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Theater Construction Management System, Site Design Module

Site Design Applications for the Theater Construction Management System

by
E. William East

The Theater Construction Management System (TCMS) is a collection of construction management and engineering software packages integrated by data links that allow data sharing between functional areas of the construction management process. The philosophy of TCMS development is to use commercially available software wherever possible, thereby allowing the Army to use the best software available without directly absorbing the costs associated with software development. This study investigated the possibility of using a commercial computer-assisted design and drafting (CADD) program in conjunction with geographical information systems (GISs) to automate the process of site design. Current (and most commonly used) site design practices were reviewed; the requirements and conceptual basis for such a software integration were developed; and two potential advanced technology site design applications were outlined.

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The Theater Construction Management System (TCMS) is a collection of construction management and engineering software packages integrated by data links that allow data sharing between functional areas of the construction management process. The philosophy of TCMS development is to use commercially available software wherever possible, thereby allowing the Army to use the best software available without directly absorbing the costs associated with software development. This study investigated the possibility of using a commercial computer-assisted design and drafting (CADD) program in conjunction with geographical information systems (GISs) to automate the process of site design. Current (and most commonly used) site design practices were reviewed; the requirements and conceptual basis for such a software integration were developed; and two potential advanced technology site design applications were outlined.

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FOREWORD

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This research was performed by the Facility Systems Division (FE), of the Infrastructure Laboratory (FL), of the U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was E. William East. Alan Moore is Acting Chief, CECER-FF, and Dr. Michael J. O'Connor is Chief, CECER-FL. Special acknowledgement is given to Jennifer Liu, USACERL, for developing some of the figures for this report. The USACERL technical editor was William J. Wolfe, Information Management Office.

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CONTENTS

CONTENTS (Cont'd)

TABLES

TABLES (Cont'd)

FIGURES

FIGURES (Cont'd)

SITE DESIGN APPLICATIONS FOR THE THEATER CONSTRUCTION MANAGEMENT SYSTEM

1 INTRODUCTION

Background

The Theater Construction Management System (TCMS) is a collection of construction management and engineering software packages integrated by data links that allow data sharing between functional areas of the construction management process. The philosophy of TCMS development is to use commercially available software wherever possible. Developing innovative means to integrate these software packages through the TCMS will allow the Army to use the best software available without directly absorbing the costs associated with software development. It may be possible to use a commercial computer-assisted design and drafting (CADD) program in conjunction with geographical information systems (GISs) to automate the process of site design. The first step in determining the feasibility of such a combination is to review current (and most commonly used) site design practices, and to outline the requirements and conceptual basis for the software application.

Objective

The objectives of this study were to (1) identify how automated tools for site design may be included within TCMS, (2) outline potential advanced technology site design applications, and (3) research and compile a wide variety of information on current site design practices.

Approach

This study proceeded in several distinct phases:

1. Literature on current site design practices was reviewed.
2. Specific needs of TCMS in the area of site design were determined.
3. Previous analyses of commercially available site design software were reviewed.
4. Types of projects most likely to benefit from a TCMS Site Design Module were identified.
5. A conceptual basis for including commercial site design systems in TCMS was developed.
6. Two advanced technology applications to site design were outlined.

Scope

This study was limited to site design as practiced by Army engineers. Differences between site design as conducted by the civilian engineers and engineers are identified as appropriate. Since the TCMS is designed to operate on personal computers (PCs), this study focuses on PC-based software.

Due to the wide variety of possible site design projects, this study did not attempt to prioritize system requirements for all types of projects. Instead, the field was narrowed by evaluating project type.

Mode of Technology Transfer

It is anticipated that the information developed in this study will be used to develop site-design applications for the Theater Construction Management System.

2 TCMS REQUIREMENTS ANALYSIS

The Theater Construction Management System (TCMS) is being developed to fill the gap between the Army Command and Control System (ACCS) and the Maneuver Control System of the Engineer Command and Control System (MCS-ENG) (Crawford et al. 1989). The ACCS is being developed to provide automated information transmission and analysis to support decisionmaking processes. Combat engineers are the focus of the MCS-ENG. TCMS addresses engineer functions that support sustainment engineering activities.

To prioritize TCMS development, functional requirements of the system were identified. Requirement analysis was conducted by:

> (1) summarizing and describing the unique organizational environment within which the engineer soldier must operate, (2) identifying areas of the engineering functions most adaptable to automation, (3) dividing these functions into areas to be researched as a part of this project and areas to be covered in other work units, and (4) determining the primary facets of the research to be performed under this research work unit (Crawford et al. 1989, p 8).

The first step in identifying TCMS requirements is to identify these "sustainment tasks" that Army engineers must accomplish. In terms of site design, there are three distinct sustainment tasks: (1) Mission Dependent Site Selection, (2) Design, and (3) Project Documents. Each of these three tasks applies to the site design module of TCMS.

Mission Dependent Site Selection

Mission Dependent Site Selection is the process of identifying the most appropriate location for the particular construction project at hand. The interaction of the project with the natural environment, the construction project type, the relationship the project has with other ongoing or completed projects, and developing the project infrastructure are all factors at this stage. The site selection process for the Army engineer is often quite a bit more difficult than for their civilian counterparts. Army engineers typically operate in areas where the natural environment (or enemy action) have prohibited previous government or commercial development. Mission Dependent Site Selection may also be further impeded by constraints of other projects (or enemy locations). In addition to the difficulties of the site selection in a general location, military engineers must construct projects rapidly, a factor that prohibits them from conducting site investigations to validate the site selection decision.

Design

Design sustainment tasks consist of six related subtasks:

1. Establish installation layout
2. Determine facility geometry
3. Earthwork calculations
4. Select and adapt standard designs (AFCS)
5. Generate original facility designs
6. Repair/rehabilitate/retrofit designs.

Project Documents

The Project Documents sustainment task consists of three subtasks: (1) Drawings, (2) Bill of Material (BOM) listings, and (3) Specifications.

The second step in identifying the TCMS requirements was to estimate the relative ease of providing automation support for each of the engineer unit sustainment tasks (Crawford et al. 1989). Three types of estimates for each general sustainment task were developed: (1) Supportability, (2) Importance, and (3) Availability. "Supportability" is an estimate of the amount of a task that may be completed using computer technology. "Importance" refers to the savings that may be received if the task is automated. "Availability" reflects the amount of commercially available software that can be purchased.

This study found that most of the tasks associated with site design could be automated and that this automation would yield significant savings. It was also found that many software packages are available to support design. Chapter 3 of this report gives an evaluation of commercially available site design software.

The study found that development of project documents could be automated, and that there are many benefits of automating the task. However, the study concluded that there was little software to assist in developing project documents. Chapter 6 of this report discusses automated techniques necessary to develop project documents.

3 SITE DESIGN SOFTWARE EVALUATION

A previous study (Meier and Williamson 1989) surveyed the civilian Corps of Engineers to identify: (1) hardware requirements, (2) engineering functions, (3) system requirements, (4) vendor support, and (5) cost of site design and civil engineering software. Following this survey, a software evaluation was conducted. While the study focused on software requirements and evaluation for civilian Corps of Engineers applications, the results form a basis for the conclusions of this study.

Table 1 identifies the software capabilities that were used in the evaluation process and Table 2 lists the software packages evaluated. More specific information on each software package may be found in Meier and Williamson (1989), which concluded that the WESCOM software provided the best overall capability. Other systems thought to provide good capabilities were CivilSoft and CEAL.

Frequent program improvements and additional program releases can put even the best software reviews out of date. Vendors have indicated that capabilities not previously included in the reviewed version of their software have now been included. Thus a new evaluation of the software packages might improve the rank of many programs.

Traditional software reviews try to identify the "best" software. Unfortunately, the software identified is ranked according to a set of criteria that may not apply to all office situations. In addition, users frequently resist standardization of software. This is because users learn the "look and feel" of an individual type of software and are reluctant to change from programs already in use.

Rather than conducting a new software review, an alternative approach is to identify those characteristics of projects (the contractual arrangement, personnel involved, and available computing power) and to use these characteristics to determine the required software features for a specific office. With those specific software features, the reviewer can pick the software best suited for a specific office.*

Table 1

Software Capabilities

PC Based
Screen Plot/Graphics
GOGO
Contouring/Mapping
DTM
Earthwork
Profiling/X-Sections
Utilities
Interfaced W/CAD Sys.
Management Cap.
Layers or Similar
Support

Table 2

Commercial Software Evaluated

WESCOM	Design Plus
CLV/CEAL	DCA
CivilSoft	Z Pennock
AUTOCOGO/MAP	C&G
PLUS 3	InterGraph
AROSE	PACSOFT
CONCAP	GDS
MTI	Computer Vision

* For an example of this selection method see E. William East and Jeffrey G. Kirby, *A Guide to Computerized Project Scheduling* (Van Nostrand Reinhold, NY, 1990), pp 104-118.

4 IMPLICATIONS OF MILITARY ENGINEERING ON SITE DESIGN REQUIREMENTS

Three criteria are particularly important to matching scheduling software to a specific office: (1) size, (2) type, and (3) complexity of the project. The size of the project will determine how much overall software capacity is needed, as well as the requirements for user interface functions. The type of project will determine the number of features needed to support the project. Project complexity refers to the depth of the work to be accomplished, and will determine the robustness of the features required to support project size and type.

The following information, taken from interviews with civilian and military Army engineers, reviews project size, type, and complexity as they relate to site design applications.

Project Size

Military engineers work on projects of many different sizes. For small projects located in an area with sufficient infrastructure, marked up copies of Army Facility Component System (AFCS)* drawings may be sufficient to support site design requirements. The design of small projects in remote areas is often accomplished by sketches on the back of envelopes.

Larger projects such as runways, base camps, enemy prisoners of war camps, and road construction require site design software. Available design software can do structural design and analysis, retaining wall design, hydraulic models for runoff analysis, earthwork calculations, and computer-aided design and drafting. Specifics of software should be matched to each project.

Project Type

Types of construction projects were evaluated by briefly reviewing: (1) the organization of military engineer units, and (2) the most frequent projects accomplished by these units.

Construction engineer units are typically organized around either vertical or horizonal construction. Vertical construction generally refers to construction of infrastructure to support personnel, including structures such as barracks, offices, control towers, etc. Horizontal construction refers to infrastructure to support transportation, such as roads, bridges, landing strips, etc.

Vertical construction units are typically composed of workers whose primary skills are in carpentry. These crews often double up as plumbers, electricians, or whatever tradesmen are needed to construct vertical structures. These crews may also be assisted by specialty equipment units. The specialty equipment units are often built around machine shops, welders, or cranes.

Horizontal construction units are used primarily for road or runway construction. These units are built around the unit's equipment, which often contains dump trucks, scrapers, graders, bulldozers, and compactors.**

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* An annotated bibliography of references ordered by subject area can be found in Appendix A of this report. More detailed information on AFCS can be found in the noted sources.

**For a further description of construction equipment, see David A. Day and Neal B.H. Benjamin, *Construction Equipment Guide* (John Wiley & Sons, New York, 1991).

Army engineers were interviewed to identify the most common type of construction. These interviews indicated that most Army construction is horizontal. Based on that result, this study focused on sustainment tasks in horizontal construction.

Project Complexity

Interviewed military engineers indicate that "detailed" planning takes place for any operation that requires more than one horizontal unit for more than a week. For noncritical situations in developed areas, design and planning may include newly developed project plans from AFCS drawings. Noncritical projects in remote areas may require less detailed planning. In critical situations, existing structures may be used for military purposes, or construction engineers may start a project with relatively little design or site investigation.

Military engineers must complete their jobs quickly, with minimum documentation. This type of construction has been called "build-design." Very little time is allowed for detailed site evaluation or even site-specific adaptation of designs.

Military engineering projects are completed faster than civilian horizontal construction projects, which are typically contracted through fixed-price contracting. The range of planning and design for military engineer projects runs from "design-build" projects to "build-design."

Facility acquisition typically follows a two-step process: (1) to develop a complete design, and (2) to construct the project based on that design. Military-engineered projects are more flexible than projects in the civilian sector, which allow few changes to the design without a complex procedure. For example, the military engineer in charge of a project may individually choose to substitute materials as a result of individual occurrences unique to the function of the building or to the local availability of equipment, labor, and materials.

The "design-build" approach is now more frequently used in the civilian sector. This approach allows construction to begin without having a complete design. The initial portion of the design is completed as the construction starts, and the design and construction proceed concurrently, with the design staying some weeks (or days) ahead of the construction progress. This approach is often taken on construction in remote sites where existing conditions must be discerned from indirect sources such as photographs.

"Build-design" is a less traditional approach used to expedite construction where there is little time for preliminary site investigation. Design decisions are made by construction engineers as the project is built. The construction may be documented as the project progresses, and this documentation will be loosely referred to later as the "design."

Target Project Type

During interviews with military engineers, the size, type, and complexity of the projects to be included within TCMS were discussed. Based on these interviews, it was determined that the most assistance may be provided in the area of site design if the most frequent type of project accomplished by military engineers was targeted for integration within TCMS.

All interviewees agreed that horizontal construction projects were the most prevalent type of military engineering project, and that low-volume roads were the most common type of horizontal construction project built. From the Army engineers' point of view, then, low-volume roads are the most appropriate choice for integration within a site design module of TCMS.

In addition to considering the usefulness of integrating low-volume road construction within TCMS, the implications for future research in this area should also be considered. A literature review was conducted in the area of design and construction of low-volume roads, and it was found that this area of Civil Engineering is very mature. (Most of the references found during literature reviews were written in the 1960s and 1970s.)

The body of recent research in this area will help to implement advanced technology applications in the domain because some of the necessary knowledge and decision structures typically followed by practitioners have already been developed. Appendix B to this report describes these structures.

Implications of Project Size, Type, and Complexity

The priority of "Design," "Project Documents," and "Mission Dependent Site Selection" (identified in the TCMS requirements analysis study) should also be evaluated based on the size, type, and complexity of the type of project proposed for site design integration within TCMS (low-volume road construction).

In any construction project, most costs occur during the construction phase. This construction cost is, however, determined to a large degree by the initial design. Figure 1 shows how any construction phase can influence final project cost. While Army engineers may not be primarily focused on cost, since engineer units are paid regardless of their productivity, the graph implies that, if designs approach some optimum, then projects will be accomplished in an efficient and timely manner.

Figure 1 shows that developing proper designs can have the greatest impact on project costs. This focus—on design development—should be made on the type of site design application (e.g., low-volume road construction) to be incorporated into TCMS. Ranking the TCMS sustainment areas of site selection,

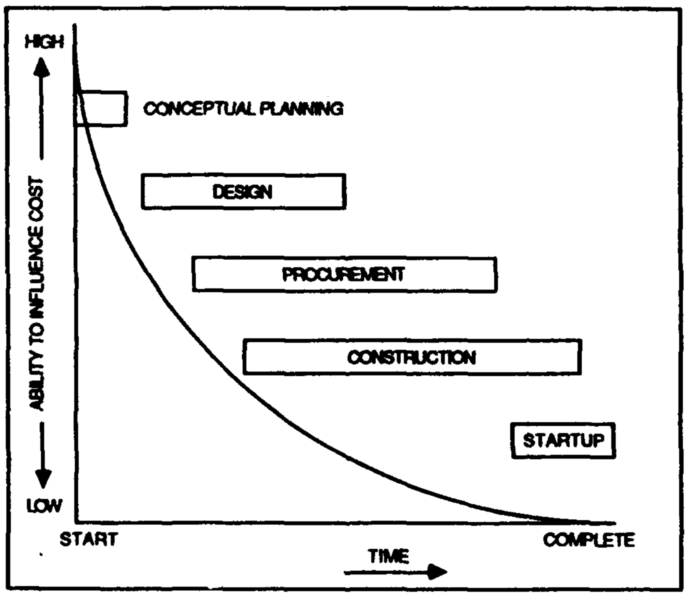

Figure 1. Ability To Influence Project Cost.

design, and documentation reflects, not necessarily their ease of implementation within TCMS, but the impact of the implementation on Army engineer operations.

Site Selection

Figure 1 illustrates that "master planning" (conceptual planning and design) has the largest impact on the overall project cost. In military engineering, low-volume road construction site selection may be considered equivalent to master planning. The military engineer beginning the site selection process would be given starting and ending points of a required road. Based on the type of project and available information, various levels of effort may be spent on site selection.

The three project acquisition types to be incorporated into TCMS should be evaluated for usefulness in developing site selection applications. If a design-build approach is taken, site selection process will already have been determined by master planners on military reservations. Under a build-design approach, site selection will be done for military expediency. The most flexible type of acquisition process, in terms of site selection, is the concurrent design and construction (build-design) process.

Design

Following site selection, the specifics of creating the design have the next greater impact on the overall cost of a construction project. The type of project acquisition process has the largest impact on the effort spent on design. In the first of the two steps (design and construction), more significant effort is spent on design. Engineers with prior design experience will typically create or adapt sets of plans and specifications for each project. For the expedient (more rapid), "build-design" process, often an inexperienced officer will be required to design and construct a portion or an entire project. In design-build projects, the emphasis is on developing an expedient design that allows workers to continue working—even though this approach may not always produce the best results.

Site selection and design are closely related for both design-build and build-design projects. Alternate road layouts may be compared based on cost and time required to complete the project. The iterative process of design and review may, however, be overlooked because of time constraints.

Documentation

One aspect of each of the three different project types never changes—the paperwork. Project documents include daily and weekly reports, project quantity reports, and as-built documents. Information on daily reports must be manually totaled and included in weekly and project quantity reports.

Figure 1 shows that documentation has little if any impact on the overall cost of a project. The most significant impact of documentation may be to improve reporting, improve communication with logistics and other organizations, and in the two-step process, provide background for claims settlements.

Another aspect of documentation that should be considered is that of standard project documents. Standard project documents include Army Technical Manuals and the Army Facility Component System. Technical Manuals provide design guidance for military engineers.

Since the AFCS system is required for use on military construction projects, its applicability to the site design effort of TCMS should be considered. The section below discusses the practical use of AFCS as discussed during interviews with Army engineers.

Interaction With AFCS

The AFCS is a military engineering construction support system that assists in selecting, planning and constructing facilities (USACE, Huntsville Division 1986). AFCS provides design and logistics data to support facility and installation requirements. The primary justification of the AFCS system appears to be to smooth the information flow between logistics organizations and military engineers (USACE, Huntsville Division, undated).

The AFCS is meant to provide standards for rapid deployment efforts. AFCS facilities are designed for temporary duty with a maximum life of 2 years. Two sets of construction standards are provided with AFCS: (1) standards based on a brief life of up to 6 months, and (2) standards for facilities with a maximum life of 2 years.

TCMS has been designed to use AFCS drawings and the TACAPS system that provides the interface to AFCS data, therefore, any site design module of TCMS should consider the implications of site design applications on the AFCS system.

Military engineers adapt AFCS drawings for specific projects on two levels.* The first adaptation occurs at the Engineer Command (ENCOM) level, and the second set of design changes occurs at the construction site. During peacetime, site adaptation occurs due to (1) labor availability, (2) equipment availability, (3) materials availability, (4) facility function, and (5) need for cost control.

In remote locations, local labor must often be used to support military engineering tasks. Military engineers often have to modify AFCS designs to support the capabilities of local labor forces. For example, masonry structures have been built using slurry concreting rather than mortared joints at each course due to lack of skilled masons.

Equipment limitations may also require modifications to AFCS drawings. For example, jump towers and other vertical structures may not be built to the elevation specified in the AFCS since Army engineer cranes have a shorter reach than the platform for the specified tower.

Materials availability will always be a problem with site-adapting AFCS drawings to local conditions since AFCS assumes that materials available in the United States are also available in less developed areas. Even when materials are available, material substitution is often done to use materials at hand, or to account for the fact that AFCS facilities are often not used for their originally intended functions. For example, office type buildings may collapse under additional impact loads of training if they are used in that function. At one base, sections of telephone poles were used for columns to replace the lumber specified in the AFCS.

Cost reduction may also be a reason to modify AFCS plans. In one example, firing range buildings were deleted from the AFCS design in lieu of trailers that could be placed on the site at significantly less cost.

Often changes to AFCS drawings in civil engineering disciplines such as structures or soils are not accompanied by similar changes in the electrical or mechanical areas. One extreme case of this occurred when the number of persons to be housed in a very large base camp was less than the specified AFCS base camp by over 1000 persons. While the number of structures was decreased, the mechanical, plumbing, and electrical systems were not downsized.

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* Interviews with several individuals suggested that AFCS was not used. A general discussion of AFCS is, however, outside the scope of this report.

Furthermore, some engineers have reported that AFCS drawings are not available to the construction field engineers. Often construction battalions have been provided with the hand-drawn copies of AFCS drawings that contained drafting and copying errors, and that were done without regard for drawing standards.

Summary

Based on the implication of the various types, sizes, and complexities of Army engineer projects, the integration of low-volume road projects within TCMS was determined to provide the most benefit for TCMS users. The remainder of this report discusses an investigation of how to integrate low-volume road projects within TCMS. The focus of this investigation was to provide applications that may reduce the cost of construction in: (1) site selection, (2) design, and (3) project documentation. The remaining chapters in this report discuss: current design practice, application of commercially available software, and the development of advanced automation technology.

5 APPLICATION OF COMMERCIAL SITE DESIGN SOFTWARE TO TCMS

In keeping with the general philosophy of TCMS development to use commercial software, this chapter will discuss the use of commercial software in TCMS.

Computer Aided Drafting for Site Design

It would be inappropriate to attempt to define a single piece of software that supports all users' needs since different users will have different needs for sophisticated software features (East 1988). Those users who do not need the most sophisticated system will receive maximum benefit by using a less sophisticated (and less expensive) system. Users who need sophisticated features will find less sophisticated systems to be inefficient. Thus, different users settle into using software packages that they are comfortable with, and will resist change.

An appropriate method for commercial software analysis is to identify how detailed user needs force software vendors to include specific capabilities in their packages (East and Kirby 1990). For example, to provide horizontal construction design for Army engineers, commercially available software will need to provide the following minimum capabilities: (1) Screen Plot and Graphics, (2) Coordinate Geometry (COGO), (3) Contouring and Mapping, (4) Road Layout, (5) Earthwork, and (6) Profiling and Cross-Sections. These minimum requirements should be provided for offices that are constructing individual or independent projects.

For large offices running several related projects concurrently, the following features (above those described above) would be needed: (1) Interfacing with CAD Systems, (2) Management Capabilities, (3) Layers, (4) User Programming Utilities, and (5) Enhanced Support Capabilities.

More specific features of site design/civil systems are included in the Meier and Williamson report (1989).

Various commercial site design/civil engineering systems may be integrated using a phased approach. The first phase would include integration of the software with TCMS through direct database or CAD interfaces. One example of a commercially available software package that would allow CAD interfaces is DCA software.

The second phase for the use of site design/civil engineering software within TCMS will require that future versions of TCMS provide an "accessible" data structure. This data structure would be able to accept data from many different types of commercial systems through a standard data exchange format. Such a format has been developed for project scheduling and estimating systems and could be developed for this application (East and Kirby 1990, pp 187-198).

Road Design System

The U.S. Forest Service has developed a system to assist in designing a range of roads from low-volume single lane roads to double lane paved roads (USDA 1984). The system is a set of FORTRAN programs that performs: traverse and topography calculations, horizontal alignment and offset calculations, and earthwork calculations. The system provides mathematical analysis and reports the results to the user. The program is available from the National Technical Information System (NTIS), 5285 Port Royal Rd., Springfield, VA 22161.

Although the Ready Design System (RDS) may be customized to meet the needs of the Forest Service, it appears to have the same capability of commercially available systems. The commercial systems, developed for personal computer platforms, appear to be more applicable to TCMS than does the RDS system.

Electronic Data Exchange

Survey instrument manufacturers have developed proprietary formats to allow the transfer of data from surveying instruments directly to topographic and coordinate geometry systems. To take advantage of this useful data transfer capability, vendors of civil/site design software have included a number of the proprietary data exchange protocols within their systems.

As the civil/site design software manufacturers continue to improve their software, they will continue to enhance the various data exchange protocols in coordination with other vendors and hardware manufacturers. The Corps of Engineers may have a unique role to play as coordinator in the development of industry wide specifications for data exchange.

The transparent exchange of data to and from TCMS will be one of the most critical aspects of future TCMS development. One potential way that this data exchange could occur is for various data sources to know where related data exists. If data is cross-referenced in this way, then the type of data exchange format would be transparent to the user. The user may, for example, ask the computer to develop a topographic map of a particular area. The system would then use the information about data references and retrieve surveying data for the requested area to develop the topographic map.

Computer Aided Drafting Standards

Regardless of the phased integration of site design/civil engineering software, some standardization in the use of the software is very appropriate. The civilian Corps of Engineers have convened groups of specialists to develop CADD standards for eight different disciplines (Engineering Manual [EM] 1110-1-1807, 1990). The different disciplines are: (1) Civil/Site, (2) Survey/Mapping, (3) Geotechnical, (4) Architectural, (5) Structural, (6) Mechanical, (7) Electrical, and (8) Sanitary Engineering. Other disciplines may be included in future versions of the CADD standards.

According to the Corps CADD standard, the benefits of developing these standards are:

> consistent quality products for customers, consistent requirements for Architect/Engineer deliverables, efficiencies derived from organization wide sharing of techniques and products, and enhancement of the ability of multi-Field Operating Agency participation (EM 1110-1-1807 1990, p 1-1)

The benefits of using CADD standards for the civilian Corps of Engineers should translate well into the Army engineering community. Consistency in producing a "quality product" translates into a project that fulfills its mission effectively. Consistent "A/E deliverables" allow construction units to know what types of information to expect on drawings regardless of the project. This consistency should improve the efficiency of the construction process. "Sharing" of techniques and products will clearly be a benefit since corporate CADD experience may be captured and distributed. Having several organizational levels of Army engineers participate in design and development of as-built drawings will enhance project constructibility and maintainability.

Each civilian Corps standard contains two sections. The first section is a set of graphic standards that include guidelines for items such as: recommended drawing scales, assignment of drawing levels, and line weights and colors. The second section of the CADD standards are recommended cell libraries. Figures 2 and 3 show several of the cell libraries related to the work contained in this report (EM 1110-1-1807, 1990, pp 3-34 and 4-15).

Project Documents

Plans and specifications are perhaps the most important type of project document seen by construction engineers. Plans and specifications for military engineers are generated through the AFCS process, and the recent experience of combat engineers in the Gulf War may best illustrate the generation of use of AFCS documents.

Of the more than 200 facilities in the Middle East constructed by the engineer command, only two were designed using AFCS. The failure of AFCS to meet the needs of military engineers was attributed to five factors: (1) there are never enough engineers during wartime to use the system, (2) the designs cannot be site adapted, (3) the infrastructure requirements inherent in the design were not available, (4) materials required were not available, and (5) laborers were not available to construct AFCS facilities.

For example, AFCS design requirements for prisoner of war camps were incorrect. According to one Army engineer, there was not enough barbed wire in the entire country to construct one AFCS prisoner camp. In addition, prisoner processing and capacity were not adequately covered by AFCS.

One conceptual item regarding the use of AFCS in a mobile war setting is that various units will be billeted together in a base camp. This proved to be incorrect. Units wished to be spread out over large areas to prevent long range attacks from destroying a large number of troops.

One problem with the AFCS system is its inflexibility. However, rigidity is an inherent characteristic of a fixed standard design system that is expected to perform under a wide range of conditions. The AFCS system contains complete sets of drawings while the commercial construction industry typically uses standard designs that are only 50 percent complete (Hawkins and Penz 1991).

Expedient Construction Methods

Army engineers in a wartime setting require a more expedient construction system and technique than those presented in AFCS. A system recently developed by the U.S. Army Construction Engineering Research Laboratories (USACERL) attempts to meet these Army engineer needs by allowing users to query a large database of buildings, systems, etc. based on a number of criteria, including: (1) location of manufacturer, (2) building type, (3) construction type, (4) foundation type, (5) speed of construction, and others (Napier and Kim 1991).

One of the construction types that is important to identify is that of unique/critical equipment or materials. The use of foam domes, for example, was stopped during recent events since the construction required foam sprayers. Since the sprayer was not standard Army equipment, repairs were not practical. Once the equipment went down, the construction halted.

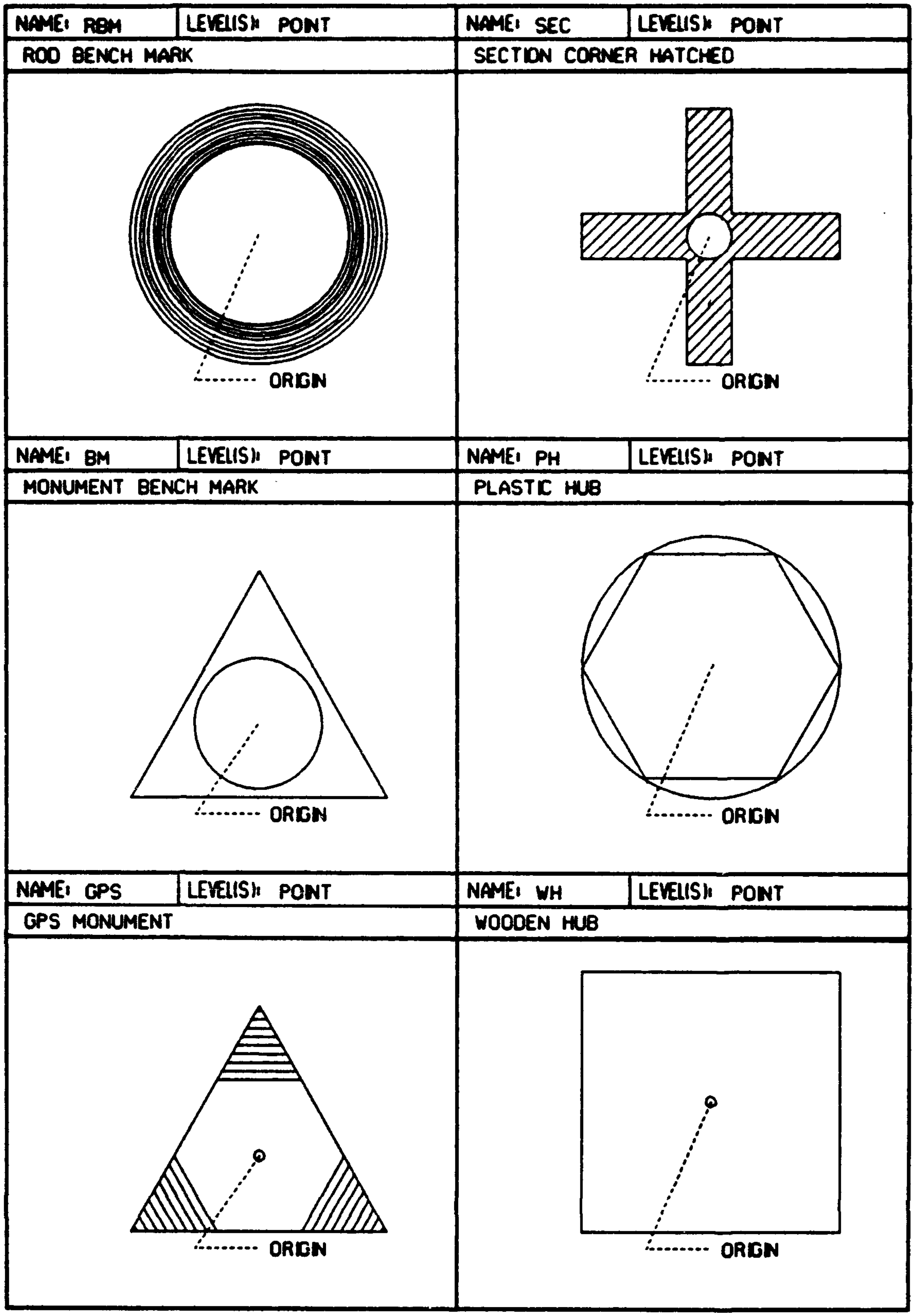

Figure 2. Portion of Civil Cell Library Standard.

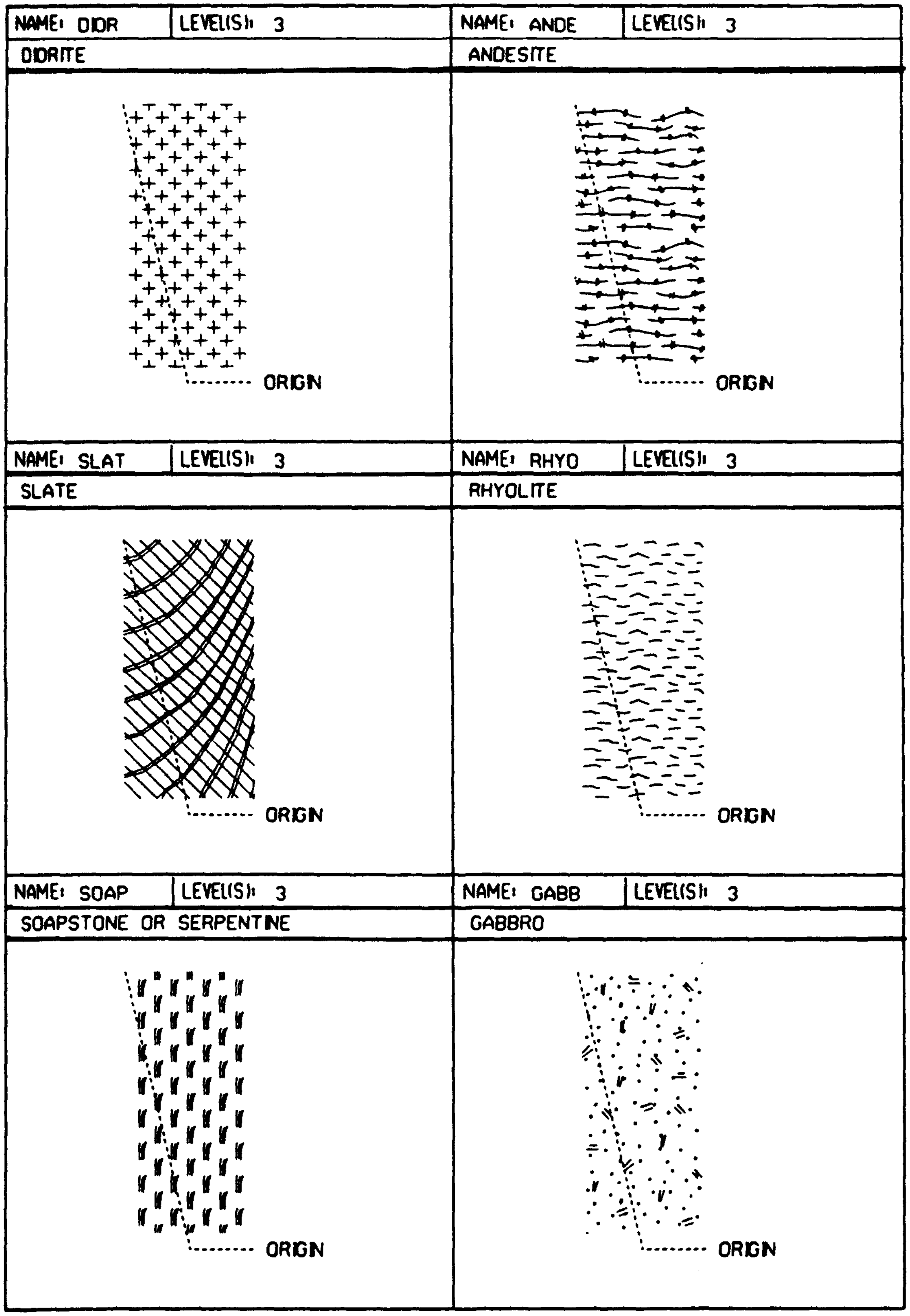

Figure 3. Portion of Geotechnical Cell Library Standard.

6 ARTIFICIAL INTELLIGENCE APPLICATIONS TO TCMS CONSTRUCTION

Civil engineers have typically been the first engineering group to apply automation technology to their trade. Previous innovations in the use of automation in civil engineering reduced the time taken to perform specific tasks, for example, finite element analysis.

The first tools to be used in civil engineering increased the speed of accomplishing certain tasks, but not necessarily the quality of the finished work. Today new types of computer tools are being created and applied to civil engineering (and related areas) that are based on the computer science field of "artificial intelligence" (AI).

AI is a very broad field that includes, but is not limited to, computer modeling of: vision, learning, language, cognition, planning, and robotics (Charniack and McDermott 1987), These have been (and continue to be) the subject of research over the past 30 years that has resulted in significant successes. Some of the applications that have been developed are: approving authorizations for credit card purchases, financial planning, planning the manufacture of aircraft components, determining computer configurations, and diagnosing problems with robots (Davis 1987).

This chapter describes research areas and products related to the site design functions of the TCMS system, specifically: (1) route planning, (2) site layout, (3) knowledge-based consultants, (4) model-based design systems, and (5) data integration. The chapter concludes with a short description of a study conducted by the California State Department of Transportation.

Planning Road Alignments

Since the most frequent type of work conducted by Army engineers is road construction, planning systems to plan route alignments should be most useful. This section describes AI applications for the route planning process. The foundation of AI applications is discussed in the context of planning systems for robotics movements. One specific application for road layout developed by the U.S. Forest Service is discussed.

AI and Planning

Planning routes for robots is a widely studied topic in AI. Early researchers in planning hypothesized that a good planning methodology could solve most planning problems. This "General Problem Solver" (GPS) applies operators to the current state (i.e., situation or environment) until the current state meets the goal state (Earnst and Newell 1969). One implementation of the GPS concept was STRIPS (Fikes and Nilsson 1971). In the STRIPS system, actions were represented by listing their pre- and their post-conditions. Three key aspects of the STRIPS system were the:

1. Initial description of the world
2. Actions that may be taken in the world
3. Desired description of the world.

To create plans in STRIPS, actions (item two above) are taken on the initial conditions (item one above) until the goal state is reached (item three above). This type of system organization tries all possible combinations of actions and intermediate conditions to derive the set of actions required to reach the goal. This type of combinatorial exploration is called the "search," and the set of all possible combinations is called the "search tree."

While it is possible to search all combinations of a situation in real world applications, it is unlikely that these searches will provide useful answers. "Heuristic" methods can help develop more appropriate searches. Heuristic methods were first developed to "prune" the search tree by developing "costs" for the path being evaluated. One simple method of developing the cost of a search path is to count the number of steps taken to reach the current state of the path; shorter solutions are of higher value (i.e., they cost less) than longer solutions.

Route Planning in Unlimited Space

While the computational sophistication described in the previous paragraphs was appropriate for moving blocks around a table, it is unlikely that the GPS approach will derive plans for robots moving across large areas of real terrain, since literal terrain is much more complicated than a "blocks" world. The robots must have a map that includes their immediate locations, be able to infer structures from sensors, and know the effects of actions (Kuipers 1989, pp 25-45). Robots developed with these capabilities will be important when developing systems for undersea exploration, toxic waste cleanup, space exploration, etc.

These systems must operate in situations where the scale of their world is larger than observations that can be made by the system itself (Kuipers 1978, pp 129-153). This type of high-level functioning requires the following types of information to be included within the system:

1. Interactions between sensors and motors
2. Patterns of action required for specific behaviors (e.g., sampling, etc.)
3. Topological data
4. Landmark vectors (mountain tops, buildings, etc.).

In addition to capturing the information described above, such a system must also integrate the knowledge/data from these sources to describe recommendations and executions of plans. Figure 4 shows the levels of interaction between the topological data and landmark vectors used in the referenced system (Lawton et al. 1987, pp 2-23). One demonstration system constructed with these types of structures can create a "least cost" path between two user-defined points within a realistic topographic environment based on changes in compass heading.

Planning Routes Within Restricted Areas

The previous example of route planning assumes that the robot's operating environment is essentially an open topography. Another type of spacial reasoning occurs when a system must plan a route through an area that contains obstacles. For example, compass headings and distance vectors that may be insufficient when the robot operates in an environment where some paths may not be taken—in areas where landslides are likely to occur, for example.

An alternative to representing the environment with vectors and headings is to represent the world by the sequence of spaces in which the robot may proceed. To navigate between spaces, the robot would need to know:

1. Shapes of objects
2. Position and orientation of objects
3. Connection paths between objects (Charniak and McDermott 1987, p 437).

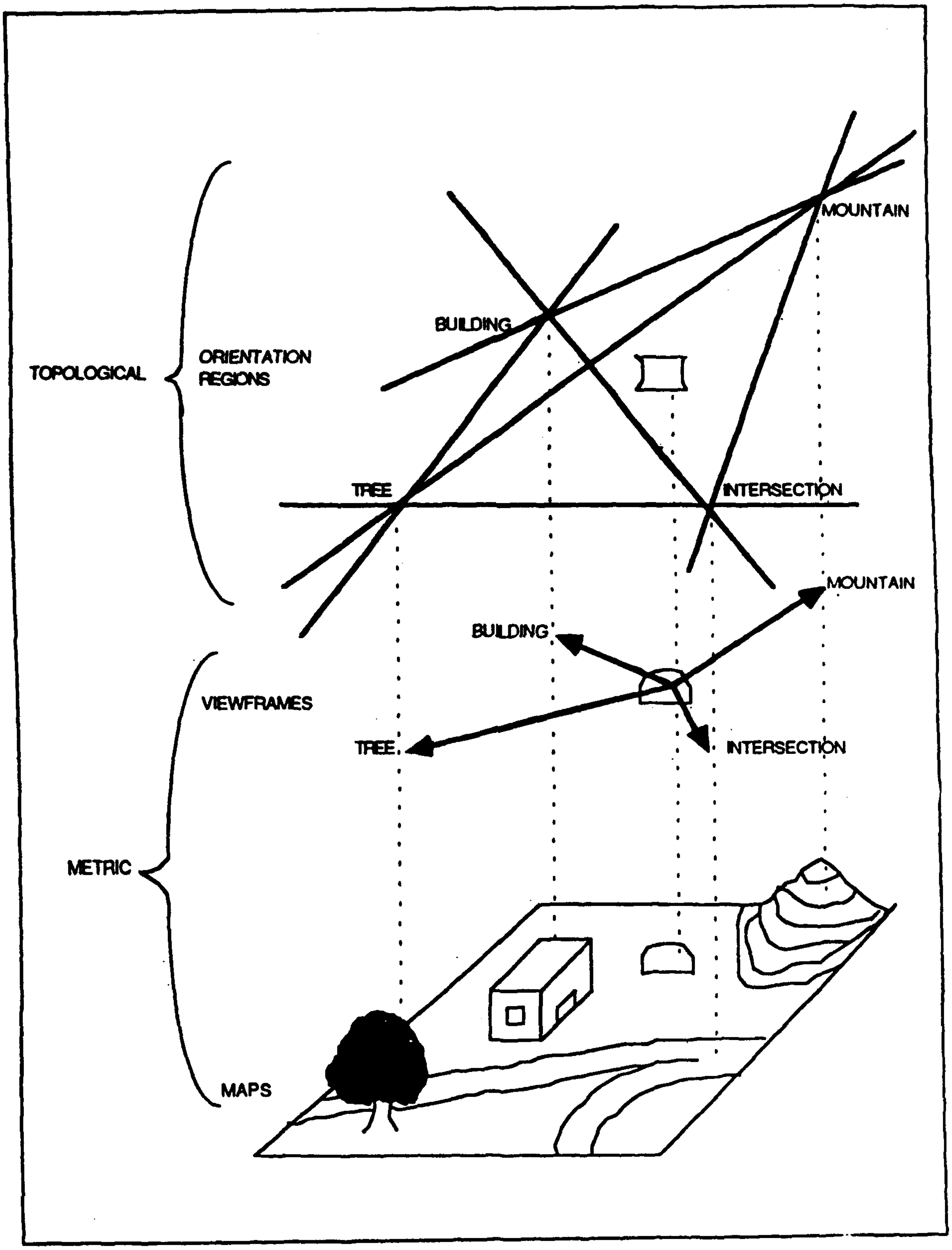

Figure 4. Spacial Representation.

For example, one recent study stored a large amount of detailed information regarding two counties in New Jersey, including: a matrix of street intersections, businesses' street numbers and names, and distances between intersections.

Many different types of search were attempted to determine an optimum technique. Each computer-generated route was evaluated for realistic usefulness. For example, one computer-generated path took too many turns to be practical. Additional distances were given to each turn to increase the "cost" of routes with large numbers of turns. The revised system provided more realistic plans.

To further improve the program's search procedure, the way humans actually navigate through unfamiliar and familiar cities was investigated. A typical search procedure was to: (1) identify important streets near the start of the path, (2) travel along a skeleton of these streets until the goal is reached, and (3) connect the streets as appropriate.

In all cases, humans required a map to find good solutions. In addition, different people used very different methods to navigate the map. Another study suggests that not only do different people plan routes differently, but different people work from different abstractions of the map ("cognitive" map (Kuipers 1978, p 132).

Road Alignment Tool

The U.S. Forest Service has developed a program to assist in generating alternative road layouts using search techniques based on road grade (Reutebuch 1988). The road layout program is a portion of the Preliminary Logging Analysis System (PLANS), which was developed to assist in planning and evaluating logging operations (Twito and Reutebuch 1987).

Through one module of the PLANS system, the user interacts with a Digital Terrain Map to identify "control" points that the road should pass through. These control points are areas such as stream crossings and junctions with other roads. Next the user attempts to connect any two points and provides acceptable grade limits that the road should follow. As the user traces the path between control points, the system identifies when the user goes outside the bounds of the specified limits.

This system also appears to have a feature that allows the computer to generate possible routes between control points. This computer-generated approach appears to be based on a type of depth-first search that uses a function of surface elevation versus grade to determine the most appropriate path.

Obstacle Planning System

One component of a system developed by the Corps of Engineers, Waterways Experiment Station (CEWES), uses data provided by the Defense Mapping Agency to find the fastest path through an area (Doiron 1992). The path-finding routines use data on slope, vegetation, streams, etc. to determine how quickly a specific military unit may move from one area to another. Another criteria used in evaluating unit movement is the route size required for a given unit to proceed. Given the route size requirements for a unit, "constriction" points, that would decrease the speed of the unit, may be avoided. The program appears to operate on a depth-first search algorithm and allows users to specify control points on the path that units must pass through.

Planning Site Layouts

In addition to route planning, much research has investigated space layout. Two recent projects serve as good examples. The first system assists construction contractors to lay out their work yard surrounding a construction project. The second system assists an architect to develop a conceptual layout of rooms within a facility.

Construction Yard Layout

SitePlan is a system that helps arrange construction yards (Levitt et al. 1989). The system contains representations for a variety of items found on a construction site. The items at a site included in the system are: (1) buildings, (2) laydown areas, (3) warehouses, (4) roads, (5) parking lots, (6) railroads, (7) trailers, and (8) site-specific physical objects. Each of these physical objects is defined by "modifiers," "contexts," and "constraints." Modifiers are attached to each physical object to determine the shape of other internal characteristics of the physical objects. The modifiers used in SitePlan are: (1) large, (2) important, (3) small, (4) efficient, (5) long term, and (6) permanent. Contexts are used to define how each physical element relates to the overall space of the construction yard. The contexts are: (1) site and (2) subarea. Constraints represent how specific physical objects relate to each other. The constraints in the SitePlan system are: (1) closer than, (2) further than, (3) adjacent to, (4) as close as possible, and (5) site distance constraint.

The user interface for SitePlan allows the computer to generate a variety of possible configurations based on a number of different search mechanisms. In the first method, the system places high priority items on the site first and then attempts to place less significant items within constraints. The next strategy includes the representation of site plan and discrete time periods within the construction process. The final method allows the computer to derive several alternative solutions by considering many configurations.

While using these techniques, the user may specify where individual physical elements are to be placed within the site. Once specific physical elements are fixed on the site, the computer will identify the spaces appropriate for other physical elements.

Conceptual Building Layout

A more conceptual type of layout problem is to develop room layouts early in the design phase (Chinowsky 1991). These layouts frequently use a graphical representation architects refer to as "bubble" diagrams. Spaces are located by finding the best balance between design constraints associated with each space. Table 3 lists type of information used by the program. Classes of spaces also have adjacency preferences used to generate and evaluate the computer solution.

Once information for each space is defined, then the user may allow the computer to generate the layout. The layout proceeds by filling the largest or most constrained space. Next, those items that have adjacency requirements are placed next to the first objects placed. This procedure (simplified here) is repeated until all spaces have been placed.

Although the system is able to automatically generate the layout, the user may prefer to interact with the system's result. This is possible within the CADDIE user interface. The CADDIE user interface allows the user to move any space around the screen with a mouse. Once the bubble has been moved, the computer reevaluates to ensure that constraints and adjacency requirements have been satisfied.

Table 3

Objects Used in SitePlan

Physical Objects:		
Building	Road	Railroad
Laydown	Site-Physical-Object	Trailer
Warehouse	Parking	
Modifiers:		
Large	Small	Long-Term
Important	Efficient	Permanent
Contexts:		
Site	Sub-Area	
Constraints:		
Closer-Than	Further-Than	Adjacent-To
Close-As-Possible	Site-Distance-Constraint	

Knowledge-Based Design Consultants

The knowledge-based design consultant is, essentially, a decision tree containing nodes that relate to very specific design choices. In the decision-tree type of system, the design choices are treated as completely independent factors in the design.

Retaining Wall Consultant

One proposed expert system application creates retaining wall designs (Adams and Hendrickson 1988, p 9). This application may be very useful to Army engineers since retaining walls must be designed quickly, often with incomplete design information. Retaining wall design requires a two-step process: (1) to consider the many alternative types of walls to determine the optimal type of retaining wall, based on site-specific conditions and constraints, and (2) to provide the optimum design of any given retaining wall system. Clearly a tremendous amount of experience is needed before retaining wall design may be properly conducted.

Alternative Materials Consultant

One application of potential interest to Army engineers is a system to advise designers on the use of alternative materials. A more robust system could be developed that would assist in the selection of alternative building systems based on the functional requirements of the building to be built. Such a system would extend the build-design system.

Another type of alternative materials consultant could be developed to advise engineers on the use of innovative materials for road construction. The system should contain details of both the material and details of construction methods since the application of specific types of materials may require different construction techniques. Often the use of alternative materials is based on the lack of traditional materials. The materials selection consultant should allow consultation on the uses of existing materials or possible substitutions given local conditions.

Model-Based Design Systems

Model-based design uses an AI concept called "object-oriented" programming. The object-oriented system has two major components. The first component is packets of data related to a particular item that is to be included within the system. These packets are referred to in AI terminology as "frames." Packets of data related to a system that would determine the Critical Path Method (CPM) schedule for a project may include the description, cost, duration, early start date, early finish date, late start date, late finish date, and float.

The packets of data, or frames, may also be abstracted to form different views of the data. For example, the construction of a barracks building may be scheduled with a CPM network of 1000 activities. The base commander may not be interested in the entire 1000-activity network and only be interested in when the project will start and finish. Another frame could be created that would take the start of the first activity and the finish from the last activity.

The key feature of frames is that a person may build a hierarchy of frames that can share data. These frames will be able to share and use the data contained in related frames. These relations are often referred to as "parent" and "child" relationships. The sharing of data between the parent and the child is referred to as "inheritance."

The second component of an object-oriented program is called "methods." Methods may be thought of as mini-programs attached to specific pieces of data within a frame. When the specific piece of data is needed by the program, the method may be used by the system. For example, if the scheduling system discussed above did not have the duration of an activity, there may be a program that asks the user to supply the duration. Other methods could, for example, use an estimating system or knowledge-base to calculate the duration.

Model-based reasoning is a way to use object-oriented programming to develop a consistent means to predict or analyze the behavior of a set of physical elements. In general, a model-based system will have frames representing the various physical components. Methods attached to specific pieces of data within the frame will be used to describe the interaction between the physical components. The combination of components and functions in a single object allows users, for example, to modify components and see the resulting change to the system.

An example model-based design system that is currently in commercial use is called the Intelligent Boiler Design System (IBDS) (Clive and Levitt 1976, pp 289-293). This system can develop high quality boiler room layouts very rapidly. The speed and quality of the layout result from the underlying model of the components of the boiler room and the relation of the components to each other.

The combination of embedded component and relational models is shown in the following example. An increase in boiler size will have an initial wave of impacts that affects the weight, capacity, and other information, of the total system. These changes modify other appropriate components in the boiler room. Increasing the weight forces the boiler's supporting structure to re-evaluate, and possibly re-design, itself. Changing the capacity of the boiler may require that larger pipes be connected to the boiler. A follow-on impact of increasing boiler capacity results from a change in pipe size. The change in pipe size also forces the pumps to be resized. Following that, resized pumps may require additional electrical connections and changes to the pump location and pads. After all issues related to the change in boiler capacity have been resolved, then the program provides the revised solution to the user.

Project Knowledge Integration

A long-term goal of researchers in construction and engineering management is to integrate design and construction. Currently, integrating project knowledge involves face-to-face meetings between project team members. Unfortunately, much project knowledge is not transferred, and cost and time growth are a result. AI and other types of automation techniques may help to transfer information between the various members of the construction team.

There are various models for this data integration. The model followed during previous TCMS development was to allow the commercial software to exchange data through defined protocols. This technique is possible given sufficient planning and adherence to strict standards. Examples of this type of data "integration" for design-build organizations may be found in the civil engineering literature. Typically, all project participants will agree to a specific protocol to update CAD drawings to a central location. As changes are made, individual design consultants may update their drawings in conjunction with the most current version of other CAD drawings. Negotiation regarding when design approaches are significantly "fixed" are a key to this type of use.

While the previous model of data integration may be implemented, there are significant costs to each of the project participants. Another technologically possible model of data integration is to develop data systems that can exchange data between related systems. Each participant in an organization should be able to define what data is required by their portion of the organization and what data is required by those up- or downstream of their organization. Based on this definition, integration may be achieved by identifying the flow of data on a wide-area network.

One example of this type of system is the U.S. Army Corps of Engineers, Resident Management System (RMS). RMS is an integrated office information system developed for Corps of Engineers construction offices. RMS emphasizes the use of automation to support quality assurance functions of the construction field office. RMS version 1.6 will allow each office to determine what data in their database can be imported. With this capability, many different organizational structures may exchange data in ways consistent with the business uses of the data.

With relatively fixed types of data, the integration process may be accomplished through correct system design. Integrating the complete design and construct process will prove to be significantly more difficult. One major problem in developing such an integrated data system is that a data storage system allows all relevant information to be kept in a common framework.

Beaven and Lawrance (1973) suggest that a database be linked with topographical information. The linking of data should be accomplished, they suggest, by standardizing project information across all project participants:

> . . . the project database concept is perhaps the most compelling reason for standards. These (standards) provide a common platform for the collection and manipulation of virtually all project-related information. Standards will . . . enhance the ability to transfer and integrate information from other systems such as GIS, cost estimating, specification development, and project management (EM 1110-1-1807 1990, p 1-1).

Developing standard storage and retrieval mechanisms will also serve to integrate decisionmaking regarding traditionally compartmentalized organizations. Making these types of changes to an organization is no simple task. Implementing advanced technology applications in other organizations has been shown to change the fundamental structure of the organization (Fiegenbaum et al. 1988). Since organizational change will be forced to occur by the interdisciplinary access to data, this type of data integration may be very difficult or impossible to implement within large, historically compartmentalized organizations.

CALTRANS Application Survey

To evaluate the application of advanced technology applications to site design for horizontal construction, a review of transportation agencies was conducted. The first study to evaluate the types of knowledge-based system projects that would be needed in transportation industry was done for the State of California (Ritchie et al. 1988). Tables 4 to 7 show the priorities of projects that the California Department of Transportation (CALTRANS) selected. These tables may help readers and future researchers to coordinate efforts with CALTRANS.

The systems recommended for CALTRANS consider a wide variety of transportation issues. Several applications identified by CALTRANS are appropriate to Army engineers. Specifically, the issues of knowledge-based consultants and planning tasks are included in the CALTRANS lists.

Table 4

Recommended for Immediate Implementation

Hazardous Waste Site Characterization
Disaster Planning and Management

Table 5

Recommendations for Implementation Within 1 Year

Pavement Rehabilitation Project Development
Design Standards Exceptions Advisor
Hazardous Waste Mitigation Options Advisor
Incident Traffic Management
Highway Planting Project Design Advisor
Assessing Effectiveness of Traffic Mitigation Strategies

Table 6

Recommendations for Implementation After 1 Year

Route Location Study Advisor
Route Concept Report Advisor
Sections 16(b) & 18 Advisor
Regional Transportation Plan Evaluation Advisor
Financial Data & Trend Interpreter
Transportation Permit Advisor
Encroachment Permit Advisor
Safety Hardware Advisor
Hazardous Waste Site Evaluation Advisor
Leaking Underground Fuel Tank Advisor
Security Analysis Advisor
Revegetation/Erosion Control PS&E Advisor
Visually Assessing Highway Projects Advisor
Bid Pattern Interpreter
ROW/Utilities Interaction Advisor
Transit Capital Improvement Project Ranking
Accident Analysis Advisor
Hydrologic Analysis Advisor
Hydraulic Analysis Advisor
Water Management Advisor
Vegetation Control Advisor
Railroad Relocation Advisor

Table 7

Recommendations for Future Implementation

Scenic Resource Evaluation Advisor
STIP/Obligation Plan Development Advisor
Technology Transfer to Local Agencies
Equipment Repair Advisor
Software Selection Advisor
Traffic Operations Center Advisor
"Landscaped Freeway" Status Advisor
Incident Response Advisor
Traffic Signal Operations Advisors
Transit Network and Operation Planning Advisor
Impact Assessment Advisor
Signal Timing Advisor
Utility Policy and Procedures Advisor
Concept Development Advisor
Environmental Planning Advisor

7 PROPOSED AI APPLICATIONS FOR TCMS SITE DESIGN

Current commercial software has improved the ability of Army engineers to complete their mission—quantitatively. The use of commercial civil engineering software, CAD systems, spreadsheets, databases, and word processing computer software allows Army engineers to perform calculations quickly and to exchange data between various members of the construction team.

Two high-potential applications that may use AI techniques to site design/planning are: (1) computer-assisted road layout and (2) model-based standard designs.

Road Layout Assistant (LAYOUT)

The road layout assistant (LAYOUT) would help Army engineers to develop initial road layouts. The primary input requirement for LAYOUT is topographic survey data of the area where the road is to be built. Today's civil engineering software can already generate the required data for LAYOUT. The survey data would be provided to commercial software, which would create a TIN file. This TIN file is a type of Digital Terrain Map (DTM) that breaks the surveyed data into triangles.

From the DTM, LAYOUT would be able to determine the least-cost alternative for road layout. Since the DTM would only provide the least-cost alternative based on grade or cut-and-fill, additional input would be needed to enhance the quality of advice provided by LAYOUT. This additional information is available from GISs.

LAYOUT would integrate GIS data with DTM data to provide a comprehensive map of the road construction area. Specifically, GIS data should be stored in some type of database associated with individual triangles within the DTM. DTM triangles may also need to be subdivided to identify differences in GIS data. For example, within a specific DTM triangle there may be several types of vegetation.

To show how the proposed LAYOUT system would work, several simulated computer screens were created. Figure 5 shows the general user interface of the LAYOUT system, consisting of three separate parts. The first and largest part is the DTM. The user would be able to scroll through and to scale the DTM to find the appropriate definition of the problem at hand.

To the left of the DTM window are "Icon/Attribute Boxes." This area contains icons relating to the construction and attributes relating to the information contained in the DTM/GIS database. Users would use a mouse to activate the options within these icons or attribute boxes.

Below the Digital Terrain Map is a "dialogue box" that allows the system to report on processing status. The box also provides an area for the user to type in various commands or answer LAYOUT prompts.

Figure 6 shows some types of icons and attributes that LAYOUT may contain. For example, the upper left box (containing a triangle) would indicate the DTM attribute of slope. When the user clicks the mouse on this box, LAYOUT would either shade or provide numerical information on the slope of each DTM triangle. The "H_2O" box would refer to the presence or absence of water along various points on the DTM. Clicking the tree or shrub attributes would cause LAYOUT to highlight the areas containing that type of tree or shrub. The two boxes below the tree and shrub boxes would allow the user to identify on the DTM what types of soil were present.

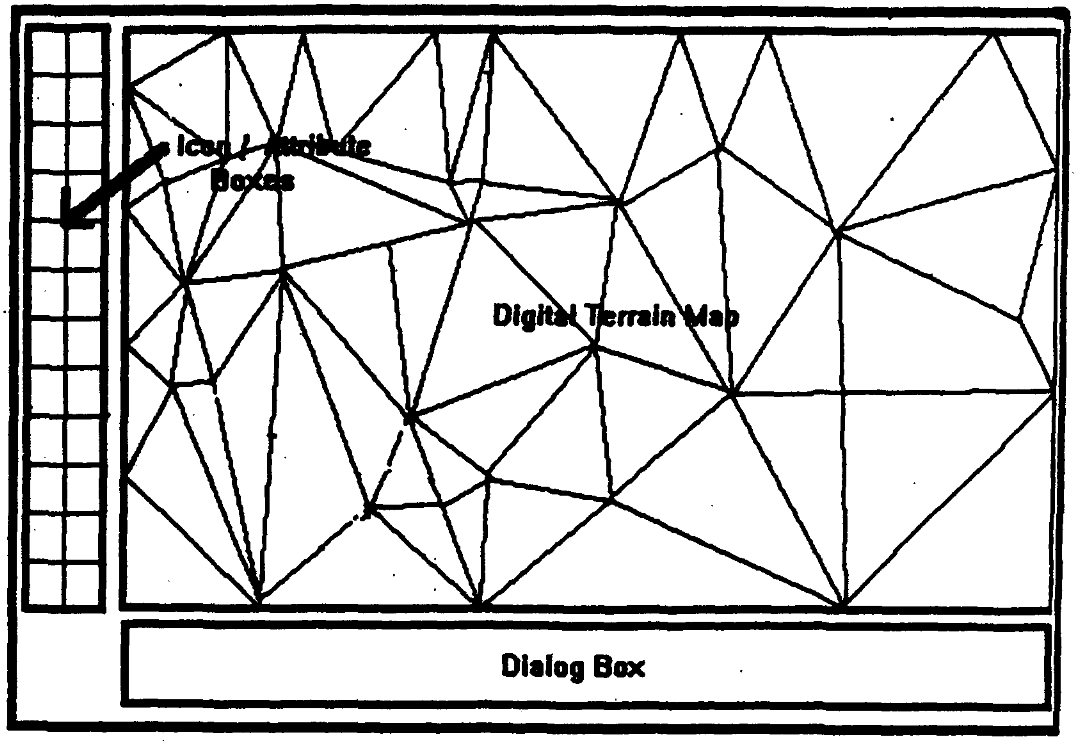

Figure 5. Suggest User Interface Components.

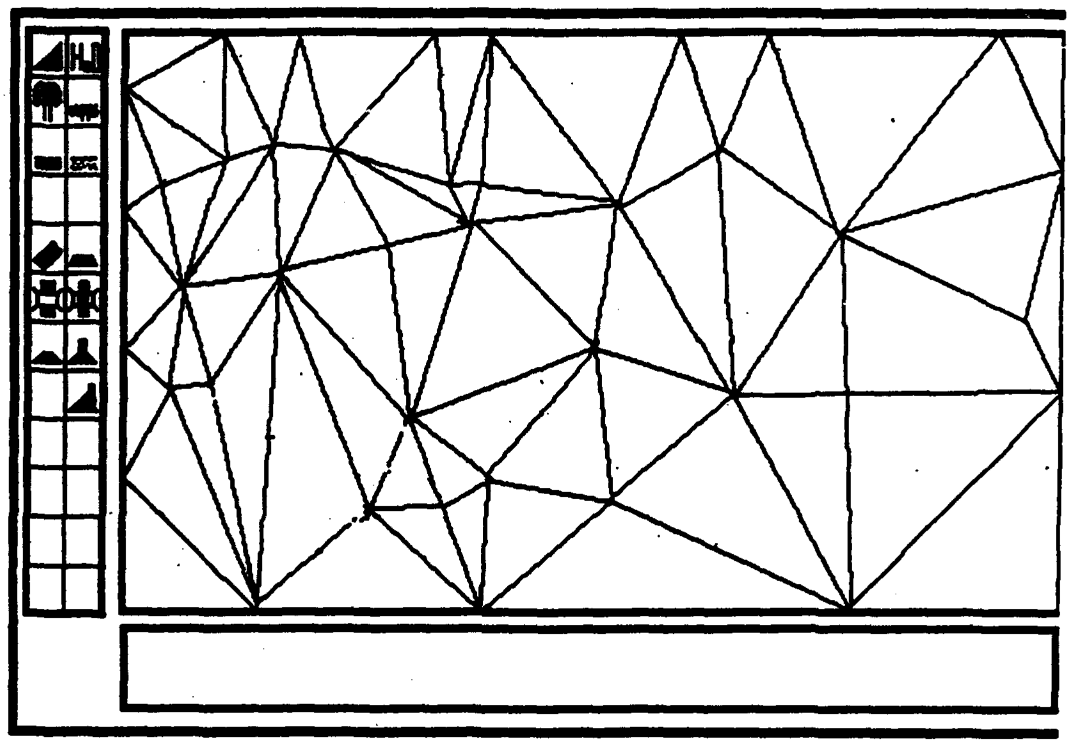

Figure 6. Example of Icon-Based Interface.

LAYOUT would show DTM/GIS database raw data in a graphic form that would simplify road layout. Another screen, not shown in this report, would allow the user to prioritize each item. Once this priority is set, the DTM could be shaded to determine those areas where high priority items would cause problems to road construction.

The second set of icons in the icon/attribute boxes describe various types of road construction. Roads, road base, bridges, tunnels, retaining walls, culverts, and other items may be represented in these boxes.

Figure 7 shows how LAYOUT would start a session. In the dialogue box, at the bottom of the screen, LAYOUT indicates that the user should place the START and END points of the road. Two new icons in the icon/attribute box, at the left of the DTM, are START and END. Clicking on the START or END icon and then inside the appropriate triangle in the DTM sets the START and END points of the road.

The user may next specify the attribute on which to base the design. Figure 7, for example, shows the highlighted triangle (the upper left item in the attribute/icon box), indicating that slope is the primary design consideration.

Once the user chooses one or more design constraint(s) to apply to the current road layout, the system begins to find the least cost design alternative. Figure 7 illustrates the start of this process. The two triangles in the DTM next to the road's designated START are shown to be the first least cost candidates in the road's path. The "+" signs inside the triangles indicated the direction of the slope of that triangle.

LAYOUT continues to select the least cost design alternative until the road reaches the END triangle. Figure 8 provides an example of a road layout based on the grade attribute that the user selected at the beginning of the design process. Such a system would allow the user to select a number of criteria which, together with the criteria prioritization, would give LAYOUT enough information to generate a road layout. Since LAYOUT is a design assistant and not meant as a designer, the user specifies which factors are most important, and when to use any factor.

Once the user has based the road layout on grade, the layout may still be modified, based on another criteria. LAYOUT will support the user's ad-hoc requests to determine the impact of various attributes. Figure 9 illustrates such an analysis. Suppose the user has now clicked on the tree icon, as shown by the highlighted box around the icon. Based on the user command, LAYOUT has moved the road layout to a more northerly route. The tree icons within each of the three triangles show that large trees have forced the road to be relocated to a more northerly course.

Standardized Design Model (DESIGNER)

The second proposed application for TCMS site design is a model-based design assistant provisionally called DESIGNER. Similar to previously discussed model-based systems, DESIGNER would use objects to capture the components function and interaction with the rest of a design. The first type of building to be included within DESIGNER should be AFCS designs, because AFCS designs contain well-defined components that may be used as starting blocks for building an AFCS component library.

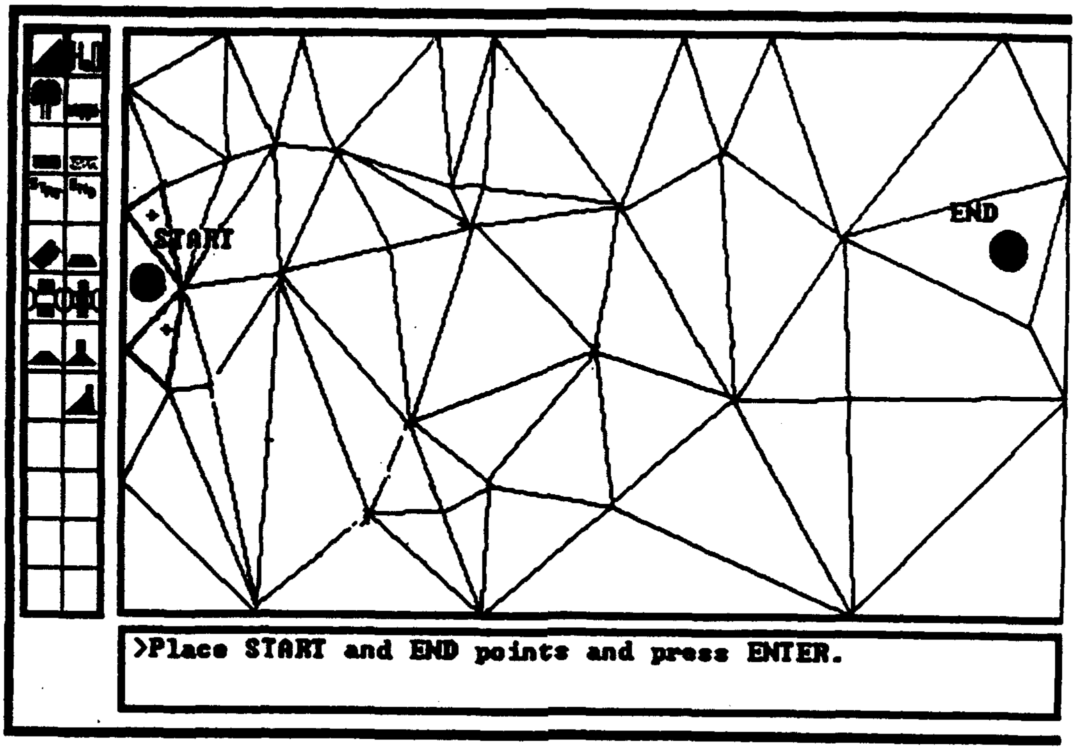

Figure 7. Simulated Start of Road Design Session.

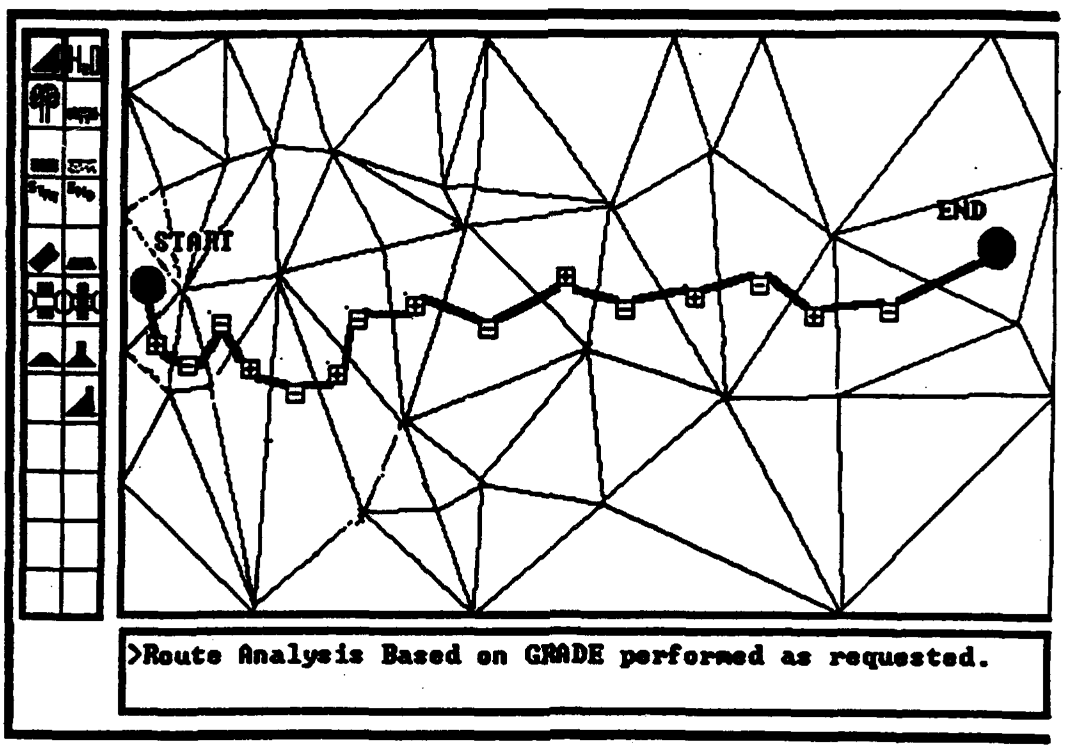

Figure 8. Simulated Route Analysis.

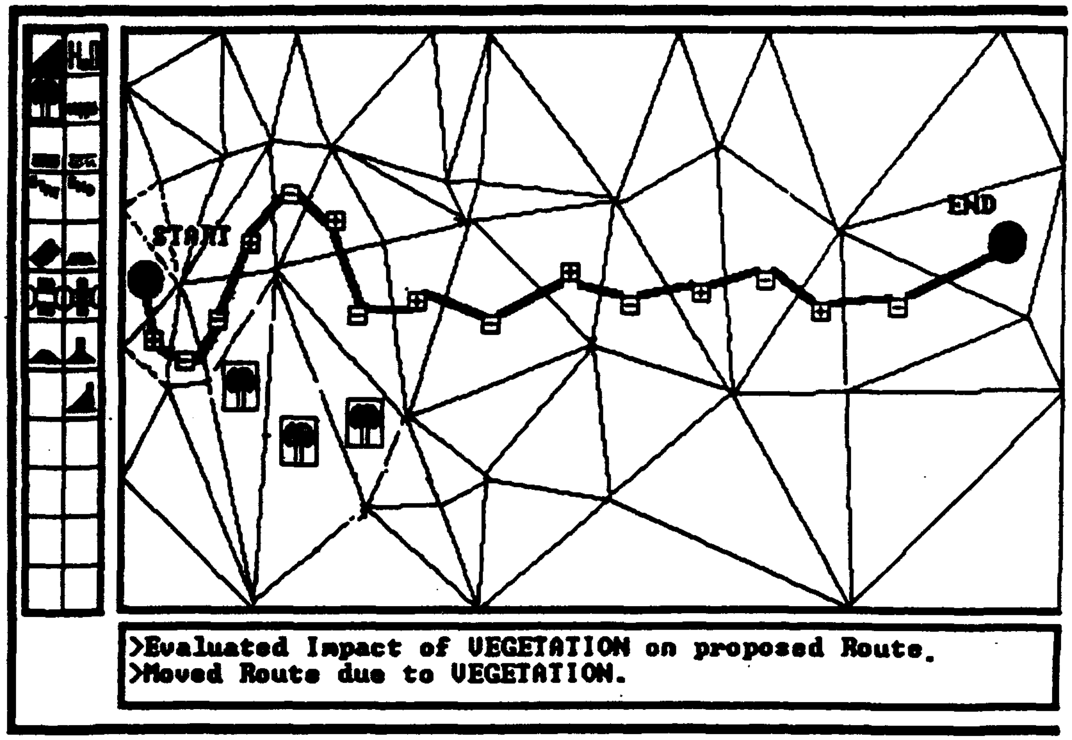

Figure 9. Simulated Ad Hoc Route Analysis.

Once a model-based AFCS building component library was built for the first AFCS design, then other AFCS designs could be included. One of the most useful AFCS designs that could be included in DESIGNER is the base camp. DESIGNER should help resolve the difficulty Army engineers have in correctly sizing base camp components. For example, a change to the number of persons who will be on a base would modify the number of shower heads, water feed pumps, water lines, and water storage and treatment facilities.

The AFCS component library should be modeled after current efforts to establish standard industrial product data formats. Using industry standards will also allow TCMS users to access other frequently used software. Functional attributes of components will assist Army engineers to substitute available materials.

There are several ways that DESIGNER could be implemented. Two important considerations to the development approach are: (1) at what level of detail will the designs be created, and (2) how the design will interact with the topographic and other environmental factors. One possible development approach presented in the following paragraphs suggests that DESIGNER create designs at a conceptual layout (similar to the CADDIE bubble diagram) and also interact with 3-D environmental factors (an extension to the SitePlan project).

Figure 10 shows one potential user interface for DESIGNER designing a base camp. There are three main regions of this interface. The first is the large box in the center of the screen. This is the DTM of the region where the base camp will be located. The view of the DTM shown in Figure 29 is a contour map. Other views of the DTM should be available. In the LAYOUT program, for example, the DTM view shown is the triangles generated from a TIN file.

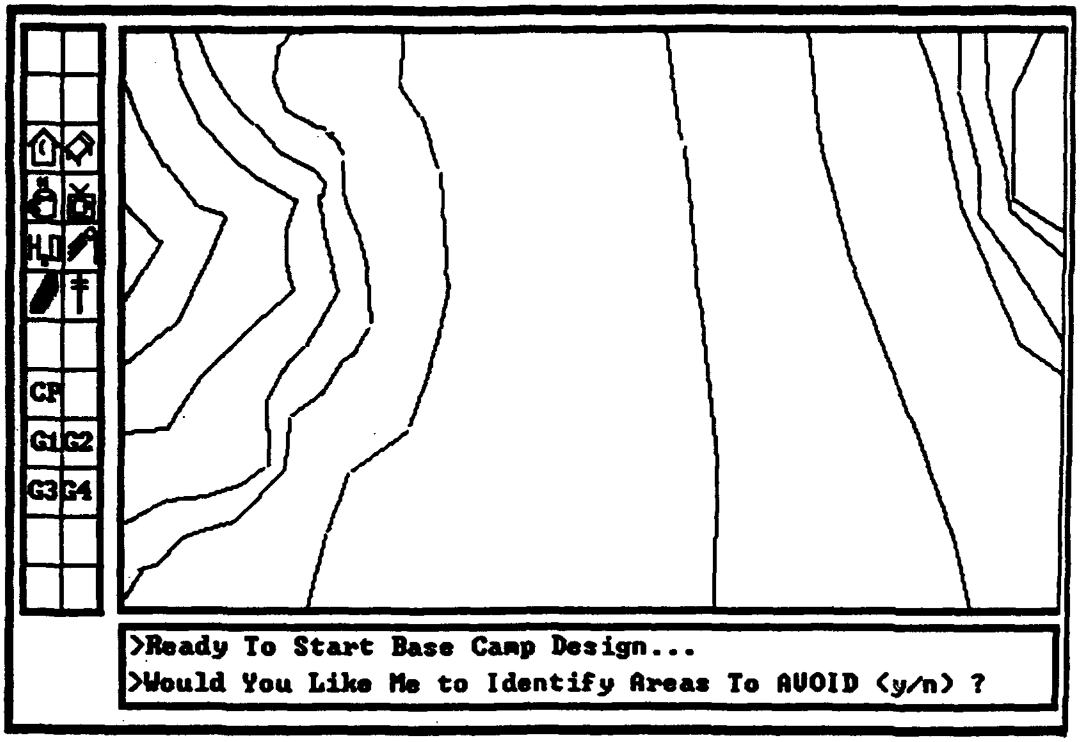

Figure 10. Example of Icon-Based Camp Design Interface.

As in the LAYOUT user interface, the two other areas of the DESIGNER user interface are the message box and the icon box. The message box is located at the bottom of the screen. The message box allows the user to type in commands to the system and receive system status and prompting messages. The icon box provides examples of the various components that the Army engineer would like to place in the base camp. For example, the icon box third from the top in the left column represents a latrine. The coffee mug below represents a mess hall. The icon boxes containing letters signify various operational components of the base camp. For example, CP represents the Command Post.

The message box in Figure 10 shows two messages: (1) the first message indicates that DESIGNER is ready to proceed with designing the base camp; (2) the second message indicates that DESIGNER will analyze the DTM to identify those areas that are too steep, or some other environmental factor, for the proper function of the base camp. Figure 11 shows the results of responding "yes" to the computers prompt to identify areas to avoid; DESIGNER has identified two areas: an area that is too steep to be used, and an area with potential problems of erosion. This capability illustrates the need to integrate GIS databases into CAD systems.

Once the user identifies those areas where they may safely construct the base camp, design may begin. To design the base camp, the engineer would click on the component that they wish to use and drag it on to the DTM. Once the item to be designed is placed on the map, then DESIGNER should prompt the user for information regarding size or number of people in the component.

Figure 12 illustrates another function of DESIGNER, that of constraint checker. In the figure several tent structures have been placed, the "CP," "G1," "G2," "G3," and "G4." Notice also that a road

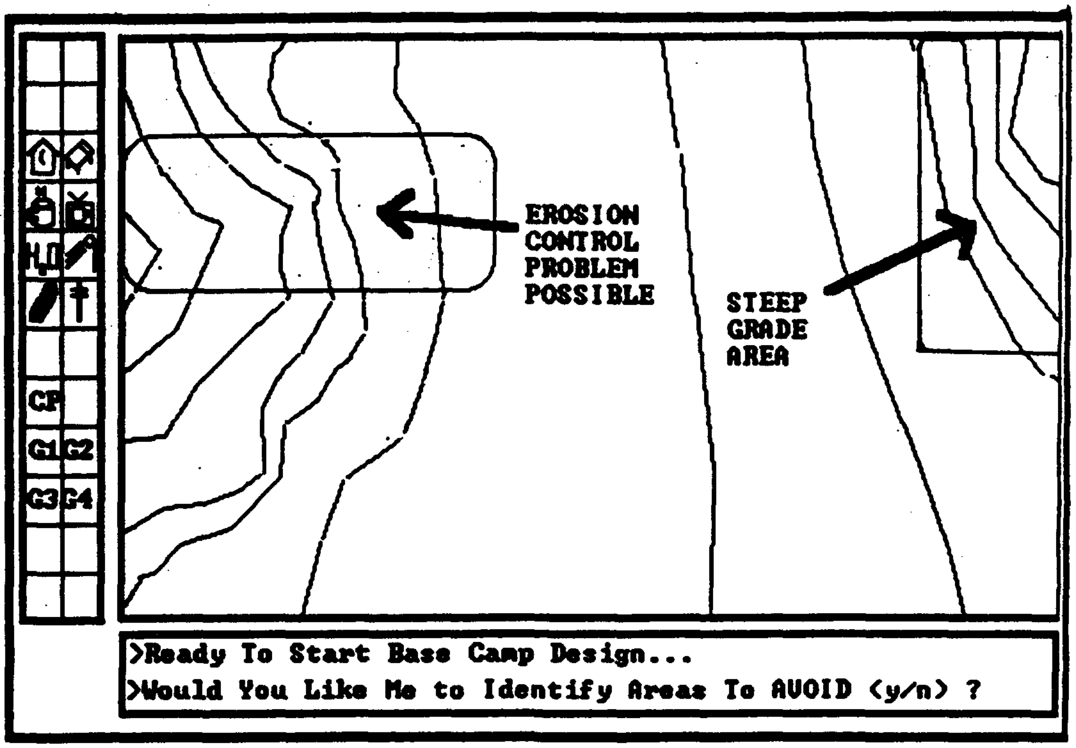

Figure 11. Simulated Topological Constraint Identification.

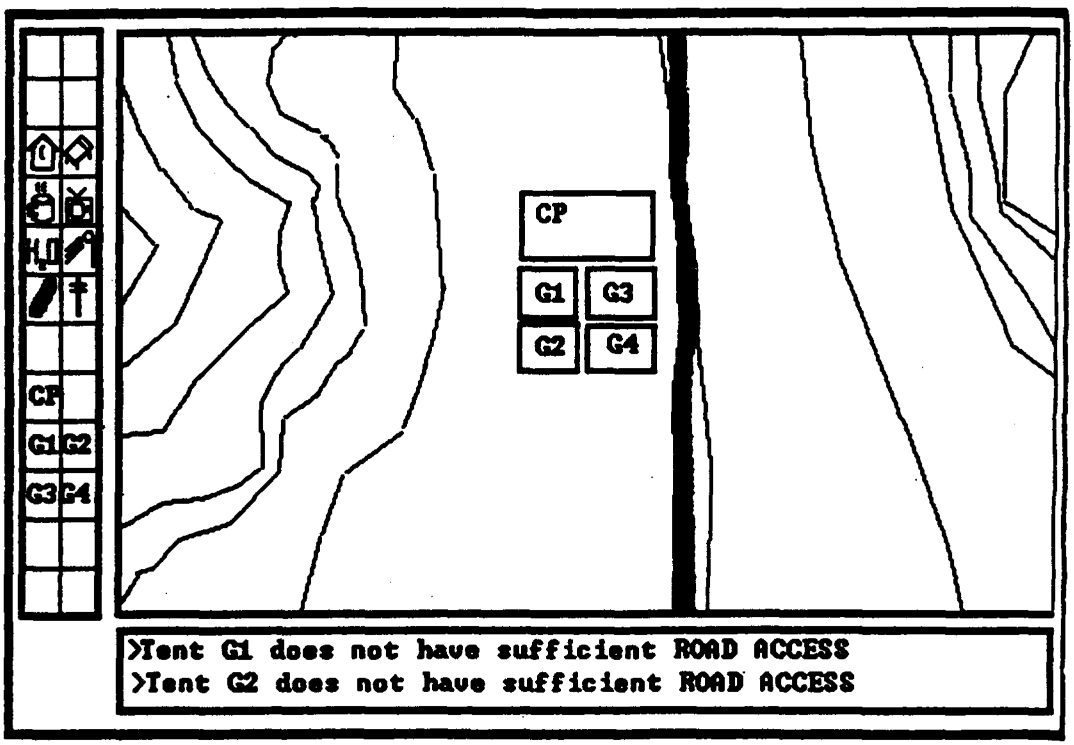

Figure 12. Simulated Component Constraint Identification.

running north and south has been placed on the site.[*] If the engineer desires, DESIGNER will review the design and identify potential problems. In the figure DESIGNER has identified that "G1" and "G2" do not have road access.

In addition to satisfying functional constraints of various design components, DESIGNER's model should allow users to exchange lessons learned at a very high level, for example the latrine must be downwind of the mess tent. If a natural user interface may be written to facilitate the capture and re-use of these lessons learned, then future base camp designers will build better camps that increase readiness and morale of troops.

LAYOUT and DESIGNER Development Considerations

Since this work has been focused on identification of opportunities to add site design capabilities to TCMS, development of LAYOUT and DESIGNER was limited. A follow-on effort should consider the following items.

For the LAYOUT system, the most important issue to consider is that of integrating CAD and GIS data. Since both are vigorously researched areas, LAYOUT system development may be based on joint development between disciplines. In addition, system designers may want to consider search techniques other than the typical "least-cost" search. For example, land element identification may help to pre-process raw GIS data.

The first challenge to designers of DESIGNER system will be to create a useful object-oriented model of standard designs. Much work will also be required to create databases of alternative components that could be used in standard designs. Facility components may also include specification and lessons learned to assist in developing useable project documents. DESIGNER may also be integrated with estimating, scheduling, and CAD systems.

[*] Note that the use of "common sense" orientation in which a vertical line from the top of a page to the bottom runs from north to south, provides a very natural user interface.

8 CONCLUSION

Current commercial software has improved the ability of the Army engineers to complete their mission in a quantitative way. The use of commercial civil engineering software, CAD systems, spreadsheets, databases, and word processing computer software allows Army engineers to perform calculations more rapidly and exchange data between various members of the construction team. As the quantity of computer-generated data multiplies, the practical usefulness of the tools decreases since users will not have the time or patience to analyze the data.

This rep t proposes two projects that will assist Army engineers to do site design in a qualitative way: a road l ,out assistant and a model-based designer. These two systems can qualitatively enhance the way Army engineers approach the numerical data typically produced by commercially available software, because these systems present the data in an intuitive, graphical way, which facilitates higher level design decisions.

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APPENDIX A: Annotated Bibliography by Subject Area

AFCS

TM 5-301-(1 through 4), *Army Facilities Components System - Planning*

provide material cost, logistical, and engineering data for use in construction planning support. The four volumes contain information useful in various climatic conditions.

TM 5-302,

contains drawings in Standard designs for AFCS projects are contained within several volumes.

TM 5-303, *Logistics Data and Bills of Materials*

contains bills of materials for all AFCS facilities. Related to each item in the bill of materials is the projected manhours for construction, logistics data, national stock numbers, and amount of material required for construction.

Stock Item Master File

contains information on all hardware items within AFCS. Building components are cross-referenced with other military and government organizations to a national stock system.

APPENDIX B: Review of Current Design Practice

A review of current design knowledge needed for low-volume road construction will help explain the environment in which military engineers operate. Topics in this chapter are ordered by their impact on the cost and time of construction.

The overall goal of any road construction is to find the "least cost" alternative for getting from point A to point B. The cost associated with design alternatives are based on obstacles between points A and B. For example, if there is a steep mountain between A and B, the designer will usually want to go around the mountain. These obstacles may also be thought of in a more general sense as design constraints. The mountain itself would not be a design constraint, but eliminating unnecessary changes in road grade or gradient would be a design constraint. The following sections identify and discuss design constraints. The ordering of these constraints is not meant, necessarily, to imply priority since each particular design may emphasize certain constraints over others.

Site Selection

Site selection for highway construction involves identifying the types and characteristics of soil where the road must pass, making an estimate of the amount of needed road material, general locations for potential quarry material, and possible river crossings. This is the most crucial step in low-volume road construction since the decisions made during this phase of the project will ultimately determine the cost and duration of the project.

In many remote sites, it is impossible to conduct traditional geotechnical site investigations. As a result, remote sensing, photographic interpretation, and surface assessments are critical for the proper terrain evaluation. Army engineers often use photographic information to evaluate terrain. When possible, an iterative process of photographic interpretation and on-site assessment is used (Fookes and Sweeney 1985, 1).

Airphoto Interpretation

Much information can be gained from an experienced interpretation of aerial photographs. First the photograph allows project participants to gain an overall perspective of the present state of a large geographical area, and of the selected site. One particular photograph may also be used by any number of personnel in a variety of locations and over various time periods.

Airphoto interpretations also allow the users to glean many engineering details about the site (TM 5-330 1968, pp 2-28). First, the photointrepreter may find repeating patterns or continuity of features that imply a relationship between topography, drainage, and manmade elements. Drainage channels and potential water crossings may also be identified. The distant perspective of photographs also assists project planners since moderate vegetation will not impact the topological review. Photointerpretation allows soil and rock types, and landscape features to be identified so that initial routes for field investigations may be determined (Schuster and Drizek 1978, p 48).

Aerial photographs are used in the analysis process as a part of "terrain evaluation." The purpose of terrain evaluation is to identify "land elements," or those relatively subjective boundaries between dissimilar types of materials. A change in terrain is identified as a land element depending on whether it will impact the construction process.

> For example, a hill slope may consist of two land elements, a steep upper slope and gentle lower slope. To an engineer each slope element is important when considering slope stability and amounts of cut and fill. Other examples of land elements are very small river terraces, gully slopes and small rock outcrops (Beaven and Lawrance 1973, 3).

Land elements may be classified as: (1) land forms, (2) drainage patterns, (3) soil tones, and (4) vegetation.

Land Forms

Land forms are distinctive areas of land composed of different types of geologic or topographic forms. It is important to identify types of land areas that have or may cause landslides.

To use landslide areas, specific land elements should be identified: (1) land areas undercut by streams, (2) steep slopes with large masses of loose soil and rock, (3) shape line of break at the scarp, (4) hummocky surface of the sliding mass below the scarp, (5) unusual topography, such as spoon-shaped troughs in the terrain, (6) seepage zones, (7) elongated undrained depressions in the area, (8) closely spaced drainage channels, (9) accumulation of debris in drainage channels or valleys, (10) appearance of light tones where vegetation and drainage have not been re-established, (11) distinctive changes in photograph tones from lighter to darker (darker tones indicate higher moisture content), (12) distinctive changes in vegetation indicative of changes in moisture, and (13) inclined trees and displaced fences or walls due to creep (Schuster and Drizek 1978, 55),

Other types of distinct land forms, such as moraines, kames, eskers, terraces, and dunes may also be identified using airphoto interpretation. By using lists of such distinctive features, each of these different geologically homogenous areas may be identified.

Drainage and Erosion

In most types of construction, water can cause serious damage to manmade structures. This is particularly true of low-volume roads, designed as temporary and therefore to degrade slowly over time.

Since most of the problems with highway construction in mountainous conditions result from the effects of water, one of the primary goals of terrain evaluation should be to identify these potential problems. The key land elements to be considered, therefore, are those that have or may contain water. Photointerpretation can show the locations of "springs, marshes, drainage channels, water courses, and permanently flooded areas (Goodman and Jeremiah, June 1976, pp 4-6)

Drainage pattern analysis may provide information to help control erosion and to determine drainage areas, stream gradients, and clues regarding the subsurface rock composition (TM 5-330, 2-29). Figure B1 shows natural drainage patterns identified during terrain evaluation. For example, closely spaced drainage implies relatively impervious underlying material, while widely spaced drainage indicates pervious materials.

Airphoto interpretation can also identify the type of soil through which gullies run. For example, gullies with smooth sides and bottoms in a u-pattern generally indicate the presence of silty soil. Gullies with a sharp break in the bottom, in a "V" shape, usually indicate the presence of sandy or gravely soil (TM 5-330, pp 2-29).

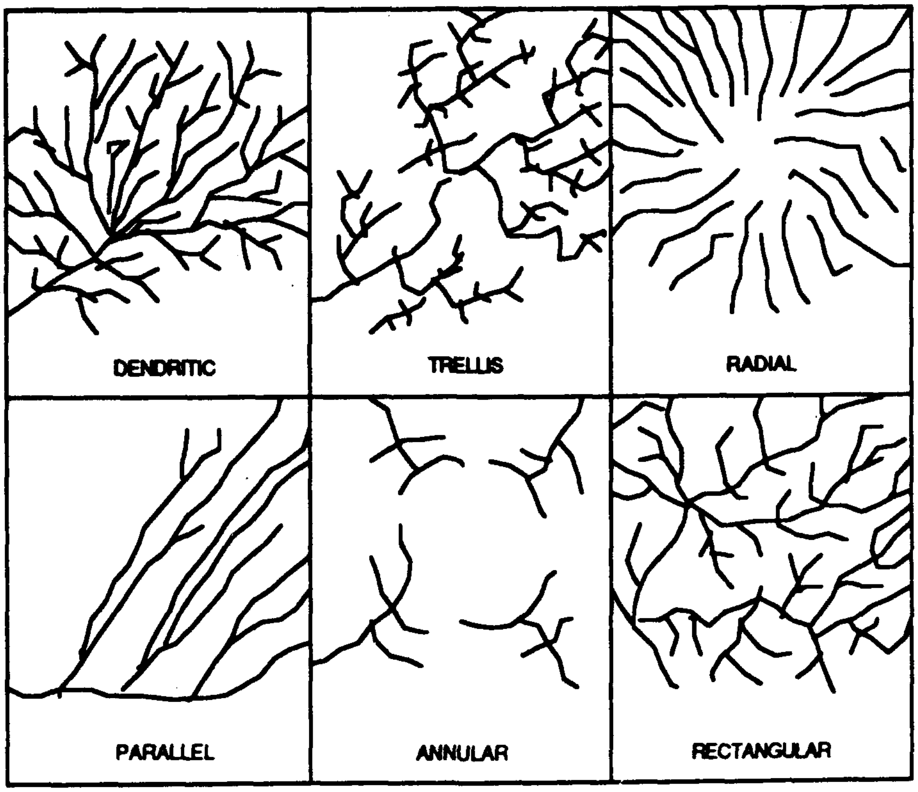


Figure B1. Natural Drainage Patterns.

Soil Tones

Since most photos used in soil identification are black and white, the presence or absence of moisture in the soil is an easily recognizable feature. Dry soil will show on the photograph as more lightly colored than soil with high moisture content. The relative distinctness of boundaries that separate areas can allow an initial estimate of soil type. Well-drained, coarse-textured soils show distinct boundaries, and poorly drained, fine-textured soils show irregular, fuzzy boundaries between tones.

Vegetation

Air photos can help identify vegetation types. Areas where the vegetation types change reflect changes in soil moisture content. For example, dark lines of vegetation found on mountain slopes often reflect the location of small or intermittent streams.

Remote Sensing

Satellite photography filtered for the infrared portion of the spectrum is a helpful supplement to airphoto interpretation. For example, interpretation of remote sensing data can lead to: (1) location of surface and near-surface moisture and drainage conditions, (2) indication of the presence of massive bedrock or bedrock at shallow depths, (3) distinction between loose colluvial materials that are present on steep slopes and are susceptible to landslides, or massive bedrock that is more stable on steep slopes, and (4) diurnal temperature changes that occur in soil masses that provide clues to the soil-water mass conditions (Schuster and Drizek 1978, p 67).

Remote sensing data is particularly important in identifying old landslides. These formations are difficult to detect with traditional photographic techniques. One technique for identifying old slide areas is to compare infrared photographs taken between rain and dry seasons. Small differences in movement between the two periods may appear due to changes in water pressure. These changes in water pressures are often characteristic of old landslide areas (Schuster and Drizek 1978).

Conceptual Road Design

Military engineers frequently must construct mountain roads that are characterized by difficult site access, slope stability problems, use of local construction materials, and greater need for erosion control (Fookes et al. 1985, p 1).

Implication of Land Forms on Road Design

There is a strong correlation between the types of land forms encountered in a particular region and the types of road cross sections that may be most frequently used for that region. Table B1 below gives some general guidelines to consider during conceptual design (Judd and Lafayette 1985, p 65).

Analysis of Design Stresses

The first requirement of road design is to evaluate the types of vehicles and loads that the road must bear. While vehicle types and loads may be somewhat fixed, the type of traffic may vary based on the cargo to be carried. One study of low-volume road traffic indicated that vehicles carrying timber, cattle, cotton, grain, sand, and gravel all had different usage patterns. Different types of trucks have different cycle times, and cargo trucks often take more trips than anticipated, and are sometimes loaded beyond capacity (Middleton and Mason 1987, p 13).

One recent study described a method to predict the years to failure for different load limits on rural Pennsylvania roads (Fernando, Luhr, and Saxena, 1987, p 145). This procedure allows users to consider the combined effect of axle-load and gross vehicle weight on the life of the road.

Grade Criteria

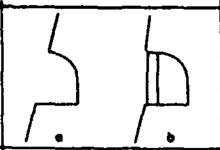
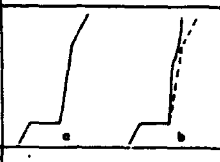
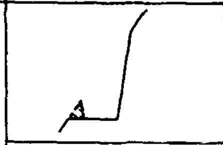
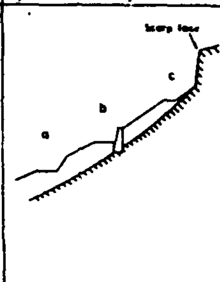
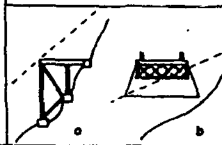
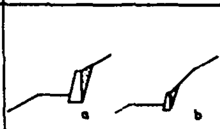
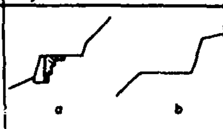
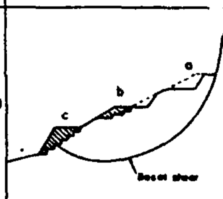
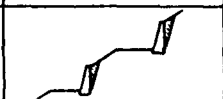
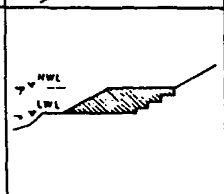
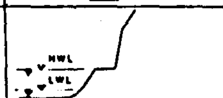
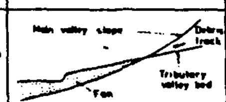
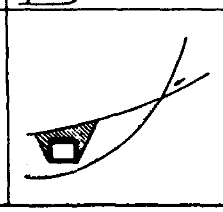
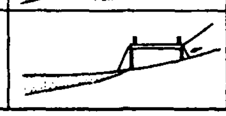
Designing the grade of a road is one of the most critical aspects of road design. Typically designed grades should not exceed 10 percent. To allow for actual conditions, a design grade of 10 percent should be changed to a grade between 5 and 15 percent. This design change is due to obstacles such as large trees or rocks not accounted for in the design (Kochenderfer 1970, p 10). Additional grade criteria may also be required to properly drain precipitation. Table B2 lists the effects of road grade on steep low-volume roads.

One recent study evaluated steep, low-volume roads within the United States (Anderson 1987, p 104). Although design criteria would typically be a maximum of 10 percent grade, over 20 percent of the roads in one particular U.S. Forest Service District had slopes that exceeded 15 percent. The most effective surfacing material on these steep slopes was found to be aggregate, since aggregate provides the best traction in wet conditions.

As an alternative to side-cut roads, ridge top construction was found to be very cost effective. According to the U.S. Forest Service Study, side-cut road costs range from $250,000 to $600,000 per mile. The ridge top road typically costs $1000 per mile to build. In addition to construction cost side-cut roads also require significant maintenance to monitor and control slope stability.

Table B1

Typical Road Cross Sections

ZONE AND MATERIAL	SITUATION	PREFERRED SECTION	REMARKS	SITUATION	PREFERRED SECTION	REMARKS
2 ROCK and SCREE	Rock slopes > 75°		Rock quality is critical a. Half tunnel unsupported in massive hard rock b. Galleried/propped half tunnel as alternative	Rock slopes 45°-75°		Full cut cross-section a. Uniform slopes, stable cut face b. Concave slopes, over-steepened cut face, with minor instability, necessary to daylight cutting.
	Rock slopes < 75° – Spur		Box, gully, or through cut. It may be desirable to excavate small outside cut-slope for ease of construction and maintenance	Screes 30°-38°		Full cut cross-section a. Stable low angle scree - unsupported face Active high angle scree - b. Middle slopes - retaining wall to limit ravelling upslope, preferably founded on rock c. Upper slopes - ravelling limited by proximity of scarp face
	Rock slopes < 75° – Gully		a. No rockfall and minor stream flow - Trestle or wall support. b. Rockfall and appreciable stream flow - Bridge crossing			
3 COLLUVIUM, TALUVIUM, and in-situ WEATHERED MATERIAL	Uniform gentle slopes < 25°		Balance of cut and fill on uniform slopes	Irregular gentle slopes and at zone boundaries		a. Full fill on concave slopes to avoid cutting toe of steeper slopes above. b. Full cut on convex slopes to avoid loading head of steeper slope below
4 COLLUVIUM, TALUVIUM, and in-situ WEATHERED MATERIAL	Uniform slopes > 30°		a. Many cuts upto 6m will be wall supported to full height b. Many cuts > 6m supported by toe wall only	Irregular slopes and at zone boundaries > 30°		a. On concave slopes economic section is small cut and small retained fill. b. On convex slopes cut may be possible
	Unstable areas – Mudflow		Stabilising pad of granular material	Major pre-existing slip		a. Full cut alignment unloads heel of slip. b. Half cut, half fill for minimum disturbance at neutral point. c. Full fill alignment loads toe of slip.
	Unstable areas – Eroding gully		Wall supported fill with culvert Crossing point at resistant outcrop			
	Hairpin bends on slopes > 30°		Preferred cross-section is upper line cut, lower line fill	Hairpin bends on slopes > 30°		Second choice cross-section. Avoid upper line on fill above lower line on cut.
5 ALL SLOPE MATERIALS + ALLUVIAL FANS and RIVER DEPOSITS	Normal river valley		Causeway section above flood level. Avoid cutting into Zone 4 slopes. Flood protection works essential	Gorge slopes > 75°		Half tunnel / galleried section. Careful estimation of H.W.L. necessary in constricting gorges.
				Gorge slopes 45°-75°		Full cut section.
	Body of tributary fan with flood flow only		Body of fan should be crossed at grade. Bridging is preferred as below for higher line crossing throat of fan.	Major aggrading fan		Cut and cover tunnel. Difficulty is to establish that fan will continue to accumulate throughout economic life of the road.
	Tributary fan with permanent flow		Bridge tributary at throat of fan with high approach embankments. Avoid bridging on the body of the fan			

NOTES

The cross-sections are simplified. The following limitations should be noted

1. The slope angle ranges are approximated.
2. The implications of changes of slope immediately above and below the line and the use of split level carriageways are not developed here
3. The stabilisation and control measures which are necessary on many cross-sections have been omitted for clarity. Similarly no distinction has been made between walls and revetments
4. The influence of rock structure and weathering has not been explored here. This will be a major consideration for all rockwork design

(Source: *Engineering Geology*, Vol 21 [Elsevier Publishing, 1985]. Used with permission.)

Table B2

Effect of Road Grade on Steep Low-Volume Roads

Item Impacted by Grade Change	Effect on Price	Effects on Quantity
Excavation	Stays roughly the same	Amount of excavated material decreases rapidly for ridge top roads
End haul	Could increase or decrease	Would vary with excavation volume
Rocking costs	Increase slightly	Decrease if road length decreases sufficiently
Culverts	Stay the same	Increase
Maintenance:		
Blading	Increases on roads steeper than 16 percent	Decreases; less length to maintain
Ditching	Increases	Decreases; fewer sidehill roads
Surface treatments to improve traction	Stay the same	Increase
Log haul:		
Unassisted	Increases slightly	Stays the same
Assisted	Stays the same	Increases
Design and administration	Costs increase 20-40 percent	Stay the same
Clearing and grubbing	Decrease for ridge top roads	Decrease for ridge top roads

Orientation Design

Another consideration for road alignment is the orientation of the road to the sun. Roads on south and west slopes typically receive more sun than those on the north and east slopes. Thus, roads on south and west slopes will dry faster than those on north and east slopes.

In addition to orienting a road based on compass orientation, the road designer should consider the relative position of natural drainage structures and the road to be designed. In most cases, roads should be built upslope from any streams, springs, etc. to minimize drainage requirements and maintenance costs (Kochenderfer 1970, 22).

Landslide Analysis/Design

One of the constraints to road design is to account for landslide potential. The design process provides three options for landslide protection: (1) avoidance or elimination of the problem area, (2) reduction of forces that may cause a landslide, and (3) increase of forces resisting landslide motion. A life-cycle economic analysis should determine which design alternative to take.

A landslide area may be avoided altogether if the problem is identified during the site investigation. Table B3 gives several rules of thumb that may be useful for identifying landslide areas. If the problem area is identified early, alternate routes may be selected, or the landslide area may be eliminated by removing all or part of the slide material.

Table B3

Susceptibility of Key Landforms to Landslides

Topography	Landform or Geologic Materials	Landslide Potential*
I. Level terrain		
A. Not elevated	*Floodplain*	3
B. Elevated		
1. Uniform tones	Terrace, lake bed	2
2. Surface irregularities, sharp cliff	Basaltic plateau	1
3. Interbedded-porous over impervious layers	Lake bed, coastal plain, sedimentary plateau	1
II. Hilly terrain		
A. Surface drainage not well integrated		
1. Disconnected drainage	Limestone	3
2. Deranged drainage, overlapping hills, associated with lakes and swamps (glaciated areas only)	Moraine	2
B. Surface drainage well integrated		
1. Parallel ridges		
a. Parallel drainage, dark tones	Basaltic hills	1
b. Trellis drainage, ridge-and-valley topography, banded hills	Tilted sedimentary rocks	1
c. Pinnate drainage, vertical-sided gullies	Loess	2
2. Branching ridges, hilltops at common elevation	Loess	2
a. Pinnate drainage, vertical-sided gullies	Flat-lying sedimentary rocks	2
b. Dendritic drainage		
(1) Banding on slope		1
(2) No banding on slope	Clay shale	
(a) Moderately to highly dissected ridges, uniform slopes		1
(b) Low ridges, associated with coastal features	Dissected coastal plain	1
(c) Winding ridges connecting conical hills, sparse vegetation	Serpentinite	
3. Random ridges or hills		
a. Dendritic drainage		1
(1) Low, rounded hills, meandering streams	Clay shale	1
(2) Winding ridges connecting conical hills, sparse vegetation	Serpentinite	2
(3) Massive, uniform, rounded to A-shaped hills	Granite	2
(4) Bumpy topography (glaciated areas only)	Moraine	
III. Level to hilly, transitional terrain		
A. Steep slopes	Talus, colluvium	1
B. Moderate to flat slopes	Fan, delta	3
C. Hummock slopes with scarp at head	Old slide	1

* 1=susceptible to landslides; 2=susceptible to landslides under certain conditions; and 3=not susceptible to landslides except in vulnerable locations.

If the slide area cannot be avoided or eliminated, then additional steps may be needed to change the sliding or resisting forces. Tables B4, B5, B6, B7, and Figure B2 list techniques to help designers align roads through landslide areas.

In addition to the information regarding retaining walls presented in the previous tables, additional information on retaining wall construction that may be of interest to the reader is included in Patel et al. (1989).

Base and Wearing Surface Design

Based on an analysis of loading requirements and the conceptual road design/layout, the detailed design of the road may proceed. The construction of low-volume roads has typically emphasized developing cut/fill requirements for moving earth along the road alignment. However, the design of the road surfaces and subgrades is also of critical importance to the usefulness of the road.

TM 5-330, *Planning and Design of Roads, Airbases, and Heliports in the Theater of Operations* contains the design method used by Army Engineers. This method, as well as those of other agencies, was reviewed in 1988 by the U.S. Army Waterways Experiment Station (USAWES). The study found that the standard design procedures are sensitive to a number of variables including the number of axles of the vehicle, variation in thickness of gravel, and vehicle tire pressure. These studies indicated that the reliability of most design procedures and the designs they produce was very low.

Road Failure Modes

One way that designers may validate their design assumptions is by reviewing various types of roadway failure modes. One study (Cos and Rolt 1986) of failures of low-cost roads in New Zealand identified five different road failure modes (Figure B3). The first mode, cracking, is caused by a loss of waterproofing in the surface of the road. Once water has penetrated the road surface, the surface becomes brittle. Under loading by vehicles, the surface cracks, causing further water penetration.

The second road surface failure mode is ravelling, in which water under the road does not disperse. The accumulation of water in specific areas under the road causes a loss of shear strength of the road base so that the road begins to pothole. A longer term accumulation of water under the road results in potholes, the third road failure mode. Once again, moisture under the road surface decreases the shear strength of the base.

Rutting, the next mode of road failure, is actually the normal behavior of roads. Loading and unloading the road surface over a long period of time normally results in rutting. The speed with which the deformations appear, however, depends on the strength of the road. Rapid rutting, the last mode of road failure, is the result of use of unsuitable materials or inadequate compaction.

Seasonality

Since patterns of moisture are typically seasonal, climatic conditions play an important part of road design. Two recent studies have been conducted to evaluate the strength of roads under seasonal moisture patterns. The first approach was a study to develop an in-place strength test for aggregate surfaced roads that accounts for varying climatic conditions (Alkire 1987, p 314). Another study actually developed an index that would accurately predict the durability of roads (Visser 1987, p 222). Figure B4 shows the results of the study that compared subgrade strength of roads over time.

Table B4

Design Procedures To Avoid Landslides

Category	Procedure	Best Application	Limitation	Remarks
Avoid problem	Relocate highway	As an alternative anywhere	Has none if studied during planning phase; has large cost if location is selected and design is complete; also has large cost if reconstruction is required	Detailed studies of proposed relocation should ensure improved conditions
	Completely or partially remove unstable materials	Where small volumes of excavation are involved and where poor soils are encountered at shallow depths	May be costly to control excavation; may not be best alternative for large slides; may not be feasible because of right-of-way requirements	Analytical studies must be performed; depth of excavation must be sufficient to ensure firm support
	Bridge	At sidehill locations with shallow-depth soil movements	May be costly and not provide adequate support capacity for lateral thrust	Analysis must be performed for anticipated loadings as well as structural capability to restrain landslide mass

Table B5

Design Procedures To Reduce Driving Forces

Category	Procedure	Best Application	Limitation	Remarks
Reduce driving forces	Change line or grade	During preliminary design phase of project	Will affect sections of roadway adjacent to slide area	
	Drain surface	In any design scheme; must also be part of any remedial design	Will only correct surface infiltration or seepage due to surface infiltration	Slope vegetation should be considered in all cases
	Drain subsurface	On any slope where lowering of groundwater table will effect or aid slope stability	Cannot be used effectively when sliding mass is impervious	Stability analysis should include consideration of seepage forces
	Reduce weight	At any existing or potential slide	Requires lightweight materials that are costly and may be unavailable; may have excavation waste that creates problems; requires consideration of availability of right-of-way	Stability analysis must be performed to ensure proper use and placement area of lightweight materials

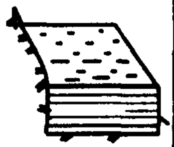
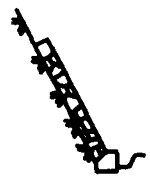
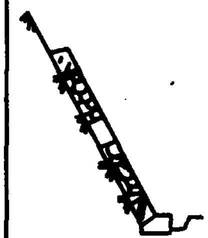
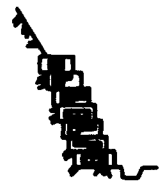
Table B6

Design Procedures To Increase Resisting Forces

Category	Procedure	Best Application	Limitation	Remarks
Increase resisting forces	Drain subsurface	At any slide where water table is above shear plane	Requires experiences personnel to install and ensure effective operation	
	Use buttress and counterweight fills	At an existing slide, in combination with other methods	May not be effective on deep-seated slides; must be founded on a firm base	
	Install piles	To prevent movement or strain before excavation	Will not stand large strains; must penetrate well below sliding surface	Stability analysis is required to determine soil-pile force system for safe design
	Install anchors	Where rights-of-way adjacent to highway are limited	Involves depth control based on ability of foundation soils to resist shear forces from anchor tension	Study must be made of in situ soil shear strength; economics of method is function of anchor depth and frequency
	Treat chemically	Where sliding surface is well defined and soil reacts positively to treatment	May be reversible action; has not had long-term effectiveness evaluated	Laboratory study of soil-chemical treatment must precede field installation
	Use electroosmosis	To relieve excess pore pressures at desirable construction rate	Requires constant direct current power supply and maintenance	
	Treat thermally	To reduce sensitivity of clay soils to action of water	Requires expensive and carefully designed system to artificially dry out subsoils	Methods are experimental and costly

Table B7

Recommended Sizes of Retaining Structures

REVETMENT WALLS						
REINFORCED EARTH	DRY STONE			BANDED DRY STONE MASONRY	MASONRY	GABION
						
0.8H	0.14H	0.2H	$0.4+\frac{H}{10}$	0.50m	0.50m	2m
0.8H	0.14H	0.2H	$0.4+\frac{H}{10}$	0.50m	0.50m	2m
—	—	—	—	—	—	—
vertical	3 : 1	4 : 1	5 : 1	2 : 1	3 : 1	2 to 5 : 1
vertical	3 : 1	4 : 1	5 : 1	2 : 1	3 : 1	2 to 5 : 1
3m to 25m	4.5m	4m	3m	3m to 6.5m	1m to 6.5m	1m to 8m
Granular backfill preferred. Length and density of reinforcing strips, meshes, and fabrics to be specified. Check for possible corrosion of strips and facings. Avoid locations where backfill is satruated.	Pack stone perpendicular to outer slope. Specify minimum stone size.			Masonry bands 0.45 - 0.60 thick. Dry stone panels up to 2.45 x 2.75. Dowels grouted into rock face may be added.	Weepholes at 2.00 centres generally closer if slope is wet.	Step front face > 0.2 < 0.5 otherwise as for walls.
	Revetments shaped to suit overbreak in rockface.					
Huge potential - particularly if used with low cost materials. Used more as stable fill platform for road rather than slope support.	← Least durable → ← Little used → ← Most durable → ← Non ductile structures most susceptible to earthquake damage → To prevent major erosion, rock fall, slope degradation - particularly where vulnerable structures at risk, or where retrogressive, slip development possible.					
AMERICAN FRENCH PRACTICE	INDIAN ROADS PRACTICE				AUTHORS' FILES	
2, 4	2, 4			2, 4	2, 4	2, 4

NOTES

1\.
Techniques shown in other tables for drainage and erosion control are simple and many such techniques may be used on one site. However wall construction requires special skills and practised labour. For good quality construction select one type of wall and the corresponding revetment and use this throughout the site.

2\.
This list of wall and revetment types is by no means comprehensive. Simple earth and rockfill buttresses are not shown. The more complex walls in concrete, concrete crib, circular metal bin, rectangular steel bin (Schwarzholl, 1975) and other types of construction are not shown but may be appropriate if materials availabe.

3\.
The typical dimensions shown rely both on well-drained backfill and a good foundation. Foundation and overall stability should be checked. Bearing pressures may be assessed using Fig. 22.

2\. Free rock face and coarse debris slopes.
3\. Ancient terrace and degraded valley slopes.
4\. Active lower slopes.

Table B7 (Cont'd)

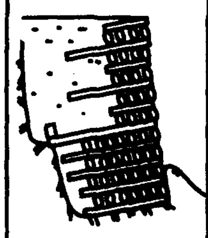
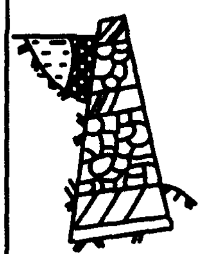
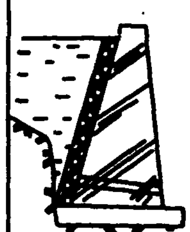
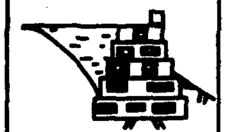
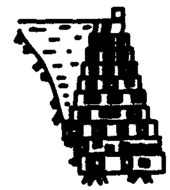
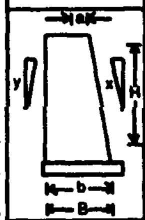
		RETAINING WALLS					
TYPE		TIMBER CRIB	DRY STONE	BANDED DRY STONE/MASONRY	MASONRY	GABION	
						LOW	HIGH
DIAGRAMATIC CROSS SECTION							
CONSTRUCTION NOTES: TYPICAL DIMENSION 	a	2m	0.25H	0.75m	0.50m	2m	2m
	b	—	0.5H	0.4H + 0.30m	0.9H to 0.45H	0.7H to 1.0H typical	0.5H typical
	B	—	0.5H + 0.67m	0.5H + 0.60m	1.25H to 0.61H	—	—
	x	4 : 1	3 or 4 : 1	3 : 1	10 : 1	6.7 : 1	6.7 : 1
	y	4 : 1	vertical	vertical	varies	3.3 : 1	3.3 : 1
RANGE OF HEIGHT		3m to 9m	1m to 3.5m	3.5m to 12m	1m to 10m	1m to 6m	6m to 12m
GENERAL		Foundation slope 1 : 4. Timbers square or rounded - 0.15 ø with stone rubble well packed behind timbers, 10% of headers to extend into fill.	Pack stone perpendicular to the outer slope. Hand packed rubble stone behind wall.	Masonry bonds 0.45 - 0.60 thick. Dry stone panels up to 2.45 x 2.75. Rubble packing to wall. Compact remaining fill area in layers < 0.15 thick.	Weepholes at 2.00 centres generally, 1.00 in open voided soils 0.50 thick rubble backing.	Stone to be hand packed. Stone shape important, blocky preferable to tabular. Specify maximum/ minimum stone size, see Fig. 21 No weathered stone be used. Compact granular backfill in layers < 0.15 thick.	
		1. Foundations to be stepped up if rock encountered in excavations. Structure should be dowelled onto rock. 2. All require durable rock filling of small to medium size. 3. Drainage of wall bases not shown. Usual to provide permanent drainage for base excavation					
APPLICATION		← Least durable → (Timber crib, Dry stone, Banded dry stone/masonry) ← Most durable → (Masonry) ← Accomodates differential settlements → (Gabion) ← All these types traditional and proven → (Timber crib to Masonry) ← Non ductile structures most susceptible to earthquake damage → (Timber crib to Masonry) 1 Design as conventional retaining walls. Important limitation is wall height as shown above. 2. Use of both as cut slope and fill slope support. 3. Choice of wall type depends on material availability and local experience: also on shape of backfill wedge as illustrated by cross sections above.					
REFERENCE SOURCE		MILITARY ENGINEERING PRACTICE (U K)	INDIAN ROADS PRACTICE		AUTHORS' FILES	AUTHORS' FILES	
MOUNTAIN ZONE		2, 3, 4	2, 3, 4	2, 3, 4	2, 3, 4	2, 3, 4	2, 4

Table B7 (Cont'd)

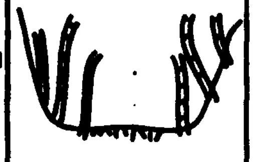
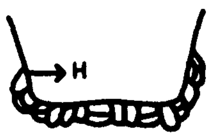
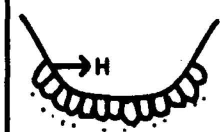
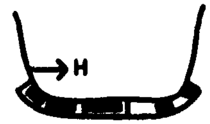
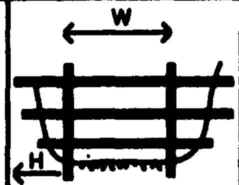
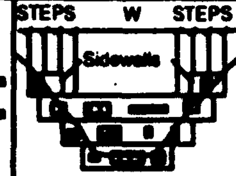
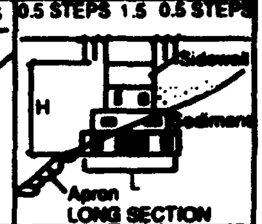
	TYPE OF PROTECTION	BAMBOO PLANTING OR SIMILAR	RUBBLE MASONRY	DRY STONE PITCHING	GABION MATTRESS	CHECKDAMS: TIMBER	CHECKDAMS: GABION
	DIAGRAMMATIC CROSS SECTION OR LONG SECTON						 
	CONSTRUCTION NOTES AND TYPICAL DIMENSIONS	Plant type and spacing to be specified; typical densities 1 plant or tree per 2 - 10m^2 of gully side, seek specialist local advice if possible.	Thickness of masonry 0.5. H to suit esimated flow depth and extent of gully side instability, generally 0.50 minimum.	Thickness of pitching 0.4, minimum stone dimension 0.2, loxg axes of stones vertical, bedded on 0.1 thick gravel layer. H to suit flow depth and gully side instability.	Thickness of mattress 0.3 - 0.5, erodible bed may require buffer filter or impermeable underlay (e.g. polythene). H to suit flow depth, and gully side instability.	Minimum diameter of timbers 0.3, keyed 1.0 into gully bed and sides, timber spacing to be specified. H = 1 to 3m.	Gabions keyed 0.5 minimum into gully bed and sides. H = 2 to 6m. L = H + 0.5, may be reduced and keyed into gully bed if good rock encountered in foundation. Standard gabion box size 2x1x1m, mesh to be specified.
GULLY CHARACTERISTICS	BED SLOPE	10°- 40°	0°- 30°	0°- 15°	10°- 30°	15°- 40°	
GULLY CHARACTERISTICS	RELATIVE ERODIBILITY OF BED	Low - Moderate	Moderate - High	Low - Moderate	Moderate - Very High	← Low - High — Note that erosion may be accelerated below crest of checkdam or masonry apron may be required in gully bed and	
GULLY CHARACTERISTICS	SIZE OF BED LOAD	Small - Large	Small - Medium	Small - Medium	Medium - Large	Medium - Very Large	Medium - Large
GULLY CHARACTERISTICS	GULLY SIZE	Small - Very Large	Small - Medium	Small - Medium	Medium - Large	Large - Very Large	Medium - Large
	MOUNTAIN ZONE	2, 3, 4	2, 3, 4	2, 3, 4	2, 3, 4	← 4 —	

Table B7 (Cont'd)

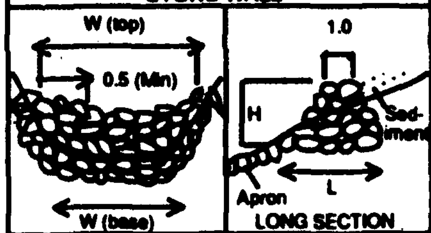
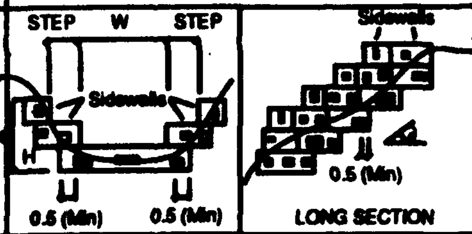
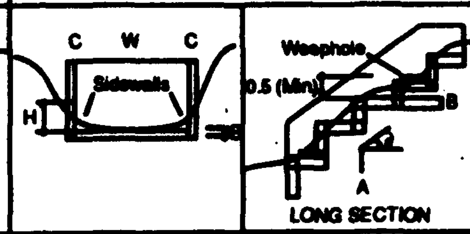
STONE WALL	GABION CASCADE	MASONRY CASCADE	CLASSIFICATIONS AND NOTES
			Width of protection works (W) and size of steps for cascades and checkdams to suit gully width and angle of side slopes. Length of protection works, number and spacing of checkdams along the gully bed to be specified.
Stone layers keyed 0.3 minimum into gully bed and sides, minimum stone dimension 0.2, bedded on 0.1 thick gravel layer. H = 1 to 3m. L = 1.33xH, may be reduced and keyed into gully bed if good rock encountered.	Gabions keyed 0.5 minimum into gully bed and sides. H = 1 to 4m, generally to suit estimated flow depth and extent of gully side instability ∂ (angle of cascade) to suit gully bed angle. Erodible bed may require buffer filter or impermeable underlay. Standard gabion box size 2x1x1 or 1x0.5x0.5m for small gullies and flows, mesh to be specified.	H to suit estimated flow depth and gully side instability, minimum 0.5 clearance of sidewall over front edge of cascade steps. A varies 0.2 (low angle) to 0.6 (high angle) depending on angle of cascade (∂), see below. B varies 0.15 (low angle) to 0.4 (high angle). C varies 0.15 (low angle) to 0.5 (high angle) ∂ to suit gully bed angle. Weepholes required on each vertical step.	All dimensions in metres. Construct sidewalls and edges of all protection works flush with existing ground levels on gully side.
	20^0 - 45^0	30^0 - 60^0	
→ and pitched boulder, gabion mattress along base of side slopes.	High - Very High	Moderate - High	Relative Erodibility / Annual Incision (metres) / Examples Low / 0 - 0.1 / Hard rocks, rocksteps and waterfalls. Moderate / 0.1 - 0.5 / Weak rocks, channels with thin alluvial cover. High / 0.5 - 1.5 / Thick terrace deposits, alluvial fill. Very High / < 1.5 / Tipped soil from road construction.
Small - Medium	Medium - Large	Small - Medium	Maximum Bed Load / Particle Size Small / Fines and sands Medium / Gravel Large / Cobbles Very Large / Boulders
Small - Medium	Medium - Large	Small - Medium	Gully Size / Cross Section Area (m^2) Small / 1 - 2 Medium / 2 - 5 Large / 5 - 20 Very Large / > 20
→	2, 4	2, 4	Mountain Zone 2. Free rock faces, debris slopes. 3. Ancient terrace, degraded valley slopes. 4. Active lower slopes.

Table B7 (Cont'd)

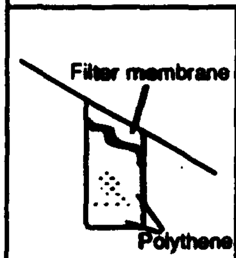
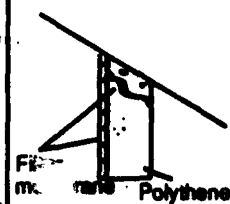
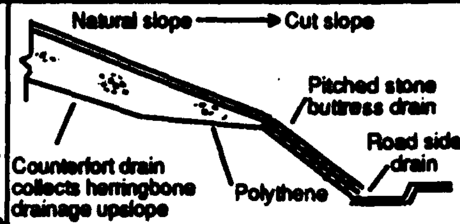
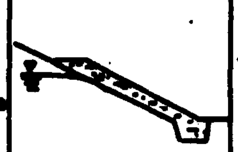
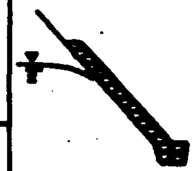
DRAINAGE OF SHALLOW SLIDES AND SATURATED SOILS					NOTES
HERRINGBONE DRAIN		COUNTERFORT / BUTRESS DRAIN	FILTER REVETMENT DRAIN		
		 LONG SECTION	 LONG SECTION	 LONG SECTION	Other combinations of cut off / filter drains and variation in cross section shape are possible, depending on site conditions and availability of local materials.
Typical section 1.0 - 2.0 deep, 0.5 wide at 3 - 8 spacing, 0.2 thick cobble layer and filter membrane on top of drain for surface protection.		Counterfort filter drain 0.8 wide, < 2.5 deep at 3 - 15 spacing with filter membrane around sides and heavy duty polythene laid on invert, benched foundation for slopes > 30. Cut slope buttress drain 0.8 wide, < 2.0 deep, 2no 0.1 ø drainholes feed masonry "side drain." Cut slope masonry drains (cascades on steep slopes), omitting buttress drain also used.	0.3 thick gravel.	0.3 thick dry stone.	All dimensions in metres.
Upslope filter membrane omitted but graded filter infill specified for high flow condition.	Upslope filter membrane with clean gravel infill for low flow condition.		Gravel or dry stone laid on filter membrane or 0.1 thick sand bed.		Approximate catchment area drained and required drain capacities to be assessed by simple analytical methods (e.g. Rational formula for catchment studies, Manning's formula for drain velocities).
Aligned crosslope in herringbone pattern to connect with counterforts.		Aligned directly to downslope.			Permeability of filter membranes to be checked in relation to soil grading and anticipated flow in coarse soils.
< 35°	< 35°	< 45°	< 30°	30°- 45°	
X ——→		←—— F X ——→	←—— F ——→		Design for specific location will require specification of F Filter material grading. G Allowable gradient. X Cross-section dimensions.
Interception of throughflow seepage and springs.			Control of ground water at emergence over large areas of a cut slope in soils or soft rocks.		All methods shown are small-scale only. For major eroding channels employ gully protection methods listed in Table 16. Stepped cascades (Table 16) are used to channel large flows down steep slopes.
Drainage of shallow-seated instability above cut slopes.		Counterfort channels herringbone drainage, also gives some mechanical support if dug fully through unstable material. Stabilisation of shallow debris slide and mudflow materials.			
—— 3, 4 ——→					2. Free rock face and coarse debris slopes. 3. Ancient terrace and degraded valley slopes. 4. Active lower slopes.

Table B7 (Cont'd)

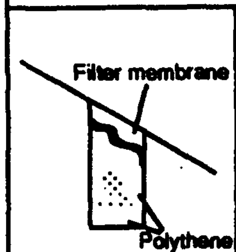
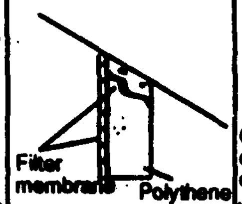
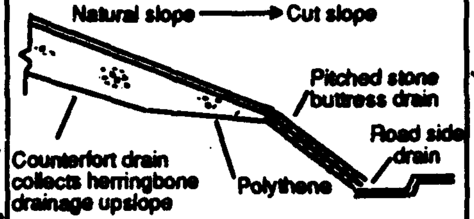
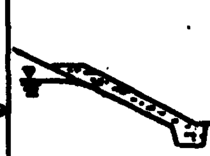
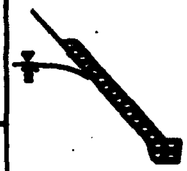
DRAINAGE OF SHALLOW SLIDES AND SATURATED SOILS					NOTES
HERRINGBONE DRAIN		COUNTERFORT / BUTRESS DRAIN	FILTER REVETMENT DRAIN		
 Filter membrane; Polythene	 Filter membrane; Polythene	 Natural slope ——→ Cut slope; Pitched stone buttress drain; Road side drain; Counterfort drain collects herringbone drainage upslope; Polythene; LONG SECTION	 LONG SECTION	 LONG SECTION	Other combinations of cut off / filter drains and variation in cross section shape are possible, depending on site conditions and availability of local materials.
Typical section 1.0 - 2.0 deep, 0.5 wide at 3 - 8 spacing, 0.2 thick cobble layer and filter membrane on top of drain for surface protection.		Counterfort filter drain 0.8 wide, < 2.5 deep at 3 - 15 spacing with filter membrane around sides and heavy duty polythene laid on invert, benched foundation for slopes > 30. Cut slope buttress drain 0.8 wide, < 2.0 deep, 2no 0.1 ø drainholes feed masonry "side drain." Cut slope masonry drains (cascades on steep slopes), omitting buttress drain also used.	0.3 thick gravel.	0.3 thick dry stone.	All dimensions in metres.
Upslope filter membrane omitted but graded filter infill specified for high flow condition.	Upslope filter membrane with clean gravel infill for low flow condition.		Gravel or dry stone laid on filter membrane or 0.1 thick sand bed.		Approximate catchment area drained and required drain capacities to be assessed by simple analytical methods (e.g. Rational formula for catchment studies, Manning's formula for drain velocities).
Aligned crosslope in herringbone pattern to connect with counterforts.		Aligned directly to downslope.			Permeability of filter membranes to be checked in relation to soil grading and anticipated flow in coarse soils.
< 35°	< 35°	< 45°	< 30°	30° - 45°	
X ——→		←—— F X ——→	←—— F ——→		Design for specific location will require specification of F Filter material grading. G Allowable gradient. X Cross-section dimensions.
Interception of throughflow seepage and springs.			Control of ground water at emergence over large areas of a cut slope in soils or soft rocks.		All methods shown are small-scale only. For major eroding channels employ gully protection methods listed in Table 18. Stepped cascades (Table 16) are used to channel large flows down steep slopes.
Drainage of shallow-seated instability above cut slopes.		Counterfort channels herringbone drainage, also gives some mechanical support if dug fully through unstable material. Stabilisation of shallow debris slide and mudflow materials.			
——— 3, 4 ——→					2. Free rock face and coarse debris slopes. 3. Ancient terrace and degraded valley slopes. 4. Active lower slopes.

Table B7 (Cont'd)

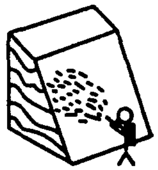
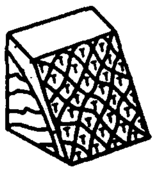
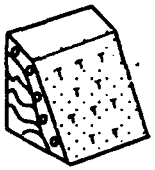
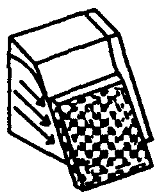
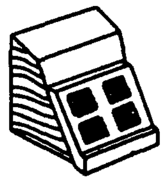
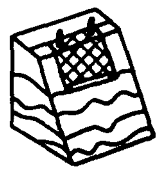
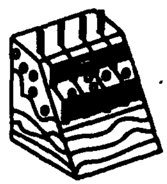
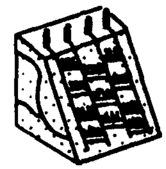
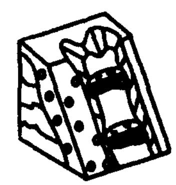
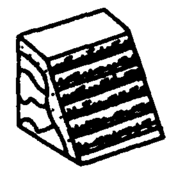
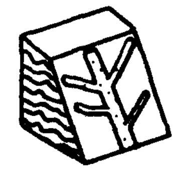
FULL SLOPE FACE					NOTES
BITUMINOUS TREATMENT	COMPLETE TURFING	MULCHING	FILTER LAYER	REVETMENT	
					1. These measures are appropriate for application to slopes 25° throughout mountain zones 2, 3, and 4 in the circumstances listed. 2. The methods of controlling erosion by modifying slope geometry are not shown. These include terracing and benching the slope to maintain the same average slope angle or simple flattening or steepening of the slope face. 3. Specialist advice should be sought for methods of seeding, turfing, and topsoiling to assess the suitability of local materials and techniques. 4. This table is by no means comprehensive. Many varieties exist depending on availability of local materials. 5. Successful erosion control usually involves a combination of construction and revegetation techniques.
Seeding and fertilizing followed by spraying a bitumen emulsion to seal the slope face during germination. Bitumen often cut-back with up to 50 % solvent and applied at a rate of 1 : 2 litres/m². May require initial replacement of 0.1m topsoil.	Contiguous strips of sods laid diagonally over slope face and tamped into place. May require initial replacement of 0.1m top soil.	Seeding and fertilizing followed by placing 0.05 - 0.1m thick old straw cover over slope face. May require initial replacement of 0.1m topsoil.	0.3 - 0.5m thick dry stone (cobbles/boulders) on slopes > 30°. 0.3 - 0.5m thick gravel on slopes < 30°. Laid on filter membrane or 0.1m thick sand bed. Pitched boulder facing preferable on steeper slopes.	Facing of masonry and dry stone packing, gabion mattress, sand or concrete bagwork, timber crib work, etc. For details see Table 13.	
Bitumen sealing skin is the fixative.	Sods staked onto the slope on a 2m grid.	Straw mat staked onto slope on a 2m grid. Alternatively cover straw with mesh and log.	Filter keyed into toe of slope.	Depends on type. All are generally devolled into slope face at intervals and keyed in at toe.	
	Highly erodible cut and fill slopes prone to rapid fill development.	Cut and fill slopes subject to long-term degradation.	Protection of spring sites against backsapping erosion. Protection of seepage zones exposed in cuts, particulrly for perched water tables.	Steep cut slopes subject to and susceptible to vigorous erosion particularly where consequences of failure are severe and major retrogressive upslope development of erosion is possible. Used to protect relatively steep basal slopes and allow cuts of reasonable angle to be constructed where daylighting problems occur (partial face protection).	
	Cohesionless silts and sands.	Colluvium, taluvium, and residual soils.	Colluvium and residual soils particularly sands and silts.	Generally residual and transported soils, weathered rocks.	
	25°- 35°	25°- 45°	25°- 40°	40°- 70°	

Table B7 (Cont'd)

PROTECTION METHODS	CLASS	SLOPE HEAD		PARTIAL SLOPE FACE			
	TYPE	WIRE MESH AND LOG	BAMBOO AND LOG FENCING "HURDLING".	BRUSHWOOD AND LOS PENCING "WATTLING"	DRY STONE TERRACETTES	CONTOUR TURFING	HERRINGBONE AND TRENCH/COUNTERFORT DRAINS
DIAGRAMMATIC SKETCH							
CONSTRUCTION NOTES	DESCRIPTION AND TYPICAL DIMENSIONS	12 SWG hexagonal mesh, mesh size 0.20x0.16m. 8 SWG selvedge fixed with metal staples above head of slope 0.2m ø logs. 4m long woven in and dug into slope.	Fences formed with 0.1 - 0.15 ø upright logs or bamboo stakes at 2m intervals, interwoven with bamboo strip lattice. Stakes anchored min. 1m into ground. Fences spaced at 3 - 5m intervals downslope and offset in plan across the slope. Preferable to add 0 - 1m thick topsoil or turfing between fence lines. Method suitable for both slope head and face protection. Fences can also be made of wire mesh.	Fences formed of 0.2m ø logs, 4m long, dug into slope with slight crossfall: brushwood sticks 0.3m high placed upslope of logs. Spaced at 4m intervals downslope with adjacent fences offset in plan. Preferable to add 0.1m thick topsoil or turfing fence between fence lines.	Simple dry stone walls up to 2m high with granular back-fill and surface spread with topsoil and vegetated.	Continuous strips or individual sods laid in contour lines 0.1m wide, 0.3 - 0.5m spacing. Tamped into place.	Herringbones 0.5 - 0.8m wide, 1 - 2m deep at 3 - 10m intervals downslope, connected to trench drains 0.8 - 2.0m wide up to 2m deep at 5 - 20m intervals. Graded filter infill or open gravel/cobble infill with filter membrane lining.
	FIXING DETAILS	Mesh woven around 0.2m ø stakes dug min. 1m into ground or existing trees at 4m intervals along the slope, 3 - 6m above the head of the slope.	2no.8SWG ties inter-laced to secure fences, tied back to 0.2m 0 stakes dug min. 1m into ground or existing trees of 2m intervals along the slope. 3 - 6m above the head of the slope.	8 SWG ties to sevure logs to 0.2m ø stakes dug min. 1m into ground or tied to existing trees at 4m intervals along the slope, 3 - 6m above the head of the slope. Additional stakes required on the slope face if slope is > 10m high.	Base and back of wall benched into slope with 0.5m wide steps. End of walls cut into sides of small gullies or erosion scars.	Sods anchored onto slope with small wooden stakes at 2m intervals.	Drains dug fully into slope. Drain outlets connected to road drainage or led to natural gully channels. Benched foundation for drains on steeper slopes.
APPLICATION		Principle use on slopes with unstable near-surface horizons, susceptible to minor collapse and retrogressive development of instability upslope e.g. loose soils under surface layer strengthened by root network. Minor uses as mulch, retention grid or rockfall control.	Protection of large embankment or spoil tip slopes.	Highly erodible cut slopes.	Natural or induced slope failure scars or small eroding gullies. For major gully protection works see Table.	Highly erodible cut and fill slopes.	Cut slopes and natural slopes above road cuts subject to long-term softening and degradation.
SOIL TYPES		Humic and organic soils, taluvium and scree.	Colluvium, taluvium, scree, cohesionless spoil tips.	Cohesionless silts and sands.	Generally residual and transported soils.	Cohesionless silts and sands.	Softened orgillaceous rock, residual soils, colluvium.
SLOPE ANGLE		30°- 45°	30°- 45°	25°- 35°	35°- 45°	25°- 35°	25°- 45°

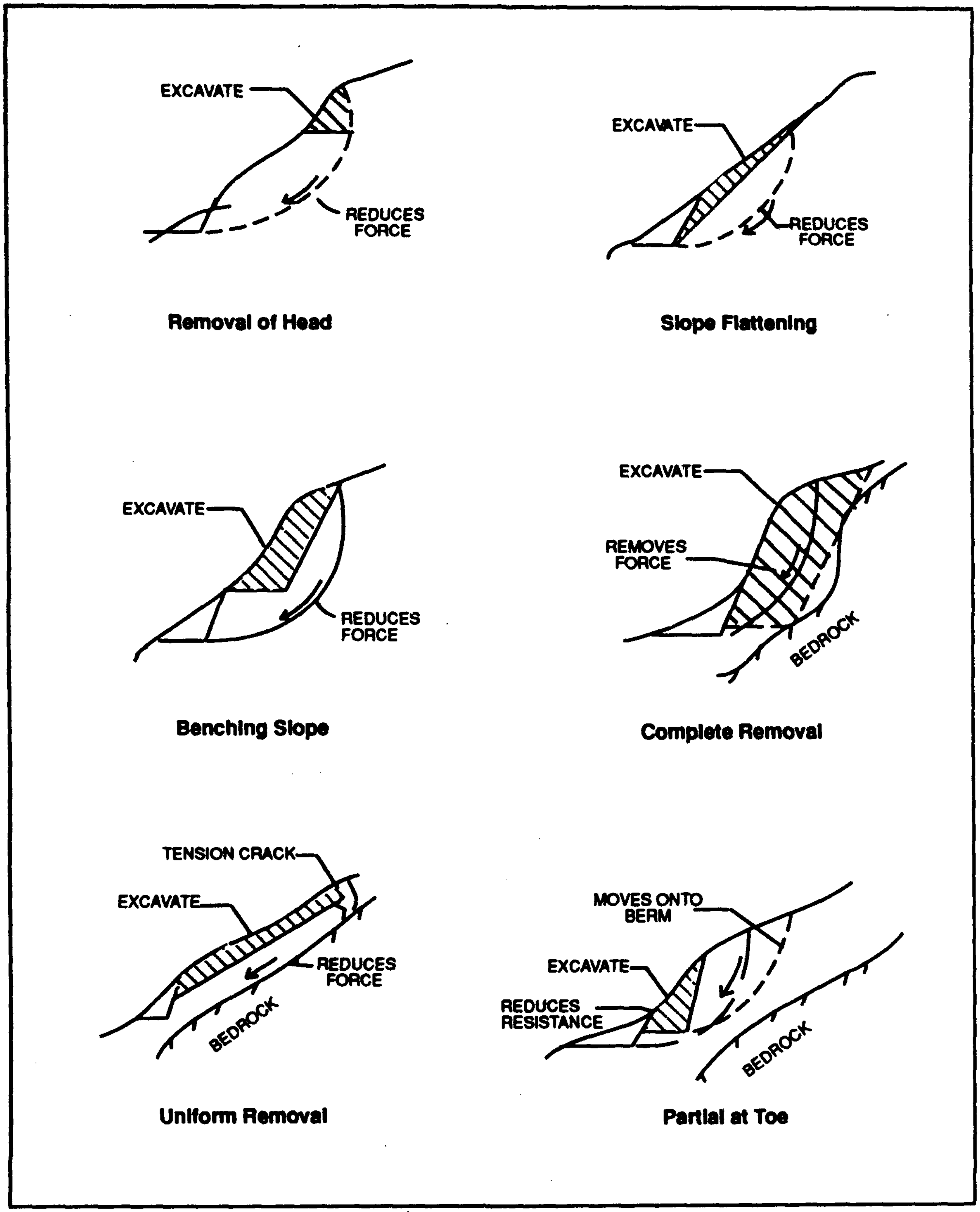


Figure B2. Excavation Techniques for Slope Stabilization.

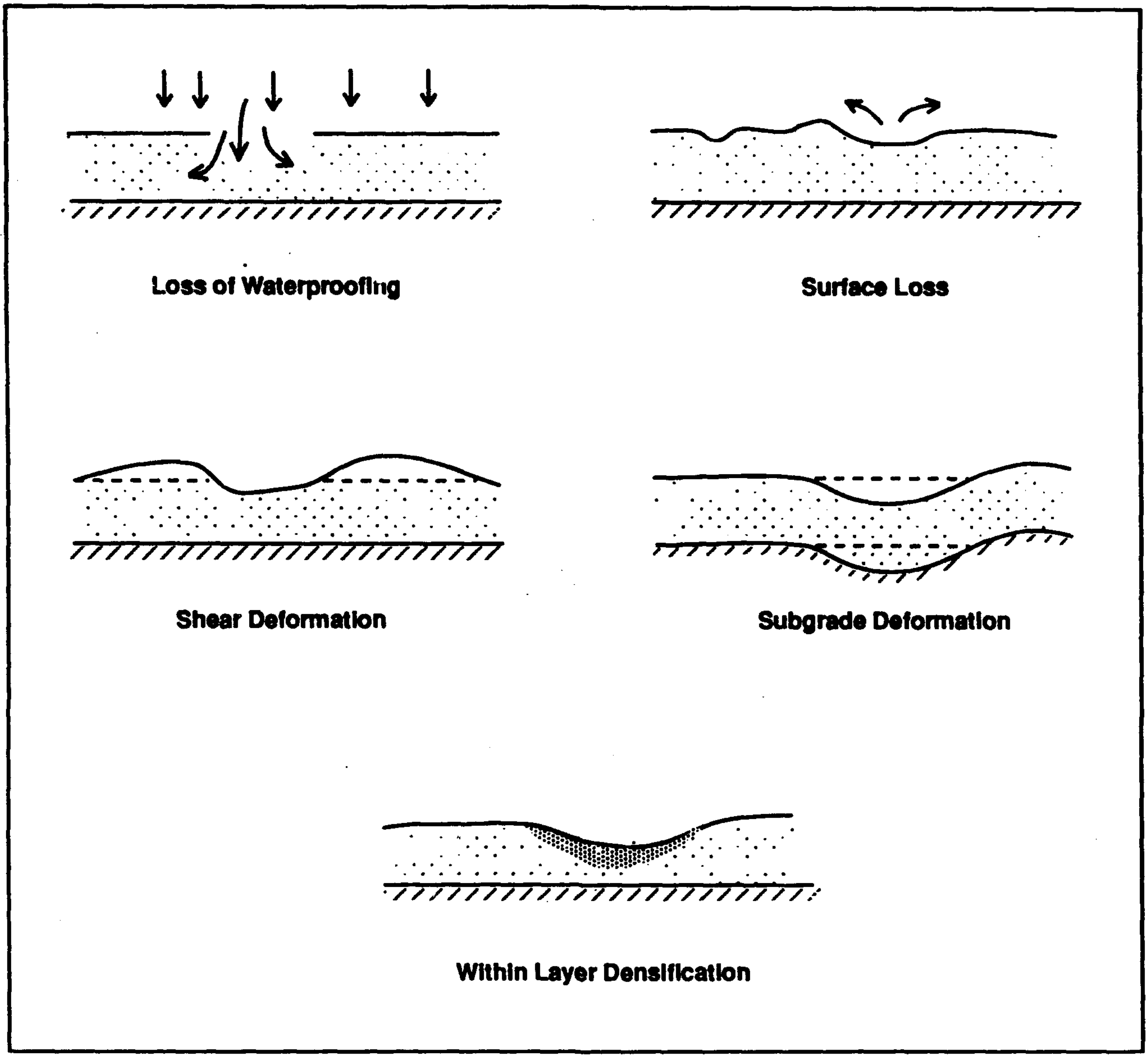


Figure B3. Surface Failure Modes.

Seasonal weather impacts may be complicated by seasonal usage patterns, which may be particularly damaging to the roads if heavy usage corresponds with periods of low strength. For example, heavy traffic during the spring thaw is more likely to damage a road than the same traffic on the road when the water is frozen. One way to identify changing soil strength due to changing soil moisture is by deflection tests (Allen and Bullock 1987, p 140).

Another study described higher usage and maintenance costs when using roads during high moisture periods (Richter and Hsia 1987, p 132). The study suggested that traffic loads and volume be limited during critical periods. If reducing traffic during sensitive periods is not possible, then the pavement may be strengthened, more intensively maintained, or simply allowed to deteriorate.

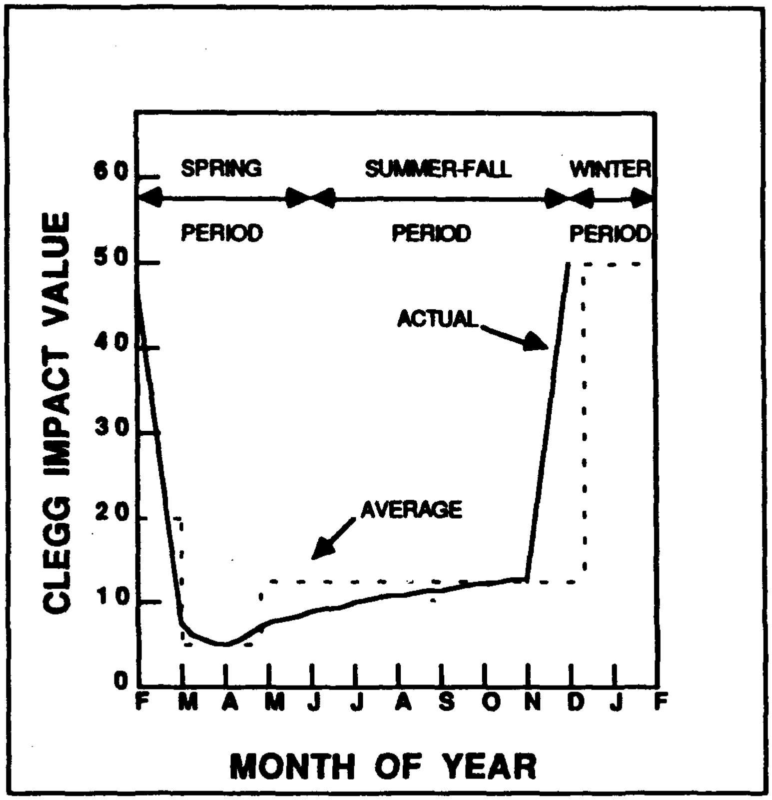


Figure B4. Subgrade Strength Versus Time of Year.

Since Army Engineers must work in a wide variety of conditions and climates, individual expert systems may be developed to assist in construction in specific conditions/climates. For example, in an arid climate, soil shear strength changes over wide ranges in moisture content should be considered (Fredlund and Rahardjo 1987). The Transportation Research Board's Research Records may provide much of the technical analysis to begin development of individual design tools for Army engineers.

Alternative Materials

The traditional material for the base course of low-volume roads is graded, compacted earth. Depending on the length of time the road needs to be used, the type of traffic, and other factors, additional applications may be made to build up the road surface. In very expedient construction an asphaltic material called "tack coat" is used to stabilize the soil and reduce dust. For more permanent types of low-volume roads, crushed stone or aggregate may be applied to graded, compacted earth.

While asphalt and aggregate are the materials commonly used in road construction, many studies have discussed alternative materials. The use of readily available materials is essential for expedient construction of military roads. Table B8 synopsizes studies conducted on the use of expedient materials. Several of the highly ranked alternative surfacing systems are described here.

The use of low-grade materials has several benefits for Army construction. Low-grade materials are often more readily available than traditional construction materials. The use of low-grade materials may lessen environmental problems in areas adjacent to the project. For example, use of materials derived from mine waste lessens mine tailing disposal problems. Since the source of alternative materials may be closer to the project site, hauling costs can be reduced. Finally, the use of these materials frees higher grade materials for critical roadway areas, or other projects.

Table B8

Characteristics of Alternate Surfacing Systems

Type of Material	General Description	Cost	Years
Wood or Bark Chips	12-14 in. of wood or bark chips	$3-7/yd³	1 - 3
Chemical Stabilization	Lime, lime fly ash, Portland cement, asphalt emulsion, NaCl, $CaCl_2$, MgCl, lignin sulfonate	$0.25-0.45/ft² (varies greatly)	5 -10
Geotextile and Geogrid Separation	Tensar grids, various fabrics under crushed rock	$0.05-0.40/ft²	1 - 3
Marginal Aggregate	Single or double layer of sand sealed with CRS-2	$0.15-0.25/ft²	1 - 3
Metal Mats	Aluminum or steel mats	$8.33 and $0.90 /ft² respectively	5 -10
Reusable aggregate w/o geotextile separation	6-18 in. of crushed aggregate on subgrade	$0.05-1.10/ft² (construct) $0.20-1.30/ft² (recover)	5 -10
Reusable aggregate w/geotextile separation	6-18 in. of crushed aggregate on fabric	$1.00-1.50/ft² (construct) $0.50-1.00/ft² (recover)	5 -10
Membrane encapsulated soil layer	6-14 in. subgrade soil encapsulated with various membranes	$0.50-1.30/ft²	3 - 5
Geoweb stabilization (expandable grids)	8-in. dune sand filled plastic grids, sealed w/asphalt	$1.05-1.30/ft² $1.50-2.00/ft² (in place)	5 -10

The reason that alternative construction materials are useful is that the overall structural strength of the entire road system (i.e., surface, base, subbase, shoulders, drainage, etc.) determines the quality of the road. In evaluating the overall strength of roads, one study identified the plasticity index, plasticity modulus, and in-situ strength of the road as highly correlated with the extent of pavement distress (Pinard and Jackalas 1987).

The first types of materials evaluated were wood chips, bark, sawdust, planks, and other biodegradable materials. These materials had good performance during tests. The roads constructed from these materials were very durable and had low dust levels compared to other alternative materials. The only impact on construction was that use of these materials required chipping the wood prior to placement. The study found that use of biodegradable materials was a very inexpensive method that could be used on temporary, low-grade roads of 1 mile or less and that carried little traffic. Biodegradable material may also be used in the construction of road shoulders.

Chemical stabilization is a widely used technique. Lime, Portland cement, emulsified asphalts, fly ash, sodium, calcium, or magnesium chloride are some of the types of chemicals used in road construction.

The stabilizer may be used either as a wearing course or as base stabilization. Limited potholing and rutting were experienced during testing; however, it was not clear from the test if these problems were the result of the stabilizer or water infiltration under the stabilizer from the road shoulder.

The selection of a chemical stabilizer is also important to its usefulness since different stabilizers react best with specific soils or rocks. Usually clayey soils work best with stabilizers. Some stabilizers, such as asphalt cut with diesel fuel, may not always be available to Army engineers. In addition, special expertise may be required to mix or apply some of these agents. Regardless of these detriments, the study found that the use of chemical stabilizers may be the most cost-effective alternative surfacing method.

One particular chemical stabilizer, lignin sulfonate (a by-product of the pulp and paper industry) has been successfully used to stabilize subgrade. Lignin sulfonate produces a good traction surface with high bearing capacity when used on soils ranging from clayey sand to sandy gravel. The stabilizer serves to fill the voids in the sandy soil to provide additional cohesiveness.

The literature contains many examples of case studies of both successful and unsuccessful use of specific types of stabilizers on specific road systems. One design consideration always to consider is the impact of moisture on the stabilizing agents. Under some conditions, moisture in combination with stabilizing agents may cause significant reduction of road quality. In one road system where lime was used to stabilize the soil prior to aggregate placement, the lime actually accelerated the failure of the roadway because plastic fines washed from the gravel road surface were absorbed by the lime rather than being washed from the road bed (Pinard and Jackalas 1987, p 89).

Geotextiles, another alternative surfacing system, are used in large strips to separate wet, weak, or fine-grained subgrades, from the road material. Large strips of the material are used to span areas where traditional construction techniques may have required bridging; for example, in swampy areas. According to a study conducted at USAWES, geotextiles can offer "substantial savings" in aggregate thickness in roads over soft clay (Webster and Watkins 1977).

In one study conducted by USAWES, rock filled wire baskets, called gabions, were used as a road base course over soft ground. The result was found to be "extremely good." In addition, the gabions that may freely drain water were thought to be useful for areas of low elevation or with little drainage. Although the tested gabions performed well, commercial gabions investigated "appeared to be overdesigned for strength, and were time-consuming to install" (Webster and Watkins 1977).

New alternative surfacing systems will be proposed as long as there are roads to build. This report can only present the work of those who have studied the particular systems in some depth. Regardless of the new types or applications of alternative systems, a procedure to analyze the applicability of various alternative materials may be very useful. The tables below provide a synopsis of the evaluation of the alternatives discussed in the tables above. The limitations and constraints for each system are provided in Table B9. Table B10 lists the unique requirements of each system. Table B11 provides the recommended applications of each system (Takallou, Layton, and Hicks 1987, p 11).

One particular alternative that did not perform satisfactorily was the use of metal mats. Metal mats are described in some detail in the Army road design manual. It is recommended that engineers considering metal mat construction review the literature for further information before using metal mats.

As with any study, additional work may conflict with current results. The previously described study indicated that marginal aggregates were not a cost-effective alternative. In light of additional work, it may be, however, that the assumptions under which the previous study was conducted may not be fully

Table B9

Limitations of Alternate Surfacing Systems

Surfacing Material	Subgrade Soil Type	Road Geometrics	Years
Wood or Bark Chips	None	Not recommended on steep grades	1 - 3
Chemical Stabilization	Depends on Chemical	None	3 - 5
Geotextile and Geogrid Separation	Effective on Weak	None	Same as quality aggregate
Marginal Aggregate	None	None	2 - 3
Sand Seal Subgrade	Not on weak subgrades	Not recommended on steep grades or sharp curves	3
Metal Mats	Not recommended on weak soils	Not recommended on steep grades or sharp curves	5000 passes
Reusable aggregate w/o geotextile separation	Recommenced for firm subgrade	None	Same as quality aggregate
Reusable aggregate w/geotextile separation	None	None	Same as quality aggregate
Membrane encapsulated soil layer	Organic clays, wet/fine grained soil	Not recommended on steep grades	Unknown
Geoweb stabilization	Weaker sandy soils	Not recommended on steep grades	Unknown
Lignin Sulfonate	Clayey sand (SC) to sandy gravel	None	3 - 5

valid for all applications. In other countries where Army engineers operate, high grade aggregates may not be available. Engineers may need to substitute marginal aggregates.

One recent study determined that specifications for highway construction may be modified to account for the special considerations of low volume roads (Meyer and Hudson 1987, p 260). Current codes may be too restrictive since the tests are generally applied to highway construction in the United States. Table B12 lists the typical tests conducted for aggregate quality.

Untreated surface aggregate may have limited application (Table B13). However, proper screening to improve the gradation of the aggregate and washing to remove excess fines, may increase the durability of the road over normal application of low quality aggregate. Table B13 recommends limits for use of aggregates. Use of admixtures may, in some cases, extend the life of low-quality aggregate roads to that of untreated high-quality aggregate (Burchfield and Hicks 1981).

One study developed criteria for using natural gravels on roads in Ethiopia. The study showed that use of large natural gravels is cost efficient for roads with less than 50 vehicles per day (Beaven, Robinson, and Aklilu (1987). For roads with over 50 vehicles per day the natural gravel should be crushed and screened. (The natural gravels reported in the study provided a very strong but rough surface.) Figure B5 shows the relationship between surface roughness and vehicle operating costs.

Table B10

Unique Requirements of Alternative Surfacing Systems

Potential Surfacing Type	Construction, Recovery, and Maintenance Technology	Special Equipment	Special Expertise
Wood and Bark Chips	The same as aggregate roads	Chipper	None required
Chemical Stabilization	Requires special mixing equipment	Pulva-mixer or twin disk harrow, distributor tanker	Special expertise needed to spread and mix additives
Geotextile or Geogrid Separation	Special construction methods necessary	None required	None required
Marginal Aggregate	None required	None required	None required
Sand- or Chip-Sealed Subgrade	None required	None required	None required
Metal mats	None, mats easily placed together in field	Fork lift of truck-mounted crane, pressure washer, mobile welder	None required
Reusable Aggregate without Geotextile Separation	None required	None required	None required
Reusable Aggregate with Geotextile Separation	Requires special technology for the recovery of the materials	Sewing machine and special recovery system	Trained laborers need to sew the fabric around recovery beam
Geoweb Stabilization (Expandable Grids)	Special knowledge needed for subgrade preparation, geoweb placement filling, and compacting the surface	None required	Trained laborers needed for parts of construction
Membrane Encapsulated Soil Layer (MESL)	Special knowledge needed for laying the fabric, applying emulsion, and compaction	None required	None required

An Australian study discussed control of aggregate shape and grading criteria (Dickinson 1984). Of particular interest was the report of "washing" placed aggregate base course with diesel fuel. Washing the aggregate eliminated dust and allowed the asphalt surface course to bind more efficiently with the aggregate.

Shoulder Design

Road shoulders serve three functions: (1) to guide vehicle parking or turnouts, (2) to reduce road base moisture content, and (3) to reduce road impact on the environment.

A way to expand the typical road shoulders is to use "filter strips," which are protective strips of absorbent, undisturbed forest soil between the road and streams. These should be used when the road is

Table B11

Potential Applications of Alternate Surfacing Systems

Potential Surfacing Types	Potential for Future Use	Degree of Quality Control	Applicable Situation
1. Wood and Bark Chips	High	Low	Any subgrade with wood and bark chips available
2. Chemical Stabilization	High	High	Depends on the chemicals, clayey soils best
3. Geotextile or Geogrid Separation	High	Medium	Wet and fine-grained subgrades Weak subgrades
4. Marginal Aggregate	High	Low	Any subgrade
5. Sand- or Chip-Sealed Subgrade	Low	Medium	May not work
6. Metal Mats	Low (Alum.) Med. (Steel)	High	Economical only on short sections
7. Reusable Aggregate without Geotextile Separation	Medium	Medium	Firmer subgrade to control rutting and intrusion of fines into the aggregate
8. Reusable Aggregate with Geotextile Separation	Medium	Medium	Soft subgrade of low strength may experience strength increase
9. Membrane Encapsulated Soil Layer (MESL)	Low	High	Economical only on short critical sections
10. Geoweb Stabilization	Low	High	Uniform sands and critical sections
11. Lignin Sulfonate Soil Stabilization	High	Low	Dry climates, requires a surface seal

* High - applicable for up to 80 percent of USFS local mileage; Medium - applicable for up to 50 percent of USFS local mileage; Low - applicable for less than 10 percent.

**High - good technical supervision; Medium - moderate supervision; Low - little supervision.

close to a stream, and should allow at least 100 ft between the road and the stream. This strip allows mud and contaminated water to be absorbed and filtered by the soil before the water enters the stream.

If there is insufficient space between streams and the roadway, as often happens in steep terrain, then the slash material cleared from the road may be piled between the road and the stream. The embankment serves to slow water flowing from the road to the stream so that sediment will drop and the water will be absorbed into the ground more easily.

In the northwestern United States, chipper machines are used to produce wood chips for embankments. The embankments are then covered in several feet of dirt and planted with grass seed.

Table B12

Typical Tests for Aggregate Quality

AASHTO Test	Title	Purpose
T-89	Determining the Liquid Limit of Soils	To determine the amount of soil binder material present for classification and specification check.
T-90	Determining the Plastic Limit and Plasticity Index of Soils	To determine the range of moisture in which a soil remains in a plastic state and to determine the effect of moisture on the soil material and specification.
T-27;T-88	Sieve Analysis of Fine and Coarse Aggregates or Particle Size Analysis of Soils	To determine the partial distribution of fine and coarse aggregates using the mechanical analysis.
T-96	Resistance to Abrasion of Small Size Coarse Aggregate by use of the Los Angeles Machine	To test sizes of coarse aggregate smaller than 1.5 in. (37.5 mm) for resistance to abrasion.
T-210	Production of Plastic Fines in Aggregates	To determine the durability of aggregates by indicating the relative resistance of an aggregate to produced detrimental clay-like fines when subject to degradation.

Table B13

Recommended Limits for Untreated Surface Aggregate

		Limiting Values per Environmental Region			
Material Property	**Current Practice**	**Cold/Dry**	**Cold/Wet**	**Hot/Wet**	**Hot/Dry**
Gradation					
%-200(.075) sieve	8 Min	6 Min	6 Min	6 Min	6 Min
Max. Part. Size, in (mm)	1 (25)	1.5 (38)	1.5 (38)	1.5 (38)	1.5 (38)
Plasticity					
Liquid Limit, %	35 Max	55 Max	40 Max	35 Max	55
Plasticity Index, %	4-9	2-15	2-9	2-9	2-15
Degradation					
L.A. Abrasion, %	40 Max	50 Max	50 Max	50 Max	50 Max
Durability Index	35 Min	35 Min	35 Min	35 Min	35 Min

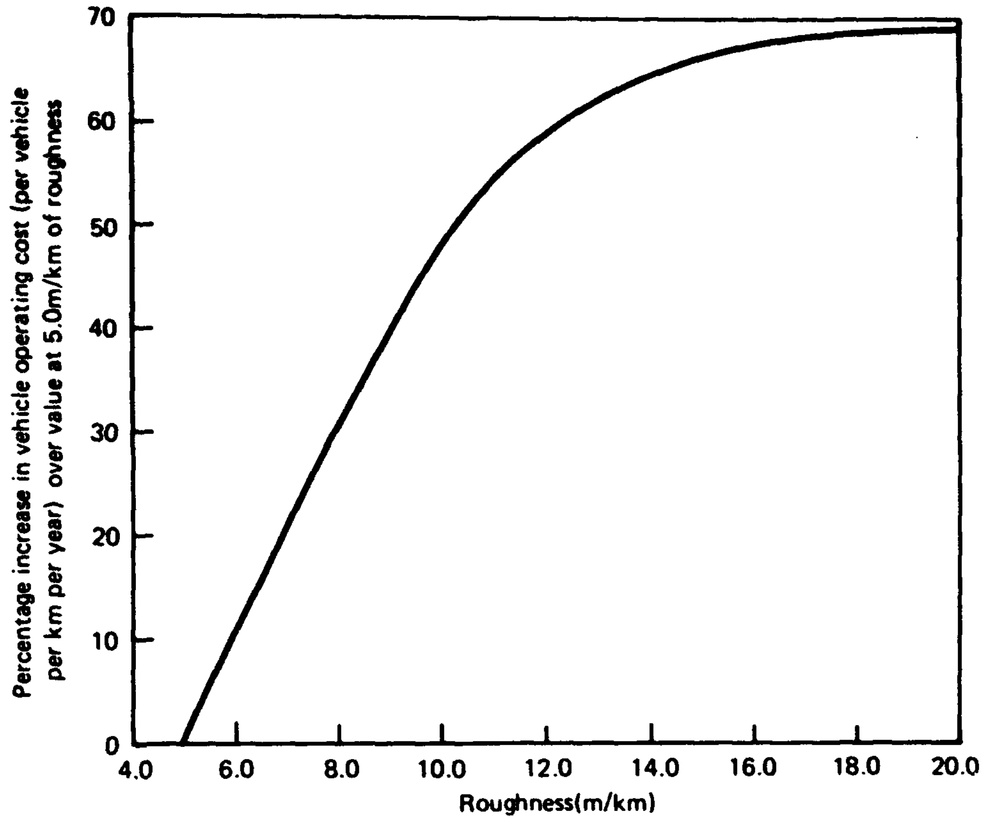


Figure B5. Vehicle Operating Cost Versus Roughness.

The use of such embankments can reduce future maintenance costs and environmental impact of road runoff on nearby streams (Bowman, Lidell, and Schulze, 1987, p 48).

Assuming that timber is available, the use of slash may be an effective alternative for embankments. The use of wood chips, while potentially more effective, may not be possible due to the need for wood chipping equipment. Even if equipment is available, reliance on a single piece of nonstandard equipment may cause difficulties.

A study conducted to evaluate drainage of rural roads in New Zealand shows that, if shoulders do not perform properly, the result will be something called the "bathtub effect" (Figure B6). Australian transportation researchers have reported success in New Zealand with improved shoulder design as well as 49 percent maintenance cost savings for roads with sealed shoulders (Oliver 1987, p 196). The design of sprayed asphalt in Australia may be found in *Principles and Practice of Bituminous Surfacing: Vol I - Sprayed Work* (National Association of Australian State Road Authorities, 1980).

If proper shoulders cannot be included in road design, then the designer should consider drainage. The most cost effective type of drainage may be a high-void, crushed aggregate channel covered with filter fabric. Figure B7 shows the recommended placement of the drains (Note: The top half of the figure shows the placement of drains on new roads, and the bottom half shows the placement of a drain in existing roads.)

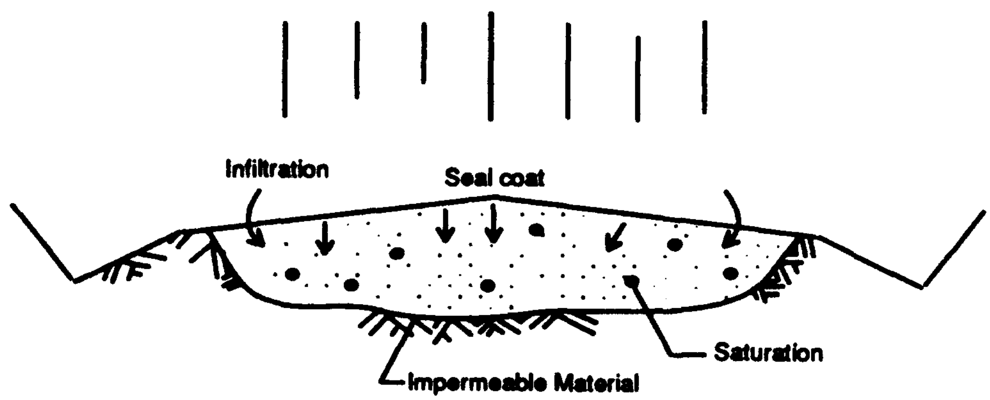


Figure B6. Bathtub Effect.

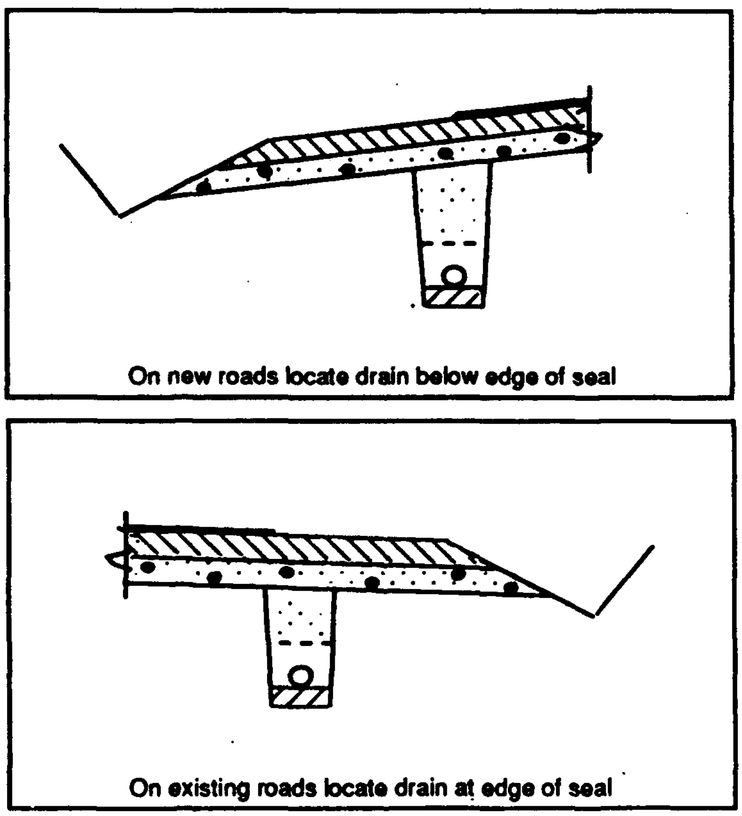


Figure B7. Subsoil Drains for Pavements.

Drainage Constraint

As with most other types of construction, the action of water on the project may be the most damaging natural action that occurs. Erosion of the roadway can cause significant additional maintenance cost, and may even completely block an entire road system.

Water damage to road surfaces may occur by removing road base or decreasing the strength of the road material. On flat surfaces, water may accumulate on top of the road surface. Water soaking into the road surface causes a reduction in strength of the road surface, typically leading to "washboards."

Minimum Grade Design

The simplest way to drain a flat road is to provide a minimum of 3 percent grade for all roads (Kochenderfer 1970, p 10). The construction costs of maintaining such a grade may increase the first costs of the project, but the slight grade will ensure that water drains off the road surface into adjacent drainage structures.

An alternative to constructing a drainage control grade is to identify more efficient road grades. Identification of naturally sloping roads may be a very cost-efficient alternative even though some road designers may not be accustomed to using the natural topography to provide a drainage slope.

Grade Break Design

Another type of drainage structure that results from the road grade is "grade breaks," grade changes in areas of relatively flat gradient. The grade break should be ± 5 percent of the road grade. On steady slopes, grade breaks keep water from running along the road surface for the entire area of similar gradient.

Broad-Based Dip Design

In more mountainous areas, a more specialized type of grade break, called "broad-based dips," is also used to provide drainage. Broad-based dips are used for cross drainage in situations where no intermittent or permanent streams are present along the roadway. Figure B8 shows the construction of broad-based dips, and Table B14 lists the recommended spacing of these structures.

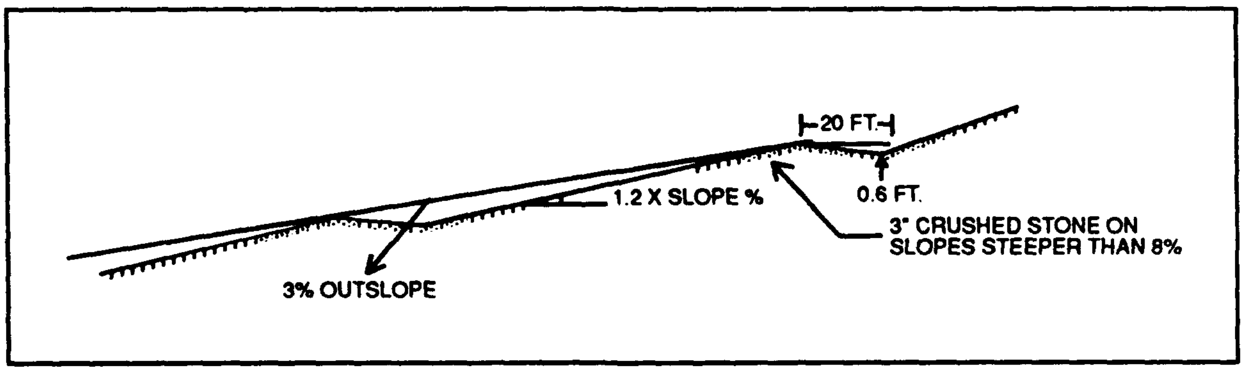


Figure B8. Broad-Based Dip Construction.

Table B14

Recommended Spacing for Broad-Based Dips

Road grade (percent)	Spacing (feet)
2 - 4	300 - 200
5 - 7	180 - 160
8 - 10	150 - 140

The broad-based dip is a construction detail that allows: (1) water to flow across the road without using a culvert, (2) water to be captured after flowing down a road, and (3) storage of water during periods of heavy rainfall.

Culverts

Culverts are the most commonly used device for diverting water (Kochenderfer 1970, p 8). They are used to divert water, and to keep dissolved sediments from accumulating in nearby streams or on roadbeds. In addition, culverts carry runoff under roads, reducing the potential for road erosion. Figure B9 shows typical culvert construction (Transportation Research Board 1986, p 18).

Metal culverts are the most common type of culvert used in all forms of construction although circular concrete culverts are also used. Army Technical Manual 5-330 provides detailed information on the design and installation of these types of culverts. The manual also describes "box" culverts, which are made of a variety of materials including timber, logs, or concrete, and may be required in remote sites since the cost of transporting metal or concrete circular culverts may be prohibitive.

The U.S. Department of Agriculture, Forest Service often uses culverts made of timber gathered from nearby logging operations. These wooden culverts may be of the boxed type, also called "closed" culverts, or the top of the culvert may be open at the road surface. Figure B10 shows both closed- and open-topped culverts (Kochenderfer 1970, p 15).

Open-topped culverts are useful for intercepting intermittent runoff flowing down road surfaces. The basic "u-shape" of the culvert, and spreaders ensure that the culvert walls remain in place. These culverts are well suited for very low volume road construction. During periods of heavy use, the top of the culvert often fills with road debris.

Carefully placing the culverts in the road can help the runoff to flush debris from the culvert. The proper position of the open-topped culvert is at a 30 degree angle across the road at an area where the road is outsloped (Figure B11). The angle of the culvert with respect to the road's centerline also assists drivers since only one tire should be crossing the culvert at any given time.

"Treads" are an additional construction technique that may be used with the open topped culverts (Figure B12). Treads reduce the amount of debris that accumulates within the culvert and add stiffness to the culvert walls.

Broad-Based Dips vs. Culverts

As might be expected, the initial costs of broad-based dips are significantly less than the cost of culverts. In one study, 6 hours were required to construct 19 broad-based dips. The comparable time for

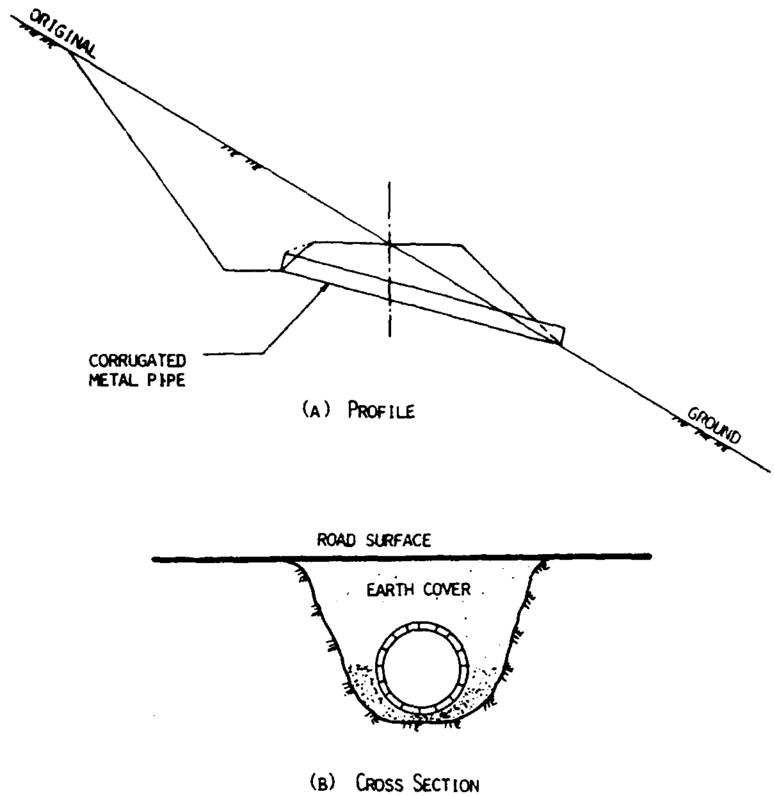


Figure B9. Low Volume Road Culvert Cross-Section.

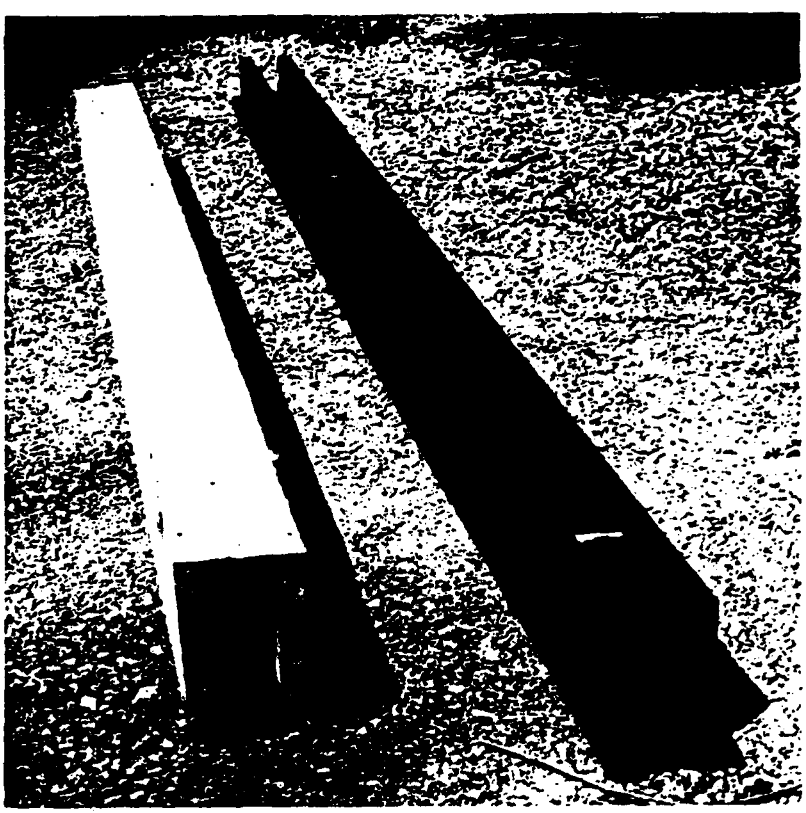


Figure B10. Closed- and Open-Topped Culverts.

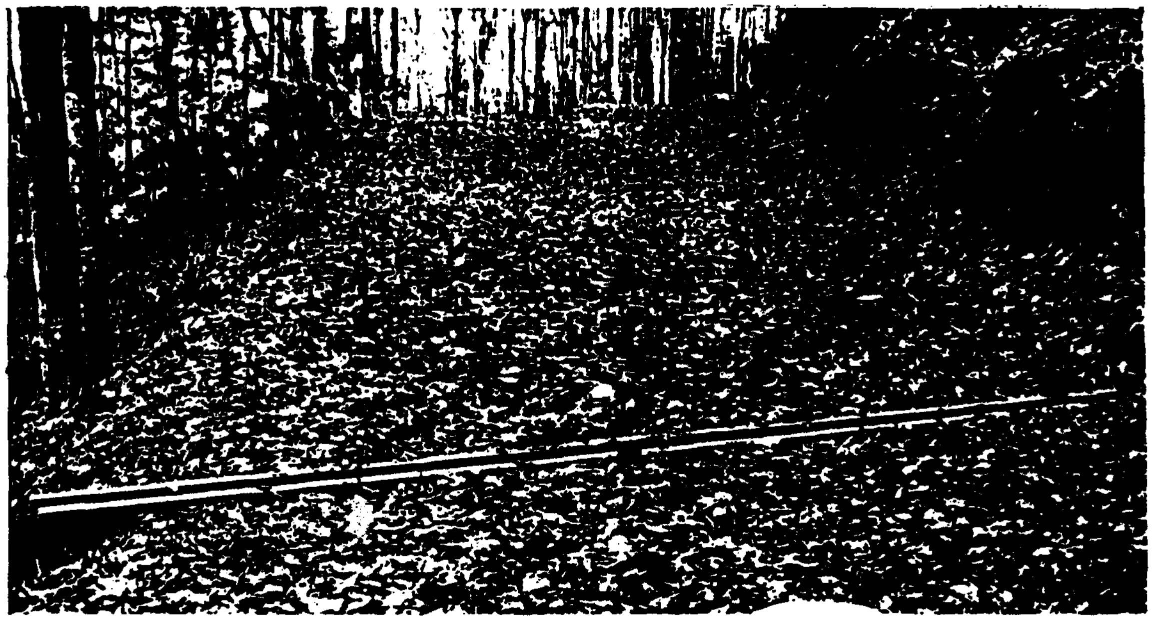


Figure B11. Open-Topped Culvert at Angle.

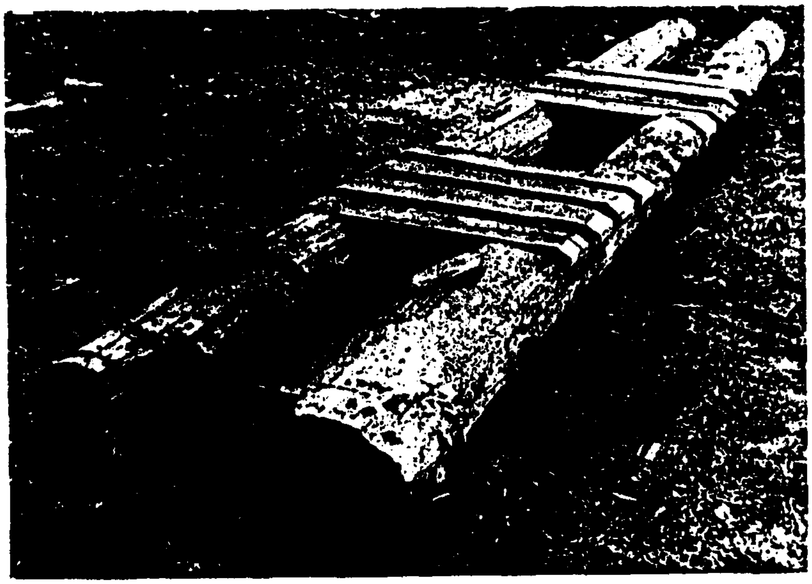


Figure B12. Open-Topped Culvert With Treads.

installation of 19 culverts would have been 47 hours. Since construction in remote locations would require large culvert transportation costs, alternatives to culverts, such as the broad-based dip, become an economical option (Kochenderfer and Wendel 1980).

Broad-based dips are less costly than culverts because they require less construction equipment. Culvert installation is labor intensive, and typically requires a backhoe, tamper, and hand tools in addition to typical road construction equipment. Construction of the dips requires only the typically used road construction equipment such as bulldozers, scrapers, or graders.

One of the more interesting aspects of the study was interviews with construction contractors. Construction contractors interviewed indicated that they preferred culverts. The study concluded that the reason contractors prefer culverts was because they have little experience with broad-based dip construction (Kochenderfer and Wendel 1980).

To assess the maintenance costs of the culvert versus the broad-based dips, researchers assumed that traffic would be heavy for the road's first 5 years, and then level off over a total 20-year road life. Based on these assumptions, culvert maintenance costs were determined to be approximately $8.33 per culvert per year. Researchers estimated that the yearly cost of regrading broad based dips would be $10.00 per year.

Road user cost from well-constructed broad-based dips was found not to differ from roads with culverts; however, many broad-based dips were found not to be constructed properly. Improperly constructed dips may cause additional vehicle wear since drivers must change gears to slow down as the truck passes through the broad-based dip.

Well-constructed broad-based dips did not adversely impact the speed of vehicles on the road. Over a period of 10 miles, an increase of only 1 minute of travel time was experienced. Since vehicles on logging roads move slowly, this additional time is negligible.

An economic analysis showed that, if fewer than 15 vehicles per day are using a road, then broad-based dips are appropriate (Kochenderfer and Wendel 1980). For military engineering options, however, the stated assumptions may not be appropriate. For example, military roads are rarely designed for a 20-year life. Reducing the life of the road by 10 years would significantly increase the number of vehicles per day that could economically use a road constructed with broad-based dips. Patterns of intense use for 5 years may also be overstated for military construction.

High Water Constraints

Precipitation runoff poses a risk of relatively immediate failures of roads through scouring, ponding, etc. It is up to the designer to create plans and specifications that reduce these risks. Another type of risk associated with water that must be addressed during the design phase is that of high water tables.

Road cuts risk failure more due to groundwater than to any other aspect of highway construction (Goodman and Jeremiah, June 1976). Some examples of problems that may occur are seepage from cut faces, compaction of fine sands, limiting equipment access, and construction material damage. The cuts most likely to develop this condition are those where an aquifer is cut into by road construction. If the piezometric head is high, then there will be water problems on the construction site. Even if the aquifer is not cut, drainage may still be necessary if the piezometric head is high enough. Figure B13 illustrates the situation.

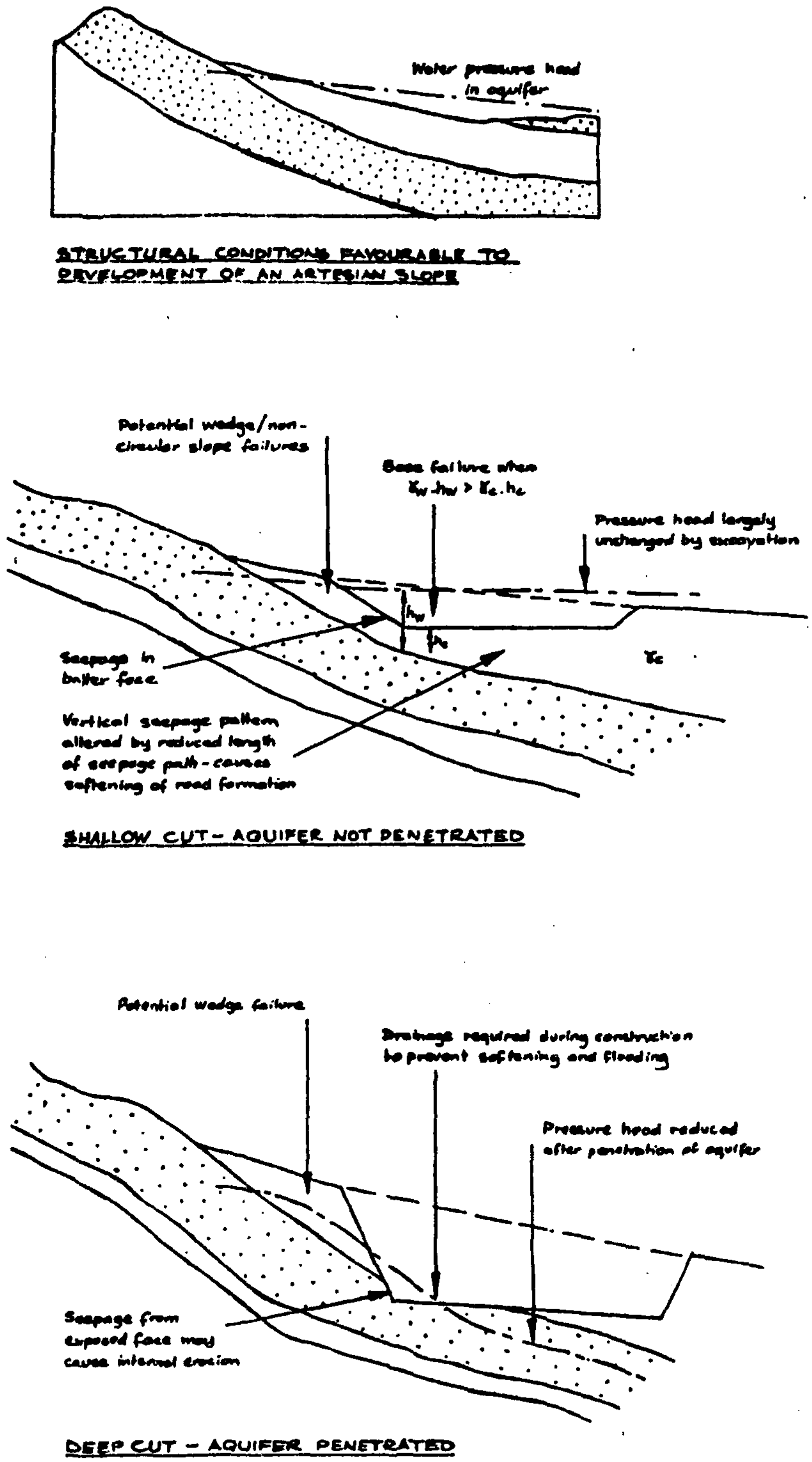


Figure B13. Groundwater and Stability Problems in Artesian Slopes.

There are three available options to alleviate problems with groundwater: (1) to construct barriers (e.g., sheet piling, bentonite curtains, or other types of walls), (2) to reduce the water pressure by pumping, and (3) to use gravity drainage (Goodman and Jeremiah, June 1976).

Army engineers typically use gravity drainage. Although Goodman and Jeremiah recommend patterns of drainage shown in Figures B14 and B15, perforated pipe is frequently not used in military construction. Table B15 lists various methods of slope surface drainage and provides construction notes and typical dimensions.

The preceding paragraphs have discussed aspects of slope drainage commonly used in rural road construction. Table B16 illustrates a wider variety of the types of erosion protection techniques that may be used. The table also provides some design criteria information and construction details.

Stream Crossing Design

Stream crossings should be minimized due to the cost of construction and maintenance of stream-crossing structures. When a stream crossing is required, special consideration should be given to its location. Poor locations include deeply cut streams where large bridges must be constructed, or soft muddy stream banks that require soil stabilization and bridge foundation work. The most efficient location for stream crossings are areas with firm, rocky banks where the stream narrows.

Turning Radii Design

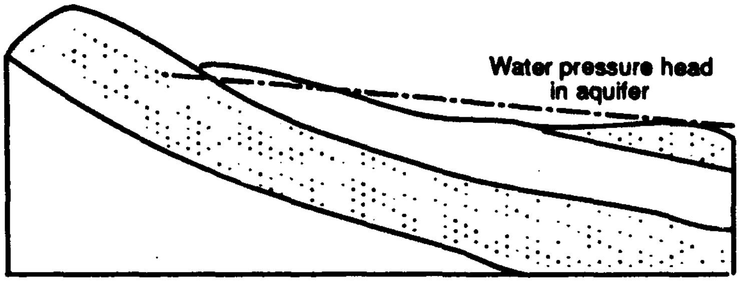
In addition to designing the stream crossing, the approaches to the crossings must also be designed. The design of the crossings must allow for the turning radii of the vehicles using the road. Approaches to the crossing should also be sloped down toward the stream to prevent water from running down the access roads. If stream water leaves the banks during high water and runs down the road, then sediment from the water will be deposited on the road, and will ultimately destroy the road.

In addition to protecting stream water from depositing sediment on the road, road runoff should not be allowed to run directly into streams. Various types of drainage structures may be used to keep fuel and oil washed off by water from directly entering streams.

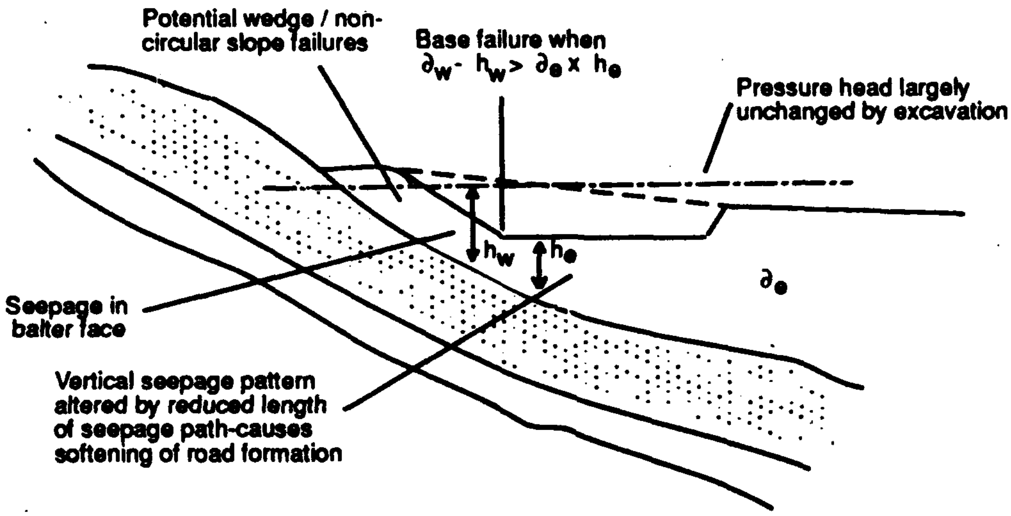
Bridge Design

Traditional bridge design follows guidelines created by the American Association of State Highway and Transportation Officials (AASHTO). Unfortunately the AASHTO code does not distinguish between low- and high-volume roads. As a result low-volume road bridges using AASHTO are overdesigned for most military engineering applications. Table B12 provides a list of the AASHTO tests used in bridge design.

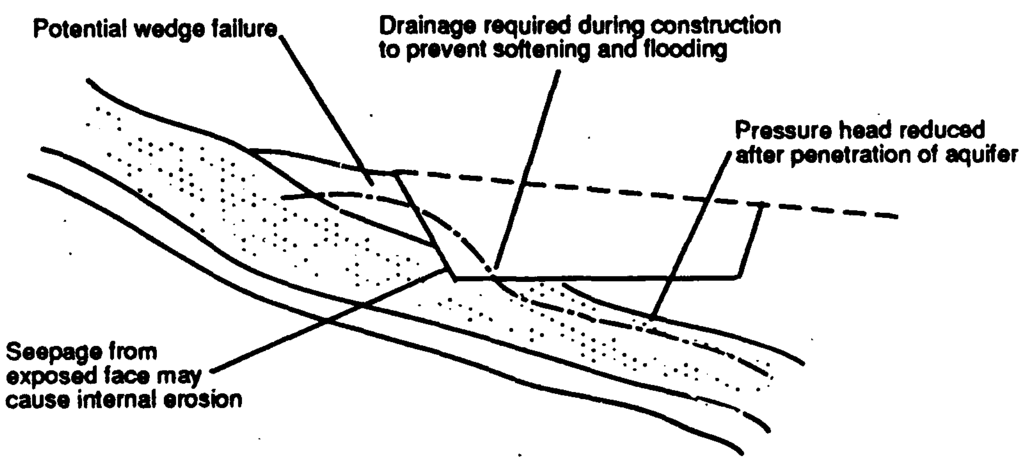
Less restrictive design criteria can lower bridge costs. Depending on the vehicles that will use the bridge, the bridge approach may be reduced, or bridge deflections may be allowed to increase. Reducing the size of components or alternative structures for abutments and stringers, or using composite sections, deck slabs, and other components, may be appropriate for low-volume bridge design. Relaxing traditional bridge design criteria will significantly reduce the amount of materials used and therefore save construction time and overall construction costs. Table B17 shows the reduction in components that may be realized if AASHTO standards are reduced for low-volume highway bridges.



STRUCTURAL CONDITIONS FAVORABLE TO DEVELOPMENT OF AN ARTESIAN SLOPE



SHALLOW CUT - AQUIFER NOT PENETRATED



DEEP CUT - AQUIFER PENETRATED

Figure B14. Dewatering System as Slope Drainage.

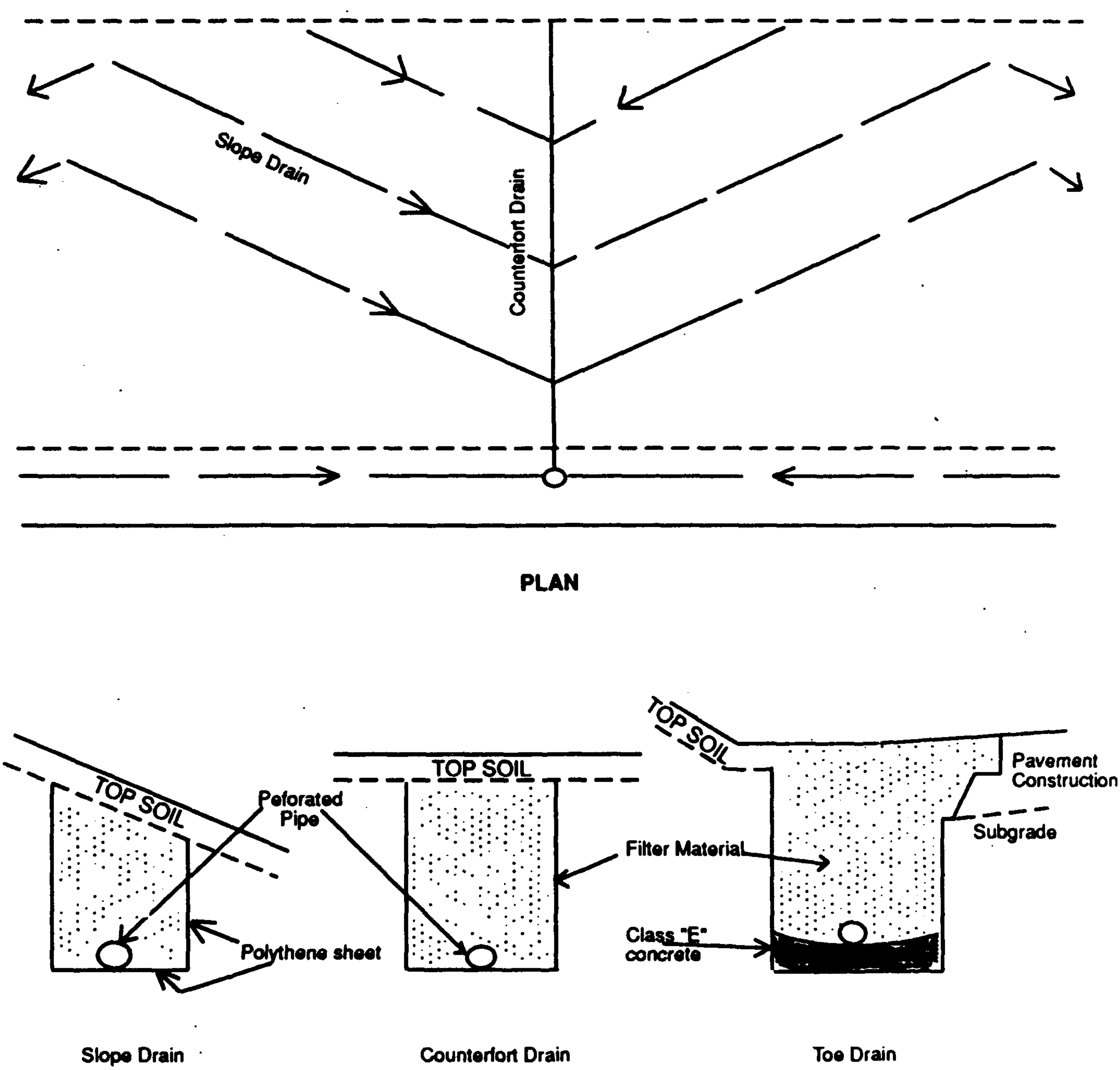
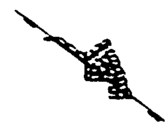


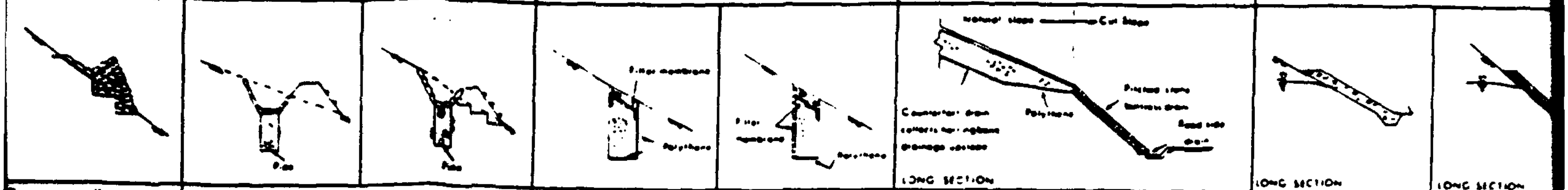
Figure B15. Typical Cutting Slope Drainage System.

Table B15

Methods of Slope Surface Drainage

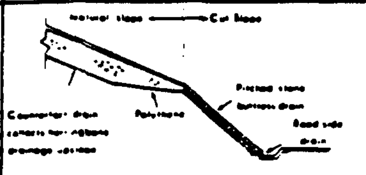
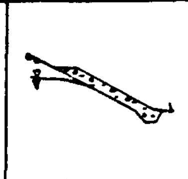
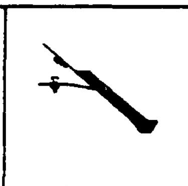
DRAIN / CLASS / TYPE	INTERCEPTION OF SURFACE RUN OFF AND NEAR SURFACE GROUNDWATER							
DRAIN TYPE	AND NATURAL DRAIN CHANNEL	PITCHED DRY STONE DRAIN	MASONRY FIELD DRAIN	EARTH BUND CUT OFF DRAIN		DRY STONE BUND CUT OFF DRAIN	COMBINED MASONRY CUT AND FILTER DRAIN	
DIAGRAMMATIC CROSS SECTION OR LONG SECTION								
CONSTRUCTION NOTES AND TYPICAL DIMENSIONS	Dished profile made by small cut and fill Bund and channel stabilized by bamboo grasses Depth 0 2 – 0 3.	0 1 thick stone pitching laid with long axis normal to slope or invert. Depth 0 2 – 0 4 base width 0 2 – 0 4	0 1 thick masonry with 2V 1H side slopes invert laid on 0 05 thick sand bed 0 1 0 weepholes set 0 5 above invert on upslope side, spaced 1 0 laterally along the drain. Depth 0 2 – 0 5, base width 0 2 – 0 5.	Compacted soil bund Heavy duty polythene covered by hand – placed stone lining of boulders minimum long axis 0 2 Drain depth 0 3 – 0 5.		Dry stone wall benched into existing slope. minimum stone long axis 0.2 Heavy duty polythene laid on 0 05 thick sand bed covered by stone lining Drain depth. 0 3 – 0 5	Field masonry drain laid on filter dra[illegible] 0 1 8 butt – jointed pipes. Simpler ver[illegible] omit surface drains or pipes depend[illegible] runoff or throughflow anticipated De[illegible] masonry 0 2 – 0 4, depth of filter < [illegible] width 0 5 – 0 8.	
				Excavated material if suitable used to form bund	Bund benched into existing slope and vegetated.		Excavated material used to form earth bund and vegetated.	Compact[illegible] benched [illegible] slope an[illegible]
	Generally contoured with small gradients (<10°) above cut slopes to existing drainage lines (e.g. gullies) or other drainage outlets						Generally contoured at low gradient[illegible] downslope to connect with cut – slope[illegible]	
NATURAL SLOPE RANGE	< 20°	< 20°	< 35°	< 20°	20° – 30°	30° – 45°	< 25°	2[illegible]
DESIGN REQUIREMENTS	← G X →						←	
APPLICATION	Interception of surface water or as diversion channel in erosion – prone soils Low flow velocities and gradients only.	Diversion of water from other drains to stable outlet or road drainage.	General cut – off drain. Diversion of water from other drains to stable outlet or highway drainage.	Interception of surface water on low permeability soils above cut slopes, gully heads and areas of natural instability. Shorter design life than masonry drains, useful for protecting cut slopes for first few years after construction until vegetation re – established.			Interception of surface water and [illegible] in permeable granular soils up to [illegible] overlying low permeability materi[illegible]	
MOUNTAIN ZONE	3	← 2.3.4 →		3	2.3.4	2.4	←	

(Source: *Engineering Geology*. Vol 21 [Elsevier Publishing. 1985]. Used with permission.)



...UNDWATER			DRAINAGE OF SHALLOW SLIDES AND SATURATED SOILS			CUT SLOPE PROTECTION	
DRY STONE BUND CUT OFF DRAIN	COMBINED MASONRY CUT OFF AND FILTER DRAIN		HERRINGBONE DRAIN		COUNTERFORT/ BUTTRESS DRAIN	FILTER REVETMENT DRAIN	
Dry stone wall benched into existing slope. ...imum stone long axis 0.2 Heavy duty polythene laid on 0 05 thick sand bed covered by stone ...ning Drain depth. 0.3 – 0 5	Field masonry drain laid on filter drain with 0 1 Ø butt – jointed pipes. Simpler versions omit surface drains or pipes depending on surface runoff or throughflow anticipated. Depth of masonry 0 2 – 0 6, depth of filter < 2.0, width 0 5 – 0 8.		Typical section 1 0 – 2 0 deep 0 5 wide at 3 – 8 spacing. 0 2 thick cobble layer and filter membrane on top of drain for surface protection.		Counterfort filter drain 0 8 wide < 2 5 deep at 3 – 15 spacing with filter membrane around sides and heavy duty polythene laid on invert benched foundation for slopes > 30. Cut slope buttress drain 0 8 wide < 2 0 deep. 2no 0 1 Ø drainholes feed masonry side drain. Cut slope masonry drains (cascades on steep slopes) omitting buttress drain also used.	0 3 thick gravel.	0 3 thick dry s...
	Excavated material used to form earth bund and vegetated.	Compacted earth bund benched into existing slope and vegetated.	Upslope filter membrane omitted but graded filter infill specified for high flow condition	Upslope filter membrane with clean gravel infill for low flow condition.		Gravel or dry stone laid on filter membrane... 0 1 thick sand bed.	
...outlets	Generally contoured at low gradients, also aligned downslope to connect with cut – slope cascades.		Aligned crosslope in herringbone pattern to connect with counterforts		Aligned directly downslope	...red on saturated areas of cut slope	
30° – 45°	< 25°	25° – 35°	< 35°	< 35°	< 45°	< 30°	30° – 45°
→	← FGX →				← FX →	← F —	
...s abovecut slopes. ...ening cut slopes for ...established.	Interception of surface water and throughflow in permeable granular soils up to 3m thick overlying low permeability material.		Interception of throughflow seepage and springs Drainage of shallow – seated instability above cut slopes.		Counterfort channels herringbone drainage also gives some mechanical support if dug fully through unstable material. Stabilisation of shallow debris slide and mudflow materials.	Control of ground water at emergence over large areas of a cut slope in soils or soft rocks.	
2.4	← 3.4 —						

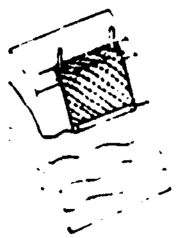
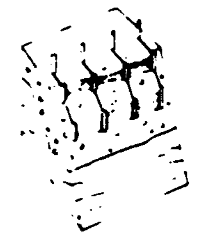
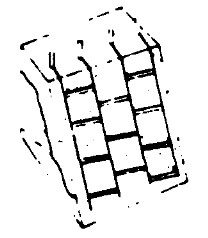
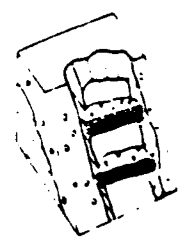
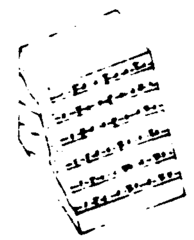
②

DRAINAGE OF SHALLOW SLIDES AND SATURATED SOILS			CUT SLOPE PROTECTION		
…RRINGBONE DRAIN		COUNTERFORT/ BUTTRESS DRAIN	FILTER REVETMENT DRAIN		NOTES
		 LONG SECTION	 LONG SECTION	 LONG SECTION	Other combinations of cut off / filter drains and variation in cross section shape are possible depending on site conditions and availability of local materials.
…tion 1 0 – 2 0 deep, 0 5 wide …acing, 0 2 thick cobble layer …membrane on top of drain for …otection.		Counterfort filter drain 0 8 wide < 2 5 deep at 3 – 15 spacing with filter membrane around sides and heavy duty polythene laid on invert benched foundation for slopes > 30 Cut slope buttressdrain 0 8 wide < 2 0 deep. 2no 0 1 Ø drainholes feed masonry side drain Cut slope masonry drains (cascades on steep slopes) omitting buttress drain also used.	0 3 thick gravel.	0 3 thick dry stone.	All dimensions in metres
…mbrane …d …ed for …on	Upslope filter membrane with clean gravel infill for low flow condition.		Gravel or dry stone laid on filter membrane or 0 1 thick sand bed.		Approximate catchment area drained and required drain capacities to be assessed by simple analytical methods (e.g. Rational formula for catchment studies, Manning's formula for drain velocities).
…slope in herringbone pattern to counterforts		Aligned directly downslope	…ered on saturated areas of cut slope		Permeability of filter membranes to be checked in relation to soil grading and anticipated flow in coarse soils.
	< 35°	< 45°	< 30°	30° – 45°	
——→		←—— F X ——→	←—— F ——→		Design for specific location will require specification of F Filter material grading. G Allowable gradient X Cross section dimensions
Interception of throughflow seepage and springs			Control of ground water at emergence over large areas of a cut slope in soils or soft rocks.		All methods shown are small – scale only For major eroding channels employ gully protection methods listed in Table 16 Stepped cascades (Table 16) are used to channel large flows down steep slopes.
…shallow – seated instability …pes.		Counterfort channels herringbone drainage also gives some mechanical support if dug fully through unstable material Stabilisation of shallow debris slide and mudflow materials.			
——— 3.4 ——→					2 Free rock face and coarse debris slopes. 3 Ancient terrace and degraded valley slopes. 4 Active lower slopes.

3

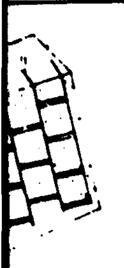
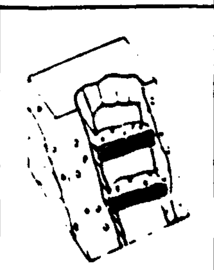
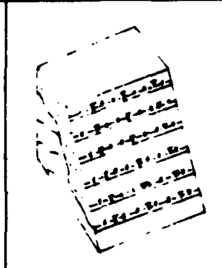
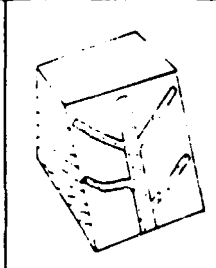
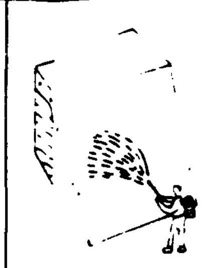
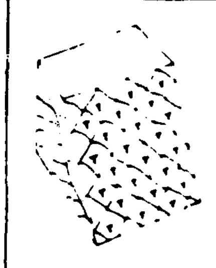
Table B16

Methods of Slope Erosion Protection

PROTECTION METHODS	CLASS / TYPE	WIRE MESH AND LOG	BAMBOO AND LOG FENCING "HURDLING"	BRUSHWOOD AND LOG FENCING "WATTLING"	DRY STONE TERRACETTES	CONTOUR TURFING	HERRINGBONE A... TRENCH, COUNTE... DRAINS
	CLASS	SLOPE HEAD		PARTIAL SLOPE FACE			
DIAGRAMMATIC SKETCH							
CONSTRUCTION NOTES	DESCRIPTION AND TYPICAL DIMENSIONS	12 SWG hexagonal mesh mesh size 0.20x0.16m 8 SWG selvedge fixed with metal staples above head of slope 0.2m Ø logs 4m long woven in and dug into slope	Fences formed with 0.1-0.15 Ø upright logs or bamboo stakes at 2m intervals interwoven with bamboo strip lattice Stakes anchored min 1m into ground Fences spaced at 3–5m intervals downslope and offset in plan across the slope Preferable to add 0.1m thick topsoil or turfing between fence lines Method suitable for both slope head and face protection Fences can also be made of wire mesh	Fences formed of 0.2m Ø logs 4m long, dug into slope with slight crossfall brushwood sticks 0.3m high placed upslope of logs Spaced at 4m intervals downslope with adjacent fences offset in plan Preferable to add 0.1m thick topsoil or turfing fence between fence lines	Simple dry stone walls up to 2m high with granular backfill and surface spread with topsoil and vegetated	Continuous strips or individual sods laid in contour lines 0.1m wide, 0.3 – 0.5m spacing. Tamped into place	Herringbones 0.5-0.8... wide 1.2m deep at 3... intervals downslope c... to trench drains 0.8 – ... wide up to 2m deep a... intervals Graded filter open gravel cobble ... with filter membrane l...
CONSTRUCTION NOTES	FIXING DETAILS	Mesh woven around 0.2m Ø stakes dug min 1m into ground or existing trees at 4m intervals along the slope 3-6m above the head of the slope	2no 8SWG ties inter-laced to secure fences tied back to 0.2m 0 stakes dug min 1m into ground or existing trees at 2m intervals along the slope. 3–6m above the head of th slope.	8 SWG ties to secure logs to 0.2m Ø stakes dug min 1m into ground or tied to existing trees at 4m intervals along the slope. 3 – 6m above the head of the slope Additional stakes required on the slope face if slope is >10m high	Base and back of wall benched into slope with 0.5m wide steps End of walls cut into sides of small gullies or erosion scars	Sods anchored onto slope with small wooden stakes at 2m intervals	Drains dug fully into s... Drain outlets connecte... to road drainage or to... to natural gully channe... Benched foundation fo... drains on steeper slope...
APPLICATION		Principle use on slopes with unstable near – surface horizons susceptible to minor collapse and retrogressive development of instability upslope e.g. loose soils under surface layer strengthened by root network. Minor uses as mulch reten-tion grid or rockfall control	Protection of large embankment or spoil tip slopes	Highly erodible cut slopes	Natural or induced slope failure scars or small eroding gullies For major gully protection works see Table	Highly erodible cut and fill slopes	Cut slopes and natura... slopes above road cu... subject to long – term softening and degrada...
SOIL TYPES		Humic and organic soils talluvium and scree	Colluvium talluvium scree, cohesionless spoil tips	Cohesionless silts and sands	Generally residual and transported soils	Cohesionless silts and sands.	Softened argillaceous ... residual soils colluvium
SLOPE ANGLE		30° – 45°	30° – 45°	25° – 35°	35° – 45°	25° – 35°	25° – 45°

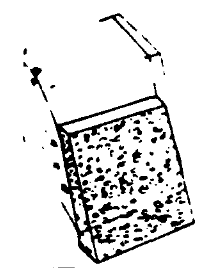
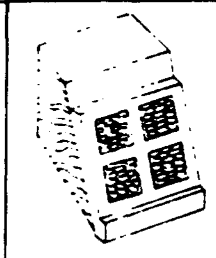
(Source: *Engineering Geology*, Vol 21 [Elsevier Publishing, 1985]. Used with permission.)

rotection

	PARTIAL SLOPE FACE			FULL SLOPE FACE			
OD AND LOG "WATTLING"	DRY STONE TERRACETTES	CONTOUR TURFING	HERRINGBONE AND TRENCH/COUNTERFORT DRAINS	BITUMINOUS TREATMENT	COMPLETE TURFING	MULCHING	FILTER LAYER
							
d of 0 2m if dug into ght crossfall cks 0 3m upslope of at 4m intervals ith adjacent n plan add 0 1m r turfing n fence lines	Simple dry stone walls up to 2m high with granular back-fill and surface spread with topsoil and vegetated	Continuous strips or individual sods laid in contour lines 0 1m wide, 0 3 – 0 5m spacing. Tamped into place	Herringbones 0 5-0 8m wide 1 2m deep at 3-10m intervals downslope connected to trench drains 0 8 – 2 0m wide up to 2m deep at 5 - 20m intervals Graded filter infill or open gravel cobble infill with filter membrane lining.	Seeding and fertilizing followed by spraying a bitumen emulsion to seal the slope face during germination Bitumen often cut back with up to 50% solvent and applied at a rate of 1 2 litres m² May require initial reple[illegible]ent of 0 1m tops[illegible]	Contiguous strips or sods laid diagonally over slope face and tamped into place May require initial replacement of 0 1m top soil.	Seeding and fertilizing followed by placing 0 05 – 0 1m thick old straw cover over slope face May require initial replacement of 0 1m topsoil.	0 3 – 0 5m thick dry stone cobbles boulders) on sl >30° 0 3 – 0 5m thick gra on slopes < 30° Laid on filter membrane o thick sand bed. Pitched boulder facing pre able on steeper slopes.
secure logs es dug min d or tied to at 4m intervals 0.3 – 6m above slope hes required ace if slope	Base and back of wall benched into slope with 0 5m wide steps End of walls cut into sides of small gullies or erosion scars	Sods anchored onto slope with small wooden stakes at 2m intervals	Drains dug fully into slope Drain outlets connected to road drainage or led to natural gully channels Benched foundation for drains on steeper slopes.	Bitumen sealing skin is the fixative	Sods staked onto the slope on a 2m grid.	Straw mat staked onto slope on a 2m grid Alternatively cover straw with mesh and log.	Filter keyed into toe of slo
le cut slopes	Natural or induced slope failure scars or small eroding gullies For major gully protection works see Table	Highly erodible cut and fill slopes	Cut slopes and natural slopes above road cuts subject to long – term softening and degradation.	Stee[illegible] [illegible]es not subject to or[illegible] [illegible]ble to vigor[illegible] [illegible]on	Highly erodible cut and fill slopes prone to rapid rill development.	Cut and fill slopes subject to long – term degradation	Pro[illegible] n of spring sites aga[illegible] backsapping eros Pro[illegible] n of seepage zo exposed in cuts particular perched water tables
ilts and sands	Generally residual and transported soils	Cohesionless silts and sands	Softened argillaceous rock, residual soils colluvium	Talu[illegible] residual soils highly [illegible] mpletely weath[illegible] ered [illegible] with pronounced struct[illegible] [illegible]nesses	Cohesionless silts and sands.	Colluvium talus and residual soils	Co[illegible]um and residual so pa[illegible]arly sands and silt
– 35°	35° – 45°	25° – 35°	25° – 45°	[illegible] – 50°	25° – 35°	25° – 45°	25° – 40°

sion.)

(5)

FULL SLOPE FACE					
...OUS TREATMENT	COMPLETE TURFING	MULCHING	FILTER LAYER	REVETMENT	NOTES
					1 These measures are appropriate for application to slopes 25° throughout mountain zones 2 3 and 4 in the circumstances listed 2 The methods of controlling erosion by modifying slope geometry are not shown These include terracing and benching the slope to maintain the same average slope angle or simple flattening or steepening of the slope face 3 Specialist advice should be sought for methods of seeding turfing and topsoiling to assess the suitability of local materials and techniques 4 This table is by no means comprehensive Many varieties exist depending on availability of local materials 5 Successful erosion control usually involves a combination of construction and revegetation techniques
...nd fertilizing ...by spraying ... emulsion to ...ope face ...amination ...hen cut-back ... 50% ... applied at ...1 2 litres m² ...e initial ...n of 0 1m	Contiguous strips or sods laid diagonally over slope face and tamped into place May require initial replacement of 0 1m top soil.	Seeding and fertilizing followed by placing 0 05 – 0 1m thick old straw cover over slope face May require initial replacement of 0 1m topsoil.	0 3 – 0 5m thick dry stone cobbles boulders) on slopes >30° 0 3 – 0 5m thick gravel on slopes < 30° Laid on filter membrane or 0 1m thick sand bed. Pitched boulder facing preferable on steeper slopes.	Facing of masonry and dry stone packing gabion mattress sand or concrete bagwork timber cribwork etc For details see Table 13.	
...ing skin is	Sods staked onto the slope on a 2m grid.	Straw mat staked onto slope on a 2m grid Alternatively cover straw with mesh and log.	Filter keyed into toe of slope.	Depends on type All are generally dowelled into slope face at intervals and keyed in at toe.	
...es not subject ... ble to ...osion	Highly erodible cut and fill slopes prone to rapid rill development.	Cut and fill slopes subject to long – term degradation.	[illegible]n of spring sites aga[illegible] backsapping erosion Prote[illegible]n of seepage zones exposed in cuts particularly for perched water tables	Steep cut slopes subject to and susceptible to vigorous erosion particularly where consequences of failure are severe and major retrogressive upslope development of erosion is possible. Used to protect relatively steep basal slopes and allow cuts of reasonable angle to be constructed where daylighting problems occur (partial face protection).	
...dual soils. ...derately weath – ...th pronounced ...nesses	Cohesionless silts and sands.	Colluvium taluvium and residual soils.	Co[illegible]m and residual soils par[illegible]arly sands and silts	Generally residual and transported soils weathered rocks.	
– 50°	25° – 35°	25° – 45°	25° – 40°	40 – 70°	

③

Table B17

Reduction in Bridge Construction Quantities Possible

Alternative	Girder Size (in)	Weight (lb/ft)	% Weight Reduction from AASHTO
AASHTO	36 x 194	194	0
One-lane	36 x 170	170	12.4
Rigid frame	33 x 130	130	33.0

Decreasing bridges to one lane may also be very appropriate for low-volume road construction. The use of warning signs and/or bumps and turnoffs may be sufficient. The authors of the study found that savings of approximately 35 percent of the total bridge cost may be saved by reducing the number of lanes.

Timber Bridges

Timber bridges are widely used in rural road construction and remain a major component of the infrastructure of the United States. Table B18 gives a state-by-state list of the number of timber bridges found in the United States (FHWA 1986, 14). In addition to these, the U.S. Forest Service maintains approximately 6000 timber bridges throughout the United States. The Forest Service also builds 100 to 250 bridges per year (Gutowski 1985).

While many of the bridges in the U.S. inventory are made of logs, modern bridge construction typically uses glue-laminated panels that span the entire length of the structure. The use of timber bridges has logistical, performance, and economic benefits. In comparison with prefab concrete deck panels, timber is lighter and therefore easier to transport and handle. Wood panels require less equipment to install and they may be installed under weather conditions that would stop construction of other types of bridges.

The performance of timber bridges is also a factor to consider in material selection. Properly treated wood bridges may have a design life of over 120 years (Brungraber 1990, p 135). One factor contributing to this long life is that wood structures are resistant to de-icing salts. Finally, wood structures are not as severely affected by material defects as other traditional materials.

Two maintenance problems that should be addressed during the design of wood bridges are (1) scarring of the wearing surface by aggregate thrown onto the roads from passing vehicles and (2) pot hole development just behind bridge abutment walls (Faurot, Mockler, and Johnson, 1987, p 147). To treat the first problem, the Forest Service has been experimenting with asphalt deck treatments or geotextile underlays.

Potholing at bridge abutment walls is further compounded by maintenance equipment that moves aggregate and dirt onto the bridge. The increase of biodegradable material on the bridge causes moisture to collect on the wood deck, increasing deck rotting. After trying several approaches, the Forest Service found the best approach was to pave up to 200 ft on both sides of the bridge with asphalt.

The technology for wood bridges has recently become quite sophisticated. Deck sections, for example, are constructed out of glued laminated panes. Although these materials must be produced in a factory, the cost of importing the wood bridge material may be less than traditional bridge material since the weight of the panels is less than that of traditional bridge materials.

Table B18

Wood Bridges in the United States

State	Number of Timber Bridges	Percent
Alabama	3,171	20.6
Alaska	238	29.0
Arizona	109	2.0
Arkansas	4,338	33.0
California	1,276	5.7
Colorado	1,449	20.0
Connecticut	37	0.9
Delaware	61	8.3
Florida	838	8.3
Georgia	1,196	8.4
Hawaii	60	5.7
Idaho	444	11.9
Illinois	255	1.0
Indiana	291	1.3
Iowa	4,812	18.4
Kansas	2,952	19.6
Kentucky	290	2.3
Louisiana	5,924	42.1
Maine	72	2.7
Maryland	237	5.4
Massachusetts	159	3.2
Michigan	421	4.0
Minnesota	1,994	15.4
Mississippi	5,920	35.3
Missouri	712	3.0
Montana	1,829	37.3
Nebraska	3,635	22.6
Nevada	59	5.7
New Hampshire	157	6.2
New Jersey	289	4.9
New Mexico	379	11.0
New York	246	1.4
North Carolina	2,060	13.0
North Dakota	1,156	21.3
Ohio	220	0.7
Oklahoma	3,880	17.0
Oregon	1,282	19.5
Pennsylvania	342	1.5
Rhode Island	17	2.4
South Carolina	769	8.6
South Dakota	985	13.9
Tennessee	1,675	9.1
Texas	5,712	13.0
Utah	242	9.9
Vermont	90	3.3
Virginia	110	0.8
Washington	1,098	16.1
West Virginia	86	1.3
Wisconsin	493	3.8
Wyoming	449	15.8

The U.S. Forest Service and bridge manufacturers have published additional information on these innovative structures (Penoyar 1986; Gutkowski and Williamson 1983; Weyerhaeuser 1980).

Low-Water Stream Crossings

An alternative to bridges is to allow water to flow over the road with a technique called a low-water stream crossing. Table B19 lists the criteria to determine the applicability of this technique (Motaged and Change 1983).

Gully Control Systems

Use of natural drainage structures, i.e., gullies, by Army engineers should be an economical option for moving water through the construction site. Erosion of vegetation within the gullies, however, can damage road construction. Once the vegetation has been eroded away, the gully may extend and eventually consume the finished road and associated man-made drainage structures.

The establishment of effective vegetative cover surrounding and within the gully is the long-term solution to keep the gully controlled. Vegetation is the key since the vegetation surrounding a gully may have a stronger influence on maintaining channel stability than does the soil in the gully (Heede, May 1976).

The best types of plants for gully stabilization are plants with low height and a deep and dense root system. Surviving trees will damage drainage channels since they divert water against the channel banks, causing added erosion. Grasses are also detrimental since they decrease the friction in a channel carrying water, increasing the velocity of the water, and thus causing more erosion.

To help the growth of vegetation within a gully, structures are often required, the least expensive of which are called "check dams" (TM 5-330). The U.S. Forest Service has had extensive experience

Table B19

Low-Water Stream Crossing Criteria

Criteria	Most Favorable for LWSC	Least Favorable for LWSC
Average Daily Traffic (ADT)	less than 5 vehicles/day	more than 200 vehicles/day
Average Annual Flooding	less than 2 times/year	more than 10 times/year
Average duration of traffic interruption per occurrence	less than 24 hours	more than 3 days
Extra travel time for detour	less than 1 hour	more than 2 hours
Possibility of danger to human life	less than 1 in 1 billion	more than 1 in 100,000
Property damage	none	1 million dollars
Frequency of using it as an emergency route	none	once/month

using check dams throughout the United States. The most common type of check dam is an inexpensive, porous structure built of loose rock (Figure B16). The specific shape of the dam depends on the size, shape, and gradation of the rocks within the dam.

Gabions are one alternative to the loose rock check dam. Before using gabions, there are several factors that should be considered. First, the wire in the gabion baskets must be corrosion resistant. Next, the overall gabion must be strong enough to resist the water load. Third, the openings within the basket should be smaller than the average rock size. Finally, flows that contain boulders and large rocks will eventually destroy gabions.

Another type of check dam is the "single fence" check dam (Figure B17). In designing these structures, care should be taken when specifying the wire mesh, placement of the dam within the channel, and spacing and securing the steel fenceposts. In general, the spacing of steel fenceposts should be less than 1.2 m to prevent stretching of the wire mesh. Posts may also be stabilized by guys placed within the dam itself and protected with rock.

Figure B18 shows a "double fence" check dam. The key component of this structure is well graded rock. Large rocks will allow jets of water to come through the structure, and in some sites water jetting has caused significant bank damage. The designer may want to consider broadening the base of the dam if large flows are to be expected.

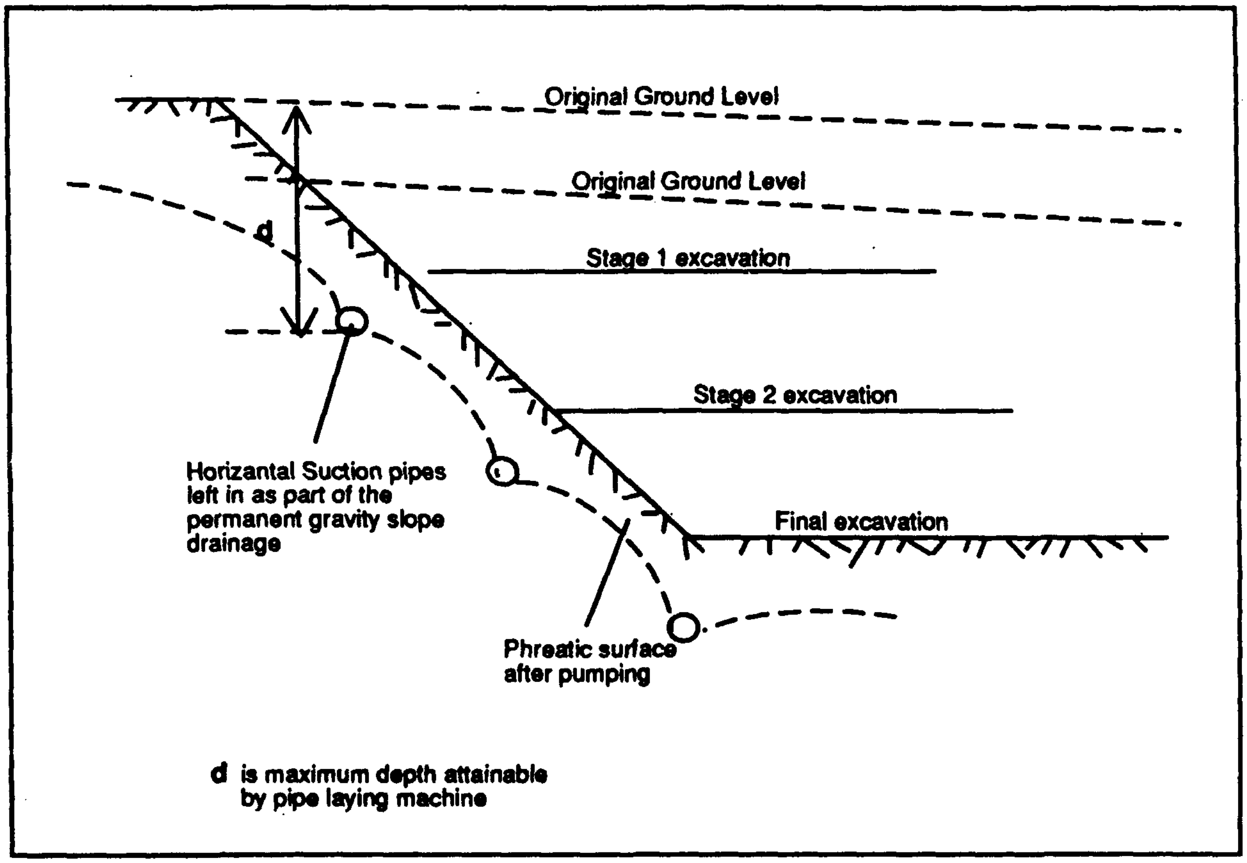


Figure B16. Loose-Rock Check Dam.

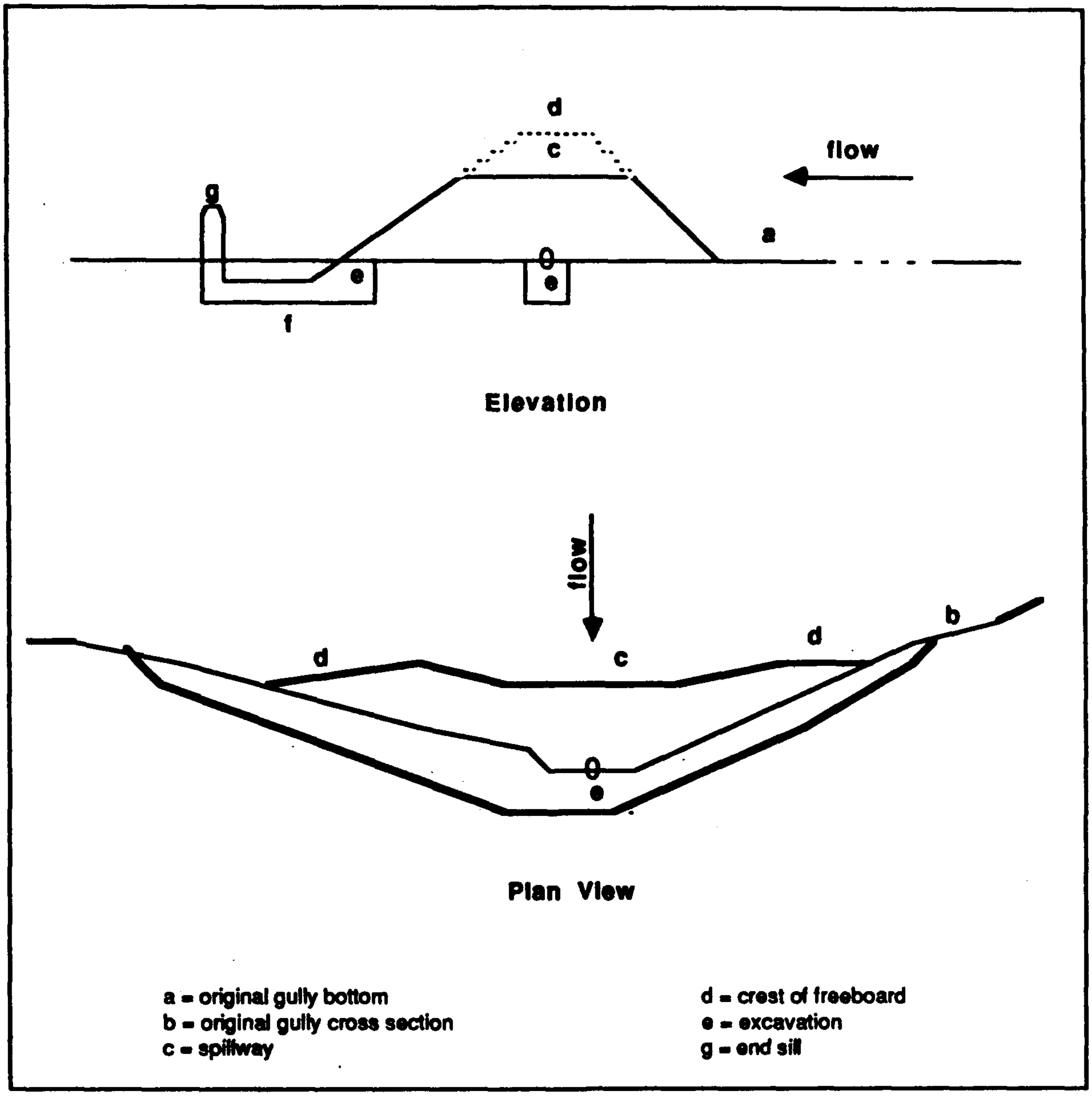


Figure B17. Single-Fence Check Dam.

In designing a double-fence check dam, it is important to ensure that all the water in the channel flows over the dam. Keying the dam into the bank will accomplish this goal. Cutting the key into the bank should be the first step in the construction of the double-fence check dam.

Checkdams assist in maintaining natural drainage structures by slowing the velocity of water flowing down the channel. Specific details of the design and construction of these dams, in particular, spacing of checkdams along the gully channel, keys, dam height, rock gradation, spillway design, dam apron, and bank protection, and dam shape requirements may be found in TM 5-330. The report also provides a method to determine the optimum dam configuration.

Stabilizing upstream of the check dam is accomplished by lining necessary parts of the channel with appropriately graded aggregate. Large, rough-edged aggregate slows the velocity of the runoff and traps sediments. Of particular importance in gully control is the head of the gully. This is accomplished by cutting out all steep-sloped material and filling the channel to slope from the top of the headcut to just above the toe of the dam (Figure B19).

Checkdams have several secondary benefits. One is an increased year-round water yield from intermittent flow due to water storage in sediment above dams. The use of this sediment may also help

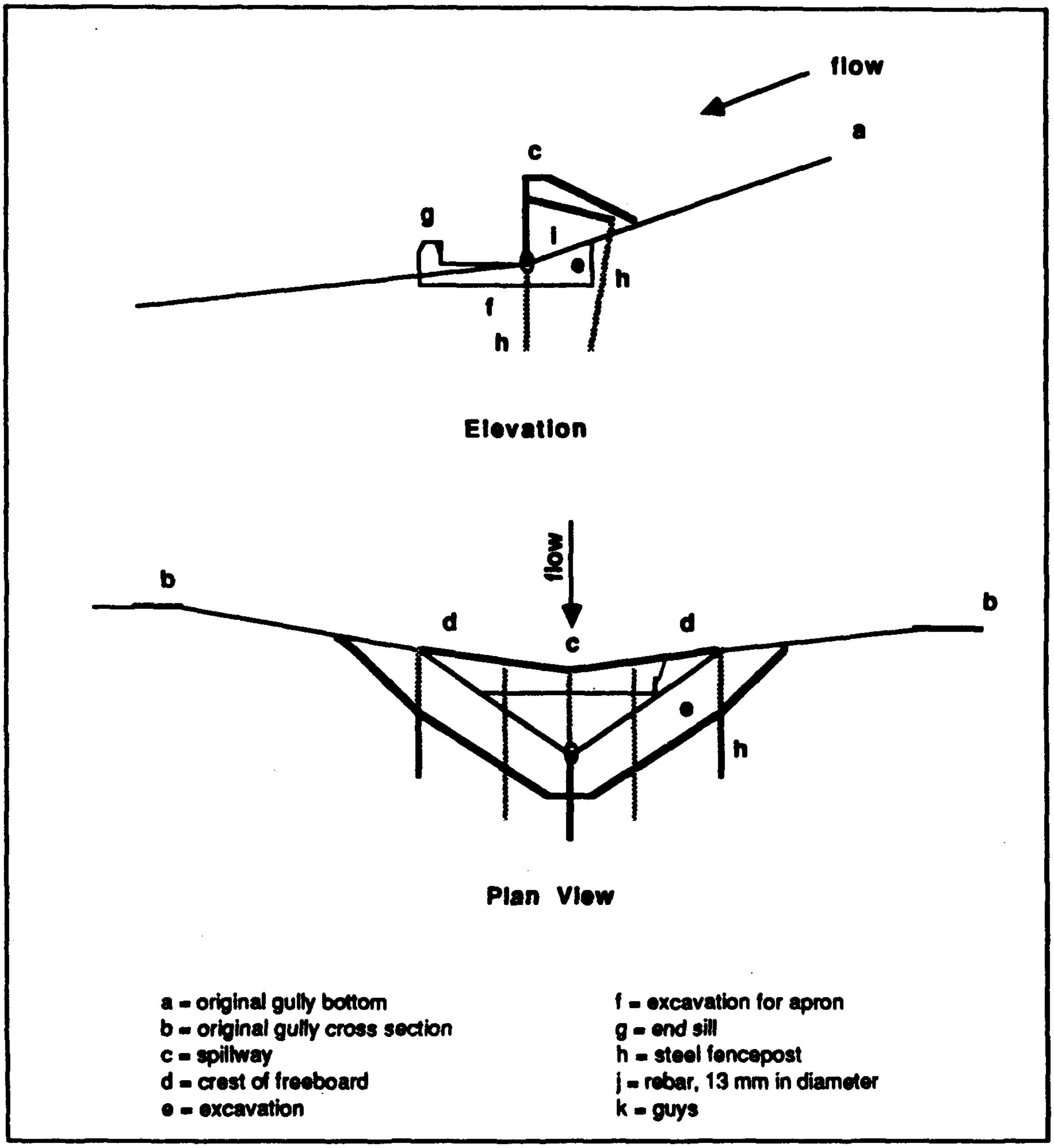


Figure B18. Double-Fence Check Dam.

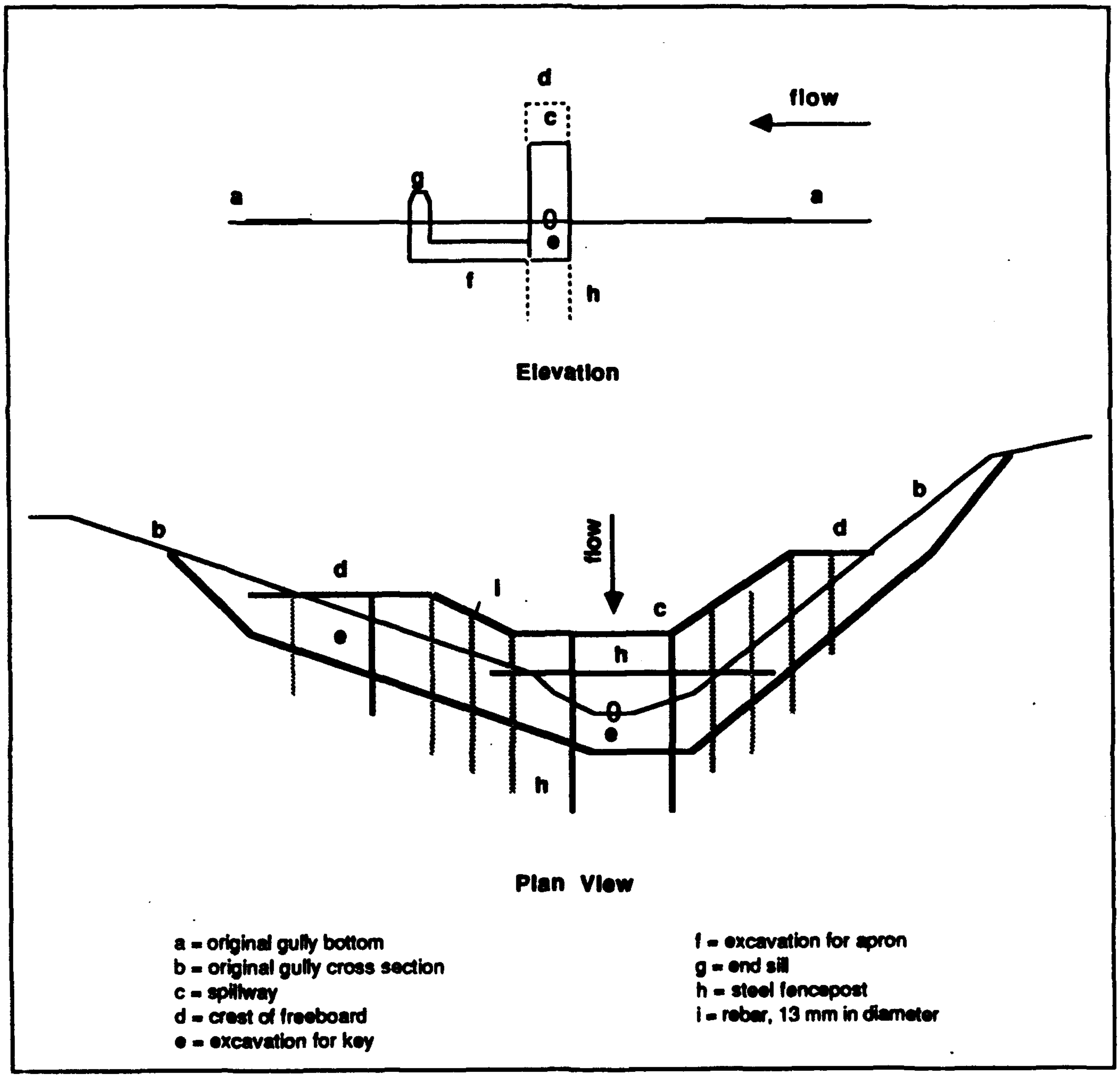


Figure B19. Gully Headcut Control.

provide arable land for farming and grazing uses. Several examples of ancient use of the check dams to create agricultural areas in very arid regions of the Southwest United States and Mexico have also been discovered. Table B20 lists the various methods for gully and erosion protection.

Design Iterations

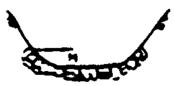
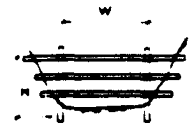
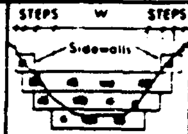
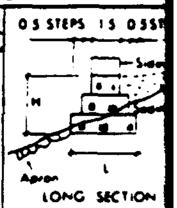
The design process for the Army engineer begins with a mission to build a road. The engineer conducts an expedient site investigation to gather information to assist in road route selection. Once an appropriate route has been selected, a detailed design process begins that completes with the development of plans and specifications to guide the construction process.

During design, engineers typically hold several design parameters constant and try to minimize the cost of other design parameters. For example, in a project in Nepal assumptions regarding the road width, distance between subgrade and water table level, and types of bridge design were held constant and cut/fill quantities were evaluated (Beaven and Lawrance 1973).

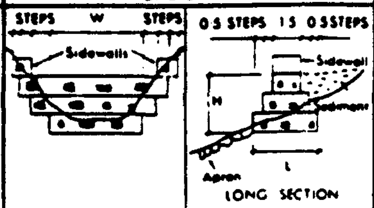
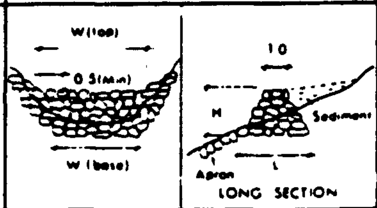
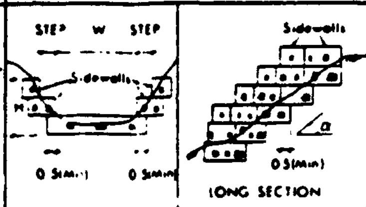
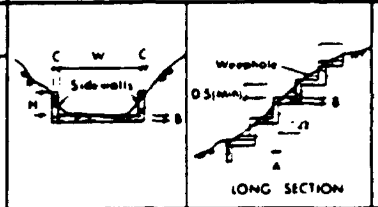
In the ideal world, the design process is an iterative one where an optimum solution for a particular set of design requirements and constraints is developed. In the real world, however, the design process is a satisficing rather than optimizing process. The designer attempts to find the first design that meets the requirements and satisfies the constraints. Adequate or good solutions are possible with experienced designers since these designers have heuristic information to identify potential problems before they happen.

Table B20

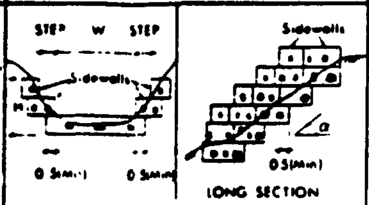
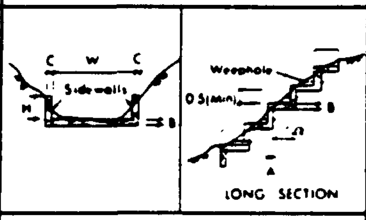
Gully/Erosion Protection Methods

TYPE OF PROTECTION	BAMBOO PLANTING OR SIMILAR	RUBBLE MASONRY	DRY STONE PITCHING	GABION MATTRESS	CHECKDAMS: TIMBER	CHECKDAMS: GABION
DIAGRAMMATIC CROSS SECTION OR LONG SECTION						 
CONSTRUCTION NOTES AND TYPICAL DIMENSIONS	Plant type and spacing to be specified, typical densities 1 plant or tree per 2–10m² of gully side, seek specialist local advice if possible.	Thickness of masonry 0.5. H to suit estimated flow depth and extent of gully side instability, generally 0.50 minimum.	Thickness of pitching 0 4, minimum stone dimension 0 2, long axes of stones vertical, bedded on 0 1 thick gravel layer. H to suit flow depth and gully side instability.	Thickness of mattress 0 3–0.5, erodible bed may require buffer filter or impermeable underlay (e g polythene) H to suit flow depth, and gully side instability.	Minimum diameter of timbers 0.3, keyed 1 0 into gully bed and sides, timber spacing to be specified. H = 1 to 3m.	Gabions keyed 0.5 minimum into gully bed and sides. H = 2 to 6m. L = H + 0.5, may be reduced and keyed into gully bed if good rock encountered in foundation. Standard gabion box size 2 x 1 x 1m, mesh to be specified.
GULLY CHARACTERISTICS: BED SLOPE	10° – 40°	0° – 30°	0° – 15°	10° – 30°	15° – 40°	
GULLY CHARACTERISTICS: RELATIVE ERODIBILITY OF BED	Low – Moderate	Moderate – High	Low – Moderate	Moderate – Very High	← Low – High → Note that erosion may be accelerated below crest of checkdam [text lost at the page's right edge] or masonry apron may be required in gully bed and [text lost at the page's right edge]	
GULLY CHARACTERISTICS: SIZE OF BED LOAD	Small – Large	Small – Medium	Small – Medium	Medium – Large	Medium – Very Large	Medium – Large
GULLY CHARACTERISTICS: GULLY SIZE	Small – Very Large	Small – Medium	Small – Medium	Medium – Large	Large – Very Large	Medium – Large
MOUNTAIN ZONE	2,3,4	2,3,4	2,3,4	2,3,4	← 4 →	

(Source: *Engineering Geology*, Vol 21 [Elsevier Publishing, 1985]. Used with permission.)

CHECKDAMS		GABION CASCADE	MASONRY CASCADE	CLASS…
GABION	STONE WALL			
				Width of p… size of step… checkdams… angle of si… Length of p… and spacin… the gully b…
Gabions keyed 0.5 minimum into gully bed and sides. H = 2 to 6m. L = H + 0.5, may be reduced and keyed into gully bed if good rock encountered in foundation. Standard gabion box size 2 x 1 x 1m, mesh to be specified.	Stone layers keyed 0.3minimum into gully bed and sides, minimum stone dimension 0.2, bedded on 0.1 thick gravel layer H = 1 to 3m. L = 1.33 x H, may be reduced and keyed into gully bed if good rock encountered.	Gabions keyed 0.5 minimum into gully bed and sides. H = 1 to 4m generally to suit estimated flow depth and extent of gully side instability α (angle of cascade) to suit gully bed angle. Erodible bed may require buffer filter or impermeable underlay. Standard gabion box size 2x1x1 or 1x0.5x0.5m for small gullies and flows, mesh to be specified.	H to suit estimated flow depth and gully side instability, minimum 0.5 clearance of sidewall over front edge of cascade steps. A varies 0.2 (low angle) to 0.6 (high angle) depending on angle of cascade (α) see below. B varies 0.15 (low angle) to 0.4 (high angle). C varies 0.15 (low angle) to 0.5 (high angle). α to suit gully bed angle. Weepholes required on each vertical step.	All dimensi… Construct s… all protectio… existing gra…
15° – 40°		20° – 45°	30° – 60°	
← Low – High → …sion may be accelerated below crest of checkdam and pitched boulder, gabion mattress …masonry apron may be required in gully bed and along base of sideslopes		High – Very High	Moderate – High	Relative Erodibility A… Low Moderate High Very High
Medium – Large	Small – Medium	Medium – Large	Small – Medium	Maximum … Small Medium Large Very Large
Medium – Large	Small – Medium	Medium – Large	Small – Medium	Gully Size Small Medium Large Very Large
← 4 →		2.4	2.4	Mountain Z… 2. Free roc… 3. Ancient … 4. Active la…

②

GABION CASCADE	MASONRY CASCADE	CLASSIFICATIONS AND NOTES
		Width of protection works (W) and size of steps for cascades and checkdams to suit gully width and angle of side slopes Length of protection works number and spacing of checkdams along the gully bed to be specified.
Gabions keyed 0.5 minimum into gully bed and sides. H ≥ 1 to 4n generally to suit estimated flow depth and extent of gully side instability ω (angle of cascade) to suit gully bed angle Erodible bed may require buffer filter or impermeable underlay. Standard gabion box size 2x1x1 or 1x0.5x0.5m for small gullies and flows, mesh to be specified.	H to suit estimated flow depth and gully side instability, minimum 0.5 clearance of sidewall over front edge of cascade steps. A varies 0.2 (low angle) to 0.6 (high angle) depending on angle of cascade (ω) see below. B varies 0.15 (low angle) to 0.4 (high angle). C varies 0.15 (low angle) to 0.5 (high angle) Ω to suit gully bed angle. Weepholes required on each vertical step.	All dimensions in metres Construct sidewalls and edges of all protection works flush with existing ground levels on gully sides.
20° – 45°	30° – 60°	
High – Very High	Moderate – High	**Relative Erodibility** / **Annual Incision (metres)** / **Examples** Low / 0 – 0.1 / Hard rocks rocksteps and waterfalls Moderate / 0.1 – 0.5 / Weak rocks channels with thin alluvial cover High / 0.5 – 1.5 / Thick terrace deposits alluvial fill Very High / < 1.5 / Tipped soil from road construction
Medium – Large	Small – Medium	**Maximum Bed Load** / **Particle Size** Small / Fines and sands Medium / Gravel Large / Cobbles Very Large / Boulders
Medium – Large	Small – Medium	**Gully Size** / **Cross Section Area (m²)** Small / 1 – 2 Medium / 2 – 5 Large / 5 – 20 Very Large / > 20
2.4	2.4	**Mountain Zone** 2 Free rock faces debris slopes 3. Ancient terrace degraded valley slopes 4. Active lower slopes.

3

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