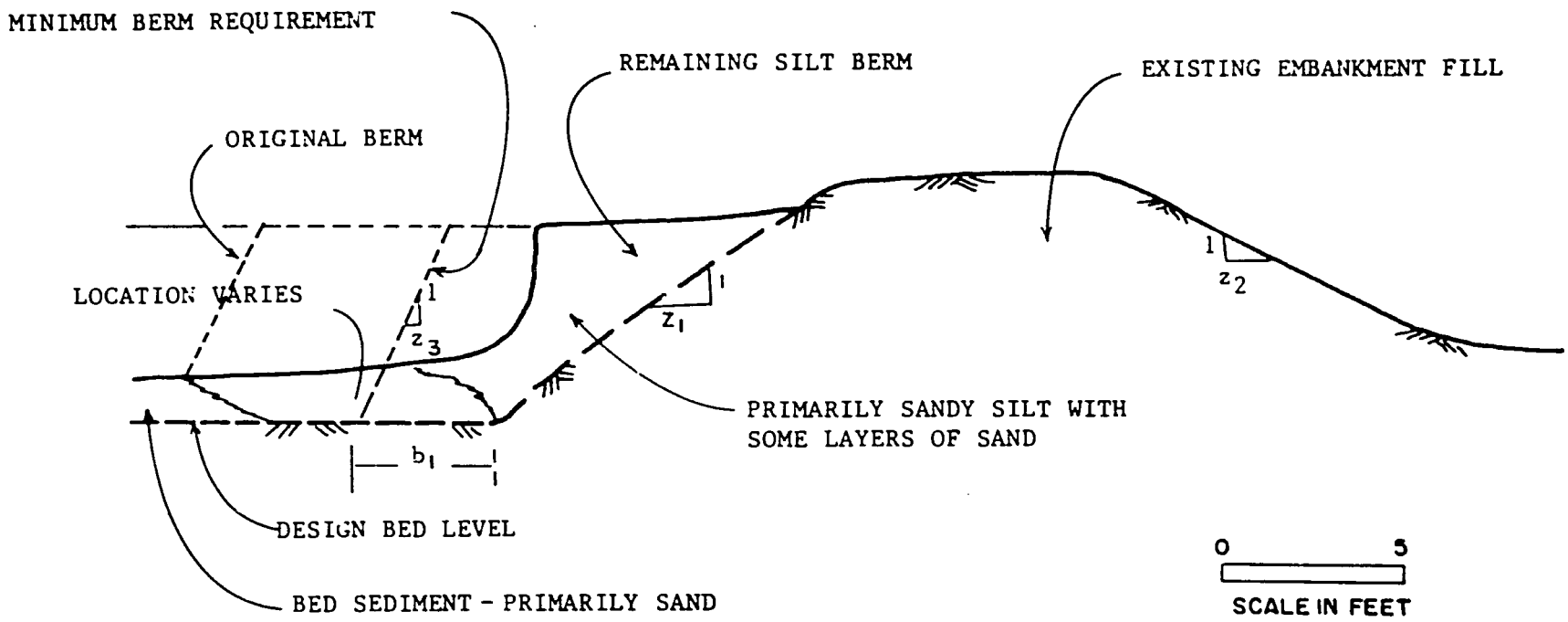
FIGURE IV-6



EROSION OF SAND LAYERS

PRC ENGINEERING/CHECCHI

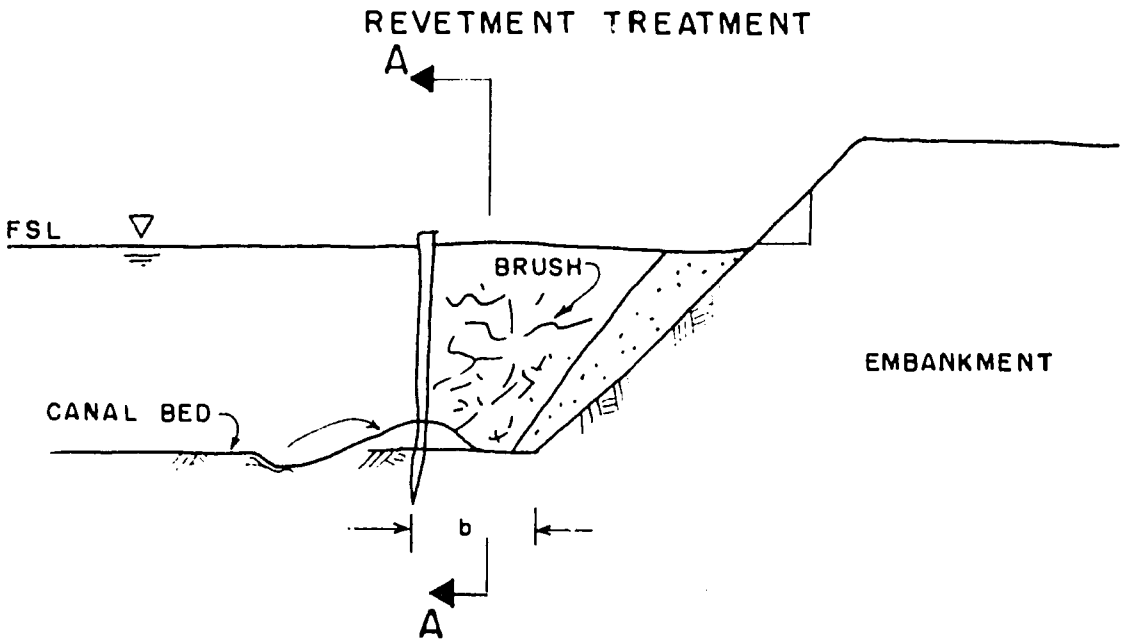
FIGURE IV-

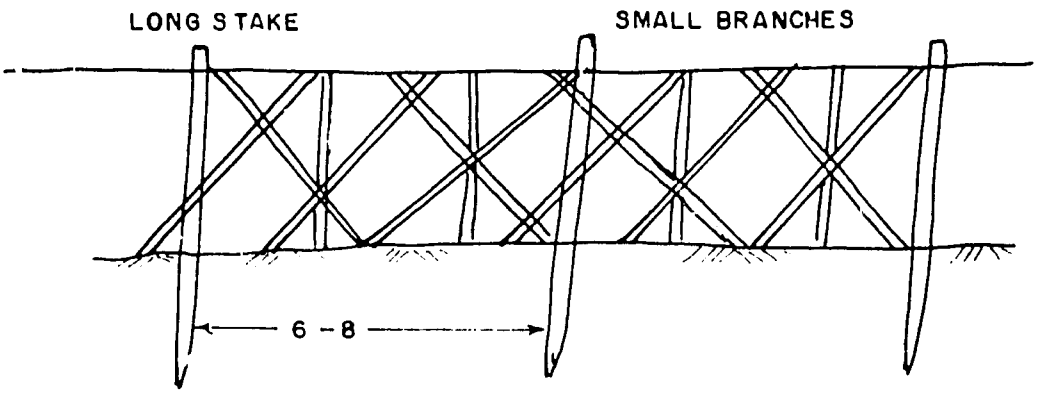


TYPICAL SEDIMENT DEPOSITION
AND BERM EROSION

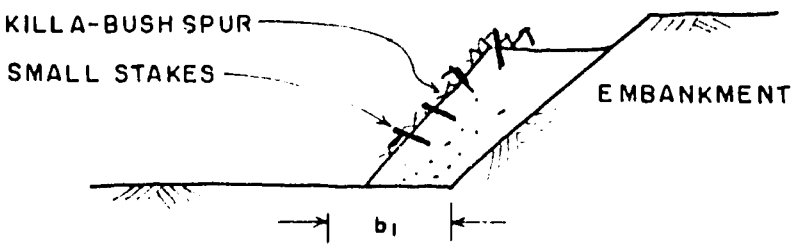
PRC ENGINEERING/CHECCHI

FIGURE IV-8



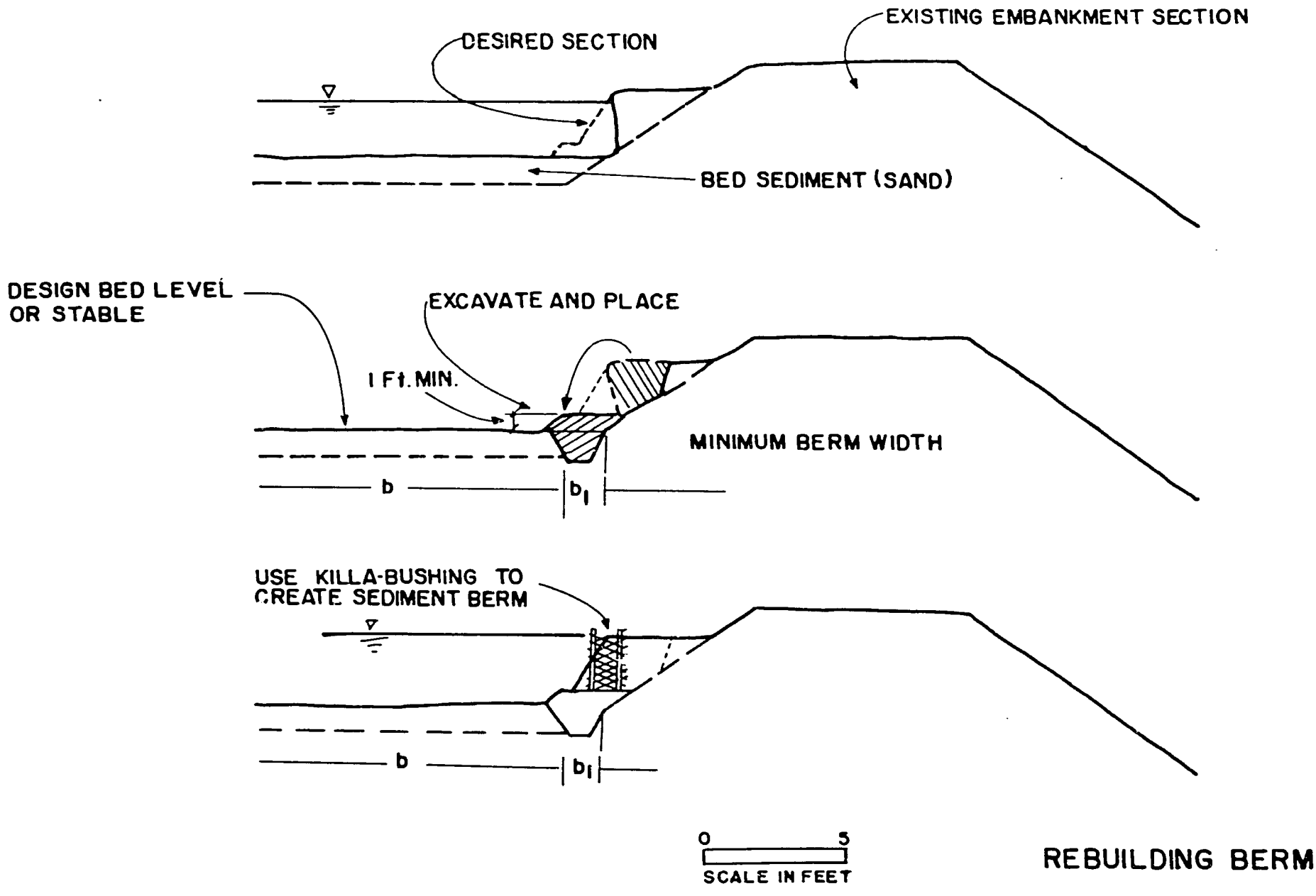


SECTION A-A



SPUR TREATMENT
SPURS 10-12 FEET ON ℄

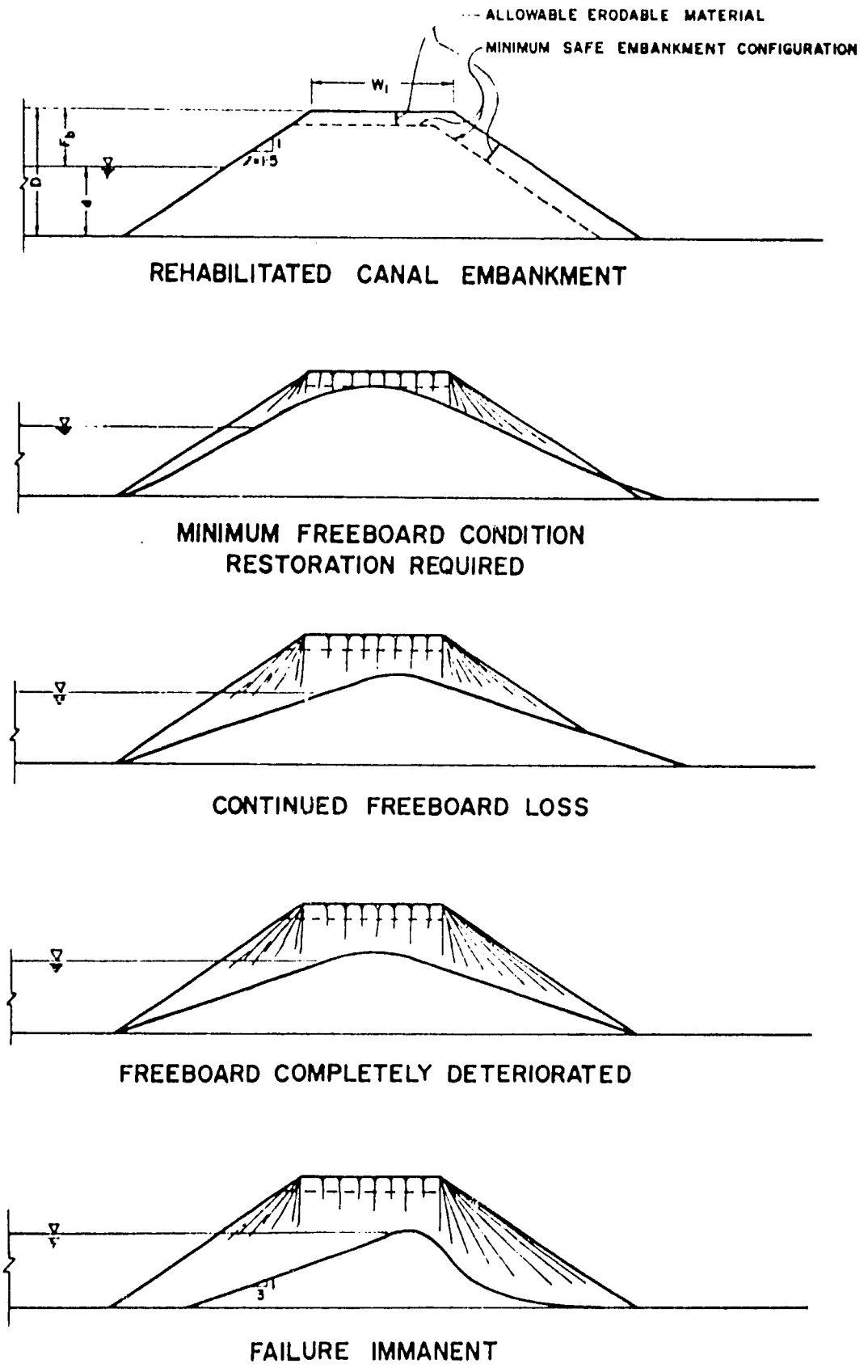
KILLA-BUSHING TECHNIQUE



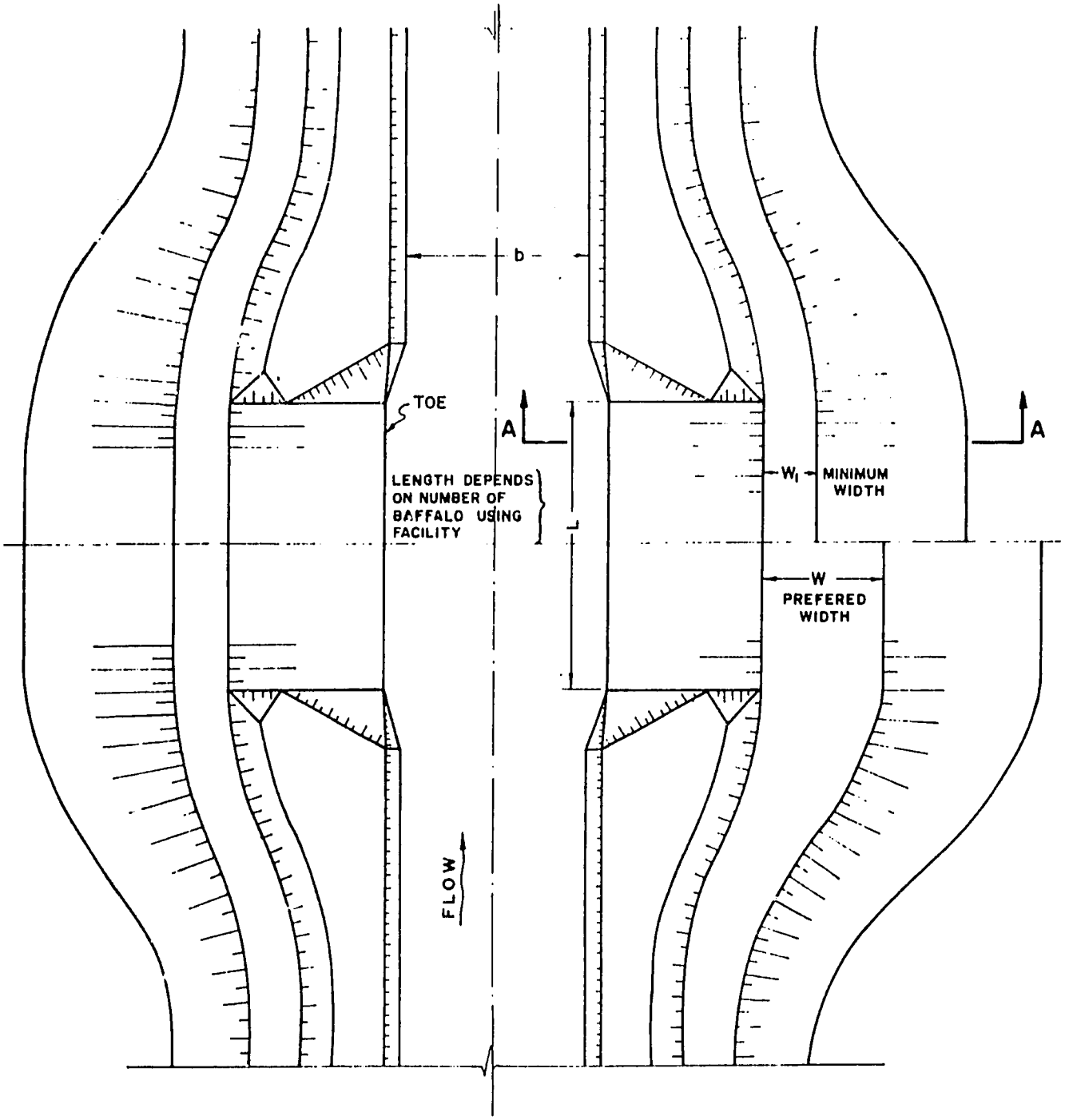
REBUILDING BERM

PRC ENGINEERING/CHECCHI

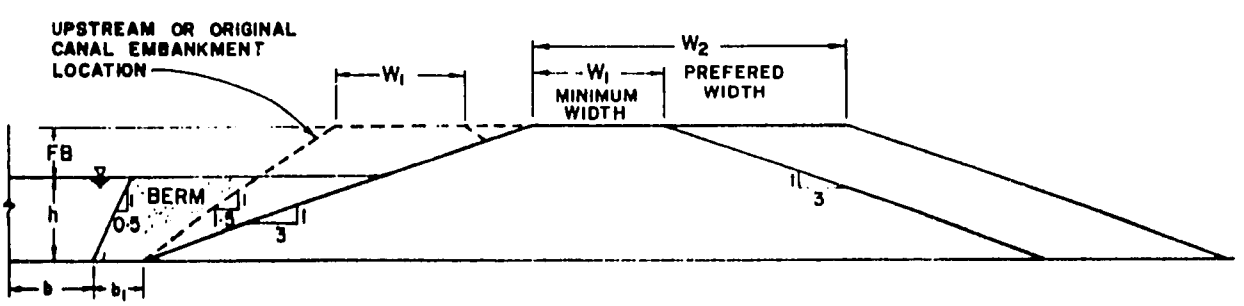
FIGURE IV-10



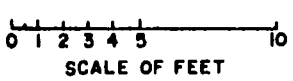
DETERIORATION OF CANAL BANK DUE TO CONCENTRATED CATTLE CROSSINGS



PLAN



SECTION A-A



SEMI-PERMENET GHAT OR CANAL CROSSING

CHAPTER V

HYDRAULIC SECTION MAINTENANCE

CHAPTER V

HYDRAULIC SECTION MAINTENANCE

The primary criteria for maintaining the hydraulic section is timely desilting. Efforts should be directed towards the prompt removal of fallen trees and floating trash. Trash will collect at headworks or inlets to distributary or minor canals. Once removed and dried, it can be burned.

A. Debris Collection

Figure V-1 shows a floating cable system that will allow floating weeds to bypass inlets to small minors. Also shown is a narrow, long tinned rake that can be fitted with a long handle. The rake is used to pull or fish floating weeds and trash out of the canals. A floating boom arrangement can also be strung across a canal at an angle so that the majority of the floating debris collects against one bank and facilitates the cleaning operation. This would be advantages in front of a cross regulator.

B. Desilting

An important hydraulic consideration of a channel is that the water level attained during operation remains close to the designed conditions. Changes in water surface elevations (levels) is very closely related to silt movements. The flow conditions in the river at head of a canal may be such that large quantities of silt are inducted into the canal. These initially tend to deposit in the upper reaches of the canal. Subsequently river conditions may change, or in winter when clear water enters the canal, this silt is picked up and gradually carried down the canal into the distributaries. Distributary head regulators are of various designs, some are silt selective, others take a proper share of silt, others are so designed either intentionally or unintentionally as to take large quantities of silt. The silt drawing capacity of different types of outlets on a distributary, also varies considerably. Thus, a change in any of these factors, upsets the silt equilibrium of a channel, and this leads to the deposition of silt, with the consequent rise in the bed of the channel and of the water level. Since all the watercourse outlets are

designed to take their authorized share at the design water levels any changes in upstream water levels can cause the nonequitable distribution of water to downstream locations.

Desilting will be required as soon as the canal cannot meet the performance standards given in Table II-1 and shown in Figure II-1. This normally would occur with a silt deposit of 9 to 12 inches depending on the design depth. In no case would the water surface be allowed to rise above 6 to 9 inches for distributary or minor canals depending on whether the design depth of flow as more or less than 2.5 feet. A second criteria must also be observed in that the canal must always be able to pass the design discharge. In other words, it is not permissible to maintain the canal water surface at 9 inches (0.5 f_b) and reduce the flow thus allowing the canal to continue to silt up.

Desilting will generally be confined to the smaller channels. Ramps should be constructed inside the wetted perimeter although some cutting of berm could be allowed. Under no circumstances should the embankment be cut by a ramp. Manual labor can use a steeper ramp than a vehicle or donkey.

The disposal of the excavated bed sediment may pose a problem when right-of-way is limited. The bed sediment must be kept off of the top of the embankment unless handled as shown in Figure IV-2(see Section 1.D, Chapter IV). The bed load sediment material is mostly comprised of fine sand at the head end of canals. Only at the tail ends will the deposited material contain significant silt mixed with the fine sand.

Where embankment erosion is a problem, bed sediment must be handled as in Figure IV-3. If the bank top width exceeds the minimum, it may be dumped over the dry embankment slope and spread out. Since embankment dimensions are more than the required, it would be permissible to dump without clearing and grubbing. Simple clearing and burning should suffice. Under no circumstances should any spoil material be left on the wet side of the embankment. If necessary, it should be doubled handled on the small canals where it is thrown up on the bank by hand. Also, no spoil material should

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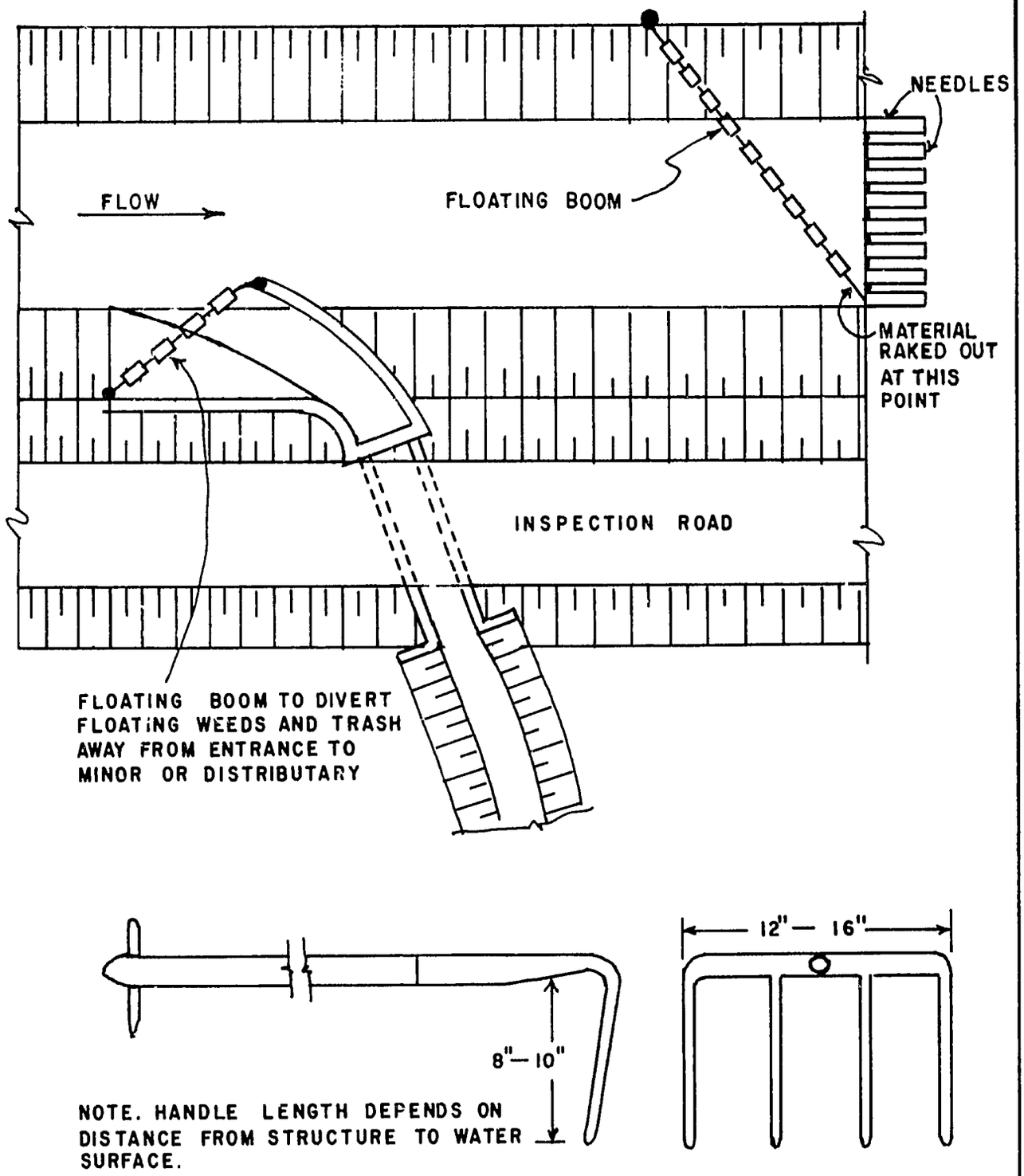
be left on the dry slope above the embankment lip that could form or curb.

Efforts should be made to sod the excavated bed sediment deposited on the embankment slope. This will prove to be difficult because there will be limited soil moisture retention in the bed sediment material to grow grass or other plant material let alone the unfertile status of this sediment. Bed material will erode and it is doubtful, compaction would help unless confined as shown in Figure IV-3.

C. Routine Maintenance

Routine maintenance with regard to the hydraulic section is mostly trash removal. Table IV-1 indicates the other routine maintenance items such as removal of trees which fall into the canal.



FLOATING WEED CONTROL

CHAPTER VI

MONITORING AND MAINTENANCE REPORTS

CHAPTER VI

MONITORING AND MAINTENANCE REPORTS

A. Introduction

Maintaining an irrigation canal in a structurally sound and functional condition can only be accomplished by repair and replacement throughout its life. A monitoring program is usually initiated to review current inspection findings, comparisons with previous examinations, evaluate conditions and provide recommendations and guidance in planning future maintenance efforts.

In order to ensure performance standards are being met and to make comparisons, a standard must be established that will allow rapid year to year comparisons of conditions along the canal. The easiest method is to compare long-sections and cross-sections taken at the same point year after year. This is an improvement over visual field inspection because the changes in the canal are plotted and not left to memory or individual impressions.

The immediate response is that the surveying and plotting of the required information require people and time which equates to costs. Therefore, a compromise must be worked out that will provide the required information yet be cost effective. The conditions on individual canals can vary significantly. Thus, a standard criteria might not be cost effective and the monitoring program might require adjustments to fit each canal. Obviously those canals which will require sediment traps will behave differently than those without.

The preparation of construction drawings and tender documents for rehabilitation would be based on cross-sections taken every 500 feet (0.5 RD) and the resulting long-section. In addition, cross-sections would be taken at all turnouts (moghas), bridges and water control structures. This would provide the basis for comparison of what happens after construction has been completed and the canal is placed back in operation.

Monitoring programs could be established for intensive and normal conditions. Intensive might be used for a period of two or three years to determine trends and locate potential problem points or reaches. A normal program would provide the minimum number of check or reference points required. The requirements for these two levels of monitoring are provided herein.

B. Monitoring Program Record Requirements

The comparison of what occurs in a canal from year to year as well as compliance with the performance standards defined in Chapter II depends on accurate surveys. The individual monitoring program is then based on the intensity of the surveyed cross-sections required.

1. Survey Requirements

The survey requirements are based on standard PID requirements. This requires that all surveys be closed on the original bench mark. To facilitate annual work permanent bench marks should be established at each head regulator on a rehabilitated canal. A standard metal disk with the proper designation and elevation stamped on it should be used. Similarly, reduced levels should be established on each outlet structure. These will allow the simplified water level measurement program to be carried out, help with H Register records and provide quick cross-checks on field conditions.

The use of computers in the design of canals would include the preparation of cross-sections and long-sections. The survey requirements for that work and monitoring are essentially the same. In fact, if the designs are computerized, then the monitoring could use the same program to print the design section and subsequent sections taken each year.

Figure VI-1 presents the basic survey requirements. It is important that the first cross-section "CXI" be taken just downstream of the head regulator as it reflects the water surface at this location. Points A through Q are the minimum number required to define the section. Addition points should be taken to show all variations in the ground levels,

embankment configuration and canal configuration. It is also important to measure the distances from the centerline of the canal to each right-of-way limit. The cross-section should indicate the structure by name.

When cross-sections are taken at canal outlets, additional points should be surveyed as shown in Figure VI-2. This data would assist in the monitoring of equitable distribution of water to the watercourse and in determining if it has modular flow conditions. When surveyed in the dry, the surveyor will have to estimate the position of the water surface at points U, V and W.

2. Program Record Requirements

As indicated above, one method would be to prepare individual cross-sections and then plot each year's data on them. This would provide a quick visual check on what has occurred. The reduced level at each structure would be checked to ensure that survey errors are not introduced. This type of record is limited to about 5 years, otherwise it becomes too cluttered.

A digital method of keeping records is shown in Exhibit VI-1. The method is adopted to hand entries or computerized at a later time.

Long-sections can be plotted from either set of cross-section data to obtain a record of what occurs along the canal bed and the top of the embankments. Initial plotting would show design bed level, FSL, minimum freeboard, rehabilitated freeboard and current right and left bank levels.

C. Intensive Monitoring Program Requirements

Surveys would be conducted annually during the closure period in conjunction with canal inspection. Sections would be taken at 0.5 RD intervals, at each turnout and where canal bed or embankment conditions appear to deviate from the average or normal. Deviations would normally be low spots in the canal embankment caused by animal trespass, bank erosion or other causes. Similarly, canal bed deviations would be locations of excess sedimentation and scour. Irregularities in the bed level are seldom

obvious because they are not abrupt.

The data would be entered into the cross-section records and long-sections prepared as required. Evaluation of the record must be made by the SDO and kept on file. Changes in operations may be required.

D. Normal Monitoring Program Requirements

The design of canals is based on uniform conditions within given reaches; i.e., bed width, discharge, depth are kept constant. Therefore, a minimum monitoring program would be one that would monitor conditions at these points. It should be noted that these points tend to concentrate towards the tail end of a canal which is where sedimentation might occur and where maintenance tends to be minimal. Changes in the design section are normally located at water control structures and outlets. Exhibit VI-2 provides additional forms that can be used in monitoring conditions in the canal.

Cross-sections located at the design points would provide adequate monitoring of the canal. Known problem points or locations could easily be added to the basic minimum. These control points would not provide information on the condition of the embankments or canal prism. The water level monitoring, used in the operation of the canal should indicate if and where sedimentation is taking place due to changes in the water surface levels. Where the canal officers are conscientious, regular inspections would suffice for monitoring the canal prism.

The canal embankment presents a different problem in maintaining freeboard as the loss of 5 inches is difficult to observe. The performance standard limits minimum loss of freeboard to 5 inches. Therefore, it is recommended that an annual canal embankment survey be made along the crest. A running level should be made along the crest of the right bank down the canal to include general elevation as well as high and low spots plus a tie to each outlet. Where low spots extend along the crest more than 5 feet both ends should be located. The left bank is similarly surveyed on the return to the headworks. The results are plotted on a long-section. Any surveyed point located below the minimum freeboard will be immediately obvious.

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E. **Maintenance Records**

All maintenance records will be kept on file at the SDO's office. This would include the monitoring records described above as well as copies of all inspection reports, work orders, written instructions etc. Records on all contracts performed on a canal will be filed including the quantities of all materials used as well as cost.

Exhibit II-1 provides copies of inspection and other forms that are related to maintenance functions.

EXHIBIT VI-1

EMBANKMENT AND SEDIMENT MONITORING

Canal Name:_____ Division:_____

Design Discharge:_____ Sub Division:_____

Location RD_____

Structure/Name:_____

Average Sediment Concentration_____

Year	Ave. Max Q Cfs	Item	Point B (Ft)	Point C (Ft)			Point O (Ft)	Point P (Ft)
		Design Dist						
		Design Elev.						
		As built Dist.						
		As built Elev.						
		Meas. Dist						
		Meas. Elev.						
		Change Dist.						
		Change Elev.						

FLOW MONITORING
CONTROL POINTS

Canal: _____ Div. _____

Discharge: _____ Sub Division _____

_____ Date _____

Downstream W.S. elev. _____ Sub Engr _____

Control Points				Current Situation				
Reach RD No.	Structure Data No.	Dir	RL	Dist. to W.S. (d) (in) (ft)	W.S. Elev	Stage ft	Est. Q cfs	Control Q cfs

W.S. = Water Surface

Q = Discharge

d = Distance from Reduced Level to Canal Water Surface.

LONG TERM FLOW MONITORING RECORD

Canal Name _____

Structure/Control point _____

Design dicharge _____

Calibrated Water Surface Level _____

Location (RD) _____

Reduced level _____

Division _____

Subdivision _____

Date of last Q Calibration _____

Date	Dist. to W.S. (d) (inch) (ft)	W.S. Elev. (ft)	Stage (ft)	Est. Q cfs	Control Q cfs

W.S. = Water Surface

Q = Discharge

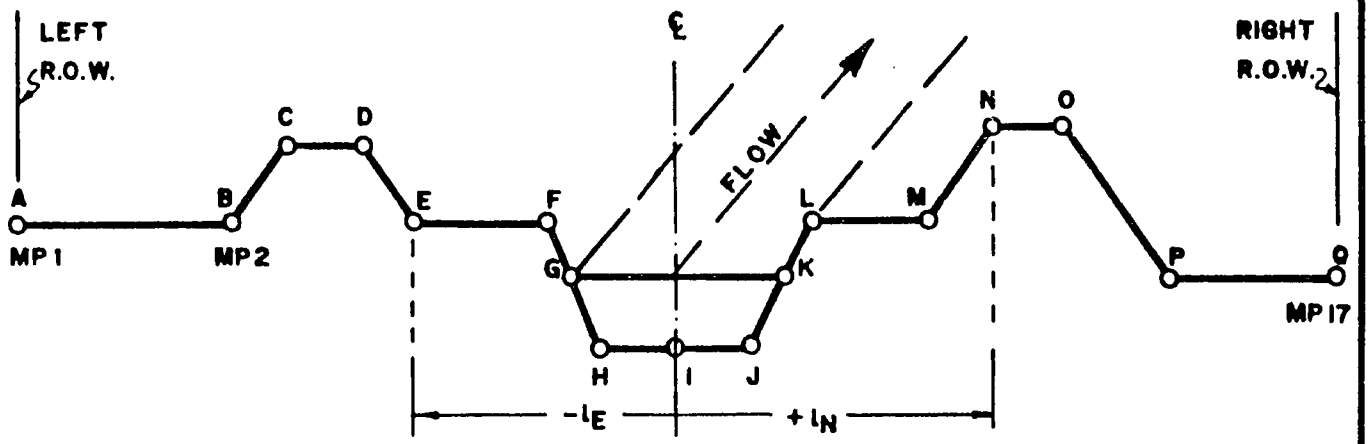
d = Distance from Reduced Level to Canal Water Surface.

Name of Canal: _____
Discharge: _____
Date: _____

OUTLETS FLOW MONITORING

Outlets		Sanctioned dimension etc					Canal Side							Watercourse Side						Measured width		Discharge Q cfs
No.	Dir.	RD	RL	Type	Sanc crest elv	Sanc width	Dist. to W.S.		Canal W.S. Elev.	Dist to crest		Crest elev	Head	Dist.to U.S.W.S.		Dist to w.c. W.S.		Depth of flow	Head Loss			
							in	ft		in	ft		ft	in	ft	in	ft	ft	ft	in	ft	

EXHIBIT VI-2
Page 3 of 3

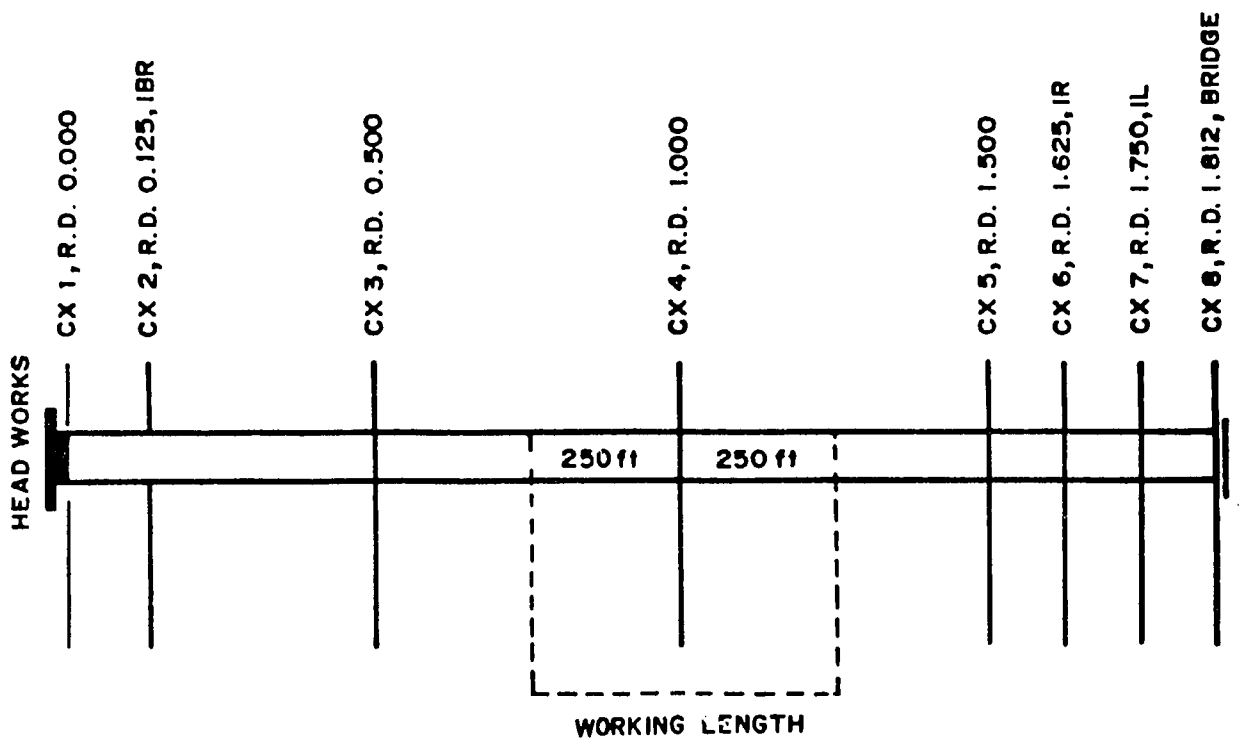


In each point A upto Q one number and two values are measured:

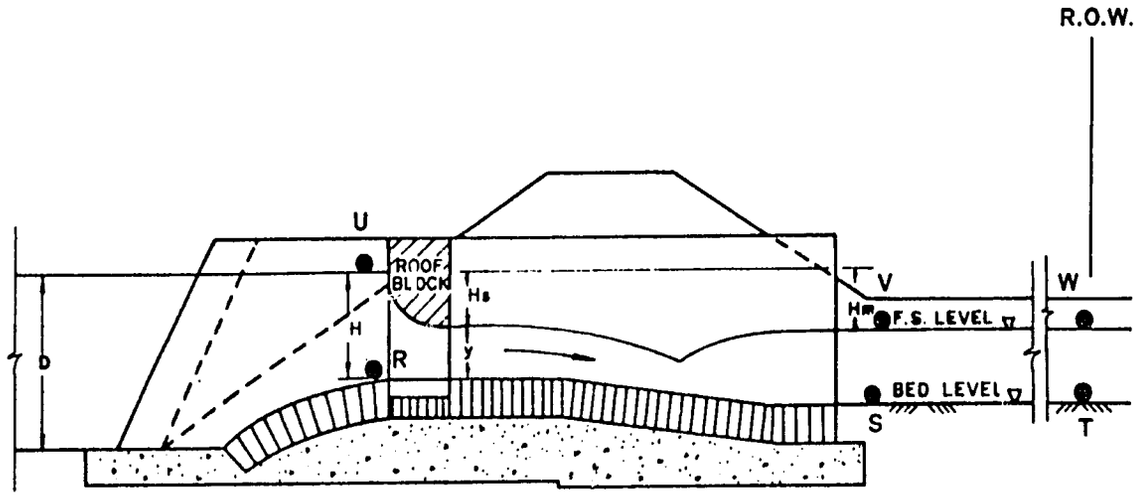
- measuring points in the cross-section, sequentially starting from point A
- level related to GTS
- distance to center line (negative or positive)
  points A - H negative
  points J - Q positive

The points A-Q are the minimum number points which must be measured in the cross-section. Additional points can be located between any two lettered points in order to define actual conditions.

In normal situations cross-sections will be measured every 500 ft, and at all structures.



SURVEY REQUIREMENTS
CANAL MONITORING PROGAM



Notes:

1. Estimate water surface level when watercourse is dry; points U, V and W.

2. Define outlet number and delivery side.

3. Define width of outlet.

4. Give canal stationing.

SURVEY REQUIREMENTS
OUTLET MONITORING PROGAM

CHAPTER VII

CONTROL OF EARTH CONSTRUCTION

CHAPTER VII

CONTROL OF EARTH CONSTRUCTION

A. General

Annual embankment maintenance is normally contracted out to either the Mechanical Circle or private contractors. This will require the XEN or the SDO to administer the contract(s) in the field. Annual maintenance include:

* Replacement of freeboard
* Replacement of eroded embankment
* Desilting
* Raincut repairs
* Grading roads

The replacement of freeboard and embankment is based on 20% of the total length of all canals being replaced each year. Rainfall and other factors remove about one inch of freeboard per year and two inches of embankment. This restoration construction will be by mechanical methods and will be performed by the Mechanical Circle. It will not be done during the closure period as other work will have priority. The new embankment material will be compacted by mechanical means.

Private contractors may also be used provided they have the equipment necessary to be able to meet contract specifications which in most cases would be soil moisture and compaction requirements. It is anticipated that compaction will be done using a 2-ton vibratory sheepsfoot roller winched up and down the embankment slope from a tracked type tractor equipped with a side boom and heavy duty cable winch. Hand methods have not proved satisfactory because of the time and manpower requirements. A contractor trying to use a small vibrator or tampers would spend a considerable amount of his time trying to avoid their use or do so only on a superficial basis. This would make inspection costly and difficult to control the non-compliance of the contractor.

Supervision of compaction will require considerable soil testing for moisture percentage and density. A simple field testing laboratory can be assembled that can be carried in a large box or trunk, that can be used to make the critical tests at the construction site. Any testing that requires travel to Lahore or any city laboratory will take too long to be of any value in monitoring a contractor and getting him to remove and replace material or to re-roll it in order to increase the density when the fill is not up to specification.

B. Specifications

The following paragraphs summarize the various standard specifications provisions used for rehabilitation of canal embankments. Their purpose is to clarify and to relate to the different types of work. However, this discussion should not be considered a substitute for the published specifications for any particular project or system. Each set of specifications includes only those standard provisions that apply to the local situation, and, in addition, modifications are made to fit each project.

1. Preparation of Embankment

A specification for preparing canal embankments for annual maintenance, which includes restoration of freeboard and embankment, is required. The specifications provisions should cover such required items as

* grubbing of stumps and small trees and their disposal
* stripping all vegetative matter, their roots and the burning or other disposal of the material
* scouring or scarifying.

The contractor receives no special payment for this work, but the cost is included in the unit prices bid in the schedules for excavation.

2. Placement of Earth Embankment

In specifications for replacing or adding to earth embankments, general provisions are made to adhere to the dimensions shown on the drawings, to

grade the tops of canal embankments, to distribute gravel and cobbles uniformly throughout the fill; and to prohibit oversize rocks, boulders or other material. Where the right-of-way does not furnish sufficient material for the required fill the contractor is required to borrow the material from areas designated by the Government. Adequate berms (8 feet minimum) are left between the embankment toe and adjacent borrow pits. The slope within the borrow pits should be maintained at 1-1/2 :1 unless otherwise specified.

The provisions in the specifications will define minimum plasticity limits (nominally 3% or greater) as well as liquid limits. This is to ensure some cohesion in the embankment material. The higher the clay content in sandy-silty soils the better. Cohesionless soils such canal bed sediment cannot be used directly in canal embankments. They must be specially handled because they will not retain compaction unless confined. Figures IV-2 thru IV-4 indicate acceptable methods for using cohensionless materials. This material is recommended for outside berm construction where existing slopes show a seepage pattern as it would provide the required drainage. Cohensionless material must be at optimum moisture content when compacted. The protective layer(s) are placed in a separate lift.

The government is responsible for obtaining right-of-way and excavation permits from the farmers for borrow areas. Provisions should be made for releveling the borrow areas.

Contractor's ramps (ramps used by equipment to drive from base to top of the embankment) must not be cut into the embankment below the full supply water level. Ramps need not be removed. The contractor received no special payment for this work.

A unit of overhaul is defined as 100 cubic feet hauled 1 mile or a fraction of a mile in excess of the freehaul limit. The freehaul limit is sometimes defined as 500 feet. There can be considerable variation in how overhaul or leads are handled in a contract. A lead normally refers to the

perpendicular distance from the center line of the canal embankment to the point of excavation. A lead is used with manual or donkey labor. Overhaul is used mostly with equipment operations. The use of hand labor may require one set of leads and mechanical equipment another. The provisions in the contract must be specific. The contractor will normally bid the work on these provisions. Unless specified, no payment is paid for overhaul.

The specifications for earth canal embankment require that construction operations be such as will result in an acceptable and uniform gradation of materials to provide for impermeability, erosion resistance, and stability when compacted, and where applicable, all stones larger than the maximum size specified (usually 3 to 5 inches) be removed prior to compaction. When blending of fine-and coarse-grained soils from different sources, the specifications usually require that the fine grain soil be placed first, followed by the coarse, after which the two are blended. The procedure is used so that no coarse lenses will be left on the bottom of any finished layer. Disking being a common method of mixing. It is important that the disk diameter is roughly four times the depth of the layer to be blended and must be properly weighted to fully penetrate the material. Light equipment will rise and not accomplish the blending/mixing for the full depth of each layer.

The addition of sufficient moisture to the fill material is extremely important to obtain adequate compaction. On fine silty-sandy soils moisture should tend to be on the wet side rather than dry side of optimum. This will tend to increase the impermeability. The material must be of uniform moisture content. Water will normally have to be added to the dry material and thoroughly mixed. The equipment requirements are the same as mentioned above. To bring the soil moisture up to the proper level (percentage) sprinkling and mixing can best be accomplished on top of the embankment. After mixing, the moist material can be pushed over the side and spread uniformly into a loose layer 6 to 8 inches thick (measured vertically from the slope).

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Compaction using a vibrating sheepsfoot tamping roller operated from a winch mounted on a track type tractor with a side boom could provide the necessary compaction in four passes per layer. The actual number of passes required is normally determined from field tests. The above should provide a 5-inch compacted layer. The specifications would normally require a compaction effort to provide a density to meet or exceed 85% Standard Proctor dry density as defined in ASTM 698.

Hand or powered tampers are used around structures. Their use on embankment is not recommended because of the difficulty in monitoring the uniformity of the compaction. Extreme care must be used in supervising/ inspecting compaction using this method. Additional testing should be required to ensure the desired compaction is obtained throughout the newly added material.

Embankment material, improperly placed and not meeting specifications, must be removed and replaced to meet specifications. This is done at the contractor's cost.

C. Embankment Construction Control Techniques

Recognition of the importance of controlling earth placement in embankments has long been known in Pakistan, but compaction specifications have not been enforced. Compaction is very important in Pakistan not only because of the factors which affect stability but also that fine silty-sands do not consolidate over time as do clayey soils. Not only must the inspector and the contracting officer be thoroughly familiar with the provisions of the specifications, but they must also have a good understanding of the design and construction principles involved and the field and laboratory tests used for control. They should secure or be provided with all available information on design assumptions; laboratory reports, other reports and specifications, and check to see whether field conditions revealed before or during construction are comparable with the assumptions made on the basis of pre-construction investigations.

Earthwork control for restoring eroded canal embankments is more specialized than for new embankments because the compaction work is not accomplished on a flat area. Outside canal banks are normally at 1-1/2 : 1 or 2 : 1 slope (H:V) which are too steep to work using normal procedures. Hauling and spreading will generally be confined to the embankment top. Uniform moistening of the material will be required. The amount of water required is that which will provide a total moisture equivalent to the optimum moisture for the compactive effort being applied.

Control of compacted soils on the embankment top or outside slope consists of inspection of the materials used, checking the amount and uniformity of soil moisture, maintaining the thickness of layers, and finally determining the percentage of Standard Proctor dry density of the fill. The thickness of the loose lift, required to result in a 5-inch compacted layer, must be determined and regularly checked. A preliminary estimate is 7 to 8 inches.

The fill material will be deposited on top of the embankment for working; moisture would be added as required, and mixed to obtain uniformity. Any blending of materials would be done on the top of the embankment as described above. The proportions would be determined by prior laboratory testing. It is the responsibility of the inspector to see that the material(s) are properly proportioned and the correct amount of water added and thoroughly mixed.

The worked material will be pushed over the side of the embankment and spread uniformly to the prescribed loose depth. The specifications paragraphs for compacting soils on a sloped embankment are much tighter than for a flat area in order to obtain the desired kneading action, uniformity and integration of soil layers required. The diameter and weight of the vibratory tamping roller, number of roller passes, and length of tamping feet are normally not specified for flat working areas but should be more closely specified for rehabilitation/restoration of sloped canal embankments. The number of passes should be determined from field testing. A determination of the height of compacted lifts is made by keeping accurate records and measuring all changes in depth to estimate the

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average thickness in the work area. If the contractor's compacting equipment is inadequate, as evident by continued low or borderline densities, the contractor can be required to obtain and use suitable equipment, add ballast to existing equipment, or provide maintenance on his equipment as required. Maintenance of tamping knobs is important not only with respect to length but also to knob size. For instance, if the unit knob pressures become too high, as from the reduction in knob size from wearing, shearing rather than compaction will take place in soft fine-grained soils, often regardless of the number of roller passes applied.

Cobbles larger than specified, usually to 3 to 5 inches must be removed prior to compaction. This is especially true for restoration of canal embankments where a relatively thin section is being placed. There are few areas in Pakistan where this would be a problem.

The inspector is responsible for controlling water content of the soil to that which is the optimum for compaction and assuring that the moisture is uniform throughout the layer to be compacted. Therefore, when large amounts of moisture are require, it may be more efficient to add most of the water at the point of excavation with only supplemental sprinkling after the layer is spread. Close proximity of water to the top of the bank may alter this approach, since pumps and a hose could be used. The length of area being worked at one time would also have an effect on the method the contractor might use to apply water. Mixing after applying water is required to produce a uniform moisture condition throughout the layer before compaction can proceed. Inspection of moisture uniformity should be made frequently by digging holes in the loose layer just prior to compaction. Unless otherwise specified, optimum moisture requirements must be enforced. Any error should tend to be on the wet side rather than the dry with fine silty-sands.

Because the top of embankment will be used for more than one operation, construction will have to be phased. This means that the loose embankment material could be left lying on the embankment several hours before the compaction operation is started. In this case, it may be necessary for

the contractor to spray a light coating of water on the material ahead of the compactor.

The adequacy of the compaction and moisture control is controlled by the field density test in conjunction with the rapid compaction control method for silty soils. Unless otherwise specified, the minimum acceptable density is 85% of Standard Proctor maximum dry density. The relative density test may be used to control the placement of cohensionless material if it provides a higher unit weight.

Inasmuch as the adequacy of compaction is specified in terms of density achieved, the inspector is responsible for taking sufficient tests to assure the adequacy of compaction for acceptance purposes. At the start of any work contract/project a considerable number of tests are required to ensure that the construction operations are producing the required results. After this has been established, the number of tests required are only those necessary to ensure that specifications requirements are being met. Because of the wide spread operations of canal work, the number of field density tests required for adequate control can not be stated. Testing requirements should be based on area as well as on volume of fill placed. The individual contractor may make a difference. Those contractors who try to meet specifications generally require less testing than those who try to circumvent the specifications. Contractors who under bid a job will always try to cut corners to make ends meet. The following is a guide for the minimum number of field density tests:

(1) One test for each shift.
(2) One test for each 500 feet of embankment completed.
(3) One test for each 5000 cubic feet placed.

Horizontal and vertical control must be available so that the inspector can adequately locate each field density test. Locations are usually defined in terms of stations (RD), offset from wet side lip of the canal top and true elevation (vertical distance down from top of embankment). The inspector is responsible for locating these tests so that a complete

representative record of the finished work is available.

The construction drawings will specify the slopes and areas that will be sodded or sprigged to grass. Inspection will ensure that the sod is secured to the slope and cannot wash off. Sprigs should be set with the root buried in soil and compacted/pressed in with a laborer's foot. The pressing action will ensure that the roots are in contact with the soil and are not in air where they would rapidly dry out.

D. Desilting Control Techniques

1. Small Channels

Desilting of small channels is accomplished with hand labor. The sediment is thrown up on the edge of the bank as the first step. It should then be rehandled and moved to the back slope of the embankment. Where no patrol road exists it can be thrown. Where the patrol road is on top of the bank, it may have to be carried back. Under no circumstances should the material be left on the inside bank to wash back into the canal with the first heavy rainstorm.

Desilting using mechanical equipment would be done by using a small backhoe mounted on an industrial tractor equipped with a front loader. The front bucket is used to smooth out the material on the back side of the embankment and ensure that it is below the embankment top so as not to restrict surface drainage or cause a concentration of water.

2. Medium-sized Channels

Desilting would be accomplished by equipment, equipment supported by labor or by labor intensive methods according to each contractors capability. Equipment would be hydraulic excavators or dragline depending on canal width and reach of equipment. Any material dumped on the embankment's wet side would have to be moved back and below the dry side of the embankment top. A road grader could be used for this operation. Where equipment is placed on the canal bed, a ramp must be constructed. The ramp can not be cut into the canal bank, but this restriction does not apply to the berm. Ramps must be removed upon completion of the work and the berm repaired.

The use of tractors and trollies would also require the construction of runways. Mechanical loading would be faster than hand loading but that is the contractorts decision. Spacing of runways is up to the contractor. Where right-of-way is not available next to the embankment, the government will have to locate areas where the excavated bed sediment can be wasted.

Sediment can not be placed on top of an embankment unless treated as shown in Figure IV-2.

The use of donkeys or hand labor will require the construction of runways. Under no circumstances will the true canal embankment be cut. Only the berm can be cut and it must be repaired on completion of the work. Material excavated by hand should not be dumped in a single location on the dry side of the embankment top. The piling of sediment on the back slope will interfere with the cross-drainage of the patrol road and cause excessive raincuts/erosion rivelets.

3. Large Channels

Large Channels may require the use of dump trucks and hydraulic excavators because other equipment can not reach the material in the center. Locating adequate waste areas may present a problem. Spoil criteria discussed above will also apply to large canals.

E. Measurement for Quantities

The contractor is normally paid for inplace quantities. This would require the measurement of the slope length and top width prior to start of construction or after stripping of the vegetative material off the embankment. This may be done on 100 feet stationing. These lengths times the depth of the layer of fill placed and compacted will give the volume of inplace compacted embankment. The depth of fill on the embankment top is measured after grading. Staking would be along the wet side embankment lip or even offset slightly because it would be out of the way and less subject to being knocked over.

The sodding or spragging of the embankment would be measured on a square foot basis.

F. Field Density Test Procedure

A method for determining the inplace density of soil, using sand for determining the volume of the test hole, is described briefly. Additional details can be found in the USRB's Earth Manual and other sources. The Standard Pakistani wedge shape can be used. The wedge has a 6-inch square base and is 8 inches deep.

1. Calibration of Sand

The sand should be calibrated before using it in the density test. Calibration is required to determine the sands weight per unit volume when poured. The poured density of the sand is affected by atmosphere moisture and changes in relative humidity. A supply of dry sand must be stored in such a manner so as to maintain a uniform dry condition. Calibration should be daily when field measurements are being made. A container of known volume shall be filled with sand. Care should be taken so that the filling does cause densification. When the container is full, the sand shall be carefully leveled using a steel straight edge. The weight of the sand in the container is determined.

2. Field Procedure

At the test site, an area roughly 18 to 24 inches square will be leveled in the embankment until a firm smooth surface is obtained. The inspector should be careful not to step on the test site nor disturb the surroundings.

The size and dimension of the hole are not too critical for canal embankments. The wedge described above should be adequate. A cylindrical shape 6 inches in diameter and 9 inches deep could also be used. In either case, sufficient sand must be available to fill the hole in the embankment.

A template with the proper size and shaped hole shall be used and placed where the hole is to be dug. The excavation should be slightly smaller

than the template. Care must be taken not to deform the hole while excavating. Hand tools are used to excavate the hole. All the material taken from the hole is placed in an air-tight container for subsequent weighing in the field laboratory. To avoid loss of moisture, the container should remain sealed when soil is not being placed in it.

The hole is trimmed to the proper dimensions. Care being taken to remove all material loosened in the process and put it into container. The weight of the container and wet soil will be measured to the closest 0.01 pound and recorded.

The volume of the hole should be determined by carefully filling the hole with calibrated density sand using a sand pouring device. The device does not need to be calibrated, but must be easily weighed in the field laboratory. Sand is carefully poured into the hole and leveled with the top of the template using a steel straight edge and all excess sand returned to the pouring device.

The pouring device is weighed prior to filling the hole and again after filling. The difference in weight divided by the unit weight per cubic foot of sand will give the volume of the hole plus the template. The volume of the template is determined in the laboratory. Subtracting the volume of the template from the combined volume gives the volume of the test hole in cubic feet.

The above completes the work required at the test site to determine inplace density. Information such as project, test number, location, elevation and other pertinent information shall be recorded. The wet soil is used to determine water content and other data in a field laboratory.

The wet density can be determined in the field by weighing the sealed container with soil and then subtracting the weight of the container to obtain the wet weight of soil. The wet weight of soil divided by the volume of test hole determines the wet density of the soil.

The dry density is determined in a field laboratory. The wet soil is placed in a container weighed and heated to 110 degree Celsius and dried for a period of roughly 16 hours to a constant weight with the lid off. The sample is cooled to room temperature in a container with the lid replaced. After cooling the dry weight of the test sample is determined by weighing. The weight of the wet soil minus that of the dry soil is the weight of water in the sample. The weight of the water divided by the weight of dry soil multiplied by 100 is the percentage of moisture in the compacted embankment. The weight of the dry soil divided by the volume of the test hole is the dry density of the embankment.

The dry density should be equal or greater than 85% of the Standard Proctor dry density determined by laboratory tests on the borrow material. The laboratory testing is done during the design stage.

APPENDIX A

DEFINATIONS OF SOME COMMON SOILS ENGINEERING TERMS

APPENDIX-A

DEFINITION OF SOME COMMON SOILS ENGINEERING TERMS

BEDROCK (ledge) - Rock of relatively great thickness and extent in its native location.

BENTONITIC CLAY - A clay with high content of the mineral montmorillonite, usually characterized by high swelling on wetting.

CAPILLARY ACTION (capillarity) - The rise or movement of water in void spaces of a soil or rock due to capillary (suction) forces.

COHESION - Shear resistance at zero normal stress (an equivalent term in rock mechanics is intrinsic shear strength).

COHESIONLESS SOIL - A soil that when unconfined has little or no strength when air-dried and that has little or no cohesion when submerged.

COHESIVE SOIL - A soil that when unconfined has considerable strength when air-dried and that has significant cohesion when submerged.

COLLOIDAL PARTICLES - Particles that are so small that the surface activity has an appreciable influence on the properties of the aggregate.

COMPACTION - The densification of a soil by means of mechanical equipment.

COMPACTION CURVE (Proctor curve) (moisture-density curve) - The curve showing the relationship between the dry unit weight (density) and the water content of a soil for a given compactive effort.

COMPACTION TEST (moisture-density test) - A laboratory compacting procedure whereby a soil at a known water content is placed in a specified manner into a mold of given dimensions, subjected to a compactive effort of controlled magnitude, and the resulting unit weight

determined. The procedure is repeated for various water contents sufficient to establish a relation between water content and unit weight.

COMPRESSIBILITY - Property of a soil or rock pertaining to its susceptibility to decrease in volume when subjected to load.

CONSOLIDATION - The gradual reduction in volume of a soil mass resulting from an increase in compressive stress.

CRITICAL HEIGHT - The maximum height at which a vertical or slope bank of soil or rock will stand unsupported under a given set of conditions.

FILL - Manmade deposits of natural soils or rock products and waste materials.

FILTER (protective filter) - A layer or combination of layers of pervious materials designed and installed in such a manner as to provide drainage, yet prevent the movement of soil particles due to flowing water.

FINES - Portion of a soil finer than a No. 200 (75-micrometer) U.S. standard sieve. (A No. 200 size particle is about the smallest particle that can be distinguished by eye.)

FOOTING - Portion of the foundation of a structure that transmits loads directly to the soil.

FOUNDATION - Lower part of a structure that transmits the load to the soil or rock.

FOUNDATION SOIL - Upper part of the earth mass carrying the load of the structure.

FROST ACTION - Freezing and thawing of moisture in materials and the resultant effects on these materials and on structures of which they are a part or with which they are in contact.

FROST HEAVE - The raising of a surface due to the accumulation of ice in the underlying soil or rock.

LIQUEFACTION (spontaneous liquefaction) - The sudden large decrease of the shearing resistance of a cohesionless soil. It is caused by a collapse of the structure by shock or other type of strain and is associated with a sudden but temporary increase of the pore-fluid pressure. It involves a temporary transformation of the material into a fluid mass.

LIQUID LIMIT, LL - The water content at which a part of soil, cut by a groove of standard dimensions, will flow together for a distance of 1/2 inch (12.7) under the impact of 25 blows in a standard liquid limit apparatus.

MOISTURE CONTENT - The percentage by weight of water contained in the pore space of a rock or soil with respect to the weight of the dry solid material.

PERMEABILITY - The capacity of a soil or rock to conduct water or other fluids.

PIPE TERMINOLOGY - The crown is the inside top of the pipe. The invert is the inside bottom of the pipe. The spring line is the horizontal line at the halfway point of the pipe. The haunches of the pipe are the outside areas between the spring line and the bottom of the pipe.

PIPING - The progressive removal of soil particles from a mass by percolating water, leading to the development of channels through the soil.

PLASTICITY - The property of a soil or rock which allows it to be deformed beyond the point of recovery without cracking or appreciable volume change.

PLASTIC LIMIT, PL - Water content at which a soil will just begin to crumble when rolled into a thread approximately 1/8 inch (3.2 mm) in diameter.

ROCK - Any naturally formed aggregate of mineral matter occurring in large masses or fragments.

SEEPAGE - The infiltration or percolation of water through rock or soil to or from the surface. The term seepage is usually restricted to the very slow movement of ground water.

SHRINKAGE LIMIT, SL - The maximum water content at which a reduction in water content will not cause a decrease in volume of the soil mass.

SOIL (earth) - Sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter.

TRENCH - Usually a long, narrow, near vertical-sided cut in rock or soil such as is made for culverts.

UNIT WEIGHT - Weight per unit volume.

VANE SHEAR TEST - An inplace shear test in which a rod with thin radial vanes at the end is forced into the soil and the resistance to rotation of the rod is determined.

APPENDIX B

ELEMENTARY SOIL ENGINEERING

APPENDIX B

ELEMENTARY SOIL ENGINEERING

Section 1 : Introduction

Soil Engineering is the application of known physical, chemical and mechanical properties of soil to its use as a primary material and as a foundation for structures. The material presented herein was adapted from the USDA Soil Conservation Service, Engineering Manual.

Section 2 : Basic Concepts

A. Soil

Soil is defined as sediments which are earth particles: 1) deposited by running water; 2) deposited in still water; or 3) other accumulations of unconsolidated particles resulting from the physical and chemical disintegration of rocks. Soil may or may not contain organic matter.

Soil, sometimes referred to in engineering as "soil mass", consists of the solid soil matter plus the space not occupied by solids. This space is called "soil voids" or simply "voids". Therefore, the term "soil" as commonly used consists of both solids and voids.

B. Soil Solids

The composition of mineral soil particles resulting from physical disintegration will remain about the same as the composition of the parent rock or the minerals making up the parent rock. For example, granite often breaks down into individual particles of its minerals feldspar, quartz and mica.

Chemical action on rocks causes decomposition of the rock. Certain acids or salts and the elements of water and air will, when associated with rock minerals under favourable conditions, combine to form new chemical compounds not present in the parent rock.

Decomposition usually happens after disintegration. The mineral content of the parent rock and how far disintegration and decomposition have progressed determine the kind of soil produced and the engineering properties of that soil.

Soil formed "in place" from parent rock is called residual soil. A large percentage of the earth's soil mass has been transported, often far from its original in the earth's crust. Soil may be transported by gravity, water and wind.

Gravity transportation may be slow and almost unnoticed or it may be rapid. Examples are loosened particles that roll or slide down a steep slope; glaciers that gouge out soil at one place and drop it at another; and large masses of earth that slowly "creep" in a downhill direction. Landslides are often violent and spectacular.

Water and wind transportation have two common characteristics. Each transports soil particles by rolling or sliding the particles along the ground surface or by picking particles up and carrying them in suspension. Each tends to separate and deposit particles according to their size.

Transportation processes are important agents of disintegration, particularly in producing very fine particles by wearing away larger particles. Except for residual soils, the kind of soil and its engineering properties are partially the result of how it was transported and deposited.

The sizes of the granular soil particles depend on the ease with which the parent rock is disintegrated and decomposed and the length of time these processes have had time to act. The shapes of granular particles are described as:

* <u>Angular</u> - containing sharp edges and points, characteristics of newly formed particles.

* Sub-angular, sub-rounded or rounded - characteristics of older particles with the sharp edges and rough surfaces worn away or smoothed off.

The size and shape of clay particles are determined by the chemical composition and molecular structure of each particular kind of clay.

C. Soil Structure

Soil structure is defined as the arrangement and grouping of soil particles in a soil mass. "Flocculent structure" describes soil held together in groups or clusters of individual soil particles called "flocs".

When not flocculated, the soil particles are said to be dispersed and the soil is called "single-grain" structure. Single-grain structure is characteristic or coarse-grained or granular soils.

"Honeycomb" structure describes an arrangement of soil particles that is relatively loose (open) but stable, somewhat resembling honeycomb in appearance.

D. Soil Voids

Soil voids are that portion of a soil volume not occupied by solids. In a natural state, the voids may be filled by liquid or gas or both.

Gas occupying the voids is usually air. In soil engineering, the air in the voids is treated as weightless. Liquid occupying the voids usually is water. Water contained in the voids is considered as incompressible in soil engineering. Although the properties of water change with temperature, these effects are usually ignored in soil engineering applications.

E. Moisture in Soil

The moisture in a soil may be described as:

* The ratio of the volume of water in the voids to the total volume of the voids.

* The weight of the water in the voids to the weight of the dry soil particles.

The optimum moisture content is the percentage of moisture in a soil, based on its dry weight, at which the maximum density is obtained under a given compactive effort.

Saturated soil has most of its voids filled with water. An example would be soil below the water table. Soil engineers often assume the voids are completely filled with water under saturated conditions because of the testing used to determine volume of voids. The assumption meets construction requirements.

Wet soil requires drying to attain optimum moisture content. Moist soil contains water very near optimum moisture content.

Dry soil contains only air in the voids (water has been removed by heating to 110° ± 5° C). Soils in this condition require the addition of considerable water to obtain optimum moisture content for standard compaction.

Saturated and dry conditions usually represent definite moisture contents while moist and wet conditions are general ranges between these two.

The soil mass, as used in soil engineering, are composed of solids plus air or water or both air and water. In the remainder of this discussion the term soil will be used broadly to include solids, water and air.

F. Volume Relationships

Figure B-1 (Sketch A) represents a definite volume of soil composed of solids and voids. Figure B-1 (Sketch B) represents the same soil with the solids and void volumes separated into their respective proportions. The

total volume is always equal to the sum of the volumes of the solids and the voids.

$$V = V_s + V_v$$

Figure B-1 (Sketch C) represents the same soil volume with some water added but not enough to completely fill the voids. The soil is now composed of solids, water and air. In this state, the volume of the voids is equal to the sum of the volumes of water and air.

$$V_v = V_w + V_a$$

The total volume is equal to the sum of the volumes of the solids, water and air.

$$V = V_s + V_w + V_a$$

G. Volume Ratios

Certain volume ratios have been found to be useful in soil engineering.

1. Void Ratio. Void ratio e is the ratio of the volume of the voids to the volume of the solids.

$$e = \frac{V_v}{V_s} \text{ (dimensionless)}$$

The void ratio value can be equal to, greather than, or less than one.

2. Porosity Ratio. Porosity n is the ratio of the volume of voids to the total volume.

$$e = \frac{V_v}{V} \text{ (dimensionless)}$$

Numerically, porosity can never be greater than one.

The equation $n = \frac{V_v}{V} \times 100$

expresses the volume of voids as a percentage of the total volume. When so expressed, it is called percent voids.

3. Degree of Saturation. Degree of Saturation S is the ratio of the volume of water in the voids to the volume of the voids.

$$S = \frac{V_w}{V_v} \quad \text{(dimensionless)} \cdot$$

Numerically, the degree of saturation cannot be greater than one. When the equation is changed to $S = V_w \times 100$, the expression becomes V_v percent saturation. It expresses the water volume as a percentage of the total volume of the voids. When the voids are completely filled with water, $V_w = V_v$, and the percent saturation equals 100 percent.

H. Weight Relationships

Figure B-1 (Sketch C) poins out that the total weight is equal to the sum of the weights of the solids, water and air.

$$W = W_s + W_w + W_a$$

or $W = W_s + W_w$ since the weight of the air is considered to be zero.

I. Percent Moisture

An important weight ratio in soils engineering is the ratio of the weight of the water in the soil to the weight of the solids. This ratio multiplied by 100 is the moisture content in percent.

$$W = \frac{W_w}{W_s} \times 100$$

J. Unit Weight and Density

Unit weight, T, is defined as weight per unit volume. For a soil mass, at any moisture state, of total weight W, and total volume V, its unit weight T is:

$$T = \frac{W}{V}$$

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Units of unit weight must be consistent with the units of W and V.

English unit system, $= \frac{W(lbs.)}{V(ft.^3)} = lb./ft.^3$

Metric Unit system, $= \frac{W(gm)}{V(cm)^3} = gm/cm^3$,

Although not strictly true, density and unit weight are used interchangeably in soil engineering and are both represented by T.

The mass of one cubic centimeter of distilled water at 4° C is 1.0 gram. Therefore, the density of distilled water at 4° C is:

$$W = \frac{1\ (gm)}{1\ (cm^3)} = 1.0\ gm/cm^3$$

in the metric system of units.

Since 1.0 gm = .002205 lbs. and 1.0 cm^3 = .00003531 ft^3

$$W = \frac{1.0 \times .002205}{1.0 \times .00003531} \quad lbs./ft^3$$

The unit weight of soil at each of three most used moisture contents have standards subscripts. They may be written as follows:

Unit dry weight, $Td = \frac{W_s}{V}$, where $V_w = 0$

Unit moist weight, $Tm = \frac{W_s + W_w + W_a}{V}$, where $W_a = 0$

Unit saturated weight, $T\ sat = \frac{W_s + W_w}{V}$, where $V_a = 0$

K. Behaviour Characteristics

Fine-grained or fine-textured soils possess unique characteristics which are important to their engineering properties. These behaviour characteristics are either physical, chemical, or a combination of physical and chemical.

Plasticity is physical characteristics defined as the property of a soil which allows it to be deformed beyond the point of recovery without cracking or appreciable volume change.

Plasticity also is a soil property. This property is recognized by the soil's behaviour known as case of moldability. A soil is either plastic and moldable or nonplastic and not moldable. All plastic soils are fine-textured but all fine-textured soils are not plastic. A soil composed of finely divided quartz (rock flour) is nonplastic while a clay soil of comparable particle size may be plastic and moldable. Mixtures of such soils will display a degree of plasticity somewhere between plastic and nonplastic.

The moisture content of a plastic soil affects its consistency or relative moldability. Consistency is defined as the relative ease with which a soil can be deformed.

Degrees of consistency are described by the terms hard, very stiff, stiff, firm (Medium) and soft, see Figure B-2. Continue to add water to a dry plastic soil and the mixture will eventually have all the characteristics of a liquid. In changing from a solid to a liquid, the material first becomes a semisolid and then plastic. A Swedish scientist, named Atterberg, developed procedures to determine the moisture content at which these changes take place. They are known as the Atterberg limits.

L. Atterberg Limits

Although fines are measured as the percentage passing the # 200 sieve, Atterberg limits are measured for materials passing the # 40 sieve This apparent inconsistency occurs because Atterberg limits were established and measured on materials passing the # 40 sieve many years before the # 200 sieve was established as the largest size for fines.

1. Shrinkage Limit (SL). The shrinkage limit is the maximum water content at which a reduction in water content will not cause a decrease in the volume of the soil mass. This defines the arbitrary limit between the

solid and semisolid states.

2. Plastic Limit (PL). The plastic limit is the water content corresponding to an arbitrary limit between the plastic and semisold states of consistency of a soil. This is the water content at which a soil will just begin to crumble when rolled into a thread approximately 1/8 inch (3.0 mm) in diameter.

3. Liquid Limit (LL). The liquid limit is the water content corresponding to the arbitrary limit between the liquid and plastic states of consistency of a soil. This is the water content at which a pat of soil cut by a groove of standard dimensions, will flow together for a distance of 1/2 inch(12 mm) under the impact of 25 blows in a standard liquid limit apparatus.

In the determination of these limits, water is gradually added to that portion of dry soil material that passes the # 40 sieve. Refer to Figure B-2. At the point the soil becomes plastic, the weight of the water in percent of the dry weight of the soil is known as the plastic limit (PL).

If water is added above the plastic limit, the soil will become liquid. At the point the soil becomes liquid, the weight of the water in percent of the dry weight of the soil is known as the liquid limit (LL). The difference between these two values is the water range in which the soil stays plastic and is called the plasticity index (PI). In practice, the percent sign is dropped when referring to numerical values of the Atterberg Limits. A material with a liquid limit of 50 percent is referred to as a LL of 50.

4. Plasticity Index (PI). The plasticity indix is the numerical difference between the liquid limit and plastic limit.

$$PI = LL - PL$$

5. Shrinkage Index (SI). The shrinkage index is defined as the numerical difference between the plastic and shrinkage limits.

$$SI = PL - SL$$

Section 3 : The Unified Soil Classification System

A. General

The Unified Soil Classification System is used in classifying soils for engineering purposes. This system is based on the identification of soils according to their particle size, gradation, plasticity index and liquid limit. (ASTM D 2487 and D 2488). Gradation and particle size are determined by sieve analyses. Plastic and liquid limits are determined by standard methods of laboratory testing. (ASTM D 423 and D 424).

B. Symbols

The Unified System, which is based on the minus 3-inch fraction of the material, uses letters as symbols of the soil's properties. The soil properties and the letters that represent them are listed below.

Gravel - G	Clay - C	Organic - O
Sand - S	Silt - M	Peat - Pt
Well Graded - W		High Liquid Limit - H
Poorly Graded - P		Low Liquid Limit - L

Soils are placed in groups having similar engineering properties according to their behavior characteristics. Each group is delineated by two of the above characteristics. The most important engineering characteristic of this group is listed first and the next most important, second.

U.S. sieve size are used in separating some classes of materials from others. The important sieves and the size of their opening are:

U.S. Standard Sieve Sizes	Size of Opening in mm.	Size of Opening in inches
3"	76.2	3"
3/4"	19.0	3/4"
#4	4.76	1/4" (approx)
#10	2.00	-
#40	0.42	-
200	0.074	-

C. Basic Material Breakdown

Soils are divided into coarse materials or fine materials by the # 200 sieve. If more han 50 percent of the material, by dry weight, is larger than the # 200 sieve, it is a coarse material. If 50 percent or more will pass the # 200 sieve, it is a fine material.

1. Coarse Materials. Coarse material is subdivided into a sand and gravel by the # 4 sieve. If 50 percent or more of the coarse portion of the material by dry weight is retained on the # 4 sieve, the material is classified as a gravel. If more than 50 percent passes the # 4 sieve, it is classified as a sand.

2. Materials With Less Than 5 Percent Fines. If less than 5 percent of the total sample by dry weight is fines, there is not enough of these fines to affect its engineering properties. In this case, only the characteristics of the coarse portion are important and the fines may be ignored in classifying the material. The classification as sand or gravel is the material's primary characteristic.

The secondary characteristic of material with less than 5 percent fines is its gradation (range of particle sizes). The material may consist predominantly of only one size of material; a mixture of coarse and fine materials with the intermediate sizes missing; or a mixture consisting of some of every size of particle. Materials in the first two groups are classified as poorly graded and those in the last group as well graded. The range of particle sizes may be obtained by shaking the sample through sieves. The results when plotted on a grain size distribution graph (see

Figure B-3) and analyzed will meet the following criteria if the material is well graded.

Gravels are well graded under the criteria of the Unified Soil Classification System when:

$C_u = \frac{D_{60}}{D_{10}}$ is greater than 4, and

$C_c = \frac{(D_{30})^2}{D_{10} \times D_{10}}$ lies between 1 and 3

$C_u = \frac{D_{60}}{D_{10}}$ is greater than 6, and

Sands are well graded when:

$C_u = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ lies between 1 and 3

where:

C_u = Coefficient of uniformity

C_c = Coefficient of curvature

D = Diameter of particles determined by a sieve or hydrometer analysis.

D_{60}, D_{10}, D_{30} = Diameter of particles such that 60 perrcent, 10 percent and 30 percent of the sample is smaller than that diameter. It is also the diameter read from a grain size distribution graph opposite 60,10,30 percent finer by dry weight, respectively.

Both conditions (C_u and C_c) must be fulfilled in order to have a well graded soil. If one or both of the conditions are not fulfilled, the soil is poorly graded.

Some materials can be classified by visual inspection of the graph. When their plot is smooth and has concave curvature upwards between the 10 percent and 60 percent lines on a grain size distribution graph, they are well graded.

All other combinations of material with less than 5 percent fines are poorly graded.

There are four classifications of coarse materials where the percent of fines is less than 5 percent. They are well graded gravels (GW), poorly graded gravels (GP), well graded sands (SW), and poorly graded sands (SP).

Classifications of the coarse materials described above are based on sieve analysis only.

3. Materials with 12 to 50 Percent Fines. If the soil is a coarse material (either sand or gravel) but has a fines content from 12 to 50 percent, the behavior characteristics of the portion smaller than the # 40 sieve will determine the secondary characteristic of the material. If this portion of the material is clayey (can readily be molded), the material is coarse grained with clayey fines. If not, it is coarse grained with silty fines. To determine whether the material is classed as clay or silt, the plastic limit and liquid limit are measured.

A plasticity chart, Figure B-4, is made with the LL as the abscissa and PI as the ordinate. On this chart, a line known as the "A" line has been plotted such that it lies approximately parallel to the plot of many basic geologic materials and originates at PI = 4, LL = about 25. For purposes of classification, all materials that plot above this line are designated as clay and all that plot below as silt. A small (cross hatched) area having a PI between 4 and 7 percent extending from the "A" line toward zero percent LL has a special dual designation and may be considered as an extension of the "A" line in separating, materials.

There are four breakdowns of coarse materials where the percent of fines is over 12 percent. They are gravels with clayey fines (GC), gravels with silty fines (GM), sands with clayey fines (SC), and sands with silty fines (SM).

4. Materials With 5 to 12 Percent Fines. Materials with a fines content between 5 and 12 percent do not have separate classification breakdowns. They have a dual classification consists of both the zero to 5 percent and the over 12 percent groups. The dual classification means that the material is borderline in its most significant engineering characteristics.

5. Fine Materials. Material is designated as being fine when 50 percent or more by weight passes the # 200 sieve .

6. Clay or Silt. Plasticity is the most important engineering property of a fine grained soil. Therefore, a fine grained material is classified according to its plasticity.

The plasticity of the fine grained soils is determined on that portion of the soil which passes the # 40 sieve. The material whose plot of the liquid limit and plasticity index falls above the "A" line (Figure B-4) is classed as a fine grained clayey material. If it plots below the "A" line the material is classed as a fine grained silty material.

Under the Unified Soil Classification System, clay or clayey is designated as any material that plots above the "A" line. Silt or silty is any material that plots below the "A" line. The break is the "A" line and is based on the PI.

7. High or Low Liquid Limit. The second most important characteristic in classifying fine grained material is its liquid limit.

Soil that has a liquid limit over 50 has a high liquid limit and may be either a clayey or silty high liquid limit material. Soil that has a liquid limit less than 50 has a low liquid limit and may be either a clayey or silty low liquid limit material.

There are four breakdowns of fine grained materials: Clayey material with low liquid limit (CL), clayey material with high liquid limit (CH), silty

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material with low liquid limit (ML) and silty material with high liquid limit (MH).

8. Organic Material. Materials containing a large percent of organic matter usually can be identified by their color and odor. The characteristics or organic materials are such that they have no easily definable boundaries. They are poor construction materials and need special consultation from an engineer, if used in construction. Some of these materials can be designated as organics of high liquid limit and organics of low liquid limit when tested by a laboratory. Fibrous organics that do not lend themselves even to laboratory tests are called peats. There are three breakdowns of organics: Organics with high liquid limit (OH), organics with low liquid limits (OL) and peats (Pt).

D. Summary

The basic outline or definition of the Unified Soil Classification System is presented in Figure B-5.

The Unified Soil Classification System has several outstanding features:

* It is simple. There are 12 materials with which technicians are normally concerned: four coarse grained materials, four fine grained materials, and four combined materials. In addition, there are three organics that require special attention, 15 in all.

* It provides important physical characteristics, such as size, gradation, plasticity, strength, brittleness, consolidation potential, etc.

* It is reliable. Engineering properties inferred by the classification are realistic.

Section 4 : Field Investigation of Soils

A. General

It is desirable to make a field identification of soils and to classify them without the use of special equipment. Soils should be described according to their color, texture and consistency and, where pertinent, their moisture content measured and recorded. Note should be made of the shape, size and gradation of coarse grained soils. The soil should then be classified according to the Unified Soil Classification System.

The classification of a soil should be made using several different field tests rather than a single test. Screening and weighing of samples is not intended. Estimates of percentages of materials by dry weight may be made using visual and finger techniques. With the exception of grain size and gradation, these tests are performed on that portion of the sample smaller than the # 40 sieve. When coarse materials that can be separated by hand are removed, the remaining material is roughly that portion passing the # 40 screen, see Table B-1.

Practice with materials of known percentages will be helpful in perfecting these techniques.

B. Field Tests

1. Determining Whether a Material is Primarily Coarse or Fine Grained.

Test 1

Spread the samples on a flat surface and examine the particles to determine the approximate grain size by visual inspection. If more than 50 percent of the sample has individual grains that are visible to the naked eye, the material is coarse. If less than 50 percent, it is a fine material.

Aggregated dry particles may appear to be sand sized grained to the eye. Saturating the sample will break these aggregated particles down. By rubbing the wetted soil between the thumb and

forefinger, sized grains can be detected as they will feel rough and gritty. Practice with samples with known percentages of sand will be helpful in estimating sand percentages.

Test 2

Fill a straight sided glass bottle to approximately 0.4 of its height with the sample, then nearly fill the bottle with water. Shake until all the material is in suspension. Estimate the percentage that settles in 25 seconds. If more than 50 percent of the material settles in 25 seconds, the material is coarse grained. If less than 50 percent of the materials in 25 seconds, the material is fine grained.

2. Classifying Coarse Grained Matereials

Test 1

Spread a representative sample on a flat surface. Determine whether more than 1/2 of the visible grains, by weight, are pea size or larger. If they are, it is a gravel; if not, it is a sand.

After determining if the material is a gravel or sand, it is further classified according to the properties of the fine content of the material. To do this, remove the coarse material that can readily be manipulated with the fingers. This can be done by spreading a thin layer of material on a surface and rolling the coarse particles to the edge or by placing a thin layer on a sheet of paper and tapping the coarse materials to the edge. Saturate the remaining material and work it in the hands. The hands will not be stained if there are less than 5 percent fines. It will be GW or GP if the material is a gravel or SW or SP if the material is a sand. The hands will be stained when there are more than 12 percent fines. Weak casts can be formed from moist materials. It will be GM or GC if the material is a gravel or SM or SC if the material is a sand.

Dual symbol materials (5 to 12 percent fines) cannot be readily classified by field procedures.

Use a second sample if there are less than 5 percent fines. Spread it out and observe the grain size distribution. If the coarse material consists of fairly well distributed particle sizes, the material is a well graded gravel or sand (GW or SW). If the corase material consists chiefly of one size particles or of large and small particles with in between sizes missing, the materials is a poorly graded gravel or sand (GP or SP).

When there are more than 12 percent fines in a coarse grained material, make the plasticity tests on the fines described below under Classifying Fine Grained Materials to determine whether the material is clayey or silty.

The material will be GC or SC if clayey and GM or SM if silty.

3. Classifying Fine Graded Materials. Remove coarse materials from the sample as explained above.

Test 1

To make the dilatancy test, prepare a pat of moist soil with a volume of about one-half cubic inch (1.6 cm^3). Add enough water to make the soil soft but not sticky. Place a pat in the open palm of the hand and shake it horizontally. A positive reaction is indicated by the appearance of water on the surface of the pat. The sample will leave a glossy appearance. The water and gloss will disappear from the surface when the pat is squeezed between the thumb and forefinger. The rapidity of the appearance of water during the shaking and of its disappearance during squeezing assist in identifying the character of the fine in the soil. A ML will have a rapid reaction; a MH and CL, a slow reaction; and a CH, no reaction.

Test 2

Dry crushing is estimated by crushing a dry clod between the fingers. A block of soil at least 3/4 inch (19 or 20 mm) in smallest dimension should be used as smaller samples may give erroneous results. Easily crushed material of low strength is a ML. Medium strength material is either a CL or MH. CH material is almost impossible to break.

Test 3

The toughness test uses the same procedures that are used in the laboratory to determine the plastic limit (PL). Wet and mold a soil sample so that it can be rolled into a thread without crumbling. The material will not stick to the hands if the correct amount of water is added. Roll the moist soil with the palm of the hand on any clean, smooth surface such as a piece of paper, to form a 1/8 inch-diameter thread (3.0 mm). Gradually reduce the moisture contenT by breaking up the sample and remolding and rolling it until the 1/8-inch thread breaks into pieces approximately 3/4 inch (20 mm) long. The material is then at its plastic limit. Circumferential breaks in the threads are an indicator of a CH or CL material. Longitudinal cracks and diagonal breaks are an indicator of a MH material.

Remold the sample into a coarse thread and pull it apart. A tough thread indicates high plasticity (CH or CL). A medium tough thread indicates a MH material. A weak thread indicates a ML material.

Test 4

To make a ribbon test, use a sample with a moisture content at or slightly below the plastic limit. The ribbon is formed by squeezing and working the sample between the thumb and forefinger.

A weak ribbon which breaks easily indicates a ML soil. A hard ribbon which breaks fairly readily indicates a MH soil. A flexible ribbon with medium strength indicates a CL soil. A strong flexible ribbon indicates a CH soil.

Test 5

A test for stickiness can be made by saturating material and letting it dry on the hands. A ML soil will brush off with little effort. A CL or MH soil rubs off with moderate effort when dry. A CH soil requires rewetting to completely remove it from the hands.

Test 6

To make a Liquid Limit (LL) test, take a part of moist soil with a volume of about one-half cubic inch (1.6 cm^3) and add enough water to make the soil soft but not sticky. Rapidly add enough water to cover the outer surface. Break the pat open immediately. A positive reaction has occured when the water has penetrated through the surface layer. If the water has penetrated, the LL is low. If the water has not penetrated, the LL is high. Visual observation of this phenomenon is much easier in direct sunlight.

4. Special Condition Test

Odor Test

Fresh damp organic soils have a distinctive, pungent, musty odor.

Acid Test

Hydrcholoric acid makes calcium carbonate soils fizz.

Shine Test

In making the shine test, be sure soil is micaceous. Rub a small clod of air-dry soil with a knife blade. A shiny surface indicates high plasticity. You are seeing the shine of the dry, high plastic fines.

5. Montmorillontie Test

To make a test for montmorillonite, drop a few drops of a saturated water solution of benzidine hydrochloride on the soil sample. The appearance of a blue or blue-green color indicates that montmorillonite clay particles are present. This test will not indicate the quantity of montmorillonite particles present.

6. Acetone Test

Place one part soil and ten parts water (by weight) in a small bottle. Stopper the bottle and shake by hand 6 times at 15-minute intervals. Filter the extract through filter paper. Mix a 50-50 solution of the filtrate and acetone. The formation of a milky percipitate indicates the presence of gypsum.

All the tests listed above are field tests meant to aid in the tentative classification of soils. The test on summarized on Figure B-6. A high degree of proficiency with these techniques can be attained by practicing each test on samples of known classification. They are not precise and are not intended to replace more accurate laboratory methods.

Section 5 : Properties That Affect Engineering Behaviour of Soils

A. Inherent Soil Characteristics

1. Soil Grains. The size, distribution, and shape of soil grains are most important in coarse grained soils. Soils strength generally increases while permeability and compresibility generally decrease with increased size and better distribution.

2. Plasticity. Plasticity is most important in fine grained soils. Soils with higher plasticity generally have higher cohesion and resistance to piping, erosion, and settlement cracks than soils with lower plasticity.

3. Density. The density of a soil mass is probably the most important single determinant of the engineering behaviour of soils. Soil strength generally increases while permeability and compressibility generally

decrease with increased density. Density can be increased by compaction and by consolidation under static loads.

B. Behaviour Characteristics

1. Strength. Shear strength of soil is made up of two elements, friction and cohesion.

In its simplest form, friction is the resistance to sliding of one block of nonplastic soils against another. It is similar to, and can be assumed to have the same action as, the resistance of a block of wood sliding down a wooden plane. The friction in soil is complicated by such factors as the irregularity of the plane, interlocking of opposite particles, and size and shape of the soil grains. The greater the weight placed on the sliding block the greater force is necessary to cause the block to slide.

Cohesion is the result of the magnetic-like attraction of particles that is noted in one form as the plasticity and stickiness of soils. It resists one block of soil sliding on another, but cohesion resistance does not increase with increased load on the block.

Both friction and cohesion of soils increase with increased density.

2. Erosion. Resistance to internal erosion or piping follows very closely the soils resistance to surface erosion. Soils with a high susceptibility to sheet erosion also have a high piping potential, and therefore are critical to earth structure safety. In contrast, soils with a low susceptibility to surface erosion such as the more plastic soils do not present an internal erosion problem.

3. Cracking. Cracking of embankments may be caused by either of two physical actions or a combination of them.

Cracking may be caused by drying. As the soil drys, it shrinks and cracks form. The finest materials develop the highest cracking potential. Plasticity is only an indirect indicator of cracking potential because

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higher plasticity means finer material. In non-plastic materials have the same grain size as plastic materials their cracking potential is essentially equal.

Cracking due to movement of embankments is a result of both the amount of movement and the deformability of the material. Deformability of embankments is a result of both the plasticity of the material and the water content at which the embankment is built. Generally the lower the water contect when compacted the more brittle the embankment and the higher the cracking potential.

4. Permeability. Permeability depends on both the size and volume of pores in a soil; hence, it increase as grain size increases and decreases as density increases.

5. Compressibility. Compressibility of a soil deals with how readily and how much it will decrease in volume when subjected to load. Compressibility depends on the volume of voids in the soil, and increases with decreasing density. The amount of settlement that will occur in a soil depends on its compressibility and on the size of the load to be placed on it. Because of grain to grain contacts, coarse grained soils may be nearly incompressible under static loads but may settle from shock or vibration. The finer grained soils are more susceptible to settlement.

6. Shrink - Swell. High swell potential occurs in highly plastic soils and is related to increase of moisture contents under low loads. The swelling capacity may be estimated from the plasticity index of a soil. Soils with a plasticity index of more than 20 usually have a medium to high swell potential; those with more than 35 normally fall in the very high category. The strength of soils after swelling is greatly reduced.

Upon drying from saturation to the shrinkage limit, soils with a low shrinkage limit will shrink more than those with a high shrinkage limit.

If possible, the placement of soils with a high shrink-swell potential should be restricted to interior zones of embankments where little changes of moisture will occur, and where loads will be imposed which will tend to prevent swell.

7. Bearing Capacity. The ultimate bearing capacity of a soil is the average load per unit area required to produce failure by rupture of a supporting soil mass. Bearing capacity is important in evaluating the ability of soils to safely support semi-rigid structures through footings, piers, or piles.

Section 6 : Site Investigation and Uses of Materials

A. General

Field decisions on specific site conditions will develop naturally when adequate information is available.

Good site investigations are dependent upon adequate background information. The first need is to gather and list all the soil and geologic conditions that affect embankment and foundation characteristics for the area being considered. As new information is developed, it should be recorded. The local history and performance of structures in similar areas and under similar conditions should be studied and evaluated.

Dams and higher levees and canal embankments over twenty-five feet (7.5 meters), need increasingly careful evaluation of foundation and embankment materials. Even embankments with less height having known or suspected unusual foundation conditions, low density materials or porous foundation strata should be carefully investigated and determination made as to the field tests or laboratory tests needed.

A minimum amount of boring and soil classification will suffice for those sites where materials and conditions are similar to other sites in the area where completed structures have performed satisfactorily. This is particularly true for canal and drain alignments.

B. Site Selection

From a soils engineering viewpoint, site selection is foundation selection plus embankment material selection and availability. A good foundation must meet certain requirements which are based on the functions of the structure to be built. The basic requirements are:

* The foundation, which includes the cut sections for canals, must be stable and safe from structural failure due to the intended loads/use of the structure.

* The foundation must not settle or swell enough to damage the structure or reduce its usefulness.

* Water must not be able to flow through the foundation at a rate that will endanger the stability of the structure or impair its usefulness.

* The water table desireably should be low enough so as not to make construction excessively expensive.

* Foundation materials should not be highly susceptible to cracking and internal erosion or piping.

C. Extent of Site Investigation

The base area of the contemplated structure should be carefully examined. Exploration into the foundation should extend as far below a given section as necessary to reveal the conditions important to safe design and construction.

Borrow areas should be explored and samples investigated for each major change in material and for a computed amount of material that is enough to build the structure plus and additional 25 to 50 percent.

Canal alignments should be auger holed and samples investigated for each major change along the alignment. Premeability tests should be conducted

in sufficient locations to determine canal lining requirements where excessive seepage loss are anticipated. Gradation curves of bank materials are required for design purposes.

D. Embankment Material

Drilling and sampling of the site should be intensive enough to accomplish the following:

* Classification of materials by the Unified Soil Classification System.

* Represent a major portion of the available embankment material.

* Determination of compaction characteristics of the embankment materials along a canal or from borrow materials by running appropriate tests or using experience data.

* Evaluation of the inplace moisture conditions in the canal alignment or borrow areas. Construction may have to be postponed until a drier period if materials are too wet for proper compaction. Moisture will have to be added during construction operations if the soils are too dry.

* Permit canal and levee embankments to be designed and placed in accordance with Design Standards and Specification.

* Suitable embankment material, in sufficient quantity, must be available either on or within an economic haul distance from the site.

E. Foundation Material

Investigation of foundation materials may be made with power equipment augers or hand excavated trenches or test pits. Sampling should be in sufficient detail to:

* Classify the materials using the Unified Soil Classification System. This may involve wet sieving through the # 4 and # 200 sieves for all coarse-grained materials in order to determine the percentages of fine sand and gravels.

* Represent all changes of materials as to depth and area that will affect the stability of proposed structures.

1. Permeable Layers. Layers will be considered permeable if they are composed of GW, GP, SW and SP. SM's or SC's with less than 15 percent fines and Gm's or Gc's with less than 20 percent fines will also be considered permeable. Layers will be considered semipermeable if they are composed of CL, CH, ML and MH materials. SM's or SC's with more than 15 percent fines and GC's with more than 20 percent fines will also be considered semipermeable.

Special control measures for stability are not necessary if the natural semipermeable material overlying the permeable material under a proposed embankment equals or exceeds the following thickness:

Permeable Layer (feet)	Thickness (meter)	Minimum Natural Blanket (feet)	Thickness (meter)
1	0.3	5	1.5
2	0.6	8	2.5
4	1.2	11	3.3
6	1.8	12	3.6
8	2.5	13	4.0
10	3.0	14	4.3

Where special measures are required they may consist of one of the following:

* Interception of the permeable layer with a cutoff trench.

* A drain in the downstream portion of the embankment penetrating a minimum of three feet into the permeable material. Where seepage losses are a major factor, the first alternative should be used if at all feasible.

Drains should be positioned at the contact of the foundation and the embankment about 2/3 of the distance from the downstream shoulder to the downstream toe.

Drain material should be a well graded sand or gravel or a designed filter material.

F. Springs and Seeps

Where springs and seeps occur under the base of the embankment or in a canal, their point of base flow must be located and uncovered. A drain should then be installed to control the flow of the water until it is clear of the embankment. Water originating upstream of the embankment centerline should be conducted upstream and water originating downstream of the centerline should be outletted downstream.

G. Piping Potential

Pipes are formed by underground erosion. Water moving through the soil carries the fine particles away and a series of eroded tubes or tunnels develop. These openings will grow progressively larger and can cause an embankment failure. Piping occurs in the same materials that are highly susceptible to erosion on the surface such as fine sands and materials containing nonplastic or dispersed fines. The presence of easily erodible materials in the foundation may call for special treatment. A drain, installed as described in Section 6.E.1. Permeable layers, is the best protection against piping. The premeable drain material should be designed on the basis of particle size and gradation in relation to the erodible

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materials. An alternative measure is to completely cut off flow through the erodible material with a trench backfilled with compacted, fine grained, nonerodible material.

H. Differential Movement

Conditions that might cause differential settlement of a structure or embankment should be throughly investigated to provide the design engineer with a complete evaluation of the site conditions.

I. Soluble Salts

The presence of soluable salts, especially gypsum, in a soil indicates potential settlement problems in the foundation or embankment. High salt content often results in honeycombed or flocculent soil structures. These soils structural units or aggregates may collapse when the soil becomes saturated and loaded.

Where salt content, especially gypsum, is greater than 2 percent in the foundation or 4 percent in the embankment material, technical assistance and laboratory tests should be requested. A soil scientist can help in identifying troublesome gypy or other salty soils. Gypsum deposits dissolve when water is present.

J. Configuration of Site

The site should be adequately mapped to show all local topographic conditions as well as the location of all borings. Test pits and other investigations conducted. Surface elevation of all drilling sites is required when deep or grouond water investigations are required.

K. Stratigraphy

Soil layers that have been laid down in valley bottoms by water pose a problem in determining how far they extend. A highly permeable layer that extends under the structure from the pool area and outlets downstream is a threat to the safety of a structure. So is a layer that stops under the downstream toe of an embankment or structure because high water pressures can develop. Very soft layers that lie between nominally strong layers can

also threaten the safety of the structure.

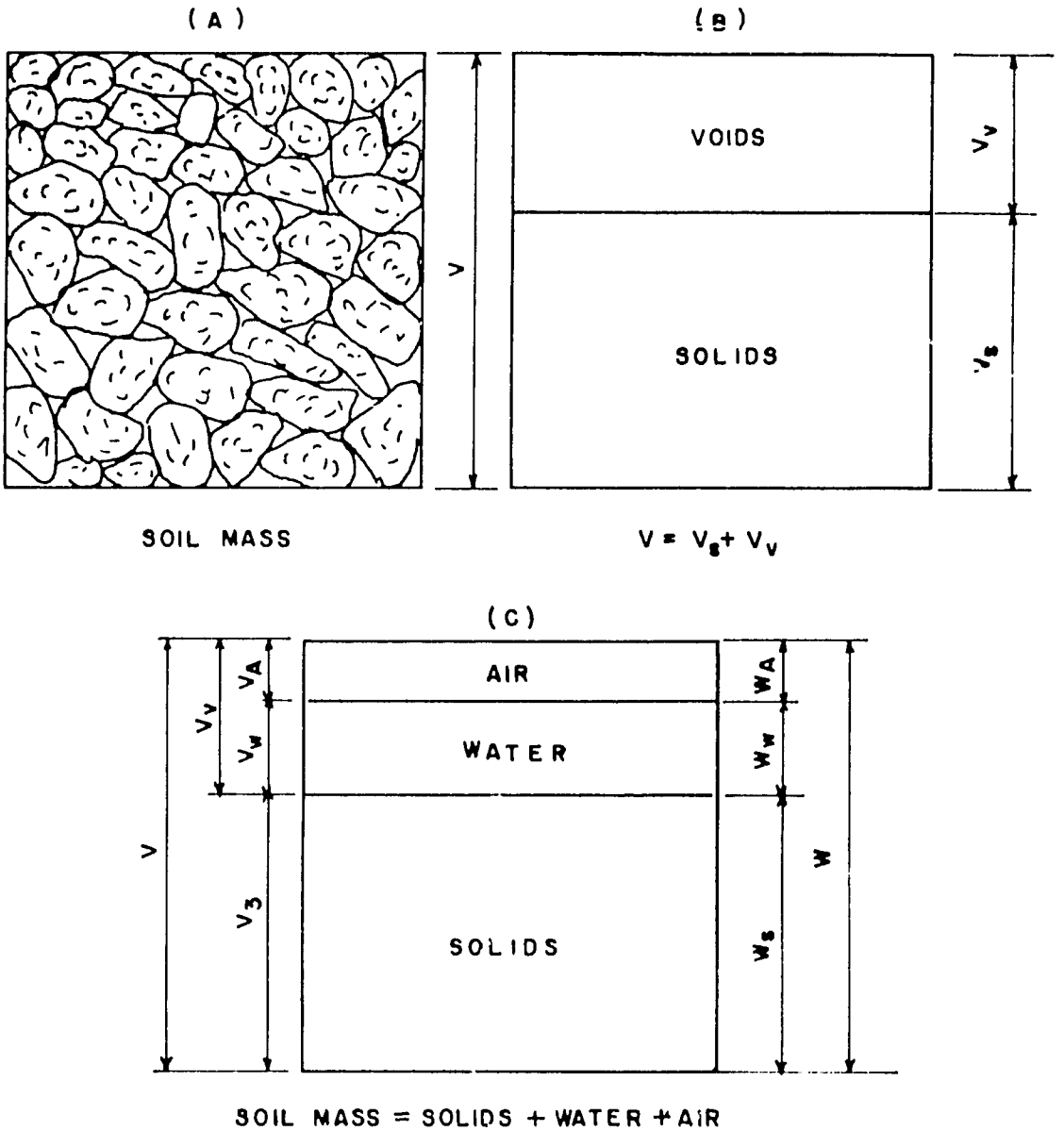
How deep a rock layer is weathered needs to be determined when the weathering creates one of the conditions already described as dangerous. If the rock face is covered by a layer of soil material, the needed investigations are more difficult.

Water table location is important to design and construction. Water at near the surface may prevent construction or require counter measures, such as predrainage. At best, it is likely that such a condition will make construction more difficult and costly. Seasonal variation in water table need to be determined.

TABLE B-1

PARTICLE SIZES

Term		Particle Size	Examples
Gravel		3" to approx. 1/4"	Lemon to Pea
1.	Coarse	3" to 3/4"	Lemon to Walnut
2.	Fine	3/4" to #4	Walnut to Pea
Sand			
1.	Coarse	#4 to #10	Pea to Rock Salt
2.	Medium	#10 to #40	Rock Salt to Table Salt
3.	Fine	#40 to #200	Table Salt to Powdered Sugar
Fines		Less than #200	



Volumes

$V = V_s + V_w + V_a$

$V_v = V_a + V_w$

Void Ratio, $e = \frac{V_v}{V_s}$

Porosity, $n = \frac{V_v}{V}$

Percent Saturation, $S = \frac{V_w}{V_v} \times 100\ (\%)$

Weights

$W = W_s + W_w + (W_a = 0)$

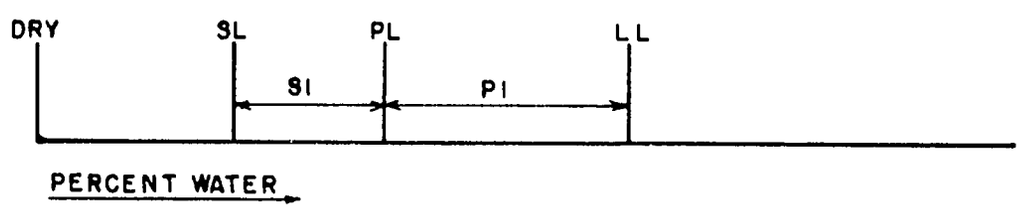
Percent Moisture,

$w = \frac{W_w}{W_s} \times 100\ (\%)$

DEFINITIONS
SOIL VOLUM AND WEIGHT

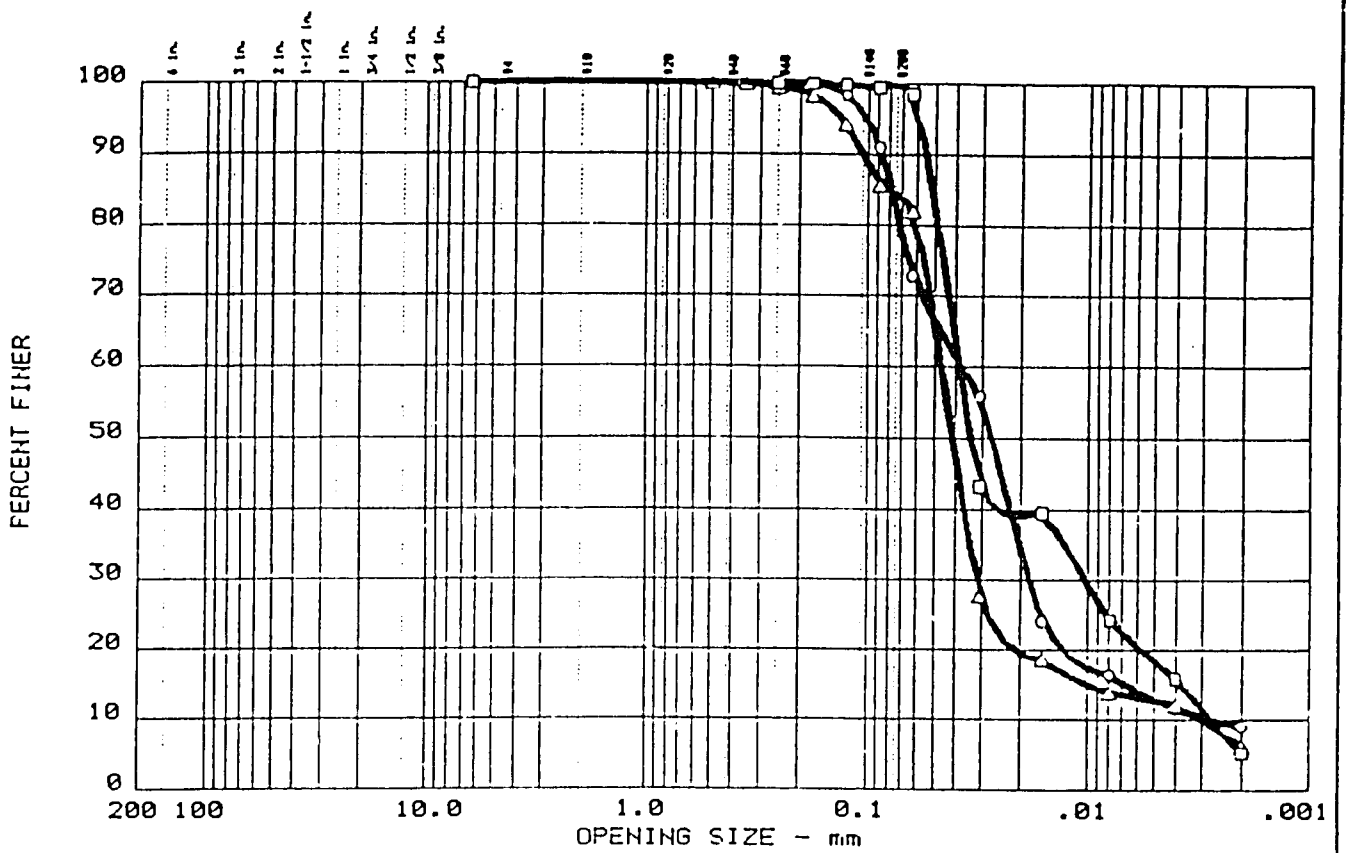
Consistency	Identification Procedure	Shear Strength tons/ ft^2 or kg/cm^2
Soft	Easily pentrated several inches by thumb	Less than 0.25
Firm(medium)	Penetrated several inches by thumb with moderate effort	0.25 to 0.50
Stiff	Readily indented by thumb, but penetrated only with great effort	0.50 to 1.00
Very stiff	Readily indented by thumb nail	1.00 to 2.00
Hard	Indented with difficulty by thumbnail	over 2.00

IDENTIFICATION OF CONSISTENCY OF FINE-GRAINED SOILS



ATTERBERG LIMITS

BEHAVIOR CHARACTERISTICS



	%+3"	% GRAVEL	% SAND	% SILT	% CLAY
○	0.0	-0.0	18.1	68.9	13.0
△	0.0	-0.0	15.5	71.6	12.9
□	0.0	-0.0	-0.0	81.6	18.4

	Classification		LL	PI	D_{60}	D_{30}	D_{10}	C_c	C_u
	USCS	AASHTO							
○	ML				0.04	0.018	0.0026	3.54	14.2
△	ML		31.0	4.1	0.05	0.031	0.0030	6.94	15.4
□	ML		27.5	N/A	0.04	0.010	0.0027	1.03	14.3

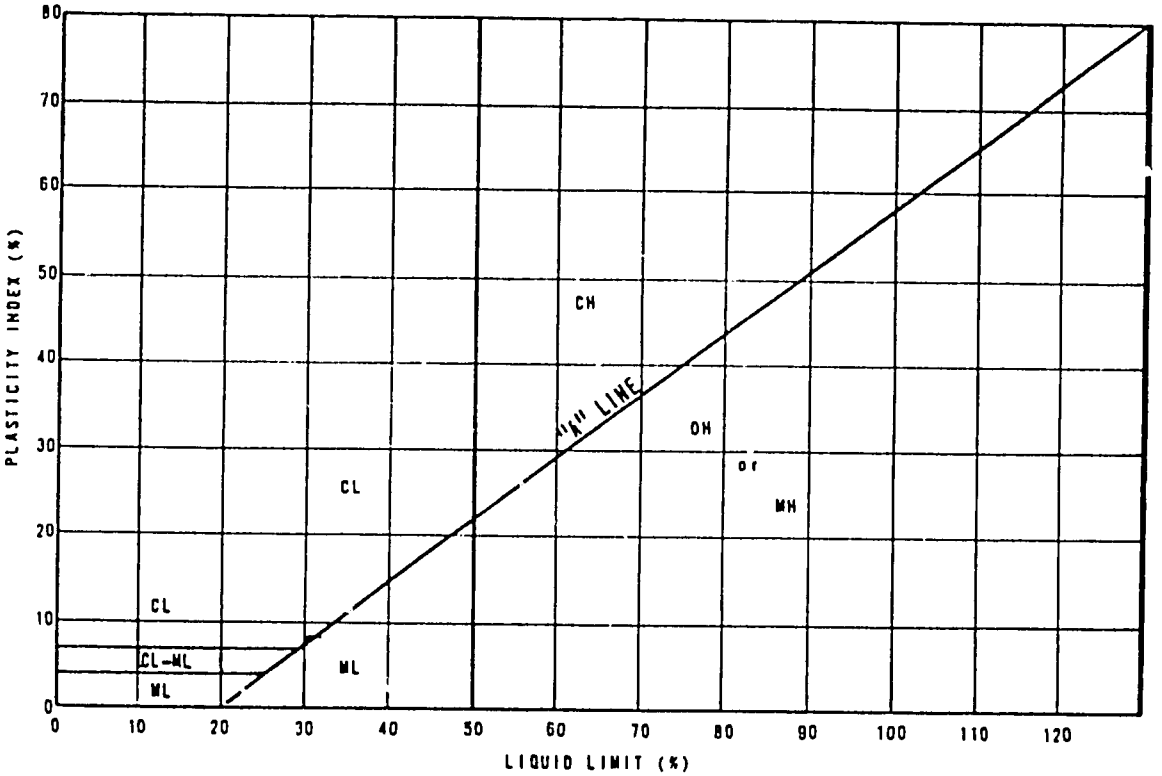
MATERIAL DESCRIPTION	TYPE OF TEST
○ B-9-1 △ B-10-1 □ B-10-2	ASTM D 422-63(72) Hydrometer analysis Mechanical analysis

Project No.: 20-1323-04(9-1)
Project: ISM-PAKISTAN
○ Location: Kachahar Disty, RD 42, stable canal bnk
△ Location: Rohri Canal, RD 770, silt berm
□ Location: Rohri Canal, RD 770, embankment
Date: 5-26-86

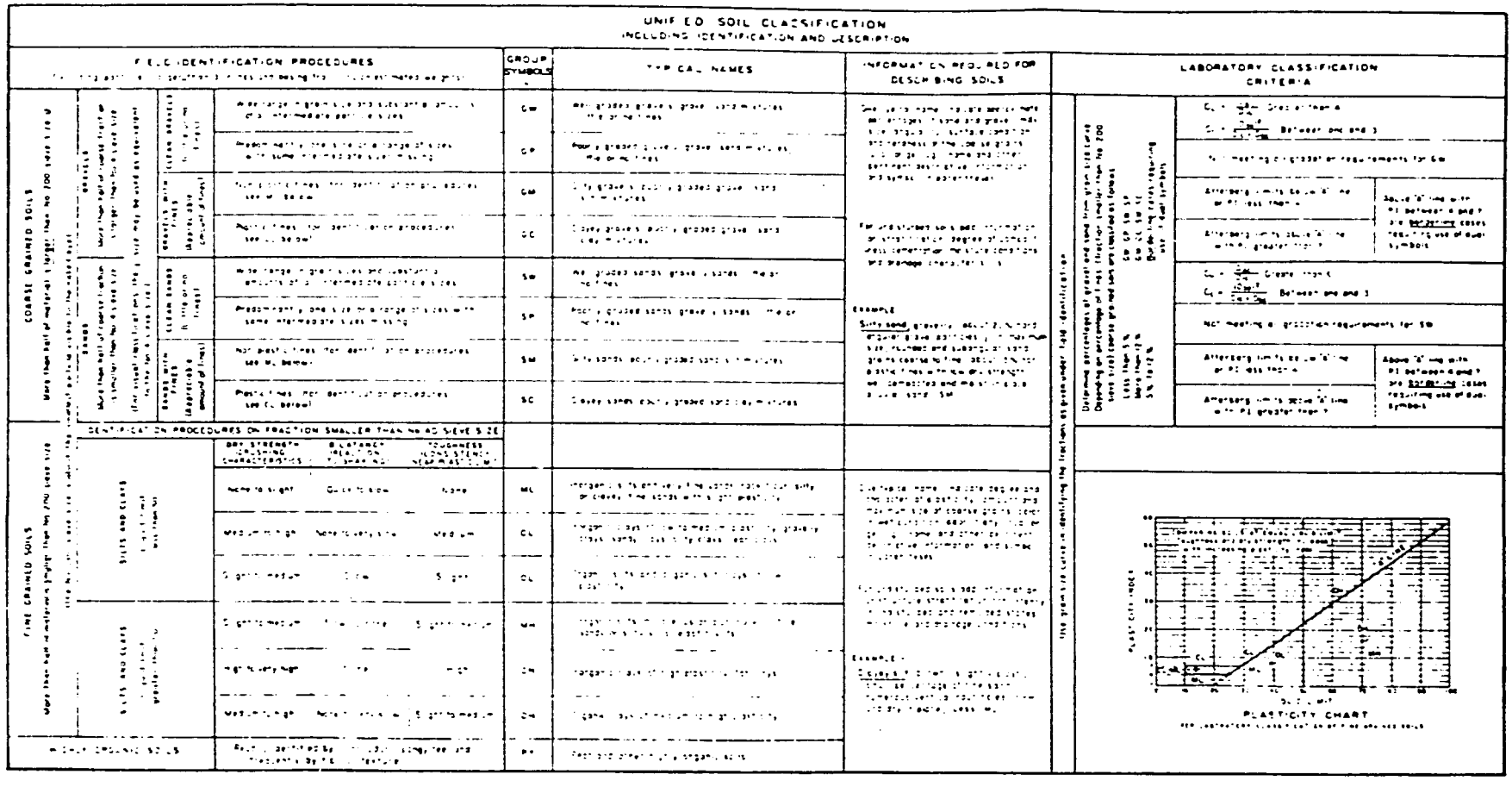
Remarks:

GRAIN SIZE DISTRIBUTION TEST REPORT
PRC Engineering

GRAIN SIZE DISTRIBUTION TEST REPORT



PLASTICITY CHART



UNIFIED SOIL CLASSIFICATION CHART

COARSE GRAINED SOILS More than half of the material (by weight) is individual grains visible to the naked eye.	GRAVELLY SOILS More than half of Coarse Fraction is larger than 1/4".	CLEAN GRAVELS Will not leave a stain on a wet palm			Substantial amounts of all grain particle sizes						GW
					Predominantly one size or a range of sizes with some intermediate sizes missing						GP
		DIRTY GRAVELS Will leave a stain on a wet palm			Nonplastic fines						GM
					Plastic fines						GC
	SANDY SOILS More than half of Coarse Fraction is smaller than 1/4".	CLEAN SANDS Will not leave a stain on a wet palm			Wide range in grain size and substantial amounts of all grain particle sizes						SW
					Predominantly one size or a range of sizes with some intermediate sizes missing						SP
		DIRTY SANDS Will leave a stain on a wet palm			Nonplastic fines						SM
					Plastic fines						SC
FINE GRAINED SOILS More than half of the material (by weight) is individual grains not visible to the naked eye.		RIBBON	None	LIQUID LIMIT	< 50	DRY CRUSHING STRENGTH	None to Slight	DILATANCY REACTION	Rapid	TOUGHNESS	Low	STICKINESS	None	ML
			Weak		< 50		Medium to High		None to Very Slow		Medium to High		Medium	CL
			Strong		> 50		Slight to Medium		Slow to None		Medium		Low	MH
			Very Strong		> 50		High to Very High		None		High		Very High	CH
HIGHLY ORGANIC SOILS		Readily identified by color, odor, spongy feel and frequently by fibrous texture.												OL OH Pt

SUMMARY OF FIELD IDENTIFICATION TESTS

FIGURE B-6

APPENDIX C

EXAMPLE OF DEVELOPING CANAL MAINTENANCE YARDSTICKS

APPENDIX C

EXAMPLE OF DEVELOPING CANAL MAINTENANCE YARDSTICKS

A. General

The improved maintenance of rehabilitated canals will consist of major maintenance of a portion of the system to be done annually and of regular maintenance of all of the system done seasonally. Annual restoration of 20% of the canal embankments is considered major maintenance while repair and maintenance of the canal prism, embankment and patrol roads is considered regular or routine maintenance.

Two general methods of performing maintenance are considered; labor intensive and machine intensive. The unit costs of each operation are given for each method.

This Appendix provides the basic for determining yardsticks. The numbers are to be considered as representative of conditions to be found in the field. The methodology presented is important.

B. Methods

Suitable work tasks (operations) for the annual maintenance program of canal embankments are:

Excavation	Labor or machine (backhoe)
Load	Labor or machine (backhoe or front end loader)
Haul	Labor (head basket, wheelbarrow, donkey of tractor-trolley) or machine (dump truck)
Placement	Includes spreading, watering and incorporation and may be done by labor or machine (dozer, grader, tantum disc, water truck).

Compaction	Machine only (compaction of all added material to a minimum density of 85% Standard Proctor requires towed or self-propelled tamping rollers).
Turfing	Labor only (no practical machines exist).

Suitable tasks for regular maintenance operations are:

Sediment Removal	Labor (head basket, wheel barrow, donkey and tractor-trolley) and machine (dredge, backhoe, dragline or scraper,).
Road Grading	Machine (farm tractor with blade or towed grader or motorgrader).
Erosion Control	Includes construction of killa-bushing, replacing brick pitching and lining and earth-work necessary to these operations and is done by labor only.

C. Quantities

The earthwork quantities required for major and regular maintenance of canals are given in Tables C-1 and C-2. All earthwork quantities are measured inplace (i.e., the volume of compacted earth in the embankment is about 60% of the loose volume). Earthwork is assumed to be in soils of medium texture located 10 to 200 feet from the toe of embankment. Embankments crests are assumed to average 5 feet above ground level.

D. Labor Intensive Alternative

1. Excavation, Load and Haul - Four types of labor intensive earthwork methods can be considered; headbasket; wheelbarrow, donkey and tractor-trolley. Headbaskets can be used in dry soil and leads up to 100 feet, wheelbarrow in wet soil and leads up to 500 feet, donkey-labor in wet soil and leads up to 1000 feet and tractor-trolley in dry soil and unlimited leads. The following gives a comparison of the unit costs of the 4 methods.

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Labor Methods	Required Laborers	Production Rate 1/ (ft/hr)	Hourly Cost 2/ (Rs./hr.)	Unit Cost (Rs./ft)
Headbasket	1	30	5.25	0.18
Wheelbarrow	2	50	10.60	0.21
Donkey	2	75	21.00	0.28
Tractor Trolley	8	90	106.00	1.18

Notes: 1/ Based on 50-foot lead (10 feet horizontal land 5 feet lift).

2/ Direct cost including labor and equipment plus 40% contractor overheads and profit.

3/ Includes excavation, loading and dumping (capacity = 90 ft^2, cycle time = 1 hour).

The Labor Intensive Alternative uses the headbasket method for leads up to 100 feet, wheelbarrow method for leads up to 500 feet and tractor-trolley method for longer leads. Donkey-labor contractors are said to be scarce while contractors owing tractor-trolleys are becoming more numerous. The unit cost of earthwork will vary as shown in the following table:

Canal Size Category (ft^2/s)	Equivalent Lead (ft)	Production Method	Production Rate (ft/hour)	Hourly Rate (Rs.hr.)	Category Unit Cost (Rs./ft)
Below 30	20	H/B	30	5.25	0.18
30 - 200	50	H/B	30	5.25	0.18
200 - 1000	300	W/B	20	10.60	0.53
1000 - 5000	300	W/B	20	10.60	0.53
5000 - 10000	500	W/B	16	10.60	0.66
10000 - 15000	500	W/B	16	10.60	0.66
Above 15000	1000	T/T	110	130.00	1.18
Lined	1000	T/T	110	130.00	1.18
Average	-	-	-	-	0.30

Notes 1/ H/B = Headbasket, W/B = Wheelbarrow, T/T = Tractor-trolley.

2/ 50 minutes/hour, 8 hours/day, 200 days/year.

3/ Includes 40% overhead and profit.

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2. Placement - Placement of earth on embankment crests and slopes includes additional of water (in most cases), incorporation and spreading. These operations can all be done by labor and their costs are shown in the following table:

Operation	Required Laborers	Production Rate (ft/hr)	Hourly Cost (Rs./hr)	Unit Cost (Rs./ft)
Spreading	1	500	5.25	0.01
Watering	1	400	15.75 1/	0.04
Incorporation	1	50	5.25	0.10
Total	-	-	-	0.15

Note 1/ Includes OM&R cost of 5 hp. kerosine driven 2x2 pump (Rs 10.5/hour).

All material will be placed dry, watered and incorporated inplace.

3. Compaction - Compaction of crest and slopes must be done by mechanical means to achieve 85% density requirements. Although several methods of mechanical compaction are in use, best production will be achieved by tamping roller (towed, self-propelled and/or vibrating). Crests will be compacted in 4 passes over 6-inch lifts (compacted) with self-propelled vibrating 6-ton sheepsfoot tamping roller. Slopes will be compacted using a combination of side boom D4 dozer and a towed vibrating 2-ton sheepsfoot tamping roller. Slope compaction will require 4 passes per 6-inch lift. The cost of these operations are given in the following table:

Operation	Production Rate(ft)	Hourly Cost (Rs./hour)	Unit Cost (Rs./ft)
Crest Compaction	6000	140	0.023
Slope Compaction	6000	350	0.058
Average:	-	-	0.05 1/

Note: 1/ Since approximately 30% of the earthwork is on the crest and 70% on the slope, the weighted average compaction would be Rs 0.05/ft.

4. Turfing - Re-establishing a grass cover on the outside slopes is a labor operation. The unit cost of turfing is as follows:

Operation	Required Laborers	Production Rate (ft^2/hr)	Hourly Cost (Rs./hr)	Unit Cost (Rs./ft^2)
Transplanting	1	50	5.25	0.10
Grass Sprigs	-	-	-	0.20
Total	-	-	-	0.30

Since there is a 10-inch depth of earthwork applied on the embankment slope, the unit cost of grassing may be taken as Rs.0.36/ft^3.

5. Sediment Removal - Removal of deposited sediment during annual closure may be done by labor methods for canals with short leads. It was assumed that all of the sediment would be deposited as follows: 40% in canals under 30 ft^3/s, 35% in 30-200 ft^3/s and 25% in canals 200-1000 ft^3/s. The quantities to be removed are given in Table C-2 and the unit costs are given in Table C-3.

6. Berm Replacement - Berms are necessary to protect the toe of embankments, particularly below structures and are formed by constructing traditional killa-bushing and hanging spurs which reduce the velocity of flow and induce sedimentation. Killa-bushing techniques are labor intensive and use tree limbs and brush usually found growing along the embankment and right-of-way. Although the cost of constructing a hanging spur is less than killa-bushing,the unit cost per cubic foot of berm formed is about the same because it is less efficient. The unit costs are as follows:

Operation	Production Rate(ft^3)	Hourly Cost (Rs./hour)	Unit Cost (Rs./ft^3)
Labor	10.5	5.25	0.5
Material	-	-	0.8
Total	-	-	1.3

7. Pitching and Lining Repair - Maintenance standards call for replacing 25 feet of dry brick pitching per year on unlined canals (mainly downstream of structures) and 50 lineal feet of mortared brick lining (full cross-section) on lined canals. The unit cost of pitching is as follows:

Operation	Production Rate(ft^2/hour)	Hourly Cost (Rs./hour)	Unit Cost (Rs./ft^2)
Pitching			
Labor	9.0	5.25	0.6
Materials 2/	-	-	5.0
Total Pitching	-	-	5.6
Lining			
Labor	4.5	5.25	0.9
Materials 2/	-	-	4.0
Total Lining	-	-	4.9

Notes: 1/ Includes hauling and placing all materials.
2/ 10 brick/ft^2 @ Rs. 0.5/brick plus sand.
3/ 8 brick/ft^2 @ Rs. 0.5/brick plus mortar.

8. Pitching Earthwork - A significant amount compacted earthwork is usually lost after failure of brick pitching and lining and must be replaced. An estimate of these quantities is given in Table C-2 and the unit costs of replacing the quantities will be the same as those calculated for providing compacted embankments.

9. Road Grading - The improved standards for maintenance of unpaved inspection roads requires grading six times per year. This operation is in addition to periodic watering done by beldars to control dust and minor repairs. Although surface grading can theoretically be done without equipment, satisfactory labor methods have not been practiced in Pakistan. It is, therefore, recommended that a 125 hp motorgrader fitted with a 12-foot blade be used for calculating the unit cost of road grading. The average production rate is 100,000 ft^2/hour and the hourly rate is Rs. 350/hour giving a unit cost of Rs. 3.5/100 ft^2.

10. Contract Administration - The Labor Intensive Alternative will require additional costs to ensure adequate performance by contractors. The items and cost break-down are as follows:

Item	Required (No./mile)	Unit Cost (T Rs.)	Yardstick (T Rs./mile)
Tools and Plant	L.S.	-	0.1
Vehicles (OM&R) 1/	0.02	20.8	0.4

Note: 1/ Based on one vehicle required per 50 miles of canal.

11. Canal Yardsticks - A summary of the yardstick costs of completing 10 separate operations necessary for major and annual maintenance of canals is given in Table C-4. All of these yardsticks are stated in Rupees per mile of canal.

TABLE C-1

EARTHWORK QUANTITIES FOR MAJOR MAINTENANCE
OF CANAL EMBANKMENTS

Size Category (ft^3/s)	Lengths (miles) Total	Lengths (miles) Annual Maintenance 1/	Top Width 2/ (feet) Path Side	Top Width 2/ (feet) Patrol Side	Earthwork Quantities 3/ ($1000\ ft^3$/total mile) Crest	Earthwork Quantities 3/ ($1000\ ft^3$/total mile) Outside Slope	Earthwork Quantities 3/ ($1000\ ft^3$/total mile) Total	Equivalent Lead 4/ (ft)
Below 30	7000	1400	4	4 5/	3.8	9.2	13.0	20
30 - 200	9290	1860	7	12	9.1	14.4	23.5	50
200 - 1000	4100	820	9	15	9.4	15.8	25.2	300
1000 - 5000	1600	320	12	20	12.2	26.2	38.4	300
5000 - 10000	580	115	12	20	15.3	33.1	48.4	500
10000 - 15000	160	30	12	20	15.3	37.3	52.6	500
Above 15000	170	35	12	20	15.3	39.4	54.7	1000
Lined	380	25	12	20	15.3	33.1	48.4	1000
Total	23280	4655	-	-	-	-	-	-
Average 6/	-	-	-	-	8.1	15.0	23.1	-

Notes:

1/ 20% of total length receives major maintenance annually.

2/ From proposed design criteria.

3/ From maintenance standards given in PRC/C O&M Report except turfing yardstick has been added which will offset cost of rain cut repair.

4/ Horizontal haul distance multiplied by the vertical lift.

5/ No patrol road on bank.

6/ Weighted according to length.

TABLE C-2

REGULAR MAINTENANCE QUANTITIES FOR CANAL PRISM

Size Category (ft^3/s)	Total Length (miles)	Sediment Removal 1/ ($1000ft^3$/mile)	Erosion Control: Berm Replacement 2/ ($1000ft^3$/mile	Erosion Control: Pitching & Lining Repair 3/ ($1000ft^2$/mile)	Erosion Control: Earthwork 4/ ($1000ft^3$/mile)	Patrol Road Grading 5/ ($1000ft^2$/mile)
Under 30	7000	17.1	0	0	0	360
30 - 200	9290	11.3	0.6	0.3	0.3	360
200 - 1000	4100	18.3	1.6	0.5	1.9	450
1000 - 5000	1600	0	3.2	0.8	2.4	450
5000 - 10000	580	0	5.2	1.1	3.8	600
10000 - 15000	160	0	6.6	1.1	4.8	600
Over 15000	170	0	6.6	1.1	6.0	600
Lined	380	0	0	6.2	6.2	600
Total	23280	-	-	-	-	-
Average 6/	-	12.9	1.0	0.4	0.9	390

Notes:

1/ Assumes 40% in "below 30" , 35% in "80-200", 25% in "200-1000"

2/ Replace annually 50 feet length of berm of varying width (2 to 7 feet) and depth (4 to 15 feet)

3/ Replace annually 25 feet length of pitching of varying depth (4 to 15 feet) and 50 feet length of full cross-ection of lining (125 feet)

4/ 5-feet width required for pitching and 1-foot width for lining

5/ Patrol road lengths times 6 passes per year

6/ Weighted according to length.

TABLE C-3

UNIT COST OF SEDIMENT REMOVAL

Size Category (ft^3/s)	Bed Width (ft)	Bed Level Crest (ft)	Equivalent Lead 1/ (ft)	Production Rate 2/ (ft^3/hr)	Hourly Rate 3/ (Rs./hr)	Unit Cost (Rs/ft^3)
Below 30	6	3.5	10	30.0	5.25	0.18
30 - 200	10	4.5	11	30.0	5.25	0.18
200 - 1000	45	6.5	13	20.0	5.25	0.26
Average:	-	-	-	-	-	0.20

Notes: 1/ One-fourth of bed width times lift.

2/ Based on equivalent lead, headbasket and wheelbarrow methods and dumping on embankment.

3/ Includes contractor overhead and profit (40%).

TABLE C-4

SUMMARY OF CANAL YARDSTICKS FOR
LABOR INTENSIVE ALTERNATIVE

Operations	Units	Size Categories - ft^3/s Under 30	30-200	200-1000	1000-5000	5000-10000	10000-15000	Over 15000	Lined	Total/ Ave 3/
Total Length	Miles	7000	9290	4100	1600	580	160	170	380	23280
Excavation, Load, Haul (L)										
Quantity 1/	Tft^3/mile	13.0	23.5	23.4	23.4	48.4	52.6	54.7	48.4	
Unit Cost	Rs/ft^3	0.18	0.18	0.53	0.53	0.66	0.66	1.18	1.18	
Yardstick	TRs/mile	2.3	4.2	13.4	20.4	31.9	34.7	64.5	57.1	
Placement (L) 2/										
Quantity 1/	Tft^3/mile	13.0	23.5	25.2	38.4	48.4	52.6	54.7	48.4	
Unit Cost	Rs/Ft^3	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	
Yardstick	TRs/mile	2.0	3.5	3.8	5.8	7.[illegible]	7.9	8.2	7.3	
Compacting Crest (M)										
Quantity 1/	Tft^3/mile	3.8	4.1	9.4	12,2	15.3	15.3	15.3	15.3	
Unit Cost	Rs/Ft^3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	
Yardstick	TRs/mile	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3	
Compacting Slope (M)										
Quantity 1/	Tft^3/mile	9.2	14.4	15.8	26.2	33.1	37.3	39.4	33.1	
Unit Cost	Rs/ft^3	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	
Yardstick	TRs/mile	0.6	0.9	0.9	1.6	2.0	2.2	2.4	2.0	
Turfing (L)										
Quantity 1/	Tft^3/mile	9.2	14.4	15.8	26.2	33.1	37.3	39.4	33.1	
Unit Cost	Rs/ft^3	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	
Yardstick	TRs/mile	3.3	5.2	5.7	9.4	11.9	13.4	14.2	11.9	
Embankment Subtotal		8.3	13.9	24.0	37.4	53.4	58.2	89.6	78.6	
Sediment Removal (L)										
Quantity	Tft^3/mile	17.1	11.3	18.3	0	0	0	0	0	
Unit Cost	Rs/Ft^3	0.18	0.18	0.26	-	-	-	-	-	
Yardstick	TRs/mile	3.1	2.0	4.8	0	0	0	0	0	
Berm Replacement (L)										
Quantity 1/	Tft^3/mile	0	0.6	1.6	3.2	5.2	6.6	6.6	0	
Unit Cost	Rs/Ft^3	-	1.30	1.30	1.30	1.30	1.30	1.30	-	
Yardstick	TRs/mile	-	0.6	2.1	4.2	6.8	8.6	8.6	0	
Pitching & Lining Repair (L)										
Quantity	Tft^2/mile	0	0.3	0.5	0.8	1.1	1.1	1.1	6.2	
Unit Cost	Rs/ft^2	-	5.6	5.6	5.6	5.6	5.6	5.6	5.6	
Yardstick	TRs/mile	-	1.7	2.8	4.5	6.2	6.2	6.2	34.7	
Pitching Earthwork (L)										
Quantity 1/	Tft^3/mile	0	0.5	1.9	2.4	3.8	4.8	6.0	6.2	
Unit Cost	RS/ft^3	-	0.18	0.53	0.53	0.66	0.66	0.88	0.88	
Yardstick	TRs/mile	-	0.1	1.0	1.3	2.5	3.2	5.3	5.5	
Road Grading (M)										
Quantity	Tft^2/mile	300	360	450	450	600	600	600	600	
Unit Cost	Rs/ft^2	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	
Yardstick	TRs/mile	1.3	1.3	1.6	1.6	2.1	2.1	2.1	2.1	
Prism Subtotal		4.4	5.7	12.3	11.6	17.6	20.1	22.2	42.5	
Contract Administration		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Canal Total		13.2	20.1	36.8	49.5	71.5	78.8	112.3	121.4	27.0

Notes: 1/ Quantities are measured in place

2/ Includes spreading, watering and incorporating

3/ Weighted by length

L Labor operation

M Machine operation

T Thousands