TIMBER CRIB RETAINING STRUCTURES

Robert L. Schuster,* U.S. Geological Survey, Denver;
Walter V. Jones, Northern Testing Laboratories, Boise;
Ronald L. Sack, Department of Civil Engineering, University of Idaho; and
Steven M. Smart,* Northern Testing Laboratories, Great Falls, Montana

A study was performed to compile standard timber crib retaining wall designs and design methods and to analytically investigate the behavior of these structures. Cribs were evaluated by studying (a) bin pressures (using the Janssen theory), (b) member stresses, (c) external stability (including lateral earth pressures), (d) differential settlement, (e) drainage, and (f) preservation of timber members. Engineering design criteria were incorporated into a computer program, and the standard designs were analyzed to detect either overstress of the crib members or potential failure of the entire crib due to external stability problems. An extensive literature search was performed, and companies, organizations, and agencies that might have knowledge of and experience with these structures were queried. The study was augmented by extensive field inspection of timber crib retaining walls.

Timber structures are an aesthetic and economical means for retaining embankments and cuts for low-volume roads. The main objective of this paper is to evaluate the use of and to develop design criteria for crib retaining structures made from dimensioned timber and backfilled with suitable local soils. Attention is given to structural quality of timber members and connecting devices, suitability of the soils as backfill, and the effect of settlement and differential wall movements on stresses in the timber members and connecting units.

The most common type of timber retaining structure is the timber crib. A crib structure is made by placing a number of criblike cells together and filling them with soil or rocks to give them strength and weight. The cribs in retaining walls are made with timber, and the cells are filled with earth to form a gravity retaining wall. Figure 1 shows the structural components of a typical timber crib retaining wall. The horizontal members are called stretchers, and the vertical members are called headers. Forces are transferred between the members at the joints. In modern designs, mechanical connectors such as drift pins or split rings are used at the joints; however, some old timber crib walls in mining areas of northern Idaho have dapped (i.e., notched) members at the joints to transfer forces between members.

Literature on timber crib retaining walls is published primarily in design manuals and textbooks on foundations and soil mechanics. Other sources of information are state and Canadian provincial highway departments, U.S. Forest Service and Federal Highway Administration regional offices, and the wood products industry. During this study, inquiries were also made to local governmental agencies that have used timber crib walls.

Tschebotarioff (15, 16) provides the most complete textbook information available on the design and analysis of crib walls. Tschebotarioff gives the criteria both for investigating the crib as a stable retaining wall and for designing the members and connections. Crib walls must be stably designed as gravity retaining walls. The crib members should be designed to resist the forces exerted by earth fill. Stretchers

*When this study was performed, Mr. Schuster was with the Department of Civil Engineering, University of Idaho, and Mr. Smart was with the Idaho Department of Highways, Lewiston.

must be designed to resist both horizontal and vertical bending; headers must resist tension (as transmitted by the horizontal stretcher reactions) and vertical bending.

USE OF TIMBER CRIB RETAINING WALLS

Historical Review

In the early part of the 20th century, timber crib structures were widely used as retaining walls and to a limited extent as dams, flood control structures, bridge abutments, and piers. Their use was especially common in the logging and mining areas of the United States and Canada. Designs for timber crib structures and the remains of walls in the Pacific Northwest have been found that date back to the early 1900s. Their use undoubtedly began as a matter of economics because both the timber and earth fill were abundant, inexpensive, and easy to use. The design and construction of these structures were probably based more on experience and intuition than on engineering judgment and analysis.

A great number of timber walls were built in the early part of this century by the mining industry in the Rocky Mountain states. Many of these walls are still standing, some in various states of disrepair. Most of the older walls that we observed were constructed of untreated logs and had dapped crib member joints. Some of these walls, particularly those with well-drained backfill, are 50 to 60 years old and are still serviceable. Undoubtedly many similar cribs built at the same time have failed.

Construction of most of the early timber crib walls was based on experience, which undoubtedly meant that there was considerable variation in the safety factor from one wall to another. Those that were built with high factors of safety are the ones still standing even though the members are in very bad condition. Those observed are the few cribs that, because of circumstances of design and construction, have survived.

Modern Timber Crib Walls

Although a few timber cribs are still constructed for mining operations and for use as bridge abutments and piers, their primary use today is to retain road cuts and embankments, particularly in mountainous areas and for low-volume roads.

In recent years, higher standards of road design have necessitated larger cuts and fills. At the same time, increasing environmental constraints have demanded that cuts and embankments encroach as little as possible on natural features such as trees and streams. The problem has been particularly critical in narrow canyons where environmental considerations prevent design of embankments that encroach on the streams at the bottoms of the canyons. Also, on steep hillsides the long cut and embankment slopes required to ensure stability are often unsightly. The solution in these cases is construction of retaining structures that shorten or eliminate the horizontal demension required for either a cut or fill slope. Timber crib walls often are used to fulfill this function.

Timber crib walls are used primarily in areas where dimensioned, structural grade timber can compete economically with other wall materials. In North America this has essentially limited the construction of timber walls (at least those made of dimensioned timbers) to areas within reasonable haul distances of sources of structural grade timber, commonly Douglas fir. As part of this study, state and provincial highway departments and federal organizations throughout the United States and Canada were queried on their use of timber crib walls. The survey indicated that timber crib structures are used primarily in the United States and Canada west of the Rocky Mountains.

An interesting exception to this is in Minnesota. In 1971 the Minnesota Highway Department constructed a 290-ft-long (88-m) timber crib retaining wall at the Goose Creek rest area on I-35 north of Minneapolis (3). The design of this wall, which ranges from 4 to 22 ft (1.2 to 6.7 m) in height, was a modification of the American Wood Preservers Institute standard design for timber crib walls (4).

A retaining structure was required in the rest area to prevent a large embankment from encroaching on a stand of prime native hardwood trees. Highway department landscape architects specified a timber crib wall because it is aesthetically pleasing. The wall, which was treated with a green chromated copper arsenate preservative, blends beautifully with its environment and is an outstanding example of compatibility between a man-made structure and its surroundings.

In recent years in western North America, selection of timber walls over other types of walls has probably been based primarily on environmental compatibility. The U.S. Forest Service, the Federal Highway Administration, and western state, provincial, and local agencies have built many timber crib walls to blend with the environment. Wood has a natural advantage over most other construction materials in this regard, particularly in forested areas. Furthermore, modern wood preserving compounds have been introduced that do not detract from the beauty of the wood.

Today more than ever landscape architects, engineers, and others charged with maintaining compatibility between necessary structures and the surrounding environment are recommending that timber structures be used where comparative costs are not prohibitive and where backfill drainage will ensure longevity of the timber wall. As long as an adequate supply of structural grade timber is available, the trend will continue.

A large percentage of timber crib walls being designed and built today are constructed of dimensioned, structural grade timber. Most commonly the members are rough cut, structural grade Douglas fir, although some specifications allow use of other timber species such as cedar or larch. Most designs specify 8 by 8-in. (20 by 20-cm) square members, but some walls have been built with 6 by 6-in. (15 by 15-cm) and 10 by 10-in. (25 by 25-cm) square members and 8 by 10-in. (20 by 25-cm) and 8 by 12-in. (20 by 30-cm) rectangular members.

Although log crib walls are not subject to exact engineering design and analysis, many have been and are being built. For example, the Washington State Highway Department has a modern design standard for log cribbing (17). This standard uses Douglas fir, cedar, or larch logs that are dapped to fit; in addition, the members are joined by ¾-in. (19-mm) drift bolts. The crib wall is strengthened by anchor logs connected to the crib structure by tie backs.

Standard Timber Crib Retaining Wall Designs

The survey conducted as a part of this study revealed that seven timber crib retaining wall designs are commonly used in the United States. The survey was in the form of written queries, field trips, and personal communications or visits with owners, designers, fabricators, and builders of timber crib walls. Of the seven wall designs, five were developed by governmental agencies and two by private interests or associations. A complete discussion and design details for each of these standard wall designs have been published (13).

ENGINEERING DESIGN CRITERIA

The survey gave considerable attention to case histories indicating failure of such walls. Rather interestingly, the study unearthed no information on total failure of a modern timber crib wall; failures were only partial with the walls still being functional. The lack of available information on walls that have failed completely demonstrates the relative efficiency of timber crib walls.

Partial failures observed on field visits or noted in information obtained from the survey were caused primarily by

1. Lateral movement of the wall,
2. Settlement of the wall,
3. Failure of members due to bending, and
4. Failure of members at the joints.

Failure may result from one or a combination of the above. In some cases partial failure was progressive, but in most cases the walls had apparently stabilized in states of partial failure.

Soil-Structure Interaction

Crib retaining walls are affected by a number of soil-structure interactions that are associated with both the internal stresses and the external stability of the retaining wall. The internal interactions consist of (a) pressures exerted by earth confined in the crib and (b) stresses in crib members and connectors resulting from earth pressures exerted by both crib fill and backfill. The external interactions are (a) the fill inside and above the crib acting with the crib as a gravity retaining wall, (b) active lateral earth pressure, (c) sliding of the wall, (d) overturning of the wall, and (e) the bearing pressure on the foundation. Each of these soil-structure interactions is dependent on the soil.

Bin Pressure

The pressures exerted on the timbers by soil contained within a crib are analogous to those exerted by grain or other granular materials on the walls of bins and silos (6). Equations developed to predict pressures exerted in grain silos have been extended to account for the so-called bin effect in timber crib retaining walls. In addition, experiments (1) have shown that the bin pressure theory used for grain is applicable to earth pressure problems.

A number of equations exist for predicting bin pressures; the two most commonly used were developed by Janssen and Airy. Although the Janssen equation was originally derived to predict pressures in grain silos, it can be modified slightly to include the effects of both soil-wall adhesion and a surcharge pressure. The modified form (9) is

$$\sigma_z = \left(\frac{\gamma A - c_a U}{\mu_1 K U}\right)\left(1 - e^{\frac{-\mu_1 K U z}{A}}\right) + q\left(e^{\frac{-\mu_1 K U z}{A}}\right)$$

where

σ_z = vertical pressure inside the crib,
σ_x = lateral pressure inside the crib,
$K = \frac{\sigma_x}{\sigma_z} = \frac{\cos^2\phi}{2\cos^2\phi}$ = Krynine's coefficient (10) of lateral pressure of soil confined in a cofferdam or crib,
γ = unit weight of material in crib,
A = horizontal cross-sectional area of crib,
U = perimeter of crib,
c_a = coefficient of soil-wall adhesion,
$\mu_1 = \tan\delta$ = coefficient of friction between fill material and crib wall,
z = depth from the top of the crib at which the pressure is calculated, and
q = average surcharge pressure at top of crib.

Airy's equations (2) were originally derived for a level surface of grain. The equations can be modified to include the effect of a wedge-shaped surcharge, which is common in retaining walls. Airy's equation (5) for a deep bin with a sloping surcharge is

$$P = \frac{\gamma b^2}{2(\mu + \mu_1)^2}\left[\sqrt{\frac{2h + H}{b}(\mu + \mu_1) + 1 - \mu\mu_1} - \sqrt{1 + \mu^2}\right]^2$$

Figure 1. Components and configuration of a typical timber crib retaining wall.

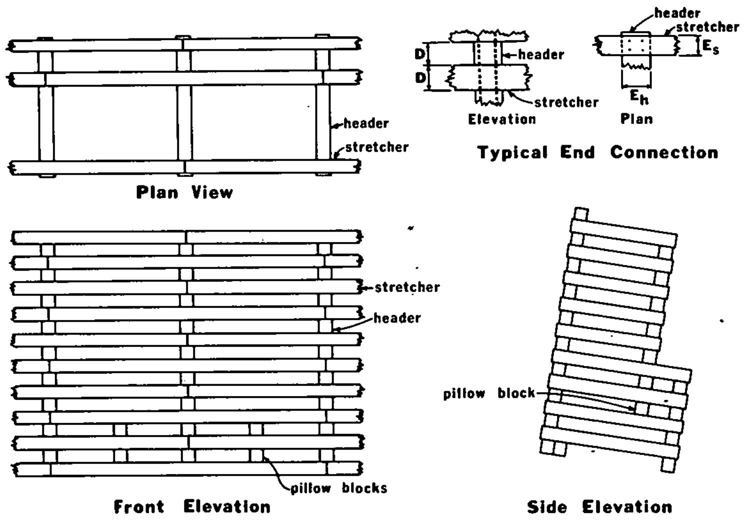


Figure 2. Comparison of Airy's and Janssen's equations for vertical crib with sloping backfill.

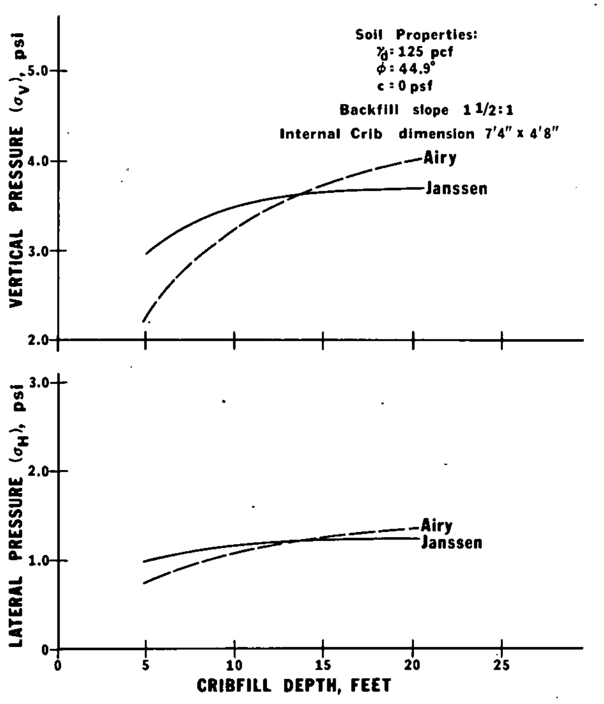
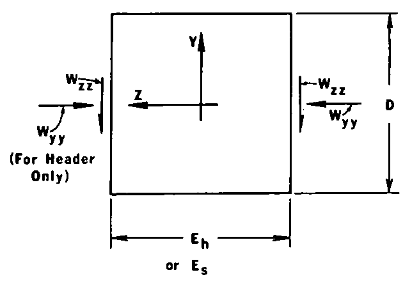


Figure 3. Forces acting on a stretcher or header cross section.



where

P = total force against a unit length of bin wall,
γ = unit weight of materials in crib,
b = width of crib,
h = depth of failure surface,
H = height of the wedge of surcharge above the bin,
μ = coefficient of internal friction in the stored material, and
μ_1 = coefficient of friction between the stored material and the crib wall.

For the design of crib retaining walls, the unit pressure, as a function of depth, is needed (5). This can be obtained by differentiating P with respect to h, or $(d/dh)(P) = p$ and

$$p = \frac{\gamma b}{\mu + \mu_1}\left[1 - \frac{\sqrt{1 + \mu^2}}{\sqrt{\frac{2b + H}{b}(\mu + \mu_1) + 1 - \mu\mu_1}}\right]$$

As shown in Figure 2, the Janssen and Airy theories predict similar vertical and lateral crib pressures for timber crib walls. However, Janssen's theory is generally considered to be the classic bin pressure theory and the most widely accepted method for calculating pressures imparted by confined granular materials in deep bins. It should be noted, however, that researchers recently have begun to question the validity of the Janssen method in predicting bin pressures for compressible granular materials such as uncompacted cement and grains (7, 12). By means of a linear density solution, Clower et al. predicted higher lateral and vertical pressures than those predicted by the Janssen equation when the uncompacted unit weight of compressible granular materials is used. Moreover, Janssen's equation may be incorrect when applied to granular soil materials that have not been properly compacted. This possibility has been borne out in instrumentation studies by Schuster et al. (14) on an actual timber crib in which measured crib pressures were approximately double those predicted by Janssen's theory.

Member Stresses

To a great extent, the performance of a timber crib retaining wall depends on the ability of the crib members to contain the enclosed soil. Analysis of the stresses and loadings in the crib members and connections is based on the earth pressure inside the crib. Accurately determining these pressures results in an economical design of the crib members. The horizontal force W_{yy} corresponds to the lateral pressure in a bin multiplied by the depth of the stretcher plus the depth of a header or 2D as shown in Figure 3. The vertical shear force W_{zz} is a friction force where

$$W_{zz} = \mu_1 W_{yy}$$

Because of the applied loading, stretchers can be analyzed as beams loaded in unsymmetrical bending and torsion. The following formula is used for calculating the maximum torsional shearing stress on rectangular shafts (8):

$$\tau_{yz_{max}} = c_1 \frac{M_t}{ab^2}$$

where

M_t = torsional moment,
a = long side of the rectangular cross section,
b = short side of the rectangular cross section, and
c_1 = 4.81 for a/b = 1.0 and 4.33 for a/b = 1.5 (use linear interpolation for $1.0 \leq a/b \leq 1.5$).

Headers are analyzed as beams loaded in tension and bending about the horizontal axis. The tensile force in the headers is equal to the horizontal reaction of the stretchers on the connection. This reaction is equal to the lateral force per unit length W_{yy} times the header center-to-center distance.

The bearing stress at the joint can be calculated by dividing the reaction at the joint by the area of the joint. The vertical shearing force W_{zz} loads the stretchers and headers in the vertical direction, causing vertical reactions at their joints. The vertical reaction at a joint is also increased by the sum of the reactions from the joints above it. The cumulative vertical force or reaction at a joint is a function of W_{zz}, and the vertical reaction can be found by integrating W_{zz} over the depth of the soil and the length of the inside perimeter that is supported by the joint.

The calculated stresses and loadings can be compared to recommended allowable values for timber (11), which include a factor of safety. The allowable values chosen for the analysis of the standard designs are those recommended for Douglas fir and western larch.

External Stability

The following factors were investigated to determine the external stability of the retaining wall designs: stability with respect to sliding, stability with respect to overturning, and bearing pressure on the foundation soil.

Differential Settlement

Individual members were checked for stress to determine their suitability to withstand all applied loads. These loadings included the effects of bin pressure and of the backfill soil. Because timber crib walls usually are constructed on either in-situ soils or a modified soil base, differential settlement of the total structure is possible. Under such deformation, the stresses induced on structural components may be different from those resulting from applied loads only. Hence, when a wall is built where the soil conditions are uncertain or unknown, the structure should be built such that the members act independently.

Drainage

Drainage characteristics of backfill and crib fill materials have a noticeable effect on performance and longevity of timber crib walls. This is particularly important in the mountainous, high precipitation areas where most timber walls are built. For example, in the northern Rocky and Cascade Mountain ranges, heavy spring snowmelt tends to saturate native soils. Therefore, timber walls in these locations should be filled with materials that will not become saturated.

Most fill materials observed in this study for existing walls and in design standards can be classified as free draining (i.e., granular). Use of free-draining materials generally ensures that there will not be a buildup of seepage pressures in the fill material. Use of these materials also helps to keep the crib members relatively dry, thus prolonging the life of the wood. One reason for the longevity of some of the older mining cribs in northern Idaho has been the excellent drainage of fill material.

Of necessity, however, walls are being built with fill materials that are not free draining. If such fill is used, it must be assumed that it will be saturated during at least part of the year; thus its design should be based on the saturated unit weights of the backfill. In addition, if saturated fill material is in contact with crib members, these members will rot faster than if a free-draining fill had been used. Inasmuch as the structural framework of a timber crib wall is ordinarily open, the structure itself does not inhibit drainage from the backfill. This is one of the advantages of crib walls as compared to some other types of walls.

Preservation of Timber

Timber in the older walls observed in this study either was untreated or had been dipped in or brushed with creosote. Creosote performs adequately as a preservative but is extremely messy and irritating to work with and does not provide a particularly aesthetic result. The members of many timber crib walls are pressure treated with preservatives such as pentachlorophenol in mineral spirits or liquid petroleum gas (natural tone) or with waterborne salts such as green chromated copper arsenate. Pentachlorophenol in heavy oil (brown tone) is used frequently, but it is also messy, although not so bad as creosote. Pressure treatment is commonly performed at a central plant where crib members are individually cut and drilled ready for assembly.

Timbers may be wholly or partly treated in the field by dipping, swabbing, or brushing with these preservatives. These methods provide only a thin surface treatment, but pressure treatment can penetrate to a depth of nearly ½ in. (13 mm). Thus these measures are not so effective as pressure treatment and cannot be expected to provide the same degree of preservation of treated members.

COMPARATIVE ANALYSIS OF DESIGNS

The performance of the seven wall designs was analyzed under conditions of common use. Each design was evaluated for use with four different groups of backfill soils providing both level and sloping backfill surfaces.

We investigated the following design criteria for external stability:

1. Sliding of entire wall,
2. Overturning of entire wall, and
3. Soil bearing pressure.

We also investigated the following design criteria for member stresses:

1. Joint bearing stress,
2. Header flexural stress,
3. Stretcher flexural stress, and
4. Stretcher torsional shearing stress.

Computations based on these criteria made it possible to determine which ones were the governing factors in wall design and at what wall height these criteria were exceeded for each soil group. To increase the speed and accuracy of the calculations, the equations, logic, and parameters were computer analyzed. A flow chart for the program is shown in Figure 4. A source listing of this FORTRAN IV program together with an example problem can be found elsewhere (13). Typical results for the analyses are shown in Figures 5 and 6.

The analysis revealed that the governing factors in the standard wall designs are the external stability criteria. The heights at which the walls exceed these three criteria are considered limiting wall heights. Failure due to sliding, overturning, and excess soil bearing pressure cannot be prevented without changing the configuration of the wall.

Through analyses of the seven standard crib wall designs, apparent weaknesses of

Figure 4. Flow chart for timber crib retaining wall analysis program.

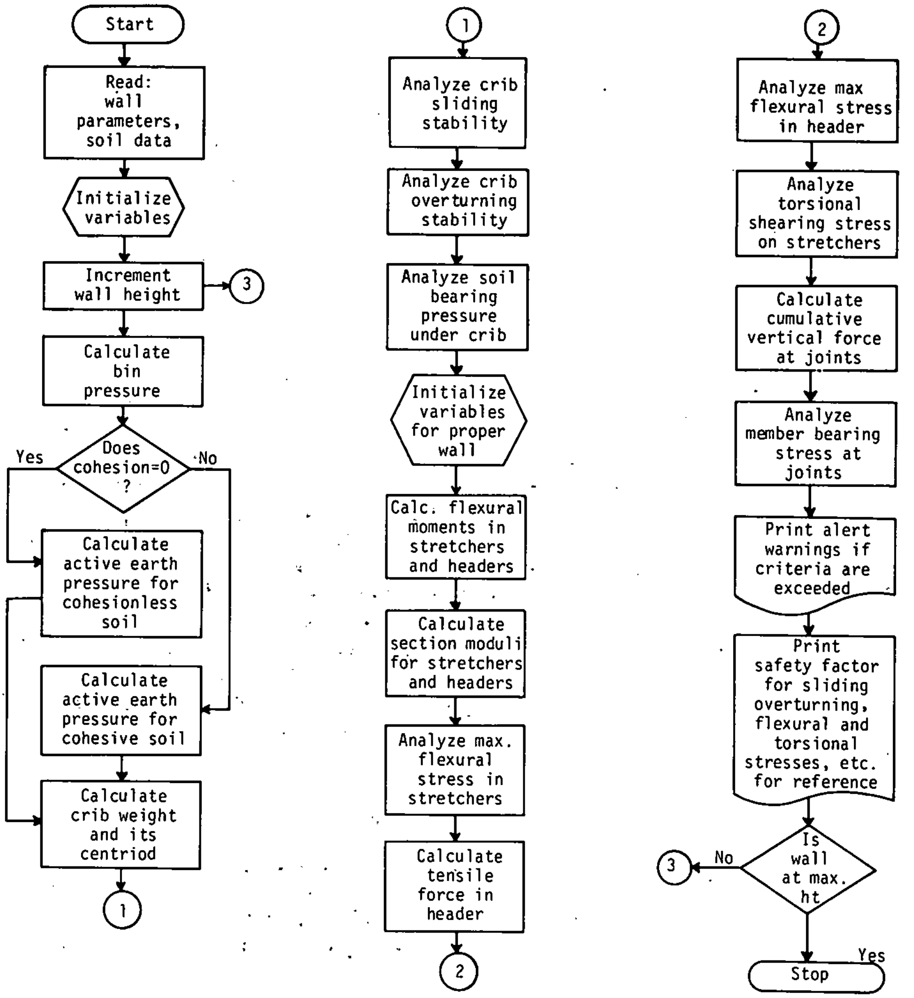


Figure 5. Heights at which member stresses exceed allowable stresses for one wall design studied.

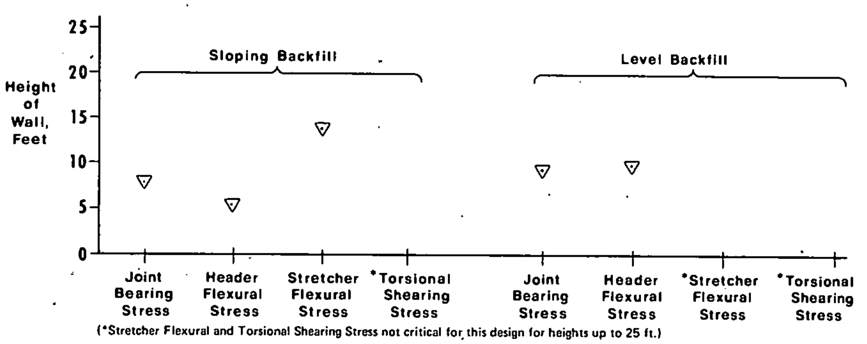
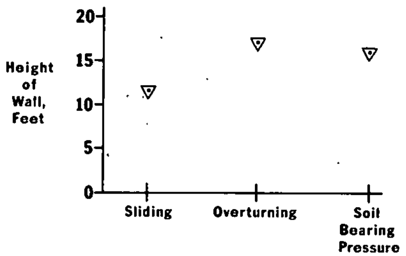


Figure 6. Heights at which one wall design studied exceeds external stability criteria.



the members were detected, and locations within the wall where additional strength should be incorporated were pinpointed. Designers of the standard cribs had recognized these weaknesses during the design process and had taken measures to strengthen the walls prior to this study. Flexural and torsional stresses can be reduced by adding blocks along the span to act as supports and to reduce the span length. Joint bearing stresses can be reduced by adding blocks at the joint to increase the bearing area.

The complete results for the comparative analyses of the timber crib wall designs are given by Schuster et al. (13) and are summarized below.

1. All the timber crib wall designs are approximately equal in their predicted performance, with three exceptions. The calculated member stresses for these exceptions are somewhat lower than those determined by the other methods. The lower stresses are due to the larger members used in these particular walls.
2. Stretcher flexural and torsional stresses do not seem to be critical points of failure in the wall designs studied. However, header flexural stresses and joint bearing stresses do need specific consideration in design. Member stresses can be reduced by using pillow blocks (Figure 1).
3. The member stresses for all of the wall designs are more dependent on the wall dimensions and member sizes than on the type of soil used as backfill. This is shown by these stresses being exceeded at the same wall height with all four groups of backfill soil.
4. The angle of inclination of the backfill surface has a substantial effect on both the internal and external stability of a timber crib wall. The critical angle of inclination is that angle equal to the angle of internal friction of the backfill material.

SUMMARY AND CONCLUSIONS

This study was conducted to investigate the behavior of timber crib retaining walls. This study consisted of a literature and field study and an analysis of the various designs. The complete findings and all the details of the study are presented elsewhere (13). The findings and conclusions are summarized below.

1. For level backfills, crib walls formed of treated, dimensioned timber and constructed in accordance with any of the standard designs can be safely built to the design heights; however, in some cases additional blocking at critical points may be necessary.
2. Crib walls formed of untreated logs have provided suitable retaining action although their design has been based mostly on experience and intuition.
3. The larger structural members of three of the seven walls observed result in rather large safety factors relative to member stresses. The smaller members of the other designs result in lower factors of safety; therefore, additional blocking must be incorporated to prevent overstressing in the highest of these walls.
4. Header flexural stresses and joint bearing stresses need specific consideration in design. In general, stretcher flexural and torsional stresses do not seem to be critical modes of failure in the wall designs studied. An exception to this occurs in those walls allowing staggered headers, which, because of the nature of the load transfer, cause large bending stresses in the stretchers. The use of pillow blocks to reduce member stresses should be considered.
5. The joint connections in some of the wall designs are sometimes difficult to fit together properly. Although split rings provide a positive joint connection, they sometimes create difficulty during erection because of the close tolerances required for field assembly. Warped or twisted timber or improper shop fabrication causes difficulty in fitting the members together. This problem can be largely avoided by the use of spike grids, which are easier to install then split rings.
6. Soils used for crib fill and backfill should be placed in layers and compacted to achieve at least 95 percent of the maximum density as determined by AASHO T-99 or ASTM D 698.

7. Janssen's bin theory was used for estimating internal crib pressures in this study. This theory generally has been considered the most rational of the methods available for calculating bin pressures, but recent studies indicate that it may underestimate the true pressures.

8. Timber crib walls are moderately flexible and can withstand differential settlements without significantly affecting the retaining action or gross stability of the wall, even if noticeable crushing of individual members occurs and weakening of the joints is experienced.

9. Subsurface conditions at proposed wall sites should be adequately determined by performing foundation investigations designed to be commensurate with wall size and complexity of foundation soils.

ACKNOWLEDGMENT

This study was made possible by a grant from the U.S. Forest Service to the Department of Civil Engineering at the University of Idaho. Special thanks are due Adrian Pelzner, Chief Materials Engineer, Division of Engineering, for his valuable advice and cooperation. In addition, technical information and cooperation were provided by numerous personnel of the Forest Service, the Federal Highway Administration, and various state and provincial highway departments.

REFERENCES

1. H. I. Ahmend. Theoretical and Experimental Analysis of the Bin Wall Effect on Lateral Earth Pressure. Univ. of Washington, MSCE thesis, 1967.
2. W. Airy. The Pressure of Grain. Minutes of the Proceedings of the Institution of Civil Engineers, London, Vol. 131, 1898, pp. 347-358.
3. Crib. Wood Preserving, Vol. 50, No. 1, Jan. 1972, pp. 5-7.
4. Improved Standard Designs of Pressure Treated Timber Crib Walls. American Wood Preservers Institute, Jan. 1969.
5. Timber Crib Design. American Wood Preservers Institute, Jan. 1967.
6. R. A. Caughey, C. W. Tooles, and A. C. Scheer. Lateral and Vertical Pressure of Granular Material in Deep Bins. Engineering Experiment Station, Iowa State Univ., Bulletin 172, 1951.
7. R. E. Clower, I. J. Ross, and G. M. White. Properties of Compressible Granular Materials as Related to Forces in Bulk Storage Structures. Trans. American Society of Agricultural Engineers, Vol. 16, No. 3, May-June 1973, pp. 478-481.
8. S. H. Crandall and N. C. Dahl., eds. An Introduction to the Mechanics of Solids. McGraw-Hill, 1959, pp. 264-265.
9. A. K. Jumikis. Foundation Engineering. Intext Educational Publishers, 1971, pp. 730-735.
10. D. P. Krynine. Discussion of paper by K. Terzaghi, Stability and Stiffness of Cellular Cofferdams. Trans. ASCE, Vol. 110, 1945, p. 1083.
11. National Design Specification for Stress-Grade Lumber and Its Fastenings. National Lumber Manufacturers Association, Washington, D.C., 1971.
12. R. E. Rowe. An Investigation Into the Change of Cracking in a Reinforced Concrete Silo Containing Cement. Magazine of Concrete Research, Vol. 11, No. 32, 1959, pp. 65-79.
13. R. L. Schuster, W. V. Jones, S. M. Smart, and R. L. Sack. A Study and Analysis of Timber Crib Retaining Walls. College of Engineering, Univ. of Idaho, Civil Engineering Rept. 73-1, 1973.
14. R. L. Schuster, R. L. Sack, and W. V. Jones. Timber Crib Instrumentation Study. College of Engineering, Univ. of Idaho, Civil Engineering Rept. 74-1, 1974.
15. G. P. Tschebotarioff. Retaining Structures. In Foundation Engineering (G. A. Leonards, ed.), McGraw-Hill, 1962, pp. 487-490.

16. G. P. Tschebotarioff. Soil Mechanics, Foundations, and Earth Structures. McGraw-Hill, First Ed., 1952.
17. Standard Plans for Road and Bridge Construction—1973. Washington State Department of Highways, 1973.