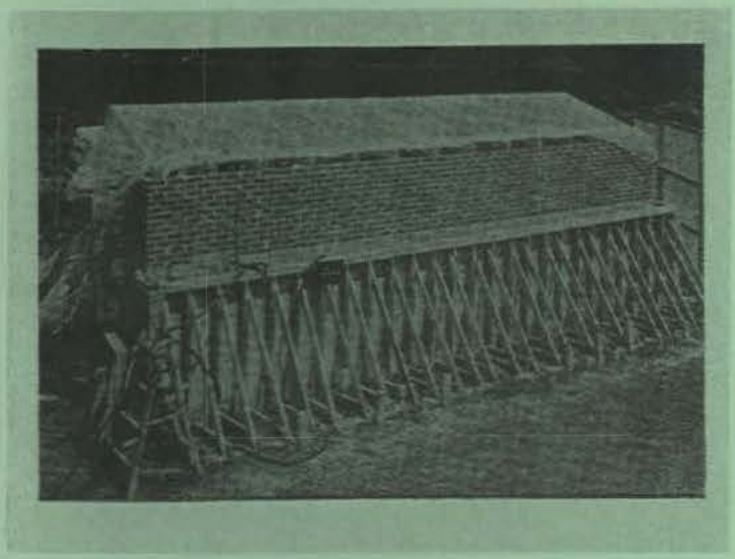

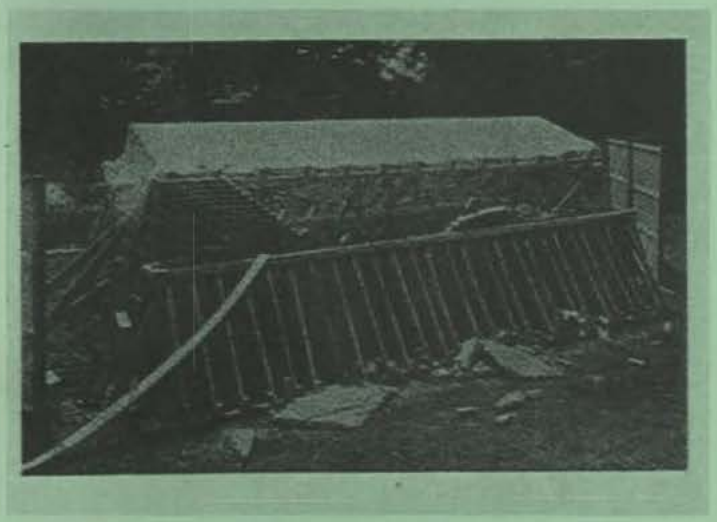

FLOOD PROOFING TESTS

[redacted]

Tests of Materials and Systems for Flood Proofing Structures

August 1988

US Army Corps of Engineers

Flood Proofing

NATIONAL FLOOD PROOFING COMMITTEE

Report Documentation Page

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14. ABSTRACT

This report presents test results which describe materials and systems that can be used to protect buildings from floodwaters. Each year flooding causes more property damage in the United States than any other natural disaster. High flood damage costs to property have produced an awareness that nonstructural methods should be developed to augment flood protection provided by dams, levees, and similar structures. Because of the frequency and extent of flooding, strong initiatives to protect buildings from repetitive flood damage losses will provide' a quick return on investment. The structural integrity of a building must be known or the building may be flood proofed to an extent that it will be excessively loaded and damaged or collapsed. It was determined by model and prototype tests that brick-veneer and concrete-block walls can withstand only approximately 3 ft of static waterhead without damage. If a building or home is loaded to excessive depths, it can fail instantaneously and possibly result in injury or death to occupants. Closures, materials, and systems were tested to determine the effectiveness in protecting homes or buildings from floodwaters. The following conclusions were derived from the tests ??? A watertight closure must have gasket material at its connection to the sidewalls and bottom and must be bolted. The connections for the closure at the sidewalls and floor must be continuous and sealed securely to the walls and the floor. ??? Water will flow freely through a brick wall and along the space at any water barrier between thicknesses of brick. ??? Two layers of brick will allow a brick wall to support greater water depths. ??? A brick or concrete-block wall can be protected against water flowing through it excessively by using a thick coating with body. This type of coating must be applied with great care or the wall will not be leakproof. ??? Clear liquid coatings, even when low head pressures are present, will not stop water from penetrating a brick-veneer or concrete-block wall. ??? Epoxy, polyurethane, and asphalt coatings were not dependable in keeping water from penetrating a brick-veneer or concrete-block wall. ??? Some cementitious coatings will stop the penetration of water (under head pressure) through a brick-veneer or concrete-block wall, but many of these coatings are not durable. Two coatings were tested which were durable and di4 stop the penetration of ~ater through a brick wall. Coatings which can be pai~tedon.are less expensive to apply and are as effective as any trowled-on coating. ??? Systems tests demonstrated that a simple continuous system is the most reliable with snap connections being less reliable. A simple system which is adequate to protect a building from floodwaters is given in this report.

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Prepared by

Structures Laboratory
US Army Engineer Waterways Experiment Station

for

Corps of Engineers
National Flood Proofing Committee

FLOOD PROOFING TESTS

TESTS OF MATERIALS AND SYSTEMS

FOR FLOOD PROOFING STRUCTURES

KEY

Manufacturer	Symbol	Product
Tamms Industries Co. Itasca, Ill.	Coating 1	Chemstop
Reintjos Waterproofing Co. Kansas City, Mo.	Coating 2	Sealcrete
E. A. Thompson, Inc. San Francisco, Calif.	Coating 3	Thompson Water Seal
US Waterproofing, Inc. Old Greenwich, Conn.	Coating 4	Five Star Waterproofing
US Army Engineer Waterways Experiment Station Vicksburg, Miss.	Coating 5	Acrylic Polymer and cement
XYPEX Chemical (Canada) Limited Richmond, B.C., Canada	Coating 6	XYPEX
Lee Waterproofing Products, Inc. Jonesboro, Ark.	Coating 7	NALLOX
HEY'DI American Corp. Virginia Beach, Va.	Coating 8	HEY'DI American Corporation Product
Dural International Corporation Deer Park, N. Y.	Coating 9	DURAL (two-part penetrating epoxy)
Dural International Corporation Deer Park, N. Y.	Coating 10	DURACRETE (100% solids epoxy)
Sears Roebuck Chicago, Ill.	Coating 11	Sears Polyurethane Coating
Other manufacturers	Coating 12	Asphalt

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report presents test results which describe materials and systems that can be used to protect buildings from floodwaters. Each year flooding causes more property damage in the United States than any other natural disaster. High flood damage costs to property have produced an awareness that nonstructural methods should be developed to augment flood protection provided by dams, levees, and similar structures. Because of the frequency and extent of flooding, strong initiatives to protect buildings from repetitive flood damage losses will provide a quick return on investment.

The structural integrity of a building must be known or the building may be flood proofed to an extent that it will be excessively loaded and damaged or collapsed. It was determined by model and prototype tests that brick-veneer and concrete-block walls can withstand only approximately 3 ft of static waterhead without damage. If a building or home is

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18. SUBJECT TERMS (Continued).

Brick-veneer walls	Flood damage	Permeability
Buildings	Flood-resistant systems	Prototype tests
Coatings	Flood-resistant testing	Restraints
Concrete-block walls	Hydrostatic water pressure	Seepage
Finite element analysis	Impermeable materials	Wall damage

19. ABSTRACT (Continued).

loaded to excessive depths, it can fail instantaneously and possibly result in injury or death to occupants.

Closures, materials, and systems were tested to determine the effectiveness in protecting homes or buildings from floodwaters. The following conclusions were derived from the tests:

- A watertight closure must have gasket material at its connection to the sidewalls and bottom and must be bolted. The connections for the closure at the sidewalls and floor must be continuous and sealed securely to the walls and the floor.
- Water will flow freely through a brick wall and along the space at any water barrier between thicknesses of brick.
- Two layers of brick will allow a brick wall to support greater water depths.
- A brick or concrete-block wall can be protected against water flowing through it excessively by using a thick coating with body. This type of coating must be applied with great care or the wall will not be leakproof.
- Clear liquid coatings, even when low head pressures are present, will not stop water from penetrating a brick-veneer or concrete-block wall.
- Epoxy, polyurethane, and asphalt coatings were not dependable in keeping water from penetrating a brick-veneer or concrete-block wall.
- Some cementitious coatings will stop the penetration of water (under head pressure) through a brick-veneer or concrete-block wall, but many of these coatings are not durable. Two coatings were tested which were durable and did stop the penetration of water through a brick wall. Coatings which can be painted on are less expensive to apply and are as effective as any trowled-on coating.
- Systems tests demonstrated that a simple continuous system is the most reliable, with snap connections being less reliable. A simple system which is adequate to protect a building from floodwaters is given in this report.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report may be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
gallons (US liquid)	3.785412	litres
inches	25.4	millimetres
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals

FLOOD PROOFING TESTS

TESTS OF MATERIALS AND SYSTEMS FOR FLOOD PROOFING STRUCTURES

PART I: INTRODUCTION

Purpose

This report presents results of studies concerning the structural integrity and the flood protection of homes and buildings. Since many such structures are built with brick-veneer and concrete-block exteriors, the experimental tests in this report deal with the treatment of brick-veneer and concrete-block walls.

Background

Each year flooding causes more property damage in the United States than any other natural disaster. Annually, flood damages average over $3 billion. In 1985 the estimated flood damage was $6 billion and affected over 250,000 structures. Average flood damage for a home is approximately $20,000 per flood and is much higher for industrial buildings. Flooding is not only expensive to the homeowner and the taxpayer, but also causes despair and worry for its victims. Effective flood protection and preventive measures can significantly reduce the expense and trauma caused by flooding.

District offices of the US Army Corps of Engineers provide, through Flood Plain Management services, information to the public regarding potential flood hazards and proper flood plain management. This includes dissemination of information on flood proofing systems, materials, and techniques. These same offices are responsible for the planning, design, and construction of flood control projects which are authorized by Congress.

Despite the construction of flood control projects and the development of public programs to reduce flood losses, flood damage to homes and other buildings in the United States has increased dramatically (Figure 1 is an example of a flooded home). The growing exposure of structures to flooding is largely due to rising land costs and a reduction in the quantity of available land for building, thus resulting in an encroachment on flood plains.

Because flooding occurs with certain frequencies, a cost-effective method

of flood proofing* buildings will eliminate these repetitive costs and provide a quick return on investment.

Excessive flood damage costs to property have produced an awareness that nonstructural methods should be developed to augment flood protection provided by dams, levees, and similar structures. In the past, nonstructural methods of flood protection have been considered but not actively studied.

Because homeowners and other members of society do not have ready access to expert guidance for protecting their homes and buildings from floods, many individual and contractor attempts at flood protection have been inadequate. Building owners need expert flood protection advice because they are usually exasperated (especially after experiencing repeated flood losses) and are willing to attempt almost anything to protect their homes. Technology developed for flood protection should be transferred from wherever developed to other Government agencies and on to the private sector. This report is part of a continuing effort to transfer such technology.

Feasible techniques to repeatedly protect buildings from floodwaters include:

- Raising and safely supporting buildings above the floodwaters.
- Moving buildings out of the flood plain.
- Using structures such as floodwalls to protect buildings from floodwaters.
- Using systems and materials to protect buildings from floodwaters.

This report concentrates on systems and materials to protect buildings from floodwaters.

The ability of a structure to withstand flooding must be understood to allow for the correct emphasis on flood protection and on remedial measures for inadequate construction before actual flood protection can begin. In many cases unless the structure is made adequate, more damage can occur to the flood protected building than would have occurred to it without flood protection.

Water is very difficult to contain; therefore, materials and methods for

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* Flood Proofing, as used in protecting buildings from floodwaters and as used in this report, does not imply absolute impermeability against moisture vapor or moisture. It suggests a negligible amount of moisture vapor or moisture penetration from floodwaters in relation to damages to homes or buildings.

preventing the flow of water into homes should not be selected only on the basis of being logical systems which appear to perform satisfactorily, but should be tested and used only after proven performance.

With today's technology, a mixture of governmental incentives, innovative developments, feasible flood protection methods, information development, and a strong network of technology transfer about nonstructural flood proofing methods to the public can significantly reduce flood damage.

Scope

Test results of systems, methods, and materials for the flood protection of buildings and homes are presented as a summary of three previous reports.*,**,†

The key findings of these reports, updated with flood protection systems and materials, deal with these items:

- Structural resistance of brick-veneer and concrete-block test wall subjected to hydrostatic water loading.
- Requirements and effectiveness of closures in reducing water entry through openings in a building.
- Structural integrity of brick and block-wall buildings as it relates to flood protection.
- Effectiveness of systems and materials in protecting buildings from floodwaters.
- Model tests and results.
- Prototype test and results.

Figure 2 shows relationships of the topics presented.

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* C. E. Pace. May 1978. "Tests of Brick-Veneer Walls and Closures for Resistance to Floodwaters," Miscellaneous Paper C-78-16, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

** C. E. Pace and R. L. Campbell. 1978. "Structural Integrity of Brick-Veneer Buildings," Technical Report C-78-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

† C. E. Pace. May 1985. "Systems and Materials to Prevent Floodwaters from Entering Building," Miscellaneous Paper SL-85-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Figure 1. Example of a flooded home

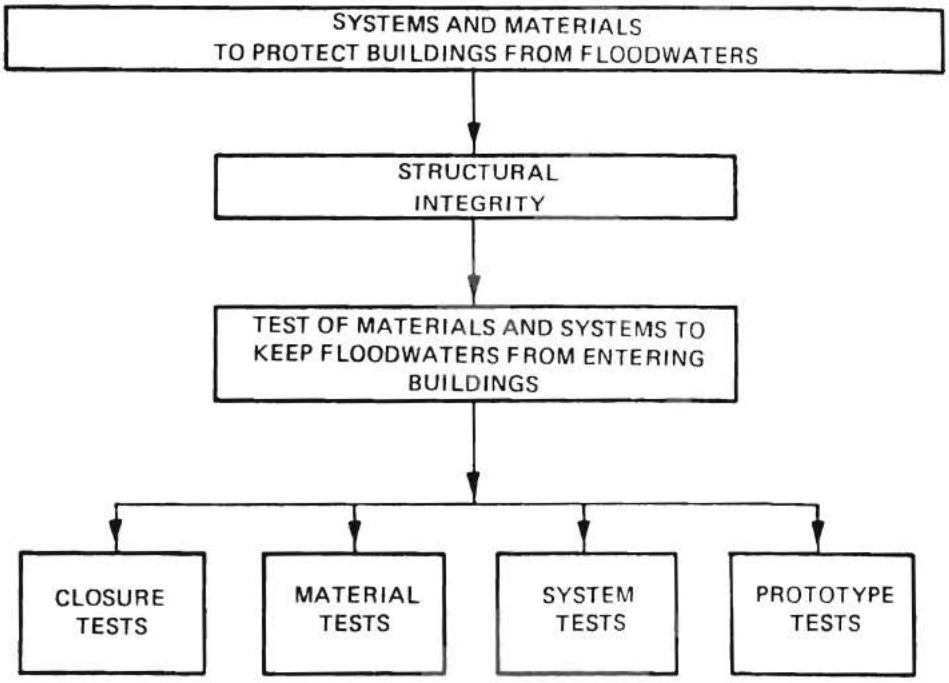

Figure 2. Flowchart presenting flood proofing report contents

PART II: STRUCTURAL INTEGRITY OF BRICK-VENEER AND CONCRETE-BLOCK WALL BUILDINGS

The evaluation of the structural integrity of brick-veneer and concrete-block wall buildings is important in the study of systems to protect buildings from floodwaters. It is better to allow water to enter a building than to subject it to water loads which will structurally damage or collapse the walls. Flooded buildings may be reusable once they have been cleaned and the water damages repaired. Thus, before an attempt is made to make buildings flood resistant, the flood risk must be carefully evaluated and a flood-resistant design level established.

The height of water loads that a building can safely support must be known to make a decision about the acceptable method of flood protection. For example, a membrane system has no supporting capacity and cannot be used where the floodwater heights exceed the safe loading for the building.

The phenomenon of how the buildings support the water loads is important in examining the weakest link in flood proofed construction and in considering building modifications.

There are many variables affecting the response of a brick-veneer and block wall; therefore, the approach used here was to obtain experimental data by testing three brick-veneer and two block walls, analyze these data, perform analytical computations, and compare them to the experimental data, then draw conclusions.

Brick-Veneer Wall Tests

Of the three brick-veneer walls built for testing, Wall 1 (Figure 3) was a typical end wall of a home. In supporting loads, this wall is most critical because the top plate has no roof rafter and ceiling joist restraints to transfer resistance through the wall ties to the brick-veneer wall. Wall 2 and Wall 3 differed from Wall 1 as follows:

- Wall 2 had a 3-ft* door in its center (Figure 4).
- Wall 3 had roof rafter and ceiling joist restraints (Figure 5).

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* A table of factors for converting non-SI to SI (metric) units of measurement is presented on page 2.

The walls were built to represent those which exist in typical home construction (Figure 6). Walls were 8 ft high by 26 ft long.

In the prototype situation, floodwaters would be on all sides of the house. If the house is sealed from water penetration, the forces against opposite walls are the same (forces caused by debris and the flow of water are neglected) and cause no lateral deflection of roof rafters at the intersection of the gable. In a like manner, there would be small deflections of the ends of the walls with movements due only to structural deformations. To simulate the real situation, stub walls (Figure 3) were constructed at 90 deg to the wall which was to be loaded. To represent the effect of the perpendicular wall framing, the end studs were braced so they would be restrained perpendicularly to the wall being tested.

The stud framing, wallboard, and wall clips as constructed for Wall 1 are shown in Figure 6. The wall clips were spaced 32 in. on centers in the horizontal direction (on every other stud) and between every fifth layer of brick in the vertical direction for all three walls.

The walls were tested by a horizontal water load which was contained by a trough and plastic liner (Figure 7). The water depth in front of the wall was increased at about 1 to 2 ft/hr. As the water depth increased, deflections of the walls were monitored. Gages were arranged in horizontal and vertical lines to give the variations of wall deflection in cross sections.

Experimental results, Wall 1

The water depth was increased at the front of the wall at a rate of about 1 to 2 ft/hr; thereby, loading the brick-veneer wall with horizontal pressure. As the horizontal load increased, the gages were monitored and the deflected shape of the wall was measured.

The deflection at any specific point on the wall, as indicated by individual gages, followed a smooth variation (Figure 8). After the water reached a 2-ft level, the wall deflection increased drastically for small increases in water depth. The wall began to react plastically and deflect large amounts for small increases in water load. Wall failure occurred for sustained loading when the water depth was approximately 2.4 ft. Without the roof rafter and ceiling joist restraints, the stud wall provided insignificant restraint and the wall could continue to deflect and fail.

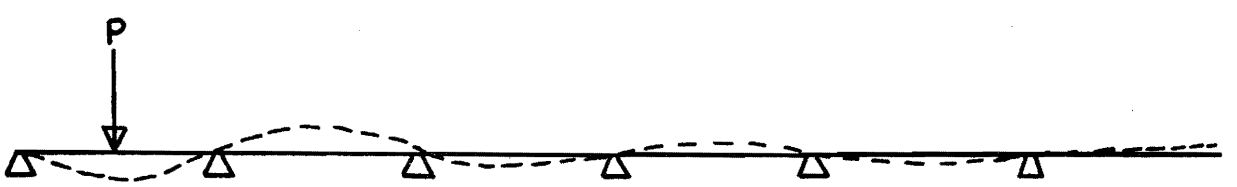
In general, much of the upper part of the wall deflected forward or toward the load for water depths no greater than 1 ft, an unexpected and

seemingly illogical response. As the water increased to depths greater than 1 ft, the entire wall began to move backward. The gages show forward wall movement during low water loads because:

- The wall at the locations of water pressure deflected away from the loading. This caused differential lenghts in those areas to be lengthened. The lengthening tended to pull the higher portions of the wall, causing the wall to cup forward toward the water loading.
- The wall began pivoting about the lower line of horizontal wall tie restraints. The lower wall ties had greater restraint than the higher ties because they were closest to the base of the studs. This caused the top part of the wall to pivot forward.

Gages below the first line of wall ties generally showed wall deflections away from the water loading, while gages located higher on the wall showed deflections toward the loading until the water depth was about 1 ft. After a water depth of 1 ft, the higher portions of the wall began to deflect back as did the entire wall. This is as one would expect because finally the water loading will dominate and the wall will be pushed in the direction of the load and even the oscillation in the wall will be superimposed only on the backward movement of the wall. While considering the wall tie restraints, an important response of the wall is illustrated; the wall oscillates between the wall ties.

These oscillations depend upon the amount of mortar caught on the ties and upon the tie locations. The deflections are similar to the deflections of a continuous beam which is loaded only in certain spans. Deflection of the beam shown in sketch below is loaded with a one-point load. There is a tendency for the beam to deflect as shown in sketch.



The wall deflections were minimal prior to a loading of approximately 2 ft of water, after which relatively large deflection increases occurred for very small load increases.

It is important to realize that the deflections of the wall, even for the maximum deflection presented, are very small. The wall deflections at 4 ft of water loading were in the range where careful observance was necessary to note

even a slight deflection (Figure 9). This means that the wall itself was seriously damaged at relatively small deflections. To be conservative, the wall deflection should be kept below approximately 0.01 in. in the direction of the water loading. The deflection of the wall is mentioned because it is probably a more reliable guide for general wall configurations than the water depth. For example, the same water depth might produce less deflection or damage on a short wall than on a longer wall. Similar damage would more than likely occur around the same wall deflection than the same water depth. If the wall deflects more than 0.01 in., there is damage and a chance that it will not support service loads or vibrations during normal operation. The deflection criteria will be practicable only after further study and failure charts are developed by computer solutions.

A severe loss of integrity began at 2 ft of water with complete loss occurring at 2.4 ft (Figure 8). The failure at 2.4 ft of water is presented in Figures 10 and 11.

Prototype tests performed on complete residential structures have now shown that 2 ft of water depth is conservative and a brick-veneer house can withstand approximately 3 ft of water loading. Wall damage will occur if loaded in excess of 3 ft, and this will be discussed in more detail in Part VI.

Experimental Results, Wall 2

As the water depth increased, the gages were monitored and the deflected shape of the wall was measured. A typical plot of water depth versus wall deflection is shown in Figure 12.

In general, the vertical sections of gage measurements showed progressively more deflection with an increase in wall height as the water loading increased. This was true for both forward (toward water loading) and backward (away from water loading) wall deflections.

The bottom and side restraints had less effect on the forward deflection of Wall 2 than for Wall 1 because of the door in the center of Wall 2.

The wall failed during the initial loading, but much of the initial deflection was recovered after the water load was removed. Some of the gages were replaced against the wall and it was reloaded. The forward deflection during reloading was less than during the initial loading, but the failure of the wall was at a lower water depth (approximately 2 ft). The results of testing indicated the following:

- In general, the wall deflected forward for low water loads, then backward, as the water depth became greater than 0.8 to 1.6 ft.
- The wall deflections were very small (thousandth of an inch in magnitude) until 2 to 2.4 ft of water loading at which time the wall began to deflect drastically backward for small increases in water depth.
- Wall 2 (with door opening) deflected more forward but approximately the same backward as Wall 1. The result was that the backward deflection caused failure of the wall at about the same load as for Wall 1. The lintel strengthened the wall at the door opening, thereby causing the opening to have little effect on the final response of the wall.

The wall deflected forward for low water loads because cord lengthening in the vicinity of the loading caused the upper part of the wall to cup forward. In an actual home, the finishing materials on the inside of the studs will give support to the wall and allow it to experience a deeper water loading than indicated by these tests. Computer solutions could be used to determine the effect of such restraints. The significant point is that the deflections recorded for Wall 2 at a given water depth should be an upper bound of deflections experienced in an actual brick-veneer house under the same loading. The failure of Wall 2 is shown in Figures 13 and 14.

Experimental Results, Wall 3

Wall deflections were comparatively less in Walls 2 and 3 than in Wall 1 under compressive loading because of the omission of wallboard in Walls 2 and 3. The wallboard is normally attached to the outside face of the stud framing, and the ties are attached to the outside face of the wallboard. This wallboard is more compressive than its supporting studs and its omission should result in less deflection. The purpose of omitting the wallboard from Wall 3 was to observe wall response and crack development along the backside of the brick-veneer wall.

Tie restraints should also vary between walls for the same loading because the amount of mortar at each tie location is randomly varied due to varying amounts catching on ties during construction. The data generated by this investigation are insufficient for determining the exact effects of such variables in relation to wall response. Such determinations can be best resolved through the use of computer code programs. Computer program solutions can also be used to delineate the significance of other variables such as wall length, boundary restraints, and material properties.

Wall 3 with its ceiling joist and roof rafter restraints represents the side or similarly braced wall in a brick-veneer dwelling. Typical plots

of water depth versus brick wall deflection for Wall 3 are presented in Figure 15. Because of the ceiling joist and roof rafter restraints, the negative movement along the top of the wall was less pronounced than that of Wall 2.

For deflections of water depths greater than 1.5 ft, the wall began to deflect drastically away from the applied loading for small increases in water depth. At a 2-ft water depth, all deflections of the brick-veneer wall were positive or away from the water loading.

The movement of portions of the support components of the brick-veneer wall toward the applied loading was the result of the cord lengthening in the brick wall, as previously discussed. This action was generally dominant over relative movement of the total wall away from the applied hydrostatic loading for water depths of 1.75 ft and below. For water depths greater than 1.75 ft the relative movement of the total wall dominated.

Total collapse of the brick-veneer wall occurred at a depth of 57 in. and at a total applied force of 18,300 lb. This failure was sudden and resulted from the failure of the supporting studs. The remains of the brick-veneer wall after failure are presented in Figures 16 and 17.

Results from the testing of Wall 3 indicated the following:

- In general, the roof rafter and ceiling joist restraints decrease the movement of the wall toward the water loading.
- The roof rafter and ceiling joist restraints are sufficient to cause a change in the failure mechanism from that which was experienced in Walls 1 and 2. The failure mechanism for Walls 1 and 2 was deflection and failure of the brick wall, while the failure mechanism for Wall 3 was beam failure of the studs and a resulting collapse of the brick wall.
- The deflection of the brick wall began to increase rapidly with water depth after about 1-1/2 ft, but the increase is not as great as was experienced for Walls 1 and 2. This is indicated by the fact that the wall did not collapse until approximately 57 in. of water loading.
- Even though the wall can withstand greater water depths, it fails suddenly and totally when the stud wall fails.

Concrete-Block Wall Tests

Since many homes and buildings are constructed of concrete-blocks, it was decided that two concrete-block wall tests should be constructed and tested to determine structural integrity and to evaluate some of the materials and systems for preventing the penetration of floodwaters through such walls.

Normal construction procedures for concrete-block wall construction were followed. Deflection gages (linear variable differential transducers, or LVDT's) were installed against each of the two block walls to measure the deflection of the walls. An independent bracing system was constructed at the back of the wall to support the LVDT gages.

Block Wall 1, before and after the testing, is shown in Figure 18. The front of the first wall was plastered, and a bulkhead was constructed in front of it to contain water to be supplied from a fire hydrant. The second block wall is shown in Figure 19. Block Wall 2 was used to test several flood protection systems.

Experimental tests

Typical deflection data for Block Wall 1 are presented in Figure 20. As the water level was raised against the surfaced wall, the plaster was weakened and was penetrated by the water; thereby reducing its effectiveness in strengthening the wall against deflection. At a water depth of 3-1/2 ft the block wall was cracked and leaking so badly that the trough could not be kept filled with water from a fire hose connected to the fire hydrant. Water flowed through the cracks faster than it could be put into the trough. Photographs of the leakage are shown in Figure 21.

The first test performed on Block Wall 2 was to partially fill (approximately 1-1/2 ft) the trough to determine the leakage through the block wall (not treated or protected in any way). The leakage through the wall was severe and the test was stopped.

The second test evaluated vinyl sheeting attached with a tubular seal and also determined the deflection shape of the wall. The third test on Block Wall 2 was to again test the effectiveness of the tubular seal. The test results of the tubular seal and vinyl sheeting are presented in Part III.

Results

The safe waterhead on the block test walls is approximately the same as that for a brick-veneer test wall; i.e., approximately 2 ft. By comparison, a home has more wall support and can withstand about 3 ft of waterhead.

Analytical Computations

Planning of analytical computations

The analytical approach was to determine the feasibility of using the

finite element method to model and analyze walls of buildings and to determine safe water loads. Analytical studies can be performed more quickly and less expensively than an experimental study, and factors such as building strength or house modifications can be analyzed.

In the analytical study, the solutions for the deformations of the experimental wall as tested can be obtained by the finite element method. The material properties, geometry, boundary conditions, and loading had to be known to model and get the solution for the brick walls. Plate elements can be used to model the brick wall if the material properties (modulus of elasticity (E), shear modulus (G), and Poisson's ratio (μ)) are known. After the analytical solution was obtained, the experimental results were used to compare and evaluate the analytical method.

In the determination of material properties, it was concluded that tests on brick or mortar individually would not give the needed properties because the wall was made of a composite of the two materials. Tests on sections of brick and mortar laid as in the walls were conducted to determine the composite properties. The E values were calculated and averaged; the average value obtained and used in the analytical computations was 5.7×10^6 psi. Shear tests were performed to give some indication of the shearing strength of the brick wall at the mortar joints. The shearing strength was approximately 10 psi.

From past experience, it was concluded that the finite element solution for the brick wall would not be very sensitive to Poisson's ratio and shear modulus; therefore, Poisson's ratio was estimated as 0.3 and G, then calculated from E and μ by the equation $G = E/[2(1 + \mu)]$. G was calculated to be 2.2×10^6 psi.

As the brick walls were constructed, samples of mortar were taken at the one-third, one-half, and two-thirds positions of construction. Specimens taken were eighteen 2-in. diam by 4-in. high and six 6-in. diam by 12-in. high cylinders. The 6- by 12-in. specimens were tested at 28 days and the average material properties for the mortar were as follows:

$f_c = 1{,}100$ psi

$E_v = 0.8 \times 10^6$ psi

$\mu = 0.11$

These values were obtained to document the characteristics of the mortar used in constructing the walls.

Aside from the material properties of the brick walls, there are three types of restraints to be considered:

- Wall clips.
- Roof rafter and ceiling joists.
- Connection of studs to base plate.

Walls 1 and 2 had only the wall clips and stud connections to baseplate restraints. Wall 3 had the additional restraints of roof rafters and ceiling joists.

First, consider the restraint of the roof rafter and ceiling joist at its connection to the top plate of the stud wall. The variables which can affect the strength of this restraint include:

- Kinds of lumber used.
- Way the connection is nailed.
- Slope of roof rafter.
- Amount of dead load on top of the roof rafter producing friction at the connection.

A test setup for roof rafter and ceiling joist restraints is presented in Figure 22.

The roof rafter slope and dead load made no noticeable difference in the strength of the roof rafter and ceiling joist restraint. The connection was nailed in the standard manner with reasonable positioning of nails into the member. Later, tests were conducted with nails driven for maximum penetration into the top plate as well as going through enough of the roof rafter and ceiling joist. Connections with nails placed for maximum penetration were slightly stronger, but as long as the nails were placed in a reasonable manner the difference in the strength of the restraint was slight. The pine lumber caused an increase in the slope of the load deflection curves (Figure 23). The maximum restraint of this connection using spruce was about 1,200 to 1,500 lb (Figure 24).

The restraint due to wall ties was determined. There are several types and thicknesses of wall ties (Figure 25) but the two most commonly used (22 and 28 gage) were tested. The test setup is presented in Figure 26. The clips have a wide variation in load deflection characteristics. In general, the 22-gage clips have a maximum strength of 100 to 200 lb (Figure 27a). The 28-gage clips have a maximum strength of about 40 to 60 lb (Figure 27b). The variation of the strength of the 28-gage clips is greater than that of the

22-gage clips. Mortar that collects on the wall tie is the main factor that affects the load transfer capacity. Figure 27c shows that the load transfer increases drastically if mortar has caught on the wall clip between the studs and the brick wall. The load transfer, because of mortar, may be at least as high as 750 lb. The amount of mortar on a clip varies from none to a considerable amount. At first, it seems that the individual load deflection curves must be known for a wide variation in wall clip and mortar restraint. Fortunately, this is not the case because, for reasonable water loads, the required load transfer is much lower than the maximum. In fact, it is within a range where the slope of all curves is very similar and one relationship will reasonably represent the load transfer relation.

The restraint of the stud connection to the baseplate is shown in Figure 28. The setup used in testing this connection is shown in Figure 29. The above knowledge of material properties and restraint conditions allowed a solution by the finite element method.

Analytical results

Since the wall tie restraints cannot be estimated, a comparison of experimental results (restrained by wall ties) and analytical results (without wall tie restraint) are presented in Figure 30. This comparison shows that analytical solutions are very promising. The deflections given by the analytical solution are somewhat greater than those from the experimental results, as would be expected. Since Wall 1 did not have roof rafters and ceiling joist restraints, the wall tie loads are not large relative to the water loading; therfore, the above comparison should be close.

Experimental Results

Flood proofing individual homes is an important aspect of the total solution of flood damage reduction. This part gives insight into the structural resistance of brick-veneer and concrete-block walls subjected to hydrostatic water loading. Useful information was obtained from the experimental data and the experimental results were used to validate the analytical method for brick-veneer Wall 1.

Brick-veneer Wall 1 was typical of the end wall of a house (no roof rafter or ceiling joist restraints). The deflections at specific points on the wall followed a smooth variation. After about 2 ft of water, the wall

deflections increased drastically for small increases in water depth. The wall had failed for sustained loading when the water depth was about 2.4 ft. The deflection of the wall is very small (on an order of magnitude of a thousandth of an inch) until the wall begins to fail. At this point, the deflection increases rapidly with water depth.

The analytical results for Wall 1 compare favorably with the experimental results.

Wall 2 was constructed identical to Wall 1 except with a 3-ft door opening in the center. The significant factors as indicated by the experimental results of Wall 2 are:

- In general, the wall deflected forward toward the water loading for low water loads then backward as the water depth became greater than 0.8 to 1.6 ft.
- The wall deflections were very small (thousandths of an inch) for depths up to 2 to 2.4 ft of water at which time the wall began to deflect drastically backward for small increases in water depth.
- Wall 2 (with door opening) deflected more forward but approximately the same backward as Wall 1. The backward deflection causing failure of the wall was about the same as for Wall 1. The lintel strengthened the wall at the door opening; thereby, causing the opening to have little effect on the final response of the wall.

Wall 3 was constructed identical to Wall 1 except it included roof rafter and ceiling joist restraints.

The significant findings from the experimental results of Wall 3 are:

- In general, the roof rafter and ceiling joist restraints decrease the movement of the wall toward the water loading.
- The roof rafter and ceiling joist restraints are sufficient to cause a change in the failure mechanism from that which was experienced in Walls 1 and 2. The failure mechanism for Walls 1 and 2 was deflection and failure of the brick wall. The failure mechanism for Wall 3 was beam failure of the studs and a resulting collapse of the brick wall.
- The deflection of the brick wall begins to increase rapidly with water depth after about 1-1/2 ft but the increase is not as great as was experienced for Walls 1 and 2. This is indicated by the fact that the wall did not collapse until approximately 57 in. of water loading had been attained.
- Even though the wall can withstand greater water depths than Walls 1 and 2, it fails suddenly and totally when the stud wall failed.

The structural integrity of the brick-veneer Walls 1 and 2 was completely lost at about 2-1/2 ft of water loading. The type restraint did cause a change in the total capacity of the wall to resist hydrostatic loading because

Wall 3 did not collapse until 57 in. of water loading was attained.

The safe waterhead on the concrete-block test walls is approximately the same as that for a brick-veneer test wall, about 2 ft.

The finishing on the inside of the studs will help strengthen the walls; however, no wave or debris loading was imposed on the walls in these tests. Prototype tests (discussed in Part VI) performed later demonstrated that the walls of a house are stronger than the test walls and can withstand about 3 ft of water head.

Modifications of the building can be designed to withstand water loads much higher than the safe water load for a particular building. The modifications to support water depths greater than 3 ft should mainly be in two areas:

- Support to the top plate of walls without roof rafter and ceiling joist restraints.
- Add thicknesses to the walls (extra layer of brick, brick planters, retaining walls, etc.) to an elevation somewhat above the expected height of floodwaters.

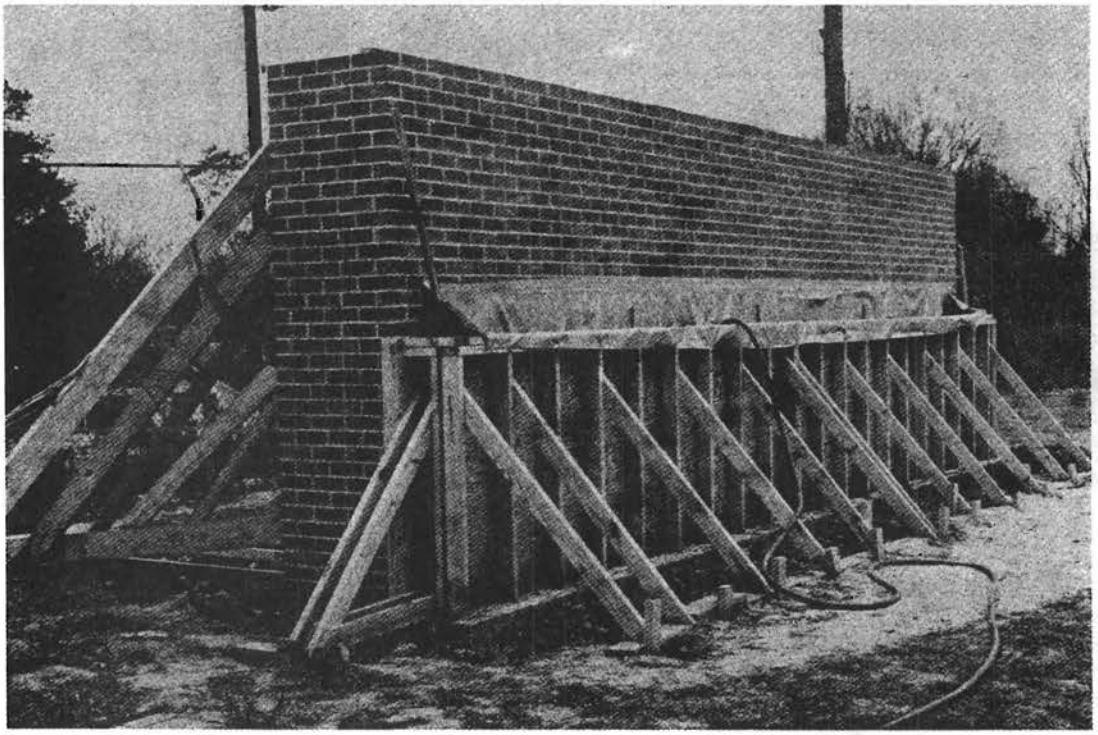


Figure 3. Overall view of Wall 1

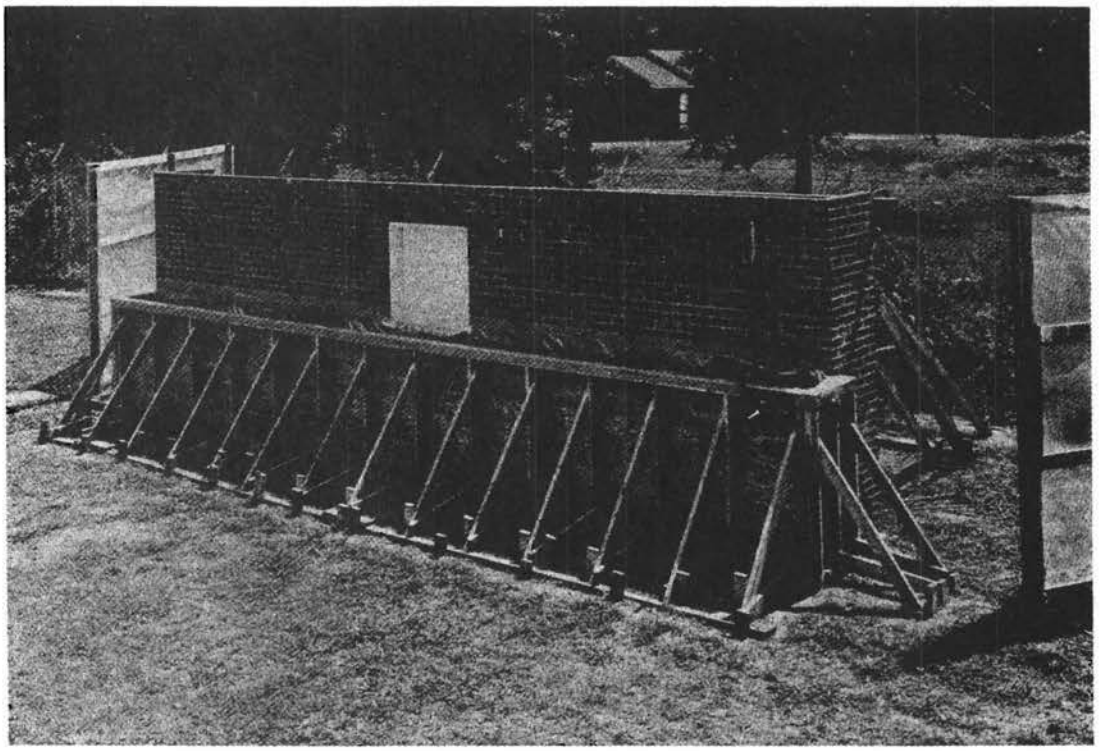


Figure 4. Overall view of Wall 2

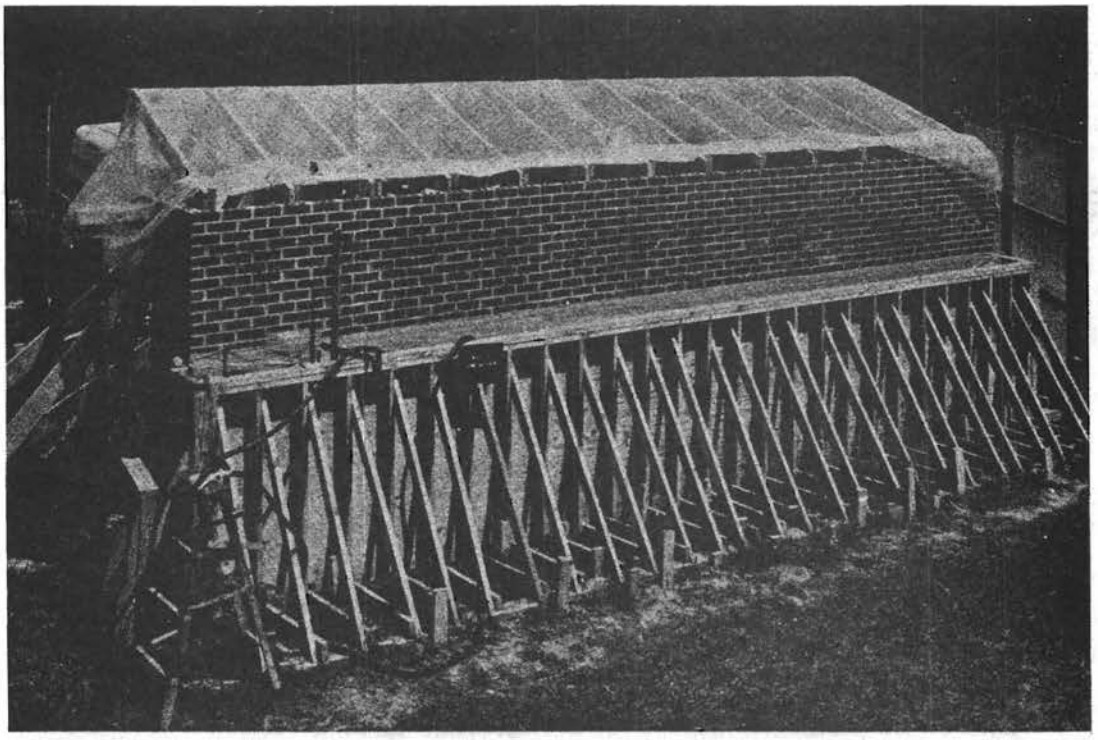


Figure 5. Overall view of Wall 3

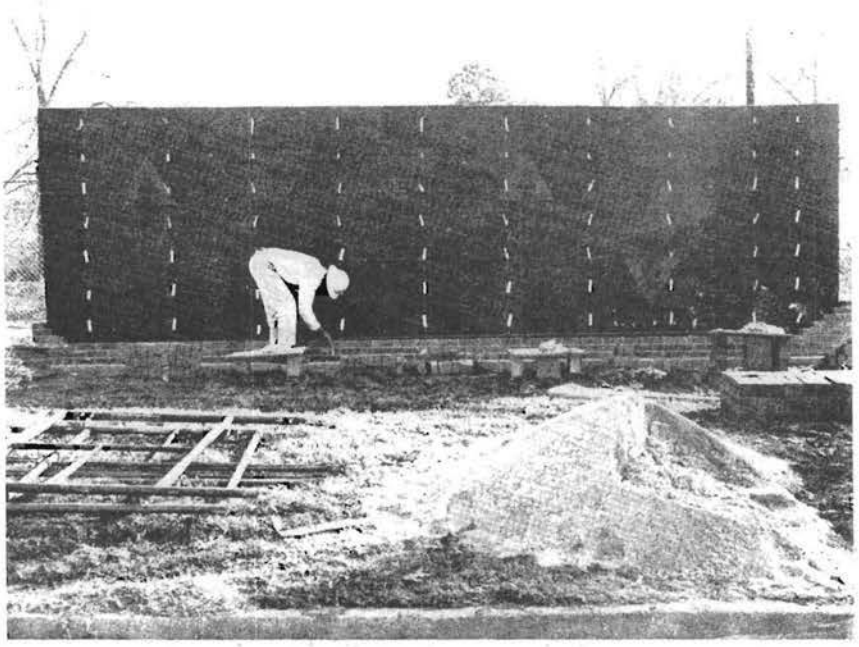


Figure 6. Stud wall, wallboard, and wall tie construction

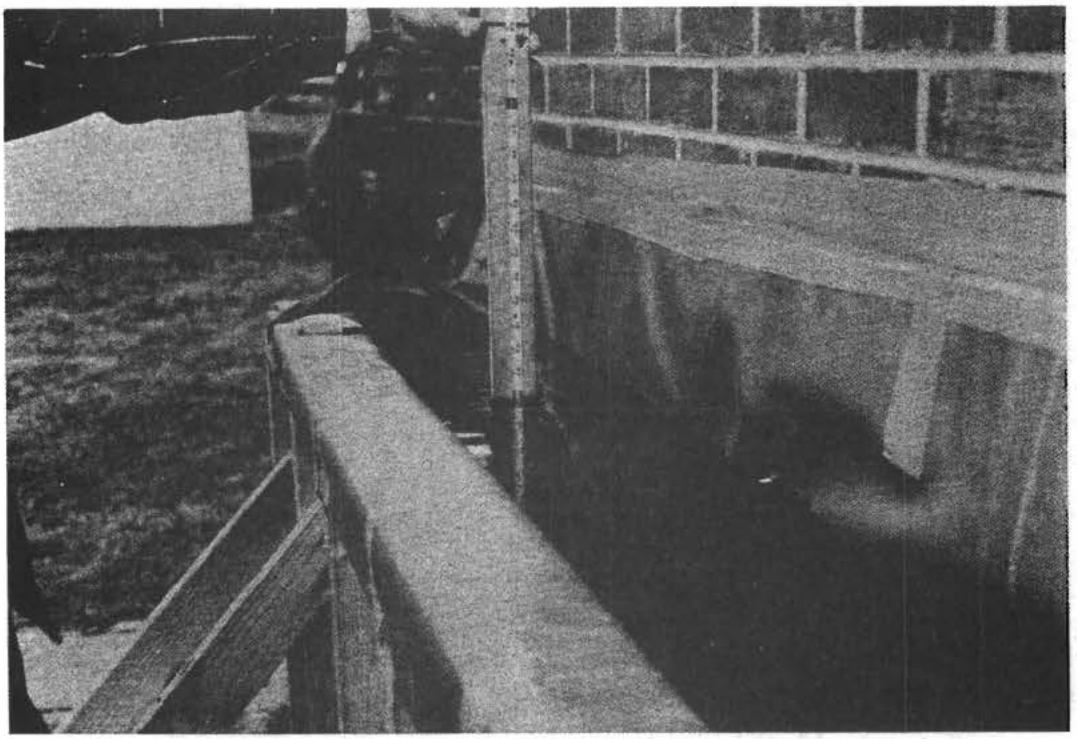


Figure 7. Trough and plastic liner containing water which causes hydrostatic pressure on the brick-veneer wall

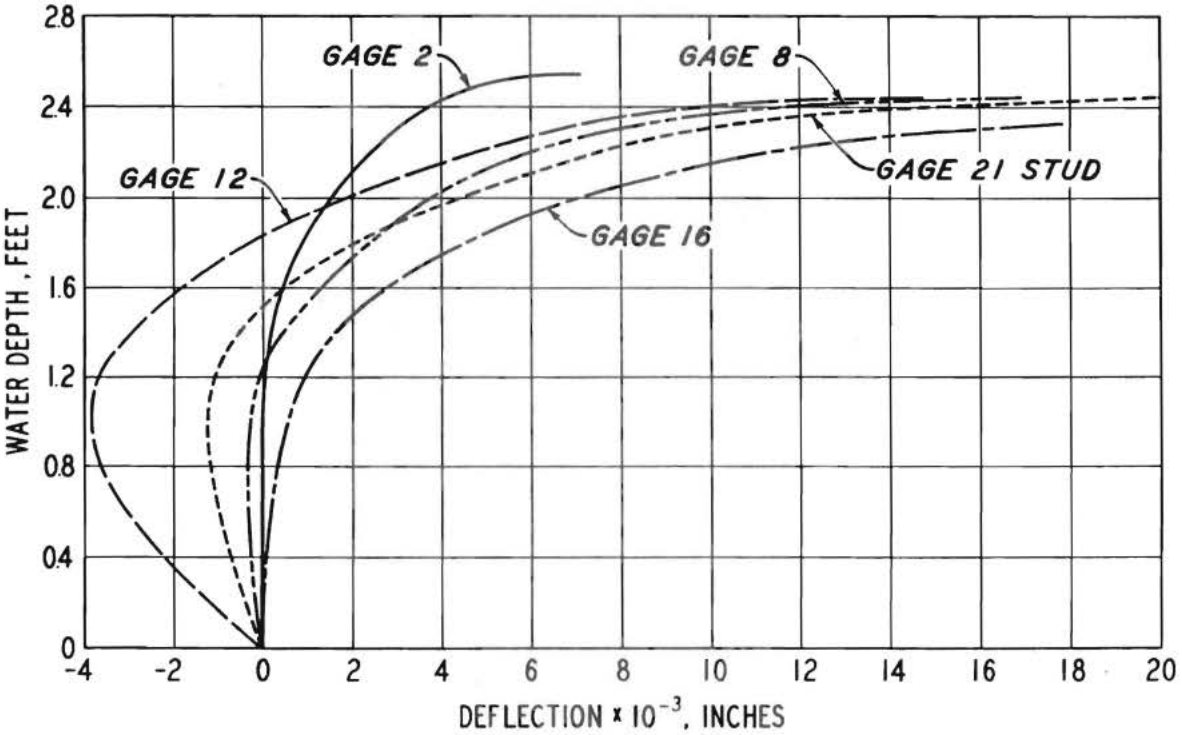


Figure 8. Wall 1. Brick-veneer wall and stud deflections, vertical gage line

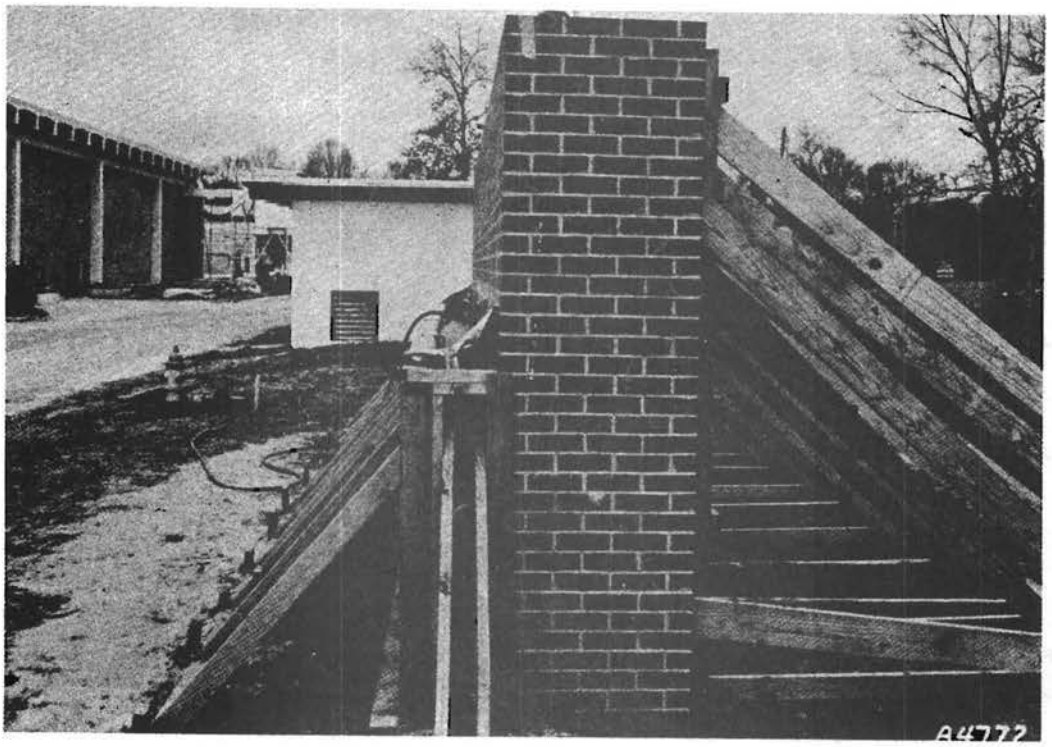


Figure 9. Wall 1. Wall deflection

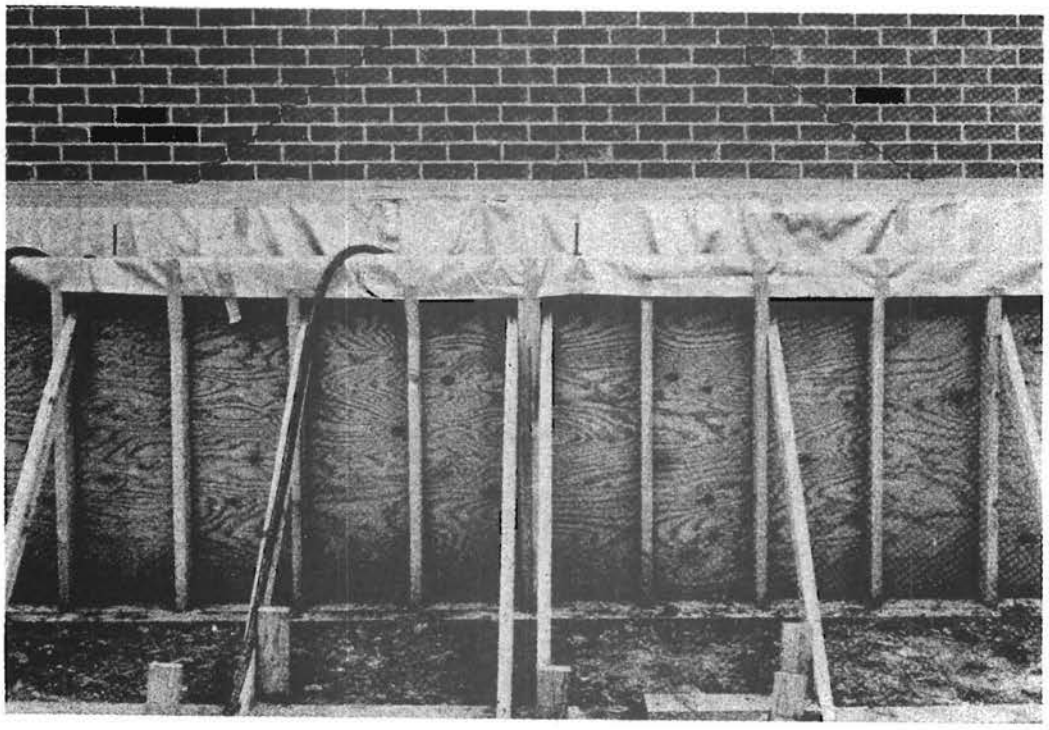


Figure 10. Wall 1. Failure pattern of wall

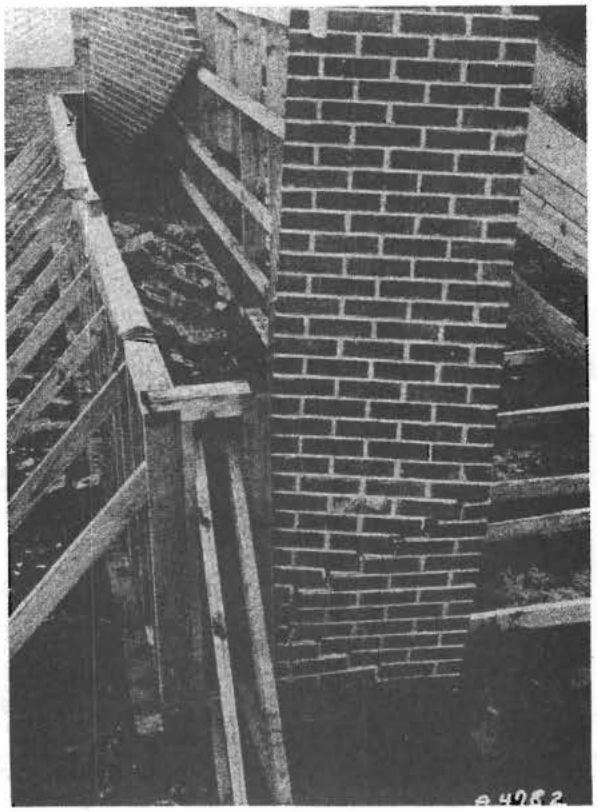


Figure 11. Wall 1. Wall failure

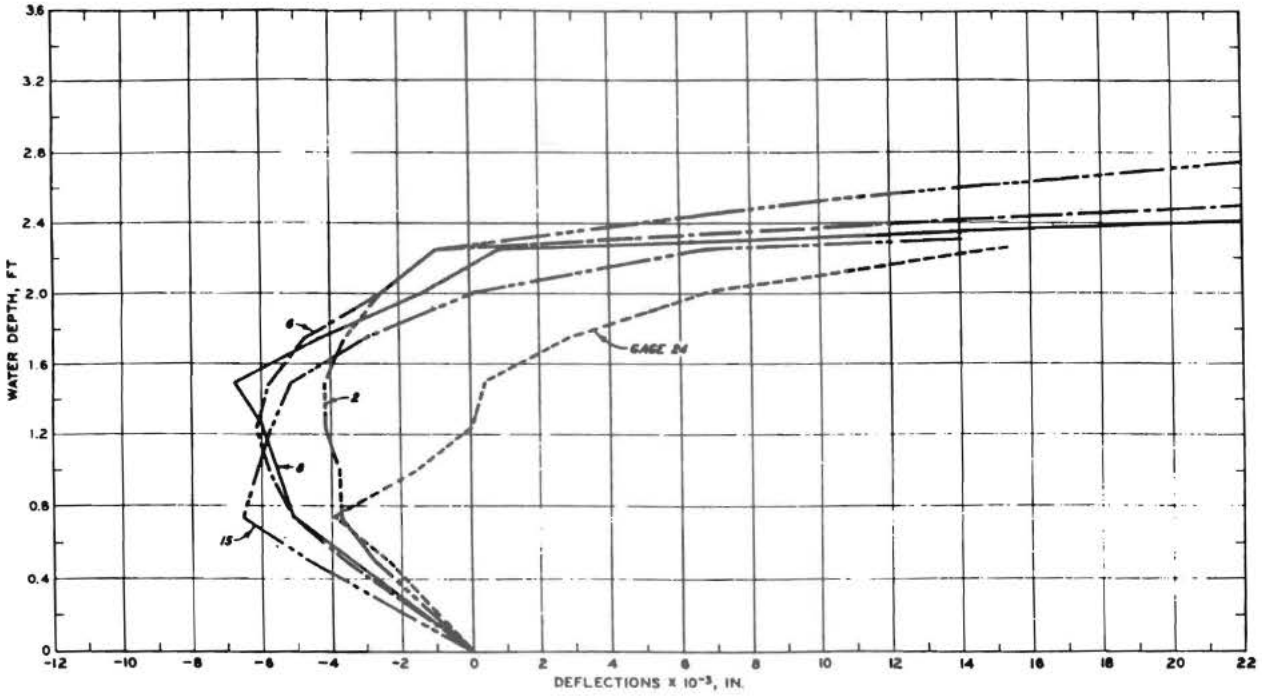


Figure 12. Wall 2. Brick-veneer wall deflections, vertical gage line, initial loading

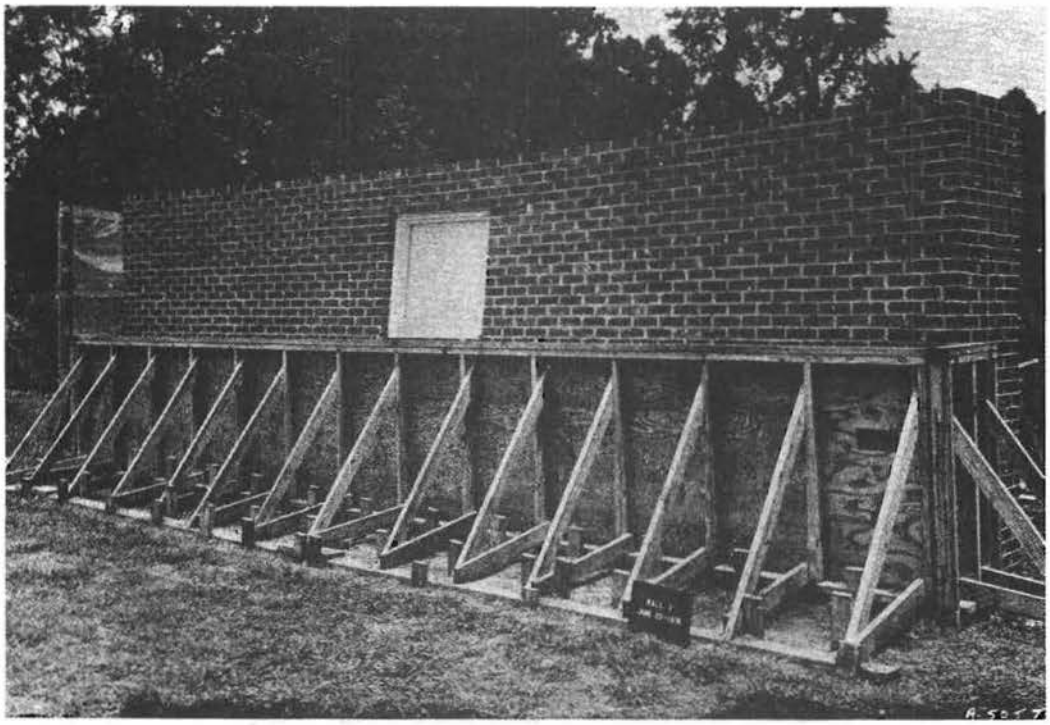


Figure 13. Wall 2. Wall failure, front view

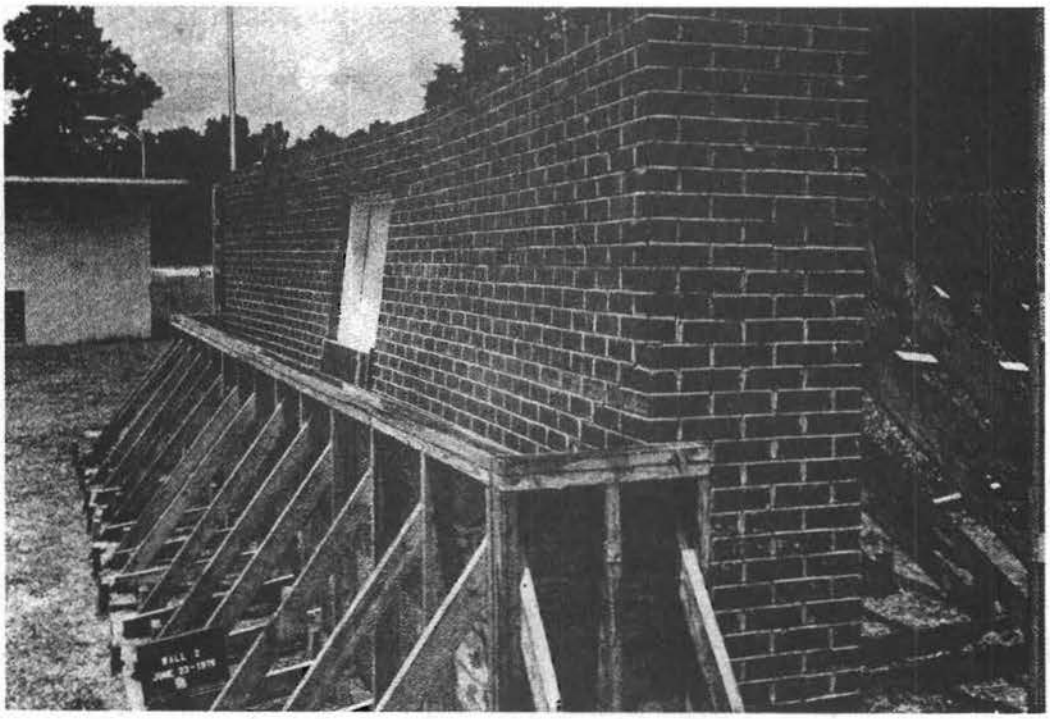


Figure 14. Wall 2. Wall failure, side view

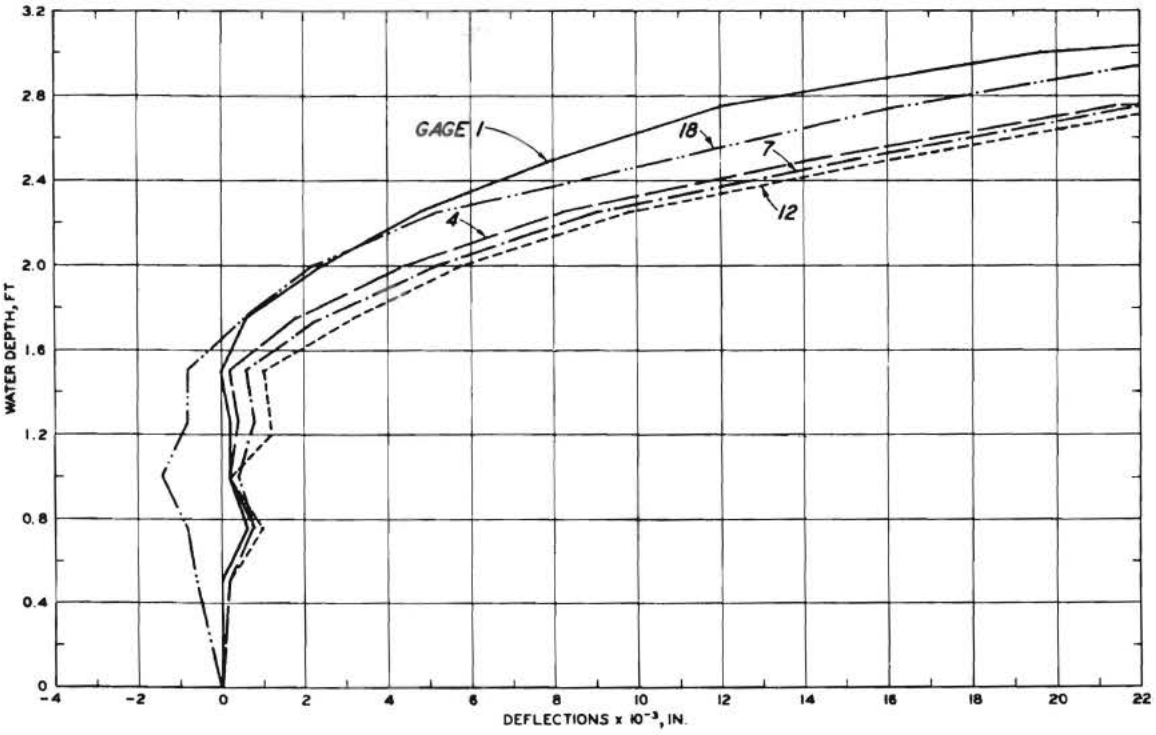


Figure 15. Wall 3. Brick-veneer wall deflection, vertical gage line

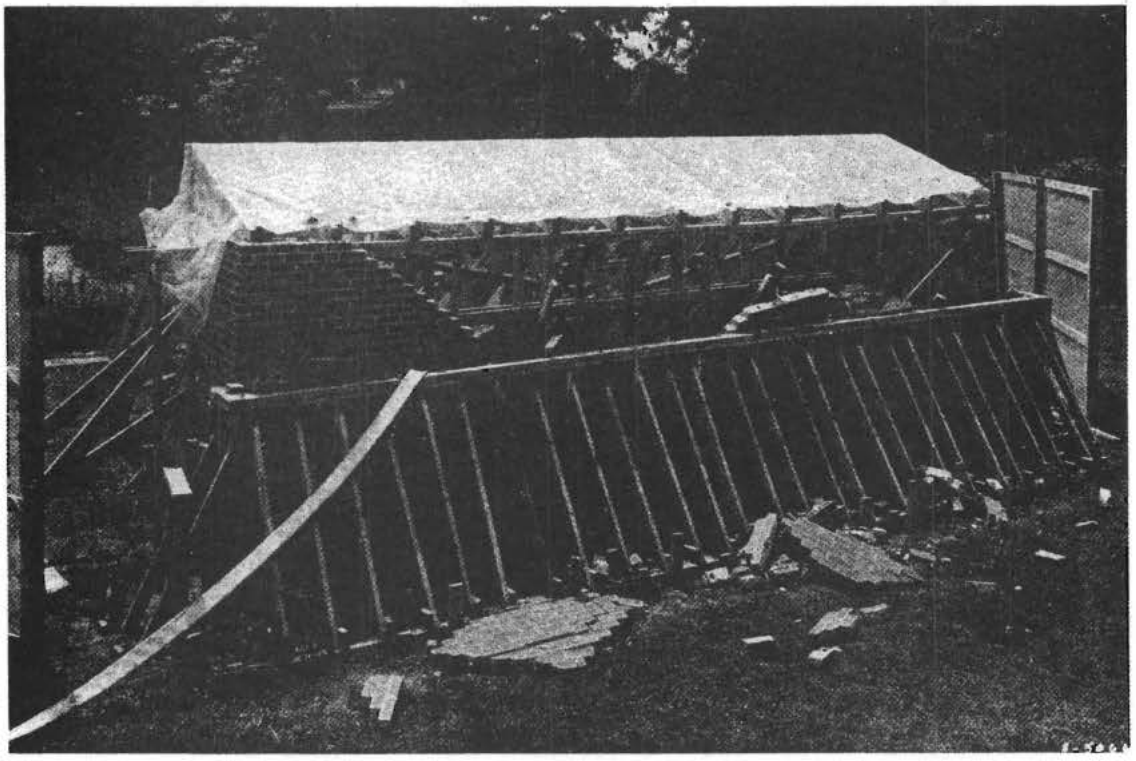


Figure 16. Wall 3. Wall failure, front view

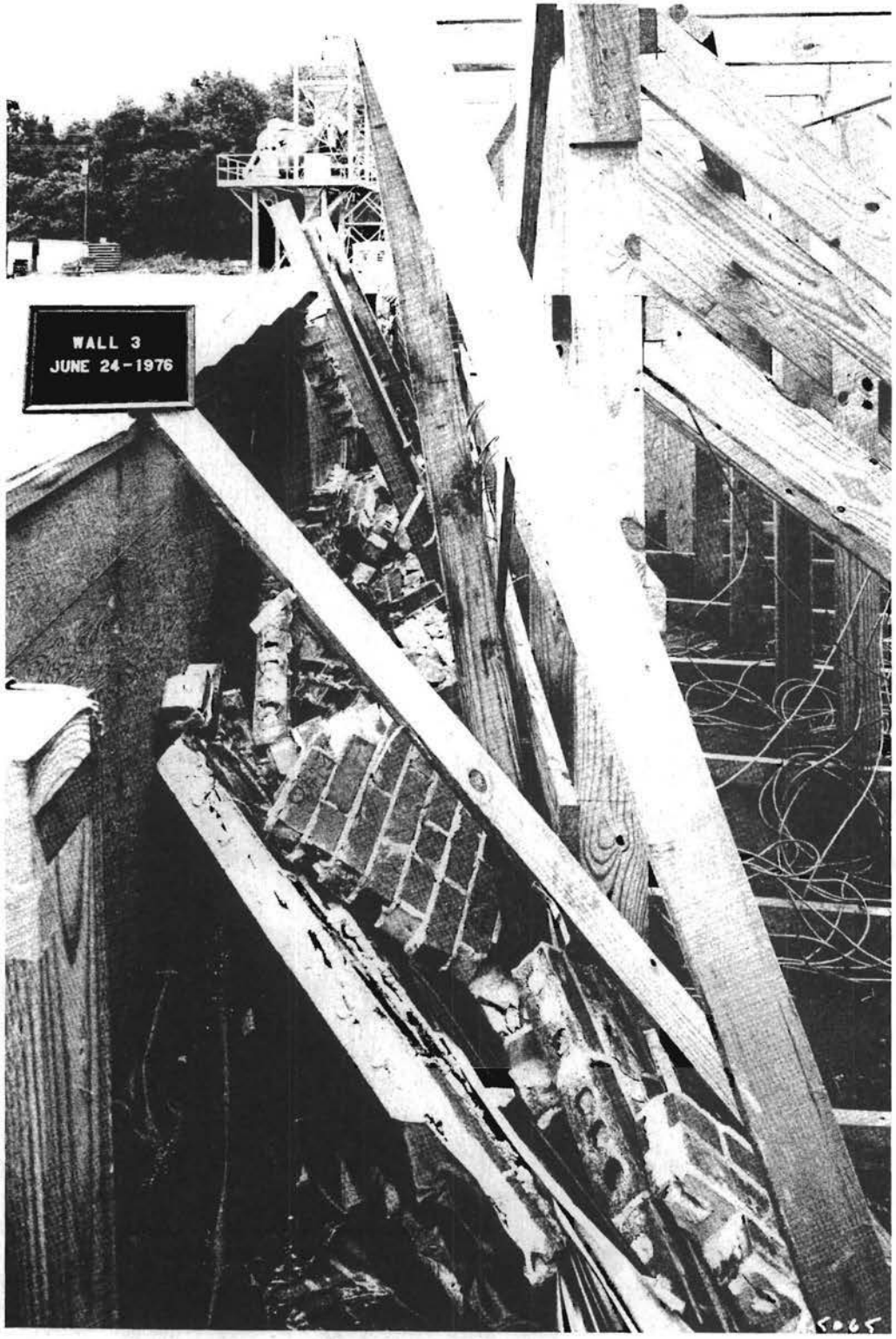
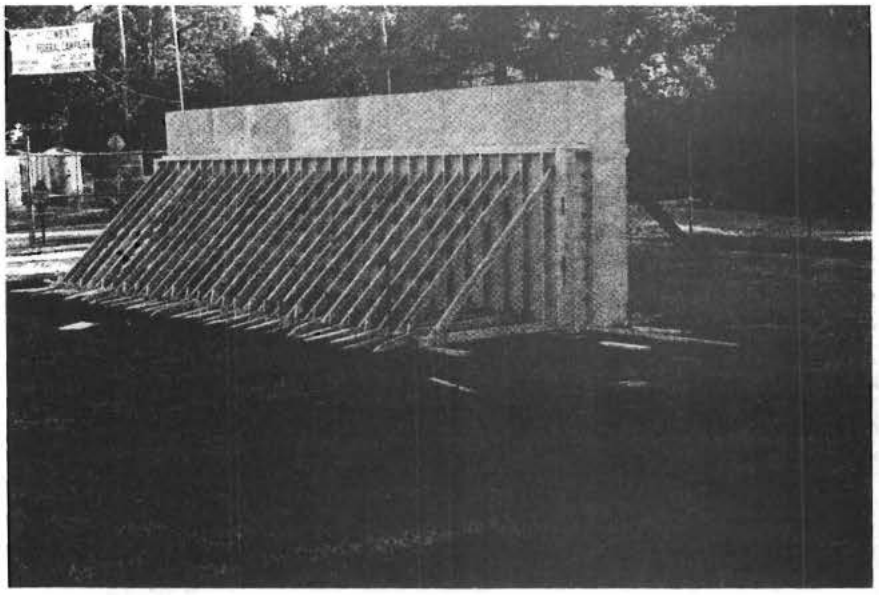
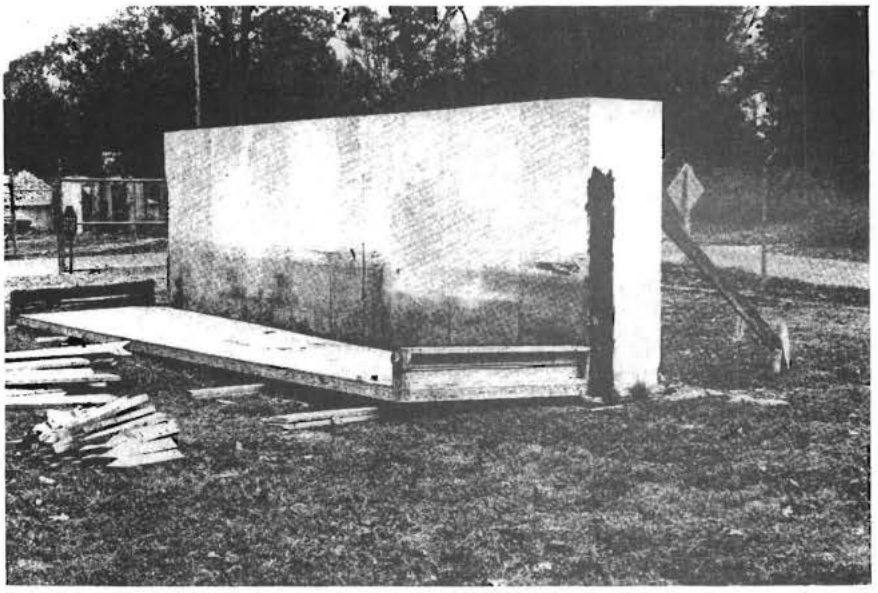


Figure 17. Wall 3. Wall failure, side view

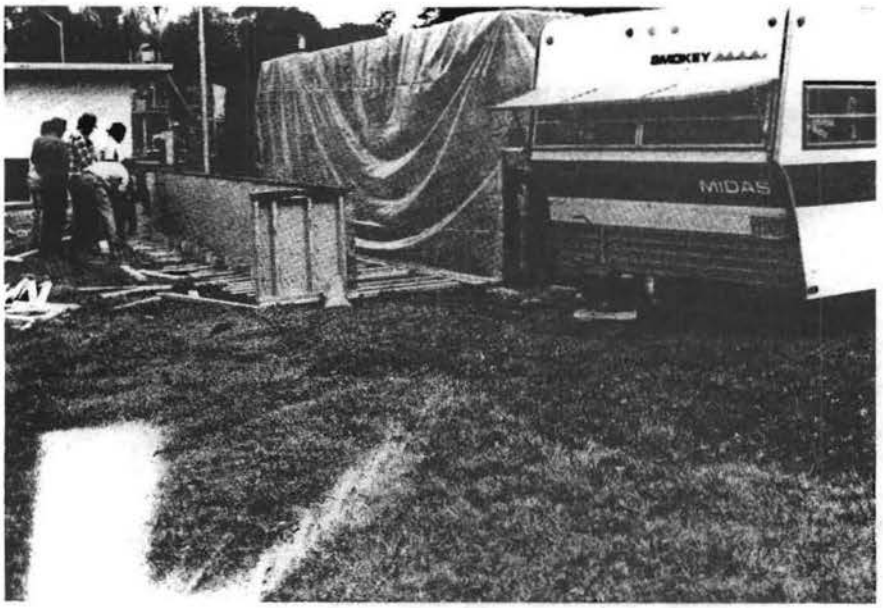


a. Before testing

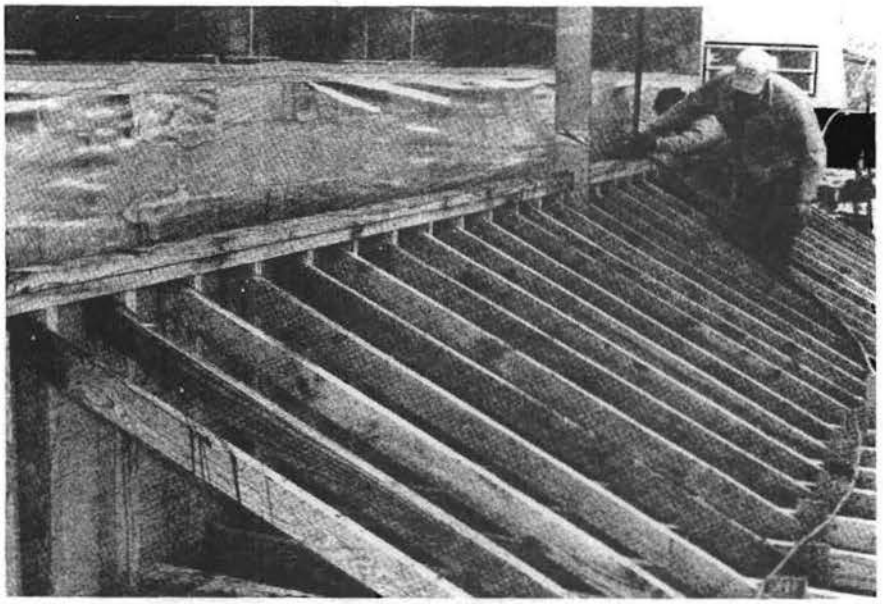


b. After testing

Figure 18. Block Wall 1



a. Preparing for testing



b. During testing

Figure 19. Block Wall 2

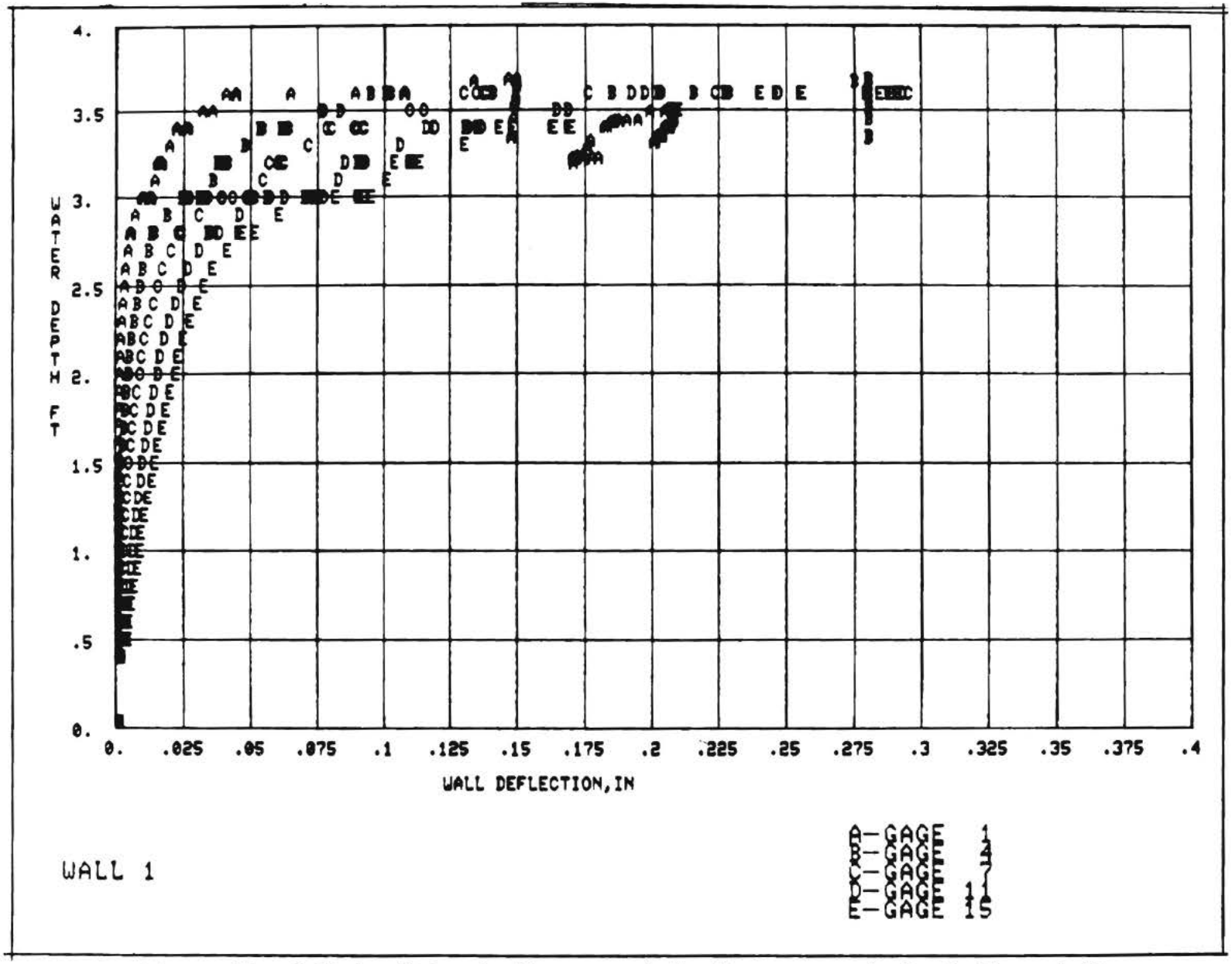
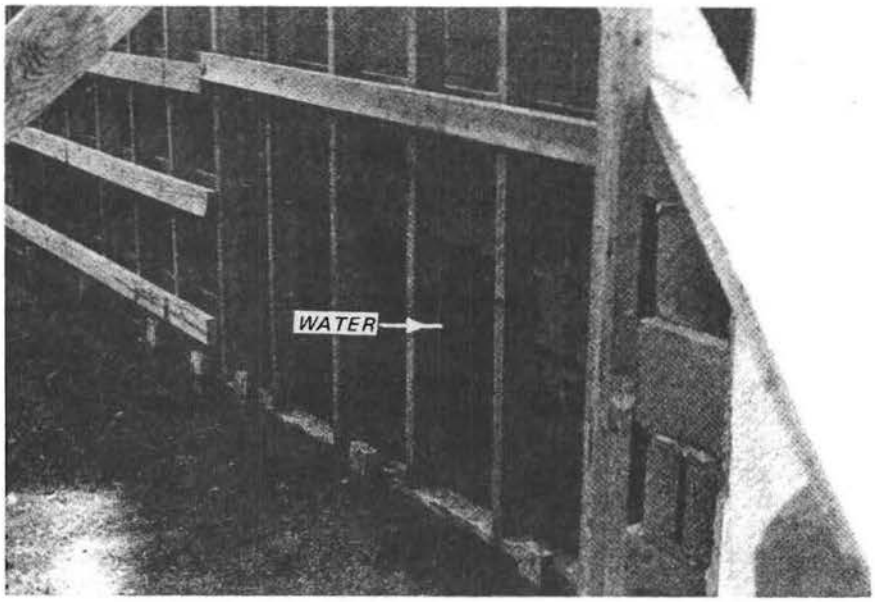
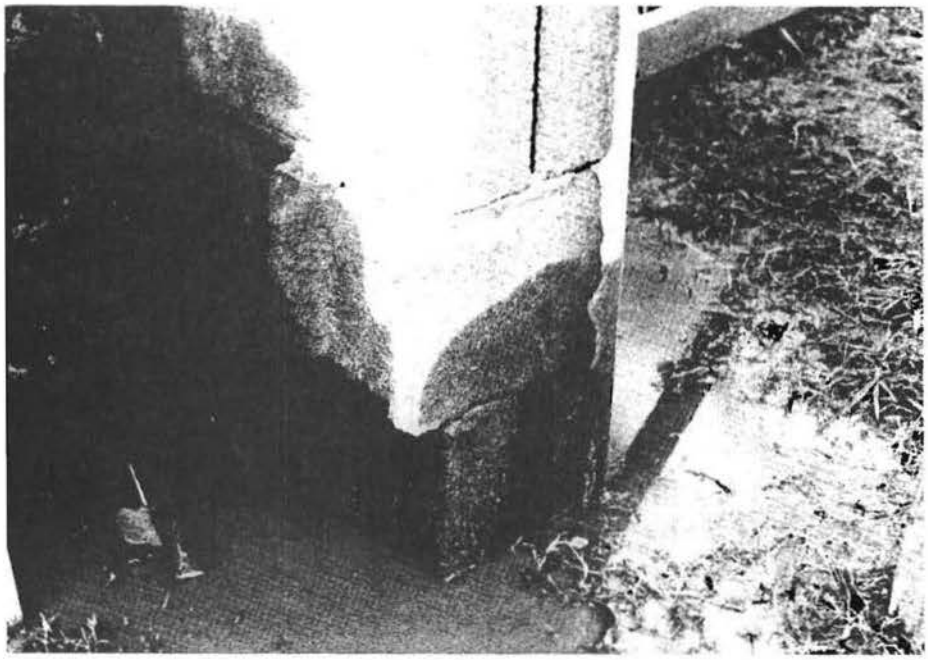


Figure 20. Wall 1. Water depth versus deflection, gages 1, 4, 7, 11, and 15



a. Stream of water coming through wall



b. Base of wall

Figure 21. Leakage through block wall

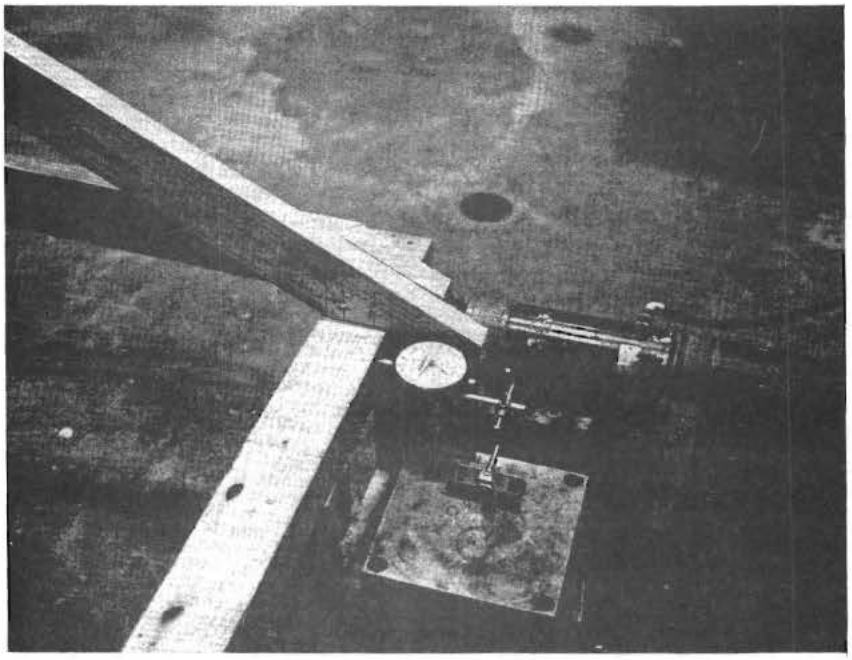


Figure 22. Nailed roof rafter and ceiling joist connection (connection has been failed)

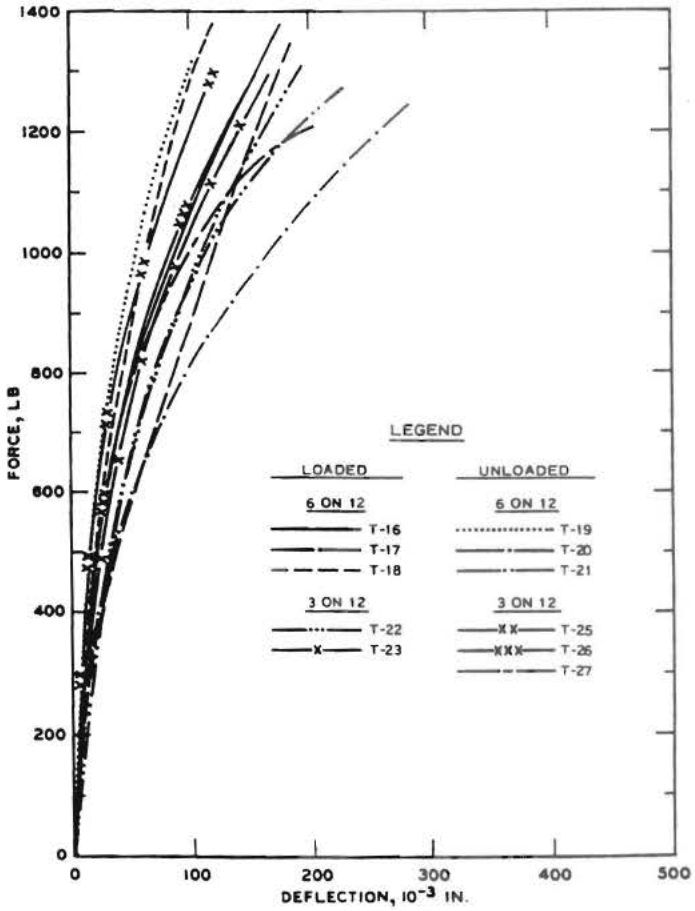


Figure 23. Roof rafter and ceiling joist load deflection curves - #2 pine (from Pace and Campbell 1978, op. cit. p 6)

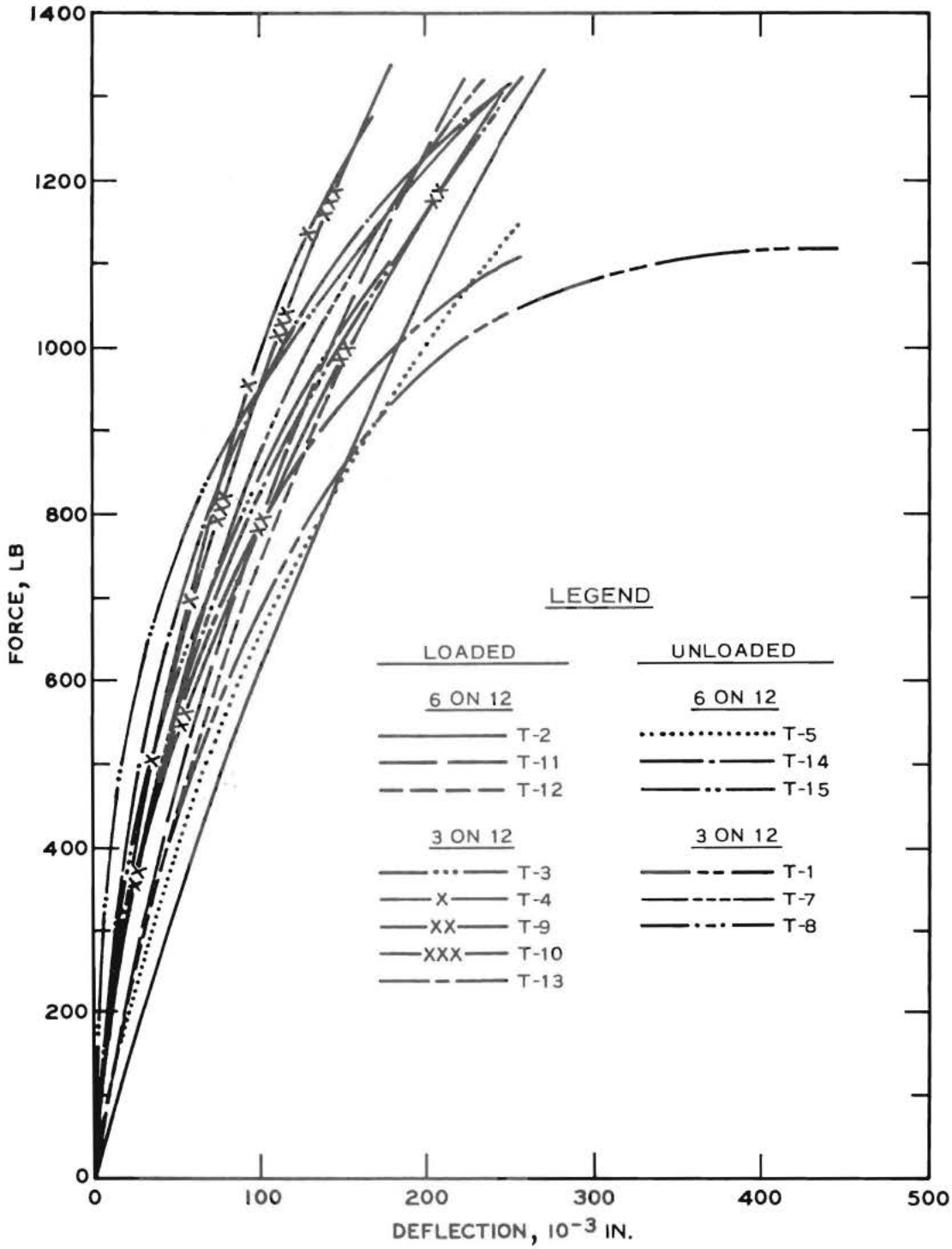


Figure 24. Roof rafter and ceiling joist load deflection curves - spruce (from Pace and Campbell 1978, op. cit. p 6)

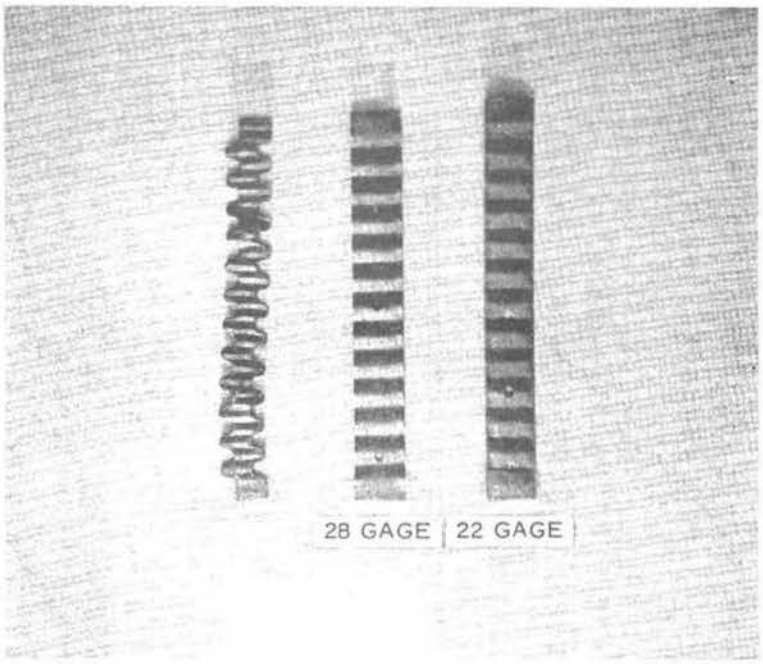


Figure 25. Three types of wall ties

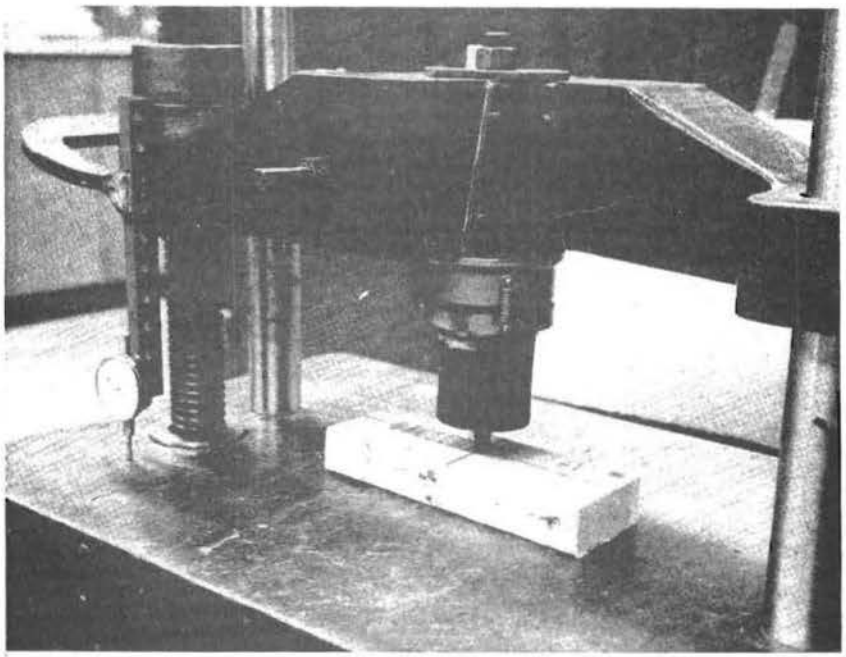
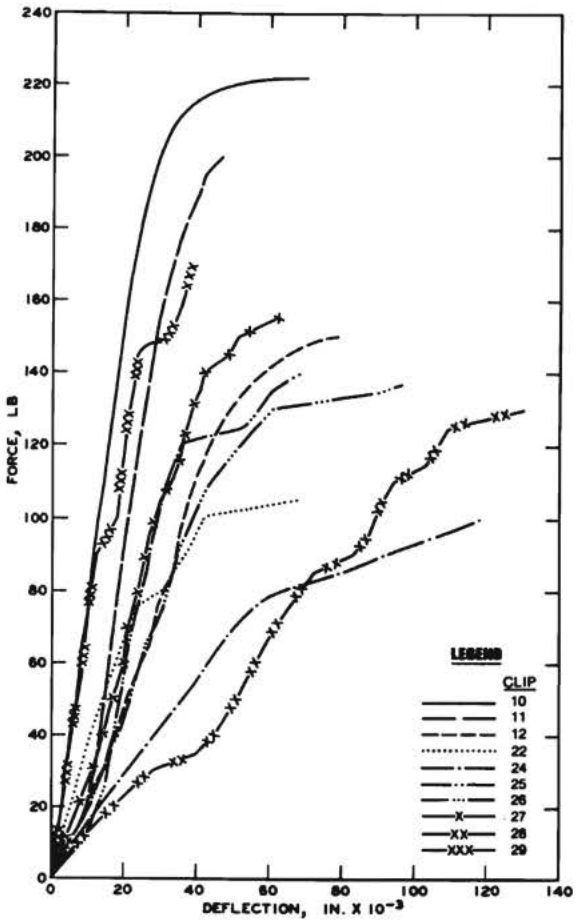
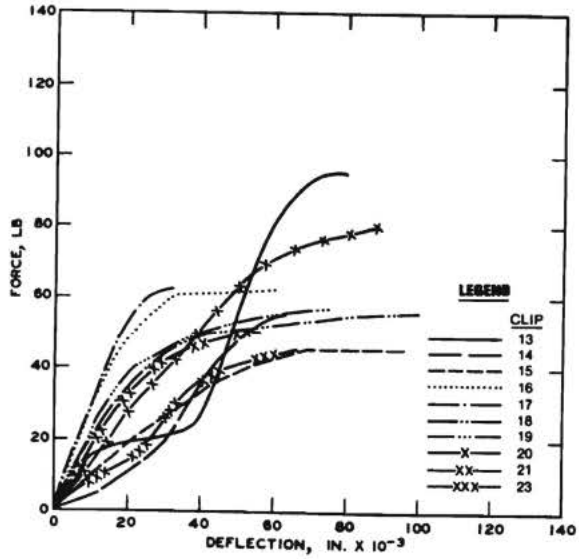


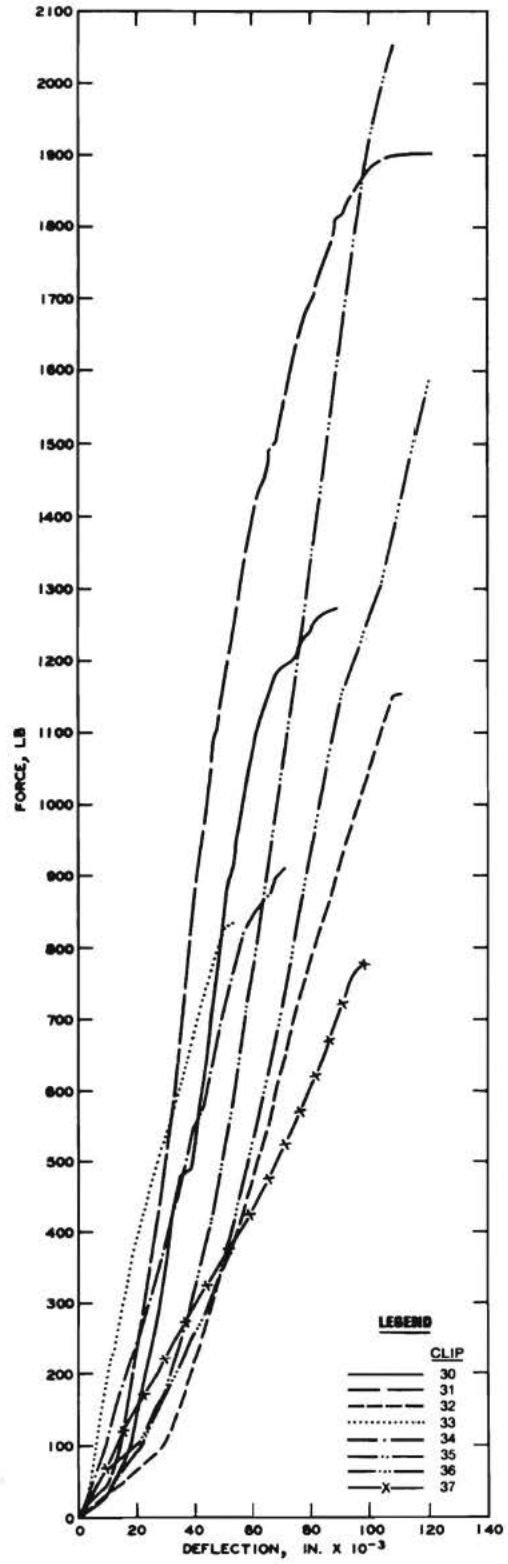
Figure 26. Test setup for wall tie tests



a. 22-gage wall ties



b. 28-gage wall ties



c. 22-gage wall ties with varying thicknesses of mortar

Figure 27. Load deflection curves for wall ties

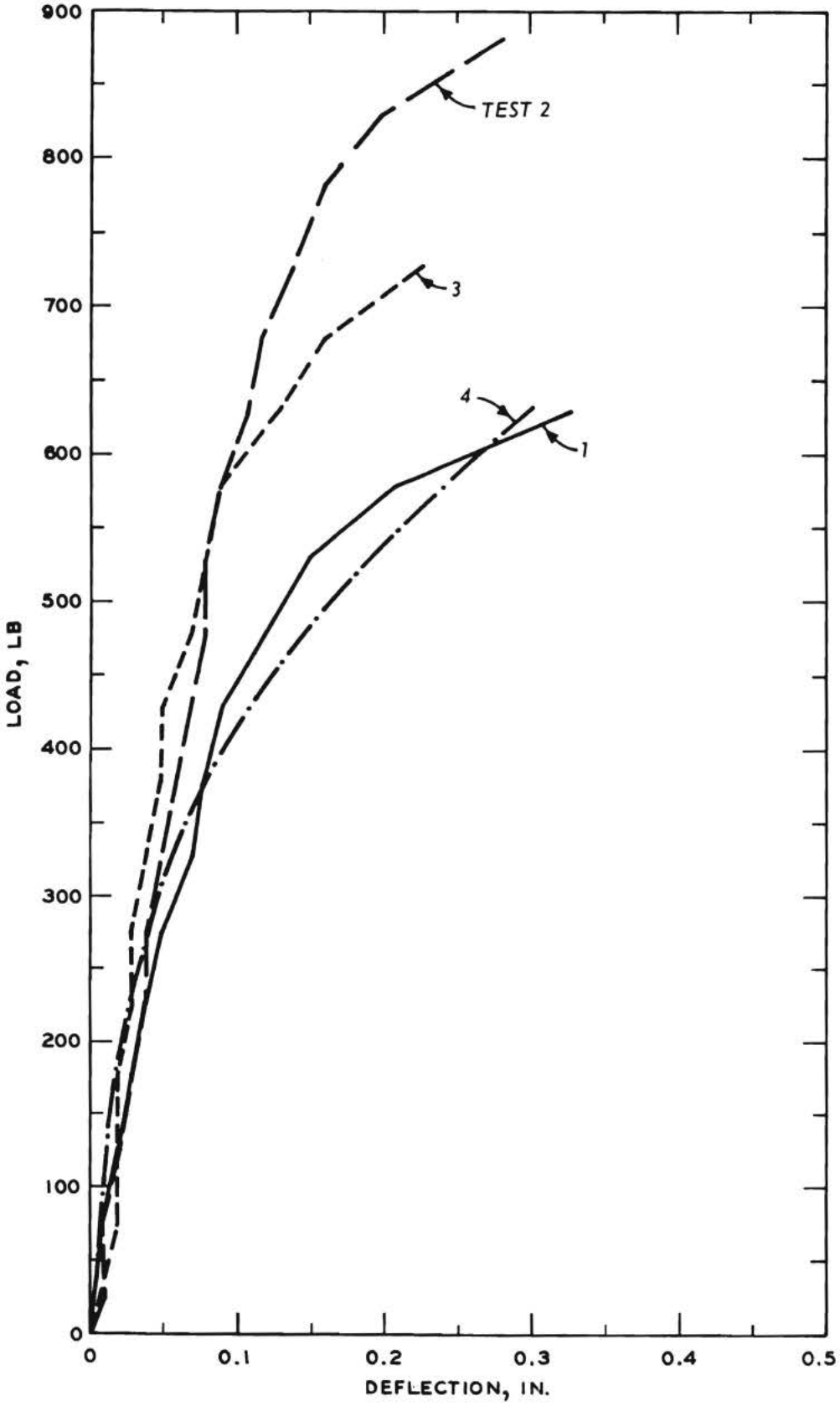


Figure 28. Stud to base plate load deflection relations

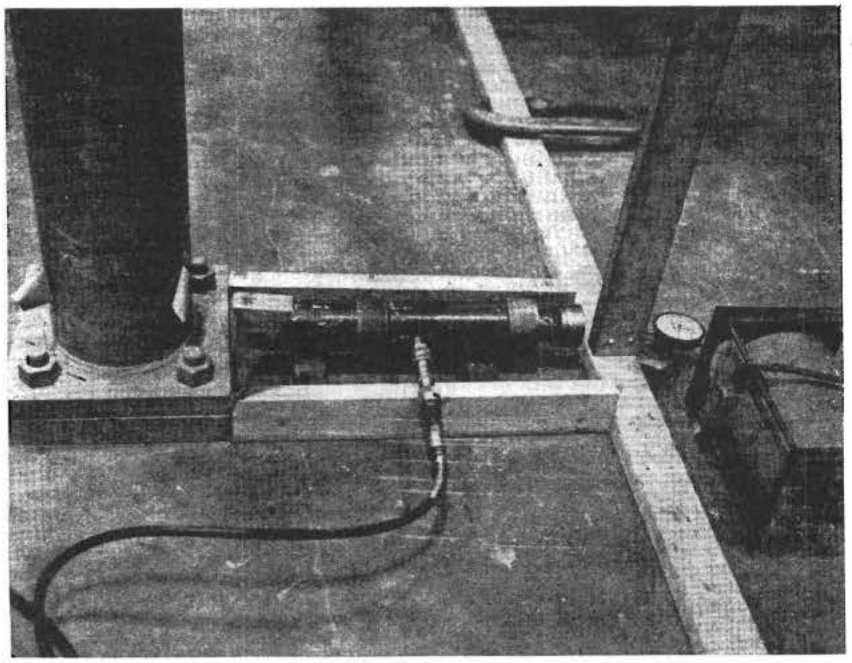


Figure 29. Test setup for determining stud to base plate restraint

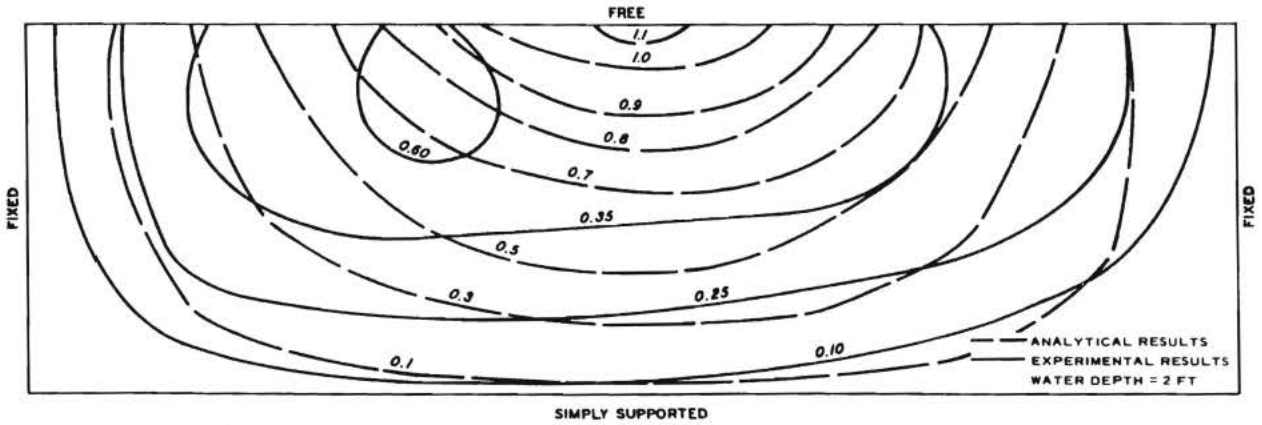


Figure 30. Comparison of analytical and experimental results (deflection is times thousandths of an inch)

PART III: TESTS OF WALLS, CLOSURES, AND MATERIALS FOR RESISTANCE TO FLOODWATERS

Experimental Test Plans

For laboratory testing, it was best to have the test walls as simple as possible but adequate for evaluating the penetration of water through the walls and the closures:

The test plans were as follows:

- Five sets of short walls were constructed (Figure 31).
- A standard door space was left between each pair of walls for the placement of a closure.
- A restraining frame (Figure 32) was installed in the door opening and from each side the closure could be pulled by springs (Figure 33) to seal it against the brick as could be done on an ordinary house.
- A bulkhead constructed of plywood and 2- by 4-in. boards (Figures 34 and 35) was placed across the walls and closures and sealed to the flood and the outer edges of the walls to contain the water. Different wall coatings and closure constructions were tested with this system.
- The deflected shape of the wall was measured as the water depth was increased.

The bulkhead was sealed to the ends of the brick wall and floor for various tests by means of rubber gasket material and one of the following compounds.

- Latex caulking.
- Weatherstrip adhesive.

If the latex caulking was not allowed to dry, it tended to become soluble. Even when the caulking was allowed to dry, the weather-stripping compound created the best seal.

Closures, Tests, and Test Results

Wall 1

The summary of tests (identical closures) on Wall 1 is contained in the following tabulation.

Test	Closure	Wall	Test Results
1	A closure constructed of plywood and 2- by 2-in. boards (Figure 36) was used. Rubber gasket material and caulking compound were used to seal the closure to the brick wall and floor. This closure was considered to be one that an ordinary homeowner could construct and use economically.	Nothing was put on the brick-veneer wall.	The wall leaked so badly that the closure could not be tested. Seven tubes of caulking were used to seal the closure to the brick wall and floor. For several openings this would be an unreasonable amount of sealing compound.
2	The same as Test 1.	Two commercially available coatings were used on the wall. One was used on half of the wall and the other on the other half of the wall. The coatings were near the consistency of water. The wall was soaked with the coatings.	The wall leaked so badly that the closure could not be tested. A thick coating with body is needed to adequately reduce flow through the wall. The low-viscosity coatings will not waterproof a brick-veneer wall.
3	Same as Tests 1 and 2.	Coated with asphalt cement. Figure 37 shows the wall after the test.	The wall continued to leak in a couple of places. After the bulkhead was removed, no flaws could be observed in the asphalt cement coating in areas where the wall leaked. This implies that great care must be exercised, even if asphalt cement is put on the wall, or water will penetrate the house. The wall leaked so badly that the closure was not tested for water.

(Continued)

Test	Closure	Wall	Test Results
3	Same as Tests 1 and 2. (Continued)		depths greater than approximately 15 in. This type closure will work, but it is impractical because it takes too much caulking, time, and care to seal it against the wall and floor.

The upper part of the wall deflected toward the water for low water depths as had been the case in the 8- by 26-ft brick-veneer prototype wall tests.

Wall 2

Since adequately reducing the flow of water through the brick-veneer wall was difficult, it was decided to use a double brick wall with a water barrier between the two layers of brick. The height of the second wall was to be a reasonable distance above the expected flood level. This wall was constructed as follows:

- A one-layer brick wall was constructed and coated with asphalt cement. Roofing felt (Figure 38) was embedded in the asphalt cement in one half of the wall, and polyethylene was embedded in the other half (Figure 40). Another layer of asphalt cement was put over the felt and polyethylene to form the water barrier. The barrier was also cupped and attached to the floor to keep water from penetrating the wall.
- Another layer of brick was constructed in front of the water barrier to protect the barrier and also to conceal it for appearance.
- The double wall added rigidity and strength, allowing more support against a greater depth of floodwaters.
- Channels were attached to the brick at the sides of the door space and angles were fixed at the base to hold a piece of plastic coated plywood as a closure (Figure 40). Two sheets of plywood (Figure 41) were used to check water penetration of the barrier. The second sheet of plywood was placed on the same side of the barrier as the water was applied to check:
  - Critical location of the closure.
  - Time involved for space between the two sheets of plywood to fill with water.

The summary of tests on Wall 2 is as follows:

Test	Closure	Wall	Test Results
1	Caulking compound was applied to the channels and angles. The plywood was then pushed, with its ends in the channels, down against the angle to form the closure.	The wall was composed of two layers of brick separated by a waterproof barrier.	The closure leaked so badly that the system could not be tested. The water did not go through the wall. Water freely flowed to the barrier, along the space between the layers of brick, and out the ends of the wall.
2	Same as Test 1 except caulking was applied more heavily to the closure.	Same as Test 1 except plywood with caulking was screwed to the outside ends of the wall to stop the water leaks along the waterproof barrier and ends of the wall.	The closure still leaked. Water did not come through the walls but flowed along the barrier and between the walls so freely that the test could not be completed.
3	The channels and angles were removed from the closure. Angles were welded to fit tightly against the sides and bottom of the doorspace. The angles were attached to the brick wall and to the floor of the doorspace using an epoxy resin adhesive. Gasket material was used on the plywood closure and it was bolted to the angles.	Same as Test 2.	The closure did not leak. Water did not penetrate the wall. Water still leaked from the outside ends of the walls.
4	Same as Test 3.	The seals at the outside ends of the walls were tightened after more adhesive was applied.	The closure and wall did not leak. However, the effort required to make this a successful system shows that it is not efficient for homeowners' use.

For a closure not to leak at its intersection with the sides and bottom of the doorspace, rubber gasket material, some adhesive, and bolts must be used to tighten and seal its sides and bottom. The two-layer wall was

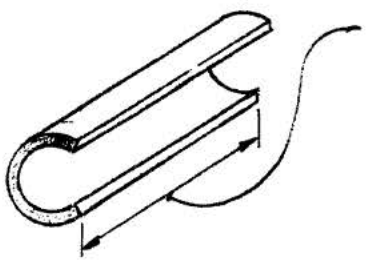
structurally more resistant to water loadings. Water will freely flow through the first brick layer to and along the water barrier.

Wall 3

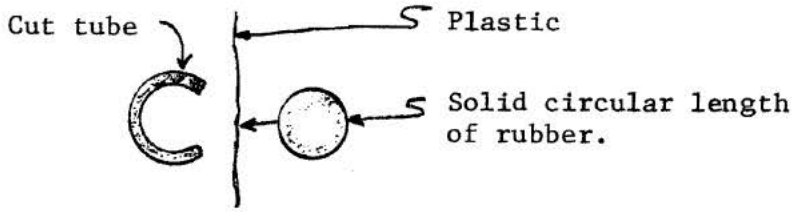
A concrete beam was cast at the base of Wall 3 to represent the footing under the brick wall. A tubular seal was used to encase and lock the plastic at the footing of the wall. The plastic was then pulled up and over the wall and closure. This formed a waterproof barrier over the wall and closure. This system is presented in Figure 42. The closure consisted of a piece of plywood placed against the wall to support the plastic.

The tubular seal at the base of the building was constructed as follows:

- About one third of the tube was cut away. The tube was epoxied to the footing with the cut surface turned to the outside.



- A solid circular length of rubber was placed against the plastic and snapped into the cut tube (schematically illustrated in the sketch below).



After only one test was performed on this brick-veneer wall, the system performed well. Other tests are necessary to determine the reliability of the system. Difficulties encountered prompted the test to be stopped. Water leakage under the bottom of the beam and base of the wall was to such a degree that further testing was useless. A particular advantage to this system is that seals and gaskets for individual openings in the structure are not necessary.

System Tests on Concrete-Block Walls

During the testing of the block walls explained in Part II, the tubular seal was tested while determining the structural integrity.

The second block wall test evaluated vinyl sheeting attached with a tubular seal and determined the deflected shape of the wall. The third test on Block Wall 2 was to again test the effectiveness of the tubular seal.

The tubular seal was judged to be inadequate since leaks occurred in Tests 2 and 3. The reasons for this inadequacy were:

- Even though the solid circular rubber O-ring component fit tightly into the cut tube, if disturbed, it came out easily, failing the seal.
- The cut tube became more flexible with use causing a greater possibility of the solid rubber cylinder pulling loose.
- The solid O-ring was difficult to turn around 90-deg bends. The solid rubber cylinder had to be cut at 45 deg and fit together at the 90-deg bends. This left a small space at the intersection of the 45-deg cuts which had to be sealed.

An aluminum seal (Figure 43) was used in Test 4. There was some leakage with the aluminum seal, and some difficulty in fitting the rubber O-ring against the plastic and into the L-shape aluminum extrusion. The O-ring could be fitted into the aluminum extrusion, but the process was slow.

Test Findings

As a result of testing, the following conclusions were reached:

- The common brick-veneer wall leaks excessively.
- The wall can be protected against excessive flow of water through it by using a thick coating with body. This type coating must be applied with great care, otherwise leaks will still exist. This solution was not successfully tested in the laboratory experiments. A water barrier which is durable, impermeable, and placed permanently between two layers of brick by a reliable placement technique will protect the wall from the penetration of water.
- For a closure to be watertight, it must have gasket material and be bolted at its connection to the sidewalls and bottom. The connections for the closure at the sidewalls and floor must be continuous and sealed securely to the walls and floor.
- Water will flow freely through a brick wall and along a water barrier in the wall.

- Two layers of brick will allow a brick wall to support greater water depths.
- The tubular seals are difficult to make watertight and, if not improved, will be too unreliable.

In the development of a system for reducing the flow of water through walls, testing performance before determining reliability is a crucial step.

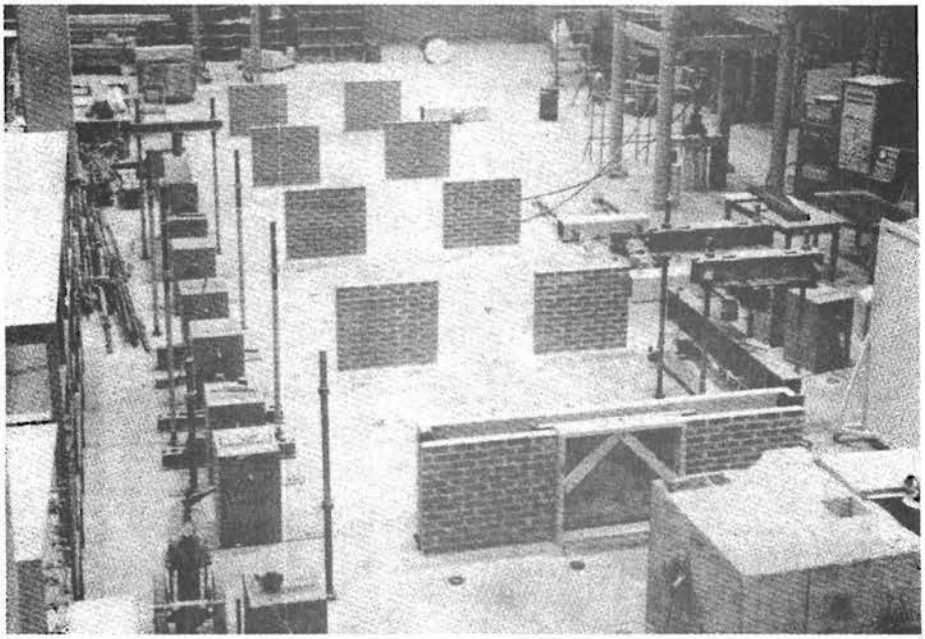


Figure 31. Five sets of short walls

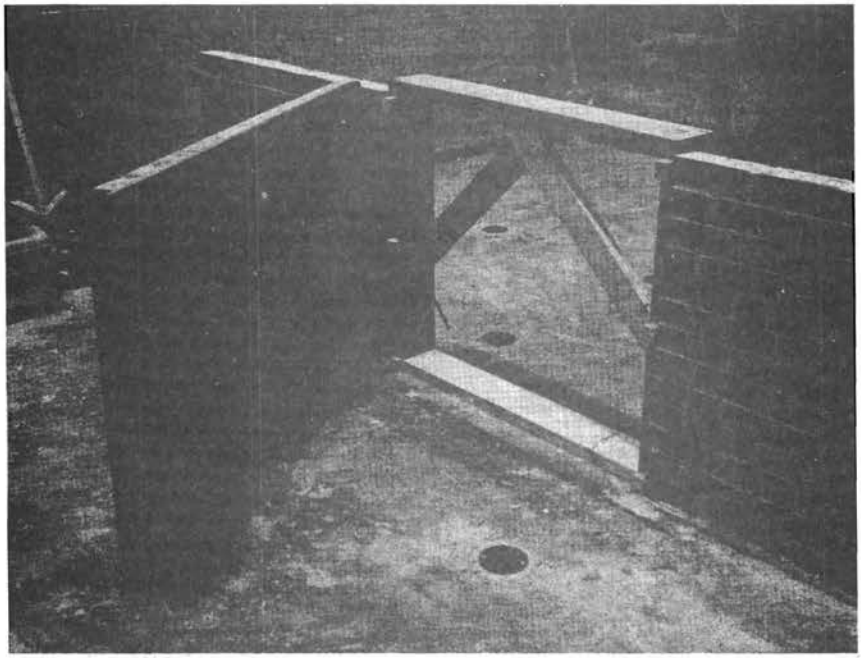


Figure 32. A restraining frame placed between the brick walls from which the closure can be pulled against the walls by springs

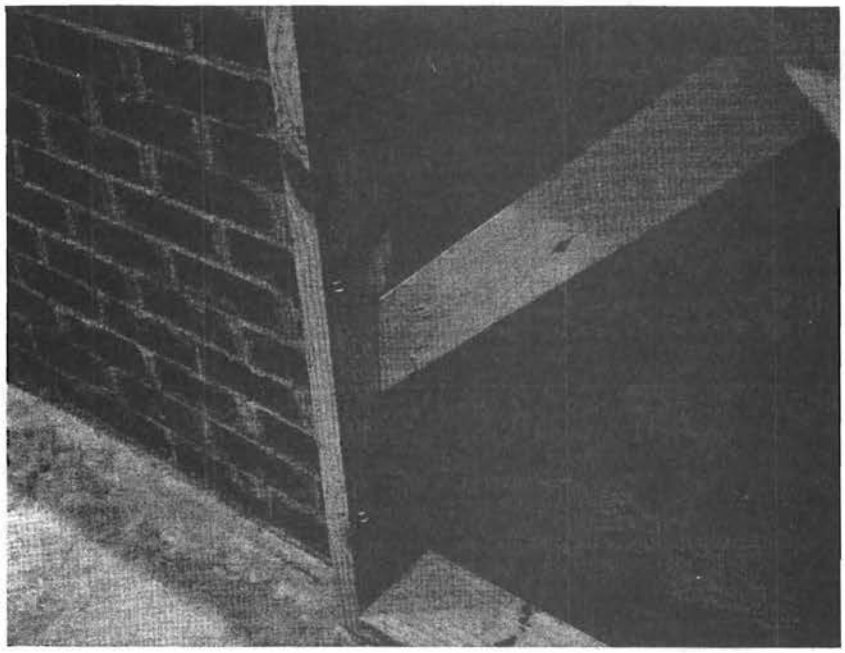


Figure 33. Springs used to pull the closure against the wall and down to the floor

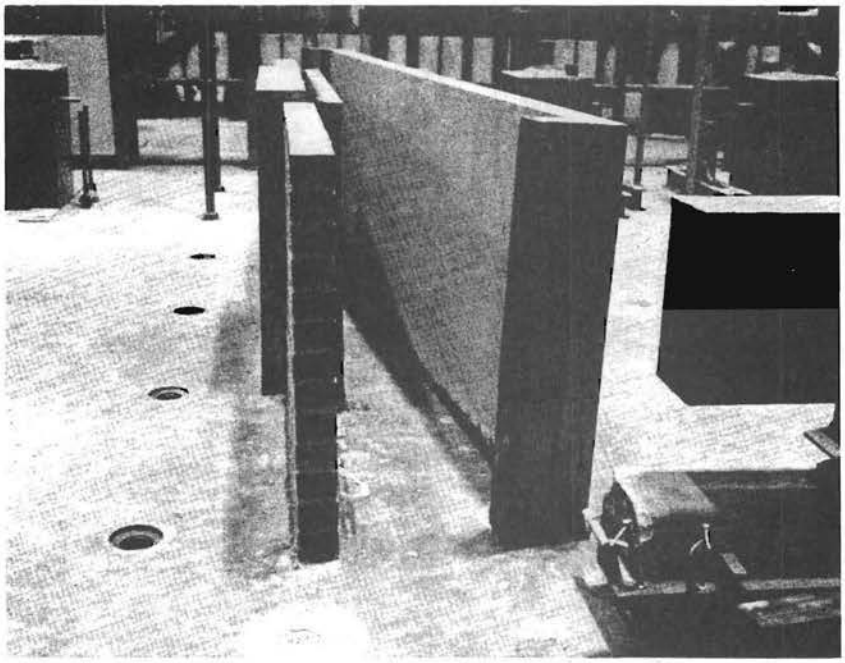


Figure 34. View 1. Bulkhead to contain water against the wall and closure

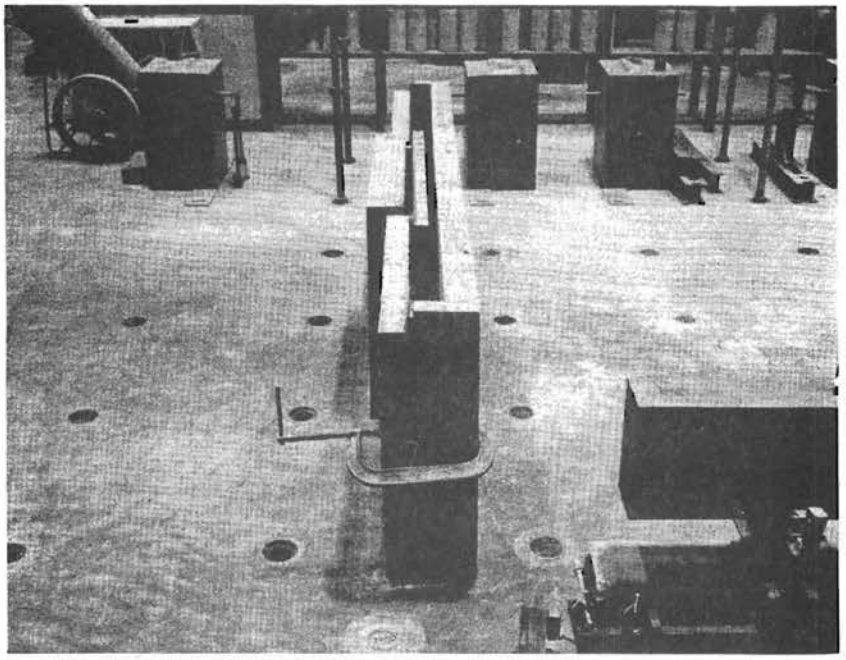


Figure 35. View 2. Bulkhead to contain water against the wall and closure

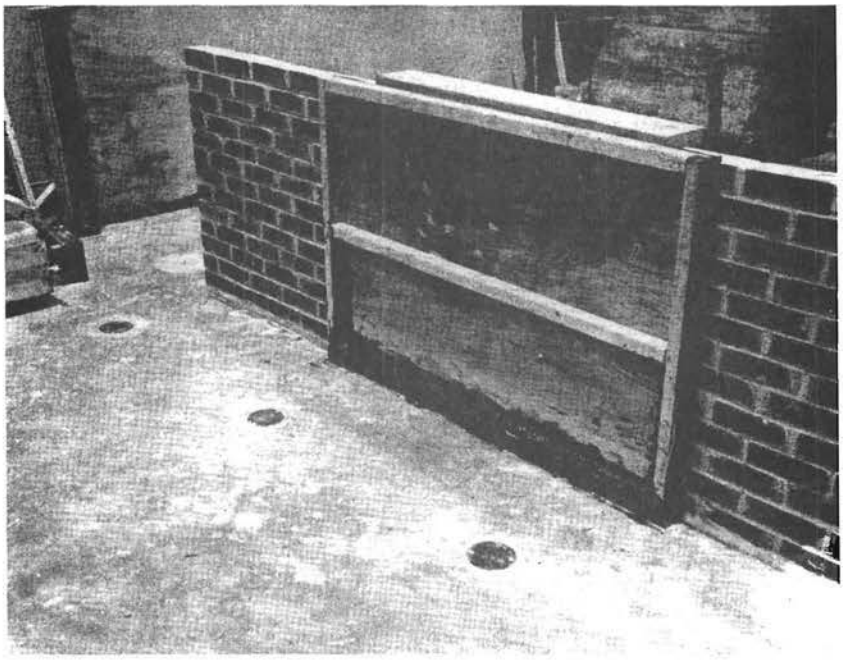


Figure 36. Closure made of plywood and 2- by 2-in. boards

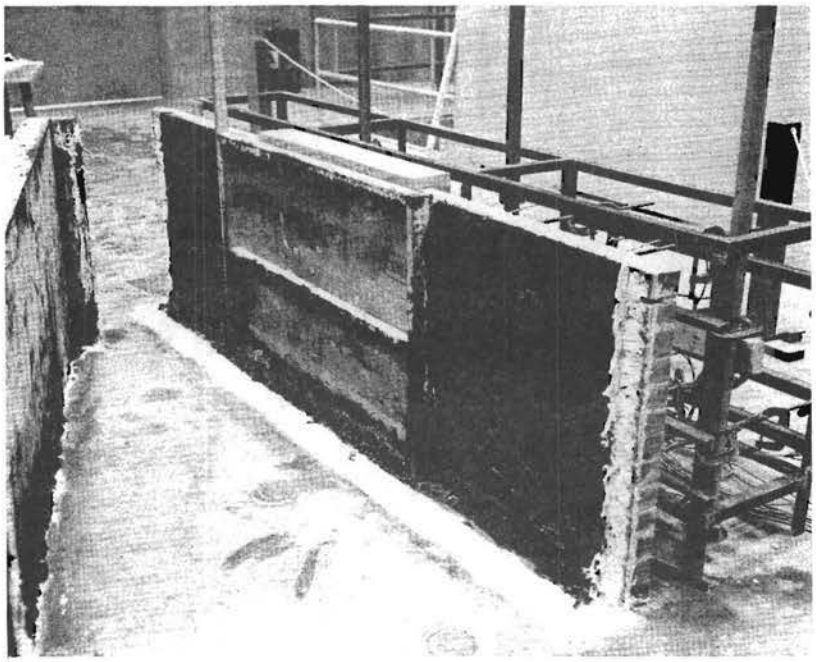


Figure 37. Brick walls coated with asphalt cement

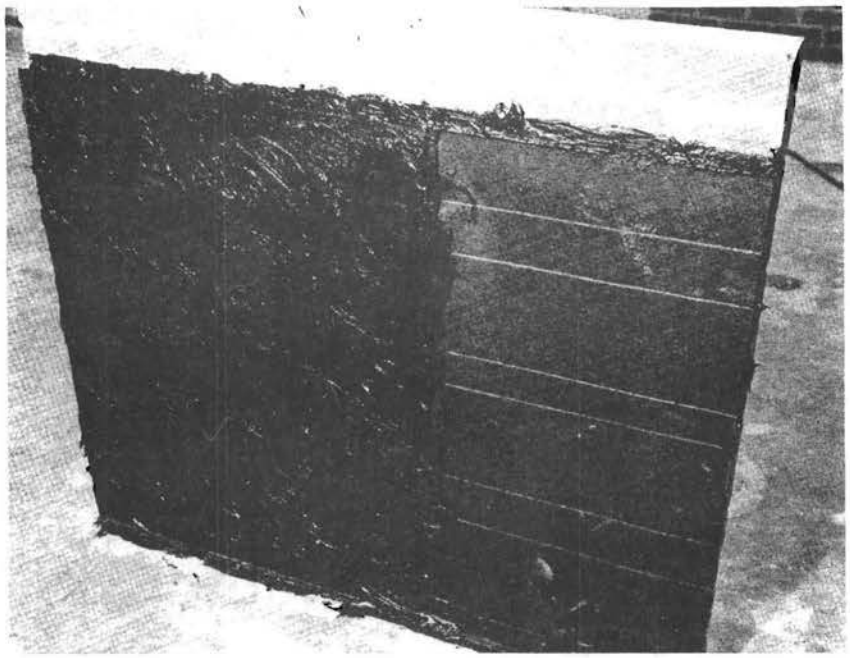


Figure 38. Water barrier composed of asphalt cement, roofing felt, and more asphalt cement

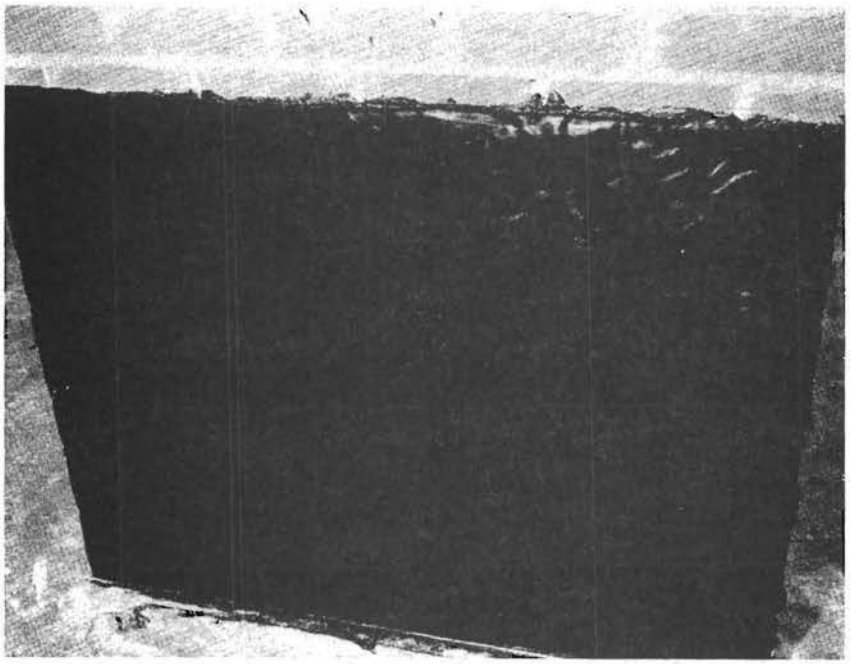


Figure 39. Water barrier composed of asphalt cement, polyethylene, and more asphalt cement

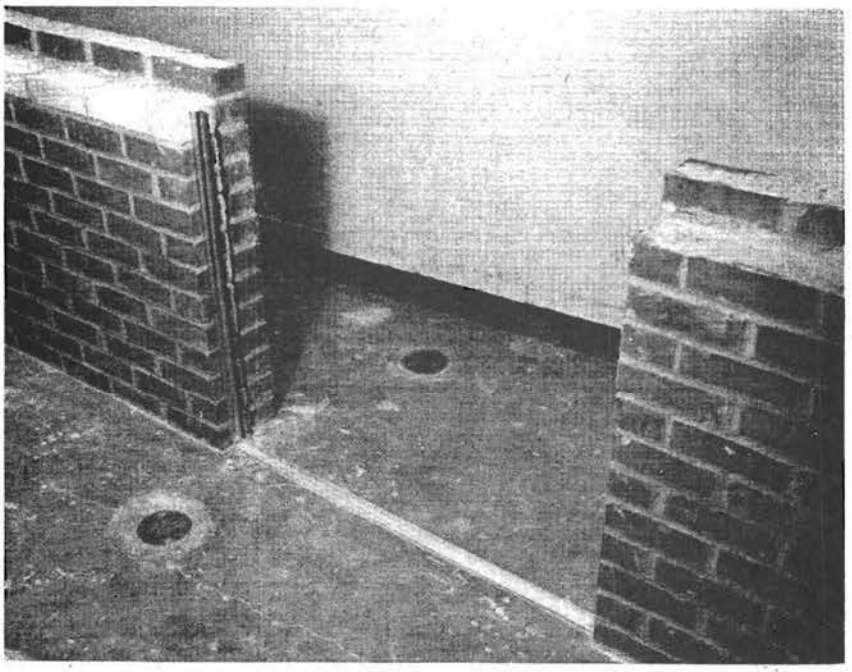


Figure 40. Channels and angles to hold the closure

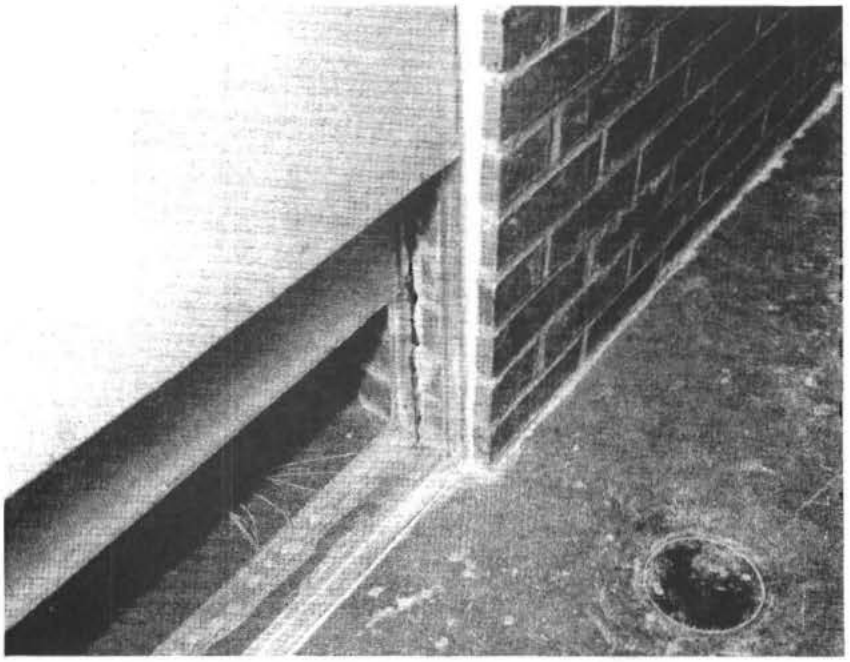


Figure 41. Two sheets of plywood used to form a closure

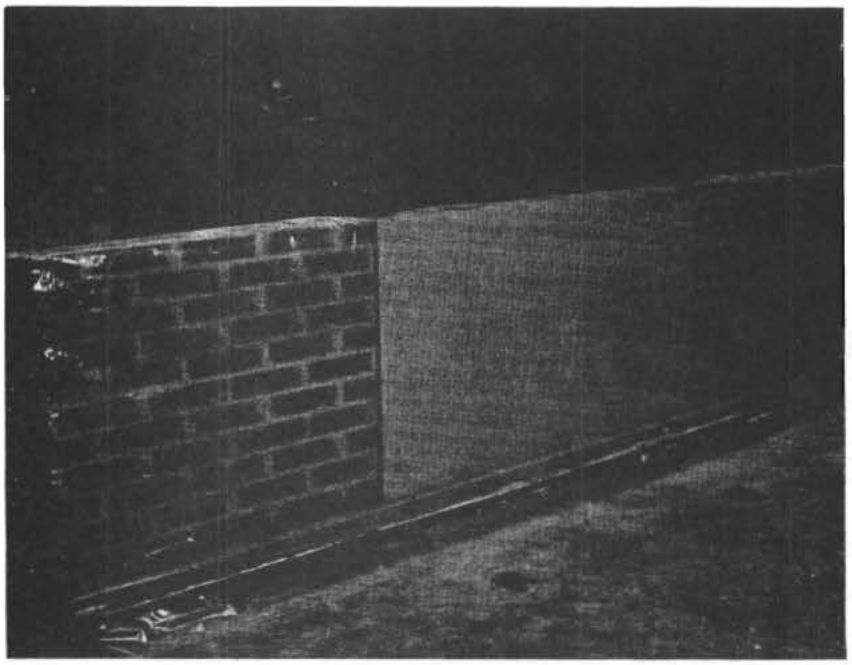


Figure 42. Footing, tubular seal, and plastic waterproofing barrier

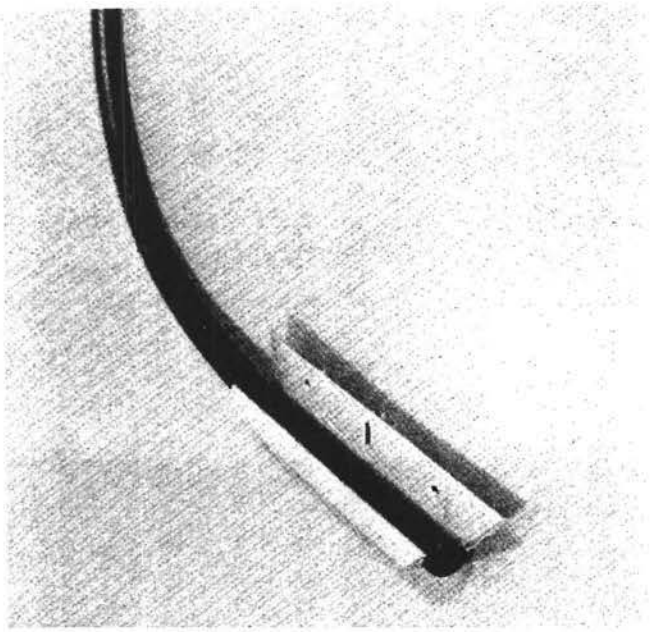


Figure 43. Aluminum seal

PART IV: SEALING MATERIALS TESTS

Building owners should be provided as many options as possible that have been proven to be successful in making homes or buildings resistant to the penetration of floodwaters. The building owner can then select the system which best meets specific needs. In some cases it is desirable to have a coating which will make a wall relatively impermeable to a head of water; therefore, it was decided to test available materials and determine their effectiveness and durability over several years.

Test Specimens

Test walls were needed for the application of the coatings. Brick cubes, open at the top, were constructed for this testing because of the expense of building prototype walls and bulkheads to test the coatings. Eight 2- by 2- by 2-ft cubes and one 4- by 4- by 4-ft cube (Figure 44) were built for testing the coatings.

The cubes were used to test the coatings in several ways. Coatings were put on the inside or outside of the cubes which were filled with water to test the effectiveness of the coating against a direct or reverse waterhead. The larger cube was used to test materials and systems by placing water on the inside of the cube and also by building a bulkhead on the outside to have a waterhead acting from the outside inward.

Materials Test Results

A search was made for coatings which manufacturers proposed for use to seal a wall against a head of water. The following coatings were obtained commercially or prepared in the lab and tested.

Clear coatings

It was desirable to find a clear coating which would make a wall resistant to water penetration. Six proprietary clear coatings listed in Table 1 (coatings 1, 2, 3, 9, 10, and 11) were found and tested. Three of the clear coatings will be discussed in Part IV, and the epoxy and polyurethane coatings will be discussed later. Each of coatings 1, 2, and 3 could be brushed or sprayed on the wall, and both techniques were used with each coating. The

clear coatings depended on their ability to coat and penetrate the wall as they were applied by spray or brush. Penetration of the coatings was uncertain on a vertical wall, even when the wall was soaked and excess coatings allowed to run down the wall. All of the cubes with the clear coatings leaked when filled with water. The coated walls did not leak as much as an untreated wall, but did leak excessively. The clear coatings were very effective at beading and repelling rainwater, but they did not keep the cube from leaking even against a small head of water. In general, the results of the clear coating tests were unsatisfactory.

Cementitious coatings

Five cementitious coatings (coatings 4-8) were obtained for testing. Four of these were proprietary products, and one was a formulation prepared by the author at the US Army Engineer Waterways Experiment Station (WES). There are many cementitious coatings which may make brick-veneer walls resistant to water penetration; however, the above coatings were the ones initially found for testing. Use of these coatings for testing does not constitute a preference over other coatings not tested. The cementitious coatings developed a good bond with the brick-veneer wall. In general, the cementitious materials made the walls relatively impermeable to a waterhead for heights which are of interest in making homes resistant to floodwaters but some of the coatings tested were not durable. Two coatings (5 and 8) have been successful over an 8-year period of time subjected to the climate in Vicksburg, Mississippi.

There were two procedures by which the various cementitious materials could be applied to the surface of a brick-veneer wall. One of the five coatings had to be troweled on the wall, while the others could be mixed to the consistency of paint and brushed on the wall. Troweling on the coating was time-consuming and thus increased the expense. It is highly desirable to use a material which can be brushed on the wall. The troweled-on coating (coating 4) sealed the cube against a waterhead with only a small leak mainly at the cube-foundation interface (Figure 45). Coating 4 was unsuccessful in terms of durability. It expanded, cracked, and began to come off the wall 3 months after it was applied and had essentially come off the wall in 3 years (Figure 46).

Three years after application of the brush-on coatings, coatings 6 and 7 showed some cracking. Coating 7 lost its bond to the brick surface and peeled

off in various places. After 8 years of service, coatings 5 and 8 showed no signs of cracking or loss of bond.

One type of material (coatings 4, 5, and 7) was so impermeable that it kept water completely away from the wall. The other type of material (coatings 6 and 8) contained some agents which seeped into the voids of the mortar joints and reacted with the cement causing expansion and a filling of the spaces. One cementitious coating of each type (coatings 5 and 8) showed long-range success after 8 years in the climate at Vicksburg, Mississippi.

Material 5, which was formulated by the author at WES, (Figure 47) was a coating with excellent impermeability and bond characteristics. The darker material (pigment added) in this photograph is coating 5. Pigment can be used to make the cementitious coating the desired color. For the maximum head of water tested (4 ft), coating 5 sealed the brick wall from both the positive and negative sides of the wall. This coating was less expensive that the proprietary products and would be excellent where a surface coating is required.

Coating 8 was as successful as coating 5 and also sealed the brick-veneer wall against 4 ft of waterhead from the negative and positive sides of the wall. Coating 8 seeped into the pore spaces of the mortar joints; it was observed to penetrate the joint and collect as a film on the opposite side of the wall. Initially, the brick-veneer wall leaked a small amount, but as the material seeped into the pore space, the leakage stopped.

The other three coatings initially caused the brick-veneer walls to be impermeable to water when applied to the positive or negative side of the wall, but they were not durable and failed with the passage of time.

Epoxy coatings

Two epoxy coatings (coatings 9 and 10) were used to seal the brick-veneer walls. One epoxy coating was 100 percent solids. In each case, the wall with the epoxy coatings leaked excessively.

Polyurethane coatings

Polyurethane coatings were not effective in keeping the wall from leaking. If moisture collected between the polyurethane and the wall, the coating turned a milky color. After approximately a year of exposure to the elements, the polyurethane coating began to crack and peel from the wall.

Asphalt coatings

Asphalt coatings were not effective unless excellent workmanship was used and even then there were possibilities of leakage. An asphalt coating is

adequate if an impermeable barrier such as roofing felt or sheet polyethylene is embedded in the coating. Good workmanship and correct application techniques must be used even when the impermeable barrier is used, or leaks may develop.

Table 1

Coatings

Material	Coating No.	Comments
Clear water-repellents	1	Repelled rainwater well. Sealed some small openings against 1 to 2 ft of waterhead, but did not seal brick or block walls against 1 to 2 ft of waterhead.
Clear water-repellents	2	
Clear water-repellents	3	
Cementitious materials	4	Expansive, hard to apply. Sealed a brick-veneer wall against 2 ft of waterhead but cracked and failed after 3 months.
Cementitious materials	5	Relatively inexpensive, good bond, good crack resistance, and was still effective after 8 years of use.
Cementitious materials	6	Good bond and cracked after 3 years of use.
Cementitious materials	7	Cracked and peeled from brick surface after 3 years of use.
Cementitious materials	8	Good bond and was still effective after 8 years of use.
Epoxy	9	Not effective in sealing a brick wall against 1 to 2 ft of waterhead.
Epoxy	10	Not effective in sealing a brick wall against 1 to 2 ft of waterhead.
Polyurethane	11	Not effective in sealing a brick wall against 1 to 2 ft of waterhead.
Asphalt	12	Reliable only if good workmanship is used and an impermeable barrier is embedded in the asphalt.

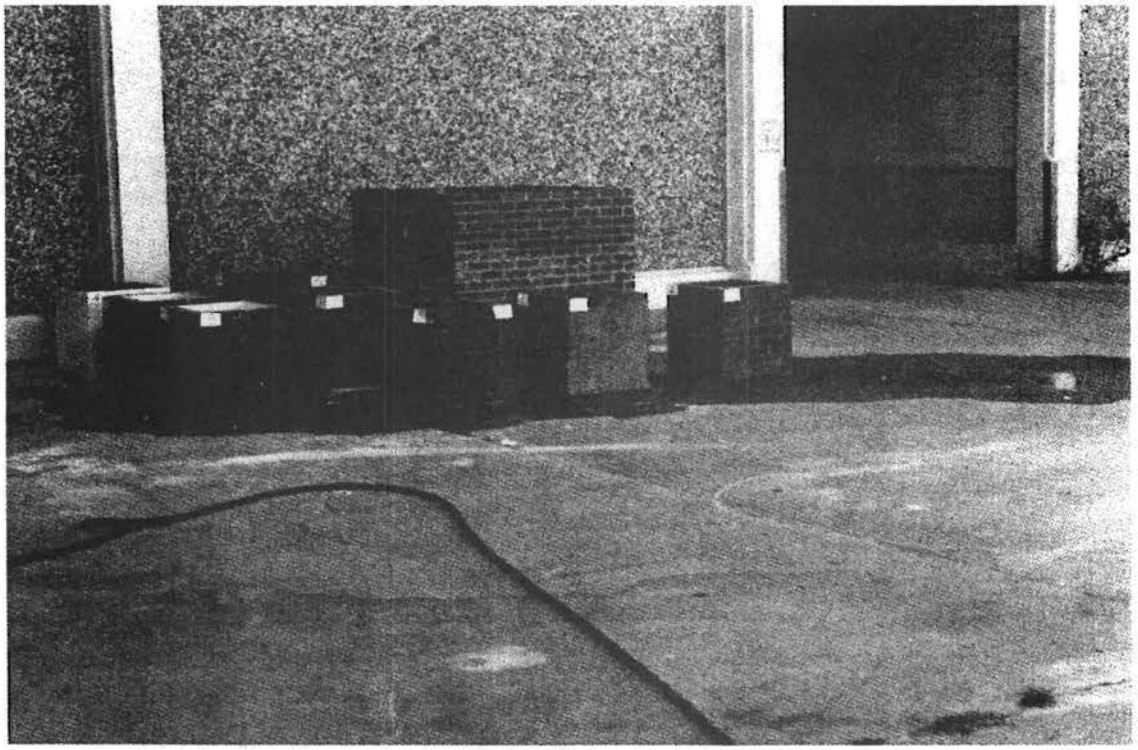
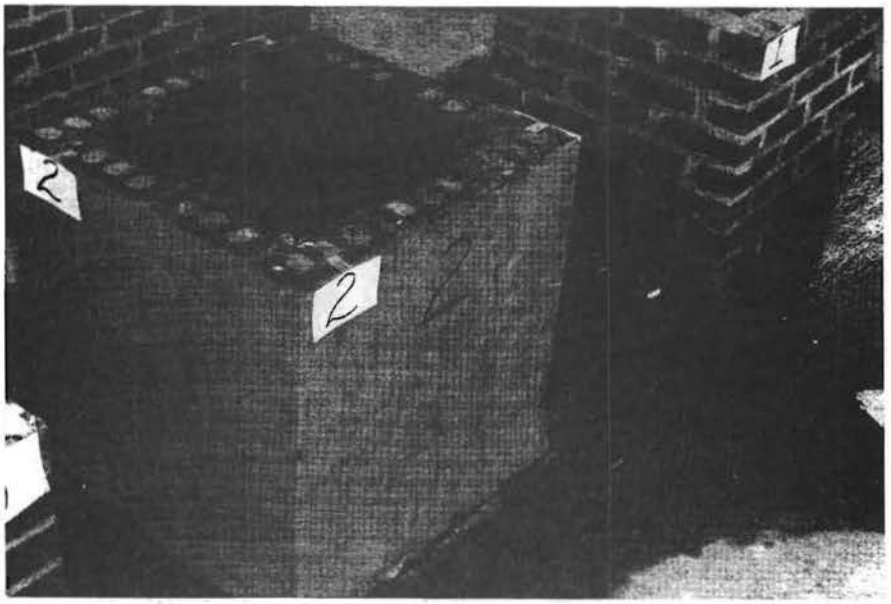
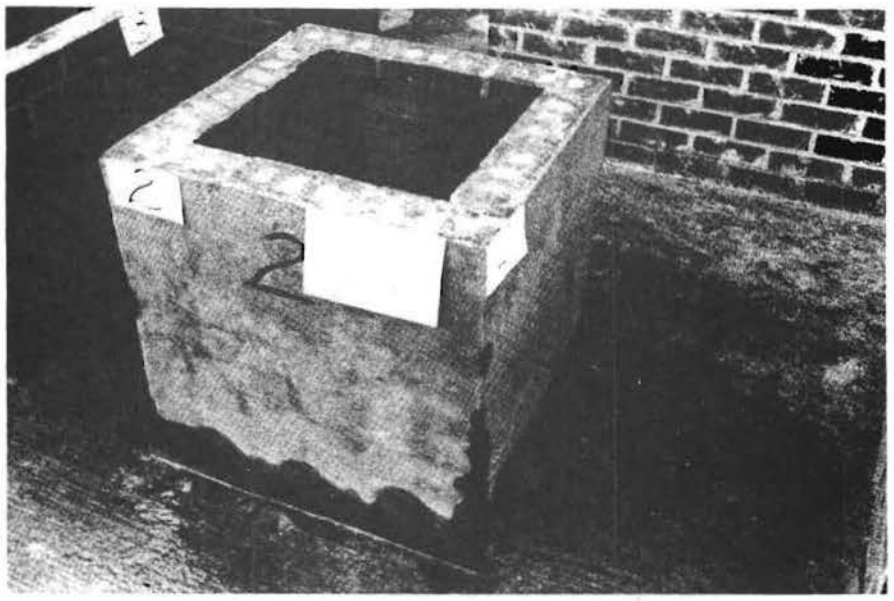


Figure 44. Brick cubes to test sealants and systems for preventing flood damage

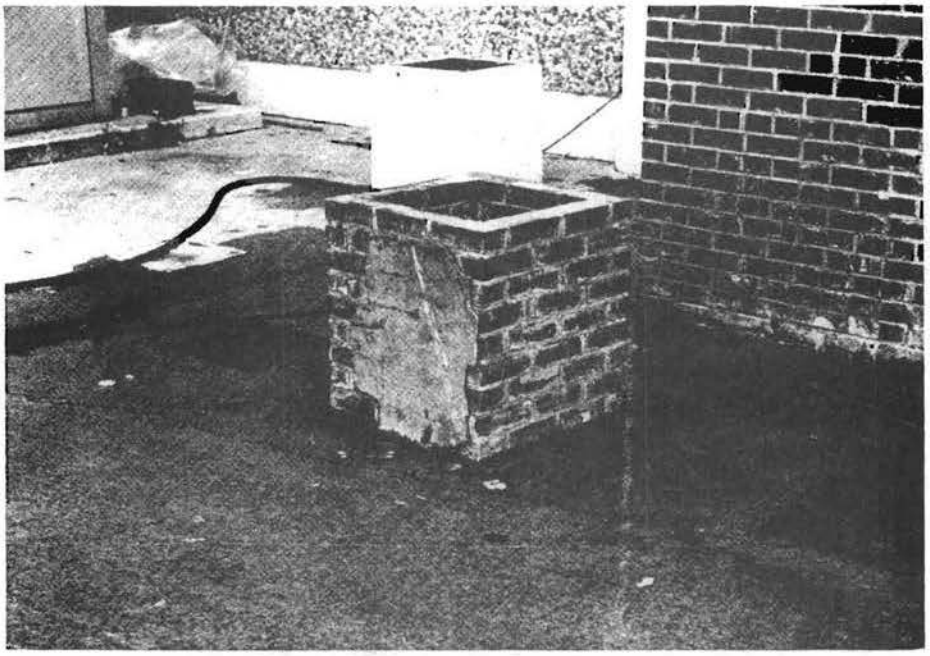


a. Two hours after cube was filled with water

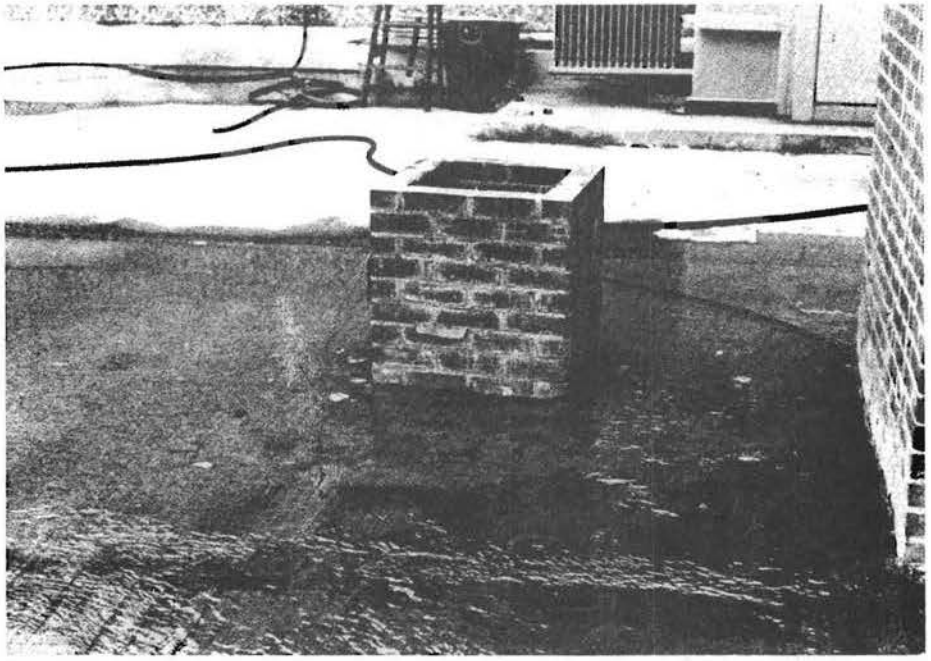


b. One day after cube was filled with water

Figure 45. Initial testing of coating 4



a. Front view



b. Side view

Figure 46. Failure of coating 4

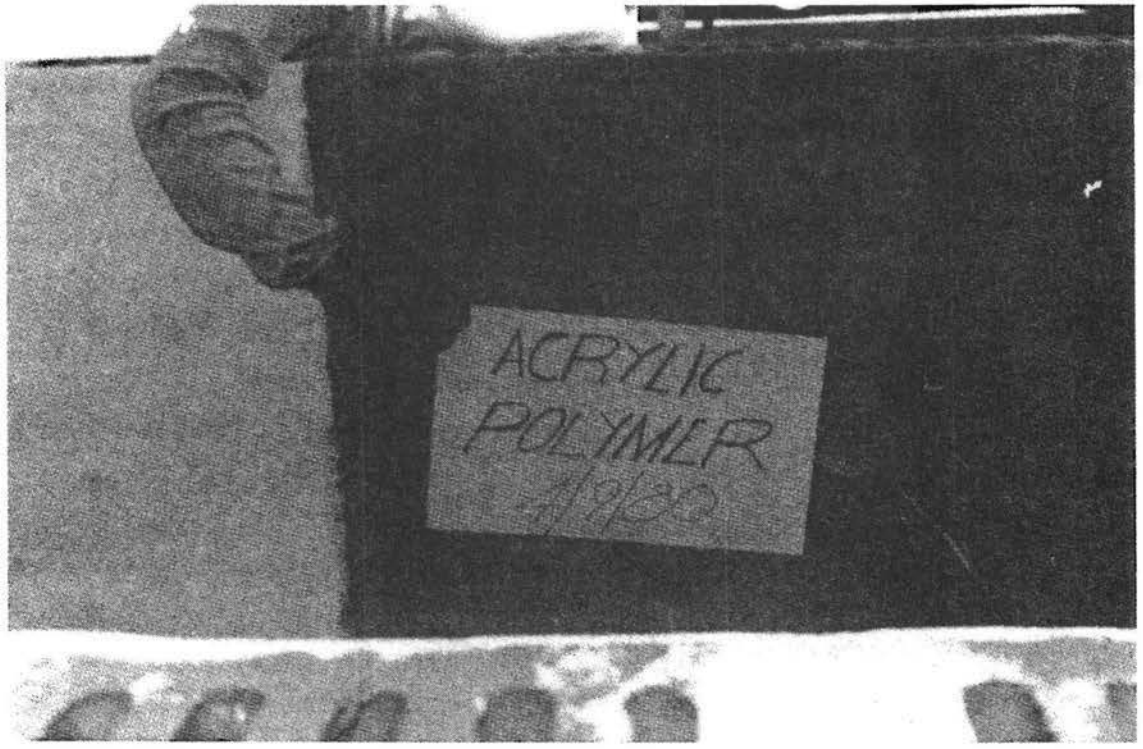


Figure 47. Coating 5

PART V: SYSTEMS TESTS ON A BRICK CUBE

The structural integrity tests of brick and concrete-block walls indicated that house walls will not withstand more than about 3 ft of water without structural damage. This result provided a baseline for systems tests to determine methods which would keep shallow-depth floodwaters out of homes and buildings.

Such structures can be strengthened in various ways; however, systems tests were performed for normally constructed homes in which the walls had not been strengthened. The systems tested would be used primarily for protecting homes in high risk, shallow-depth, flood-prone areas. Expedient membrane systems with a snap-type sealing strip at the base of the wall will be tested.

Systems tests which were performed using the block wall (Part III) and the walls of the test house at Allenville, Arizona (Part VI), indicated that details are critically important. In particular, the sealing strip at the base of the building has many potential problems, and if extreme care is not taken in installing and activating the system, it will leak.

The systems tests on the brick cube had several advantages over testing prototype walls:

- Tests were less costly and less time-consuming.
- The four corners of the cube allowed adequate testing of seal strips at corners.
- Outside and inside corners could be tested.
- Sealing of vertical seams in the waterproof membrane could be tested.
- Systems set up on the inside of the cube did not require a bulkhead to retain the waterhead.

Test Setup

Inside corners

The system tested was an expedient snap-type sealing strip at the base of the wall and a plastic sheet which would be pulled up the wall to the desired height of protection. Commercial extrusions which could be used as a seal strip were difficult to locate; therefore, a seal strip was designed and a manufacturer was paid to extrude it (Figure 48).

Five tests were made with the system using the specially designed seal strip. Figures 49 and 50 show details of the tests. It was found that care

must be taken in attaching the permanent part of the seal strip to the house. If any adhesive material adhered and stayed in the snap area, it held the expedient snap open and allowed water to enter behind the plastic.

It appeared that that corners (Figures 49 and 50) could be sealed easily. The one possibility of water entry might occur in the corner where the snap joined together. To seal this area, silicone caulk was placed under the snap, on the underside of the plastic, and at the intersection of the plastic and snap. This solution seemed entirely logical, but in practice it turned out to be extremely difficult to stop leakage at the corners.

As the plastic sheet was pulled and the snap connections made along the walls and around the corners, it was difficult to keep the plastic sheet from wrinkling. The vertical sections would not remain straight and tended to wrinkle. Wrinkles in the plastic under the expedient snaps allowed water to enter and make the system ineffective.

In general, the system can be made to work, and with careful attention to details, leaks permitting water to penetrate the walls of a building can be prevented. Water entering under the base of the house can be handled by a sump and pump system to collect and remove any seepage water before it gets into and damages the house.

After several failures, this system was tested successfully.

Outside corners

A bulkhead was constructed to hold water for four tests performed on the outside of the cube. The same problems were encountered in working with the system as described for the inside corners, although the outside corners were easier to work with and the plastic was not as easily wrinkled.

A second seal strip was found and tested (Figure 51). Again, there was a small amount of leakage at the corners of the brick cubes in the four tests. When dye (a very effective indicator) was used (Figure 52) to determine the location of the leaks, the corners proved to be the weakest part of the system. A better way to manage the corners of this system is apparently through the fabrication of a one-piece molded corner strip.

Test Results

The snap-type flood-resistant system can be effective in keeping floodwaters from a home or building if great care is taken in installation. This

system is not recommended unless a permanent installation is used where care and tests can be performed during the installation when flooding is not eminant. A cutoff barrier, sump, and pump must also be used unless some cutoff barrier is already in place (e.g., a concrete slab sealed to the base of the building and placed over an adequate area to sufficiently reduce underseepage). The two seal strips tested are shown in Figures 48 and 51. Leaks can develop in the snap-type waterproofing system if irregularities on the snap hold it open, if the plastic is wrinkled under the snap, or if the corners are not handled with care. Many minor details, depending on the particular situation, must be cared for adequately or leaks can develop.

If the physical construction of the building to be waterproofed will allow a simple system such as the one tested in Tulsa, Oklahoma (Part VI), the simple system should be used to:

- Eliminate the problems associated with the snap at the base of the house.
- Provide a cutoff barrier below the building foundation.
- Remain in place and allow easier and faster activation.
- Give much more dependability to the system.

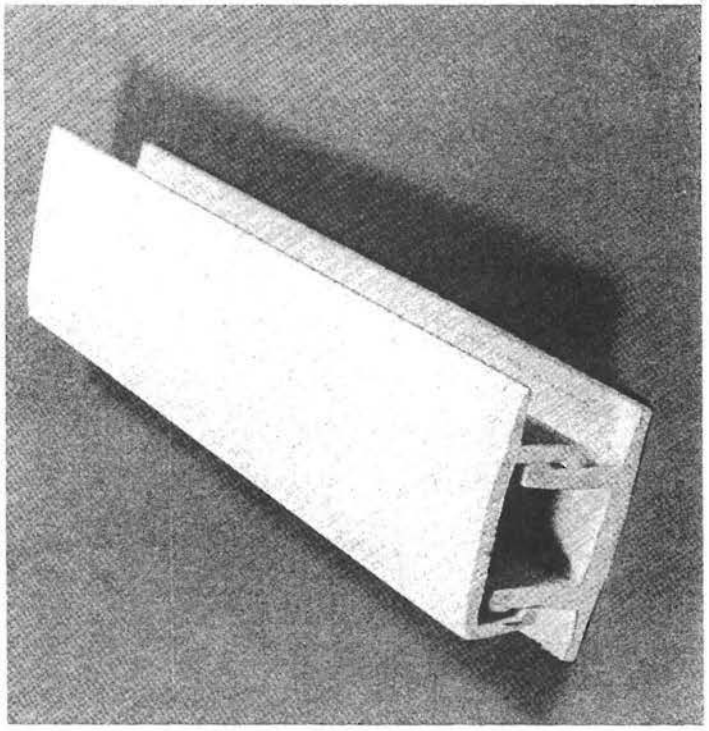


Figure 48. Designed sealing strip

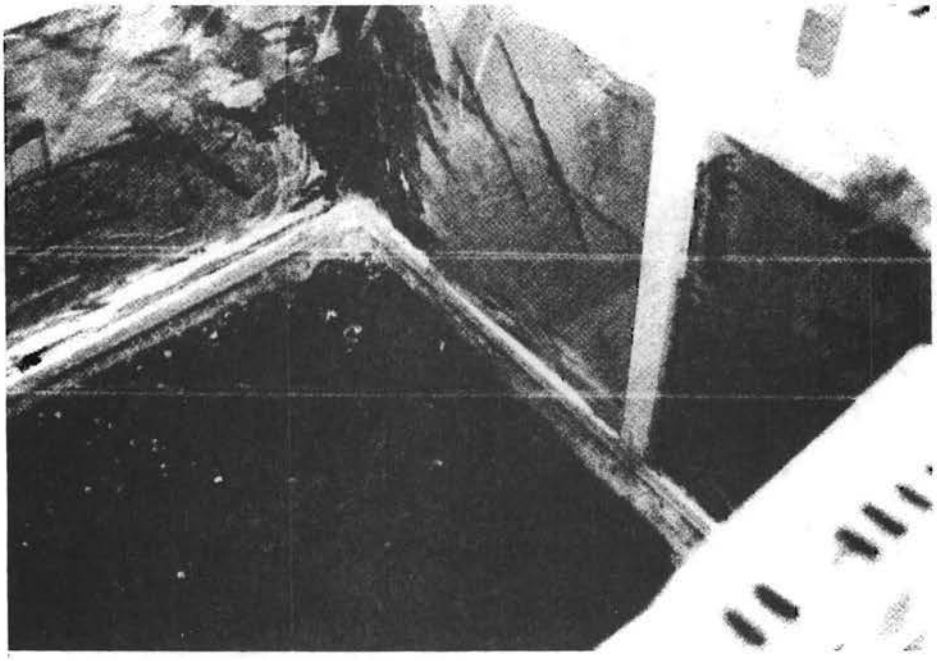
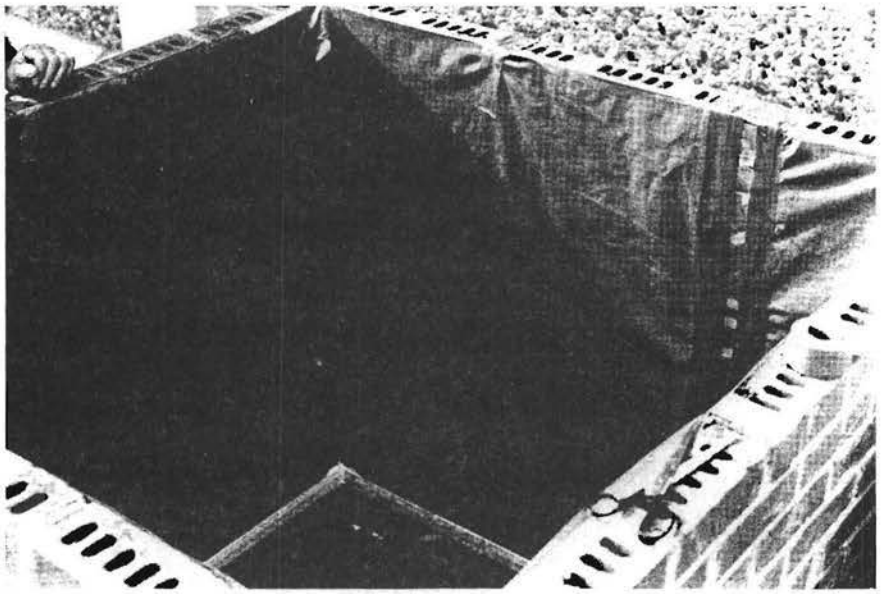
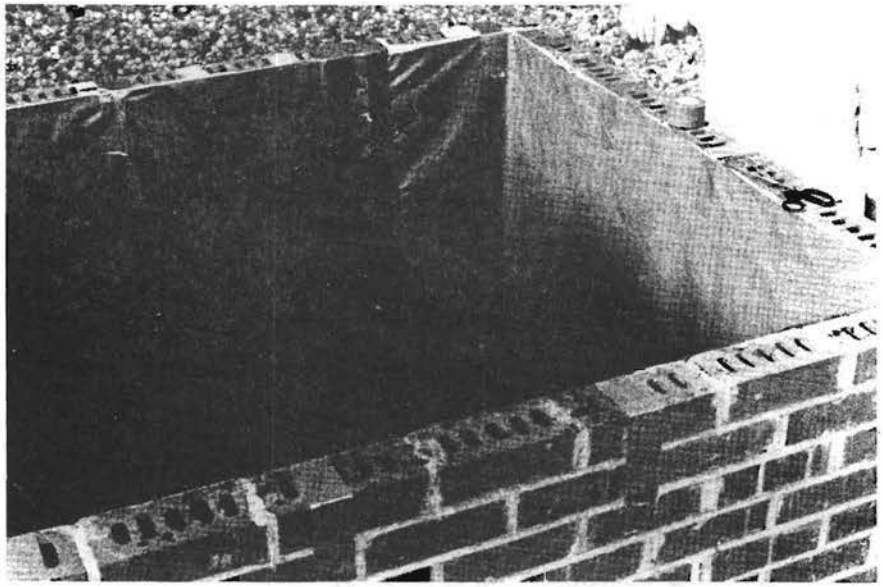


Figure 49. Seal strip snapped against plastic to form a seal



a. Seal strip corner



b. Plastic sheeting covering brick wall

Figure 50. Plastic sheeting and seal strip

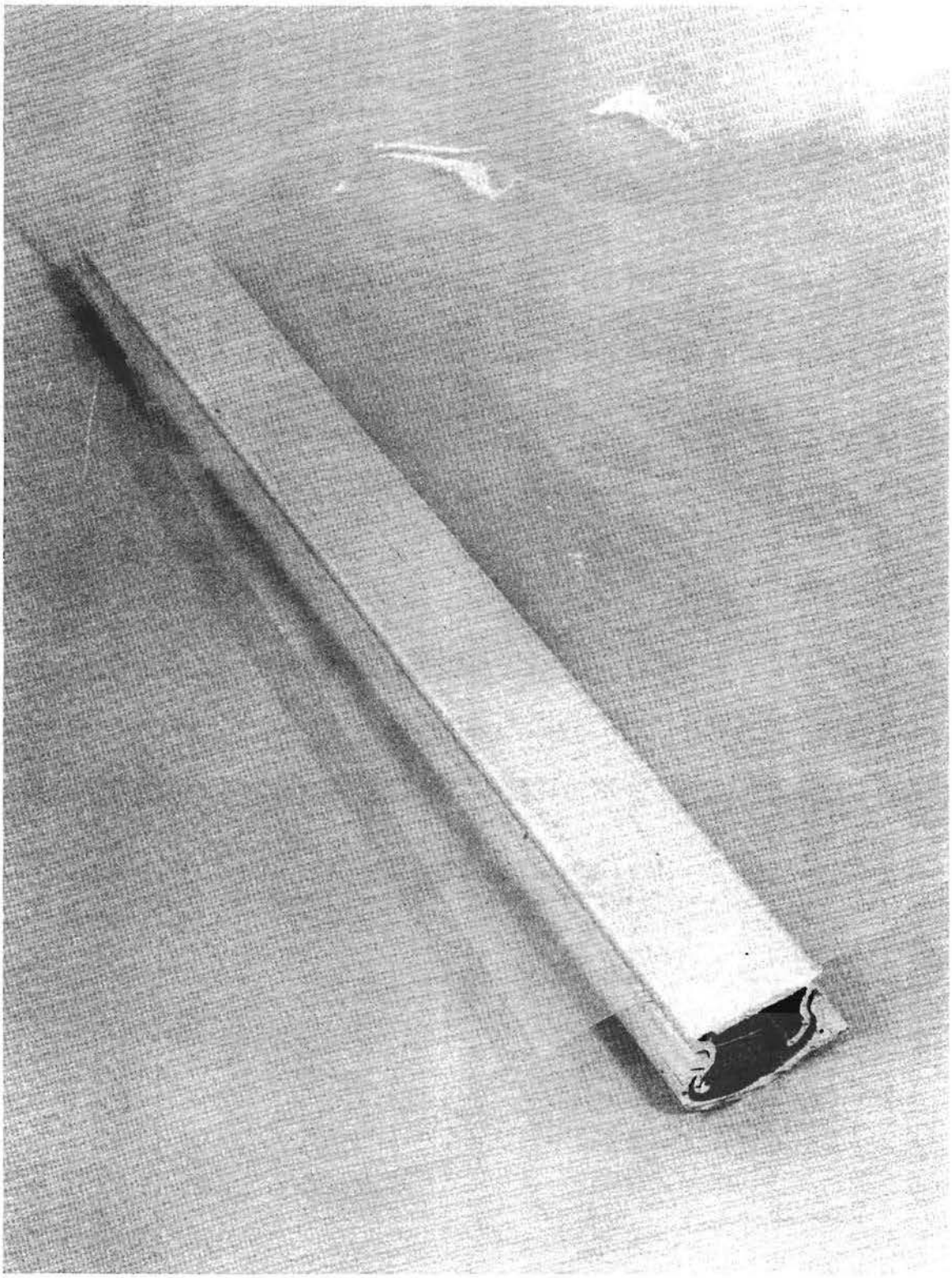


Figure 51. Commercially available seal strip

a. Front view

b. Side view

Figure 52. Dye in water leaking from large brick cube

PART VI: PROTOTYPE HOME TESTS

Allenville, Arizona

Background

Since tests had been performed to determine the structural integrity of brick and block test walls and since materials and systems had been tested for effectiveness in keeping floodwaters out of homes, the next step was to test an available water-resistant system on a prototype house. The US Army Corps of Engineers District, Los Angeles, was involved in relocating a previously flooded subdivision in Allenville, Arizona, a few miles west of Phoenix. All of the homes in the subdivision were vacated, and the homeowners were being relocated to another site. This situation presented a prime opportunity to select a suitable house on which to test flood-resistant systems.

The Los Angeles District was very helpful in acquiring the best available house and in helping with the test setup. Representatives of WES, the Lower Mississippi Valley Division (LMVD), and the Los Angeles District met at Allenville and finished test setup preparations and tested the house.

The objective of the prototype test was to (a) determine the practicality of using a durable, impermeable sheeting mechanically attached to the house slab as a flood-resistant system, and (b) substantiate earlier tests which determined acceptable design levels for such systems. Factors such as water seepage and uplift under the house and sewer closure systems were not studied in this test.

Test setup

The floor plan of the house is shown in Figure 53. The garage was not included in the testing. A plywood bulkhead was constructed in the garage along the side of the house (Figure 54), as shown in Figure 55. An earth berm was constructed around the rest of the house and tied into the plywood bulkhead (Figure 56). The earth berm and plywood bulkhead were used to retain a slowly increased water level. A plastic sheet was placed over the earth enbankment and plywood bulkhead and extended downward and under an aluminum channel, which was to act as a bottom seal for the flood-resistant system (Figure 57). The aluminum channel was attached to the house with screws and plastic inserts. The rest of the flood proofing system consisted of a reinforced plastic sheeting which had its top reinforced with gray duct tape and

secured to hooks which had been placed 2 ft apart in the outside wall (Figure 58). A properly sized O-ring was then pushed against the bottom of the reinforced plastic sheeting and into the aluminum channel. The O-ring was fitted against the reinforced plastic and into the aluminum to make a water-resistant seal (Figure 59). The total flood-resistant system consisted of this aluminum channel, plastic sheeting, and the O-ring insert around the base of the entire area of the house. Plywood reinforcement was used over door and window openings.

Two particular problems were encountered while constructing this system:

- It was difficult to find a material to bond plastic to plastic. A waterproof construction cement was used to bond plastic to plastic at places where plastic was lapped.
- Seating the O-ring into the aluminum channel was very difficult. Because of this difficulty, installation was time-consuming.

Gage system

Gages were placed on the walls inside the house to measure the wall deflection. The gage locations and numbering are shown in Table 2. Figure 60 shows some typical gage placements. The wires from the gages were run through windows to an automatic data recording system which was located in a van.

Test results

The deflections of the walls were recorded during both the loading and unloading of the house. Typical data are presented in Figure 61.

Water was obtained from a well and pumped to the test site (Figure 62). The water level was raised slowly on the outside of the house, and as the water level increased, some seepage did occur inside the house. About 1 in. of water leaked into the house during the test in which 4 ft of water flooded the outside.

The results demonstrated that house walls are stronger than individual test walls and that a prototype house can withstand approximately 3 ft waterhead without damage.

The walls of the house were damaged by a 4-ft waterhead. This damage is indicated by the test data in Figure 61. The unloading curves show permanent deformation in the walls. An inspection the next morning after the water load had been removed revealed that the brick wall had visual cracks in the mortar joints.

Plastic was placed over the earth berm and under the aluminum strip to prevent water loss through the highly pervious soil during the test. Some of

the leakage problems occurred because of this installation. It was discovered that the weather stripping material did not stick to the plastic where it was placed at the intersection of the plastic and aluminum strip. However, it should be noted that the plastic under the aluminum strip would not be present in an actual flood-resistant construction.

Tulsa, Oklahoma

Background

Previous tests on models and at Allenville, Arizona, had not included the effects of underseepage; therefore, this factor was included in the Tulsa tests along with other factors associated with static water pressure. A durable, impermeable, flexible sheeting system was tested at Tulsa.

A request for contractor interest was published in the *Commerce Business Daily** on 6 February 1984, and one contractor responded. This test was conceived with the knowledge that contractors are continuously developing systems and experimenting with materials that, when properly applied, can keep floodwaters out of homes and buildings. The test was, in effect, a demonstration project that provided commercial flood-resistant construction contractors an opportunity to test their products in a controlled environment. The contractor was responsible for the installation of the system, and the US Army Engineer District, Tulsa, coordinated the work, built a dike around the house (Figure 63), and supplied the water for testing the system. Personnel from WES inspected the test setup, observed and documented the test, and reported the results. LMVD provided the overall supervision of the project.

Test setup

The contractor had a simple, but logical, protective system. The system was composed of a fabric of vinyl-coated nylon with special fungus inhibitors (Figure 64) embedded to some depth in the ground (Figure 65, schematic of system) next to the house to reduce underseepage by creating a longer seepage path. The fabric was extended out of the ground and up the side of the house to form a continuous water-resistant barrier. A trough-like container at ground level (Figure 66) was used to store the fabric. The permanent storage system for the fabric was very efficient because the lid to the container

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* *Commerce Business Daily*, Feb. 6, 1984, Washington, DC.

could be opened (Figure 67) and the fabric rapidly pulled up on the house and connected to permanently installed snaps (Figure 68). A drainage system was installed at the base of the cutoff barrier (Figure 65) to intercept and drain any underseepage into a sump (Figure 69). It was then pumped outside the protected area (Figure 70).

The prototype house was located in Tulsa County, Oklahoma. It was in a Corps of Engineers project area and was subject to removal and salvage. To facilitate testing, the shrubbery and debris were removed from the perimeter. Installation of the system required a trench to be dug beside the footing to a depth of approximately 2 ft. After the digging was completed, the drain system was installed, as shown in Figure 65. A 4-in. perforated drainpipe was placed at the base behind the protective fabric, and a filter system of rocks was placed over the drainpipe. An adhesive was spread on the house wall at ground level to seal a 2- by 4-in. board to the house. The 2 by 4 was then attached to the house by drilled holes, inserts, and screws.

The protective fabric was positioned in the trench and on the house. A 1- by 4-in. board was placed against the fabric and attached to the 2 by 4. The storage compartment for the fabric was attached to the 1 by 4. Once the storage compartment had been attached to the fabric and to the house, the backfilling of the trench was begun. The fabric was tightly positioned against the foundation at all times as the backfilling and tamping was accomplished. The backfill was compacted in 6-in. layers to achieve a density which would minimize the seepage of the floodwaters. Since the test was performed about 2 days after compaction of the backfill, the fill did not have time to settle and reduce permeability. It is believed that the early testing of the system caused the seepage to be more severe than would have occurred with a better-compacted backfill.

The upper snaps (Figure 68) for attaching the protective fabric to the house at the desired elevation were installed. The top elevation of the protective sheathing should be the depth of flood protection plus 6 in. to 1 ft of freeboard to protect the house from waves caused by boats, wind, etc. (As stated earlier, the maximum depth to which a house or a building should be made resistant to floodwaters is approximately 3 ft.)

A backwater valve was installed in the sewage drain line to keep the floodwaters from backing up into the house through the toilet and bathtub. This was accomplished by cutting the 4-in. drain pipe leading from the house

and placing the valve in the line. The valve was enclosed in a plastic standpipe with a screw-on lid to provide easy access.

For the purpose of this test, plywood sheathing and wooden braces were used to provide support for the protective fabric around the patio and porch. These areas could be equipped with decorative railings of the desired height to serve as permanent support for the fabric. A temporary brace can be installed at the time the system is to be used. Temporary bracing can also be prepared for garage doors (which have excessive span) to support them when a water load is acting on the door.

The fabric was raised from the permanent storage compartment and attached to the house by permanently installed snaps. A levee had been built around the house; and, with the fabric in place, the house was ready for testing.

Testing

Water was pumped into the area between the house and the dike (Figure 71). The water level was raised to a 1-ft head on 23 May 1984 and was held overnight. On 24 May 1984, the water level was raised to produce a 3-ft head on the walls of the house which was held for approximately 24 hr.

Test results

As the water level was being raised to the 1-ft head, underseepage developed rapidly but stabilized in about 2-1/2 hr to 10 gal per min. There was some movement of fines into the sump, but the water cleared up during the night of 23 May 1984. The pump (Figure 72) ran for about 40 sec and then cut off for about 50 to 55 sec after the water level in the sump had been pumped down to a set level. This cycle continued until the raising of the water level around the house resumed at approximately 9:50 a.m. on 24 May 1984.

As the water level was being raised toward the 3-ft level, the underseepage increased. At 11:00 a.m. on 23 May 1984, the seepage level became too high in the sump (the level setting for the pump cuton and cutoff was too high). This development allowed the seepage water to rise excessively and caused some water to seep under the garage door (Figure 73) which was the lowest level for the house. The limits on the sump pump were changed, and the water was kept at a lower elevation in the sump which decreased the rate of seepage under the garage door.

There was a little seepage around the baseboards of some rooms (Figure 74). After the test, the cause of this seepage was found to be a leak at the lap of the fabric. The lap of the fabric was heat-treated but was not

sealed adequately, and a small leak at the lap caused water leakage behind the seal and into the house.

In general, there was too much underseepage during this test. A larger pump had to be put into the sump with the smaller pump. The large pump pumped continuously and the smaller pump ran intermittently.

Also, the fabric was not placed deep enough in the ground to lower underseepage to an acceptable level. The fabric was placed about 2 ft below the ground without any knowledge of how this embedment would decrease the underseepage. Onsite tests and tabular or graphical data should be used to determine the depth of cutoff to control underseepage. For example, percolation tests could be performed onsite, and the values could be used in charts to determine the underseepage for various depths of fabric embedment. From this analysis, a depth of fabric could be determined which would control underseepage to a tolerable level. Such an analysis would also allow the selection of a sump pump which could handle the underseepage.

Construction details must be considered carefully if any flood proofing system is to work properly. For example, fabric laps must be very carefully sealed, drains properly installed, and all construction adequately braced. Merely sealing to the extent that it is believed the barrier will work is not sufficient when attempting to make a barrier impermeable to a head of water. If attention is not paid to these details and the possibility of a leak is present, it is highly probable that a leak will occur.

The backwater valve worked well. It was found that it is important to embed the pipe in the filter material such that fines are not leached away and the filter will pass clear water easily. An appropriate filter cloth should be used to cover the filter material to help in stopping the movement of fines and to produce an effective filter.

No holes should be placed in the fabric by screws, nails, etc., when connecting the system to the house, since doing so produces a possibility for leaks.

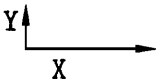
Table 2

Gage Designation and Location

Room	Gage*	X, Y Coordinate: Reference Corner Location in House	X, Y Coordinate: Coordinates
Kitchen	1-ES	NE	86-1/2 in., 24 in.
Kitchen	2-NW	NE	60-1/2 in., 29 in.
Br 4	3-NW	NW	60 in., 24 in.
Bath	4-NE	NW	26 in., 24 in.
Br 3	5-NE	NW	65 in., 24 in.
Br 3	6-WS	NW	83 in., 24 in.
Living Room	7-EN	SE	86 in., 24 in.
Living Room	8-SW	SE	84 in., 24 in.
Br 1	9-SW	SE	61 in., 24 in.
Br 2	10-SE	SW	77 in., 24 in.
Br 2	11-SE	SW	24 in., 24 in.
Br 2	12-WN	SW	24 in., 24 in.
Br 2	13-WN	SW	77 in., 84 in.
Br 2	14-WN	SW	77 in., 48 in.
Br 2	15-WN	SW	77 in., 24 in.

* Example of gage numbering:

First letter of gage designation is the direction of the wall in the room.
Second letter is the direction from reference corner.
Letter designations are: E - East; W - West; N - North; S - South;
Br - bedroom.



coordinate system

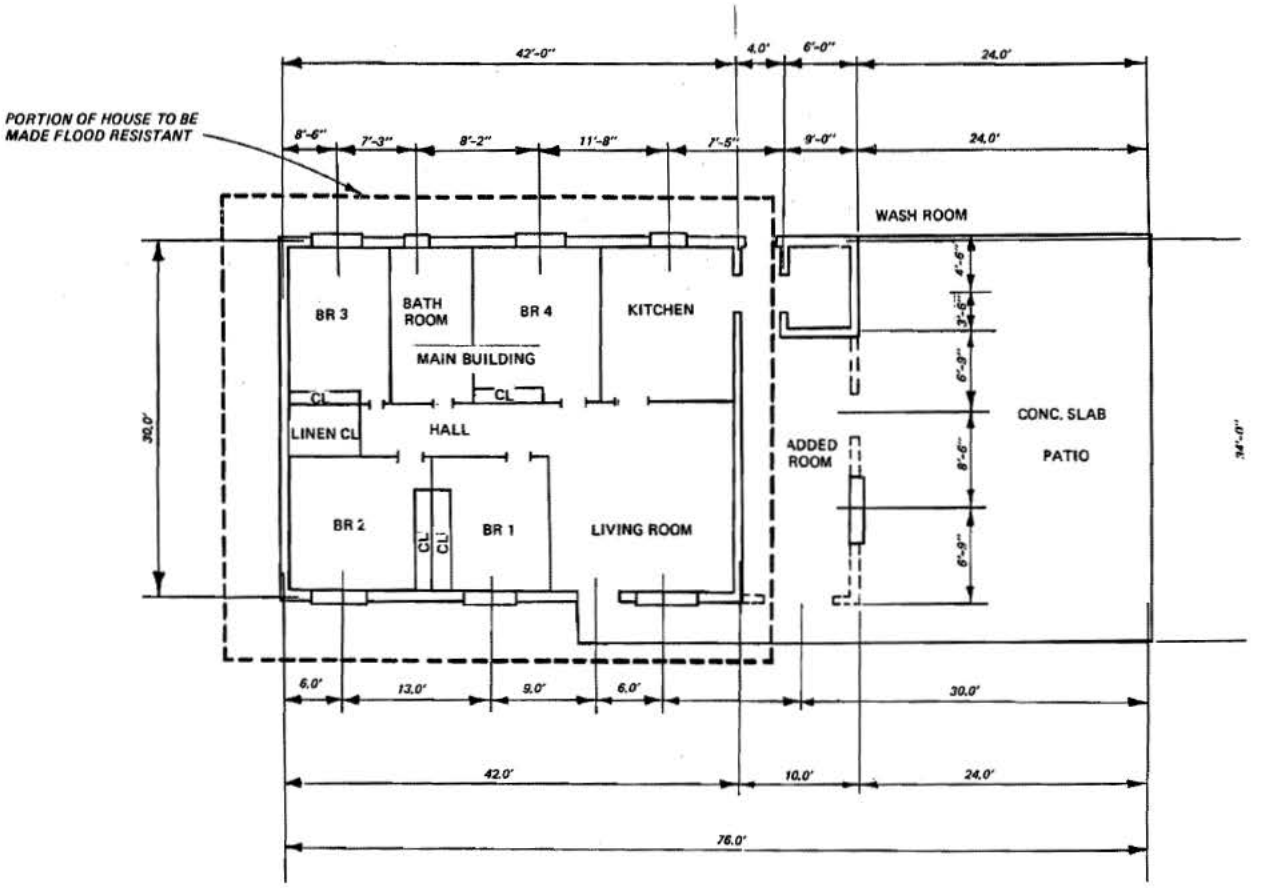
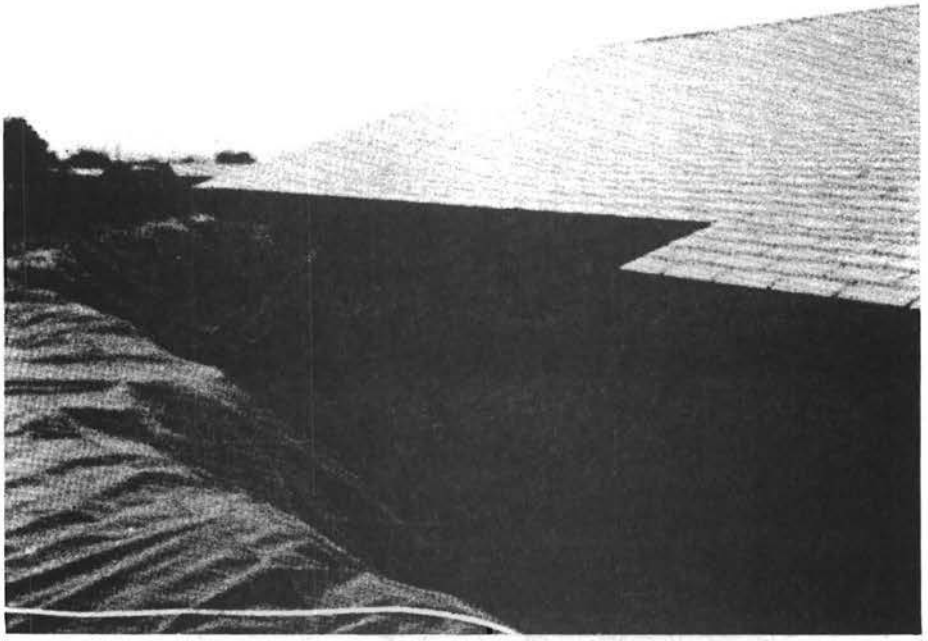


Figure 53. Floor plan of house

Figure 54. Front view of house to be made resistant to floodwaters

Figure 55. Plywood bulkhead



a. Earth berm

b. Plywood bulkhead

Figure 56. Earth berm and plywood bulkhead

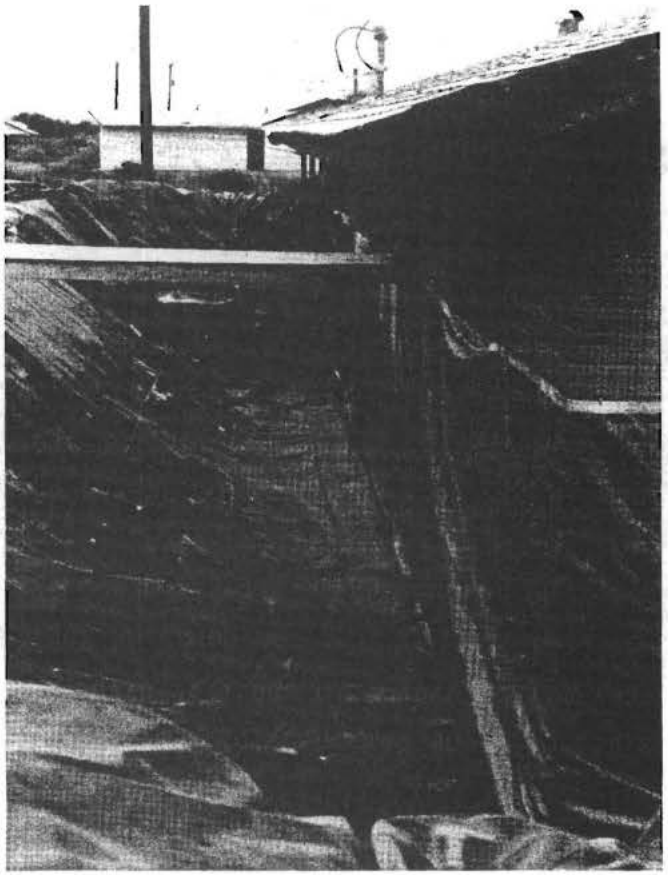


Figure 57. Plastic-over-earth berm extending down and under aluminum sealing strip

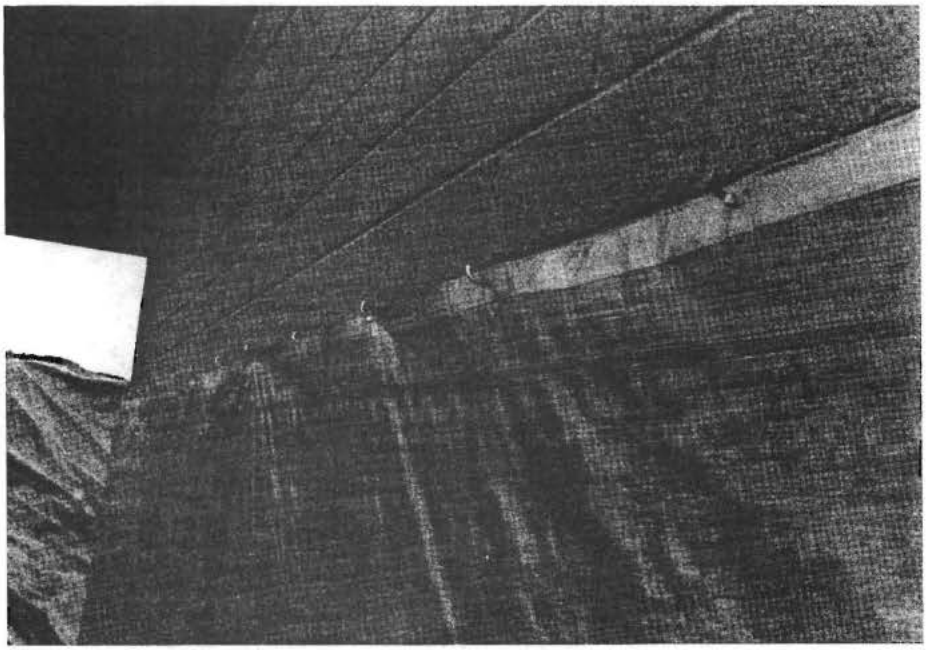
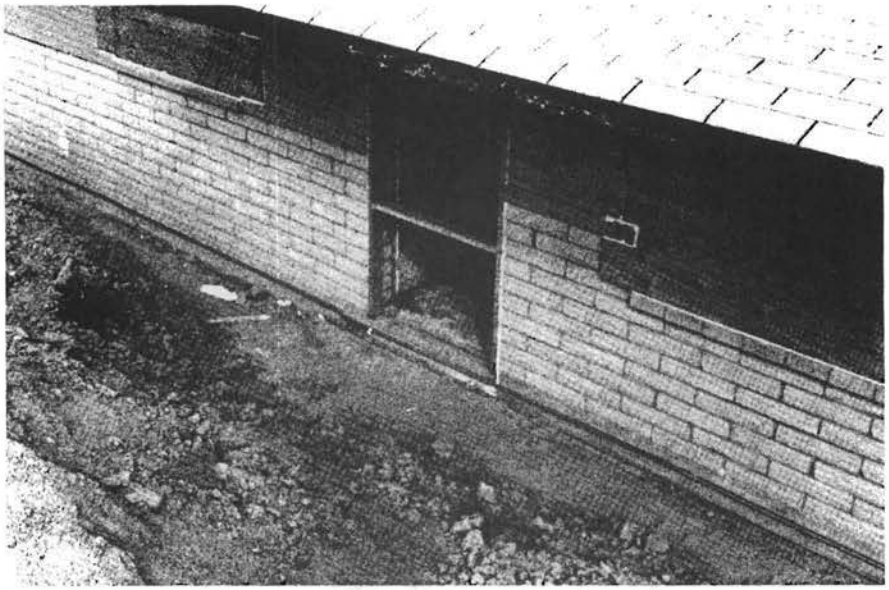


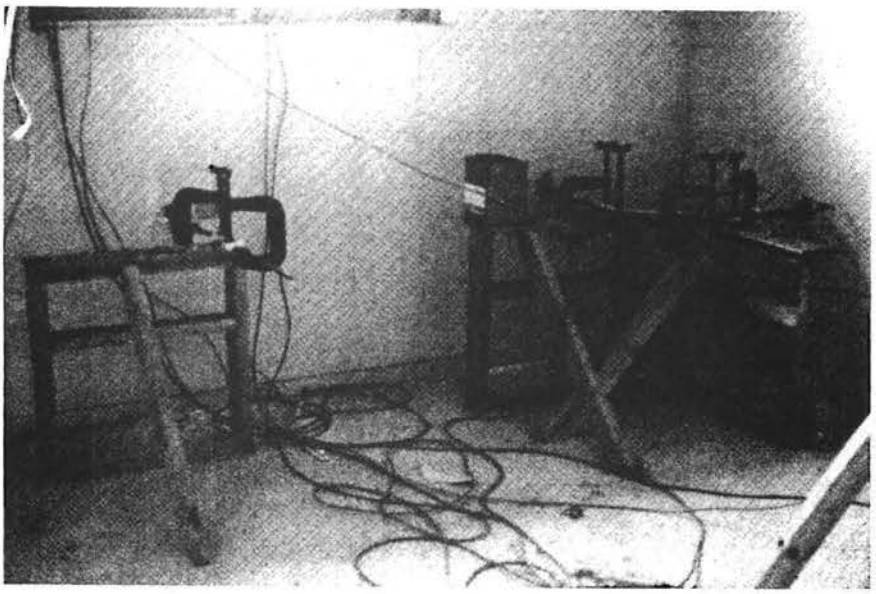
Figure 58. Hooks holding reinforced plastic sheeting



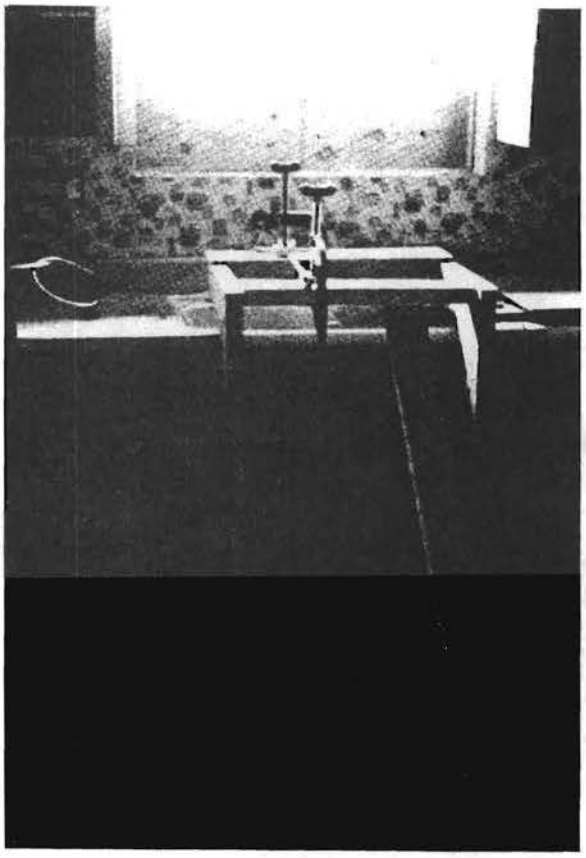
a. General view

b. Closeup

Figure 59. Aluminum strip around base of house



a. Bedroom 2



b. Kitchen

Figure 60. Gage placement

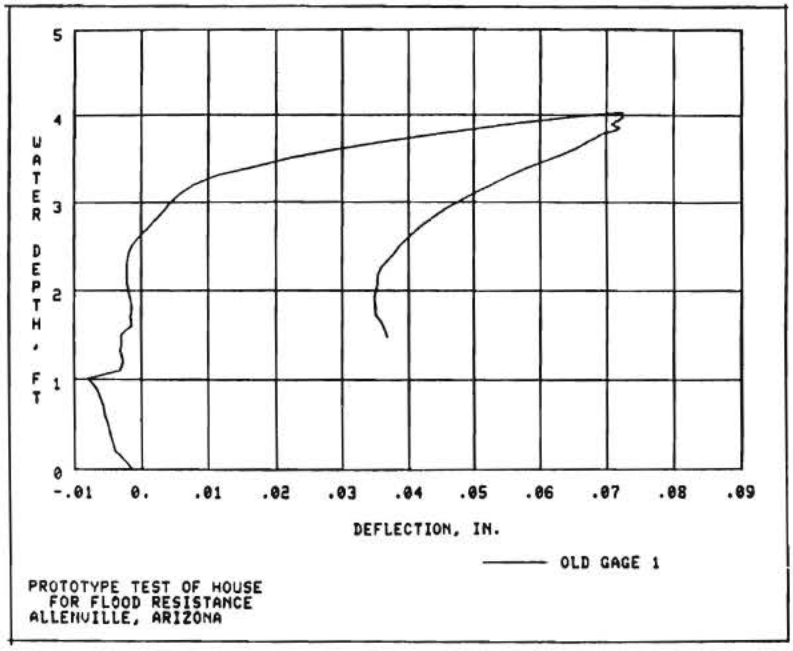


Figure 61. Prototype house test results, gage 1

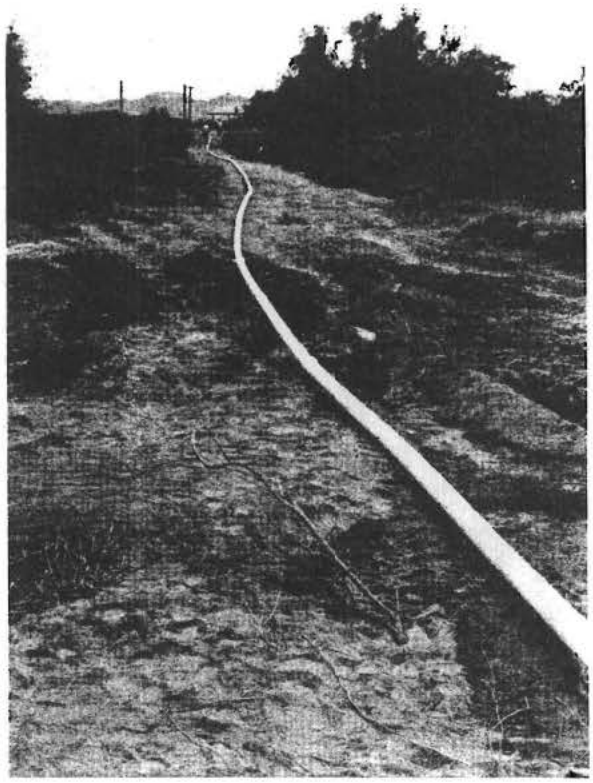


Figure 62. Pipe through which water was pumped to test house

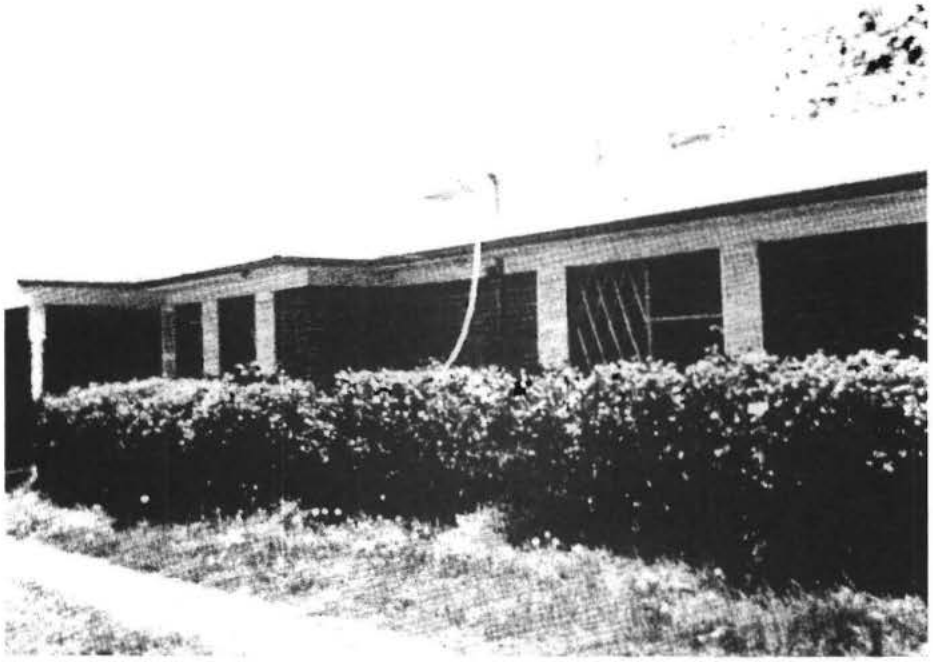


Figure 63. Prototype house, Tulsa, Oklahoma

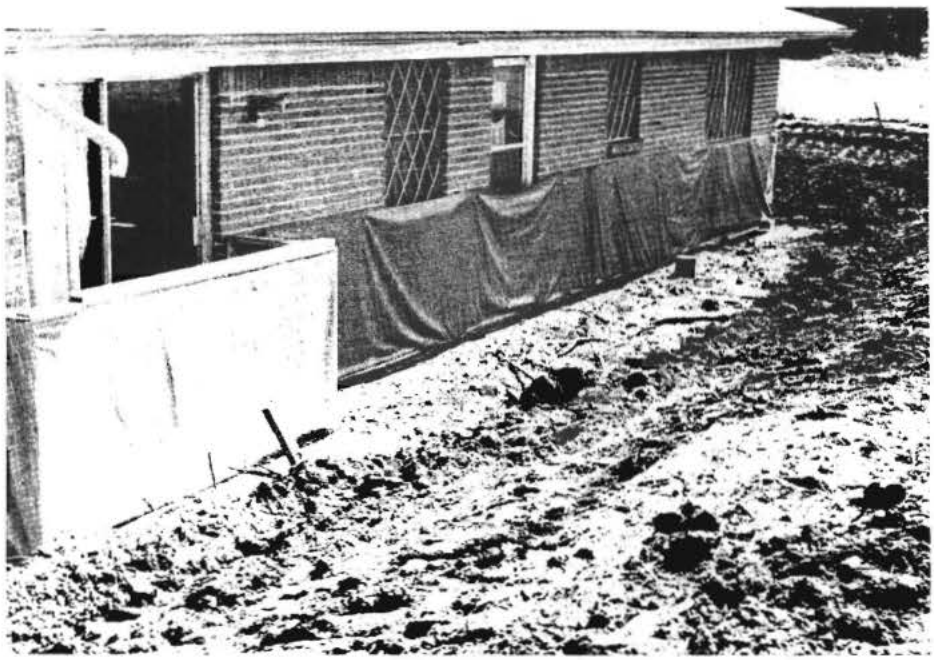


Figure 64. Vinyl coated nylon fabric, with special fungus inhibitors, used in preparing house to resist floodwaters

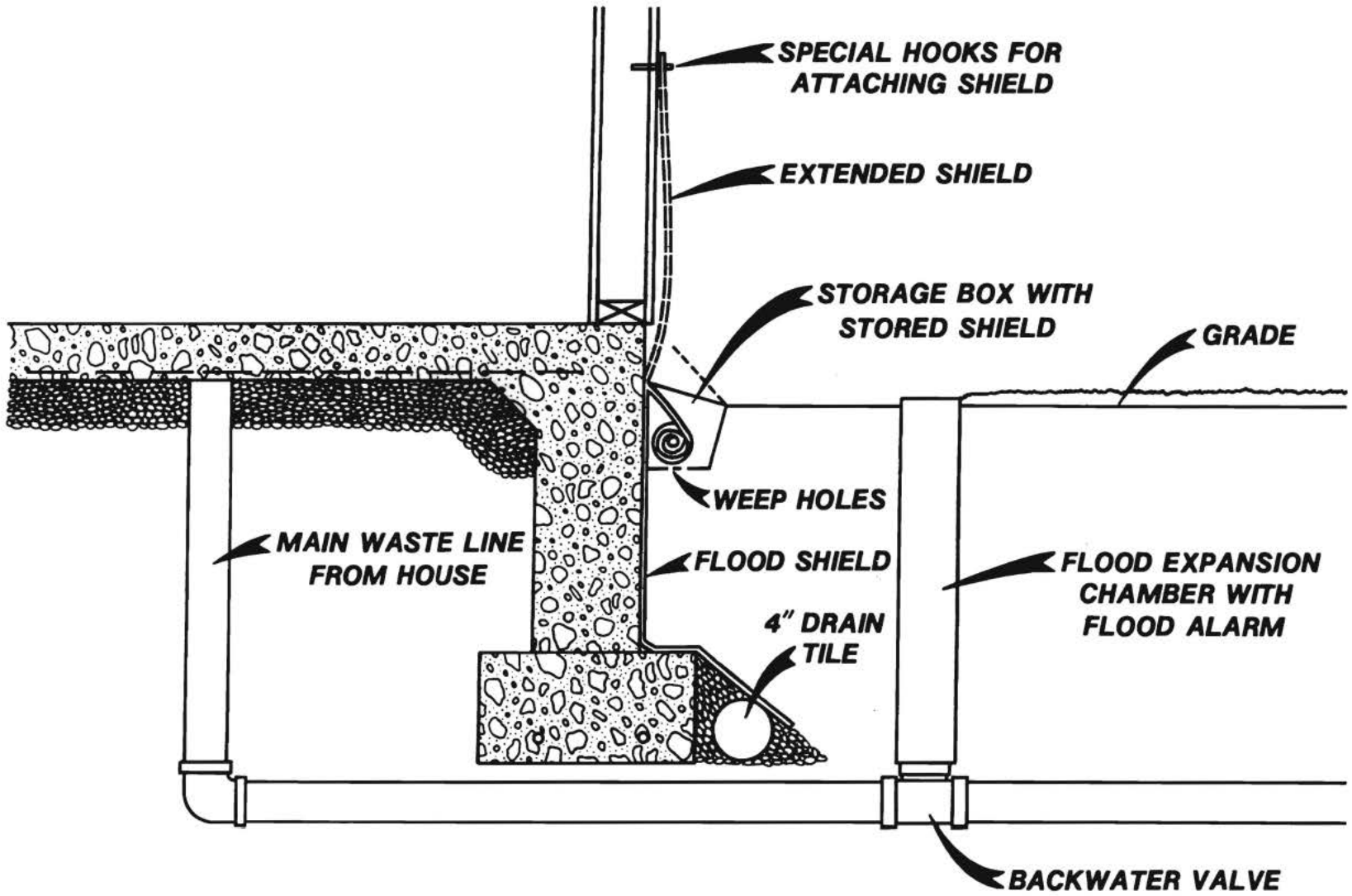


Figure 65. Schematic of embedded fabric and drainage system making up the installed flood shield

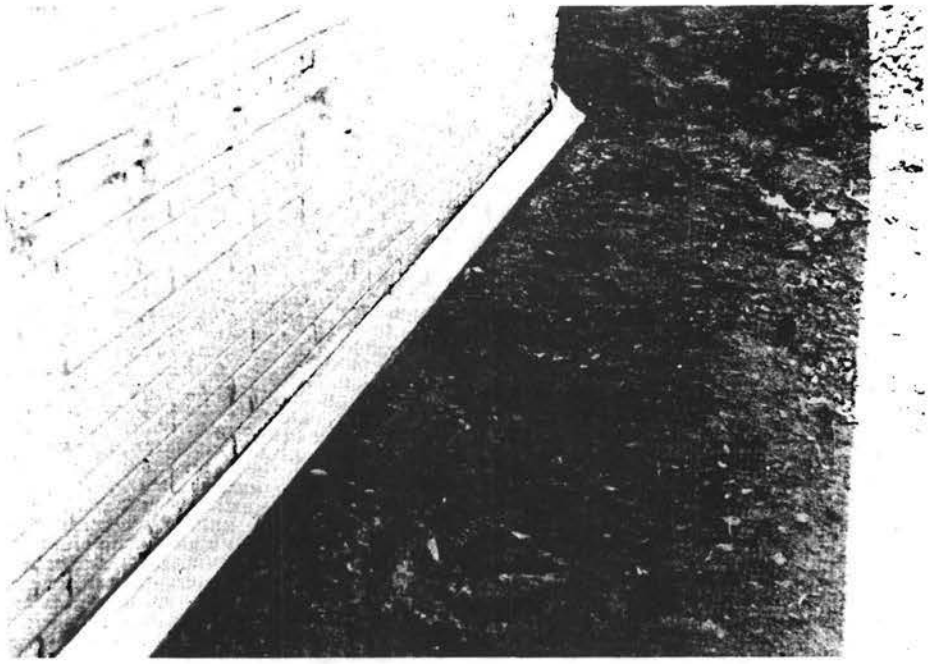


Figure 66. Trough in which protective fabric is permanently stored

Figure 67. Protective fabric being removed from storage container and attached to the house at the desired elevation

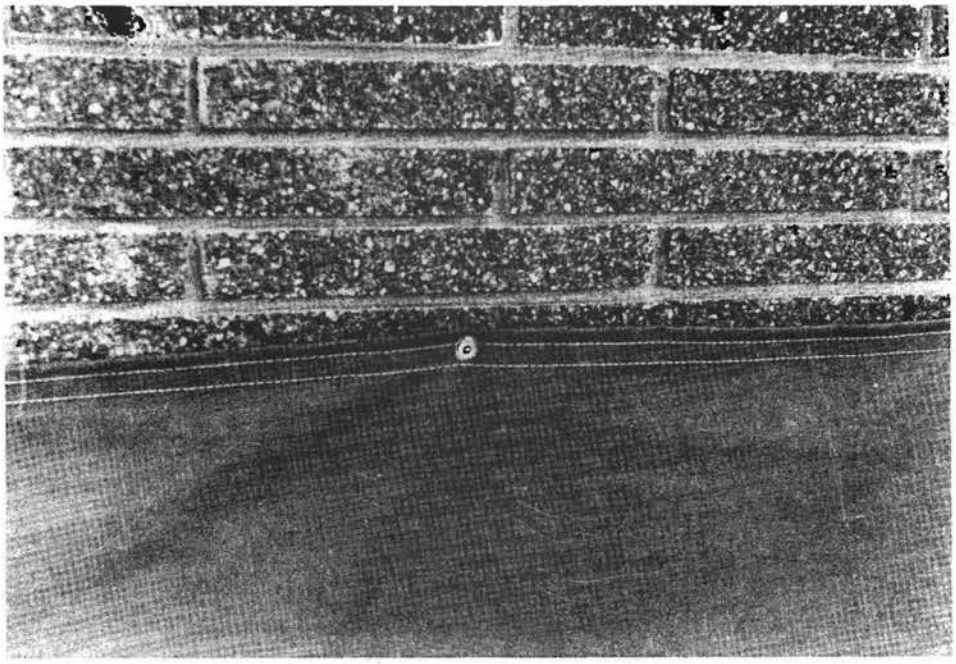


Figure 68. Permanent snap connected to the protective fabric

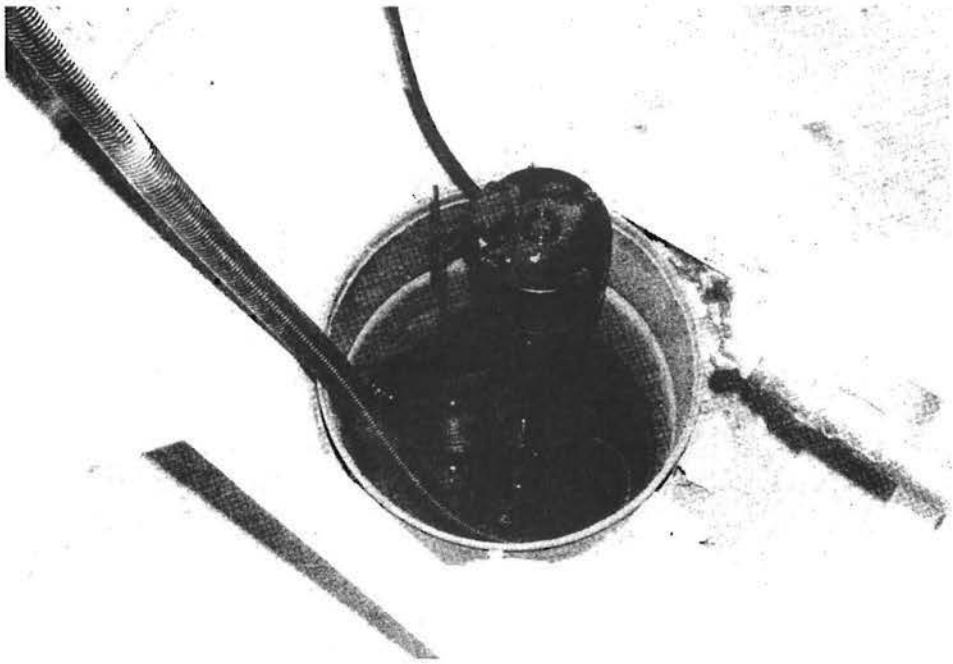


Figure 69. Sump for collecting underseepage

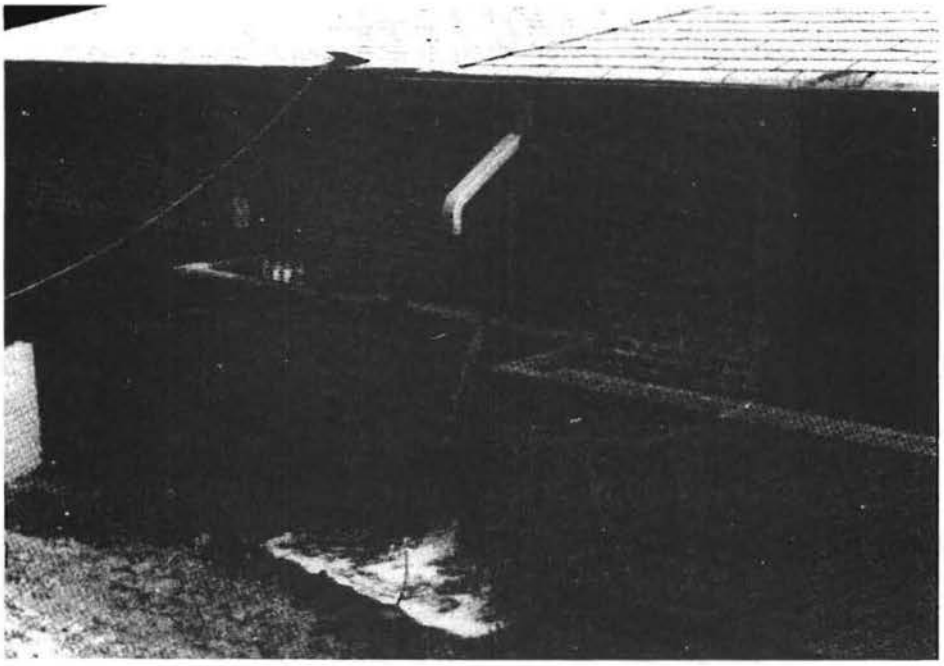


Figure 70. Water being pumped outside the protected area

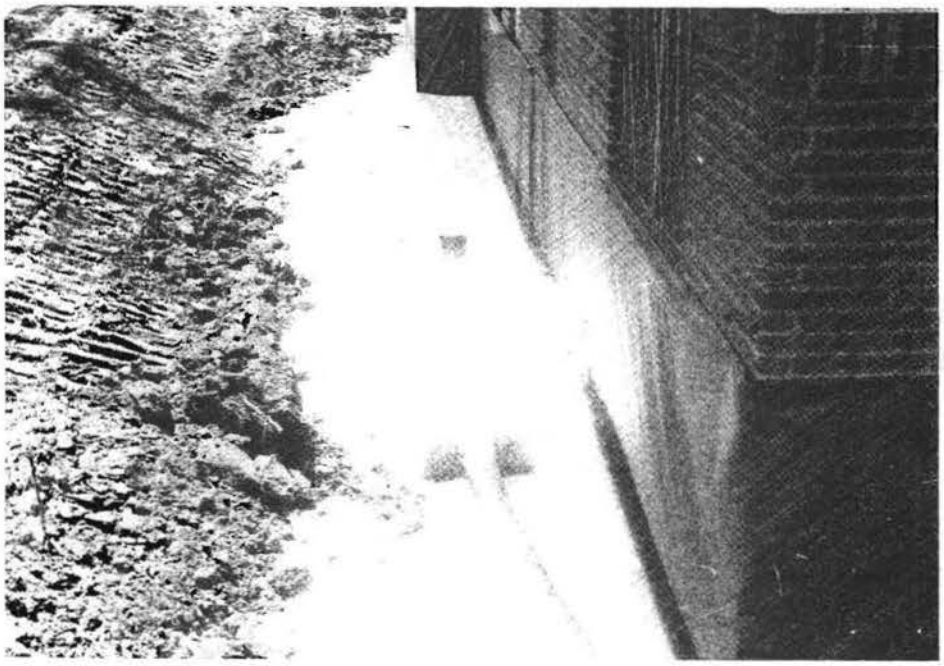


Figure 71. Water being pumped between flood shield and dike

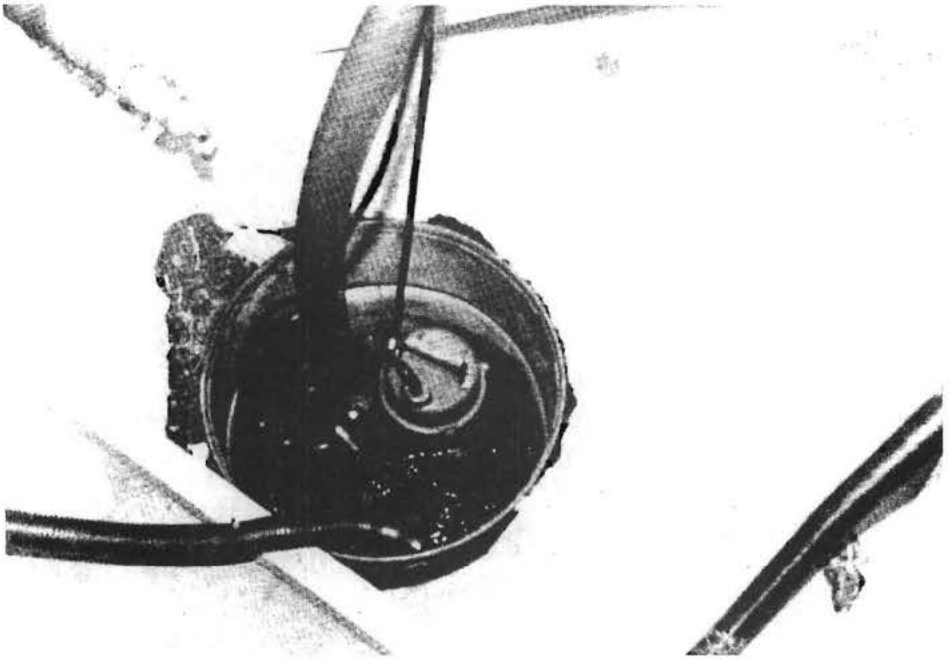


Figure 72. Pump used to keep water level low in sump

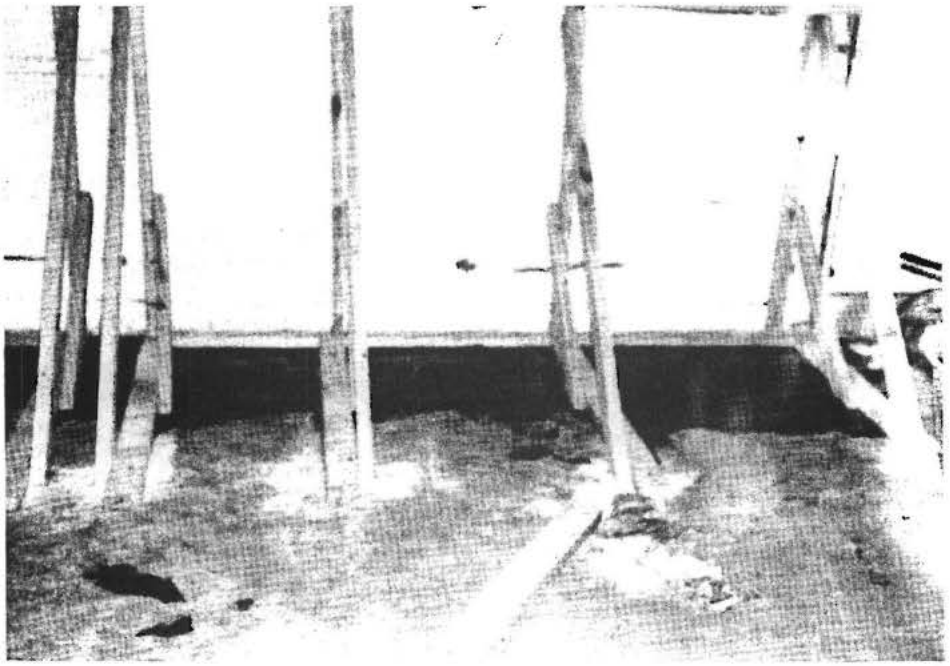


Figure 73. Water seeping under garage door due to excessive water height in sump

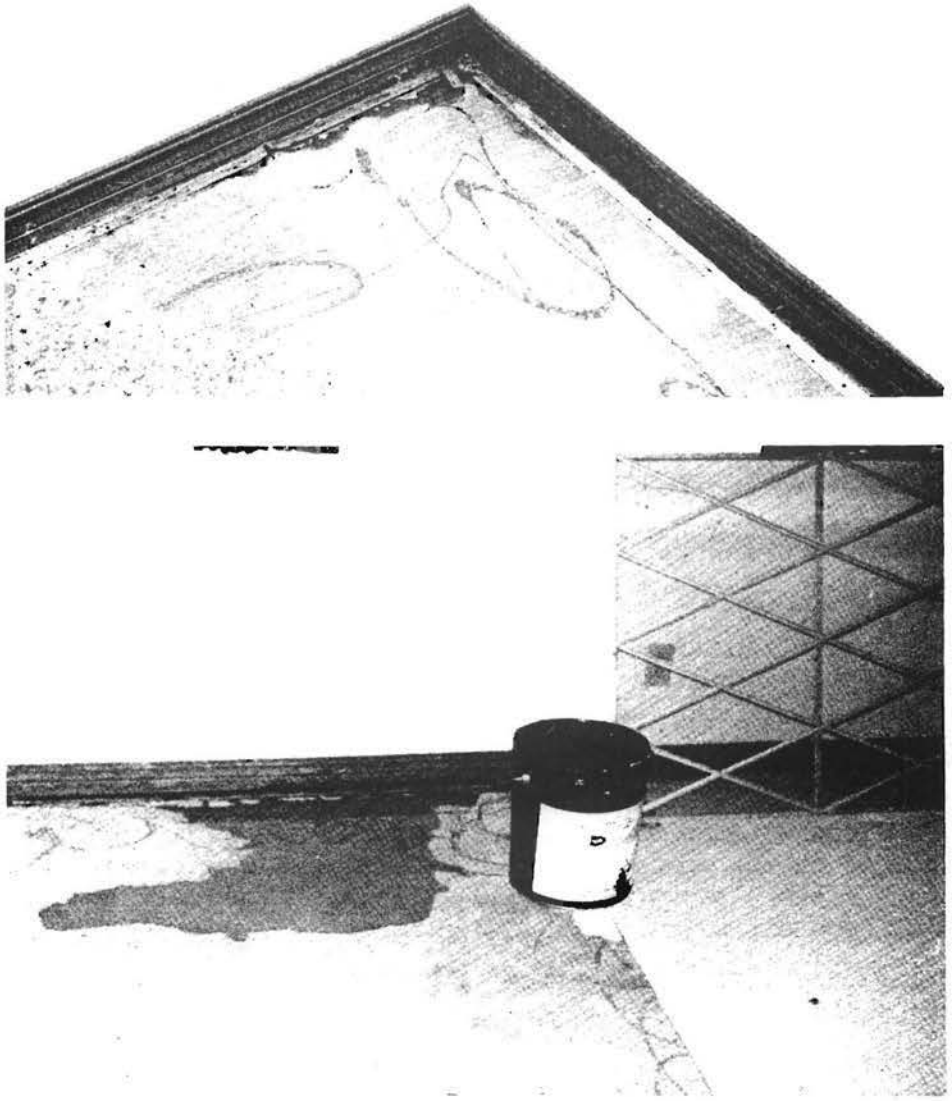


Figure 74. Seepage along baseboard due to leak in lap of fabric

PART VII: CONCLUSIONS

Results of tests performed by WES for the Corps of Engineers National Flood Proofing Committee clearly identifies materials and systems which can be used to protect individual buildings from floodwaters.

The evaluation of the flood frequency and the height of water which a building can support is a necessary part of the study of systems and materials to protect buildings from floodwaters. It is better to allow water to enter a building than use flood protection methods that subject the building to water loads that structurally damage or collapse the walls. Flooded buildings may be reusable once they have been cleaned and the water damage repaired.

Experimental data were obtained by subjecting three brick-veneer and two concrete-block walls to a static head of water.

The test walls which did not have roof rafter and ceiling joist restraint, such as the end walls of a house, failed at about 2.4 ft of water loading. The brick-veneer wall which did have roof rafter and ceiling joist restraint collapsed at 57 in. of water loading. The collapse was so sudden that persons inside could have been killed. The testing of two houses later demonstrated that the constructed house is stronger than the test walls and can safely withstand about 3 ft of waterhead.

As a result of closure and preliminary material tests it was determined that:

- The common brick-veneer wall leaks excessively.
- The brick-veneer or block wall can be protected against excessive water penetration if it is coated with a material which is thick and durable or is protected by an impermeable material.
- For a closure to be watertight, it must have gasket material and must be bolted at its connection to the sidewalls and bottom. The connections for the closure at the sidewalls and floor must be continuous and sealed securely to the walls and floor.
- Two layers of brick will allow a brick-veneer wall to support greater water depths.
- Seals made by snap connections at the base of a building for membranes which extend up and protect the walls of a building are difficult to make watertight and are difficult to make work and should be used only as permanent installations and where more reliable systems are not applicable.

Sealing materials are only one component of a system to protect buildings from floodwaters but they may be useful in specific situations. The tests on sealing materials showed that:

- Some clear coatings were very effective at beading and repelling water, but would not keep a brick or block wall from leaking against a small head of water.
- Of five cementitious coatings which were tested, only two have proven successful over an 8-year period in the climate at Vicksburg, Mississippi. Both coatings can be mixed to the consistency of paint and brushed or rolled on the wall. One is a proprietary coating which seeps into the pore space and seals the wall, and the other is a coating formulated at WES, which has excellent bonding properties and is relatively impermeable to a head of water.
- Epoxy, polyurethane, and asphalt coatings were not dependable in keeping water from penetrating a brick-veneer wall.

Systems of durable, impermeable, flexible sheeting tests on brick cubes and prototype houses demonstrated that a simple continuous system is the most reliable. Snap connections are not reliable. The simple system given in this report is adequate to protect a building from floodwaters.

Although further studies can aid in developments which will help owners protect their building from floodwaters, the systems and materials described in this report will allow the protection of buildings from floodwaters which do not exceed a depth of 3 ft.

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