MUD-BRICK VAULT AND DOME CONSTRUCTION.

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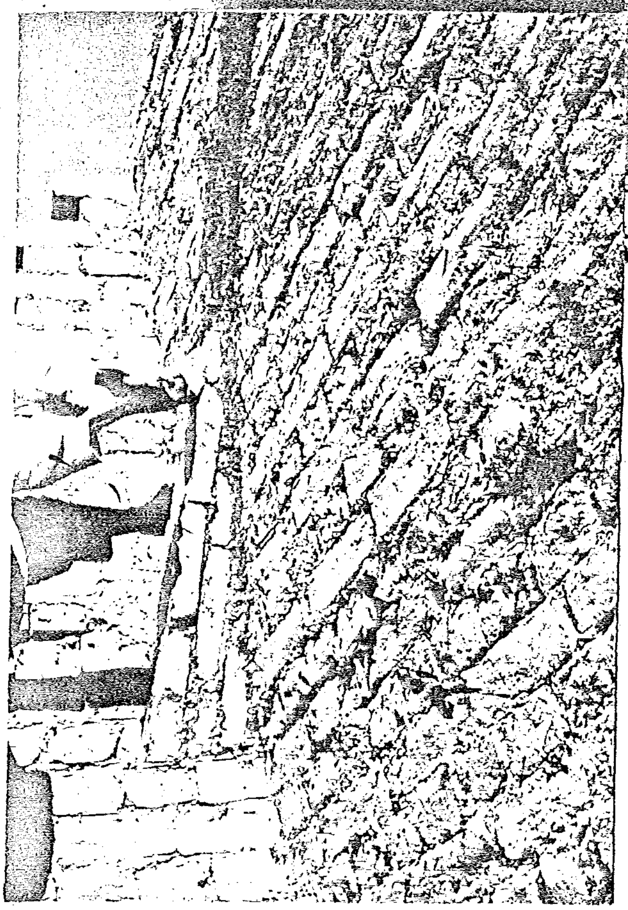

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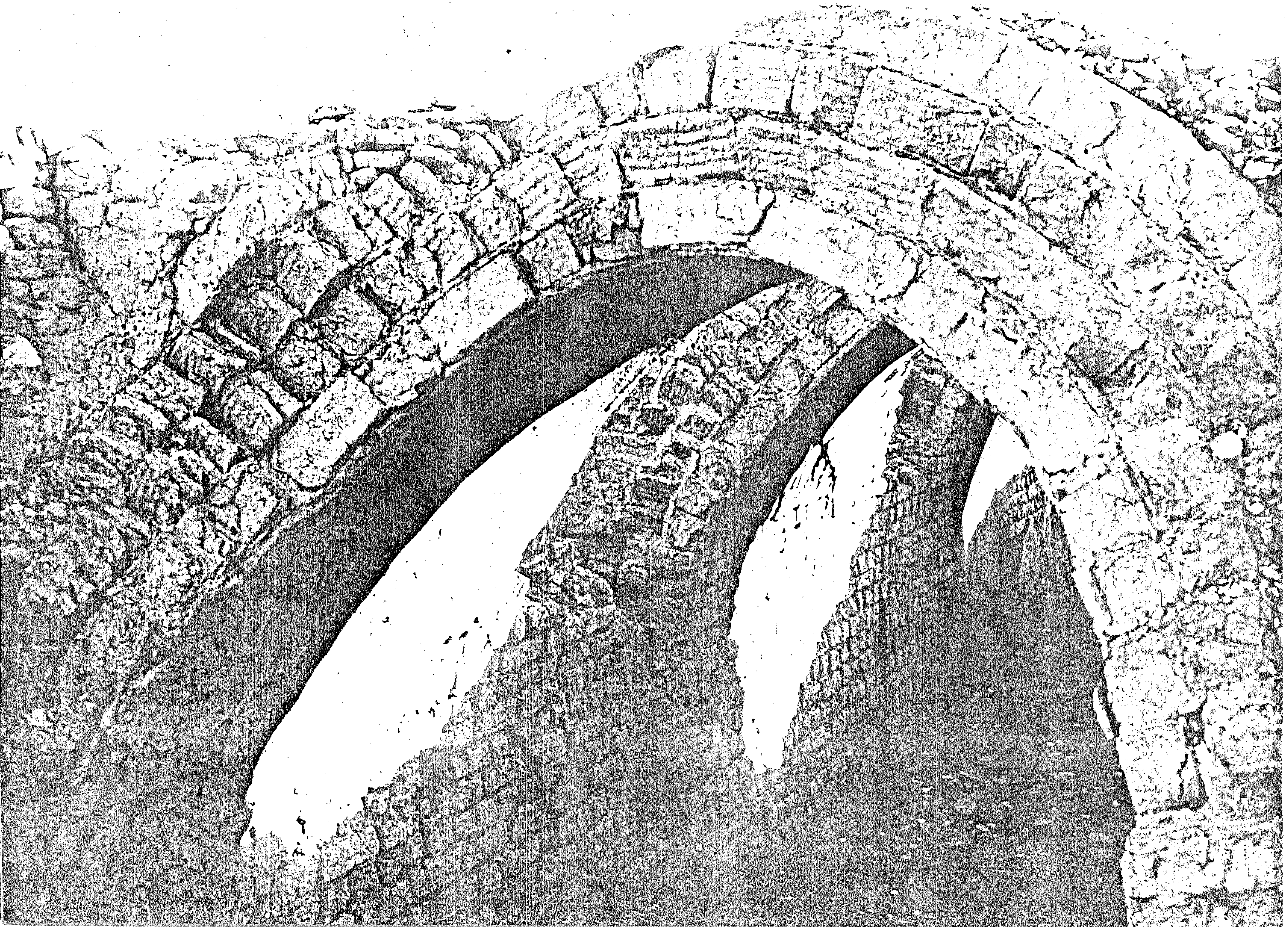
RAMASSEUM, LUXOR, EGYPT



INTRODUCTION

Mud-bricks have been used widely in hot dry areas for over 4000 years. The earliest prominent example is the Ramesseum in Luxor, Egypt.

Over these 1000's of years its use has been developed to a high level and whole villages from Iran to N. Africa a test to the potential and durability of the material.

Mud-brick combined with vault and dome roof spans have a variety of interlinked arguments in their favour and after the first prejudices against the use of traditional materials in favour of 'new technological wonders' are put aside, the material and building techniques deserves a fair investigation.

These arguments are briefly that mud and straw, the two basic ingrediants are widely available and cheap. The technique is easy to master and extensive building programmes can be initiated in a de-centralised manner that is, not dependent on major building industries and required infrastructure to produce and distribute the building materials. Thick mud walls have a definite climatic advantage preserving a constant cool temperature within the house for most of the day. Finally on a more intangible but perhaps just as important a level, mud-brick vault and dome housing appeals aesthetically, and does not violate in the spaces formed the cultural traditions of living. This and the related report attempts to investigate the above arguments.

ANALYSIS OF MATERIAL.*

1. SUITABLE SOILS

A thorough study of the characteristics of the soil available is always necessary before construction work is undertaken.

Mechanical analysis of the soil is not an infallible index as to the soils behaviour in brick making. Actual structural tests should be made before accepting or rejecting any soil for brick making. A good brick should be made with clay containing the amount of sand just suggicient to eliminate cracking when drying.

Although the addition of sand to natural clay soil weakens its strength, yet it reduces the shrinkage and cracking, and its addition is desirable as long as the strength remains satisfactory.

Clay may be added to sandy soils to increase their strength. Also two or more types of soils may be added together to produce a more satisfactory soil.

Soils favourable foh brick making should be free of loam and organic matter. The most favourable soils may consist of 60-70% silty clay and 30-40% fine sand.

Any soil having the percentage of sand or clay exceeding the above limits may be considered unsatisfactory. Clay or sand should be added to bring the proportions within these limits.

* From a thesis and experiments carried out at Cairo University under the direction of Prof. Ibrahim.

If either emulsified bitumen or cement is used, much care must be taken to obtain thorough mixing. Although the traditional method of using barefeet and hoes to mix cannot guarantee quality control their use over thousands of years have proved satisfactory. If quality control must be insured, mechanical mixers need to be used.

2. MOISTURE CONTENT

The essential control to ensure good brick quality is the moisture content. The optimum amount of water is a critical measurement. Both dry density and compressive strength vary directly with initial moisture content up to a maximum at some optimum valve of moisture beyond which both strength and density decrease from the maximum values. This is because too much moisture in the mix will dry out in the completed brick leaving voids. Such voids weaken the bricks compressive strength and its dry density is effected as the voids allow further moisture absorption.

The allowance limits for optimum moisture for bricks of compressive strength above 20 kg/cm^2 are from 20% to 35% in direct proportion with the amount of clay in the soil and in inverse porportion to the mean grain size. If straw is added this limit may reach up to about 45%.

Higher initial moisture content than optimum is better than lower. The mud can be filled and allowed to dry until the most desirable consistancy for molding.

3. STABLILISERS.

Adobe bricks without stabilizers are poor in quality, as they are very much affected by humidity and weather, their shape is irregular and their strength is inferior to other types.

Addition of stabilizers, however, is more likely to produce a cheap type of brick which may have a good number of properties of the red burned brick. The stabilizer is used to give the brick a better shape, durability and in some cases greater strength.

Although the strength of mud brick stabilized with straw or bitumenous emulsion is lower than that of the unstabilized adobe brick, it is found to be adequate for any load bearing commonly found in structures for dwellings.

Straw being often the cheapest and most available stabilizer is satisfactory, as it holds the brick together during initial drying, but it reduces slightly its compressive strength. If too much straw is added to a mix or if it becomes bunched in a brick, the brick will weaken considerably. So, no more than 2.5% by weight should be added.

The use of bitumen in the place of straw is only desirable in some parts where straw is either expensive or unobtainable, and its transportation would not be too costly.

Bitumenous emulsion must be especially designed for high efficiency in mixing with the fine particles present in soils to make good stabilized bricks. When buying bitumen for making bricks, the builder must necessarily rely upon the recommendations of the manufacturer and should be certain, first, that he has clearly explained what the bitumen is going to be used for, and second, that the bitumen recommended is an emulsion which has previously been used to make satisfactory stabilized bricks.

Samples of bitumen stabilized bricks should not average more than 2.5% moisture absorption by weight. The bitumenous emulsion merely saves as a waterproofer. A soil containing a higher percentage of fines will require too much bitumen to waterproof the bricks, it will be difficult to mix and is apt to crack in drying.

No more than 3 to 5% by weight of bitumen should be added to stabilize soil, as higher percentages weaken the adobe bricks to a certain extent.

The use of straw and bitumen together has been found to be more satisfactory.

The percentages recommended to be added together to soils favourable for brick-making to produce good stabilized abode bricks are for straw 2%, and bitumen 3%.

4. BRICK SPECIFICATIONS.

A series of test bricks of the full size to be used in a building should first be made to determine suitability of the soil, the proportion of sand and mixture required to prevent serious cracking and the proper amount of stabilizer for the particular soil chosen.

Adobe brick may be considered satisfactory and adequate for any load bearing commonly found in structures for dwelling, if its properties fulfil the following suggested specifications.

i. Small surface cracks are allowable in the bricks, but if these cracks extend through the bricks from one face to the other, the brick should be rejected.

ii. Bricks should be uniform in size, free of voids and sufficiently firm to haul, stack and handle without appreciable breakage or crumbling of the corners. The surfaces of the bricks should show good resistance to barasion when rubbed with the hand.

iii. Bricks should be cured not less than 30 days or until they have reached a constant weight, before they are laid in a wall.

iv. The compressive strength of the bricks should average 20 kg/cm^2 with a tolerance to 2.0 kg. less per cm^2 for one brick in a series of three.

v. The modulus of rupture for the bricks should average not less than 3.0 kg/cm^2 with tolerance to 1.0 kg/cm^2 for one brick in a series of three.

MUD-BRICK TYPES

There are basically two different types of mud-brick.

1. Wall Bricks. These are heavier and thicker, dimensioned 15 x 25 x 6 cm. and with a straw to earth mix of 60/80 lbs. of straw per cu. m. of earth.

2. Vault Bricks. These need to be lighter and flatter. The vaults weight is distributed to the one mirror wall primarily and therefore a lighter brick eases this pressure. The way it is laid makes it an advantage to be flat. One surface also has two parrellel grooves to help the bricks stick together by suction. The mix is 120 lps. of straw to cu. m. of earth making it thus lighter.
   The dimensions are 15 x 25 x 5 cm.

   Domes can be built using either type.

METHOD OF MAKING MUD-BRICK.

The simplest and still effective way of making mud-brick is the traditional one.

A wooden hand mould of the required size is used.

Clear out the space of ground on which the mud-bricks are to dry, so that is is clean and level.

Sprinkle a light layer of sand over the space. Simply fill the mould with the prepared mix , tamping it down. If it is a vault brick the parallel grooves can be drawn across the surface using the index and forefinger.

MAKING MUD BRICKS

Raise the mould up lightly leaving the formed brick to dry.

If the mud sticks to the mould or when it is clear the moulded brick does not lie firm and shaped it is an indication that the right mix has not been used.

Bricks should not be used before being thoroughly dry. They should be cured for not less than 30 days under average hot dry climatic conditions until they have reached a constant weight before they are used. It is advisable to shade the bricks for the first two to three days as this tends to equalise drying and results in less cracking and shrinking of bricks.

PROCESS OF CONSTRUCTION.

SETTING OUT

i) Where possible, the positioning of the building should be related to surrounding reference points, so that the position of the building can be determined in relationship to other objects, and at least one corner of the building can be fixed. These reference points can be one of the following:-

a) Surrounding buildings.

b) Surrounding landscape marks or planes.

c) Pre-established site location points - eg.a firm stake driven into the ground.

ii) For determining the different levels of the building all measurements should be taken from one reference level, usually the top of a strong wedge, hammered into the ground at a chosen point.

iii) Having basically located the position of the building, reference strings are then placed, accurately determining the corners of the building.

Nails to hold these strings can be fixed onto

a) Existing reference buildings.

b) Onto a timber frame. This surrounds the whole site, forming a rectangular ground frame, so that is has at least 1.5 m. outside the building line, to avoid damage during ensuing excavation.

The use of a timber frame removes the need for any other reference points and will be described below.

The frame must be levelled as far as possible, by placing it on long and short wedges. Nails for holding the reference strings can be be fixed to a combination of a) and b).

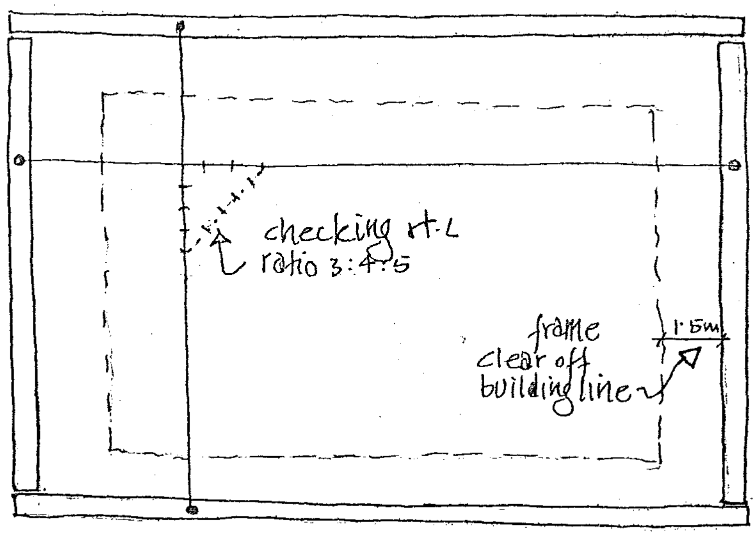
iv) Lay out two perpendicular strings representing the building reference corners, and check the angles are right angles by measuring a triangular ratio of 3:4:5 at the reference corners in the absence of a right angle frame.

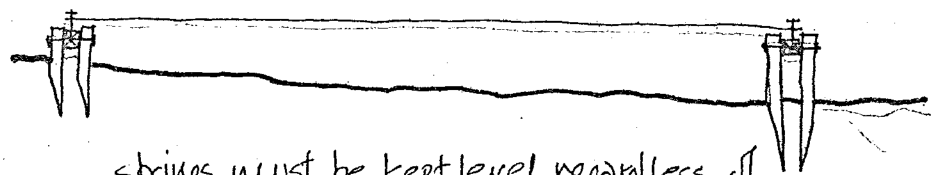
v) Lay out the building plan centre lines or plan grid using strings stretching between labelled nails, for each line and check that the angles are correct. The nails are labelled so that the strings can be replaced as needed.

vi) Set out external and internal dimensions and angles, using these strings.

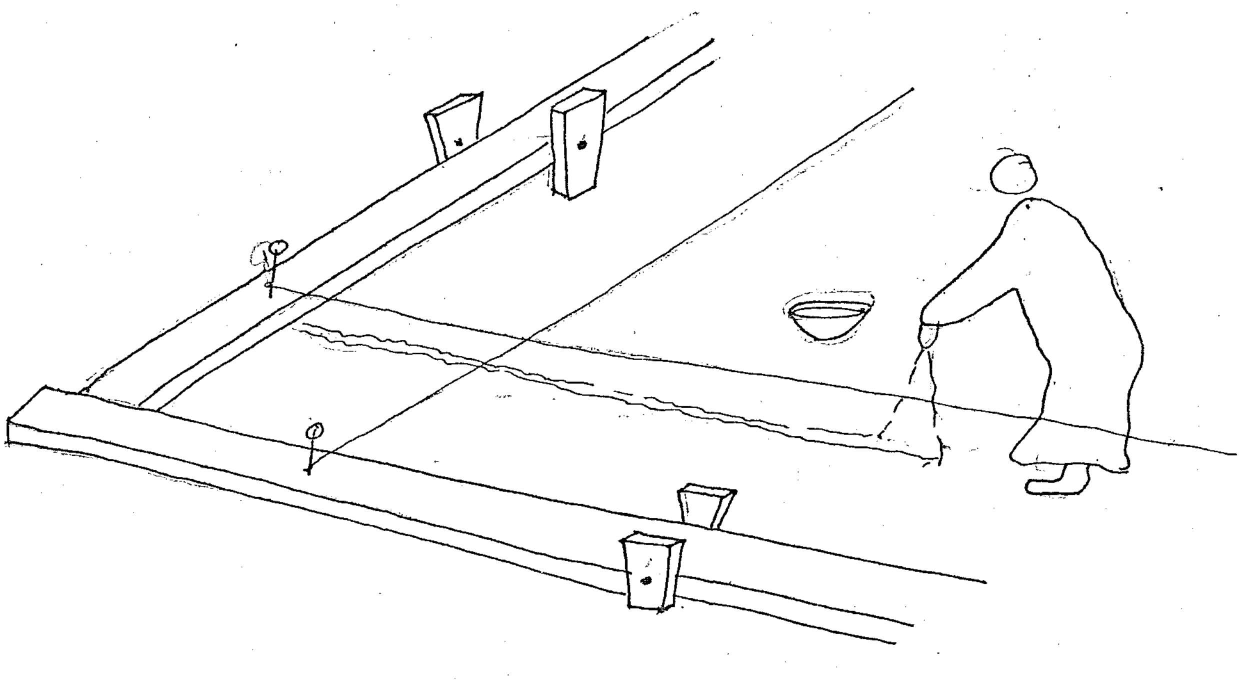
vii) Stretch first wall strings to determine wall thickness and draw this on the ground by using sand or white powder

viii) Repeat this process for each wall of the building.





strings must be kept level regardless of site.



timber frame to layout plot in abscence of handy reference points.

ix) Dig out area marked for foundations, at least 10 cm. wider on the top than at the bottom to allow for collapse of sides to trench.

x) Check bottom foundation dimensions by stretching each wall string for the second time and using plumb line to relate to the base of the trench.

xi) Check that the bases of the foundation trenches are level by using wooden posts and spirit level. Relate this level to original level determined in step ii)

The foundations can now be laid.

FOUNDATIONS.

A variety of foundation types are illustrated in fig. 1-7 Soil tests for stability are essential prior to building Unstable soil, that is clayey soil which normally has a high moisture content and is liable to give unevenly under pressure or even to rise with the absorption of water can cause damage.
The test house built used foundation type figure 4.

After setting out foundations -

i) Dig ditches 1.10 metres deep. Use level stakes 250 mm high. Make width of ditch wider than necessary to allow for inaccuracies. Clear walk-way round edges for ease of movement, transporting materials to and from site.

FOUNDATIONS.

STABLE SOIL.

Fig 1.

Insure soil is not limestone dissolvant - otherwise use only red brick.

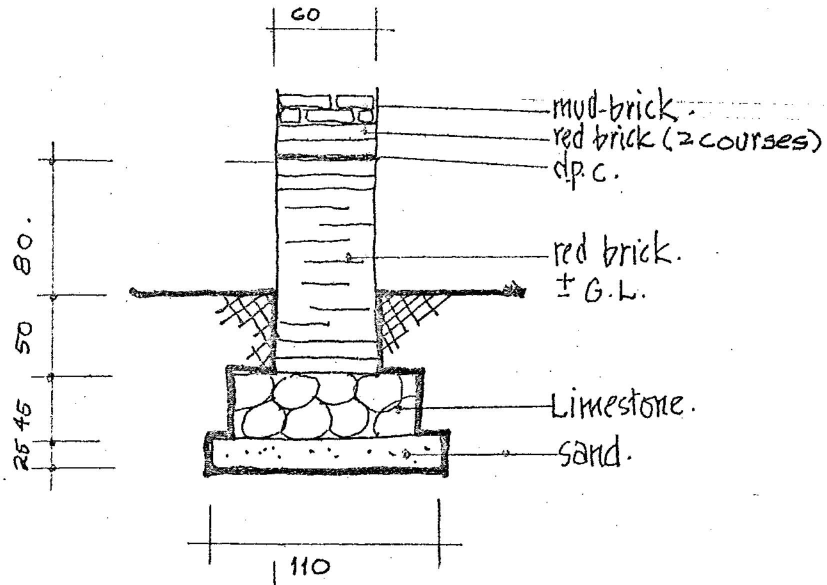
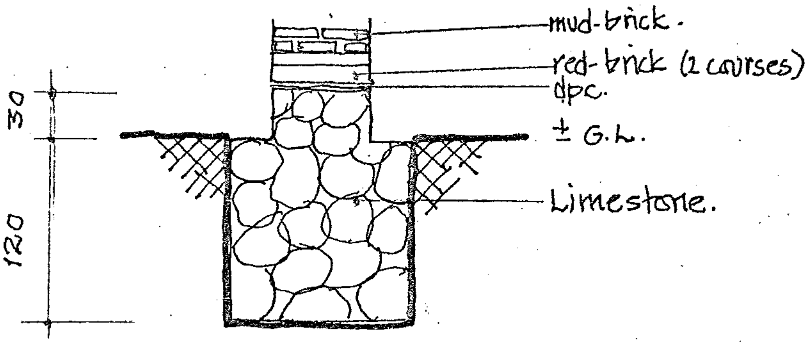


Fig 2.

If limestone is readily available and cheap and soil is not dissolvant.



UNSTABLE SOIL.

Fig 3.

moderately unstable.

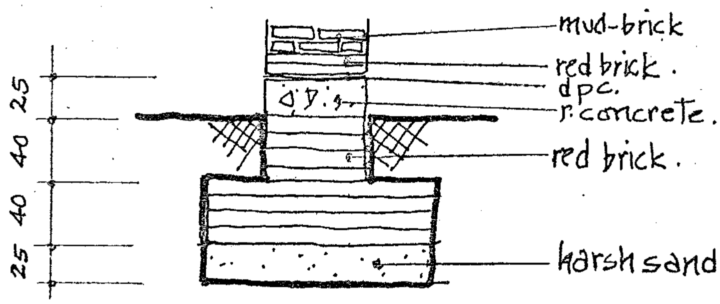
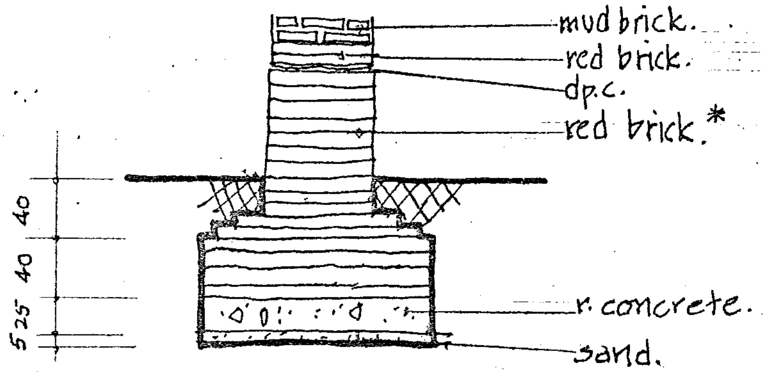


Fig 4.

unstable.

* normally 2 courses above G.L.

* in test house 5 courses to suit uneveness of ground surface.



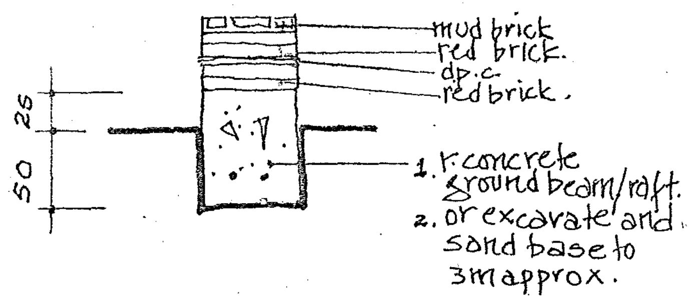
FOUNDATIONS.

UNSTABLE SOIL.

Fig 5.

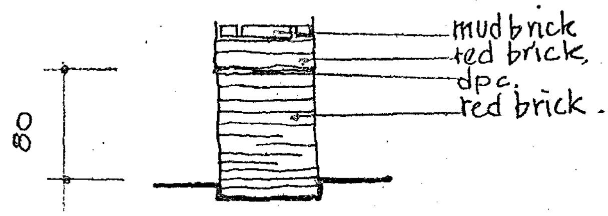
Very Unstable.

essential to consult soil mechanic.



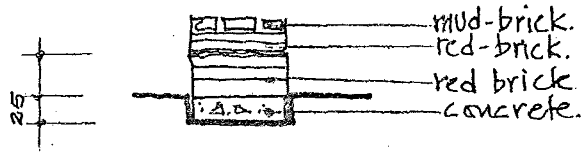
ROCKY SOIL.

Fig 6.



SANDY SOIL.

Fig 7.



d.p.c. only where possibility of rising damp. rarely used in practice. all measurements are approximates precise sizes will depend on structural calculations & soil.

ii) Pour 250 mm concrete into ditch, and level to stakes.

iii) Allow concrete to dry - approx. 1 day - and pour 50 mm sand over.

iv) Mark out footings, starting with outer edge, and line out string lines, before laying first course of red brick. For each successive course of brick footings, string guides and plumb lines should be used to ensure wall lines up horizontally and vertically.

WALLS

i) After five courses of red brick, step wall in to 600 mm width where vault and dome thrusts not applied. (rest of wall remains 800 mm width)

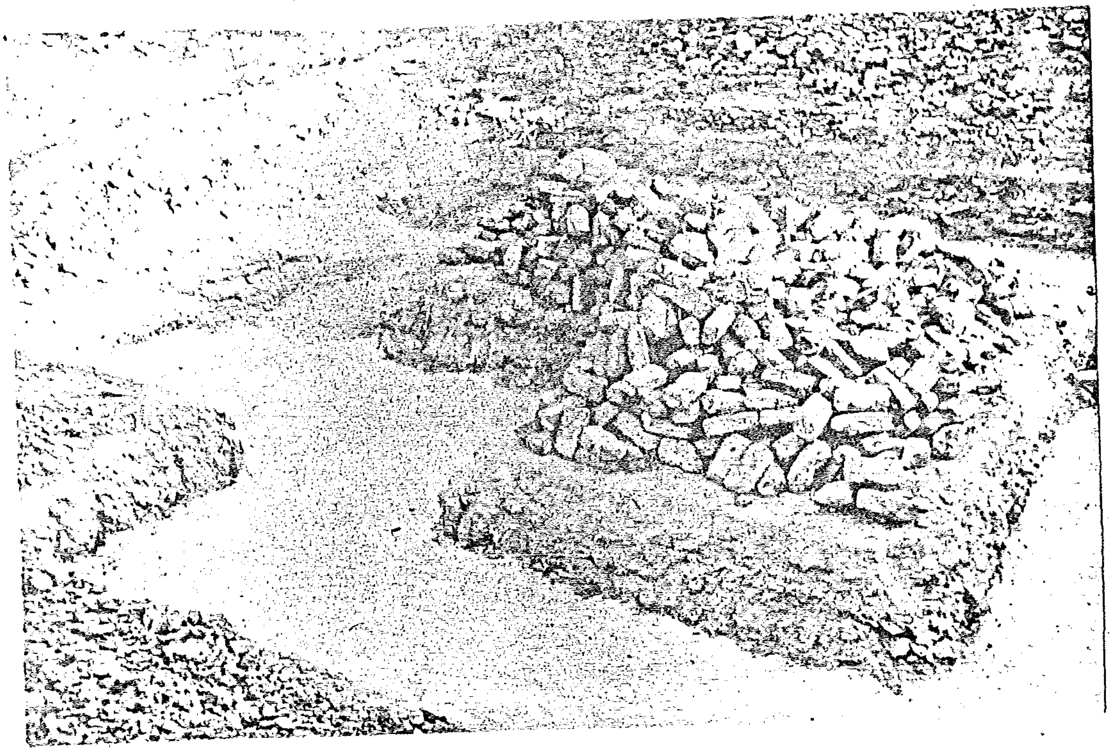
ii) After tenth course of red brick, cement over last course, pour bitumen and sprinkle sand.

iii) When the bitumen has dried add two more courses of red brick.

iv) Start building mud-brick walls. Ensure each successive course bonds over the last, to avoid long vertical cracks.

Walls to be built up to the required height for the spring points of the vaults, and the cill height of the windows. The vertical sides of each window should be built up to the point where the arch over the window is to start.

1.



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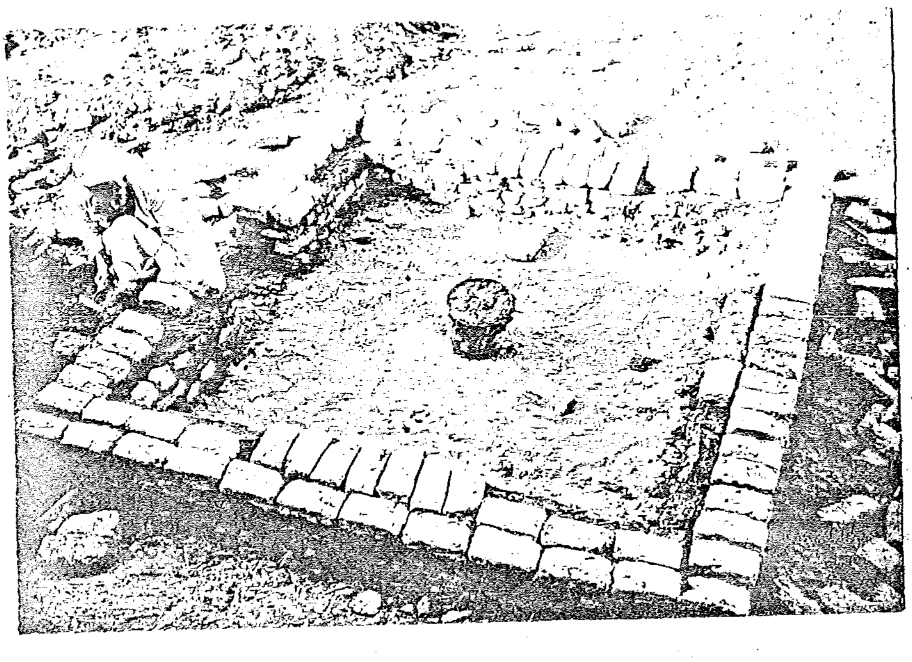

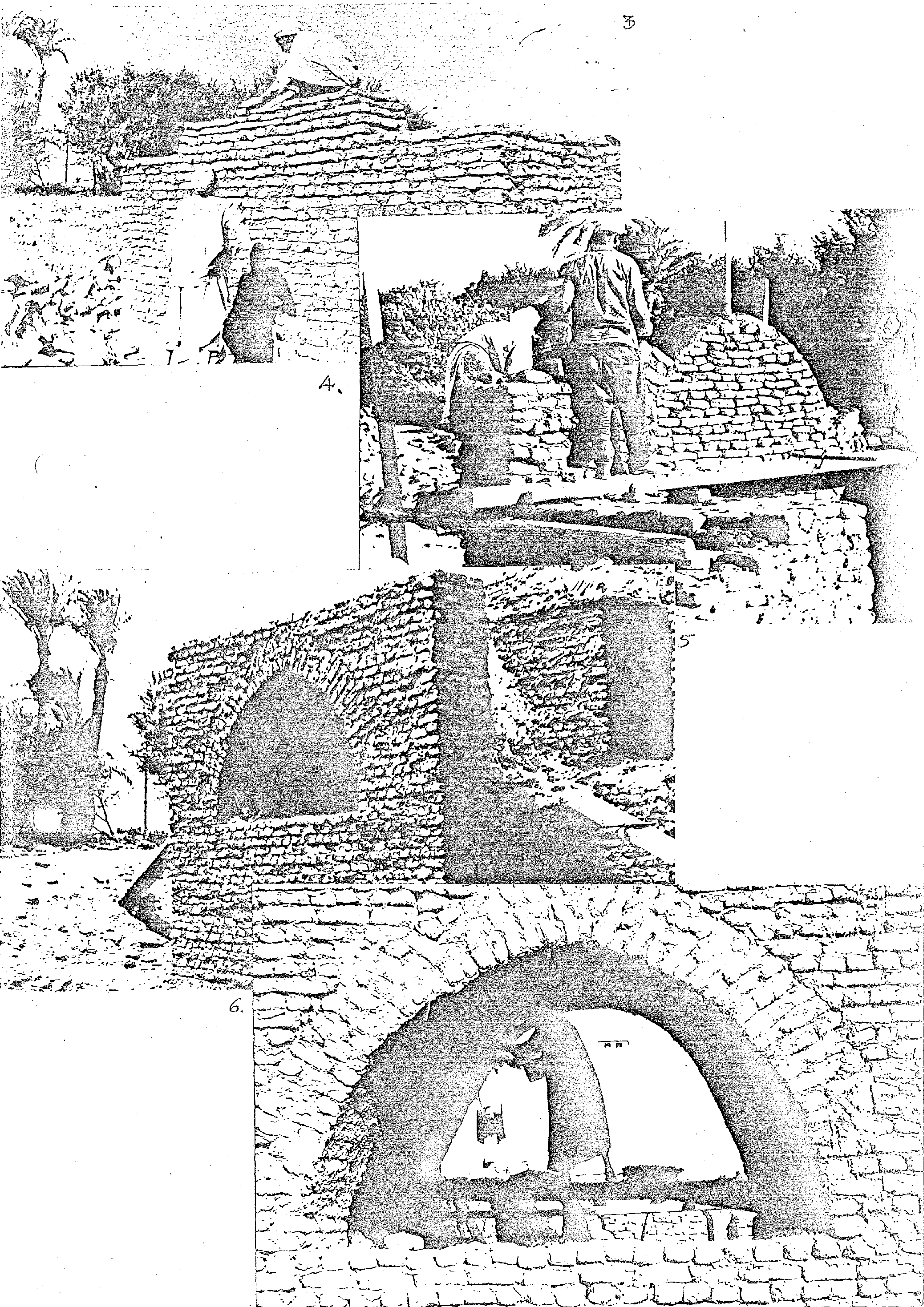

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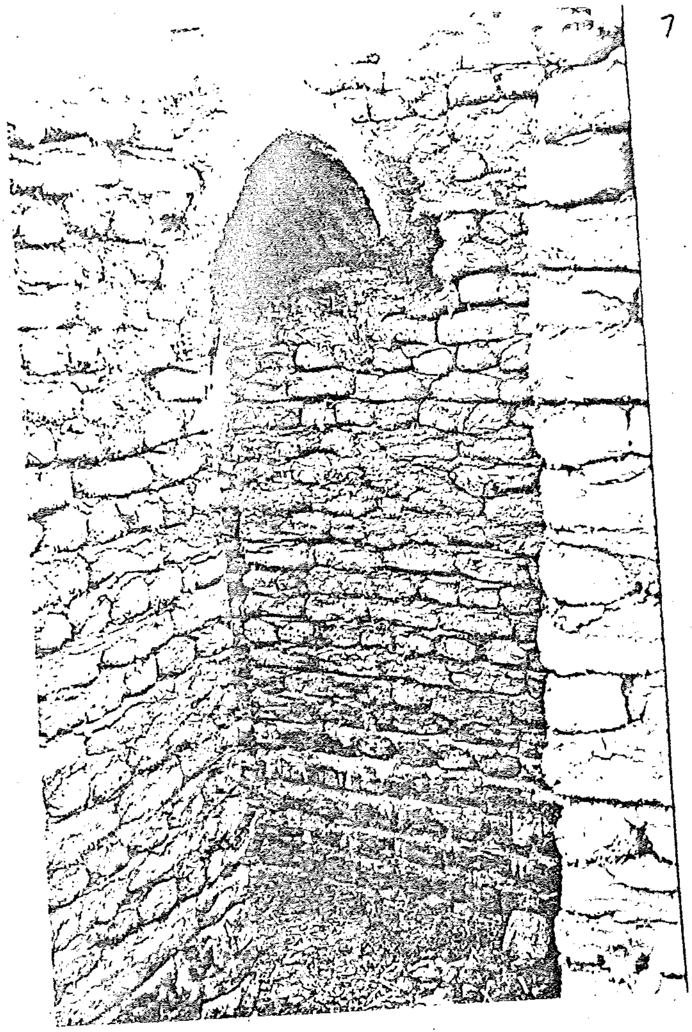
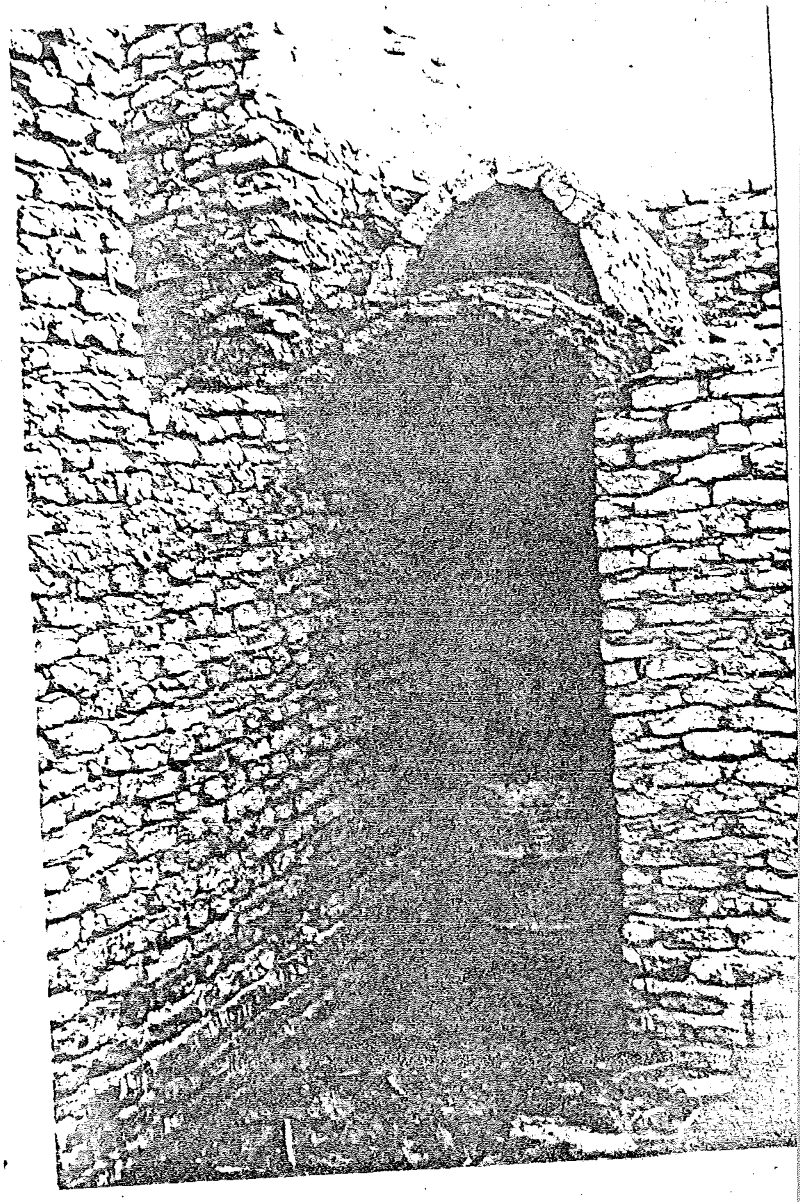




8,

OPENINGS

(photographs 3-8)

To build the arch over a window, fill in the window opening with bricks, using no mortar, so that the bricks form the same curve at the top as will be formed by the underside of the arch to be built. This is then covered liberally with mud morter until a smooth curve is achieved, and then covered with sand, providing the formwork of the arch.

To build the arch over the window, vault bricks or ordinary wall bricks may be used, but not mixed.
Place the first brick of the arch at a slight angle off the horizontal, and build up over the formwork so that the bricks at the centre are placed in a near vertical position, forming the key brick of the arch. At least two courses of bricks should be laid in this manner, and in the case of large arches, these bricks should be bonded together.

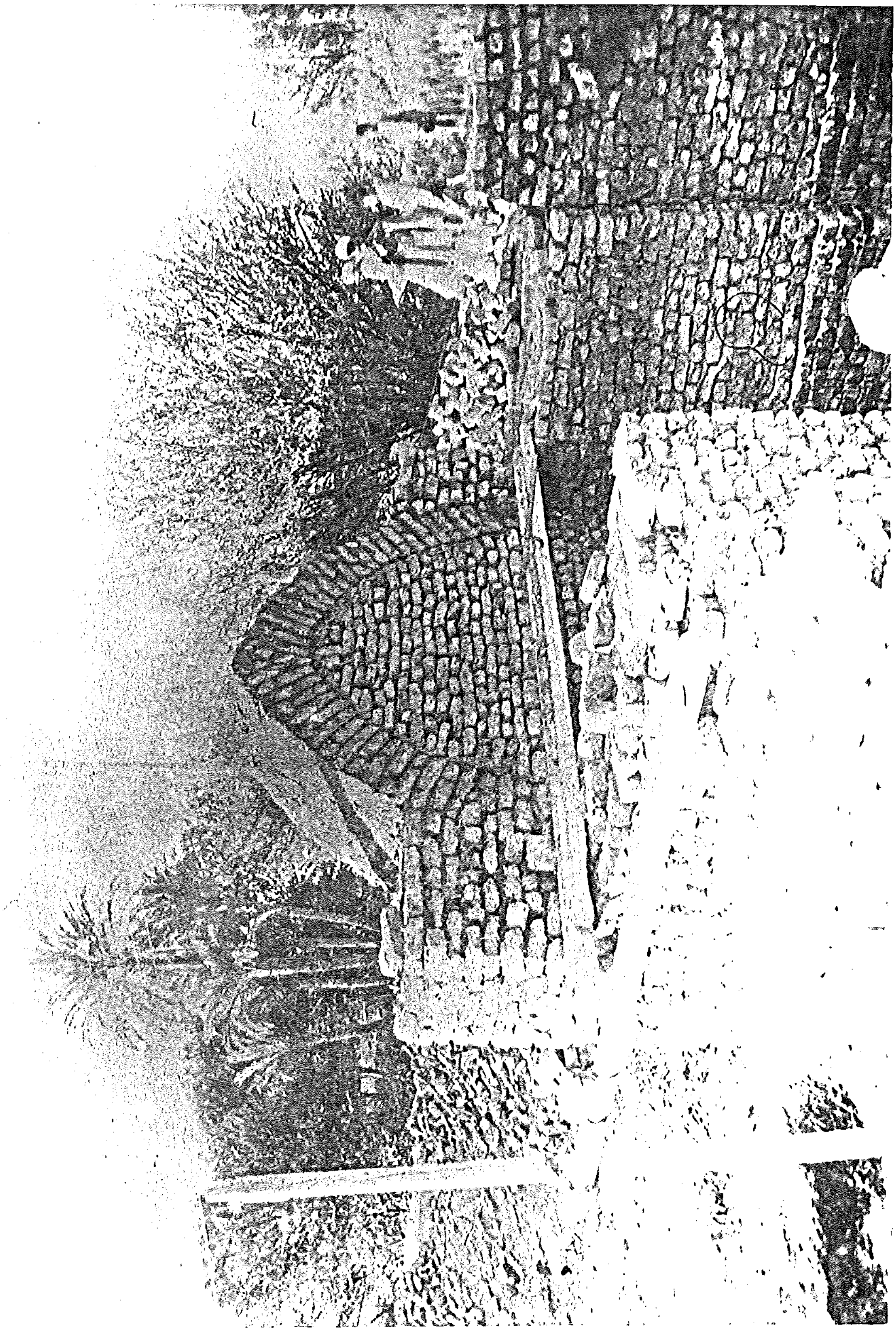
For arches over doorways, the same princdple is followed, but in order to save time and labour, a sheet of thin timber or corrugated iron can be bent to the correct curve, and used as a substitute for the brick support. This depends on the availability of such materials.

VAULTS

(photographs 9-15)

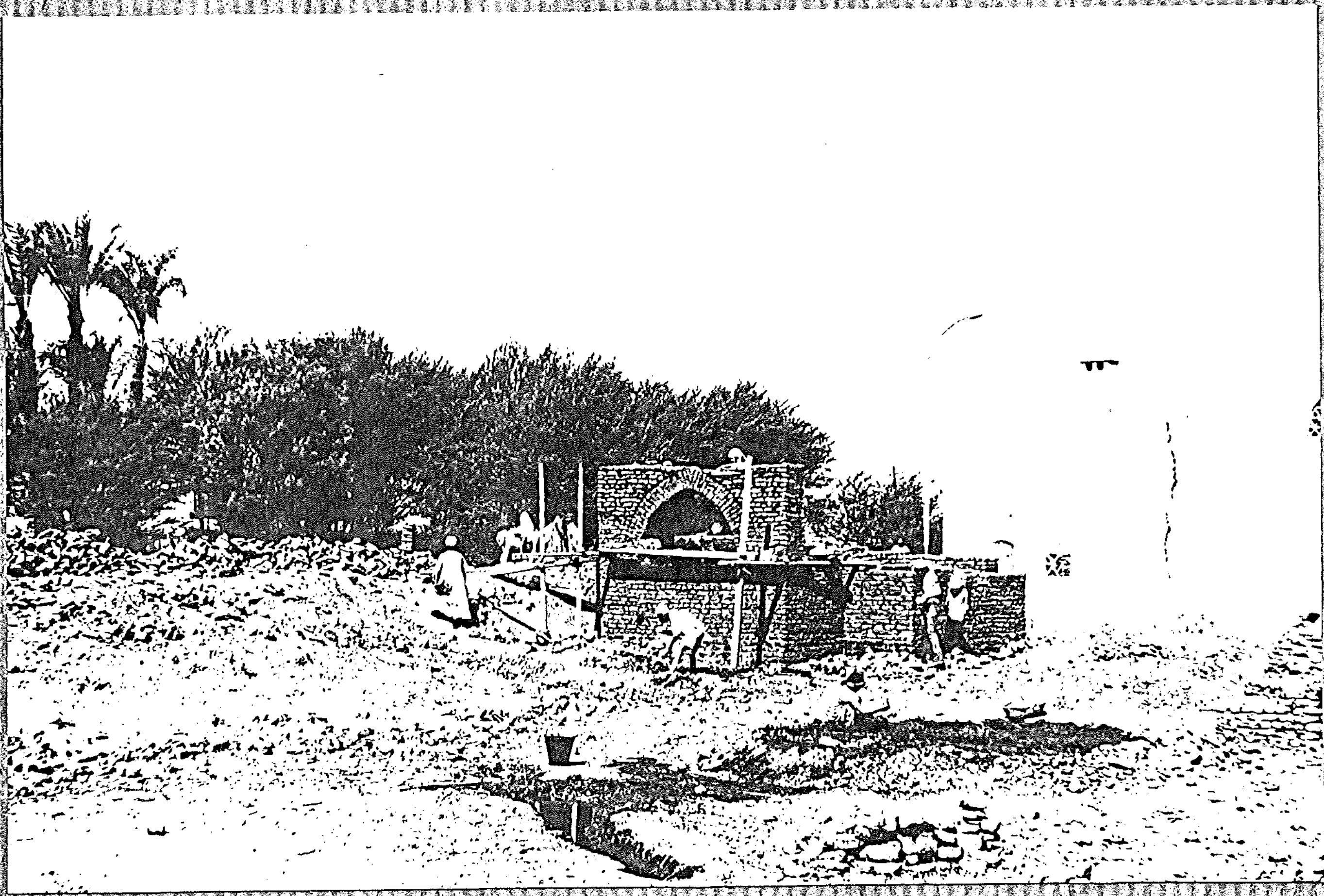
When the side walls of the proposed vault have been built up, to the required height, the end wall is then built up to a height sufficient to cover the whole end of the vault, to allow the vault to lean onto this end wall or mirror wall.

CONSTRUCTION OF ARCHED WINDOW

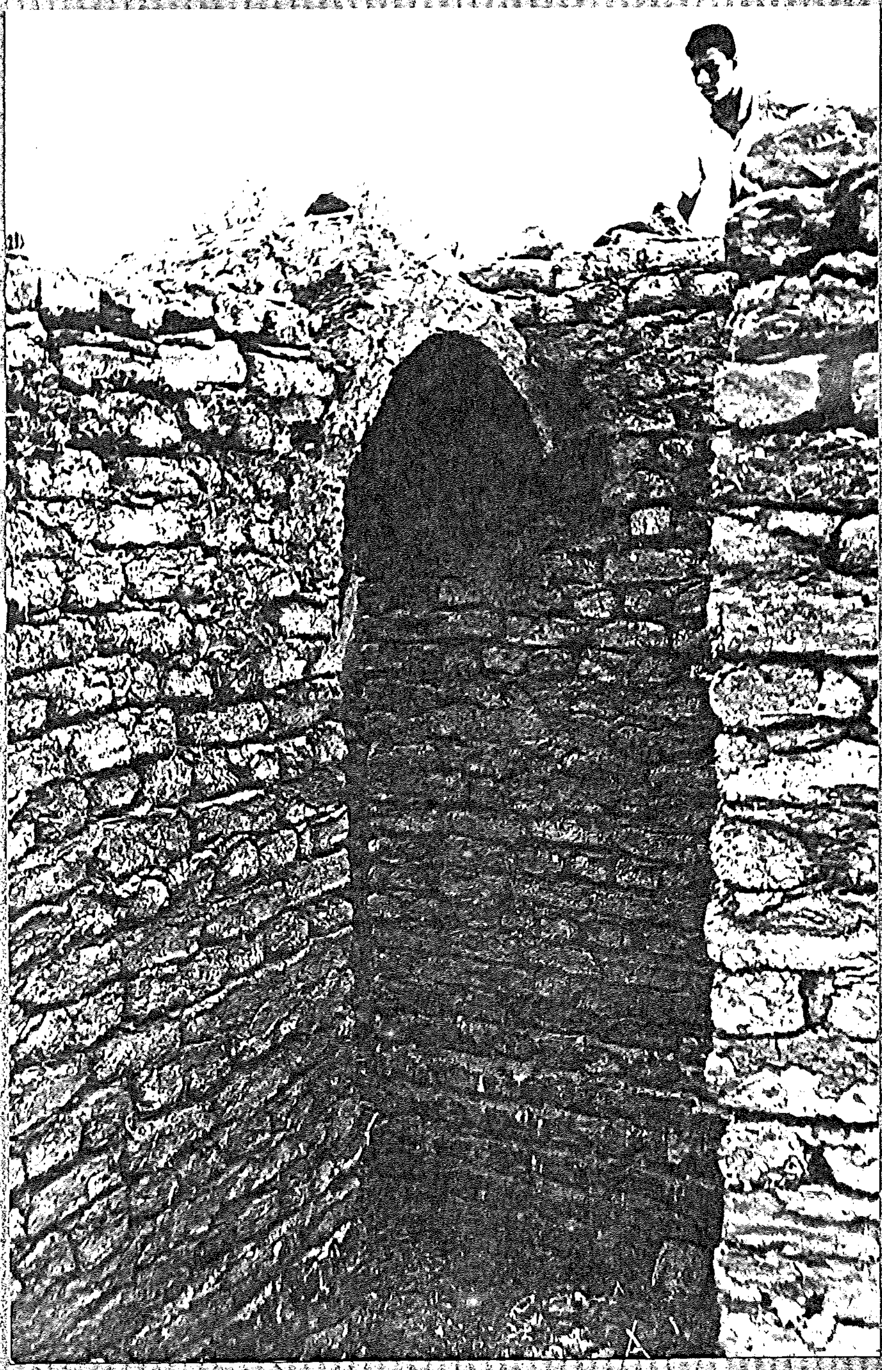


CONSTRUCTION OF ARCHED WINDOW

ARCHED WINDOW- COMPLETED



GENERAL VIEW OF HOUSE AND SITE



ARCHED DOORWAY

Planks are placed across the two side walls for the builders to sit or stand on to build the vault.

The curve used for the vault is in between a catenary and parabolic curve. The height of the vault from the spring point of the arch to the internal head of the arch can be calculated, by taking the width of the vault divided by two, and adding 10% of this dimension. Hence, in the case of a 3 metre width vault the height will be;

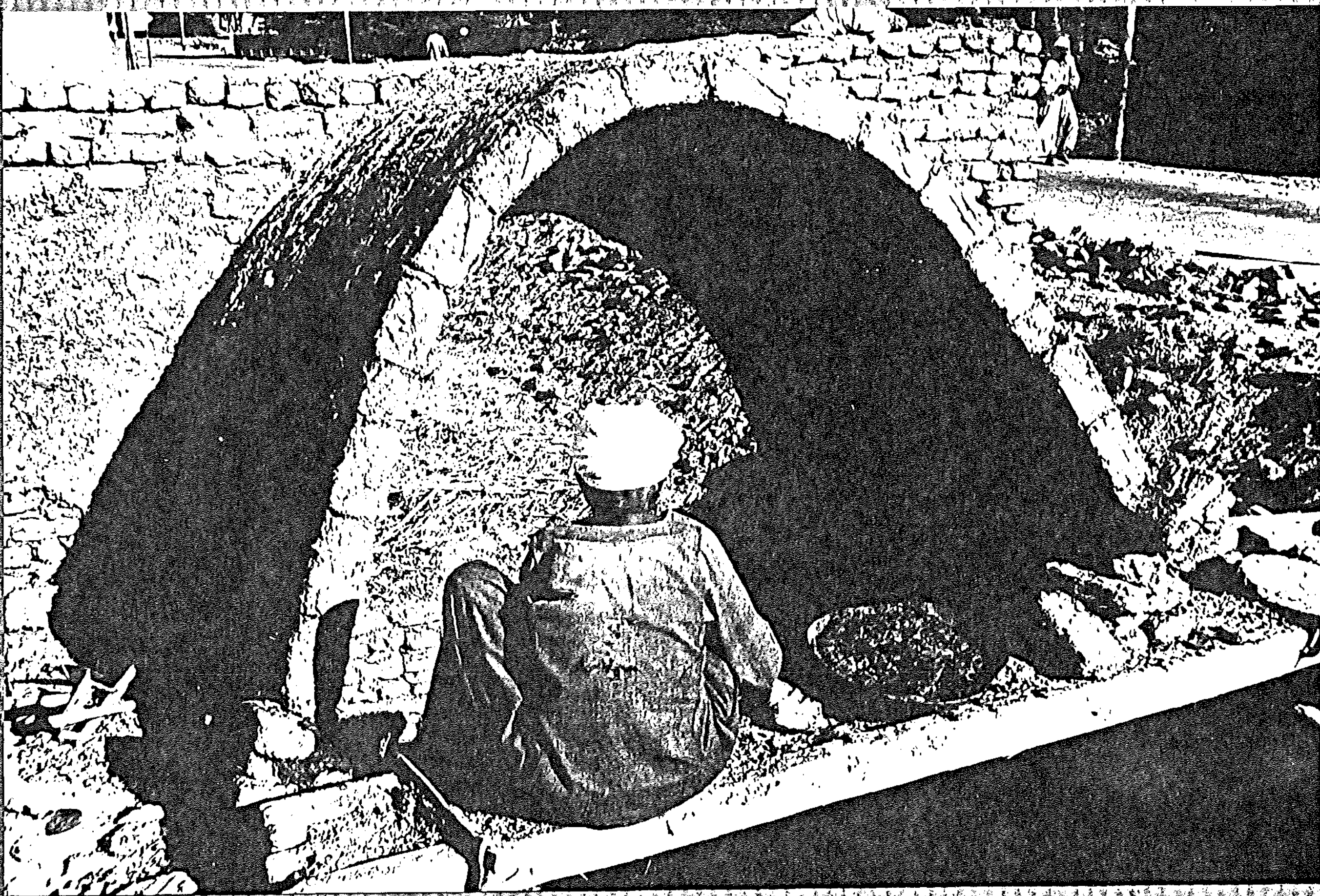
$$\frac{3}{2} + 10\%$$

$$= 1.5 + 10\%$$

$$= 1.65 \text{ metres}$$

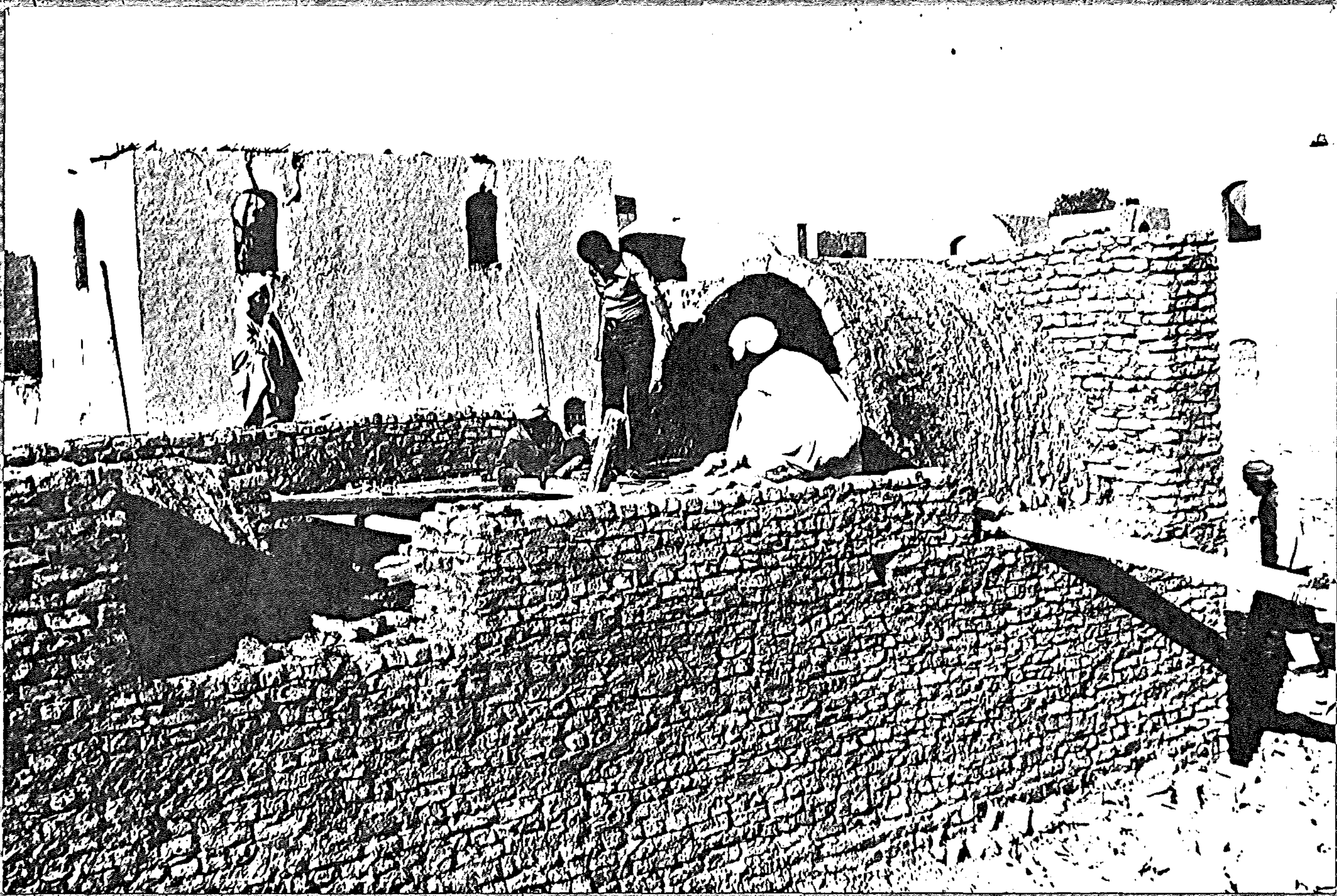
The curve of the vault is drawn by hand on the end wall, using mud. When the curve is correct and symetrical the edges are cleaned off with an adze, the only implement used in building the vault.

The first brick is tapered and stood on end on the top of the side wall, the grooved face of the first brick against the mud mortar of the curve drawn on the end wall, and the brick is then tapped into place. A small wedge shaped brick is placed over this brick to taper off the end of the first brick. Then mud is placed at the foot of the first brick and against this a little wedge-shaped packing is placed, so that the next course of bricks leans slightly towards the end wall, instead of upright. In order to break up the line of the joints between the bricks, the second course is started with a half brick placed on its longest narrow edge, on top



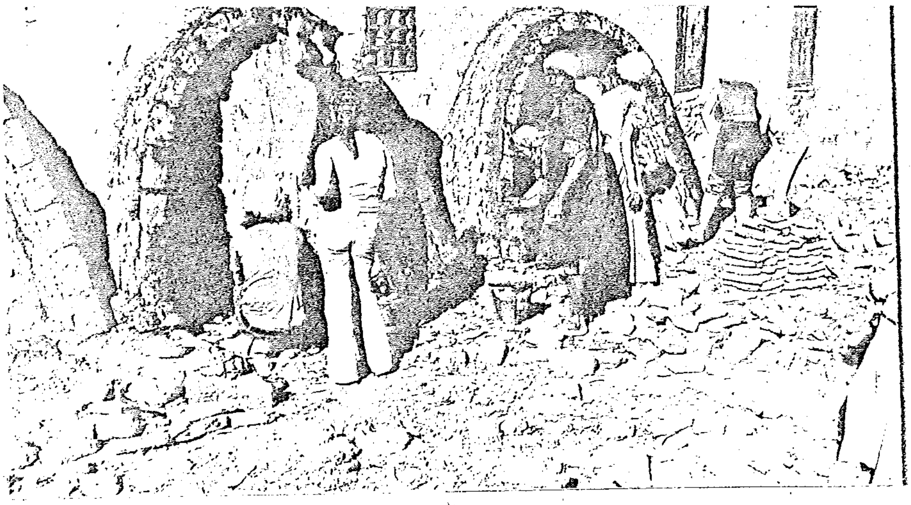
VAULT FROM ARCHED WINDOW OPENING

VAULT FROM NORTH MIRROR WALL



GENERAL VIEW - VAULT AND WALLS

12.



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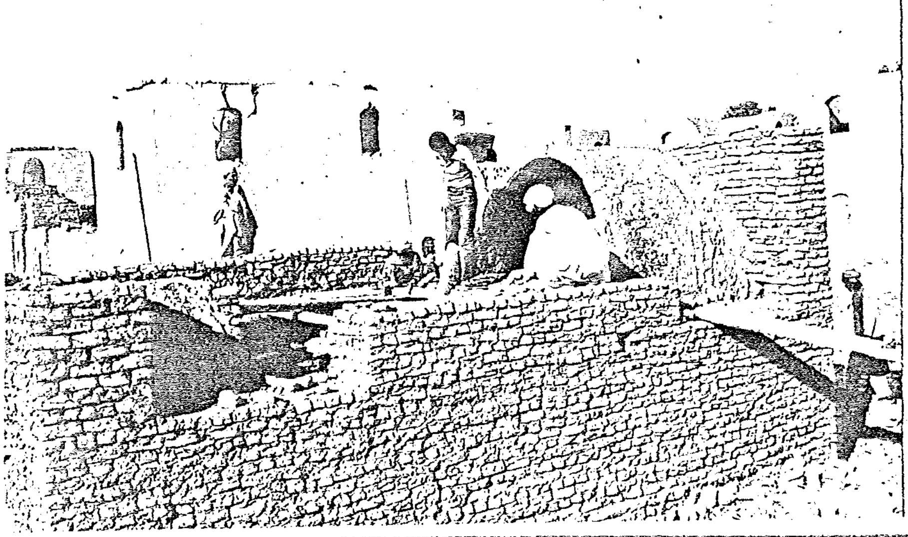
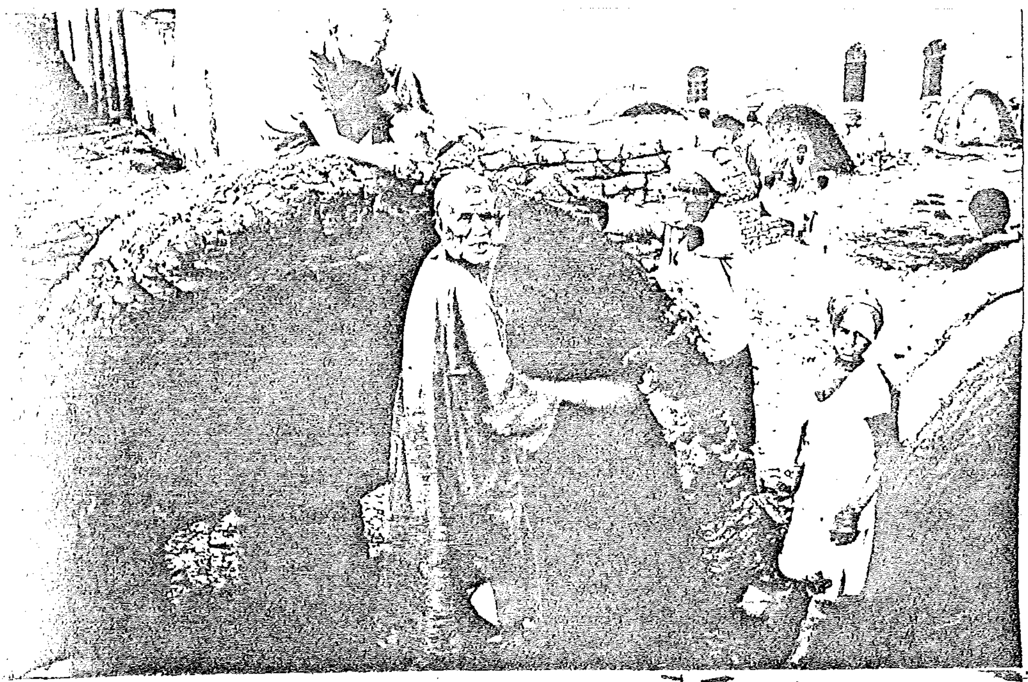
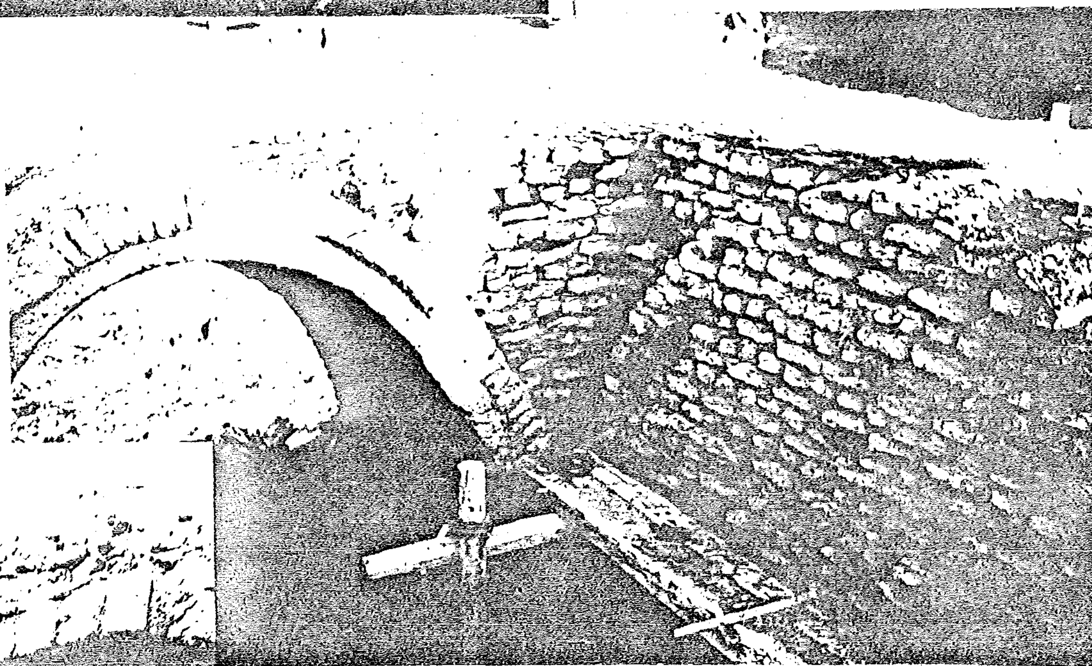


of which is placed a whole brick, following the curve drawn on the end wall. If the joints are in a straight line, the strength of the vault is reduced. The second course of bricks is $1\frac{1}{2}$ bricks high. The third will be three bricks high, also leaning towards the end wall in the same manner. In this way the inclined courses are built out, each course rising higher than the last round the outline of the vault, until the two curves from either side of the vault meet at the middle. At the top of each complete course of bricks, small pieces of chipped stone or broken pottery are tapped into fill in the gaps between the bricks. (to ensure that the forces of the vault are carried down through the brick course to the supporting side wall. Mud-mortar tends to contract and would leave gaps if it was the only filling).

At the stage where there is one brick thickness at the head of the vault in a 2.5 or 3 metre wide vault, the vault at its base will be 6 bricks thick. In a smaller vault the complete course will be achieved after fewer brick courses, but in all cases the same principles are followed. The over-all effect is that the complete curve leans against the end wall, providing an inclined face to lay succeeding courses on, so that the bricks have plenty of support. This inclination is enough to stop the bricks slipping off even a smooth surface. In this way the whole vault can be built with no extra support or centreing. There is no limit to the length of the vault.





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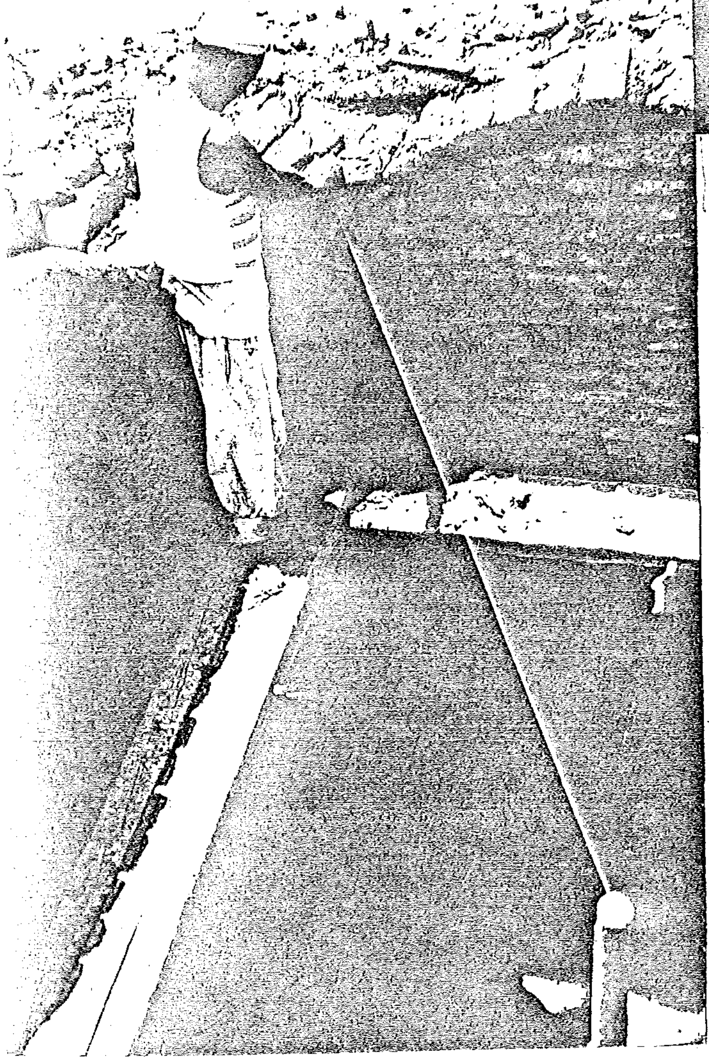


18.

DOMES.

(photographs 16-27)

Whilst a house can be constructed using only vaults, a further possible development is the use of a dome to cover a central space. Although the mud brick vault is strong, for safety the span is limited to 3 metres under normal conditions. A dome is capable of safely spanning 5 metres, its spherical shape having all the features of a shell with double curvature, and is therefore stronger. In the case of the test house built for the report, a dome of 3 metres in diameter was constructed in the centre of the house, using the following construction method. The dome used is a Byzantine dome.

Supporting Arches.

The dome must rest on a square, in this case each side measuring 3 metres. In the test house the square is made up of vaults on two of the sides, and plain walls on the other two. The end of the vault has two courses of brick work laid over the top of the vault, one on top of the other, to give sufficient reinforsement to take the forces of the dome, and to connect the sloping face of the vault so that at the head of the vault these two brick course project out to form the straight side of the square. These bricks can be trimmed so that the square is accurate. In effect the end of the vault has an arch built over it, following the same principle as for arches over openings.

Pendentives.

Pendentives are spherical triangles formed between the supporting arches of the domes.

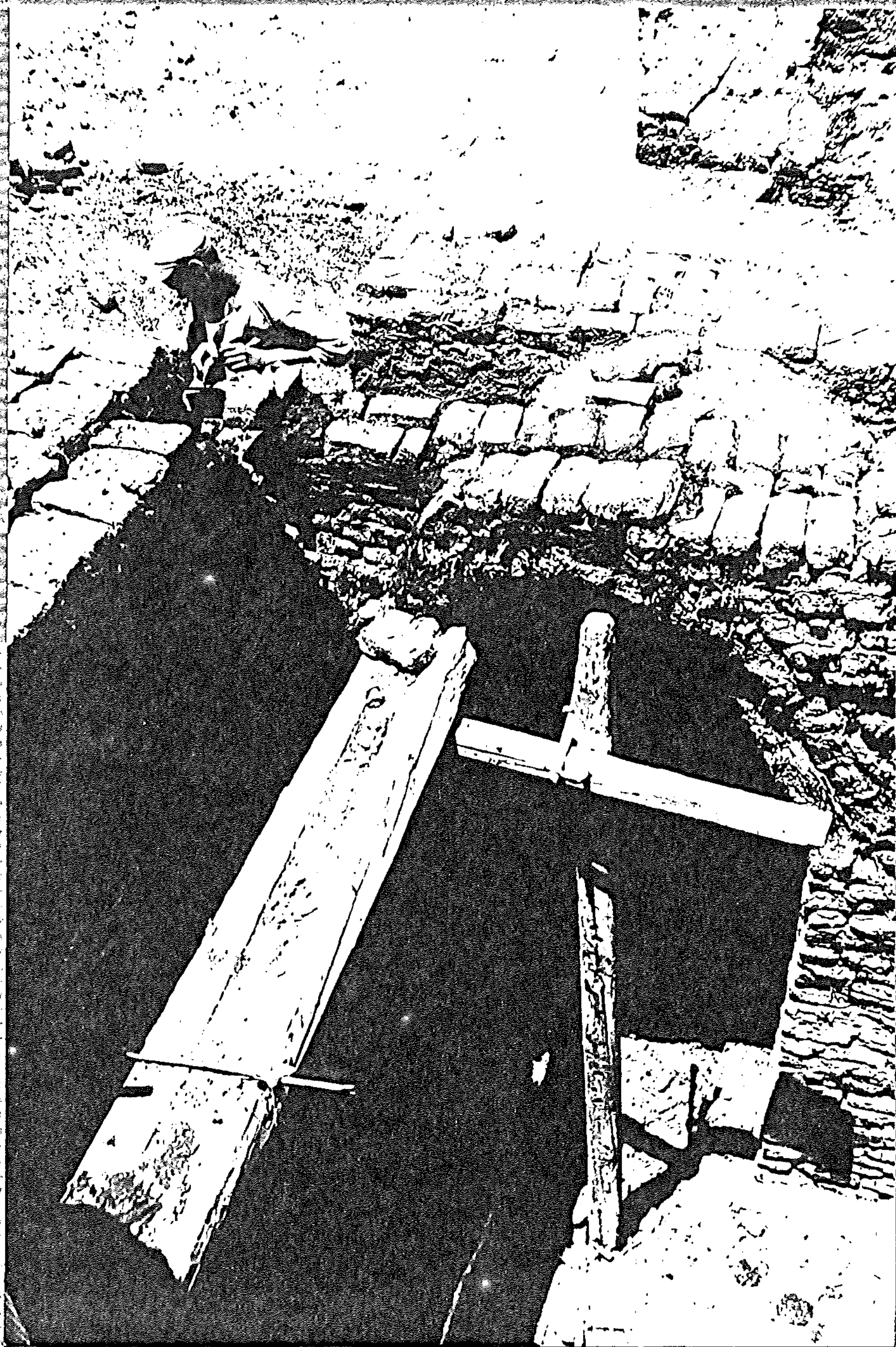
Each brick of the pendentives is placed with the use of the string from the centre post, so that the first brick to be laid at the bottom of the V will be in the far corner of the dome, whilst every successive course of bricks laid over it will project slightly out to the centre of the dome. Each brick is positioned so that its flat surface is on the same plane as the point from that brick to the centre post, and its distance to the centre post is $\frac{1}{2}$ the diagonal of the square. In this way a segment of a sphere will be built up. The sides of this segment will follow the curves already formed by the supporting arches or false arches of the side walls. At the point where the pendentives reach the same height as the top of the arches, the first complete circle of the dome will be built.

Dome.

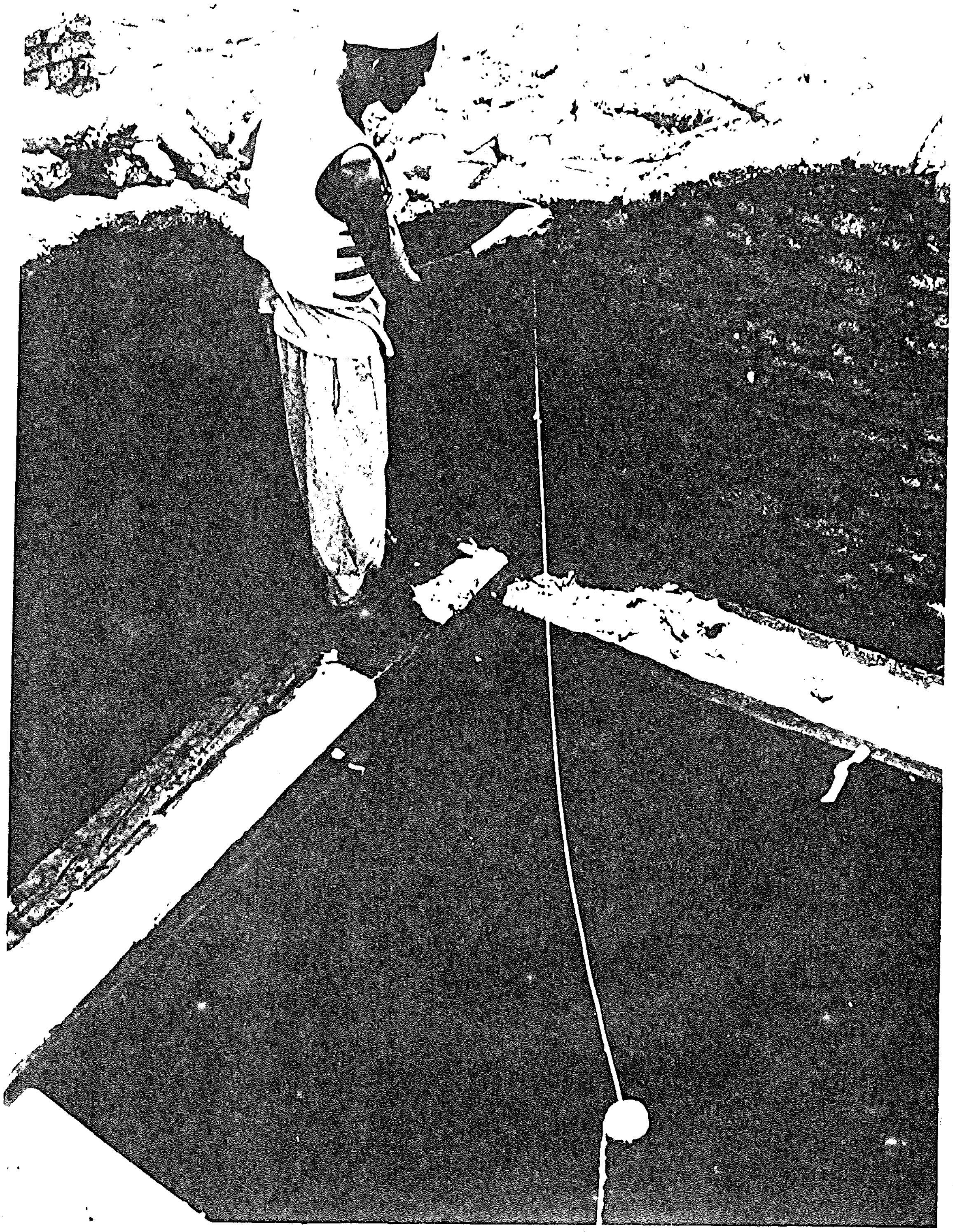
As in the case of the pendentives the bricks in each completed circle are placed at an increased angle to the course below and protruding a little further out. Each brick is placed with referance to the centre post string, forming the sphere it outlines.

The finished height of the arches over the vault need bear no relationship the the vault itself. All the dimensions for the dome and supporting arches or false arches are achieved by the following system.-

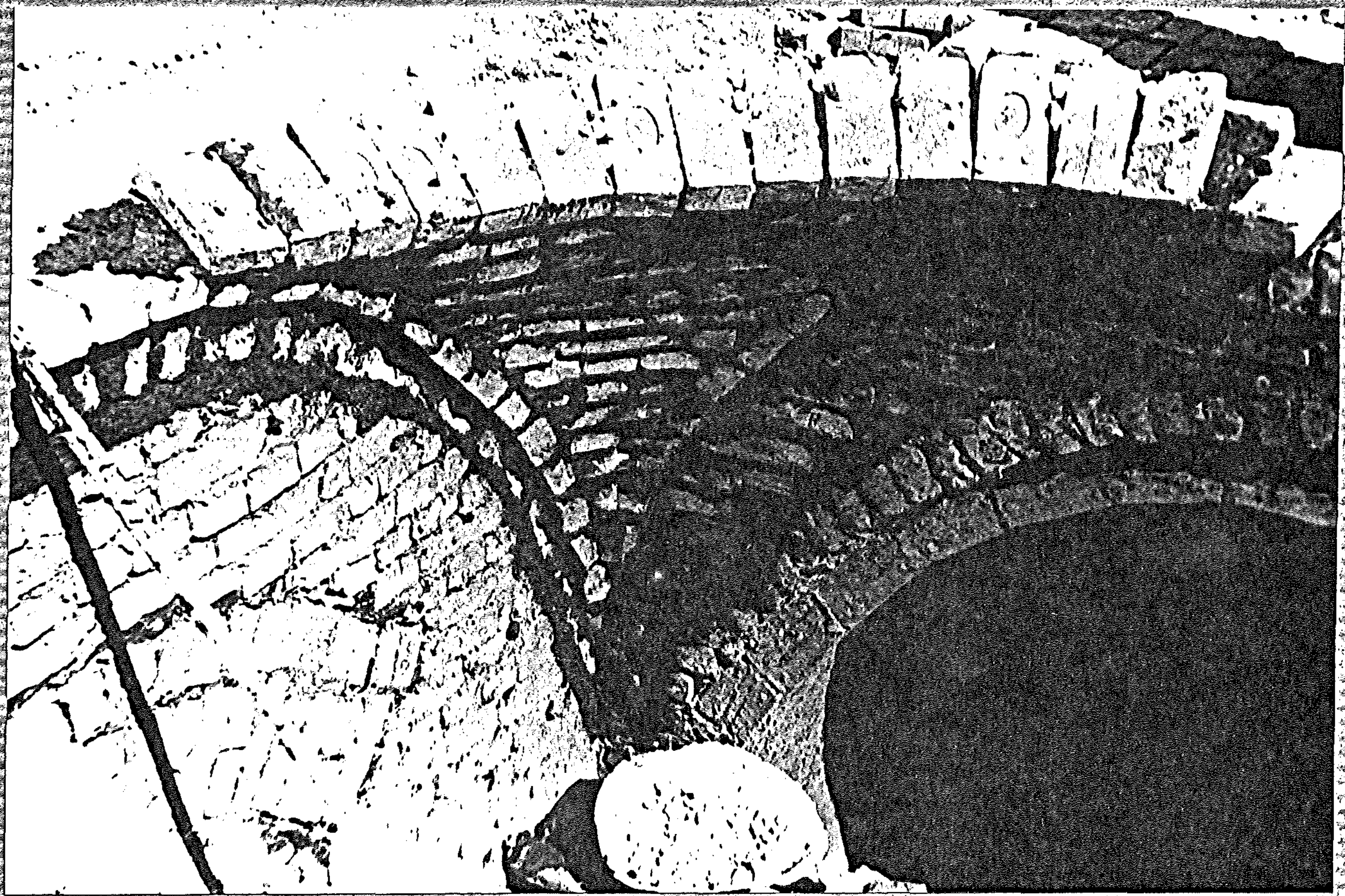
Having completed a square, a post is placed upright in the exact centre of the dome, with the top of the post at the same distance from the top of the dome as the dimension from the centre of the post to one corner of the square. A piece of string is attached to the centre of the post, having a length ½ the diagonal of the square. This piece of string, when pulled taut gives the correct placing and angle (by following the line of the string to the centre of the post) of each brick to be placed in the dome. The exact height of the post is a matter of choice, depending on how high the dome should be from the ground and subtracting from this height, the dimension of ½ the diagonal of the square. By holding the end of the string at the corner of the square, and then drawing a curve in the exact line of the straight side of the square of the dome, the curve of the supporting arches can be determined. In the case of the arch of the vault the arch must then be built up to follow this curve. In the case of the plain wall, the inner course of bricks are built up to follow the same curve, producing a solid wall with a curved top or arch, whilst the back of this same wall is built up straight, continuing to the corners, and forming the back of the pendentives.



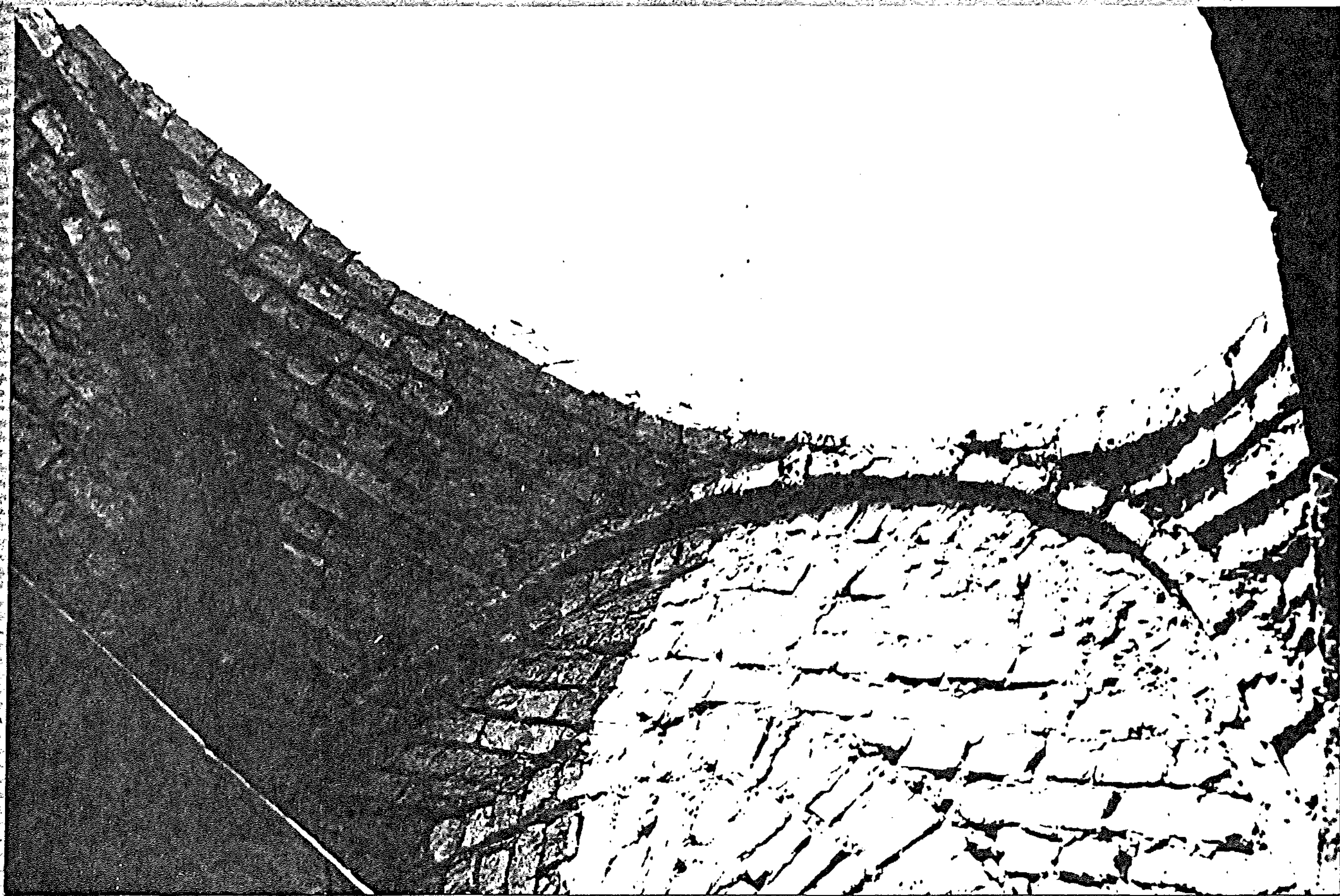
SUPPTING ARCH OF SOUTH WALL
OR



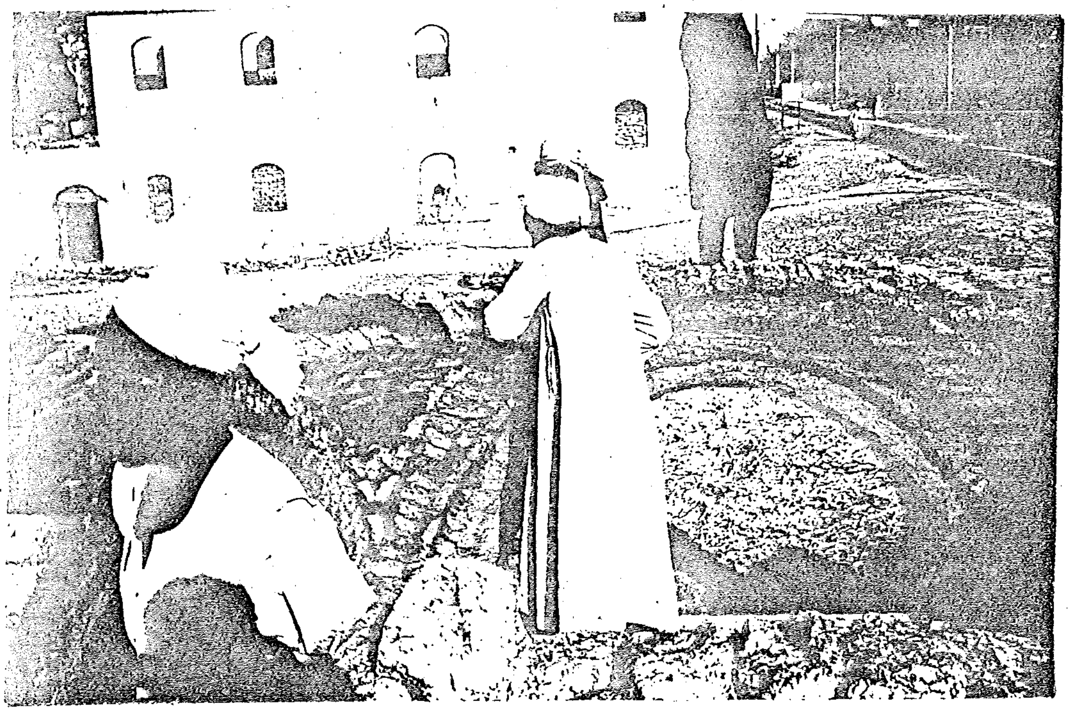
CONSTRUCTION OF PENDENTIVE



PENDENTIVES AND ARCHED SUPPORT WALLS



FIRST COURSE OF DOME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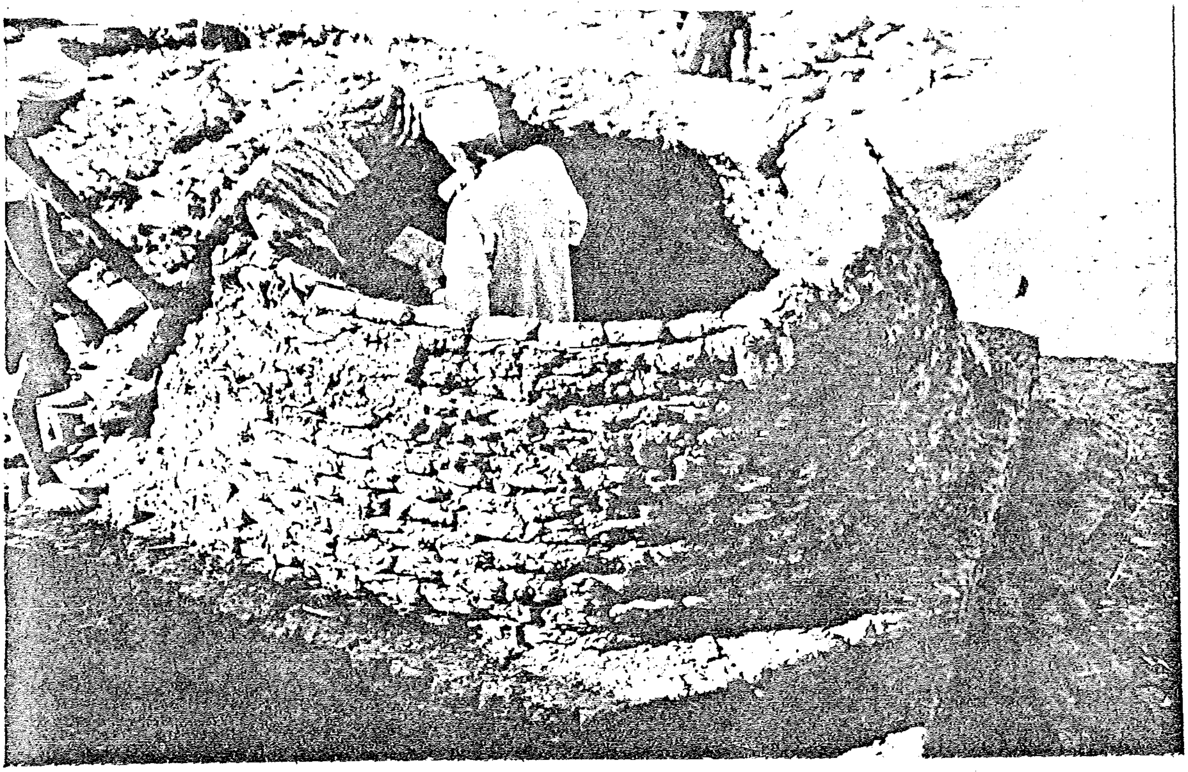
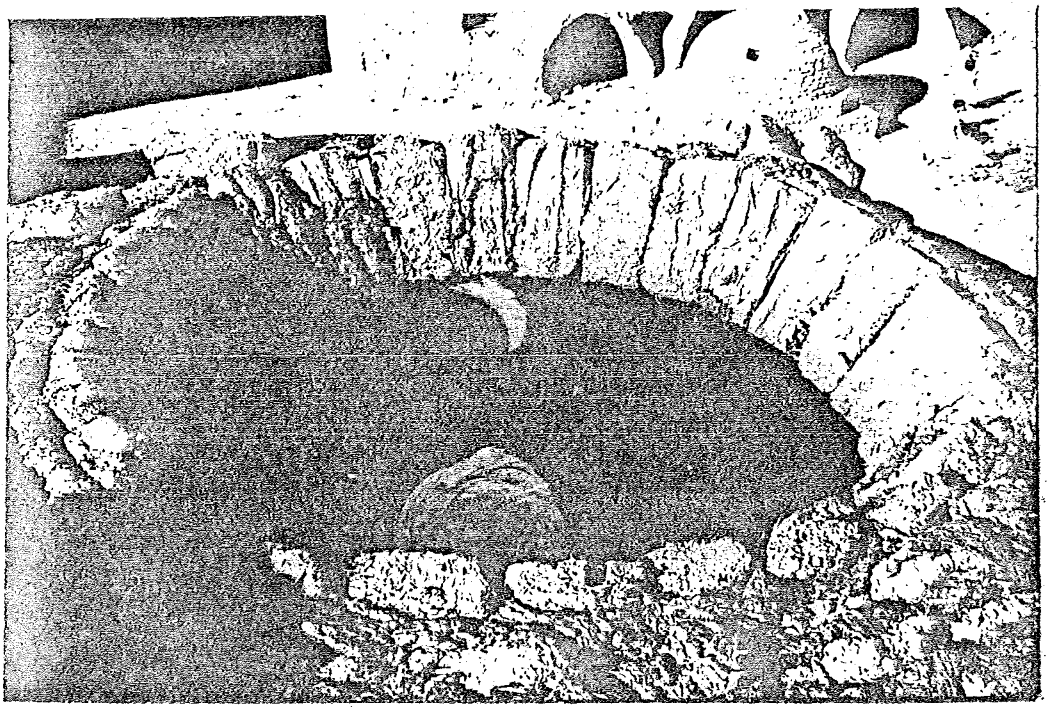
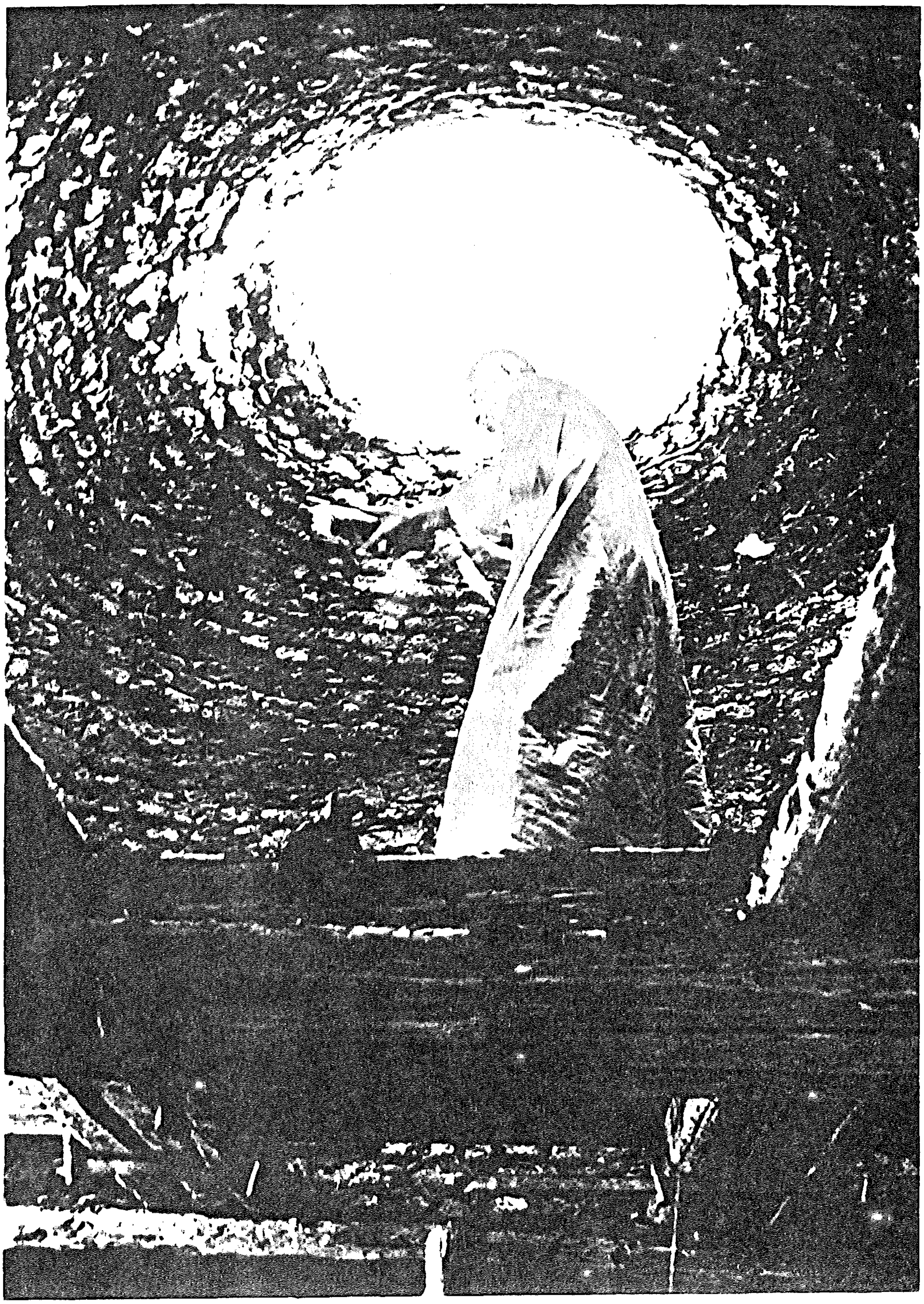



24.

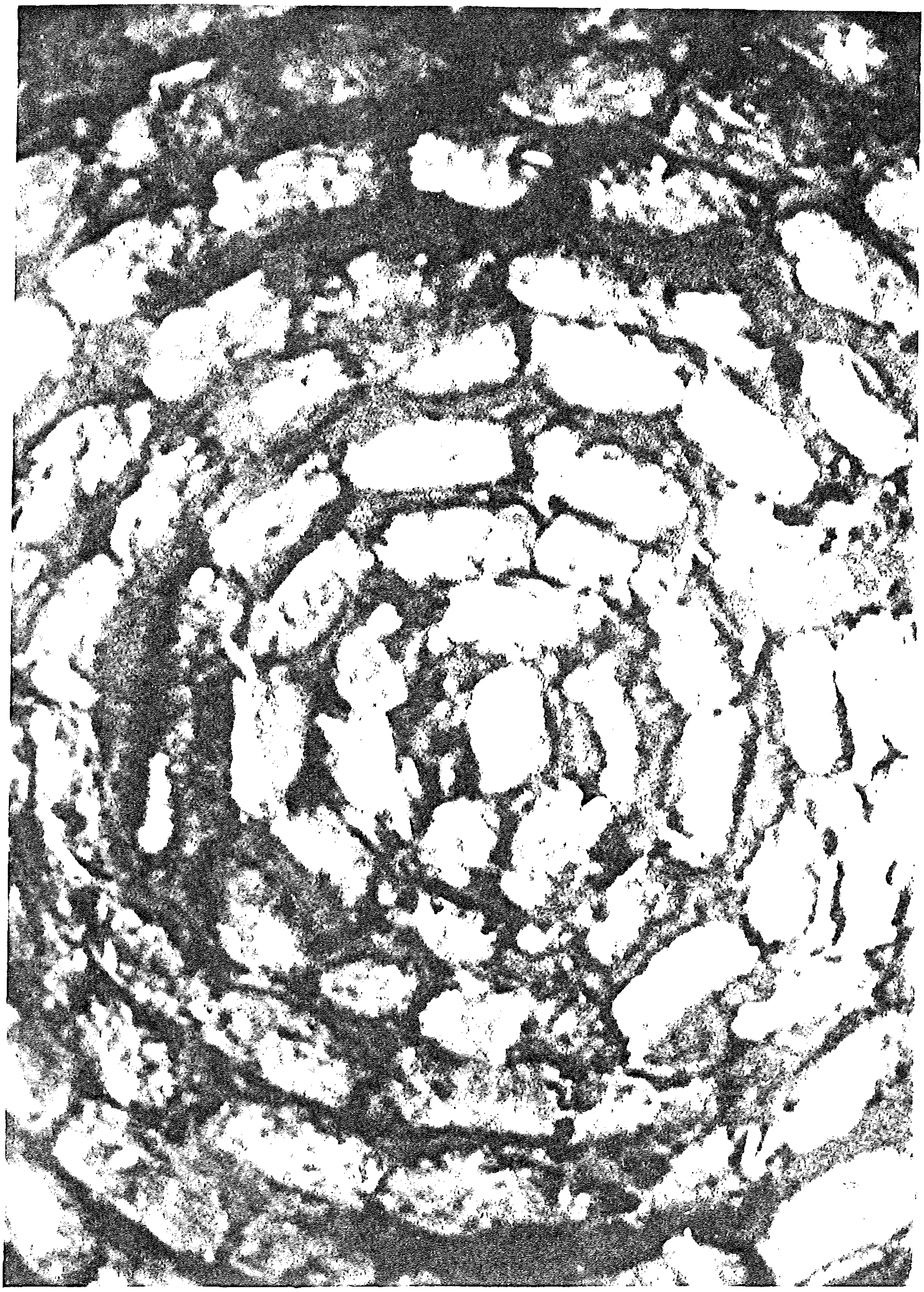
CONSTR. OF DOME - note angle of brickwork

The circumferance of the opening gets smaller as the angle of the string from the post increases, so that the final bricks of the dome are placed directly above the post, in a tight circle, until that circle is too small to place whole bricks and the last opening is filled in with bricks cut to fit. Any gaps in the top of the dome are packed in with chips of stone or broken pottery, to ensure that the whole dome is under compression. The bricks near the top of the dome will be cut in a wedge shape not only on the flat wide surface, but also on the narrow surface, so that in both dimensions the brick is narrower at one end than the other.

On completion of the dome the post is removed. Single bricks can be left out in the dome to provide small openings for light.

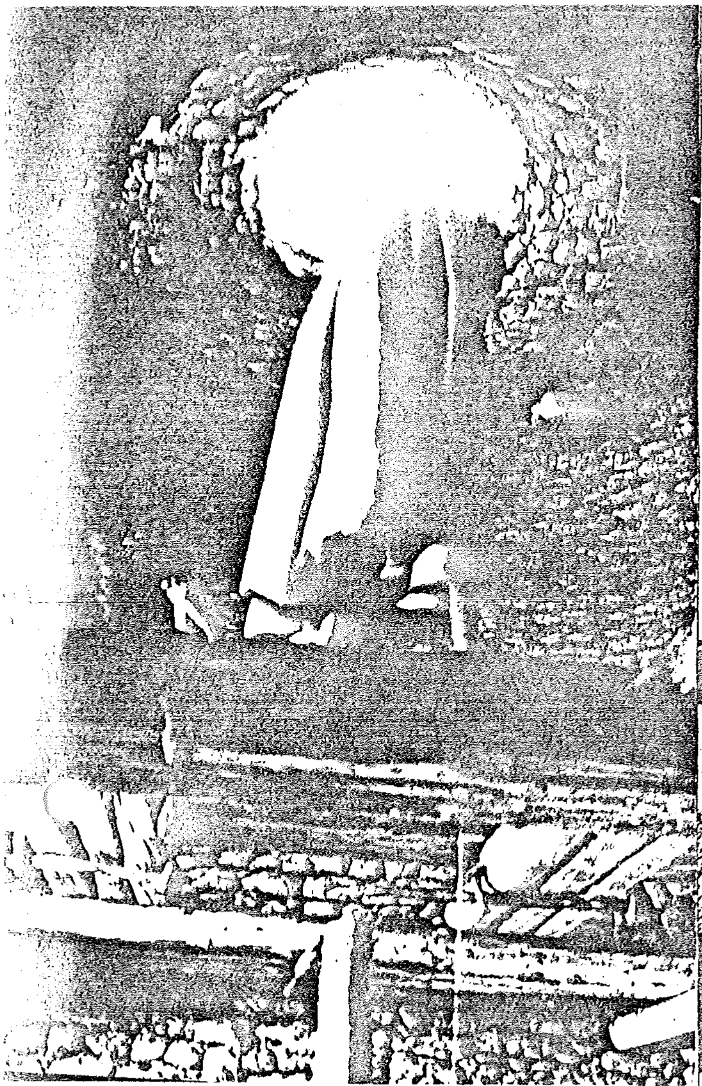


INTERIOR OF DOME



INTERIOR VIEW OF COMPLETED DOME

25



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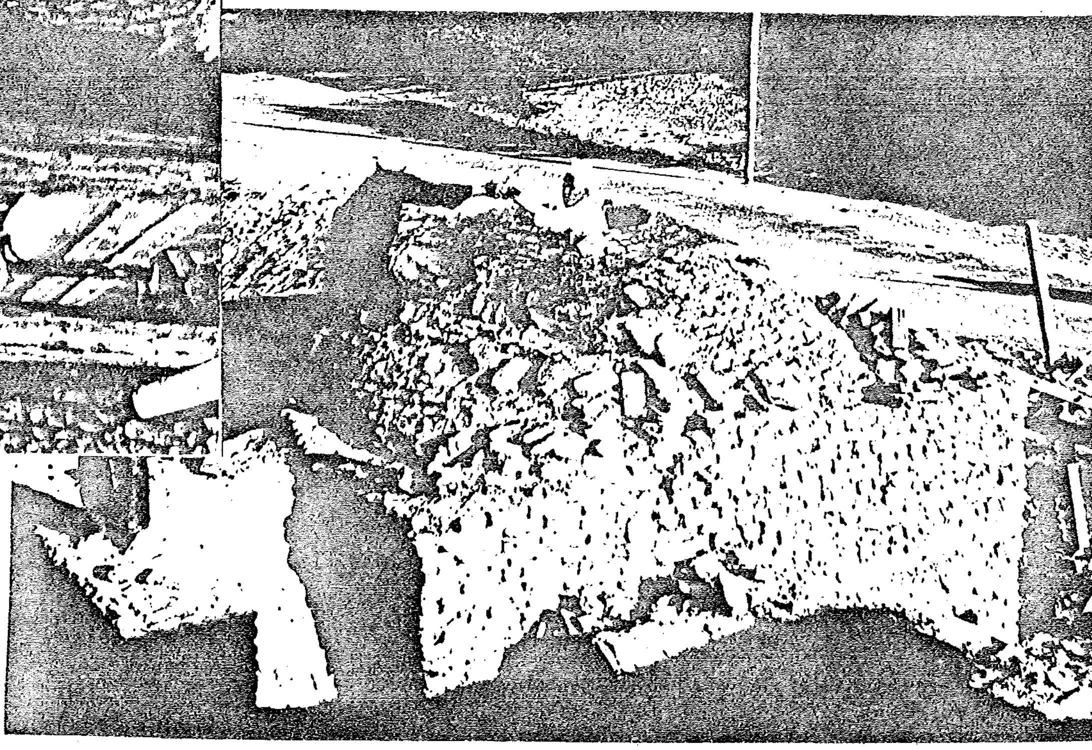

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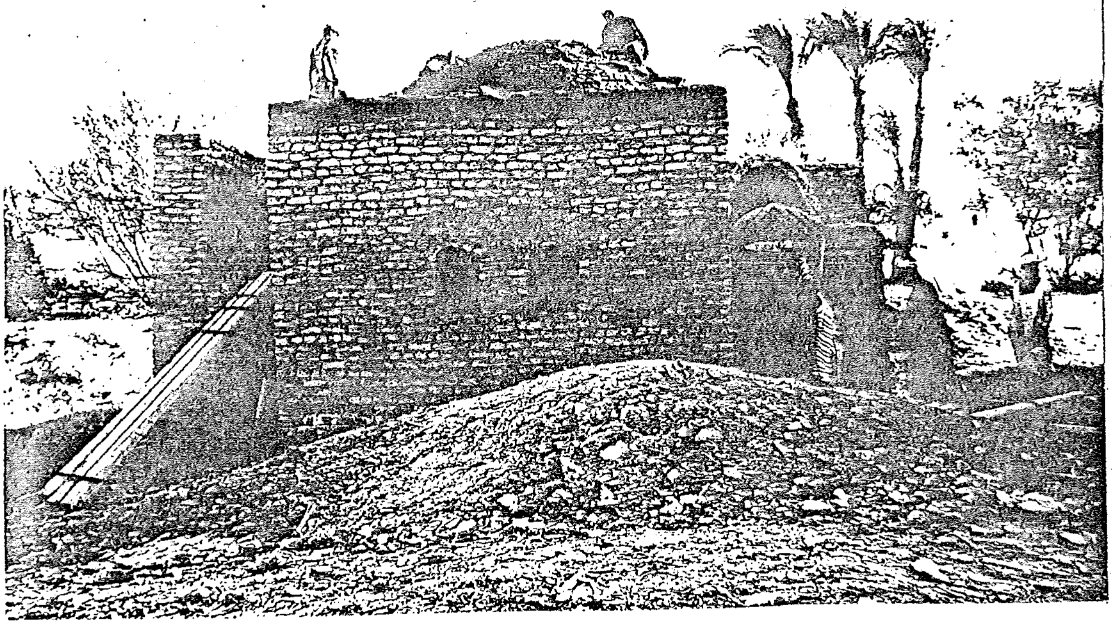

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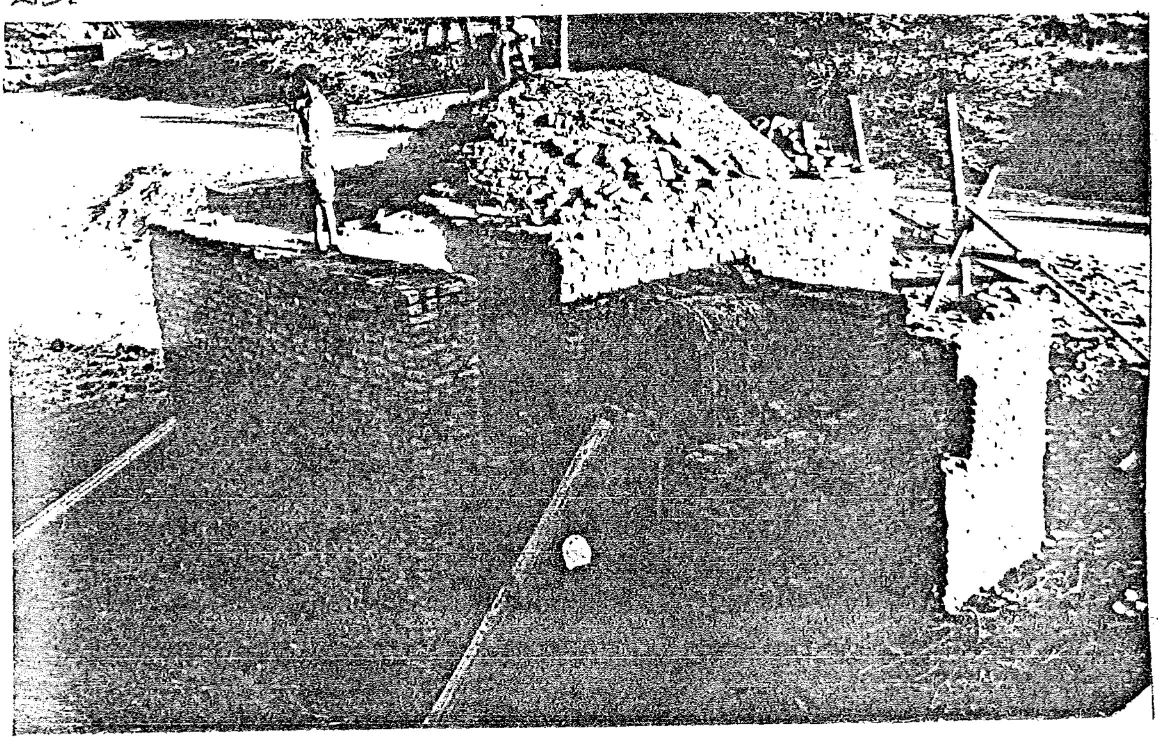
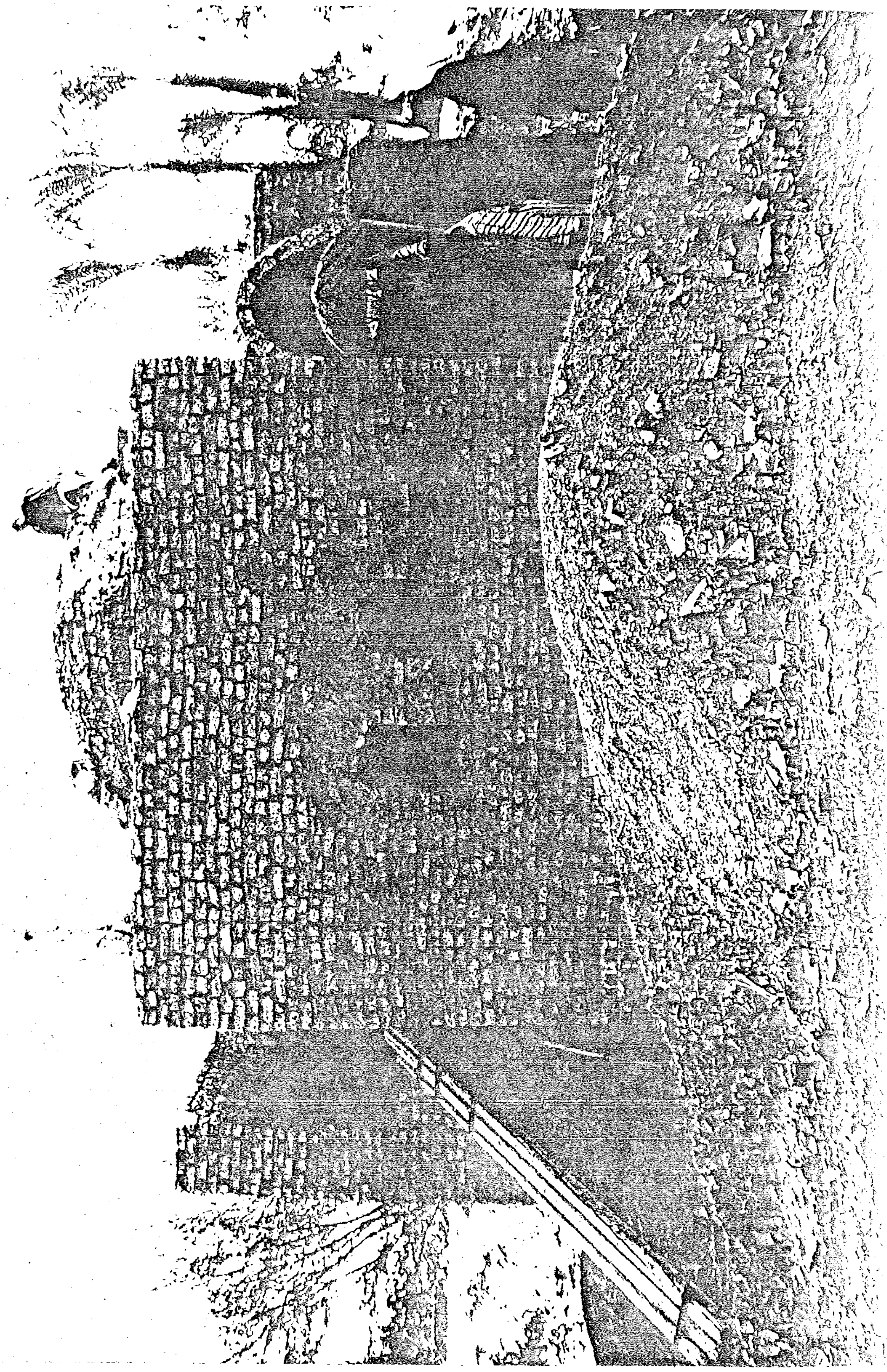
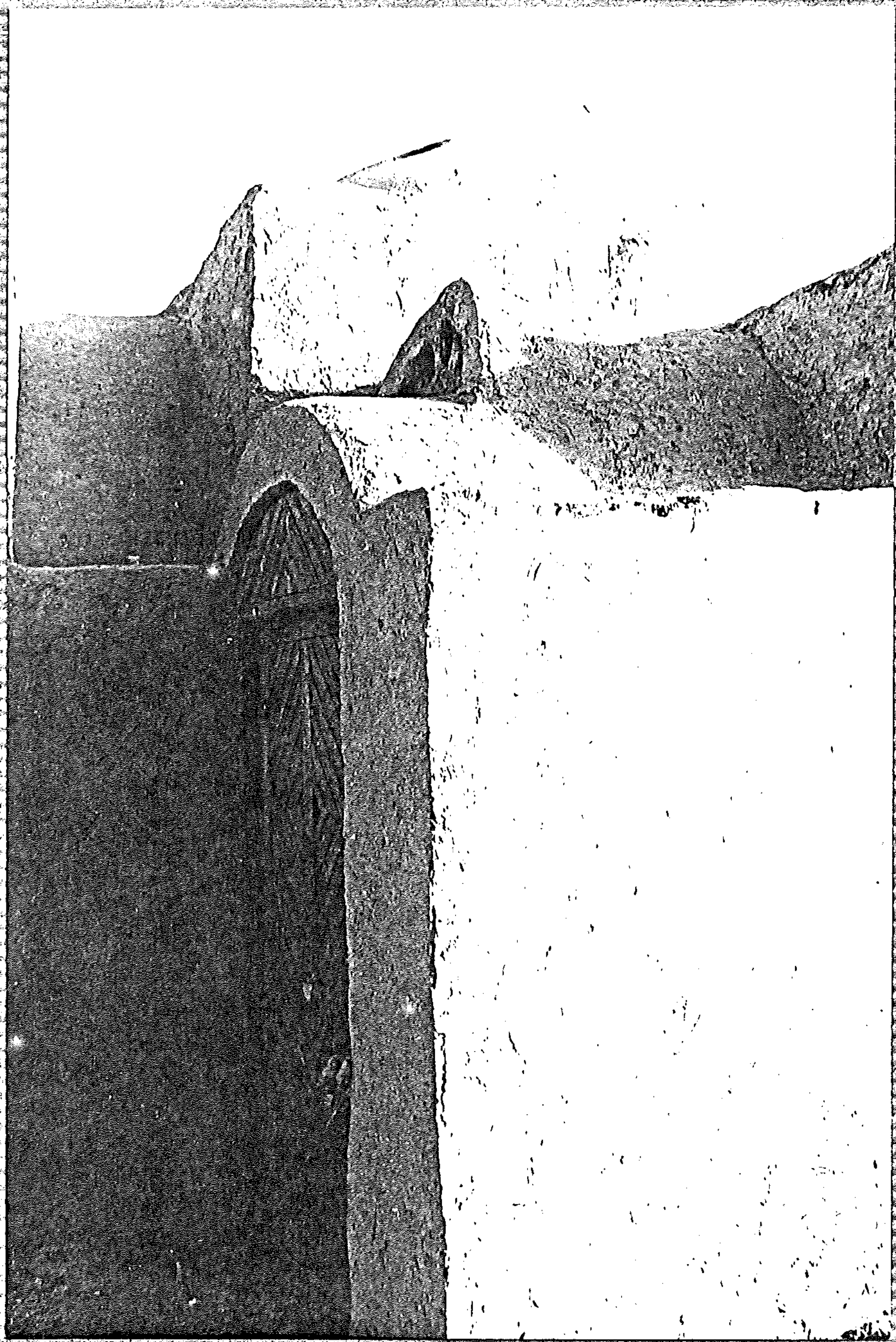
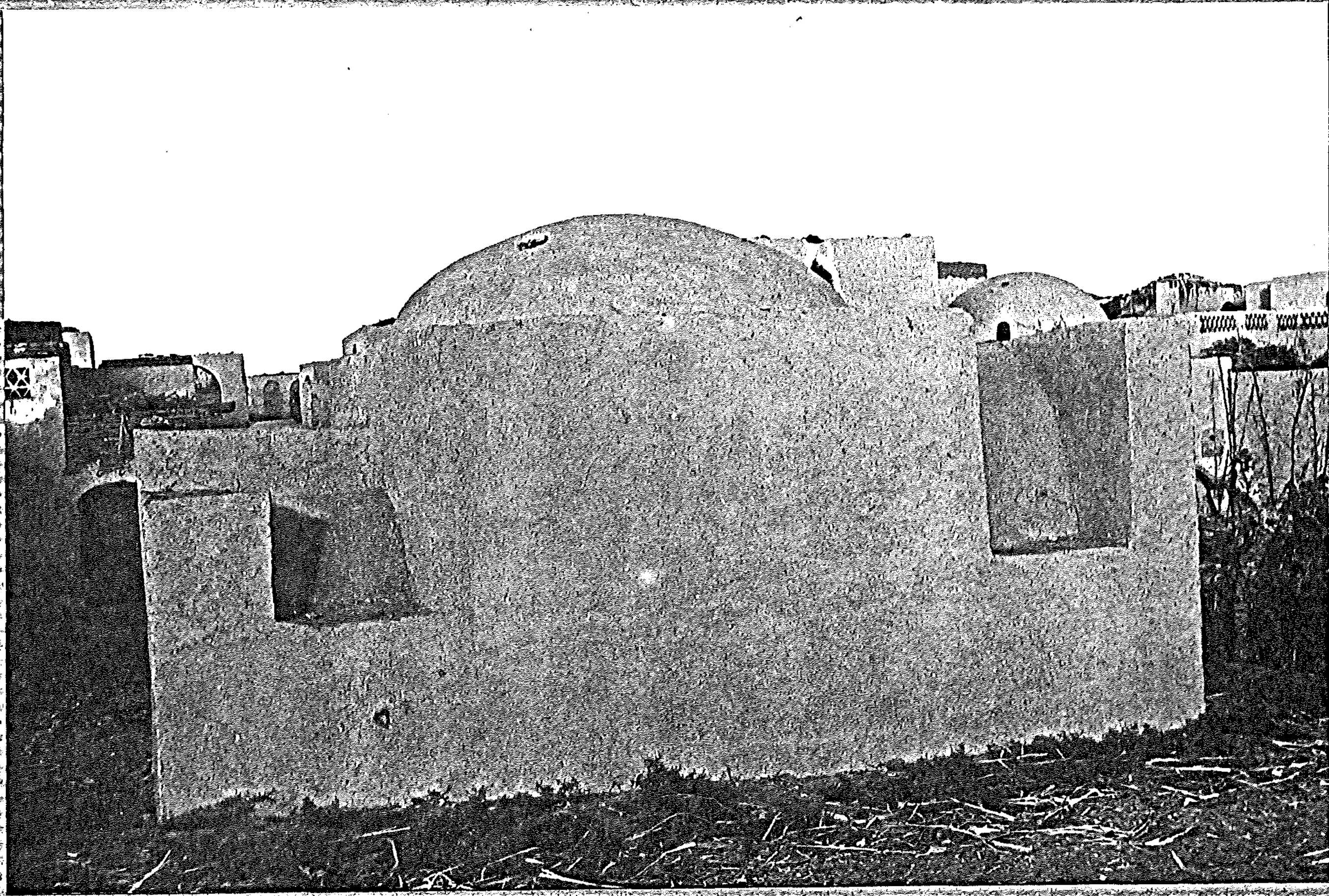




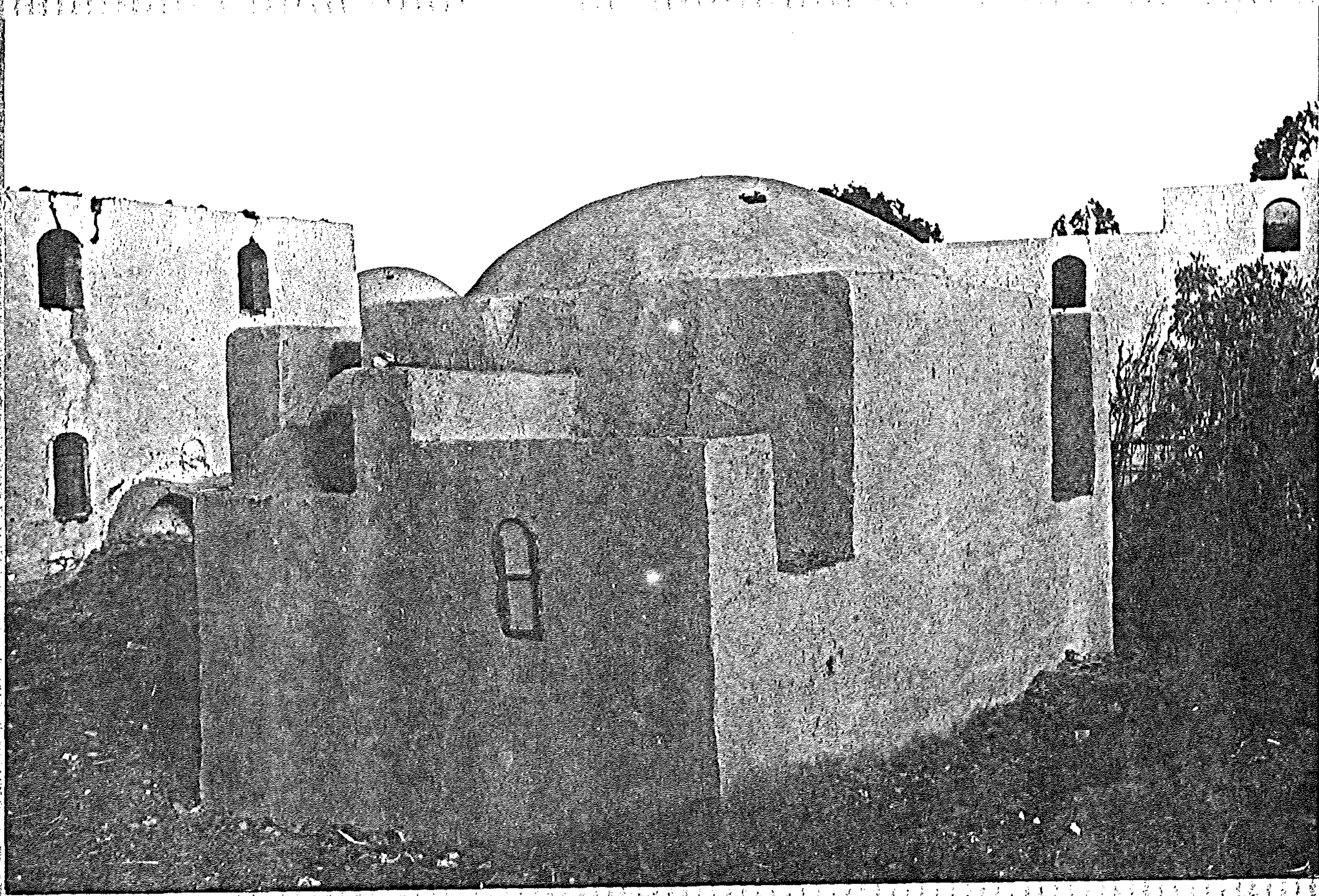
COMPLETED PLASTERED HOUSE – north wall



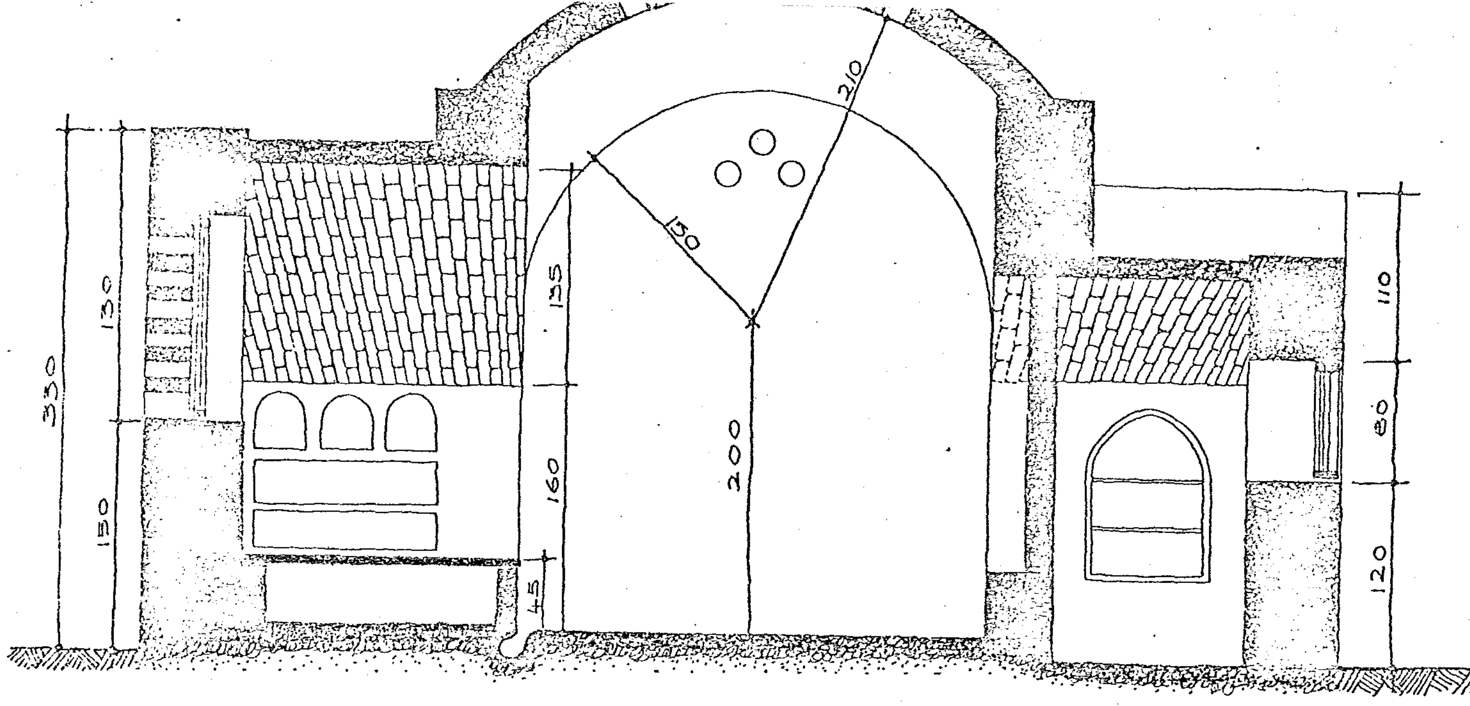
COMPLETED HOUSE – DOORWAY



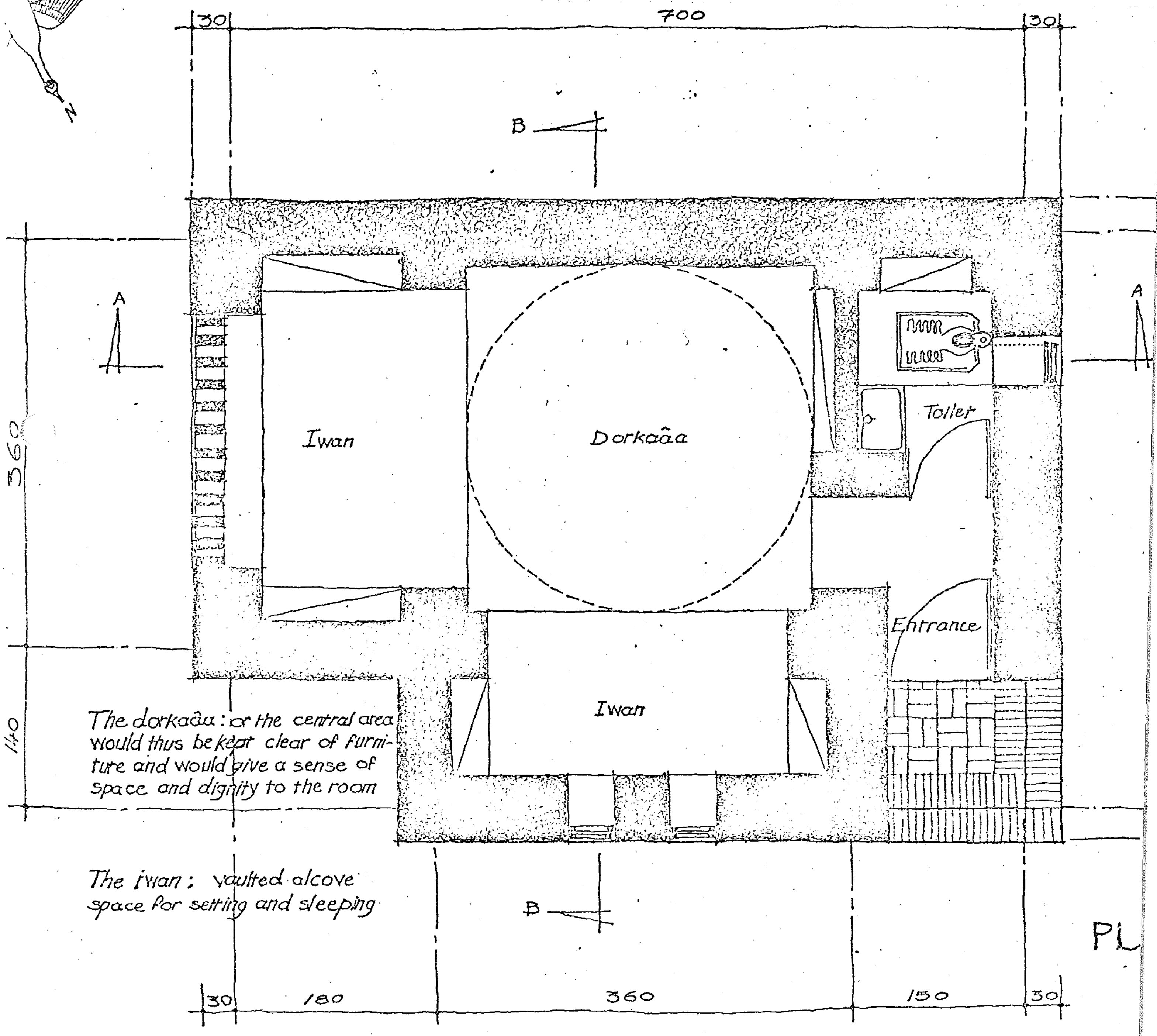
COMPLETED HOUSE - VIEW OF SOUTH WALL



COMPLETED HOUSE VIEW OF WEST WALL

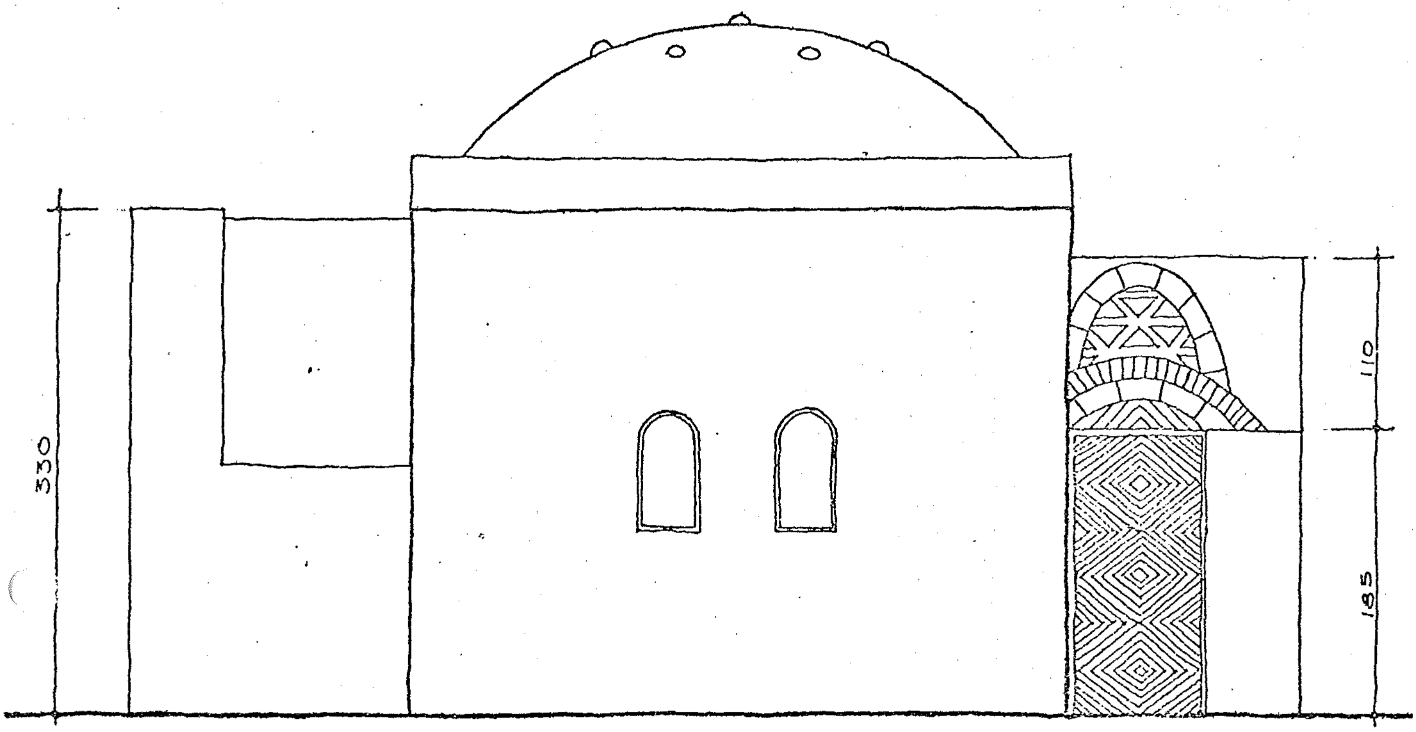


SEC.A-A

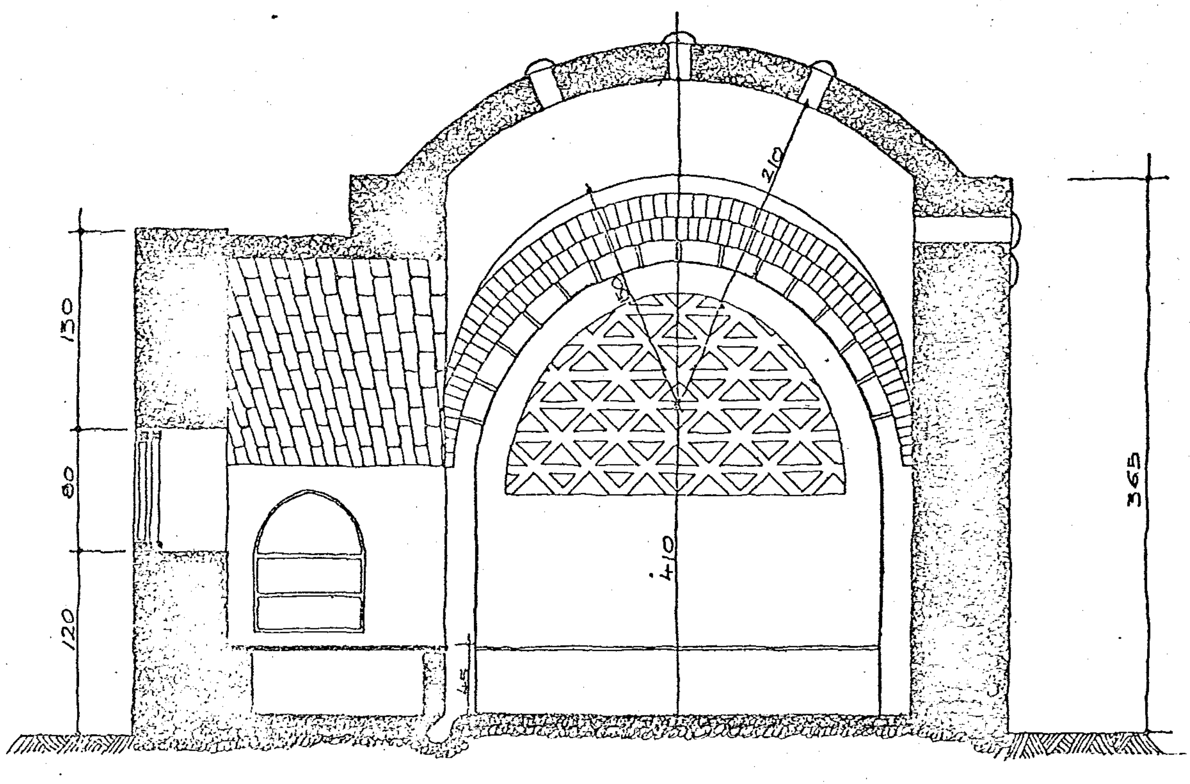


The dorkaâa : or the central area would thus be kept clear of furniture and would give a sense of space and dignity to the room

The iwan : vaulted alcove space for setting and sleeping



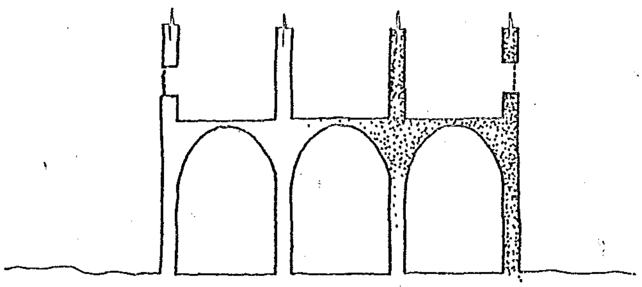
NORTH ELEVATION



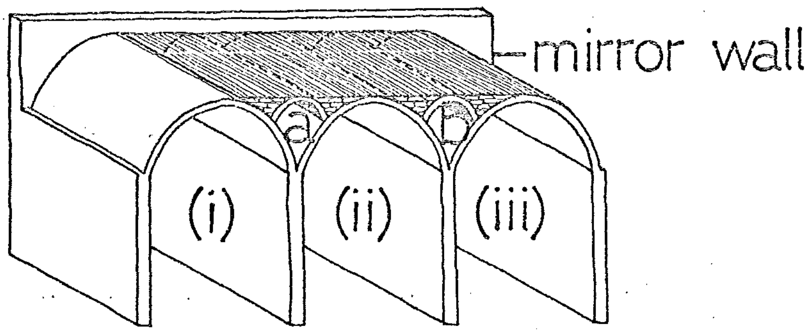
SEC. B-B

TECHNIQUES OF MUD BRICK VAULT CONSTRUCTION.

The transformation of a series of mud brick vaults into a flat roof or floor in a mud brick multi-storey building eg.

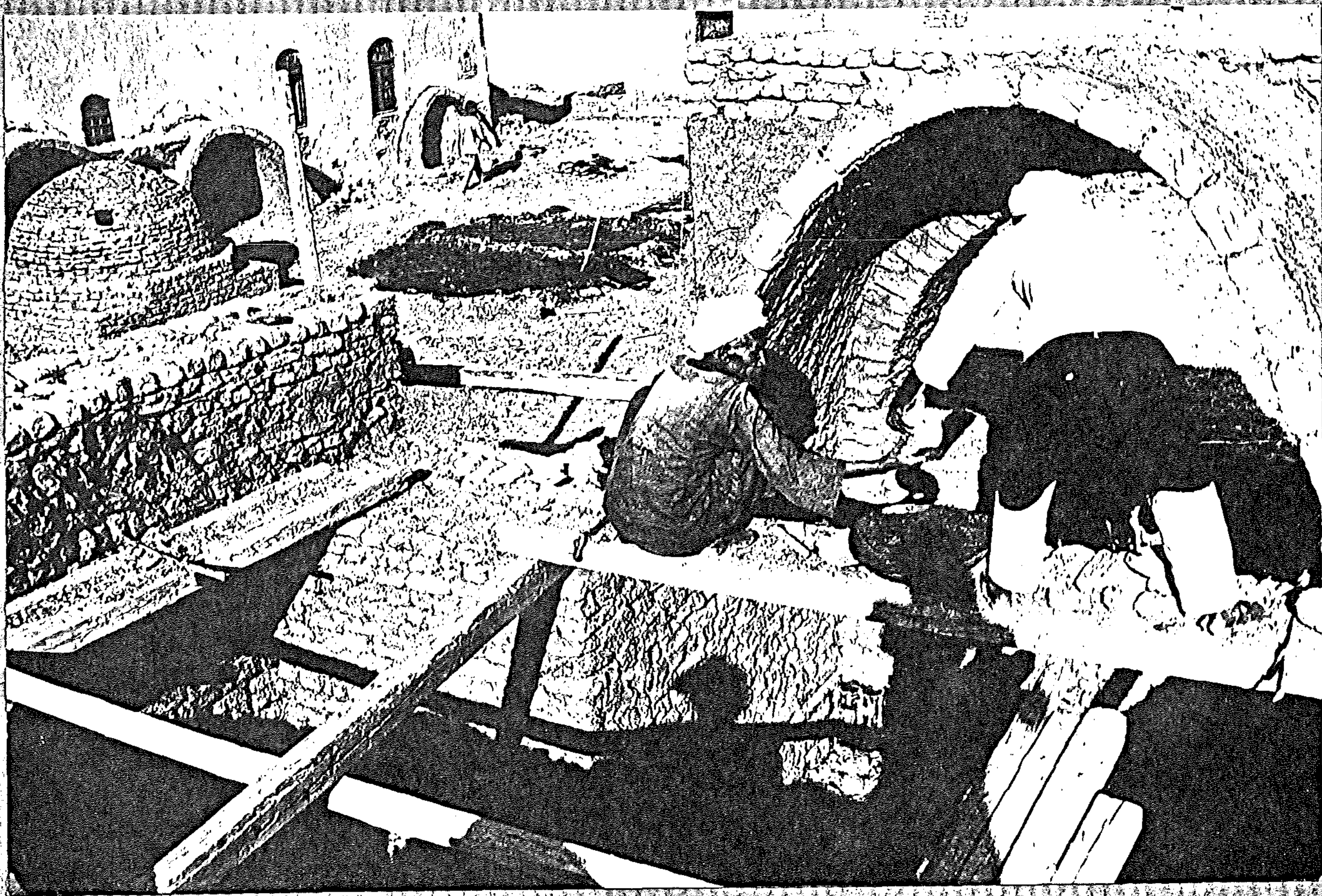


Using the existing vaults (i),(ii),(iii) as the 'spring walls' or supports and the same 'mirror wall' as was used in their construction, two smaller, 'bridging' vaults (a) and (b) are constructed in exactly the same way as the large vaults.



The tops of these small vaults should line up with the tops of the large vaults, (i),(ii),(iii).

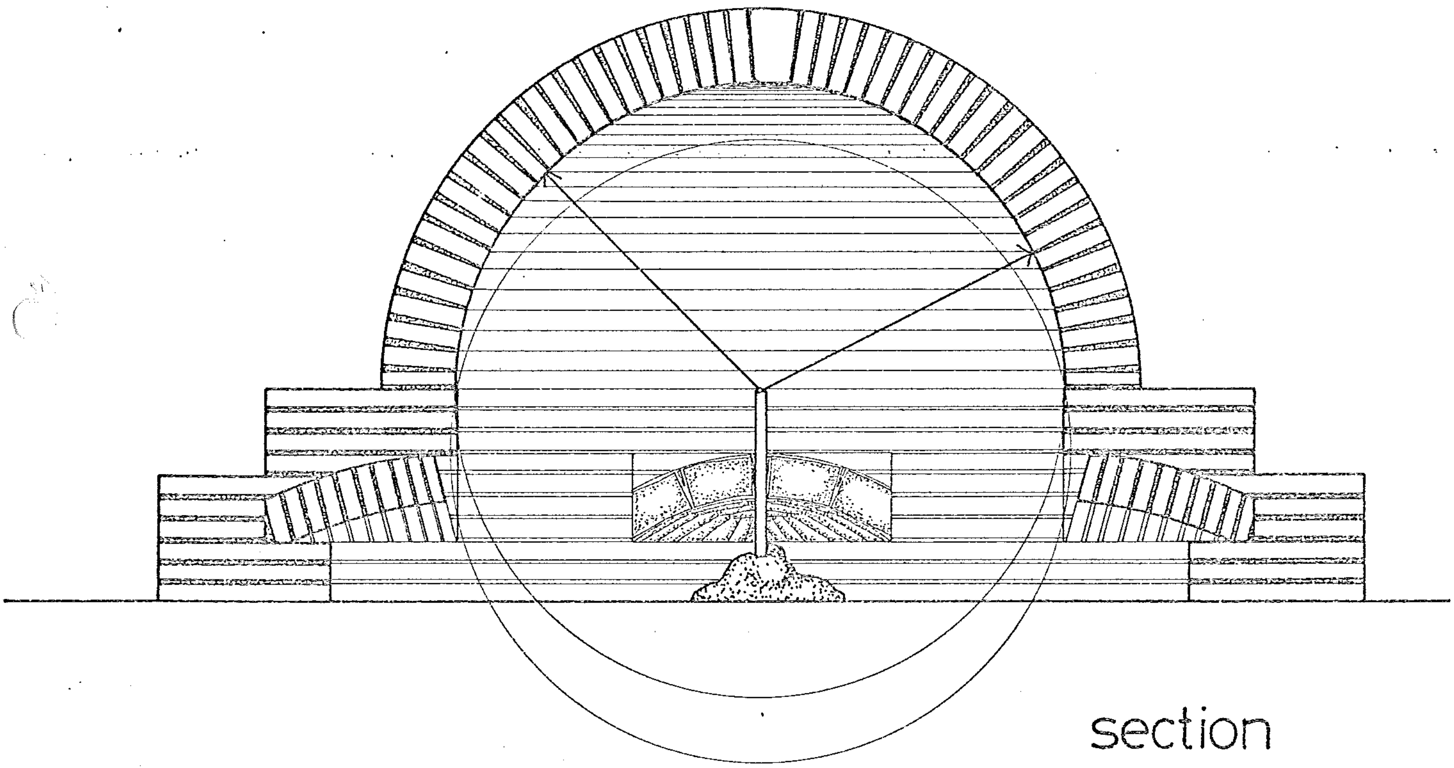
In this way the gaps left between the large vaults are filled in the lightest and most economical way. All that remains in order to obtain a level roof or floor surface is to fill in the gaps between the small vaults and large vaults with layers of vault bricks, laid flat, and plenty of mud mortar smoothed level. If these gaps are still large, yet smaller vaults can be built to span the distance before packing with mud and bricks



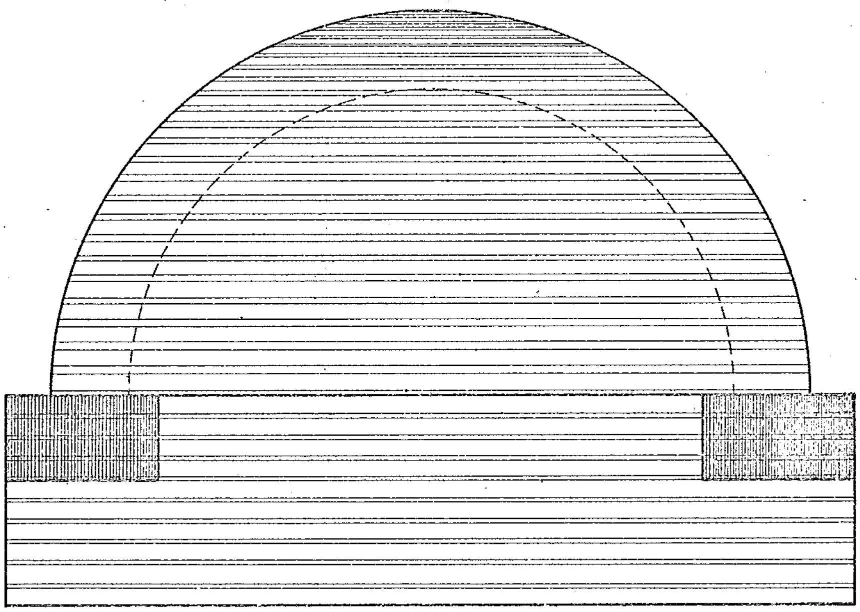
VAULT AND WALLS practice vaults and dome behind

MUD BRICK CONSTRUCTION: SASSANIDE DOME CONSTRUCTION METHOD

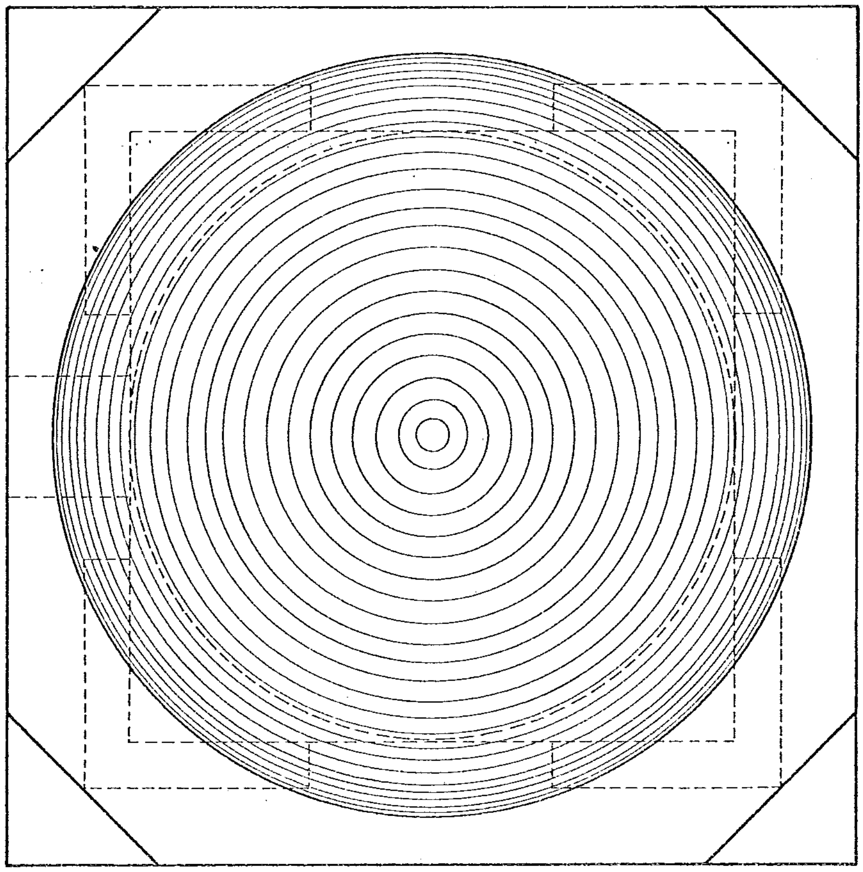
Part of the training programme at Gourna, before starting on the construction of the house, was the erection of a small, 2 metre square, mud-brick Sassanide dome resting on a low mud-brick wall which formed the square support.



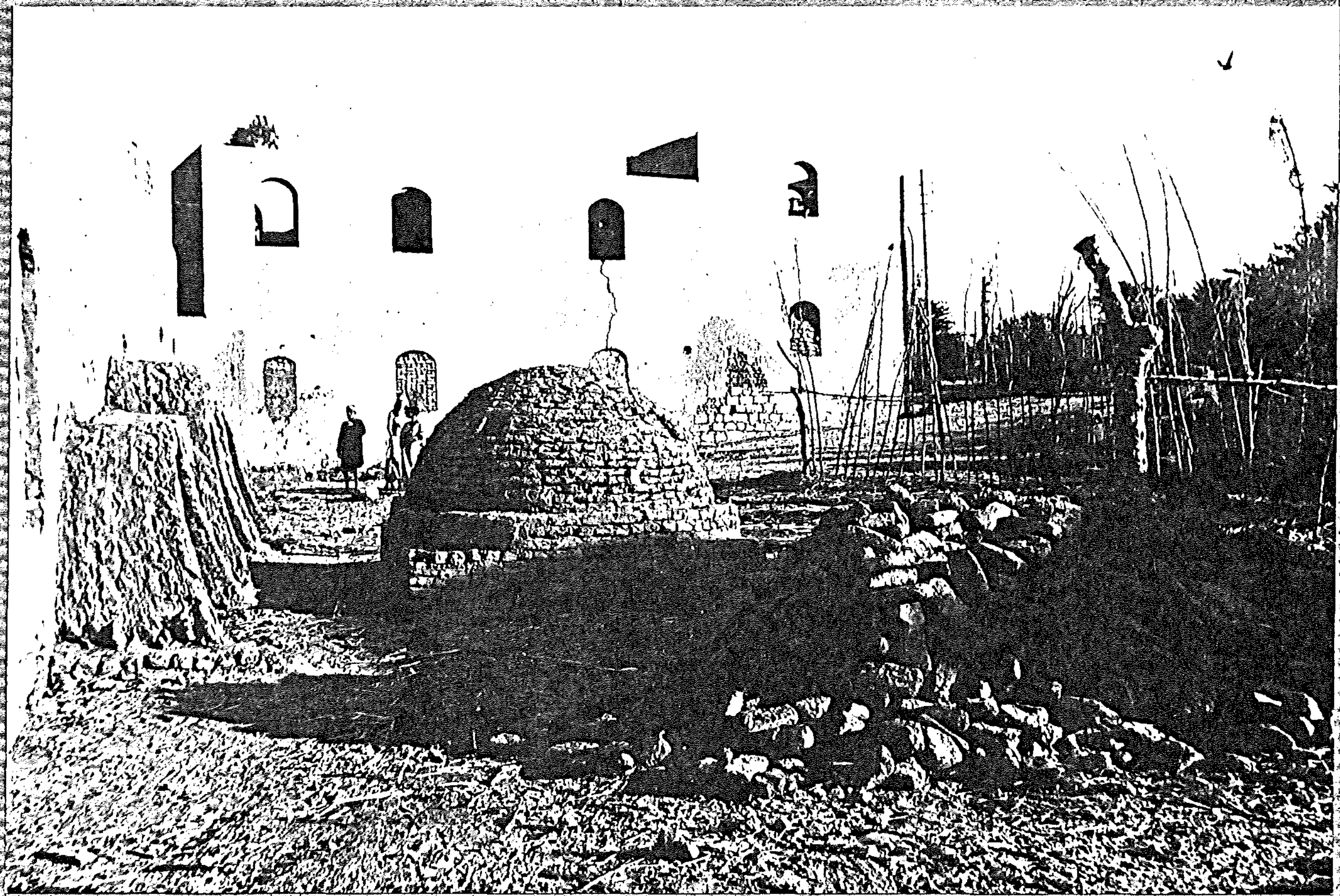
section



elevation

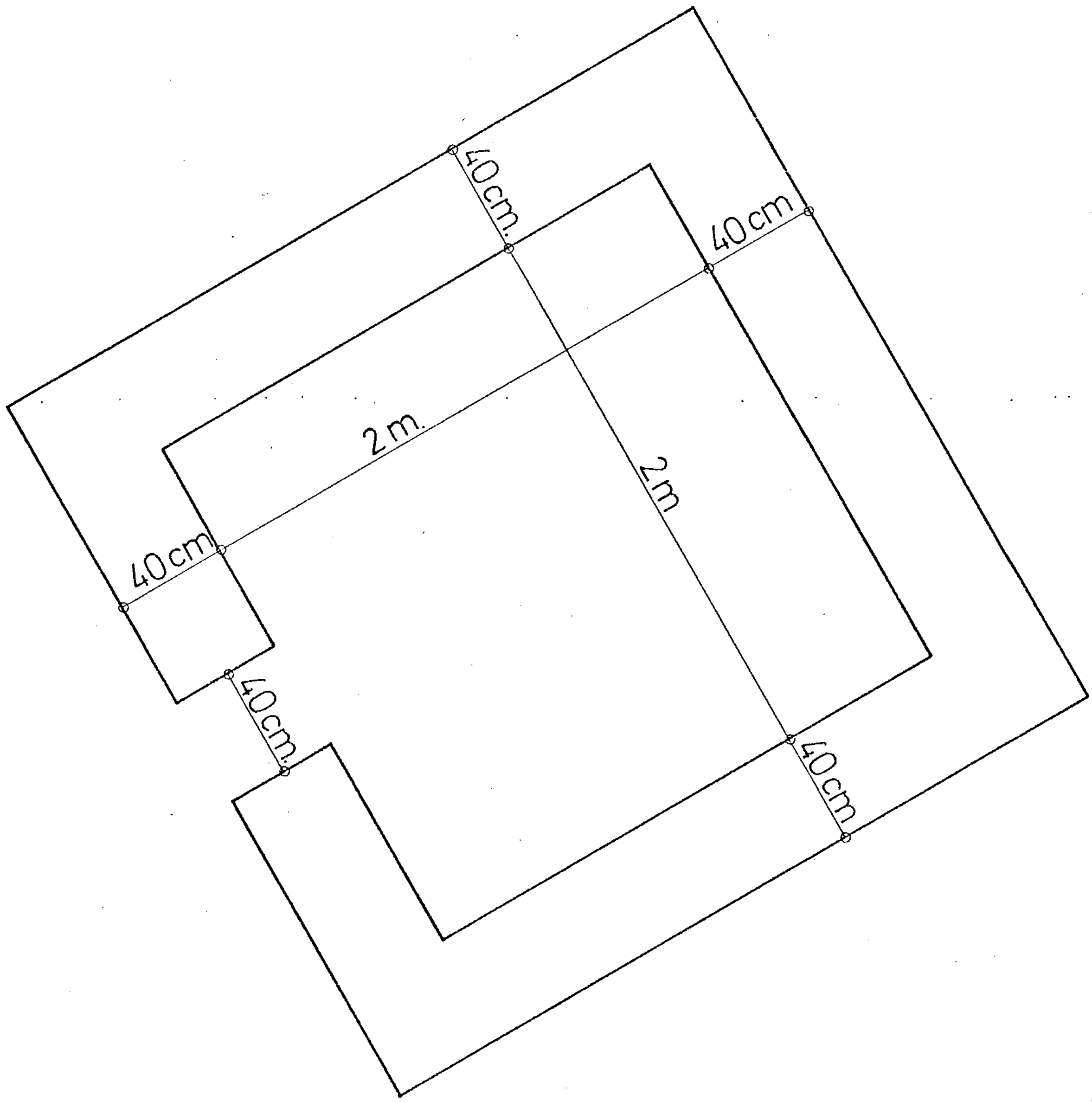


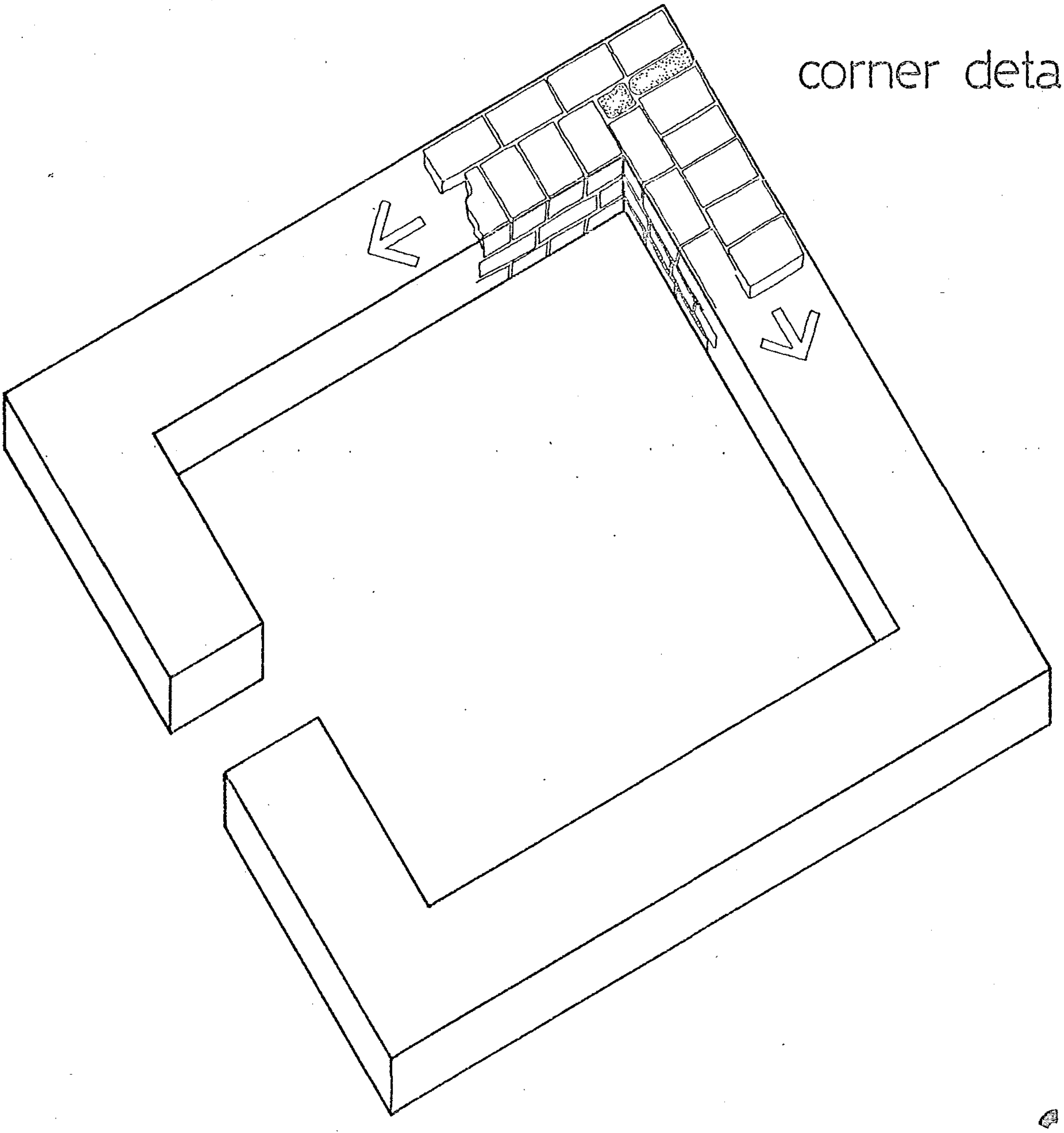
plan



PRACTICE VAULT AND DOME

The square plan is marked out and three courses of wall bricks laid in alternating courses, to avoid vertical cracking, using a mortar made of mud and straw. A gap should be left in the wall on one side. This gap later becomes an arched opening to facilitate entry and exit during the construction of the dome itself

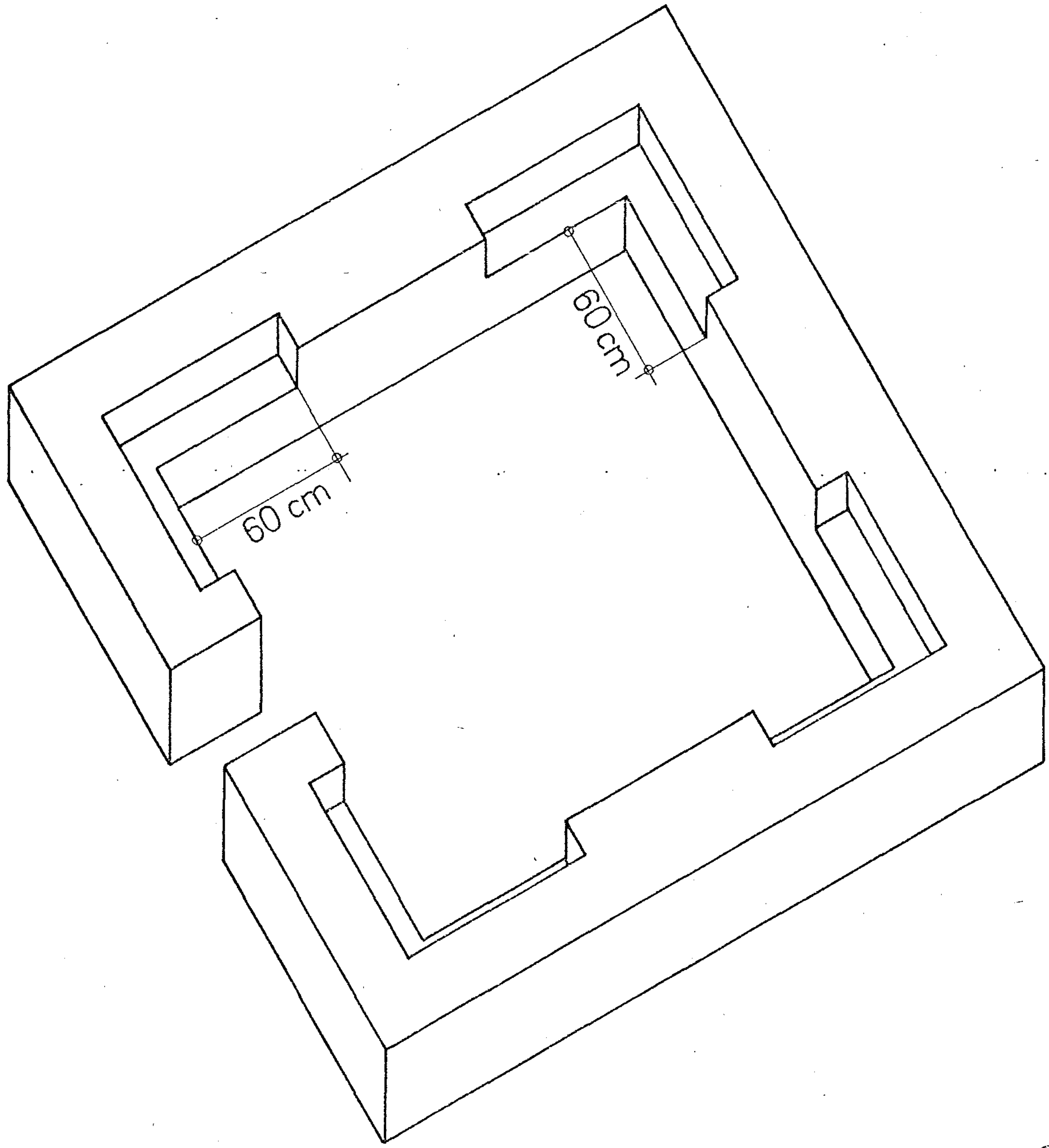


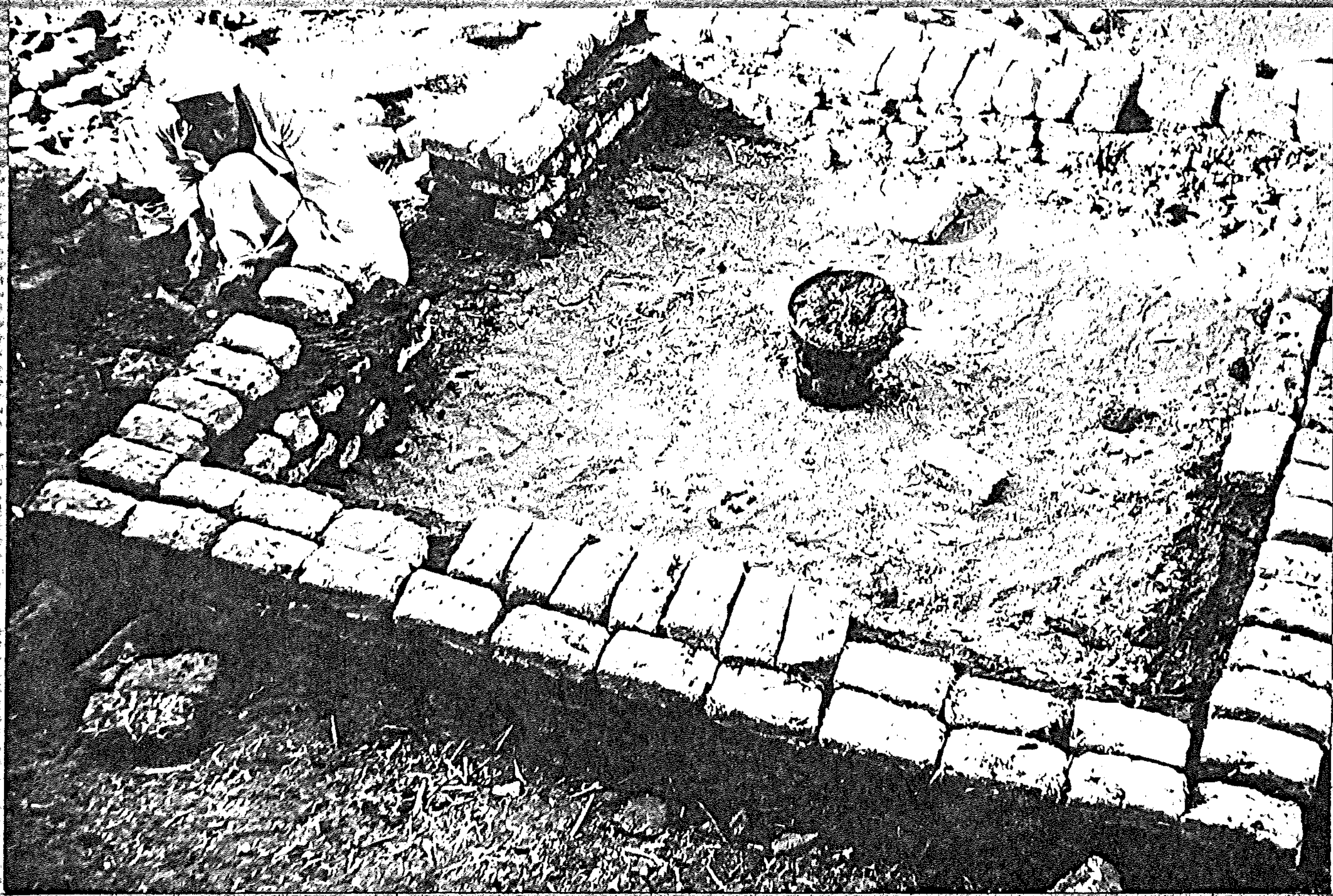


corner detail

Measure 60 cm. each way from the internal corners out along the length of the walls, so that the next two courses, 4 and 5, allow for a 90° ledge, $\frac{1}{2}$ a brick wide, in each corner, as shown below.

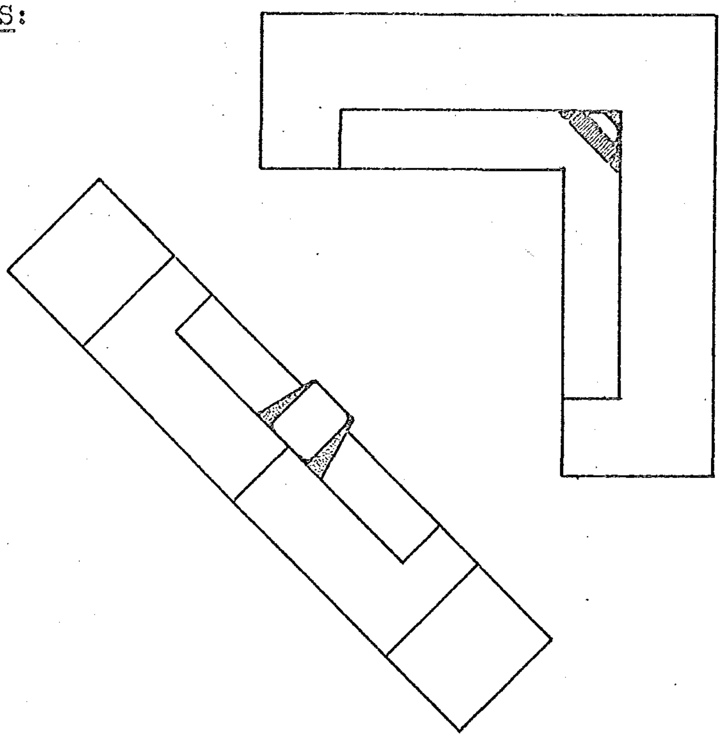
These ledges form, on completion of the 5th course, the bases of 4 squinch arches.





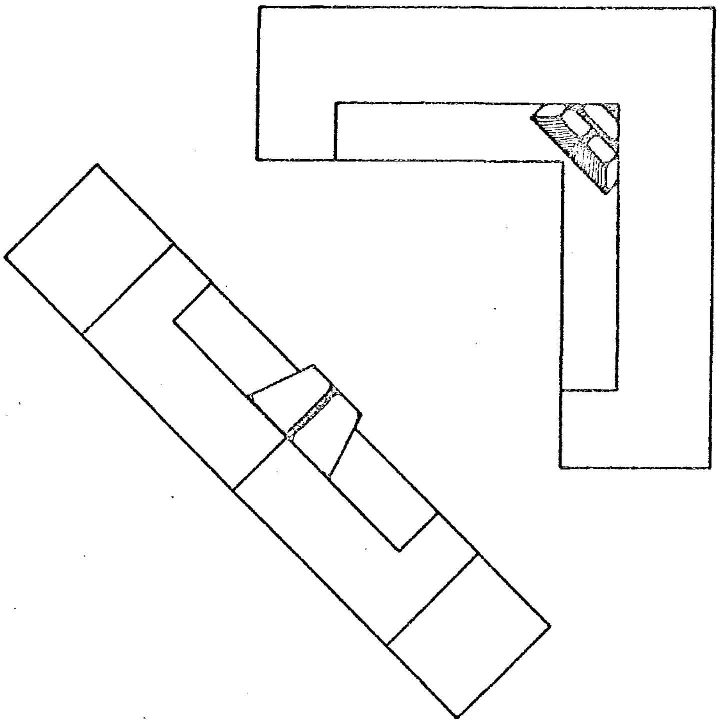
FIRST COURSES OF BASE WALL OF DOME

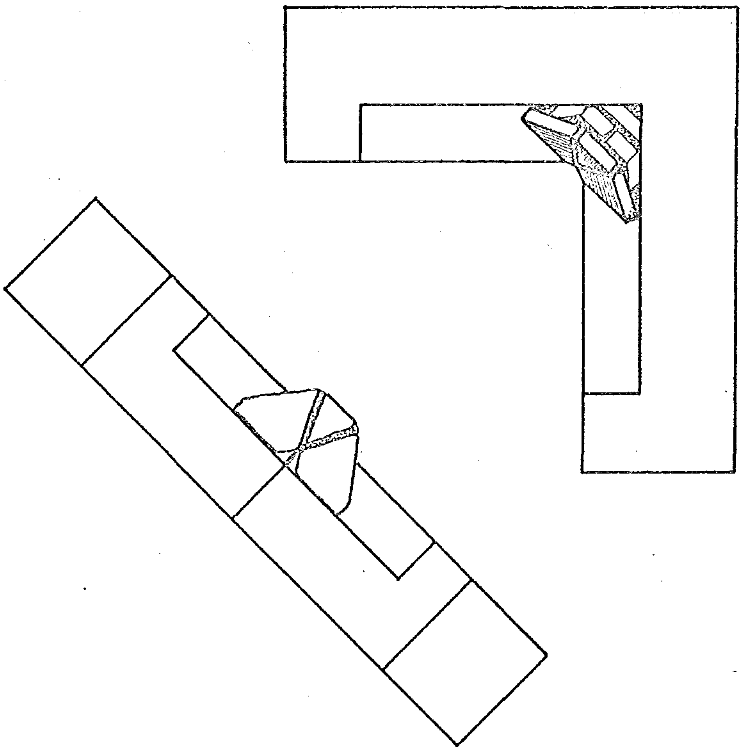
SQUINCH ARCHES:



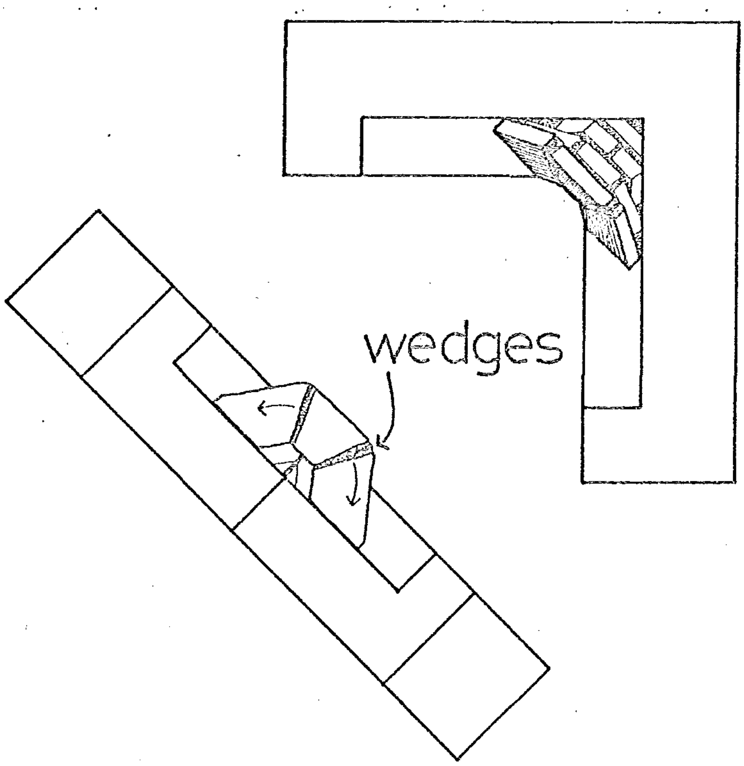
Fill in the corner with mud and ½ a vault brick, leaning at an angle against the corner.

Then lean 2 bricks, shaped to take the angle against this initial triangle, packing them with plenty of mud mortar.

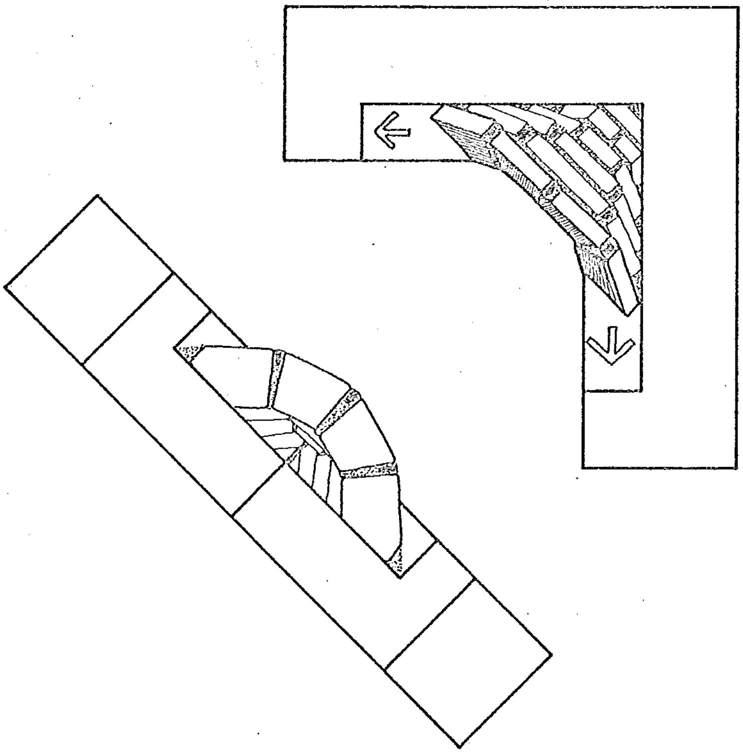




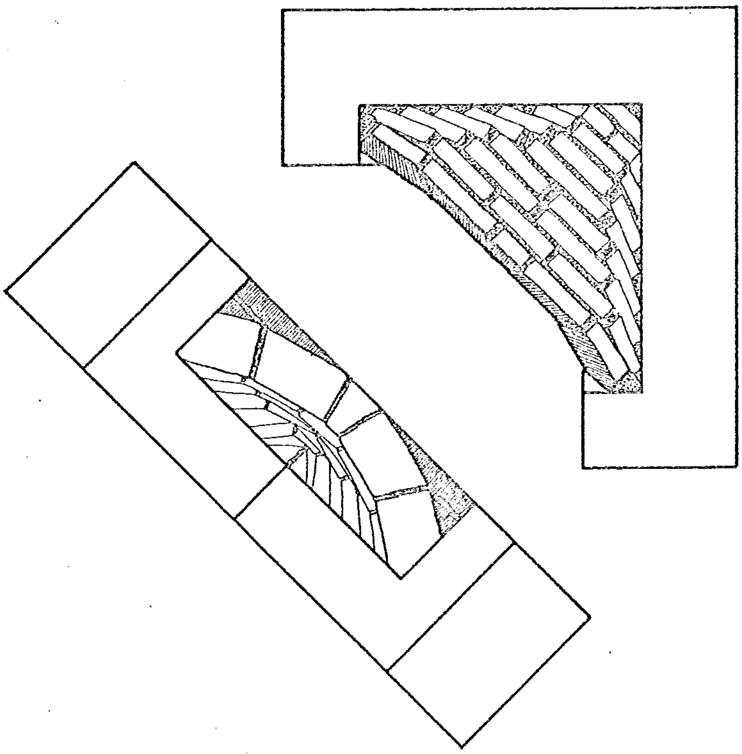
The next row is made up of 2½ shaped bricks.The small middle piece acts as a keystone(to strengthen the arch).Vault bricks are used for the construction of these arches and small bits of limestone or pottery are wedged into the gaps left between the bricks as they take the angle.These wedges also serve to strengthen the arch.They



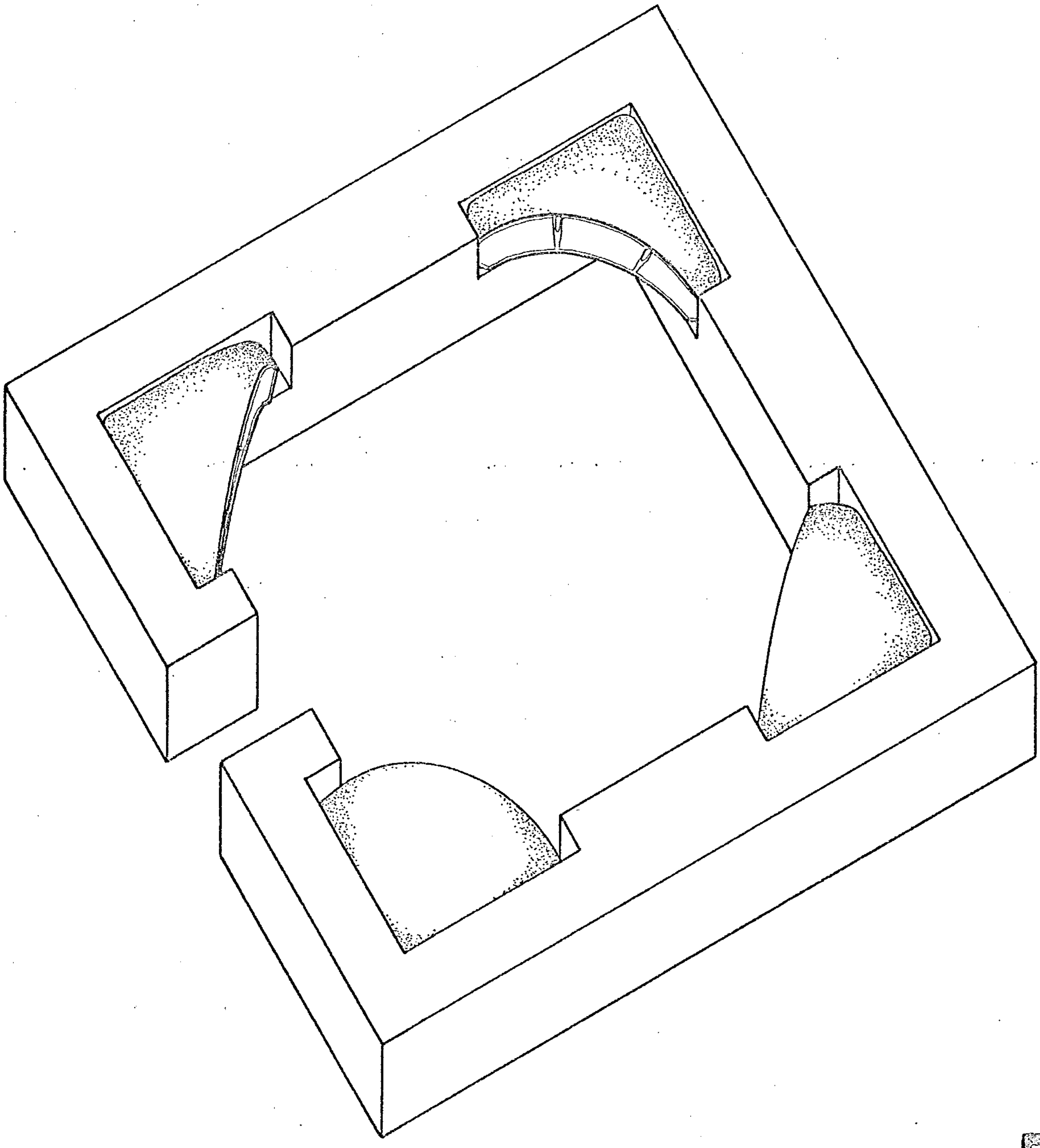
are more stable than mud mortar for this respect as they do not shrink or expand with moisture loss or gain.



Each course moves further away from the corner and rises slightly to form a low archway. Each course leans against and is supported by the previous course, in much the same way as in the construction of vaults. As the keystones or wedges are squeezed into or hammered into the mortar between the bricks they cause them to tighten up and form a solid arch

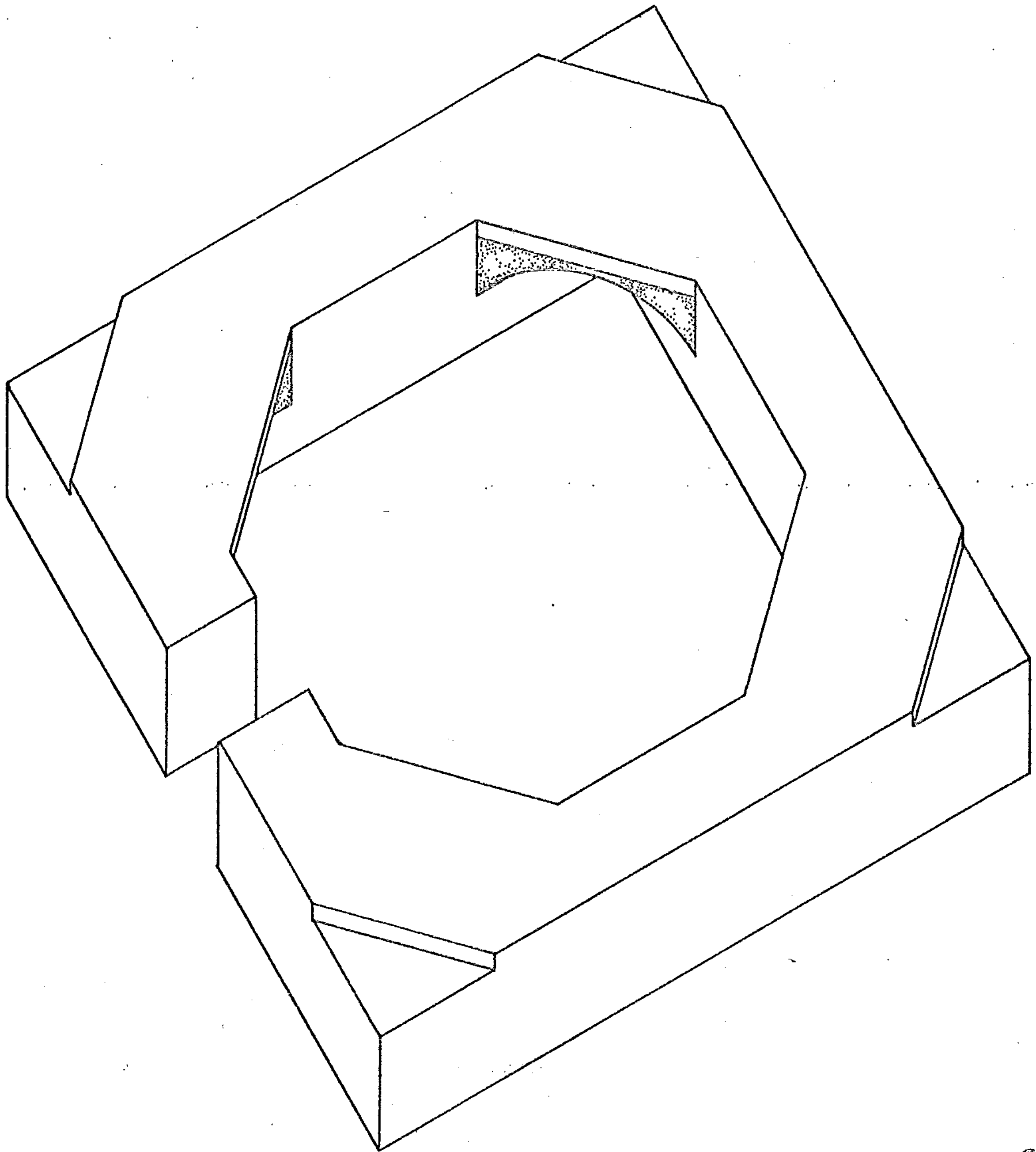


On completion, the 4 squinch arches should be liberally covered and smoothed over with mud mortar.



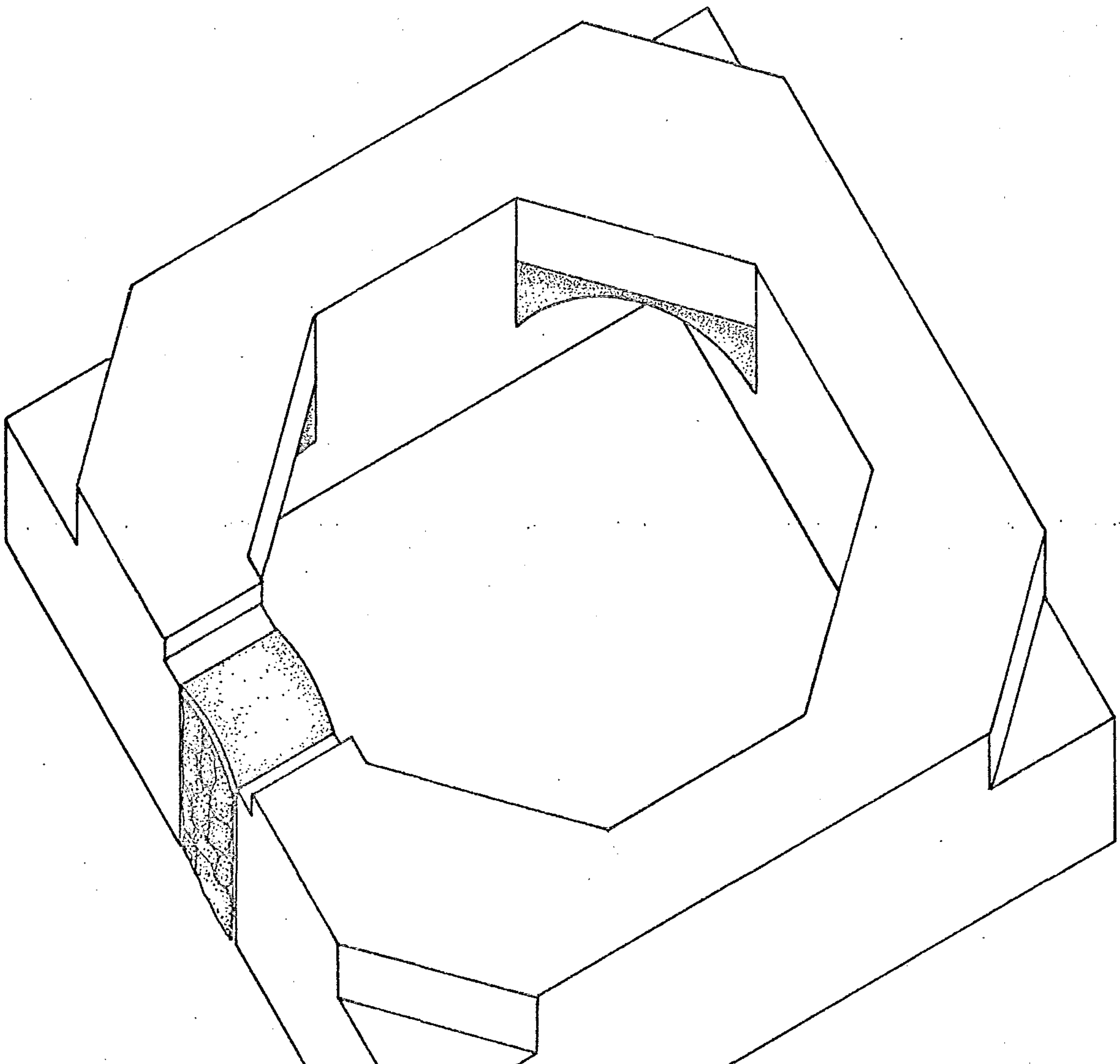
COMPLETION OF SQUINCH ARCHES

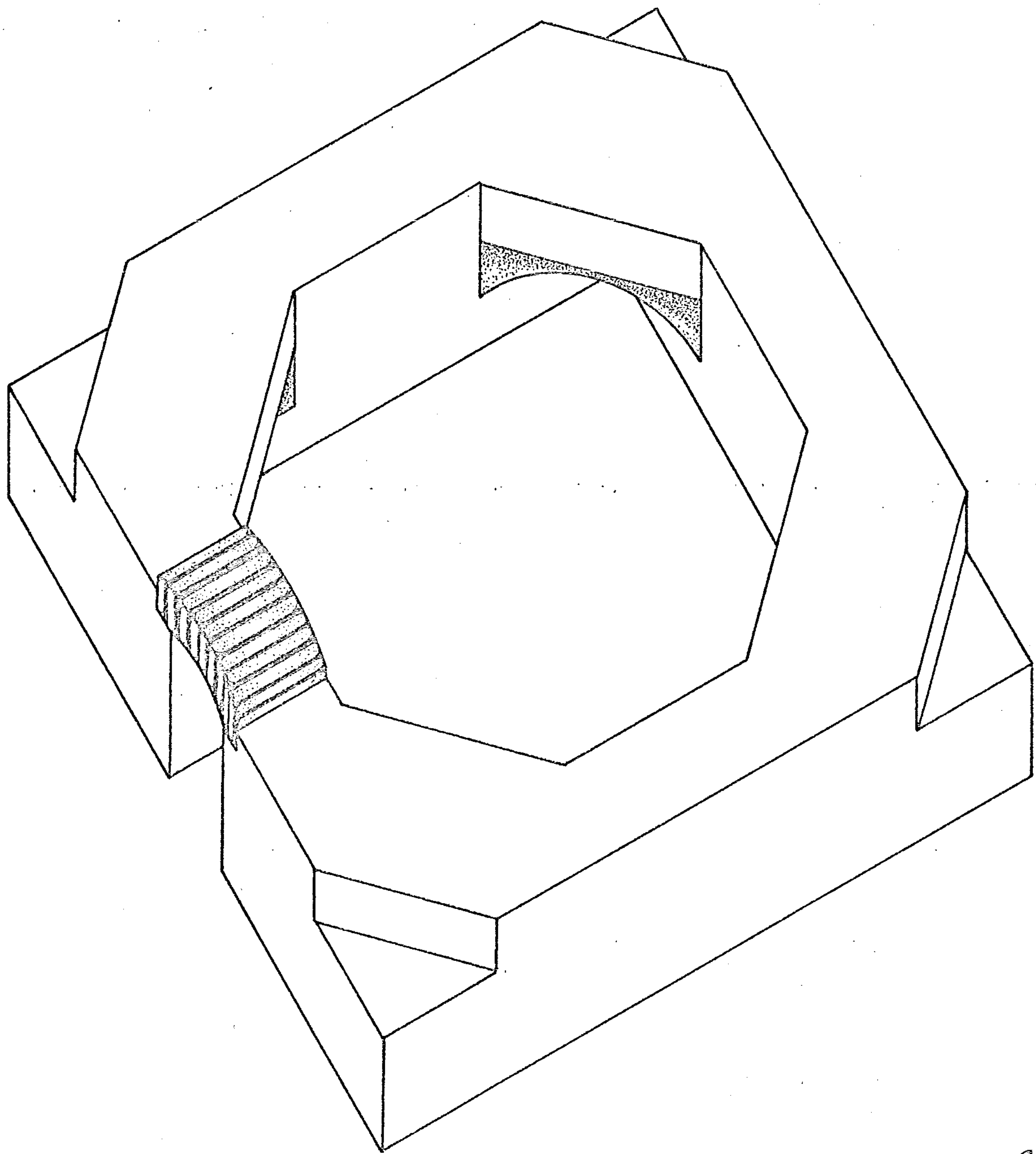
The 6th and 7th course of wall bricks should level out with the tops of the 4 squinch arches. At this point, the square plan is converted into an octagonal plan by cutting the external corners of the 7th course to meet the outer corners of the arches eg.



CONVERSION TO OCTAGONAL PLAN

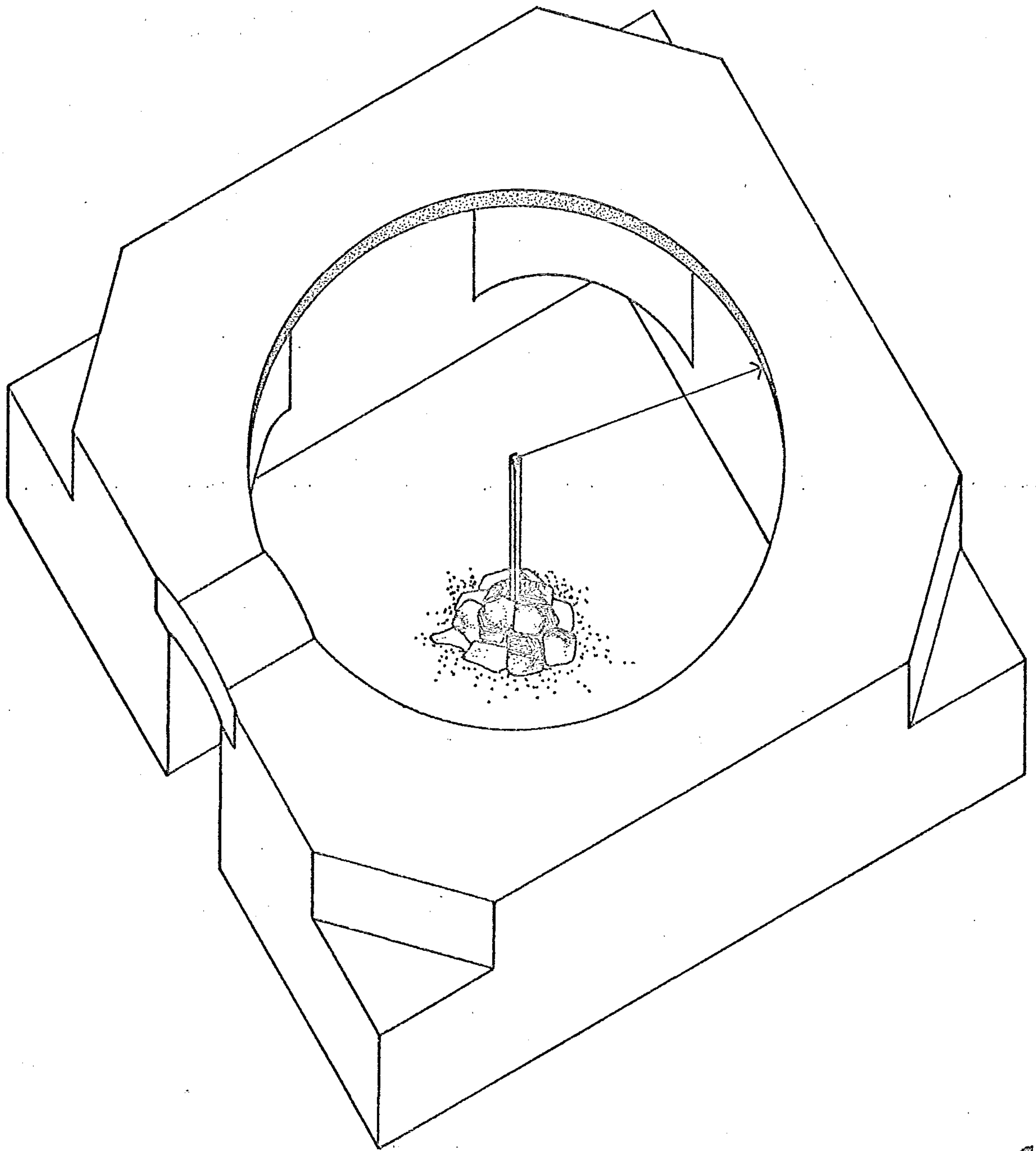
Two more courses are laid according to the octagonal plan and covering the squinch arches.(course 8 and 9).The gap originally left in the wall is temporarily filled in with loose bits of brick and rubble forming a rough curve on top,which is smoothed over with a good layer of mortar. Then,using small ledges left on the walls on either side as supports, an arch is constructed with vault bricks laid on edge.This arch is covered with a layer of mud to smooth it off and the supporting rubble infill is removed.



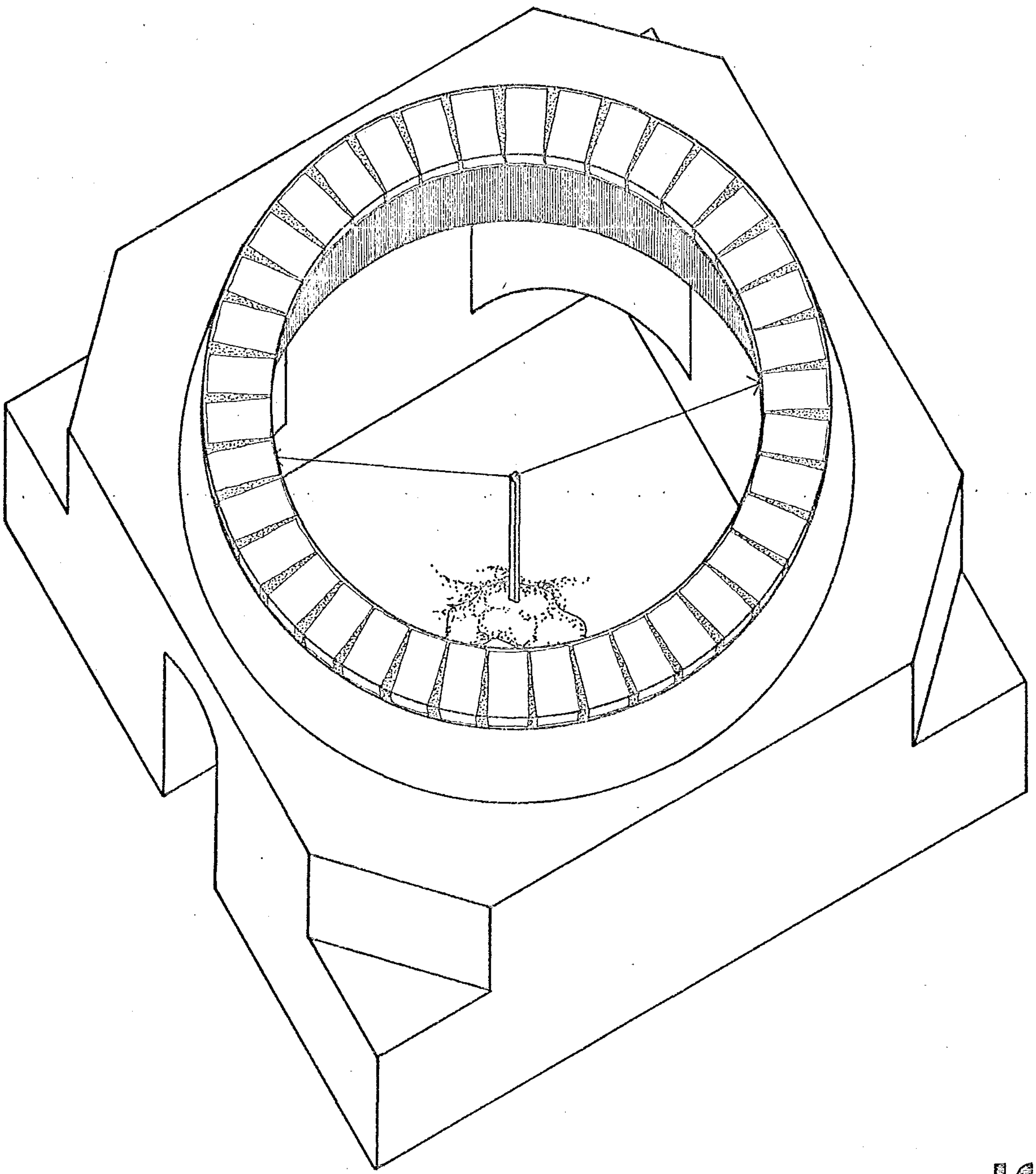


S

The 10th or 11th course of bricks should level out with the top of the arch and start taking on the circle of the dome. In fact, this course is of vault bricks and forms the 1st course of the dome, which is thereafter built entirely of vault bricks. The centre point of the plan is located in order to fix (with mud and rubble) a central pole, at the end of which is attached a string of fixed length to be used as a guide for the construction of the dome.

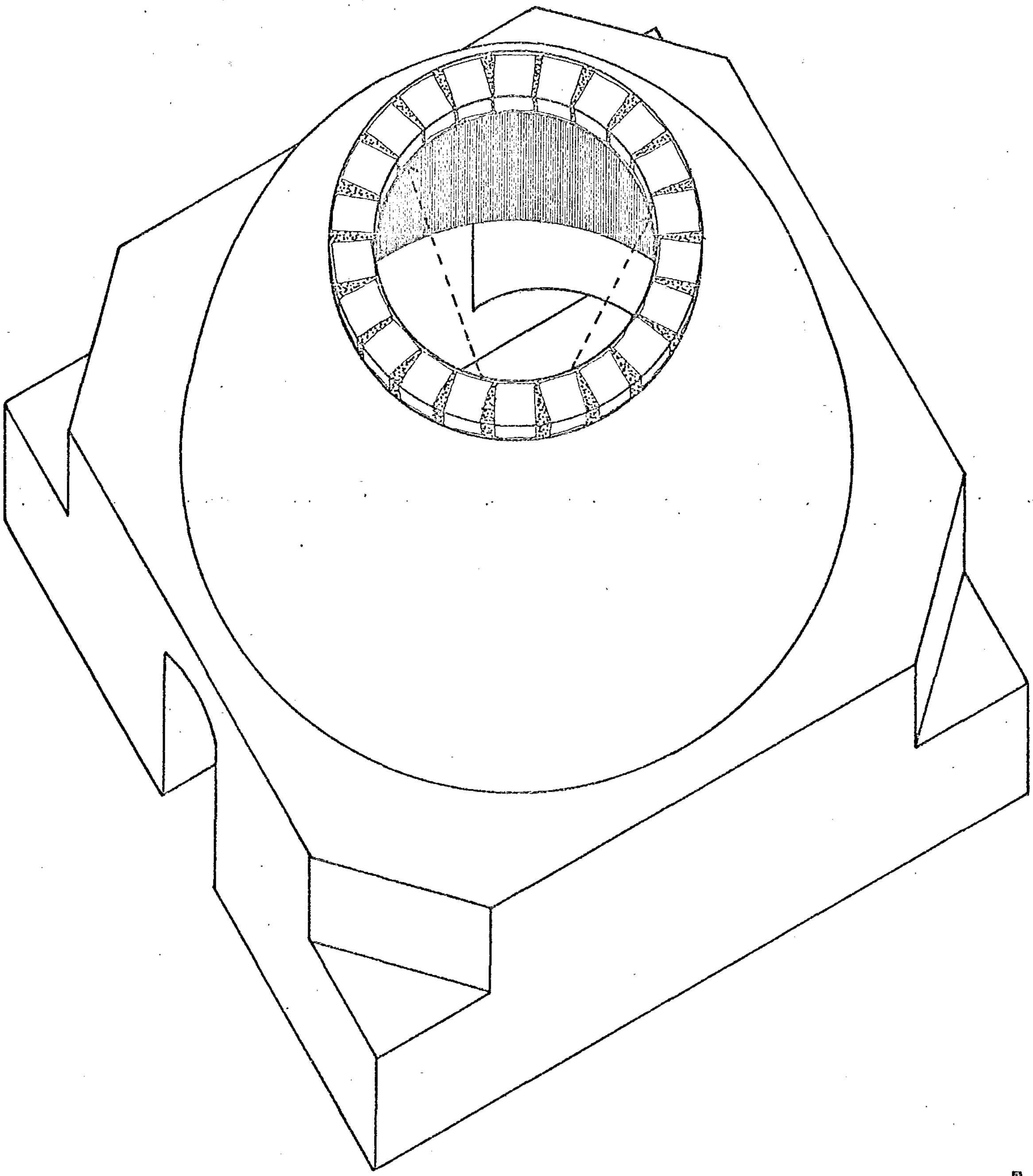


The end of the string should correspond constantly to the inner edge of the remaining courses of brickwork making up the dome. The length of the string is actually the radius of the sphere of which the dome forms a part. The height of the dome can be adjusted by using a shorter or longer pole i.e. a shorter pole leads to a flatter dome and vise versa. What one is in fact doing is raising or lowering the centre point of the sphere.

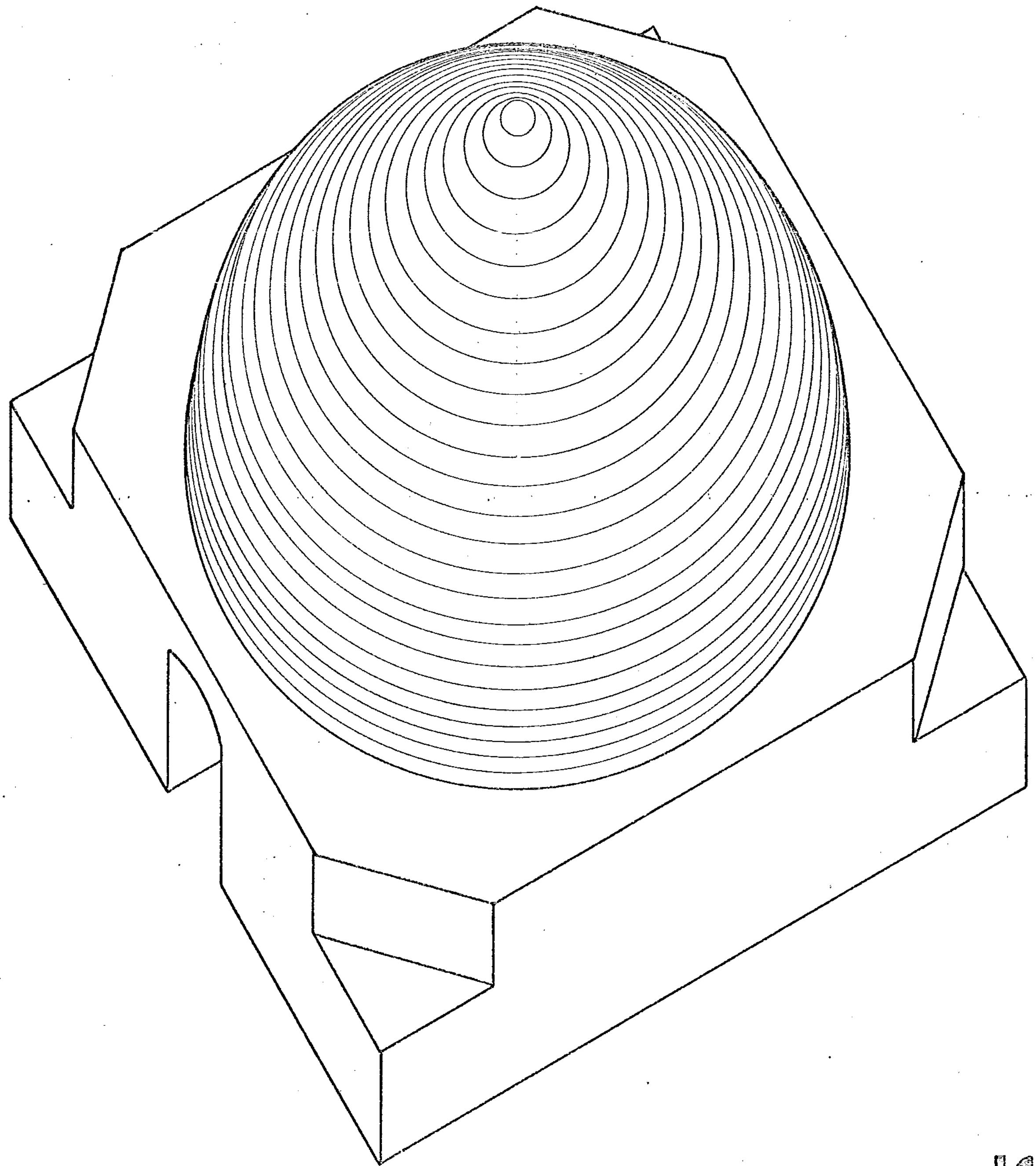


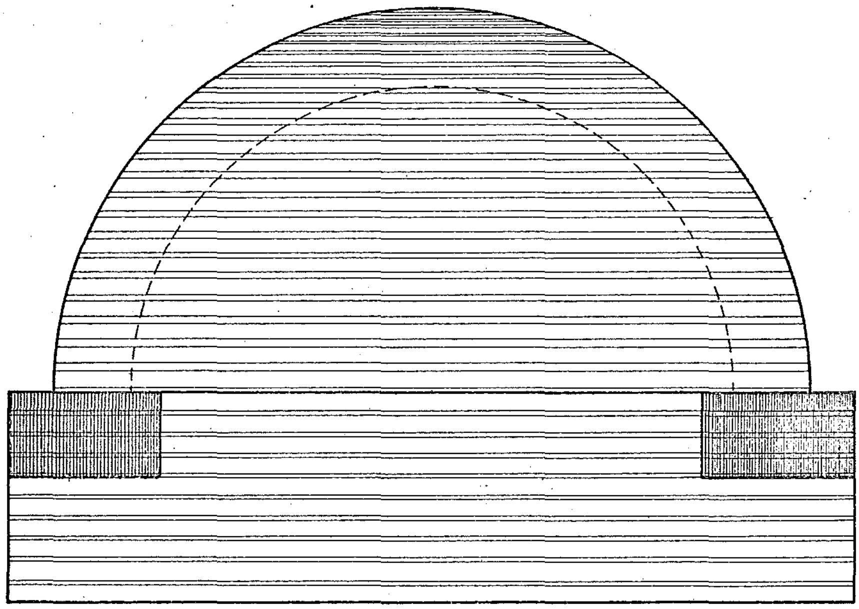
FIRST COURSES OF DOME

Consecutively smaller circles of brickwork are then laid, according to the length of the string, to form the dome. The bricks in each course are tilted up more and more from the horizontal, leaning inward, by packing mud mortar on the external side, in order to take the curvature of the sphere.
In plan, the bricks are laid flat and angled in order to take the curvature of the circle.

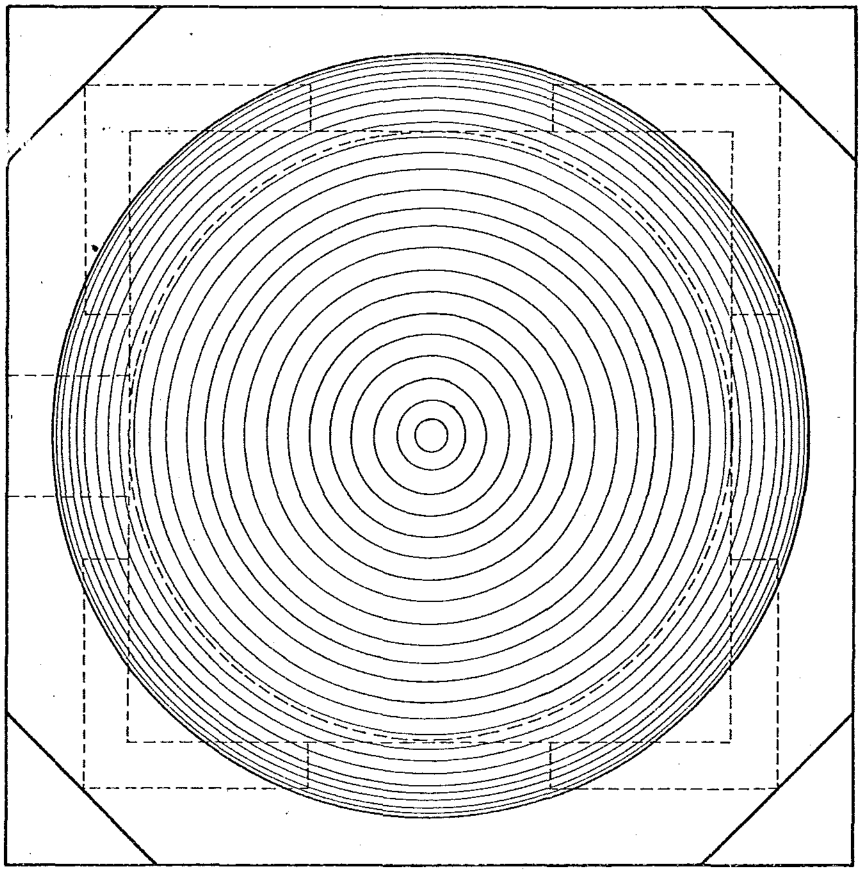


A piece of limestone or a red brick should be used to close the dome, being much more stable than mud brick and less liable to shrinkage on drying. This last stone or brick is firmly wedged into the opening at the top of the dome, increasing the compressive strength of the whole curvature.
Small windows or openings can be made in the dome itself by using the same infill technique as for the archway opening.





elevation



plan

STRUCTURAL ANALYSIS OF VAULTS AND DOMES

The basis for this study is taken from an analysis done at Cairo University,and having worked through it,I have come to various conclusions concerning the validity of this sort of analysis,which tries to put structural formulae to a system of construction,which has been successful for thousands of years.

SYNOPSIS

Both vaults and domes are considered to behave according to the theory of membrane structures(?) since their material cannot carry but very small values of tensile stresses.
One large vault and one large dome have been checked structurally to estimate the stresses,to show that they are well below the safe limits.

VAULTS

Vaults are constructed without the aid of any shuttering,following the method in fig.1. ,inclined towards the mirror wall as in fig.2.Each course is built up from both sides till it meets in the middle.

PRINCIPLES OF THE STRUCTURAL ANALYSIS.

During the construction of each course,the cohesion between the different layers of bricks,created by the mud mortar,is strong enough to hold the bricks in the incompleted course in place.
The critical condition occurs when placing the bricks very close to the crown.The mortar must be sticky enough to hold the brick in equilibrium,helped by the angle of inclination of the layers to the vertical.fig.3.

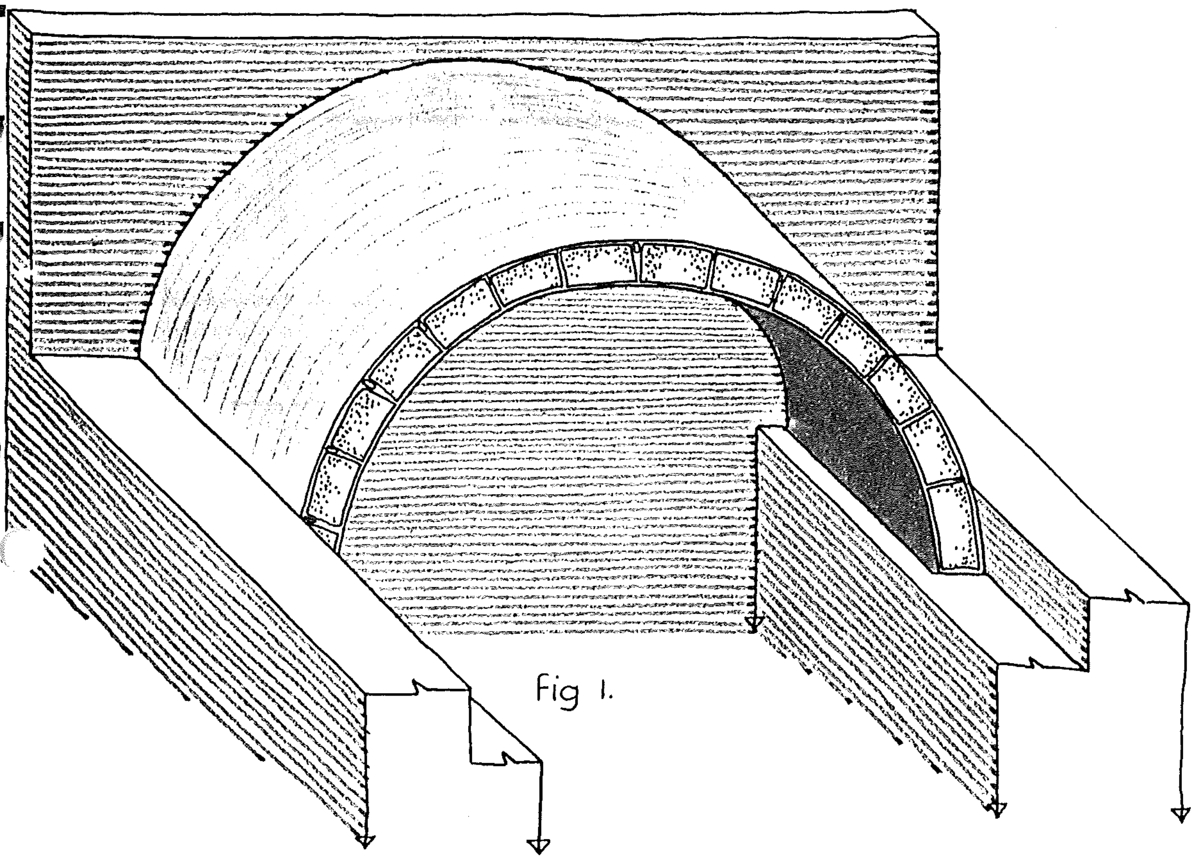


fig 1.

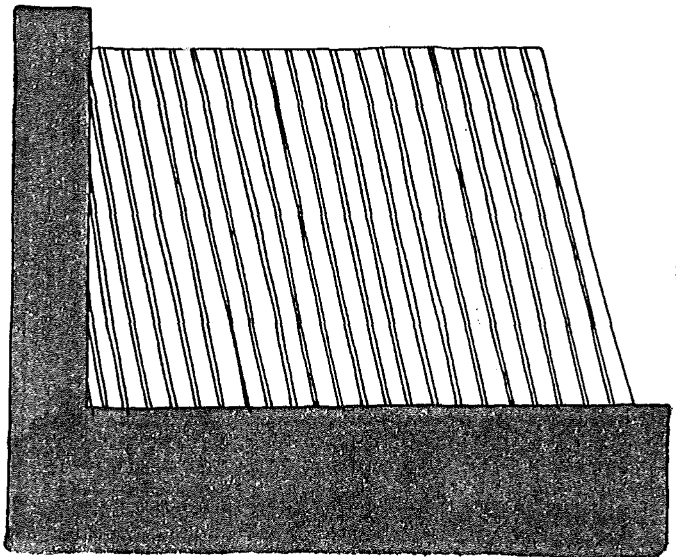


fig. 2.

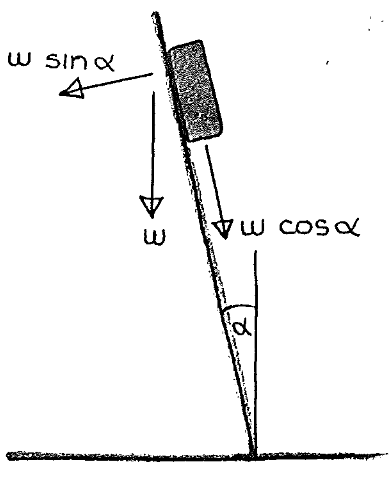


fig. 3.

VAULT ANALYSIS

Cohesion stress$\rangle$= $\dfrac{\text{~~W.Cos~~}\alpha}{\text{area of brick}}$ where cohesion$\rangle$= W.Cosα

$$= \frac{4.\text{Cos}\,\alpha}{15 \times 25}$$

0.01 Kg/cm² which is safe

What is α ?

shear cohesion $.01 = \dfrac{4\cos\alpha}{15 \times 25}$

$\therefore \cos\alpha = \dfrac{.01 \times 15 \times 25}{4}$

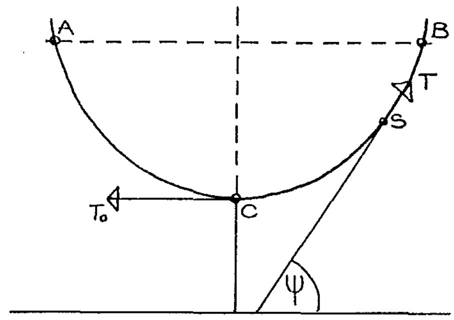
$\therefore \alpha = \cos^{-1} \dfrac{.01 \times 15 \times 25}{4}$

The arch action starts to work when the layers of the two haunches meet together at the middle, when the equilibrium of the arch is governed by the direct arch action.

The following statement ,I feel,is too much of an assumption on which to base the proof; Under the effect of own weight the line of pressure of the vault will take the shape of an INVERTED CATENARY.Then follows the Vault analysis,which I have interrupted by the proof for the Common Catenary,to explain some of the equations in the analysis.

THE COMMON CATENARY

This curve is formed when a uniform, flexible, inextensible arch swings freely under gravity under its own weight. Let T be the tension at the lowest point, C. Measuring S from C, we get resolving;



HORIZONTALLY $\quad T\cos\psi = T_o$

VERTICALLY $\quad T\sin\psi = ws$

DIVIDING $\quad \frac{T\tan\psi}{T} = \frac{ws}{T_o}$

LET $\frac{T_o}{w} = C$ .....(constant) ....(i)

$\therefore \quad S = C\tan\psi$ (which is the intrinsic equation of the curve)

[C is called the parameter of the catenary]

$$\frac{dy}{d\psi} = \frac{dy}{ds} \times \frac{ds}{d\psi}$$

$$= C\sin\psi\sec^2\psi$$

$$= C\tan\psi\sec\psi$$

INTERGRATING w.r.t. ψ

$y = C\sec\psi + k$

NOW CHOOSE OUR AXIS SO THAT $y = c$ when $\psi = 0 \;\therefore y = c\sec\psi$ ....(ii)

FROM (i) AND (ii) — (squaring and adding), $y^2 = c^2 + s^2$ ....(iii)

$\frac{dy}{dx} = \tan\psi = \frac{s}{c} = \frac{\sqrt{y^2 - c^2}}{c}$ ..... from (iii) $\quad \therefore \frac{dx}{dy} = \frac{c}{\sqrt{y^2 - c^2}}$

INTERGRATE w.r.t. y.

$x = C\cosh^{-1}\frac{y}{c} + A \qquad [e^{\frac{x}{c}} + e^{-\frac{x}{c}}]$

Since $\psi = c$, when $x = 0$, then $A = 0$. HENCE $\frac{x}{c} = \cosh^{-1}\frac{y}{c}$

$\therefore \; y = c\cosh\frac{x}{c}$ .... (iv)

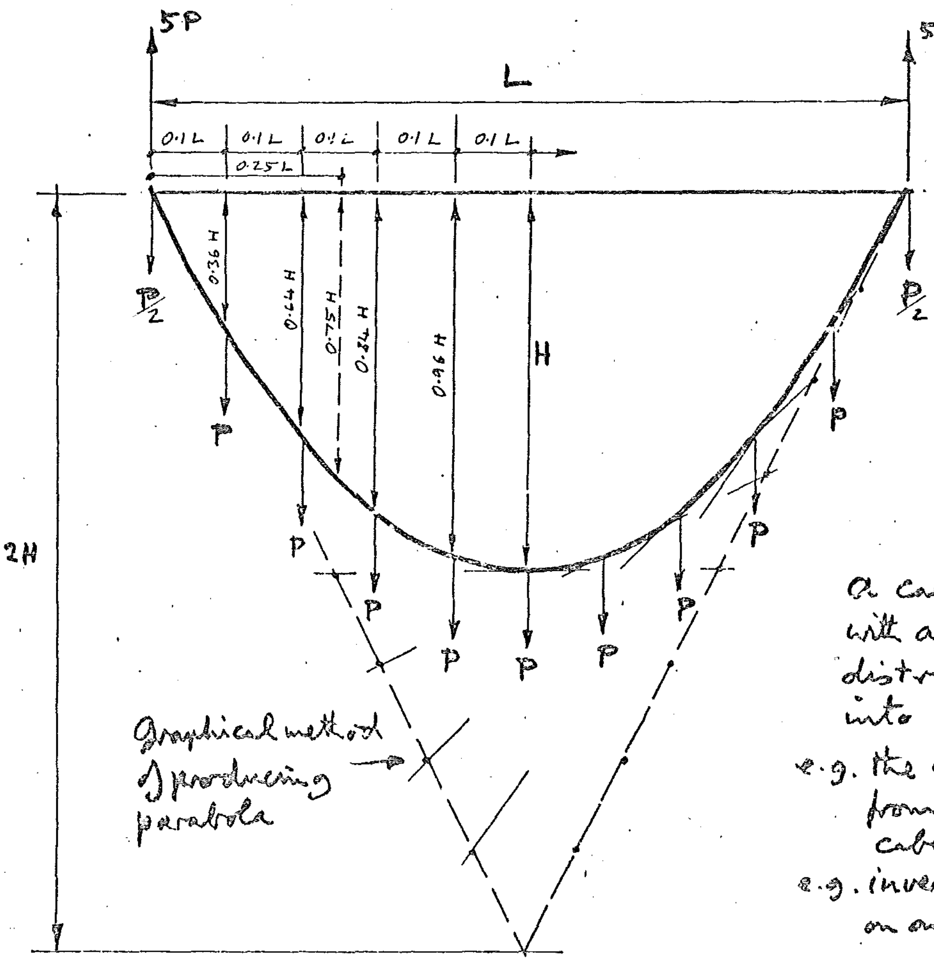
$\frac{dx}{ds} = \cos\psi = \frac{c}{y} = \frac{c}{\sqrt{c^2+s^2}}$

INTERGRATE w.r.t. s.

$x = c\,sh^{-1}\frac{s}{c} + B$, when $x = 0$, $s = 0 \;\therefore B = 0$

$\therefore \frac{x}{c} = sh^{-1}\frac{s}{c} \quad \therefore \quad s = c\,sh\frac{x}{c}$ also from (iii) and (iv)

PARABOLA



Formula for Parabola

$y = 4H\left(\frac{x}{L} - \frac{x^2}{L}\right)$

A cable with equal loads with a uniform horizontal distribution will fall into a parabolic shape.

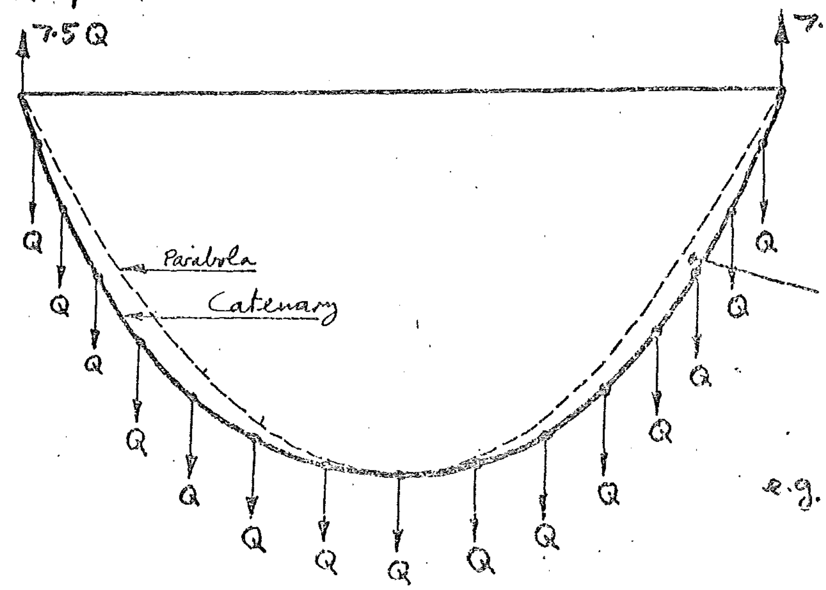
e.g. the deck loading hanging from a suspension bridge cable.

e.g. inverted, the deck loading on an arch.

If $r = \frac{H}{L}$ length S of a parabolic cable for a small value of r is given by:

$S = L\left(1 + \frac{8}{3} r^2\right)$

CATENARY



For catenary the weight per cable unit of horizontal projection is greater towards supports, where cable slope is greater, therefore catenary is lower in this region

e.g. the curve of a cable or chain due to its own weight only.

For $r \leq \frac{3}{10}$ catenary and parabola of equal sag are practically indistinguishable

Catenary is approx. $20 r^2$ per cent longer than equal sag parabola

For $r = \frac{1}{10}$ parabola $S = 1.0267 L$ Catenary $S = 1.0288 L$

VAULT ANALYSIS

$y = C \cosh \frac{x}{c}$ ——— (1)

THE SLOPE OF THE TANGENT TO THE CURVE IS GIVEN BY :

$\tan \psi = \frac{S}{C}$ ——— (2) [divide $\frac{\text{vertical resolution (b)}}{\text{horizontal resolution (a)}}$]

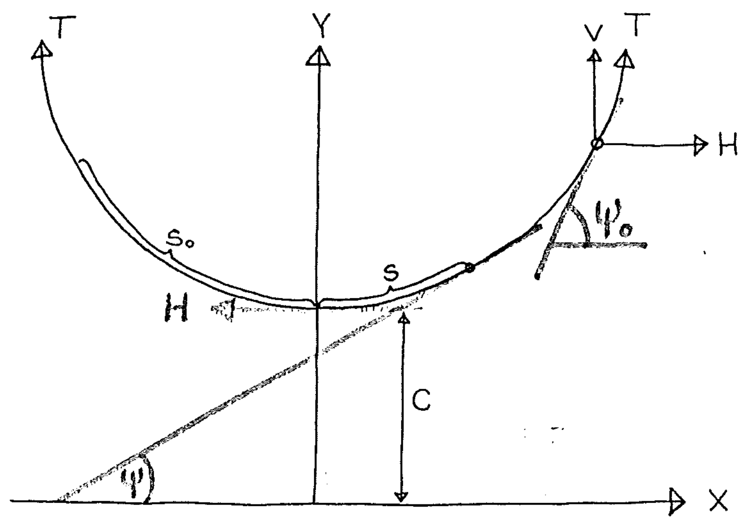
where (a) = $T \cos \psi = H$

(b) = $T \sin \psi = W.S.$

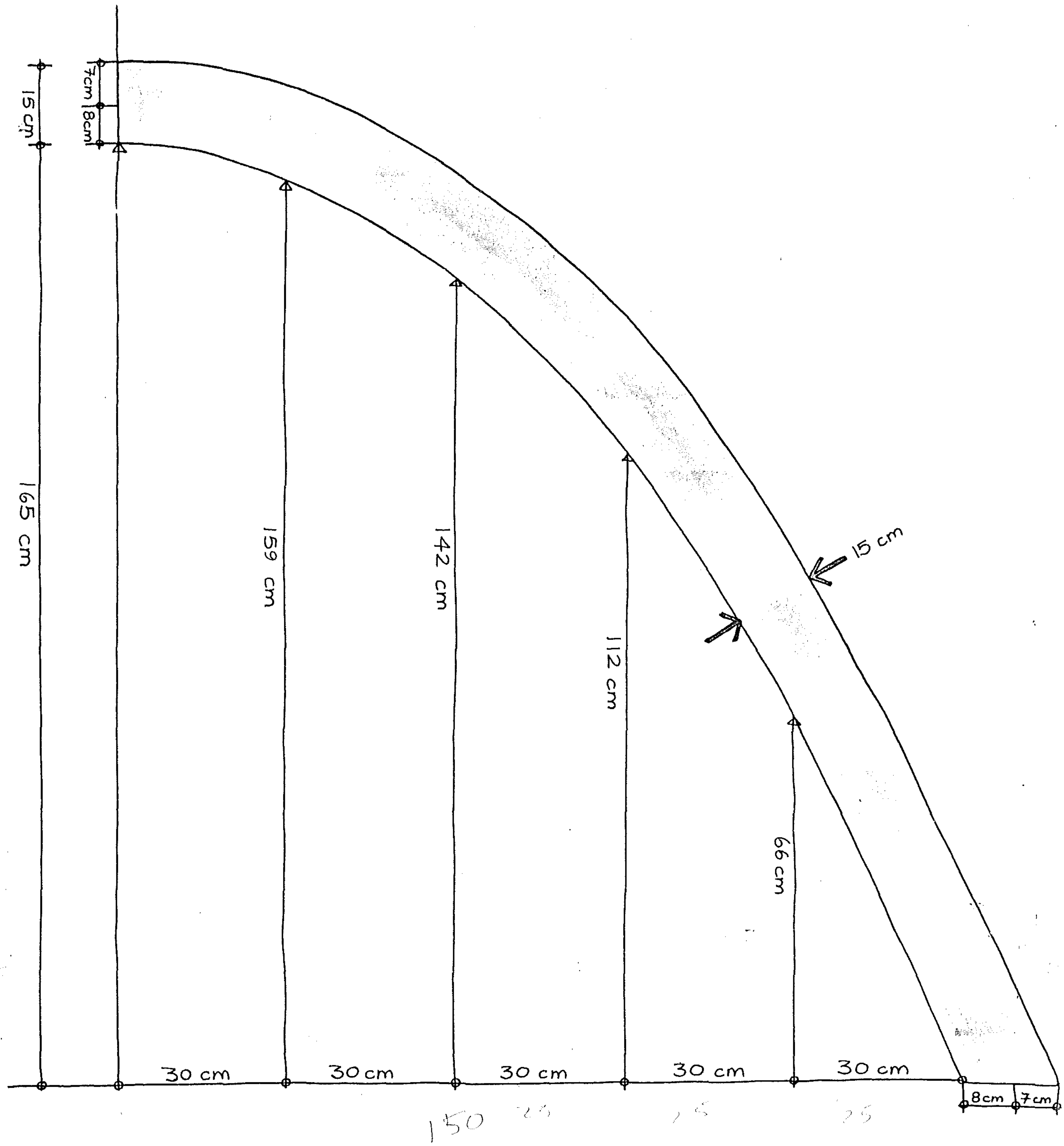
THE LENGTH OF THE ARC 'S' IS GIVEN BY : $S = y^2 = c^2$ ——— (3)

[differential calculus using (2) $dy = dy . ds$
$dx = ds . dx$

where 'C' is the parameter of the curve.
The two components of force along the catenary are given by : $H = W.C.$ — (4) const.
$V = W.S.$ — (5)



FIRST VAULT


7cm
8cm
15 cm
165 cm
159 cm
142 cm
112 cm
66 cm
15 cm
30 cm
30 cm
30 cm
30 cm
30 cm
8cm
7cm
150

FIRST VAULT

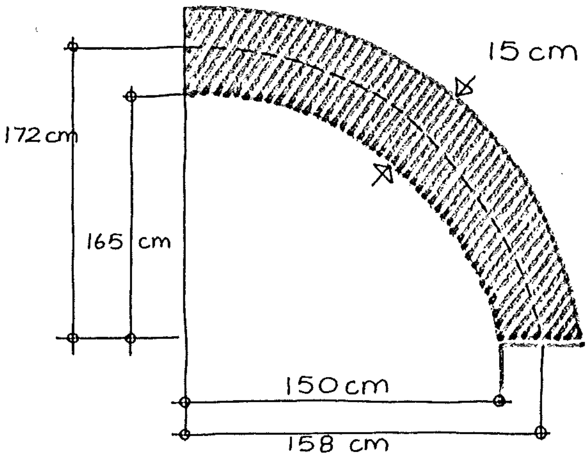
The line of pressure coincides with the centre line of the vault.(This obviously assumes that the vault has been constr-ucted to suit the catenary line of pressure.)

SOLVING EQUATION : $y = C \cosh \frac{x}{c}$

FOR : $Y_o = 172 + C$
$X_o = 158$

[172 and 158 - chosen no's.]

$\therefore$ $C = 92$ by trial
$Y_o = 264$ cm.



LENGTH OF ARC : $S_o = \sqrt{y_o^2 - c^2}$

$= 248$ cm

ANGLE OF THRUST WHERE ARCH MEETS WALL : $\tan \psi_o = \frac{S}{C} = \frac{2.48}{0.92}$

$= 2.7$

$T_o = w.y. = 240 \times 2.64$

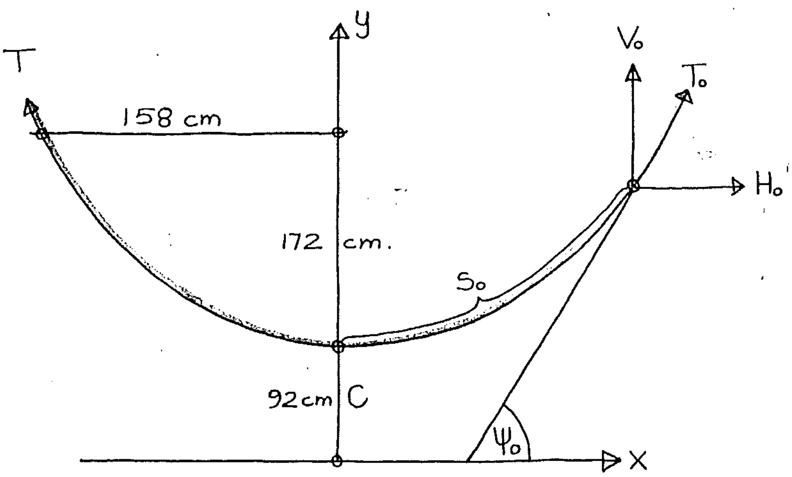
$= 634$ Kg/m

$H_o = w.c. = 240 \times 0.92$

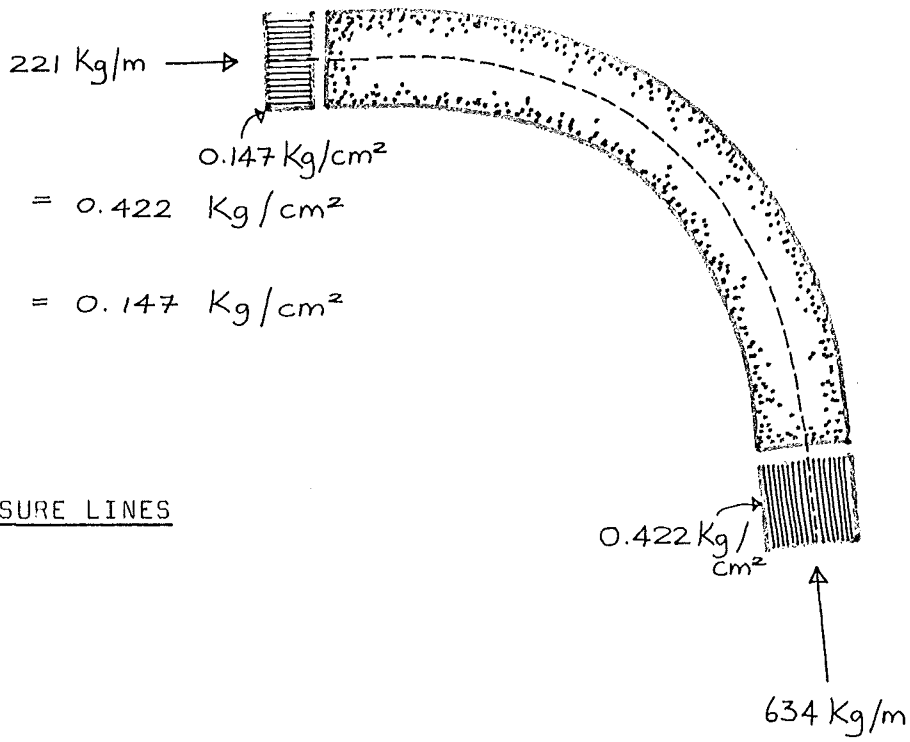
$= 221$ Kg/m

$V_o = w.s. = 240 \times 2.48$

$= 595$ Kg/m.



CHECK THE STRESSES IN THE VAULT



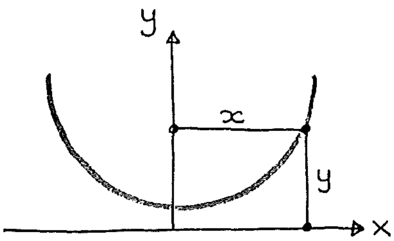
$$F = \frac{N}{A}$$

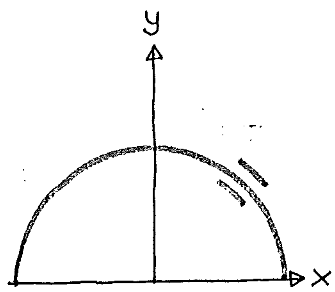
$$f_{max} = \frac{634}{100 \times 15} = 0.422 \ Kg/cm^2$$

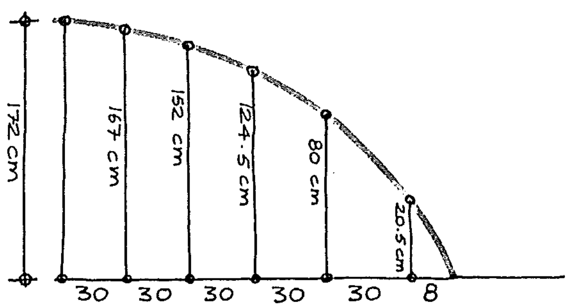
$$f_{top} = \frac{221}{100 \times 15} = 0.147 \ Kg/cm^2$$

COORDINATES OF PRESSURE LINES

X	$\frac{X}{C}$	$Y = C \cosh \frac{X}{C}$	Y
0	—	92 cm	172 cm
30	0.326	97	167
60	0.652	112	152
90	0.978	139.5	124.5
120	1.304	182	82
150	1.63	243.5	20.5
158	1.72	264	0

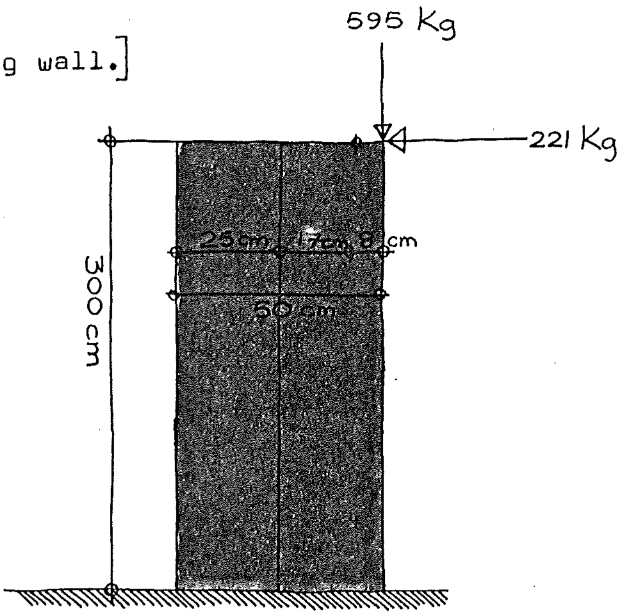






FIRST VAULT

[Check the stresses on the supporting wall.]



WEIGHT OF WALL = 3 × 0.5 × 1 × 1 × 1.6

= 2.4 t

N = 2.4 + 0.595

= 3 t

M = 0.221 × 3 − 0.595 × 0.17

= 0.663 − 0.1

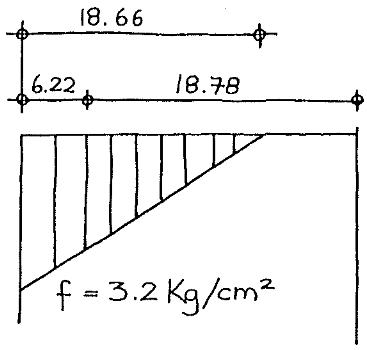
= 0.563 m.t.

$\frac{M}{N} = \frac{0.563}{3} = 0.188$

= 18.8 cm.

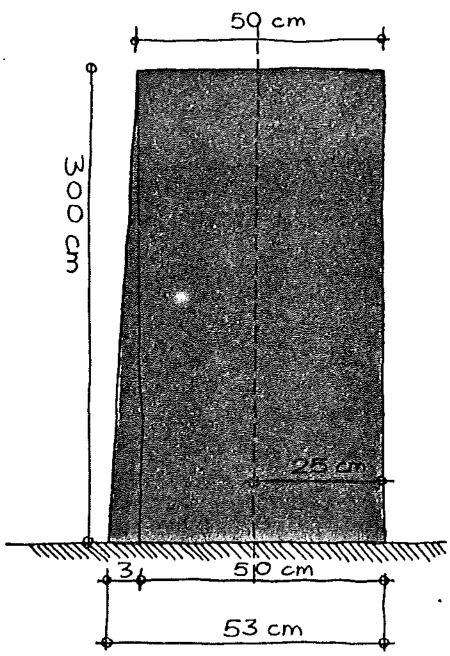
$f = \frac{2N}{3cb} = \frac{2 \times 3000}{18.66 \times 100}$

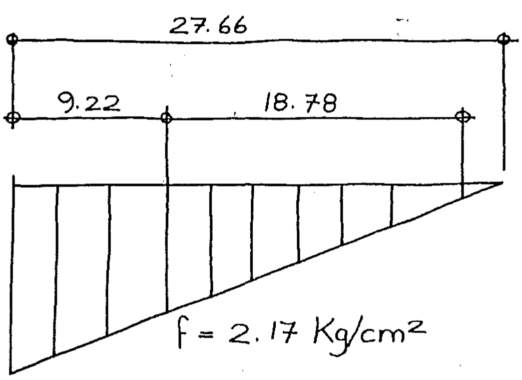
= 3.2 Kg/cm²



N.B. : FOR A SLOPING WALL OF 3 cm AT BASE OF SLOPE ANGLE.

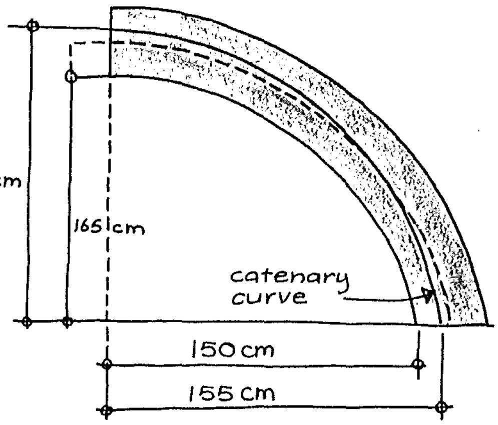
$$f = \frac{2N}{3cb} = \frac{2 \times 3000}{27.66 \times 100} = 2.17 \text{ Kg/cm}^2$$





SECOND VAULT

LINE OF PRESSURE IN THE MIDDLE 3rd ZONE



SOLVING EQUATION :

$Y = C \cosh \frac{X}{C}$ by trial

$Y_o = 175 + C$

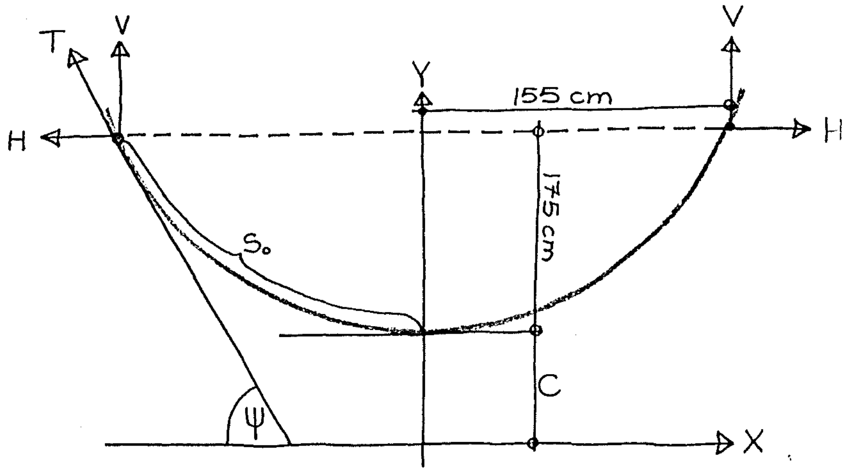
$X_o = 155$

$\therefore C = 88$ cms

$\therefore Y_o = 263$ cms

$S_o = \sqrt{Y_o^2 - C^2}$

$S_o = 248$ cm



$\tan \psi_o = \frac{S}{C} = \frac{2.48}{0.88}$

$= 2.82$

$T_o = WY_o = 240 \times 263$

$= 630$ Kg/m'

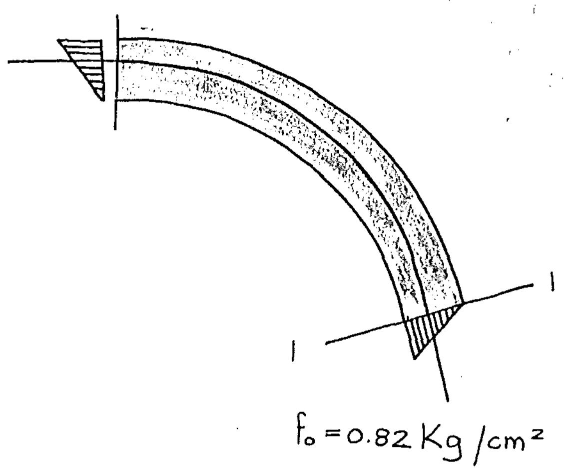
$H_o = W.C. = 240 \times 0.88$

$= 211$ Kg/m'

$V_o = W.S_o = 240 \times 2.48$

$= 595$ Kg/m'

CHECK OF STRESSES IN THE VAULT :



$\frac{f_o}{2} \cdot t.b. = T$

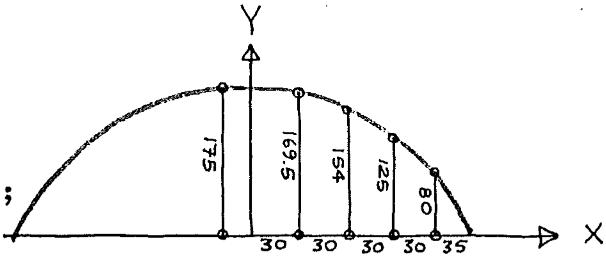
$f_o = \frac{2T}{t.b.}$

$f_o = \frac{2 \times 630}{100 \times 15}$

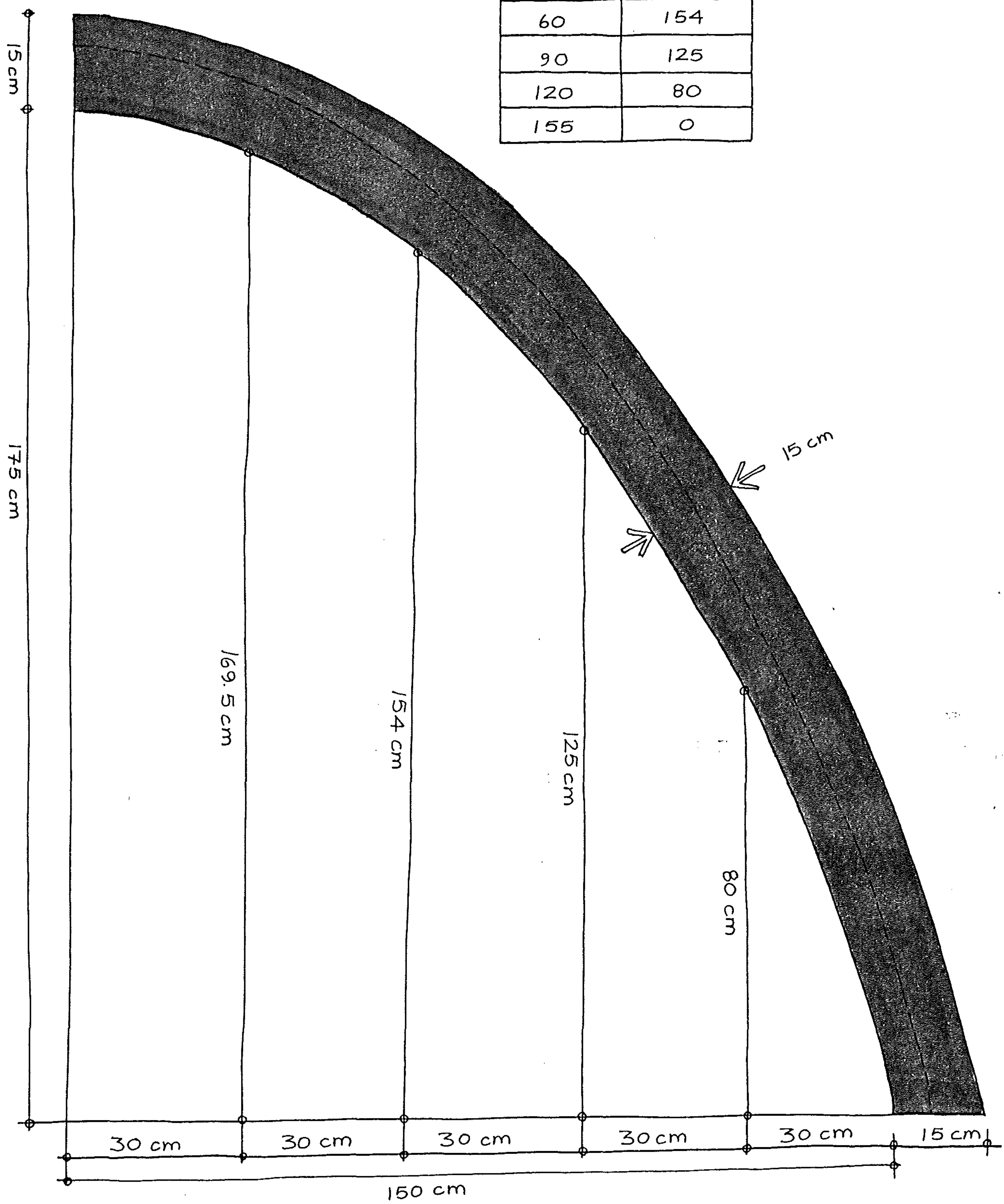
$f_o = 0.82$ Kg/cm²

SECOND VAULT

Ordinates of the line of pressure;



X	Y
0	175
30	169.5
60	154
90	125
120	80
155	0



DOMES.

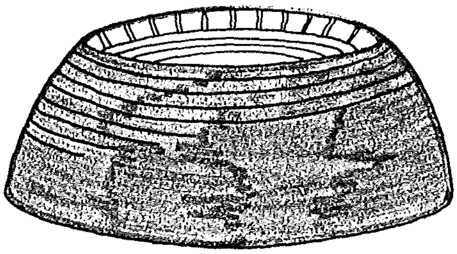


fig. 1.

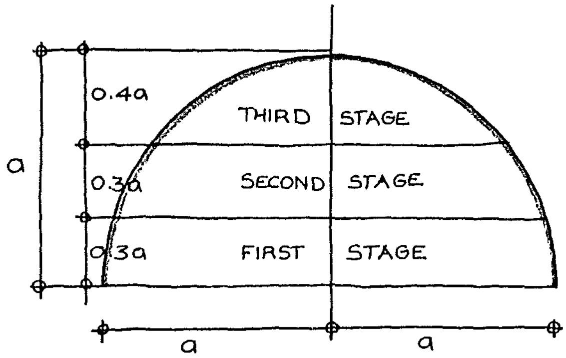
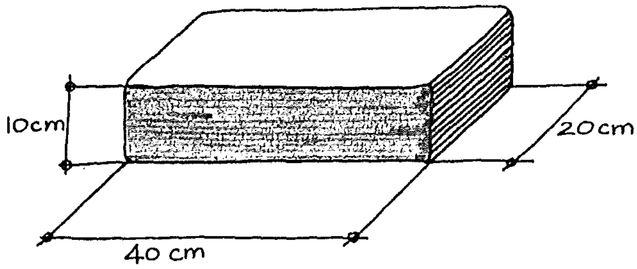
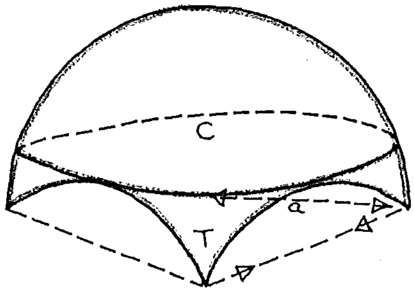


fig. 2.

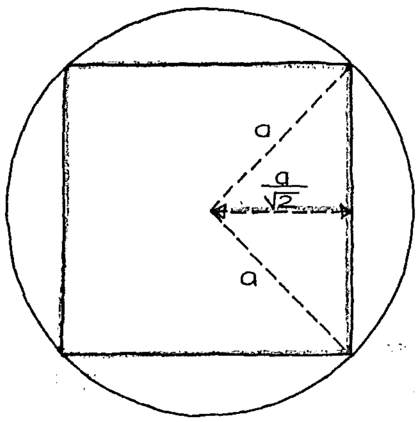


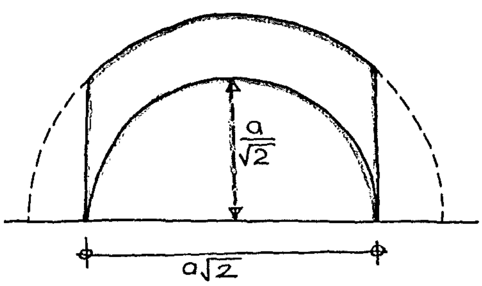
recommended brick size

fig. 3.



BYZANTINE DOME

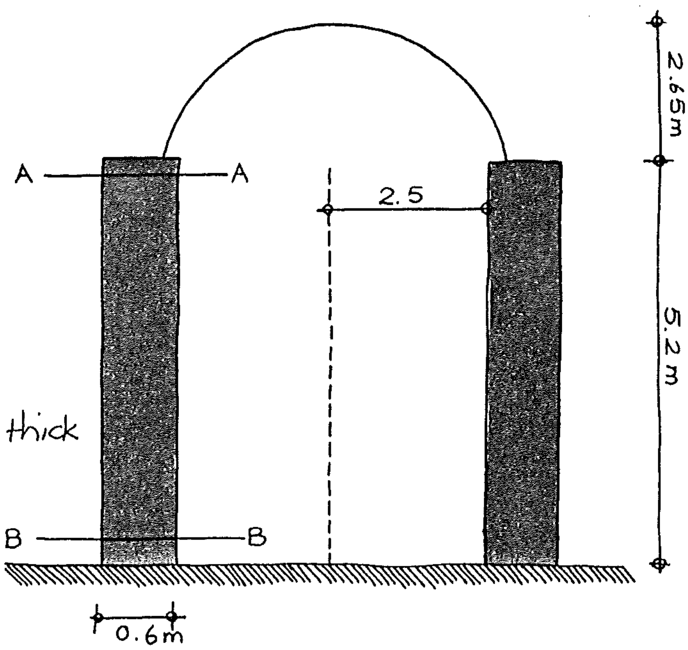




EXAMPLE

Data; Spherical Dome;

a = 2.65 m.
t = 25 cm.
wall height = 5.2 m.
wall thickness = 60 cm.



Self weight load $P = 1 \times 1 \times 25 \times 16$
$= 400$ Kg/m²/c thick

Max. tension

$N\phi = P.a.$
$= 400 \times 2.65$
$= 1060$ Kg/m'

Max. ring tensile stress $= \frac{1060}{25 \times 100}$

$= 0.42$ Kg/cm²

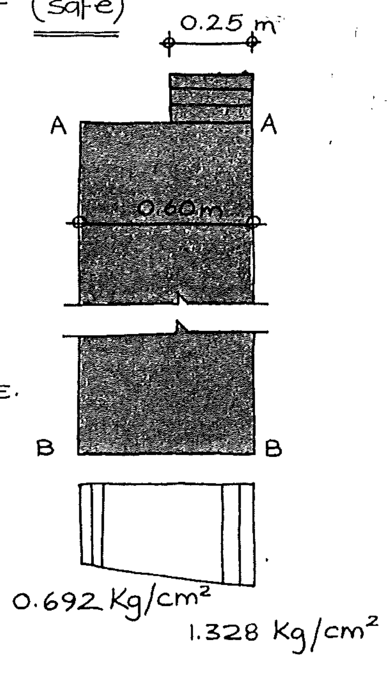
CHECK STRESSES IN THE WALL, ASSUMING THAT THE DOME MATERIAL IS STRONG ENOUGH TO CARRY THE 0.42 Kg. cm²

P.a. $= 400 \times 2.65 = 1060$ Kg/m'
Weight of wall/m' $= 1 \times 5.2 \times 60 \times 16$
$= 5000$ Kg/m'

SECTION A-A: Compressive stress $= \frac{1060}{25 \times 100}$
$= 0.42$ Kg/cm² (safe)

SECTION B-B: $M = 1060 \times (30 - 12) = 19100$ Kg cm
$N = 5000 + 1060 = 6060$
$f = \frac{6060}{60 \times 100} \pm \frac{6 \times 19100}{100 \times 60 \times 60}$

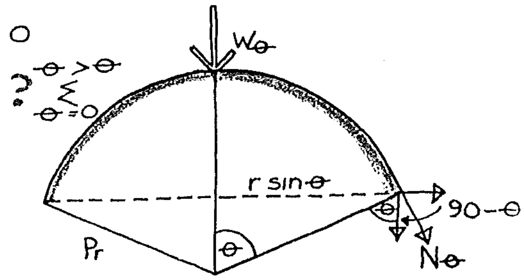
$= -1.01 \pm 0.318$
$f_1 = -1.328$ Kg/cm²
$f_2 = -0.692$ Kg/cm² SAFE.



SPHERICAL DOME

VERTICALLY : $\sum W_\theta + 2\pi\left[r.\sin\theta\right].N_\theta \sin\theta = 0$

$\therefore N_\theta = \dfrac{-W_\theta}{2\pi r.\sin^2\theta}$



$N_\theta = \dfrac{W}{\pi D.\sin^2\theta}$

from vertical res. at horizontal latitude, where angle subtended at centre is θ

HORIZONTALLY : $N\phi = \left[P_r.\dfrac{D}{2} - N_\theta\right]$

$P_r = P\cos\theta$ and $P_\theta = P\sin\theta$

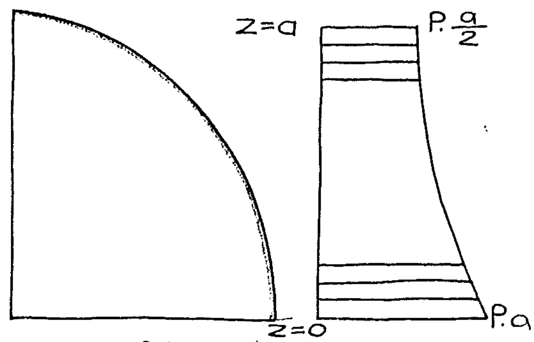
where P is the self weight/unit area of the surface $N\phi$ and N_θ are membrane forces/unit length.

$N_\theta = \dfrac{-P.a.}{1+\cos\theta}$

$N\phi = \left[P_r.a + \dfrac{P.a.}{1+\cos\theta}\right]$

$N\phi = \left[-P\cos\theta.a + \dfrac{P.a.}{1+\cos.\theta}\right]$

N_θ diagram

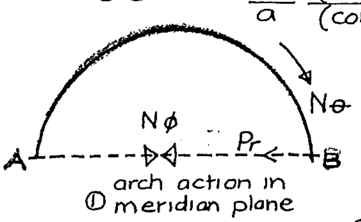


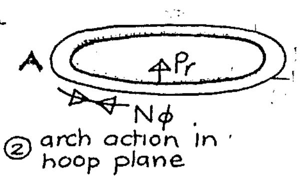
MERIDIAN $N_\theta = \dfrac{-P.a.}{1+\frac{z}{a}} = \dfrac{-P.a^2}{a+z}$

Equation of hyperbola: $\cos\theta = \dfrac{z}{a}$ $\dfrac{\text{(variable)}}{\text{(constant)}}$

HOOP $N\phi = \left(-P.z + \dfrac{P.a^2}{a+z}\right)$

$N\phi = \dfrac{P.a^2 - a.z - z^2}{a+z} = 0$





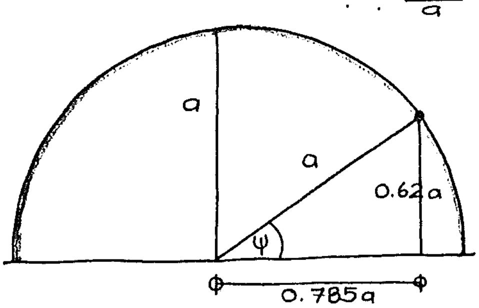
$N\phi = 0$ at

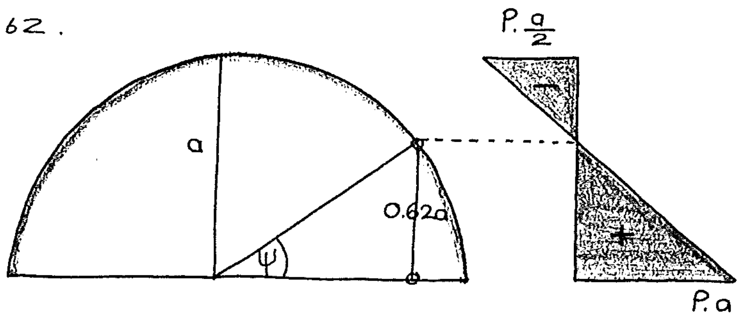
$a^2 - a.z - z^2 = 0$

$a = 1.62\,z$

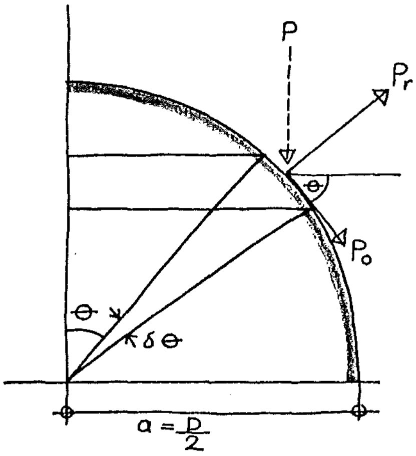
$\therefore \dfrac{z}{a} = 0.62.$

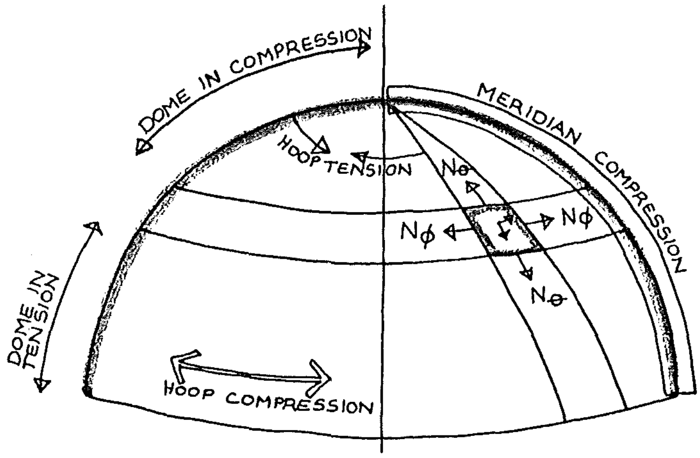
$\therefore N\phi$ is made up of components from $N\phi$ and P_r.

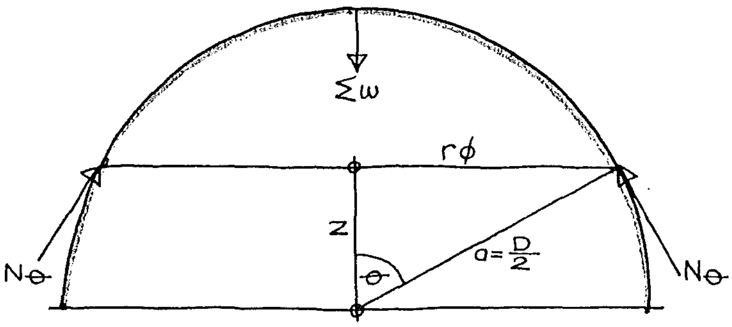


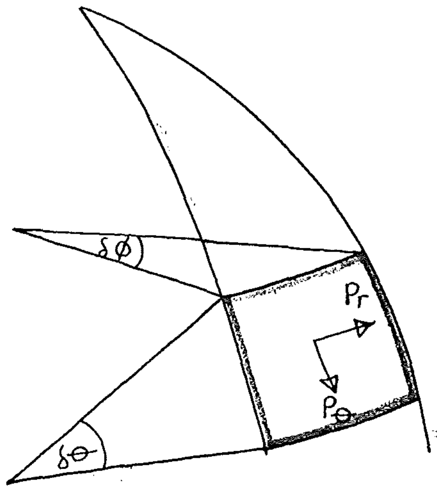


$N\phi$ diagram


P
Pr
θ
Po
θ
δθ
a = D/2


DOME IN COMPRESSION
MERIDIAN COMPRESSION
HOOP TENSION
Nθ
Nφ
Nφ
Nθ
DOME IN TENSION
HOOP COMPRESSION


Σw
rφ
z
θ
a = D/2
Nθ
Nθ


δφ
Pr
Pθ
δθ

INDIGENOUS IRANIAN ARCHITECTURE

CONTENTS:

INTRODUCTION

The development of indigenous Iranian architecture was predominantly, though not exclusively, the development of the use of mud-brick. For example, although most major sassanide buildings were in stone, yet the majority of Iranian buildings of excellence through history were executed in sun-dried mud-brick. Although today, in the north and west stone and timber are used, most indigenous building across Iran are still executed in sun-dried mud-brick. The use of mud-brick as a training tool for aspiring master masons had advantages inherent in the material; the fact that it was so cheap and easily obtainable encouraged experiment. Mud-brick building through its lines and form clearly demonstrates the major mechanical forces involved in the structure. The smallness of the unit of composition gives it great flexibility and elasticity. Thus ad-hoc adjustments can be made, even to modifying the basic brick unit, during the process of construction to respond to most structural or spatial demands that may arise.

After construction any structural error will show up, often without the collapse of the whole building. Mud brick buildings with large cracks and distortions have stood up through the years, clearly demonstrating in the structure the particular reasons for them. Thus in the absence of mathematical techniques Iranian masons, schooled for centuries in mud-brick building, were responsible for many new and complex structural forms developed to a high level of perfection*1. It can be argued that even today it is unsurpassed as an empirical method of building instruction, resulting in quick, easily apparent and reliable results and a built form practically and aesthetically in harmony with the Iranian environment. One simply has to juxtapose Iranian indigenous architecture, domestic or monumental, with 'modern' Iranian building for this point to be illustrated.

HISTORICAL BACKGROUND

Iran played a major role in the development and dissemination of mud-brick, vault and dome construction and styles such as the 'Apadana' and 'Aivan' and building elements such as the 'bad-gir'. The debate on what originated exactly where, is somewhat academic for the present paper*2. It will suffice here to simply inject some historical perspective into the subject.

By the 4th millenium B.C. sun-dried mud-brick was beginning to replace pise using shuttering as the major building technique. Originally they were oval shaped mud-lumps *3 but by the end of the 4th millenium the flat-rectangular mud-brick formed in a wooden mould began to be used in general. Houses by this time had all the basic architectural features of doors, windows, recesses, butresses, rendered and painted walls.

*1. A U Pope and P Ackerman Eds. "A Survey of Persian Art" p. 901-2, also see footnote 3 p. 901.

*2. See Hans E Wolff "Traditional Crafts of Persia"; Pope and Ackerman "Survey of Persian Art"; R Girsham "Iran"; K A C Cresswell "A Short Account of Early Muslim Architecture" to follow the debate.

*3. R Girshman Iran p. 29.

Because of the scarcity of timber, vault and dome construction was developed in Asia. Flat roofs needed timber beams, branches and matting on which a layer of mud was placed. This method is still used when there is no scarcity of timber. Early vaults used wood centering and shuttering and it was not until the discovery of gypsum mortar in this area that the use of timber even in shuttering could be entirely dispensed with. Gypsum sets almost immediately on contact and there is no danger of slipping *4. The first Iranian examples are the Ramesseum in Egypt (4000 B.C.) and in Babylonian graves and canals through Sassanide and Islamic times, (Sassanide Dyn: 224 A.D. - 651 A.D: Islamic 651 A.D.)*5, this method reached high technical and architectural standards.

"Even today it can be said that there is hardly a room that a Persian builder cannot cover with a vault, from the most horrible peasant house to the covering of a cinema in Yazd where a single barrel vault of sun-dried mud-bricks spans a hall seating 600 people" *6.

In style, form and plan, the 'Apadana' and 'Aivan' are the most characteristic of Iranian indigenous architecture. The 'Apadana' is a large room in the centre of a building with a wide hall open on one side and having small rooms at each end (see figs 1-4). Already developed in pre-Achamenian times (Achamenian dyn: 550 B.C. - 249 B.C.) it was widely used in Iran and later Iranian builders spread it through the Moslem world. The plan on the monumental scale as illustrated in Persepolis differs little from present day peasant houses in Azerbaijan and in the central province (compare figs 1-4). In detail the capitals on wooden columns in the Azerbaijan houses are stylised versions of the bull's head in Persepolis *7, which is doubtless a heritage from its antecedents - it developed from the customs of a nomadic people who were used to looking out into open space and blue skys*8.

CONTEMPORARY

Geographical Influence: Availability of Materials - Climate etc. and Building Types:

As it effects building types, Iran can be broadly divided into two; the mountain ranges with their thick forests, snow and heavy rains (225" p.a. in the Caspian Provinces*9) and the desert interior. Within the mountain ranges another two sub-divisions can be identified. The Alburg mountains of the North (the Caspain Provinces) have rather more timber, rain and snow. The house constructions are predominantly timber, with sloping thatched, tiled or shingled roofs and wide overhangs. (See fig). The Zagous mountains of the west have houses with stone or brick walls and with a flat thatched roof (See fig). In the desert areas houses are made of mud-brick with vault and dome roofs. Though these divisions are broadly accurate there are of course many more types and differences. For example brick walled, flat thatched roofed houses are also found in the Alburg mountains.

Finally, although stone is generally available in Iran, brick, particularly mud-brick, is preferred. Stone was more often used where permanence was very important, in buildings such as fortresses, caravanserais, bridges etc. otherwise the vast majority of indigenous buildings of Iran were constructed in the cheaper more flexible and rapid brick*10. Today in mountainous regions stone and rubble villages have been built for centuries while cut stone is widely used for foundations.

*4. Pope and Ackerman
*5. Pope and Ackerman pp. 415.
*6. H E Wulff p. 105.
*7. H E Wulff p. 104.
*8. Pope and Ackerman pp. 429-430
*9. H E Wulff: The Trad. Crafts of Persia M.I.T. Press 1966 p.113.
*10. Pope and Ackerman "Survey of Persian Art" p. 900-901.

WOOD CONSTRUCTION

Houses built predominantly of wood are found north of the Alburz mountains. In the low lands near the Caspian Sea the houses are raised approximately 600mm above ground on a system of alternating heavy sleeper beams, blocks and boards on which the floor of the house lies. Verandah columns ring the house and support the horizontal purlins (kasin) on which a framework of steeply inclined rafters (salju) and bamboo (kartun) battens are supported. The rush thatching is carried on this framework. Bamboo and rushes grow in abundance along the many water ways in this area.

Further upland the raised floor is not necessary and therefore the main frame is laid directly on the ground. The vertical stiles that form the room are nailed across with thin branch wood or bamboo stems and filled with a mixture of wet loam and straw (kah-gel).

In place of thatching, shingles (tahteh) or burnt tiles are also used. The tiles are either fastened with a nose at the back to attach them to the roof battens, or they are made into semi-tapered cones which are then slit into half resembling spanish tiles. Burnt tiles are made by the local potter using a fat clay.

Galvanised iron roofs are beginning to replace other roof types.

MAKING BRICKS *11

Mud Bricks: Earth for the mud-brick is taken from excavations or from a pit nearby. A pick and spade are used for digging and if the earth is being dug from a deep pit a windlass may be necessary to haul it to the surface (See fig 163). The earth is soaked in plenty of water; straw and chaff are added and thoroughly mixed by treading with bare feet. It is then mixed again using a hoe.

The brick mould is simply an open wooden frame with a handle. The brickmaker scatters a thin layer of chaff on the ground. He puts the mould on to it and fills it with the mix, smoothing any surplus off with his hand. With a quick smooth motion he removes the mould and places it next to the formed brick to repeat the operation. In this way he can make 250 bricks an hour.

The bricks are left in the sun for three to five hours depending on the weather. They are then set on edge to dry for a day or two. They can be used immediately afterwards for building. This work is only done during hot months of May to October *12. A standard brick is 8" x 8" x 1½" - 200mm x 200mm x 38mm.

MAKING BURNT BRICKS

Burnt bricks were made by Babylonians in the 4th millenium B.C.*13, and in Iran kilns in Susa and Siyalk have been excavated dating from the 1st millenium B.C.*14. As bricks are normally used for facework the clay used has to be selected and staked and be clean of impurities. The brickworks are situated near a suitable clay pit usually outside the settlement. There should also be a deposit of a gray sand nearby.

*11. The following information is substantially derived from Hans E Wulff "Traditional Crafts of Persia" pp. 110.
*12. Compared to Egyptian method (or whose recommendation) where shade and winter is preferred for a more even drying.
*13. R Girshman Iran p. 166.
*14. C Singer "A History of Technology".

The clay with 1/5 of its volume of the grey sand, is soaked in a pit filled with water and left to slake for 24 hours. (The sand makes the clay lean and after firing becomes light-cream in colour, otherwise it would turn red).

After 24 hours the mass is thoroughly mixed with wooden shovels and then hoed over. It is carried in buckets and poured into a gutter which leads to a neighbouring pit. There it is separated from course materials through a sieve and the strained clay is allowed to settle. After the first day the surplus water is scooped off from the top. Four days later the clay is normally dry enough to be moulded.

The mould is a cast-iron box with two compartments to take the narrower standard size bricks. It has four projections at the base which is used for gripping as there is no handle. A handfull of the gray sand is first put into the mould and shaken around so that it sticks to the wet surfaces. The clay is then put into the mould and levelled off either with a straight edge or wire. The mould is then turned over and emptied.

The brick is allowed to dry for a day, then turned on edge to dry for a further 3 to 4 days. It is then ready to be fired. A brick kiln *15 consists of a vaulted fireplace which goes 5-8½m below the ground surface. One vault is full of holes and serves as a grate. Steps lead down to this fireplace. The visable part of the kiln is the surrounding room over the grate. It has one opening at the ground level and one above reached by a ramp. There is a smoke outlet at the top.

The first lot of bricks are stacked through the bottom opening and the remainder form the top. The bricks are stacked with spaces between them to allow the combustion gases to pass. The top layer is packed closely and smeared with clay to cover the joints except for $1m^2$ areas which allow the smoke through. One of the openings is then closed up.

Fuel oil, *16 a by-product of the refineries, is mixed with chaff and dry stalks of sugar-beet and shovelled into the fire hole. The bricks are fired for 72 hours. Then a large quantity of the fuel mix is shovelled in and the resulting sudden lack of air begins to reduce the heat. The fire hole and smoke outlet are now also covered up with clay and the kiln allowed to cool for a further 72 hours.

The bricks are then ready for building. Those nearest the grate are usually overfired and used for constructing water basins and cisterns, common features in Iranian houses. The kiln just described has a capacity of 50,000 standard bricks 8" x 4" x 2"/200 x 100 x 50m. Khuzistan kilns have a capacity of 150,000 standard bricks.

Another type of kiln (see fig 176) consists only of the fireplace and grate. Limestone is stacked in the centre over the grate and the bricks placed around this, with spaces to allow the combustion gases to pass through and out in all directions. After 24 hours firing, the bricks are allowed to cool and except for the outer layer, they are then ready for building with. The burnt lime is just sufficient to prepare the mortar for this barch of bricks *17.

*15. Types and methods vary from province to province. Example here is from Hamadan.

*16. Previously desert shrubs (car,tarkha) (artemisia herbs alba) and wormwood was used. It has a long intense stem (the shrub).

*17. Wulff considers this method inefficient. However if firing for 24 hours produces as good bricks as the previous method with 72 hours firing and burnt lime for mortar, there is a case for it.

BUILDING

There is no distinct professional differentation between the builder, mason and bricklayer. You are either an apprentice or a master builder with apprentices working for you. No drawings are prepared for the house - the owner and builder mark it out on site with powdered lime.

FOUNDATIONS

The foundation trenches are dug approximately 18"/500mm deep and slightly wider than the walls. The excavated earth is mixed with burnt lime and water to make a soft paste. A layer of this paste about 6"/150mm deep lines the bottom of the trench and then course stone ballast with stones 150mm to 200mm in diameter is thrown in. After a second layer of paste and stones are then placed on top. This is repeated till the trenches are full. Within 3 to 4 weeks the foundations have set and wall building can commence. In time the lime-mud-stone mixture becomes as hard as rock.

WALLS

Pise or Rammed Earth

Most perimeter walls, surrounding gardens etc. are made of this technique. Earth is moderately wetted and, with chaff, kneaded with bare feet into a plastic mass. The building line is marked with a string (risman). The builder then places this earth in lumps onto the properly set foundations and along the string. If it is a low garden wall doundations may be no more than a layer of cut rock on the ground. The clay lumps are shaped freehand into a course 15"/400mm wide approximately *18. When a course is finished it is smoothed over with a trowel and allowed to set usually for 2 or 3 days by which time it should be hard enough to begin a further course until the wall is complete.

Yard walls are usually topped with a layer of burnt brick that corbels out 4"/100mm to protect the wall against rain. Garden or orchard walls are capped off with wooden sticks about 30"/250mm long x 2"/50mm thick. The sticks carry a layer of thorny brushwood or rushes weighed down with a course of a lime mixture which sets and becomes water resistant.

The walls narrow with height normally. An 8'/2.5mm high wall is 800mm at the base and 250mm at the top. Another method is to mix clay, rubble, straw and lime and firmly pack and harden it in two wooden mould making horizontal layers each 450 - 600mm high. These are still in use in Iraq, Iran and Turkey.

MUD BRICK

The courses are laid along a string which marks the building line. The bricks are laid in bond and the mud-straw mortar mix is the same as used for making the brick. The mortar is laid about ¾"/18mm thick, is spread with a steel trowel, and the level checked with a plumb-line or straight edge containing a small pendulum (sagul).

Outside walls are usually 600 - 950mm thick. Inside walls can be single brick (yakajuri), bricks on edge (tigeh), or bricks squared to form box like holes (sandupi). The transition between a vault and a flat roof or top floor is also built hollow to lessen the weight and save bricks (see fig 168).

*18. i.e. Half an Isfalian cubit
1 cubit = 80c.m.

The walls are rendered (gel rus kasidan) with a mud-straw mix (kah-gel) enriched with lime (ahak) which makes it insoluable after setting.

BURNT BRICK WALLS

The mortar (sey-ahak, maseh, malet) for burnt brick walls is a mixture of hydrated lime and sand. For modern urban buildings, sand-lime-cement mortar is often used. A specially water proof mortar, often used for reserviors, is made by mixing sand. lime, cement and wood ashes (hakestari-hamniam) and either the hairy seeds of rushes or goats hair is added for internal bonding and to prevent cracking *19.

Outside walls are seldom rendered but the joints cleaned to give an attractive finish. More recently mud-brick structures with a bonded in veneer of burnt brick on the outside have been adopted.

STONE

Many buildings today are built on a stone base approximately 1m high. Thus the brick parts are high enough to be safe from the splashing of winter rains. Ashlar masonry is widely used in the province of Fars. It is laid without mortar. When it is set in mortar a special lime and clay mixture (dugub) is used for the joints (darg, darzesand). It is applied soft and the stones set easily with a very thin joint. In a few months it sets very hard.

FLOORING

The average house floor (kaf) is made from a hard setting mixture of lime and plaster, often mixed with stone, grit and red iron oxide for colouring. Wealthier houses have stone slabs, burnt bricks or glazed tiles for flooring.

ROOFS

There are basically three types of roofs.

1. Pitched Roofs: (See Wood Construction)

In the Caspian provinces with their heavy rainfall (225"p.a.) pitched roofs are found, covered with either straw, (figs 158-159) *20, shingles (tah, teh, tet) or burnt tiles (sofal, sefal, tufal). Burnt tiles are made by the local potter (sefar gar) from a fat clay. They are flat and have a nose (dokmeh) at the back to attach them to the roof battens.

Others resemble spanish or roman tiles - i.e. slightly tapered cones slit in half. They are used widely in Mazanderan and Googan. Galvanised iron roofs (sir vaneh) are becoming increasingly common.

2. Flat Roofs: (Bam, post e bam, rubun)

These typify the houses on the Iranian plateau and at the slopes of the Zagros mountains.

Ceiling joists (tir, sardar) are placed over the walls or over heavier beams (samal) supported by columns where there is an open porch. On this, either ceiling boards (sogaf - pus) or battens (pardu, dastak) are nailed and covered with braided reed mate (hasir). A mud straw lime mixture is laid over this in thin layers. Each layer is allowed to dry and then compacted with a rolling stone (garraban) before the next layer is applied. In Fars and Isfahan the roof is approximately 250mm thick. In Azerbaijan it is 500mm thick and a much greater proportion of straw is in the mix. During construction salt is strewn on the mats and mixed with the mud to keep insects, particularly white ants and borers, away.

*19. Sir J Chardin "Travels in Persia" p. 262.

*20. For house construction see Wulff p.p. 106-107

The mix is laid on the roof in sections approximately 3m wide. In between each section a rain channel is formed slightly depressed in the centre and deepening to the edge of the roof where it ends in a wooden spout. After each rain the roof has to be compacted otherwise it would develop cracks while drying, (a roller remains on the roof) and any straw has to be immediately turned over as matting straw seeps in whicker than rain. Such roofs keep the rooms cool in summer and warm in winter.

VAULT AND DOME CONSTRUCTION

Vaulting: Introduction

In Europe vaulting was developed for a limited practical reason - the need for a light roof over a high enclosure that could be carried by walls pierced by many windows. The fundamental motives were religious and aesthetic and it's use was largely limited to buildings embodying these principles. In Asia, scarcity of timber led to the development of vaulting to meet almost every conceivable spatial problem from peasant houses to mosques to palaces. Unfired mud-brick was used because it was far more flexible and adjustable than fired brick.

Two basic forms evolved; the barrel vault and the dome on squinches. The former roofed oblong rectangular spaces and the latter roofed square spaces. A single vault or dome could normally span only a limited area, but many combinations were developed, achieving large spans and roofing the most awkward spaces.

"A view over a Persian desert town, with thousands of vaults of all kinds, defying all regularity, gives the impression that there is nothing that cannot be done with a vault built of unfired bricks" *1.

Vault construction, as currently in practice in Iran and Iraq, i.e. without timber centering or shuttering became possible with the discovery of gypsum mortar. Gypsum mortar sets almost immediately on contact and there is no danger of slipping. The first Iranian examples of such vault construction is found in the Parthian buildings of Ashor (1st Cent. a.d.)*2. But earlier examples of such construction can be found in the Ramessaum Granaries (Egypt New Kingdom 4000 B.C.) and in Babylonian graves and canals.

1. Vault or Arch constructed with centering.

Centering did not die out immediately with the discovery of gypsum but was used in a modified form. A thin layer of stone and gypsum was laid over the scaffolding and when it set it formed the centering for the bulk of the stone and mortar which constituted the vault. Thus only a very light centering was required. It as erected on the sustaining walls after they had been built up to the spring p oint level. The diameter of the vault was consequently greater than the breadth of the room.

2. Vaulting without centering using staging/mirror wall.

This type is used widely in Iran today. The courses are set vertically from the sustaining walls and leaning slightly against the staging/mirror wall. The thrusts are thus distributed between the vertical and horizontal axis, between the sustaining and mirror walls working together with the sticky gypsum mortar to minimise any possibilities of slipping. The vault described a large segment of a circle forming a parabolic ($\frac{1}{2}$ elliptical) curve.

*1. E Diez See Pope and Ackerman p. 918

*2. Pope and Ackerman p. 415

Sometimes when a large span had to be roofed the walls were gradually shifted inwards so that they approached each other in a slight curve. Thus the actual span to be vaulted was reduced.

Vault types 1 and 2 can both be found in the palaces at Firuzabad, Iran (2200 a.d.). The parabolic vault was characteristic from sassanid times (224 - 651 a.d.). The largest example of this kind without centering is the vault at Taq-i-Kisra in Tesiphon.(with a span of 84' - 25 gometres). The vault at Firuzabad, despite the use of crude, flat stones instead of bricks, spans 43½' (13.3m.).

3. Vaulting without centering or staging/mirror wall.

In constructing a brick barrel vault without staging the mason, starts at the back wall with a course describing a segment of a circle and advances with a succession of parallel courses. This method is used in Iran.

Domes.

A major problem in spanning with a dome was in resolving the square with the circle; the square room with the circular domed roof. To do this the squinch and the pendentive was developed with many interesting types of combinations.

4. Dome on Squinches.

In this type the dome if formed by 4 squinches built up from the ~~four~~ corners of the square room and meeting in the centre. A squinch is begun by laying a small arched course diagonally in one corner and advancing with increasingly larger courses until a segment of a cone is formed. This is done at each of the four corners till the half cones meet ~~at the circle~~ ~~at~~ each side of the room. The work is continued in this way until the remaining opening which is square in horizontal projection is closed. This type of dome is used widely on houses in Kl.

Dome on Squinches and Infill Walls.

In this type the squinches stop short of meeting in the circle. The spaces left in between them are filled with level courses on a gradual increasing horizontal curve until a horizontal circle is made at the crown of the squinch arches. The dome rests on this circle and is built up by continuing the horizontal circles moving inwards. It has a half elliptical cross-section.

Dome on Pendentives

The other method of bringing the upper corners of the square room within reach of the circular base of a dome was to build pendentives. Pendentives are a triangular, overhanging wall supported on either side by the walls of the square. If the triangle is built in concave courses so that its interior surface forms part of the interior of a sphere, it can be continued ~~until~~ a perfectly round setting for a dome is achieved.

Combinations

The above outline of vault and dome construction remains a very basic vocabulary for the technique, types and their potentials. Very many ingenious variations and combinations of the above were developed and are practiced today. Once the builder has mastered the above techniques, the way is open for him.

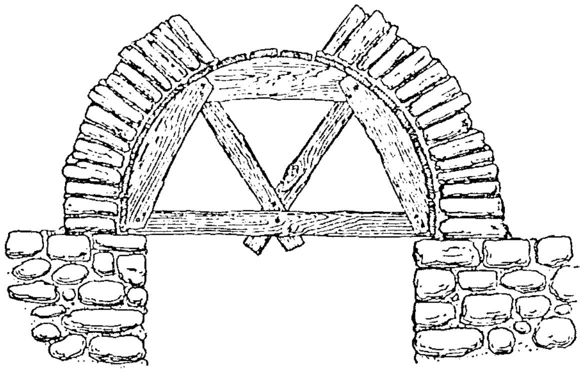


FIG. 128. Construction of an arch with centering set on the supporting members.

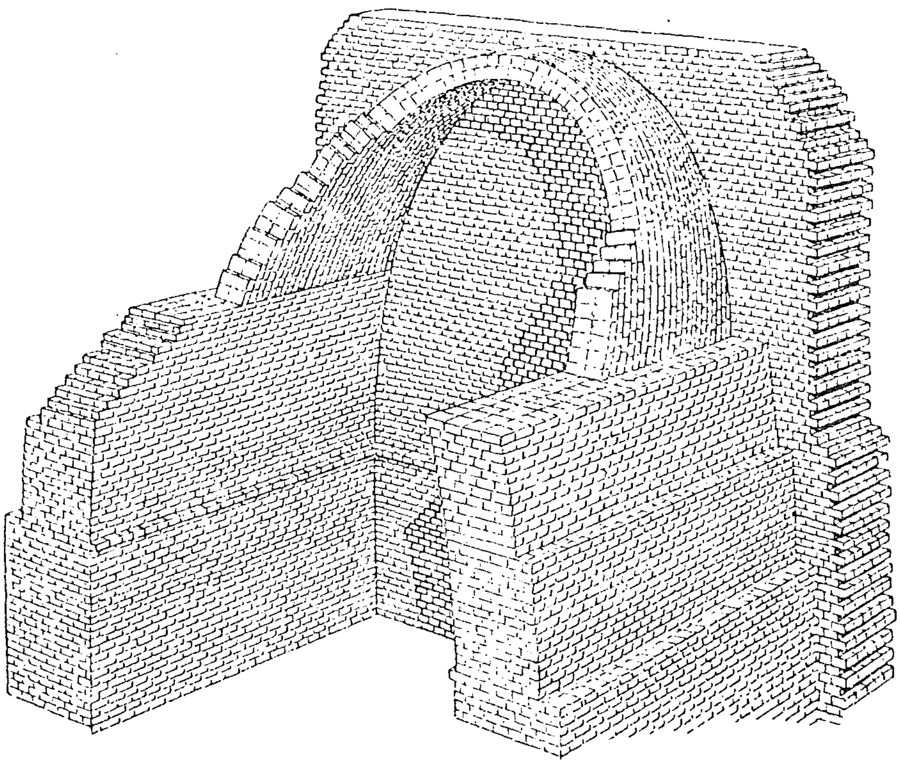


FIG. 129. Diagram of a Sāsānian barrel vault with parabolic cross-section, built without centering, with vertical semicircular courses.

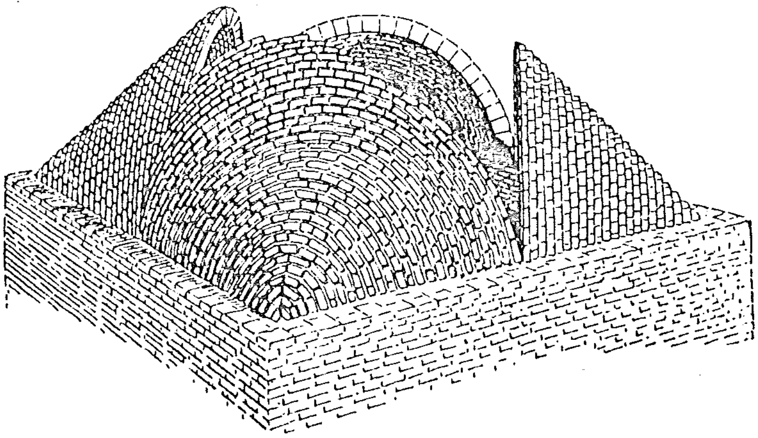


FIG. 130. Diagram of method of constructing an Iranian vault on squinches.

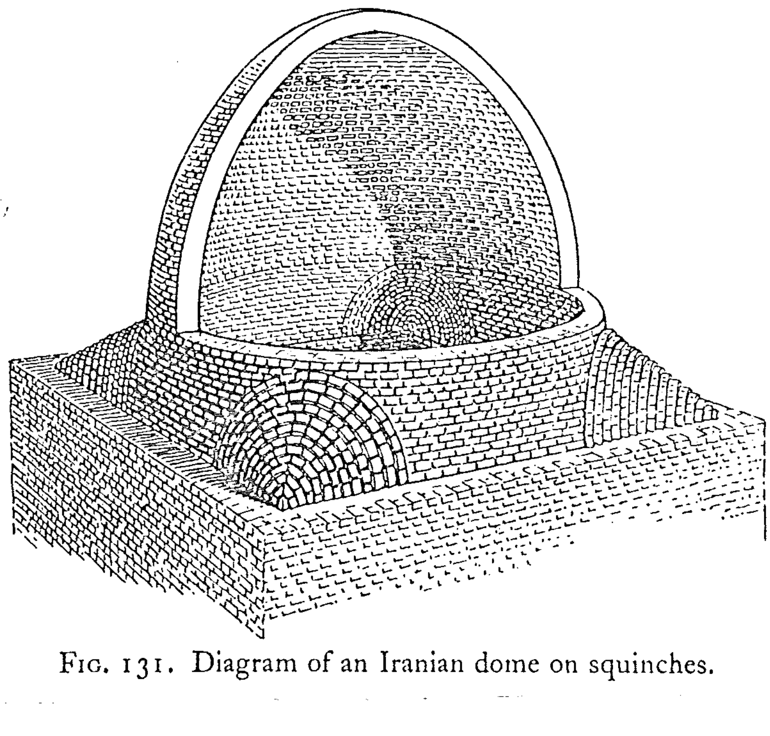


FIG. 131. Diagram of an Iranian dome on squinches.

. Between the squinches the wall is built up vertically at ββ and then filled
the face of the squinch, so that its surface Bb, Dd, has no precise geometrical
ough it is practically circular at the level of the crown of the squinches.
e corner of the lower walls and the crown of the squinch the groin gradually
(pD and mA).
f this awkward groin the tenth century produced two other solutions: first,
, as in the Mausoleum of Ismā'īl, the Sāmānid, at Bukhārā (Pl. 264 c); and

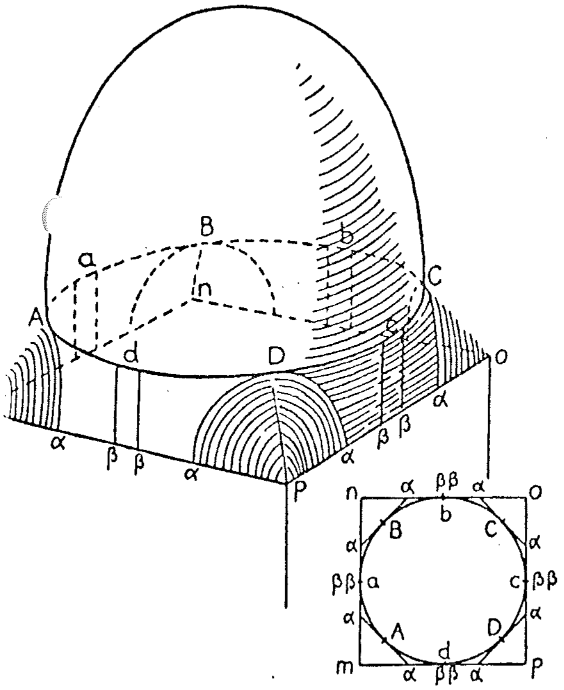


Diagram of typical Sāsānian half-cone squinch.

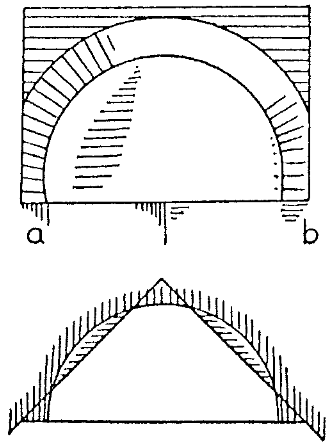


FIG. 450. Byzantine pendentive.

no h niche which blandly overrides the corner as in the Masjid-i-Jāmi',
268 A), and closely resembles a certain Byzantine type (Fig. 450),[1] though
ointed.
usoleum of Arslān Jādhib, Sangbast, this squinch exists on a monumental
60 B). Half a century later appears at Yazd, in the Duvāzdah Imām (Pl.
e first of a very long line of complicated squinch-backs, so numerous and
ey can hardly be classified here (Pls. 320, 411 A, 412 A, F, 442). Along with
jūqs used a very beautiful plain squinch with a sharp groin running from the
e walls in a smooth curve to the crown of the squinch (Pls. 305, 314).
t likely that Persian architecture could long rest content with the rather
ānian filling between the squinches. Great side-arches, uniform with the
hes, replaced the old beetling walls, and created with their spandrels a bold
rism (Pl. 260 B). On this the dome rested, projecting without further
This offered a better opportunity for lighting the dome chamber with win-
60 B, 274 C.) Aesthetic and practical considerations (see pp. 1000–1) made
justment of the polygonal to the circular form necessary, and the architect

[1] Figure after Choisy, op. cit., Fig. 102

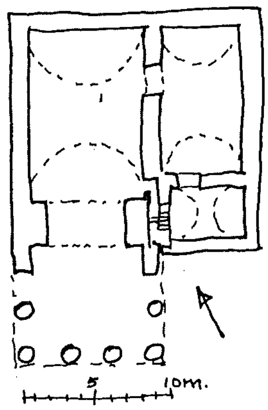
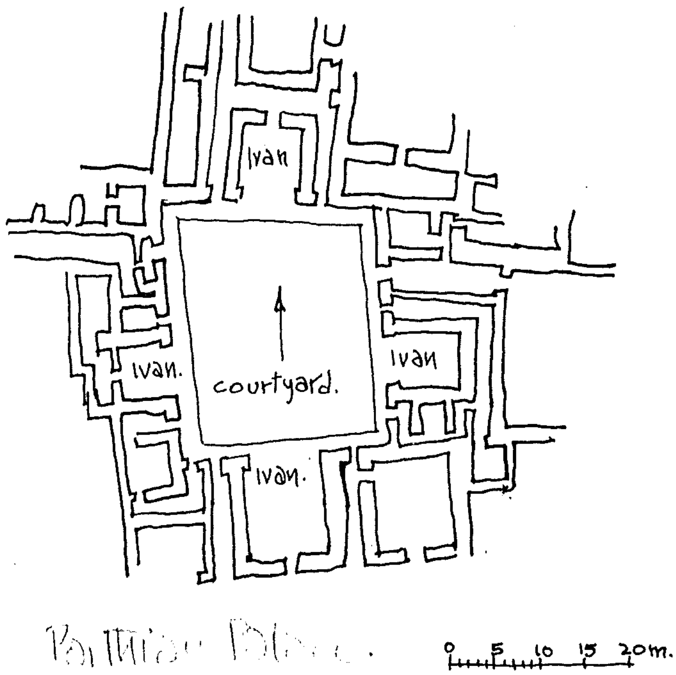


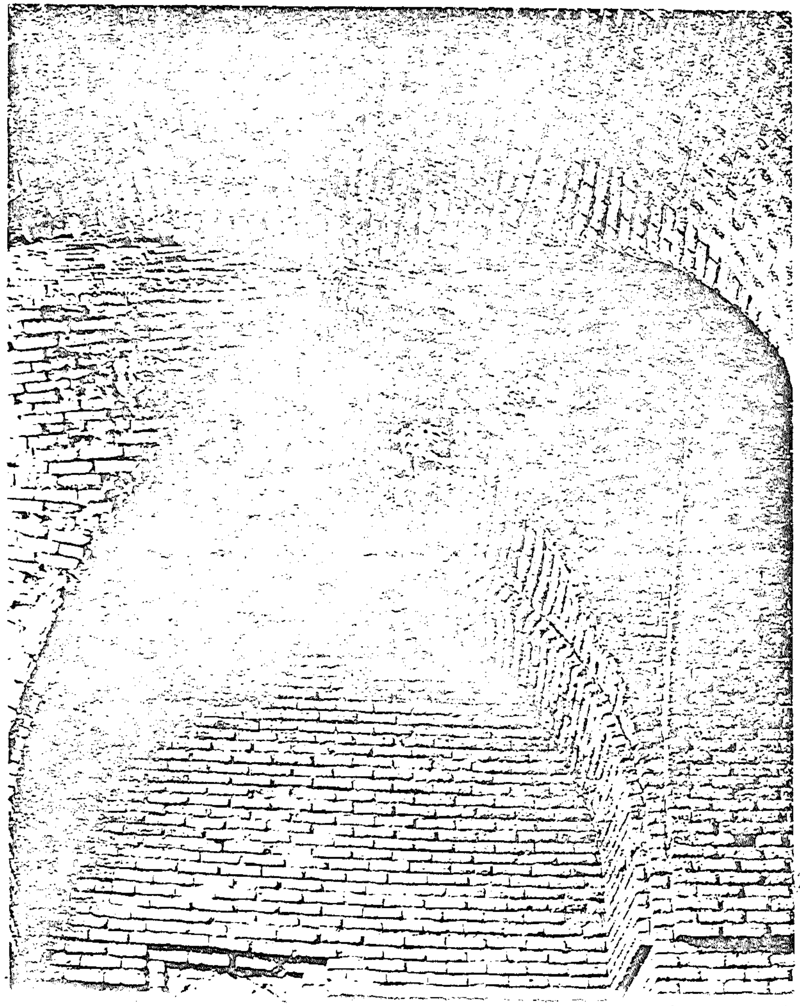
Fig. 5: 'Ivan' hse.
[illegible] Pope A. [illegible]
1432 [illegible]



Parthian Palace.

Photo. Pope

A. ARDISTĀN. MASJID-I-JĀMI', SMALL DOME (cf. Pl. 296B)



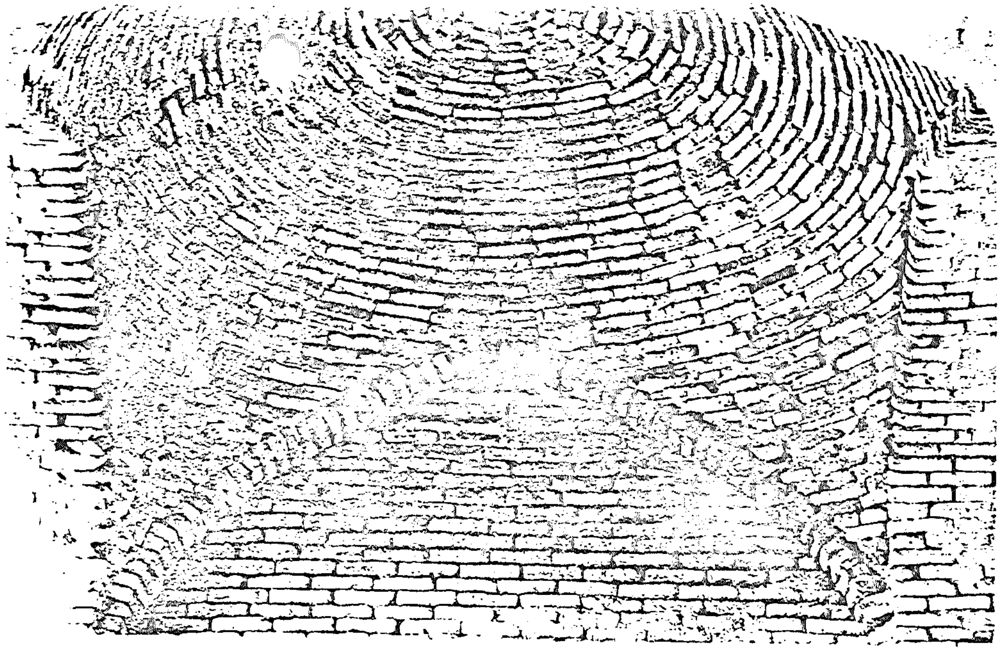
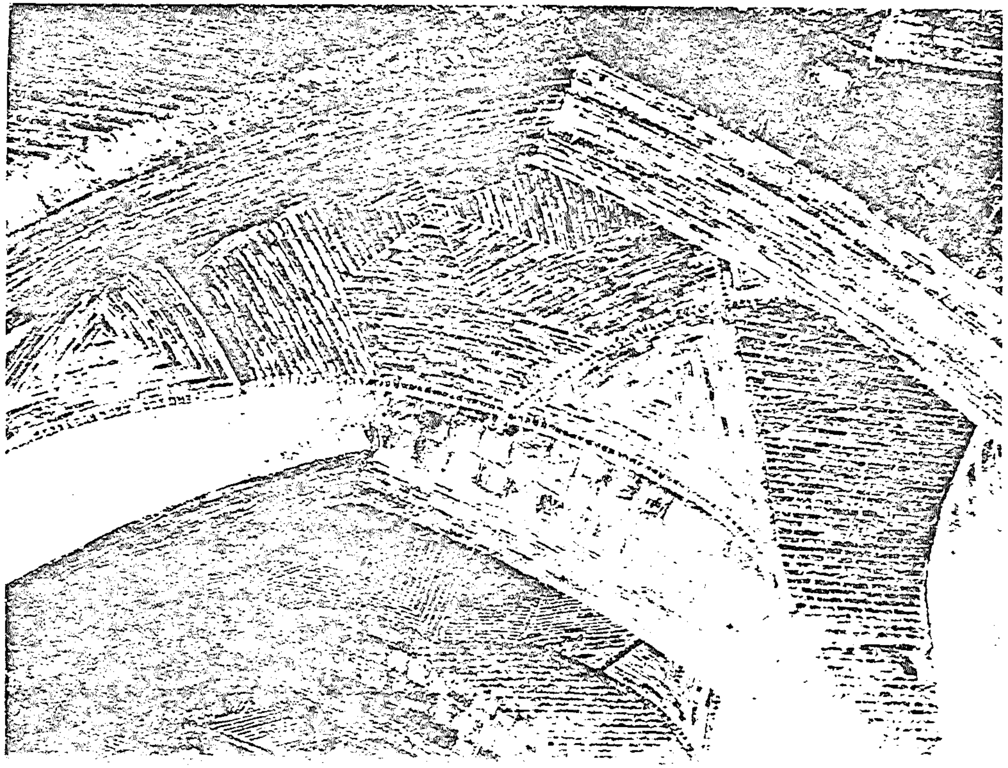


Photo. Pope

B. ARDISTĀN. MASJID-I-JĀMI', PENDENTIVE DOMICAL VAULT



9.3.2. Materials

9.3.2A Mud Brick (Adobe) Construction

Mud brick is used as one of the principal building materials in many parts of Oman. Its use depends to a large extent on the availability of lateritic (clay) soils. These are present in most parts of the country. Mud brick although was not found to be extensively used in the Dhofar coastal region. This is probably due to the limestone bed rock condition. Clay is used here although as a mortar for limestone block as well as for rendering barasti houses.

Mud brick has been used in the past in Oman for the construction of civic buildings, forts, market places as well as residential buildings. It continues today as one of the primary materials in owner built housing. The use of mud brick in building has developed to a high artistic level especially in the interior towns such as Nizwa and Hamrah, where multi-storied buildings of two and three stories are the rule.

In recent construction of public buildings mud brick has been superceded by concrete. The idea that mud brick and other indigenous materials cannot be used in modern building projects has been introduced on the grounds that these indigenous materials tend to produce environments which are physiologically unhealthy and structures which are unsafe.

Before mud brick or any other material is discounted its properties should be analized and compared to properties known about other materials. Every building material has its advantages and disadvantages and its appropriate uses. Materials should be analized and compared with reference to their physical properties and strengths, environmental responses, economic implications, ease of use, effective lives, availability, and aesthetic qualities.

Physical Properties of Mud Brick

Composition of Soils

In choosing soils suitable for the making of mud bricks its physical properties must be analized. Soils of various compositions produce bricks with differing properties and strength and resistance to water damage.

Soils are usually graded into four divisions according to the size of particles, as gravel, sand, silt and clay.

	Particle Size
Gravel	2.0 mm
Sand	0.2 - 0.02 mm
Silt	0.02 - 0.002 mm
Clay	-0.002 mm

+ organic matter + moisture

The soils cohesion properties (ability to hold together in a mass) are directly due to particle sizes. Coarse soil particles are not cohesive and rely on friction between particles for stability while a fine grain soil (i.e. with a high proportion of clay) is cohesive.

The presence of a high water content reduces the cohesive strength, and thys its plasticity, resistance to deformation and its compressive strength.

The presence of organic material such as humus in the soil is not favourable for brick making and in preparing a site for qyarrying clay for brick making the top soil or organic layers in which biological activity takes place, must be cleared away.

In making bricks of a sand-clay soil, the clay provides the cohesive strength and the sand lowers the moisture absorption and gives resistance to abrasion.

Soils having a high proportion of clay swell yp increasing their volume when wet and shrink and crack badly when drying. Sandy soils on the otherhand do not have sufficient cohesive strength to prevent crumbling.

Soils which are either predominantly sandy or have a high proportion of clay will not produce good mud brick for building. If soils are found in these conditions they must be mixed in the proper proportions to make a good brick. The clay and sand content of soils very even within short distances, physical properties of soil from one area may be quite different from soil taken from a neighbouring area.

Fig shows that the reduction fo clay percentage will cause an accompanied reduction in strength of the brick. This is attributed to the consequent decrease in cohesion which in turn is the reason for brumbling and breaking of bricks having a low percentage of clay.

The water absorption rate of bricks varies directly with the amount of clay present. When submerged in water bricks absorb at least their own wieght of water after half an hour and show signs of disintegration.

Fig shows that When mud bricks are exposed to a saturated atmosphere they absorb water to only about 4% of their weight. Bricks with a high proportion fo clay absorb slightly more. Moisture absorption stops at about 4% after 12 to 15 days.

In considering the effects of rain it is found that bricks having a greater proportion of sand are more resiliant. Rain damage varies in inverse proportion to the amount of sand present in the brick.

Water Content of Mud Brick

Brick making relies on the properties of clay in the soil when saturated with water to become plyable but still plastic. This allows the mud to be moulded into a block shape and to keep its shape when the formwork is removed. The proper proportion of water to obtain this state is usually between one quarter to one half the eirght of dry clay.

There are two stages in drying of the brick. As most of the water evaporates shrinkage of the brick corresponds to the amount of water evaporated. At a point when the brick contains 7-10% water shrinkage ceases and the brick has become hard, though remaining a dard colour due to the presence of water. Soil particles are in contact at this point and the remaining water removed is replaced by air. With drying the brick gains a lighter colour.

This means that water content of 7-10% is tolerable in mud brick construction and will not result in damage. On the other hand when water content exceeds that limit it breaks down the cohesive strength between clay particles and consequently the strength of the brick.

Cyplan) Costs

Climatic Response - Heat Transfer

The response of mud brick building to thermal conditions experienced in Oman has been tested in a series of experiments at various locations in the country (see sections 3 , &). The thick mud brick walls insulate the interior of buildings from extremes of heat and cold, in a way that no other material has shown. Exterior surfaces of mud brick walls which are exposed to solar radiation heat up to a lesser extent than wall surfaces of many other materials, becuase mud walls especially those rendered with a mud plaster have a light colour. These wall surfaces therefore reflect solar radiation rather than absorb it. Mud walls varying in thickness from 40cm to 60cm delay the transfer of heat built up on exterior wall or roof surfaces due to solar radiation from reaching interior surfaces for twenty four to thirty hours. Very little of the heat from outside surfaces reaches interior surfaces which remain roughly at a constant temperature which is an average of the daily range of outside surface temperatures.

graph
slides

The mud brick walls action of insulating the interior from heat and cold is not only due to its thichness but also its low coefficient of thermal conductivity. (i.e. the higher the coefficient of thermal conductivity the more ready the material is to transfer heat through a wall).

The coefficient of thermal conductivity for mud brick varies with the composition of the mud brick. The coefficient increases with a higher proportion of sand to clay. See fig .

In comparison to other structural materials mud brick has a relatively low coefficient of thermal conductivity at 0.50 W/M^{o}C while concrete is approximately 1.2 W/M^{o}C and limestone is 1.5 W/M^{o}C.

Mud Brick Making

Choosing soils for mud brick making.

standardization in (modern bldg)

The demands of modern construction require a scientific appraoch to the selection and composition of building materials. Individual materials must be uniform in their properties and strengths and these properties and strengths must be clearly understood. Mud brick as a material must also meet these requirements.

Builders in the past cannot be dismissed as unscientific and the reason for their successes and ingenuity put aside to intuition. What we have today has evolved over many years of testing and experimentation. It is the accumulated knowledge of many people building in response to similar problems and environments. On the other hand when new tools and techniques make themselves available they should be taken up if they prove themselves to be improvements on existing systems. Improvements have always been made and must continue. When more than one material or grade of material is available the choice of building material or system of construction must rely on the requirements of the building and the environmental factors.

We can see from fig & fig that mud brick's properties of strength and resistance to water damage vary depending on the composition of the brick. Therefore the mud brick can be designed to fit individual building's requirements. Compressive loads experienced by bearing walls in the building must be determined and the amount of moisture in the environment known in order to choose the optimum proportions of sand and clay to produce the best brick. A further non structural consideration can be made at this point. It is known that the insulation or heat transfer value of the brick (i.e. its coefficient

Brick can be engineered to suit particular requirements, strength, resistance & heat absorption

of thermal conductivity) composition of the material. Knowing the location and orientation of the building the optimum coefficient of thermal conductivity can also be attained by choosing the proportion of sand and clay.

Ideally one would like to find soils of appropriate quantities of sand and clay near the building site. Water in considerable quantities is also required nearby. If mud can be quarried near the building site and mud brick making carried out nearby there will be a great saving in time and transportation costs. This of course is not always possible. On the other hand a site may be found where there is a large deposit of soil which produces a high quality brick and a mud brick making yard established here to produce bricks for a large project or for general community use. In choosing a site not only the soil quality and economicy of transporting bricks must be considered but the eventual use of the excavated depression which is left behind.

It is not always possible to find soils of the proper composition for mud brick making in the desired area. Soils may vary in their composition even over relatively short distances. Soils from various sites may be mixed to provide the correst proportions of sand and clay for the production of suitable bricks. It therefore becomes very important to make a thorough soil survey of areas where mud brick production is proposed.

(A) In the past the mud brick mason would clear away the top soil from a number of sites and test examples of the sub soils using simple tests. Colour of the coil would be noted, black soils tend to indicate unwanted organic material, and other colours indicate presence of various chenicals and minerals. A musty smell is a good indicator of the presence of organic material. Larger particles can be graded visually and soils having gravels or very course sands will be rejected. Grain size can be determined by 'touch'. Soil if tested between the teeth can be graded (the tongue and mouth being extremely sensitive to small particles). Sandy particles will feel sharp and will grate against the teeth. Silt particles will be finer but still grate somewhat. While clay will feel powdery or even soapy. Wet samples of soil rubbed between the fingers will give similar sensations. When a ball of soil is manipulated in the hand its texture becomes apparent. If it folds together and is very plyable it has a high proportion of clay, if it crumples easily it has a high proportion of sand. If the ball of soil swells up in water it is clay, if it falls apart in water is it sandy. Many qualitative tests such as these give important information on the uses of soils for mud brick making.

Quantities of various particles in the soil can be roughly graded visually. Soil samples must be dried and pulverized. All particles which can be seen by the naked eye are separated and set aside. These are sands and gravels, the remainder being silt and clay. Two piles are made and the proportions can be estimated visually or measured.

The accuracy of the above 'traditional' tests of course depends on the experience and patience of the mason. This kind of knowledge will prove advantageous even to modern builders.

(B) The newly developed field of 'soil science' and 'soil engineering' has provided new techniques that the mud brick builder can employ to upgrade his methods of soil selection and testing.

Bore holes can be dug in various places and core samples removed. These samples indicate soil conditions at various levels below the surface at each test location. Maps and cut away sections (profiles) can be drawn showing the different soil stratta. Bearing strengths of these various stratta can also be taken. Soil samples are individually tested for chemical composition and particle size. Some of these tests must be done in the laboratory but others can be 'field tests'. The test for grain size requires drying and pulverizing the sample. The soil particles are then screened or sieved through a series of wire meshes having sizes corresponding to the various particle demensions - gravel, sand, silt and clay. The material collected in each sieve-tray is weighed and the proportion of each particle size is determined. This gives very accurate information to the brick maker.

For example:

It is determined after calculating the required compressive strength and resistance to moisture that a brick with a composition of 50% sand and 50% clay is desired for a particular building. After a comprehensive set of bore tests, it is found that there are not deposits of soil in the vacinity with the above proportion of particles, although there is a site with 20% sand and 80% clay and another with 60% sand and 40% clay. Mixing is therefore required to obtain the proper composition in the brick. In this case if soil from the first site was mixed with soil from the second site in a proportion of 2 to 1 the proper composition of 50% sand and 50% clay would be obtained.

ref. UW - Paper on Soil Cement

Traditional Brick Making

slide - Brick making: mud is collected from the supply pit and placed in a banked up enclosure size where it is mixed with water until the consistance is suitable for brick making.

brick making slides

This mixing process is usually carried out by foot though machines can be used, if available. At this stage care must be taken to ensure that the mud put into the brick mould has the correct moisture content. Too much water at this stage will result in bricks shrinking and cracking excessively in the drying process. This in turn results in a loss of strength and density in the bricks. As a rough rule of thumb if the mud sticks to the mould on removal, then the mix is too dry, and equally if the brick does not retain a firm shape when unsupported the mix is too wet.

Too much moisture in the mix will dry out in the brick leaving voids which weaken the bricks compressive strength and allow further moisture absorption. The mud must stand for a day or two before brick making to allow all the small lumps to break up into a consistant mix.

When the mud is finally ready a clean level is cleared, over which a layer of sand or dust in sprinkled to stop the brick sticking to the ground. A hand mould consisting of four wooden sides with no top or bottom to it, and of the required size of the brick is then placed on the ground and filled with the mud mix, which is tamped down to ensure a compact neat brick. The top is cleaned off and the mould is then carefully raised up to leave the formed brick to dry. Bricks should be left to dry in a shaded place for the first three days. This prevents excessive shrinkage and cracking. In fact the slower a brick takes to dry the stronger it becomes. The best bricks are therefore made during the winter. After three days bricks are turned on end so they dry evenly and lift in the sun. Bricks should not be used before they have thoroughly dried out, which usually takes at least thirty days, when they will attain a constant weight.

Two guides as to the quality of the finished brick give an indication whether it will be adequate for any load bearing commonly found in house building. Firstly, whilst small surface cracks are permissable in the brick, if these cracks extend from one side to the other the brick should be rejected. Secondly, the bricks should be uniform in size, free of voids and should stand up to stacking, handling and movement without appreciable breakage or srumbling at the corners. The surface of the brick should give good resistance to abrasion when rubbed with the hand.

A detailed description of the traditional mud brick production methods which have been rationalized and approached in a systematic scientific manner can be found in Professor Hassan Fatby's book, Architecture for the Poor.(Here he recounts his experiences in rural Egypt and shows how mud brick production can be carried out very economically to produce a consistantly good material. These experiences can be adapted and used as models for working out similat production problems in Oman.

Rammed Earth Bricks

Mud bricks of a strength greater than those made using the traditional method can be made employing brick ramming-form devices and the same basic material. These rams use a lever action to form bricks under compression. A somewhat dryer clay sand mixture is put into the mould and a stronger brick requiring less drying time is produced.

The most common brick ram machine is the man powered 'Civca Ram' produced in Columbia, South America. It requires a crew of two men to operate plus men to mix and carry the mortar. The Civca Ram can produce about 400 pressed blocks per day while Professor Fatby's experience shows that a crew can produce 3000 traditional moulded blocks per day. Other automatic or semi-mechanized techniques can produce 1500 to 2000 pressed blocks in a working day but at greater expense.

It must be remembered that high strength pressed blocks are not always necessary. The compressive strengths taken by traditionally made blocks are sufficient for most one and two storey building projects.

Improvements

Mud brick as it is used now has a relatively low strength when compated to limestone, concrete and red brick. It can only be used in campression. Even with its relatively low compressive strength substantial two and three storied buildings are the rule in many areas of Oman. Extensive multi-storied mud brick buildings have been built in many other parts of the world. Mud brick has a low resistance to water damage, this is why mud buildings tend to be found in areas of little rain, though very fine mud buildings have been built in the past in Europe as well, as far north as Britain. In areas that experience rainfall or flood damage mud construction has been adapted to respond to wet conditions.

Several methods have been employed to improve mud brick systems.

i) Firstly, the use of mud brick in conjunction with other materials can be advantageous. Limestone footings for mud walls are employed extensively in Oman where water damage to the bases of walls due to flooding is a problem (Fig). Substantial footings for mud brick walls are advisable in almost every condition. Damage to walls due to cracking or movements of the surface of the ground can largely be prevented by proper footings. Limestone, red brick or concrete can be used for footings, and these should be set below the surface for stability.

Damp proofing courses are also advisable in areas where dampness rising from the ground can damage mud brick. Commercial roll-out materials and felts are usable but the simplest method is the use of a layer of bitumen spread continuously over a levelled course on top of the footing wall. The damp proofing course must be above ground level. The mud brick construction starts above it.

Reinforcement can be introduced into the mud brick wall when additional strength is needed, such as in an earthquake zone. Vertical reinforcement can be introduced in the form of hardwood sticks or steel running through the wall. Horizontal reinforcement can take the form of a ring beam (refer to Fig) which may be as substantial as a continuous reinforced concrete member running around the walls of a structure.

ii) The second method used to improve mud brick systems is rendering or plastering wall surfaces. Sruface rendering prevents water from damaging the brick structure and also helps keep down dust from the mud surface in the interior. There are a number of materials which can be used for rendering. They vary in their ability to bond with the mud brick surface, their ability to resist the penetration of water, their durability and their availability and cost.

The simplest and most readily available material is a type of clay plaster. Special high grade clays more resistant to abrasion are used to render the walls of mud brick buildings. This is the most common type of rendering and is used universally in indigenous construction. The clay is generally of a lighter colour than the brick clay and reflects solar radiation well. Its actual composition varies from area to area but its production generally requires a period of germentation in water. It is sometimes mixed with straw to help stop cracking. This material has the advantage of binding readily to the mud surface. Replastering is generally required every three years.

Recent experimentation has shown that a very hard rendered surface which will not tend to crack can be obtained by simply using a clay-sand mixture with a high proportion of sand i.e. two parts sand to one part clay. The wall surface in this case will be darker than the one above and absorb more solar radiation.

Lime, gypsum, cement and other materials with oil or chemical bases can be used for rendering walls. These solutions may prove to be expensive and costs must be weighed against effectiveness and durability. The wall construction must be completely dried out before plastering, further settling of drying will cause cracking or flaking of the new surface.

Surfaces must be prepared. Rendering materials adhere well to rough surfaces and are less likely to crack. Walls must be dry and free from loose material. A thin wash of partland cement and water will help plaster adhere to the wall. Plastering material can be trowelled on, spread by hand, thrown or mechanically sprayed. These rendering materials tend to last 5 to 10 years, then must be replaced.
renewed.

Mud Brick (Adobe) Construction

Mud brick is used as one of the principal building materials in many parts of Oman. Its use depends to a large extent on the availability of lateritic (clay) soils. these are present in most parts of the country. Mud brick is not extensively used in the Dhofar coastal region because of the predominance of limestone. ~~[illegible]~~ Clay is used here although as a mortar for limestone blocks as well as for rendering barasti houses.

Mud brick has been used in Oman for a wide range of buildings. ~~and~~ ~~up to~~ ~~[illegible]~~ two and three storied construction is common. Although official government buildings are ~~neo~~ now built with newly introduced materials mud brick is still extensively used for domestic building in rural areas.

~~The~~ The mud brick itself is still made today in the way it has been in the past, just as the construction techniques employed in house ~~construction~~ building have not altered greatly. Mud bricks are cast in simple wooden frames or molds and left in the sun to dry before they can the used. The prior seletion of proper soils for mud brick making is very important although ~~and is of great im~~

A detailed analysis of soil composition can be made in order to grade particles and determine the proportions of different sizes. Soil samples can be graded using a soil ~~mechanic's~~ engineer's screens. These screens are actually wire meshes of different dimensions through which dried and ~~pot~~ pulverized soil samples are sifted. If a number of samples are taken in a given area, soils of various compositions can be mixed to attain the ~~[illegible]~~ optimum proportions of sand and clay to produce good bricks.

The composition of soils used in mud brick making determines ~~whether or not the~~ the finished brick's ~~will be strong~~ strength and resistance to water damage. Any sample of soil is made up of particles of various sizes. The terminologies - gravel, sand, silt, and clay are actually ~~in~~ refering to particle size, sand being a soil of relatively large particles and clay a soil of very fine particles. The ratio of sand to clay in the soil ~~is a convenient~~ determines ~~the~~ its suitability for mud brick making. Soils used in the making of mud brick must be free of organic matter so subsoils (those exposed after scraping away the fertile, humus layer) are always used.

The indigenous builder, when choosing soils for brick making would carry out a number of tests. The Colour & texture of the soil indicates the presence of organic matter, black soils are discarded. A musty smell is also ~~a~~ sign of organic matter. Particle size can be roughly determined by its texture between the fingers or between the teeth. Finally a soils behavior after compaction and being submerged in water is a measure of its composition.

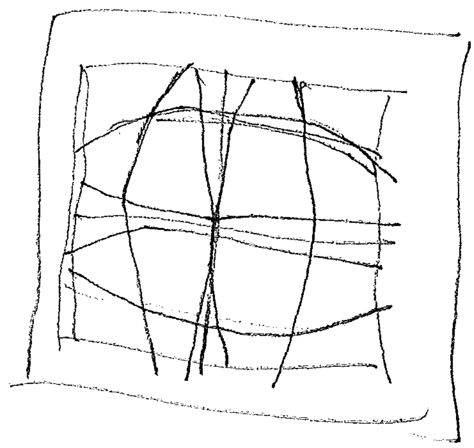
Once soils are chosen a pit is prepared where they can be mixed with water and made into a consistency suitable for molding. The mixture is put into the wooden framed mold, the mold is then removed and the brick is allowed to stand ~~for several days~~ and dry. After three days the brick is turned on end and left to dry in the sun for 30 days or more ~~for up to 90 days~~ (with periodic turning), after which time they can be used in wall construction.

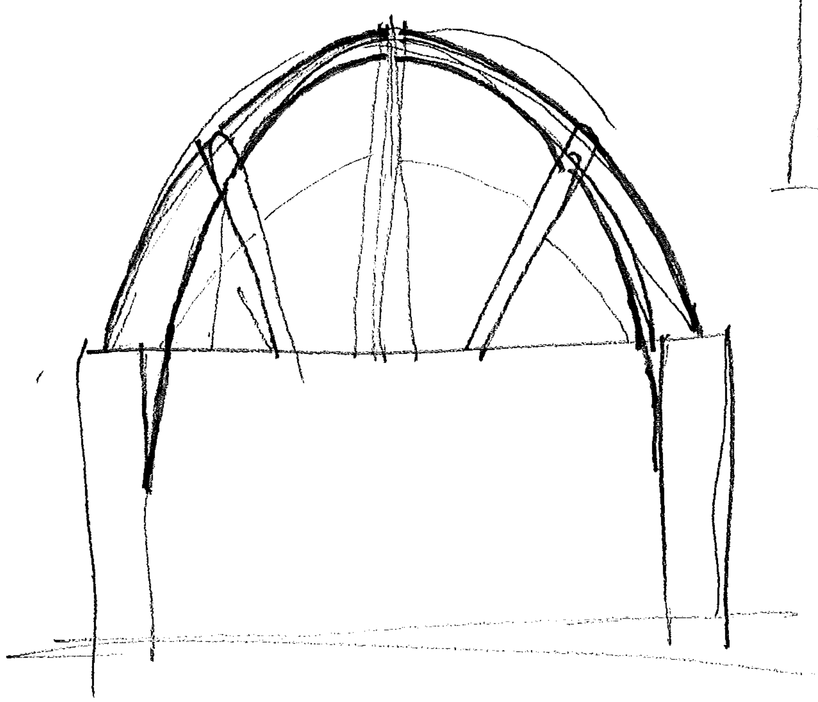
As stated earlier, the brick's strength and its resistance to water damage are dependant on its composition, particularly its sand/clay ratio. Recent experimentation has shown that mud bricks can be designed to ~~show~~ fit requirements of strength and water resistivity by the control of ~~quantities~~ the proportion of sand and clay. In general bricks with a high proportion of clay and a low proportion of sand are much stronger in compression than other bricks. ~~[illegible]~~ Fig --- shows the compressive strength of bricks corresponding to their ratio of sand-clay mixture. On the other hand bricks with a high sand to clay ratio prove to be more water resistant ~~as shown in Fig---. than those having a high clay composition~~, and tend not to swell or change their size as readily when wet as those having a high clay proporti[on]

~~Vault~~ Dome Construction

Tahoua Nigeria

using parabolic beams
-ribs





~~G~~ Gutkein

Our World from the Air.

Terry Byres
Lecturer in Economics
Indian Dept. S.O.A.S.

Improving Mud Buildings.

M. Antoine Verwilghen
Panzi Mission, B. P. 7245
Kinshasa 1, Zaire

VAULT ANALYSIS.

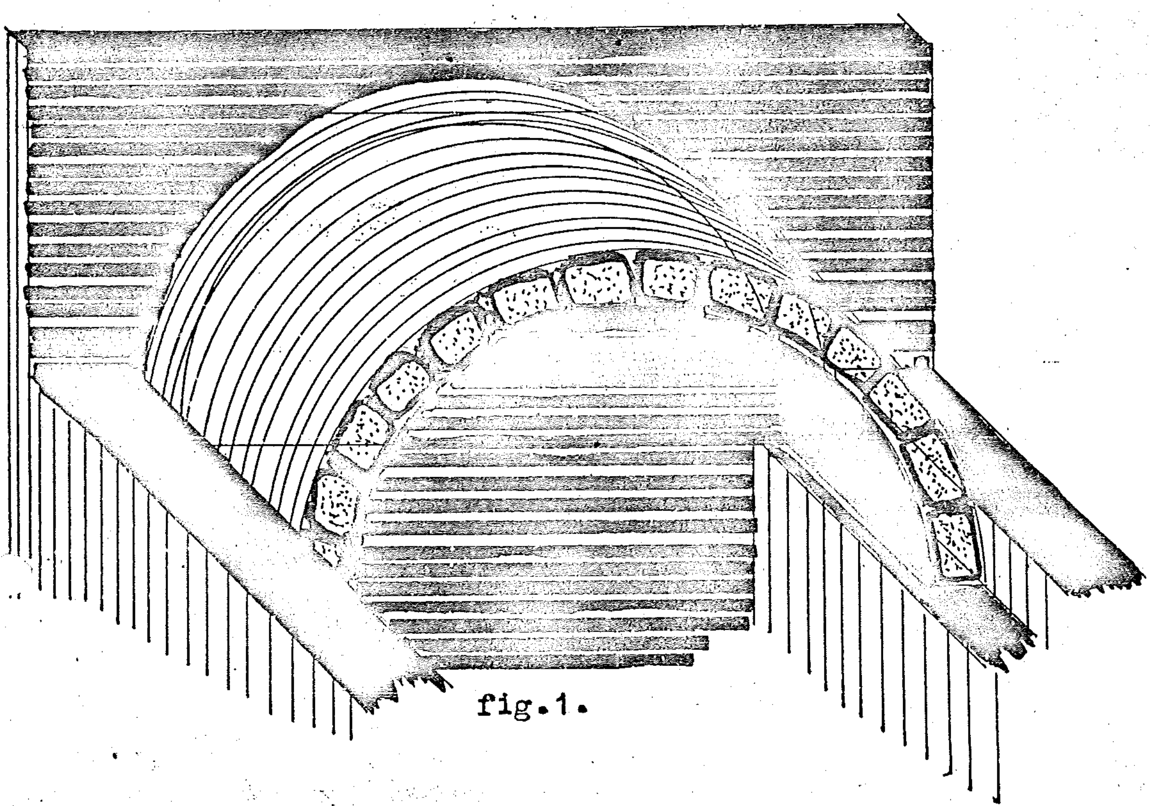


fig.1.

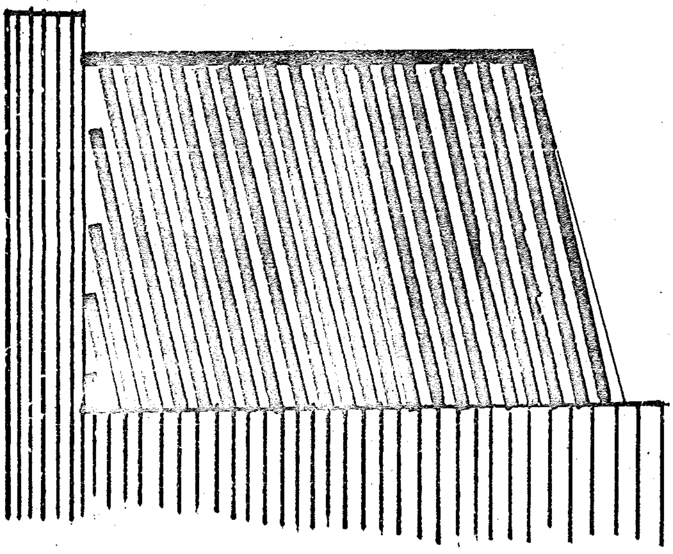


fig.2.

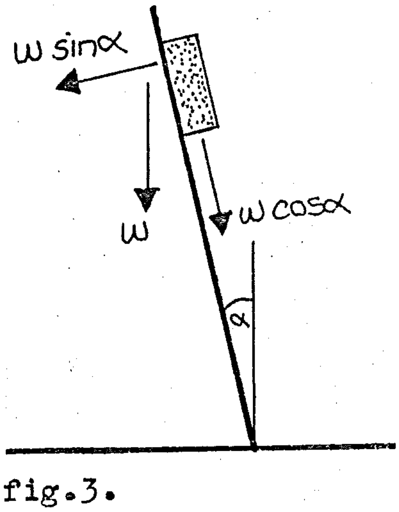
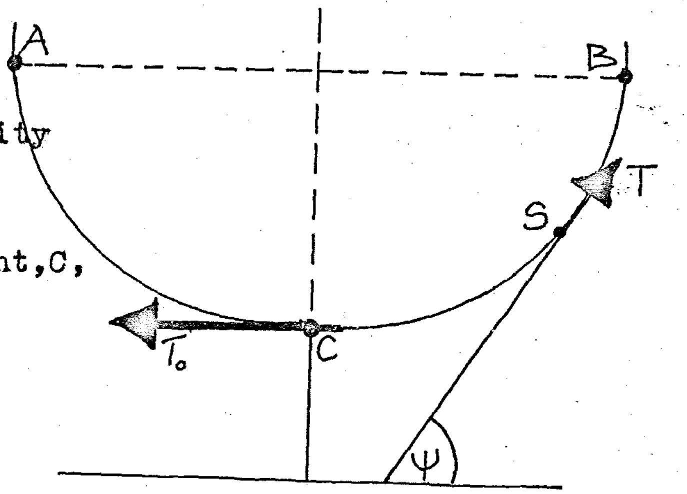


fig.3.

THE COMMON CATENARY

This curve is formed when a uniform, flexible, inextensible arch swings freely under gravity under its own weight. Let T be the tension at the lowest point, C, and measuring S from C, we get resolving;



Horizontally $\quad T\cos\psi = T_0$

Vertically $\quad T\sin\psi = ws$

Dividing $\quad \dfrac{T\tan\psi}{T} = \dfrac{ws}{T_0}$

Let $\dfrac{T_0}{w} = c$ (constant)

$\therefore\ s = c\tan\psi$ ① which is the intrinsic equation of the curve [c is called the parameter of the catenary]

$s = c\tan\psi$
$y = c\sec\psi$
$\dfrac{T_0}{w} = c$
$y^2 = c^2 + s^2$
$y = c\cosh\dfrac{x}{c}$
$s = c\,\mathrm{sh}\,\dfrac{x}{c}$
$T = wy$
[w weight/unit length]

$$\frac{dy}{d\psi} = \frac{dy}{ds}\cdot\frac{ds}{d\psi}$$
$$= c\sin\psi\sec^2\psi$$
$$= c\tan\psi\sec\psi$$

Integrating w.r.t. ψ

$y = c\sec\psi + k$

Now choose our axis so that $y = c$ when $\psi = 0$ $\therefore\ y = c\sec\psi$ ②

From ①+② (squaring and adding), $y^2 = c^2 + s^2$ ③

$\dfrac{dy}{dx} = \tan\psi = \dfrac{s}{c} = \dfrac{\sqrt{y^2-c^2}}{c}$ from ③ $\therefore\ \dfrac{dx}{dy} = \dfrac{c}{\sqrt{y^2-c^2}}$

Integrate w.r.t. y

$x = c\cosh^{-1}\dfrac{y}{c} + A \qquad [e^{+\frac{x}{c}} + e^{-\frac{x}{c}}]$

Since $\psi = c$ when $x = 0$, then $A = 0$. Hence $\dfrac{x}{c} = \cosh^{-1}\dfrac{y}{c}$

$\therefore\ y = c\cosh\dfrac{x}{c}$ ④

$\dfrac{dx}{ds} = \cos\psi = \dfrac{c}{y} = \dfrac{c}{\sqrt{c^2+s^2}}$

Integrate w.r.t. s.

$\therefore\ x = c\,\mathrm{sh}^{-1}\dfrac{s}{c} + B.$ When $x=0,\ s=0$ $\therefore\ B = 0$

$\therefore\ \dfrac{x}{c} = \mathrm{sh}^{-1}\dfrac{s}{c} \quad \therefore\ s = c\,\mathrm{sh}\,\dfrac{x}{c}$ also from ③ & ④

Since $T\cos\psi = wc$, squaring and adding we get

$T^2 = w^2(c^2+s^2) = w^2y^2$

$T = wy$

VAULT ANALYSIS.

$y = C \ \text{Cosh} \frac{x}{c}$ 1-)

The slope of the tangent to the curve is given by;

$\tan\psi = \frac{S}{C}$ 2-) ← divide $\frac{\text{vertical resolution b-)}}{\text{horizontal resolution a-)}}$ hence 2-)

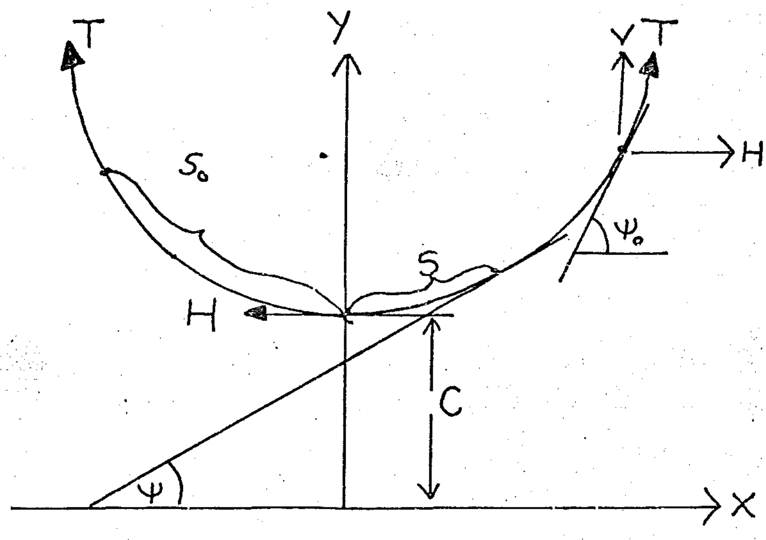
The length of the arc 'S' is given by;

$S = y^2 - c^2$ 3-) ← differential calculus using 2-) $\frac{dy}{dx} = \frac{dy}{ds} \cdot \frac{ds}{dx}$

where 'C' is the parameter of the curve. The two components of force along the catenary are given by;

H = W.C. 4-) constant.

V = W.S. 5-)

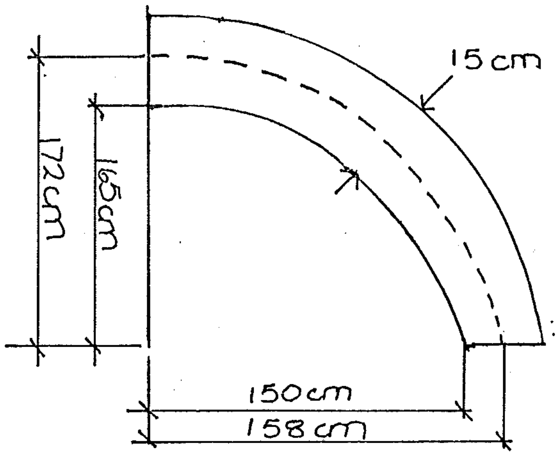


a-) $T\cos\psi = H$

b-) $T\sin\psi = W.S.$

FIRST VAULT.

The line of pressure coincides with the centre line of the vault. (This obviously assumes that the vault has been constructed to suit the catenary line of pressure.)



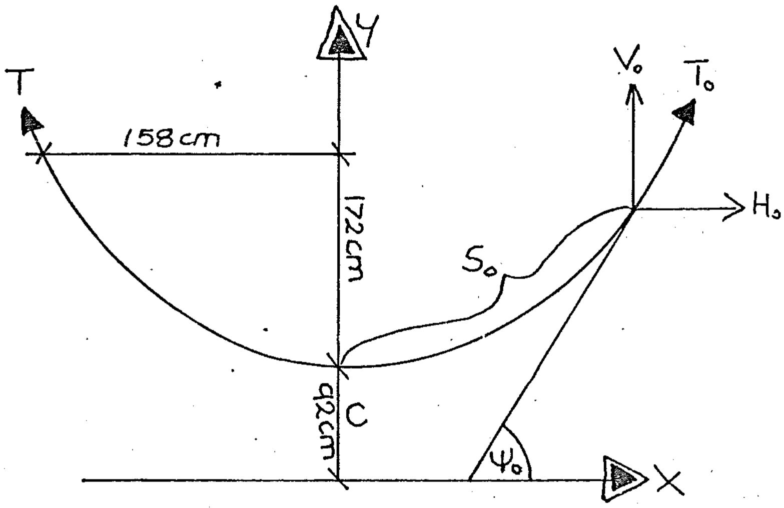
Solving eq: $y = C \cosh \frac{x}{C}$

For : $Y_o = 172 + C$ chosen
$X_o = 158$

$\therefore$ $C = 92$ by trial
$Y_o = 264$ cm

Length of Arc : $S_o = \sqrt{Y_o^2 - C^2}$
$= 248$ cm

Angle of thrust where arch meets wall : $\tan \Psi_o = \frac{S}{C} = \frac{2.48}{0.92}$
$= 2.7$

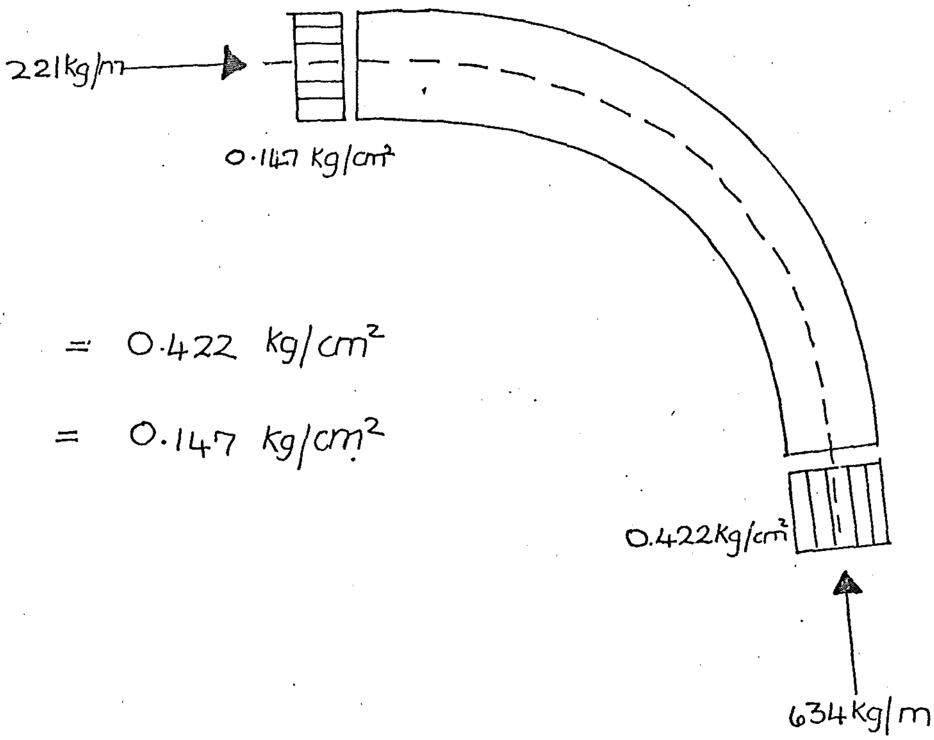


$T_o = w.y. = 240 \times 2.64$
$= 634$ Kg/m

$H_o = w.C. = 240 \times 0.92$
$= 221$ kg/m

$V_o = w.s. = 240 \times 2.48$
$= 595$ kg/m

CHECK OF STRESSES IN THE VAULT.

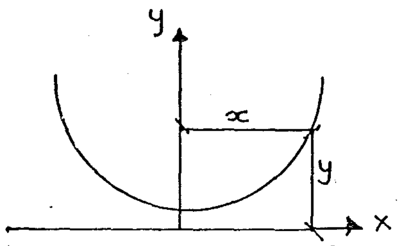


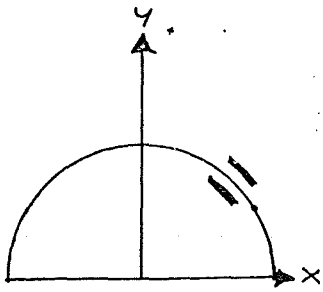
$$F = \frac{N}{A}$$

$$f_{max} = \frac{634}{100 \times 15} = 0.422 \ kg/cm^2$$

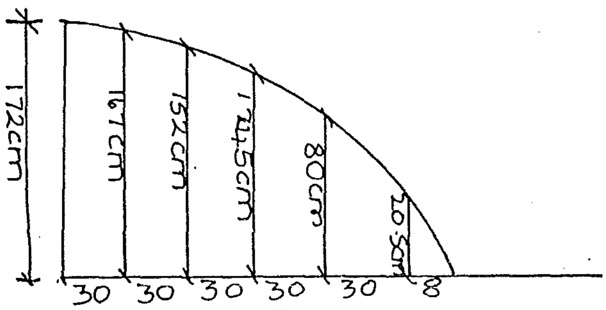
$$f_{top} = \frac{221}{100 \times 15} = 0.147 \ kg/cm^2$$

CORDINATES OF PRESSURE LINES

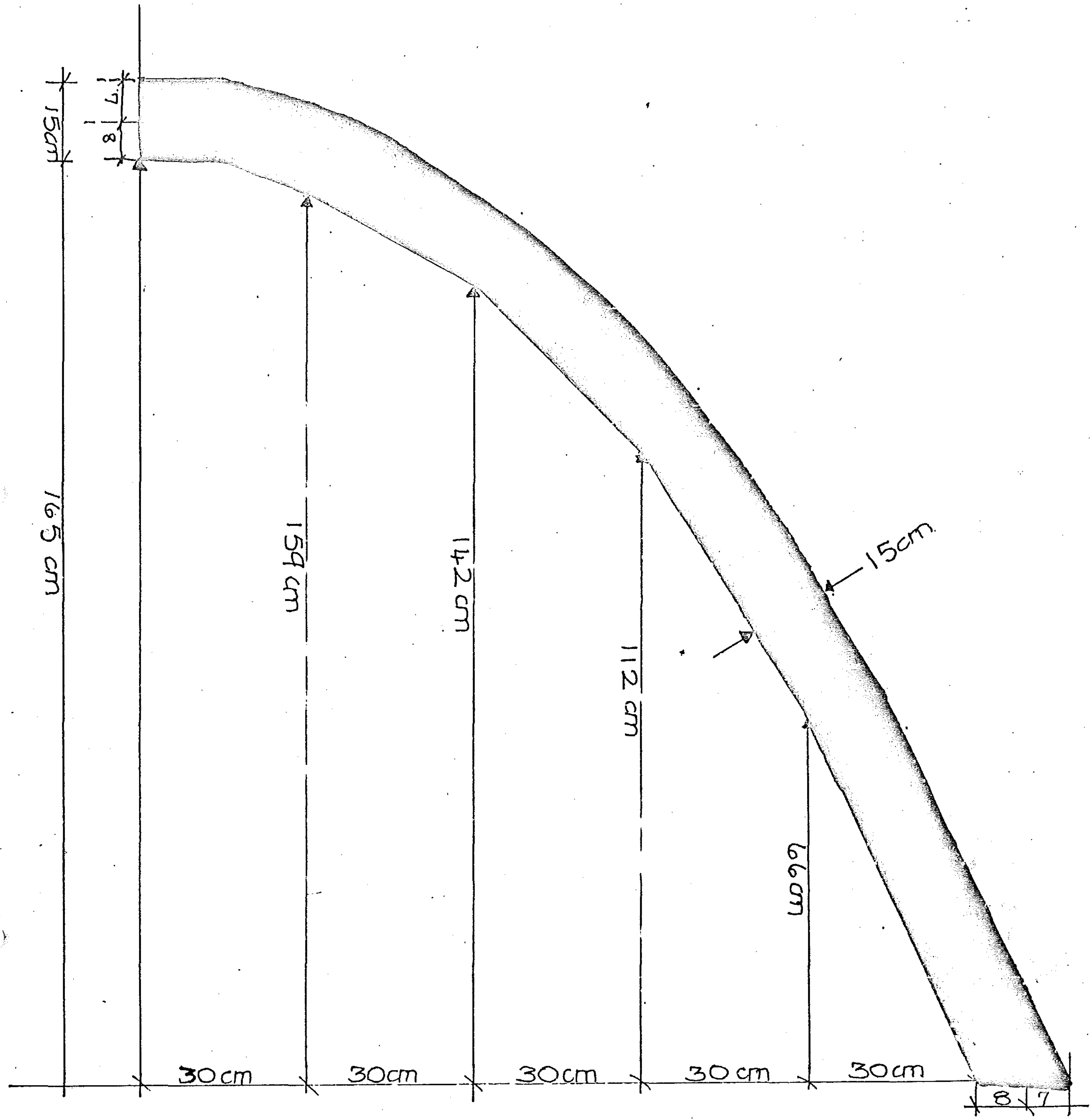




X	$\frac{X}{C}$	$Y = C \cosh\frac{X}{C}$	Y
zero	—	92cm	172 cm
30	0.326	97	167
60	0.652	112	152
90	0.978	139.5	124.5
120	1.304	182	82
150	1.63	243.5	20.5
158	1.72	264	zero

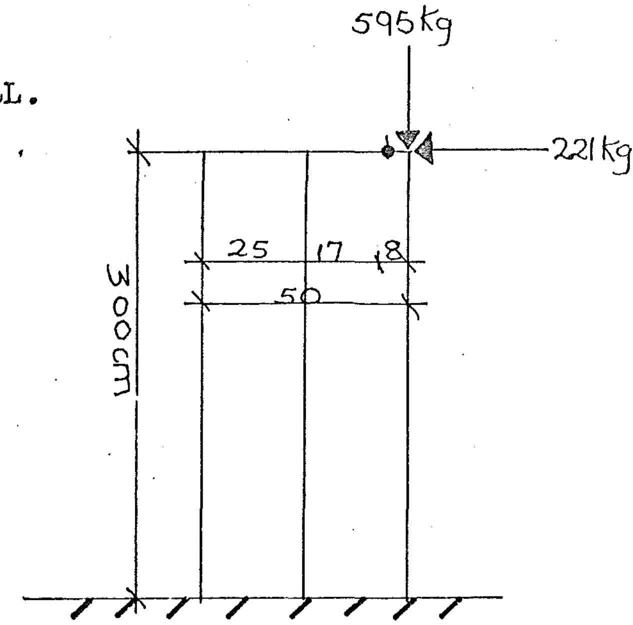


FIRST VAULT.


15cm
7
8
165 cm
159 cm
142 cm
112 cm
66 cm
15cm
30 cm
30cm
30cm
30 cm
30cm
8
7

FIRST VAULT.

CHECK OF STRESSES ON THE SUPPORTING WALL.



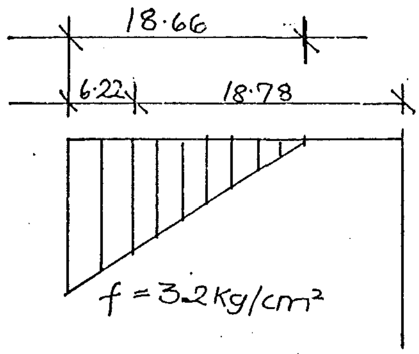
$$\text{Weight of wall} = 3 \times 0.5 \times 1 \times 1 \times 1.6 = 2.4t$$

$$N = 2.4 + 0.595 = 3t$$

$$M = 0.221 \times 3 - 0.595 \times 0.17 = 0.663 - 0.1 = 0.563\,m.t.$$

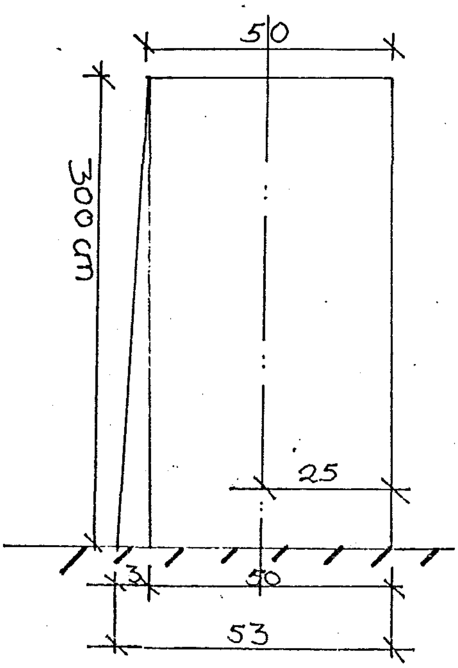
$$\frac{M}{N} = \frac{0.563}{3} = 0.188 = 18.8\,cm$$

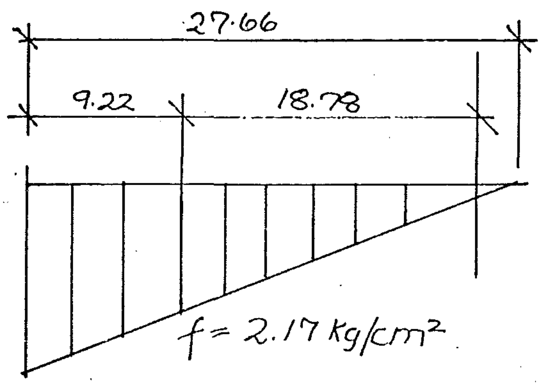
$$f = \frac{2N}{3cb} = \frac{2 \times 3000}{18.66 \times 100} = 3.2\ kg/cm^2$$



N.B. : For a sloping wall of 3cm at base

$$f = \frac{2N}{3cb} = \frac{2 \times 3000}{27.66 \times 100} = 2.17\ kg/cm^2$$





SECOND VAULT.

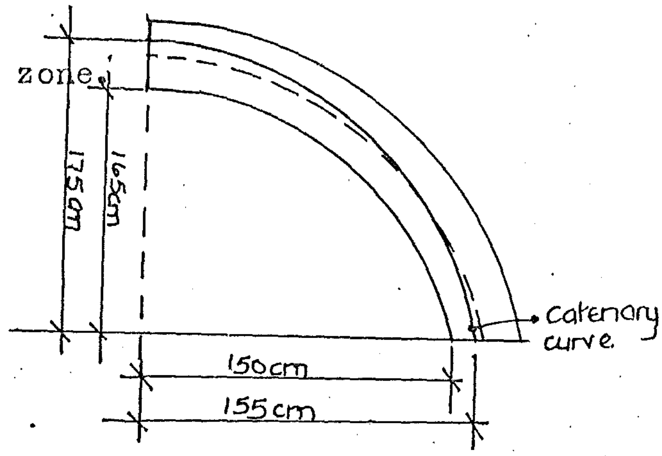
Line of pressure in the middle 3rd zone.

Solving equation :

$Y = C \cosh \frac{X}{C}$ by trial

$Y_o = 175 + C$

$X_o = 155$

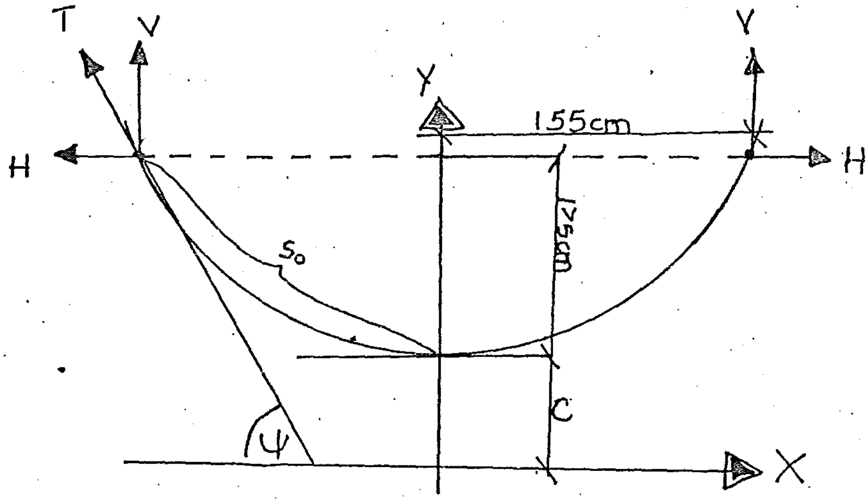


$\therefore C = 88 \text{cms}$

$\therefore Y_o = 263 \text{cms}$

$S_o = \sqrt{Y_o^2 - C^2}$

$S_o = 248 \text{ cm}$



$\tan \psi_o = \frac{S}{C} = \frac{2.48}{0.88}$

$= 2.82$

$T_o = W Y_o = 240 \times 263$

$= \underline{630 \text{ Kg/m}'}$

$H_o = W.C. = 240 \times 0.88$

$= \underline{211 \text{ Kg/m}'}$

$V_o = W.S_o = 240 \times 2.48$

$= \underline{595 \text{ Kg/m}'}$

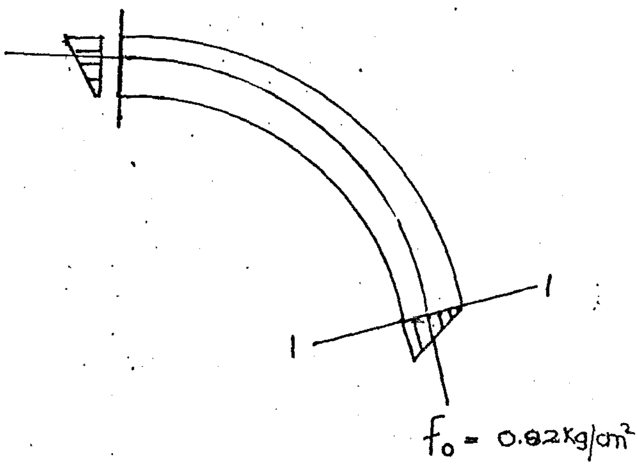
CHECK OF STRESSES IN THE VAULT.

$\frac{f_o}{2} . t.b = T$

$f_o = \frac{2T}{t.b.}$

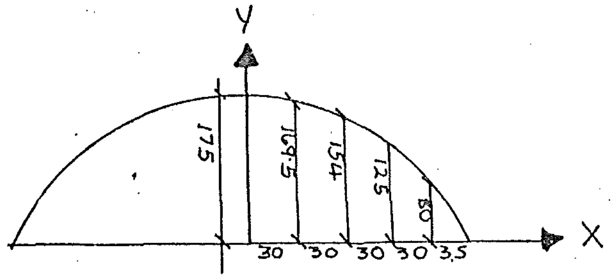
$f_o = \frac{2 \times 630}{100 \times 15}$

$\underline{f_o = 0.82 \text{ kg/cm}^2}$

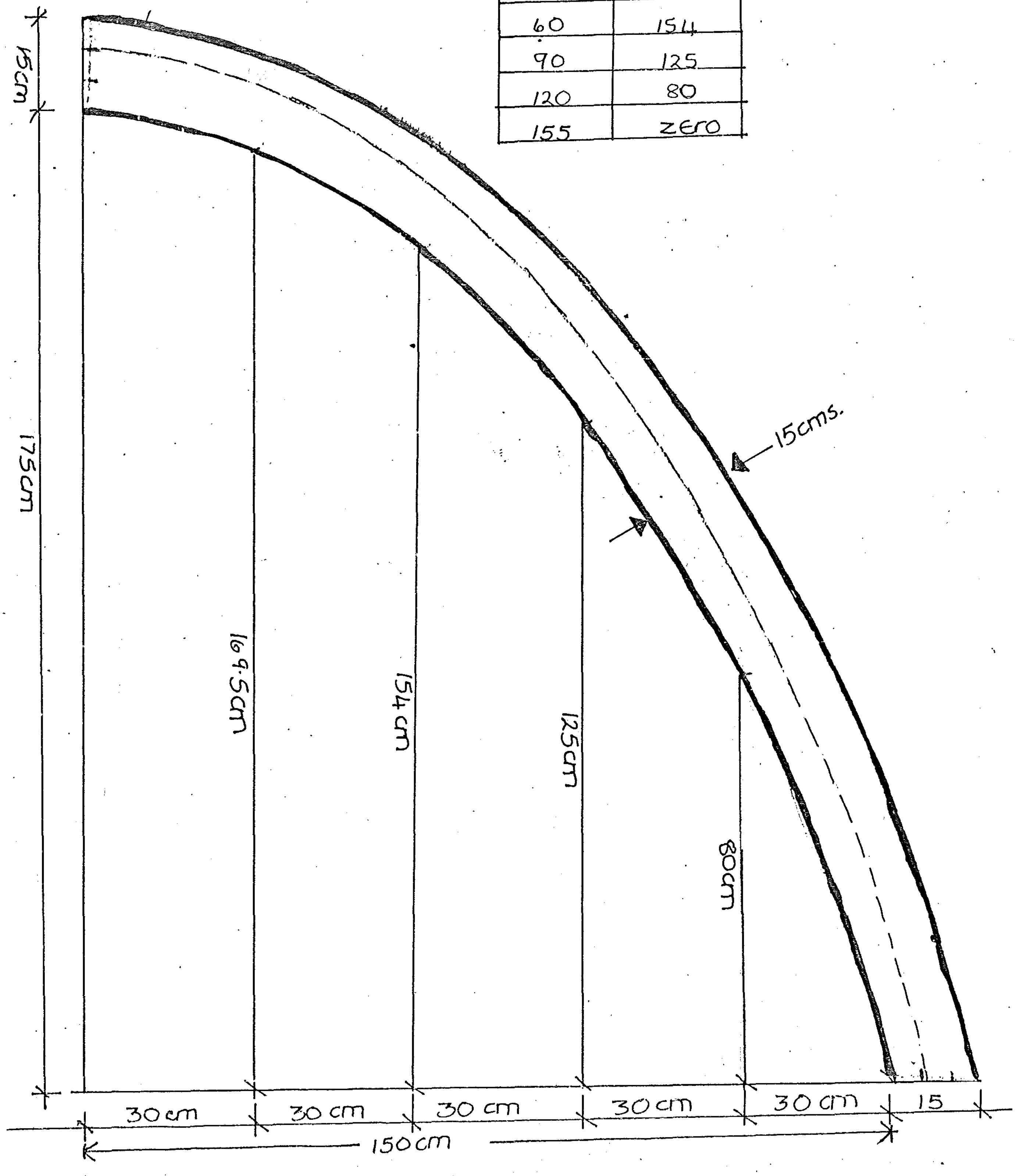


SECOND VAULT

Ordinats of the line of pressure;



X	Y
zero	175
30	169.5
60	154
90	125
120	80
155	zero



DOMES.

METHOD OF CONSTRUCTION.

The domes are constructed without the aid of any shuttering as in fig.1. It is built in ring courses,each course being completed befoe the next course is started.The job should be carried out in at least three stages,to give the mortar time to dry,since the lower part of the dome will carry some tensile ring stresses after the dome is completed.fig.2.

RECOMMENDATIONS.

1.To compensate the weakness of the tensile strength of the dome,it is recommended to construct the dome from a stronger and longer type of brick,with its long side in the circumpherential direction.fig.3.

2.It is better to use the Byzantium type of dome,since its diaphragm rise = $\frac{a}{2}$ =0.72a,which is greater than the previous 0.62a needed to get in the compression zone of N_ϕ.But less of dome is in compression.
$\theta = 45°$ under U.D.L. horizontal load.

N.B.During the stages of construction of the spherical dome,the stresses are safer since $\sum W$ during construction is less than $\sum W$ after completion at the same sec.

Ref.Theory of Plates and Shells. Stephen Timoshenko and S.Woinowsky-Krieger.

DOMES.

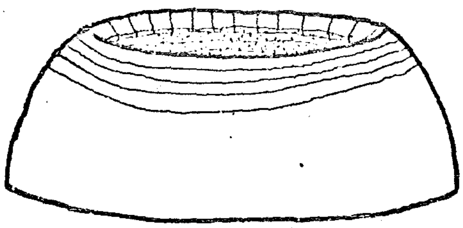


fig.1

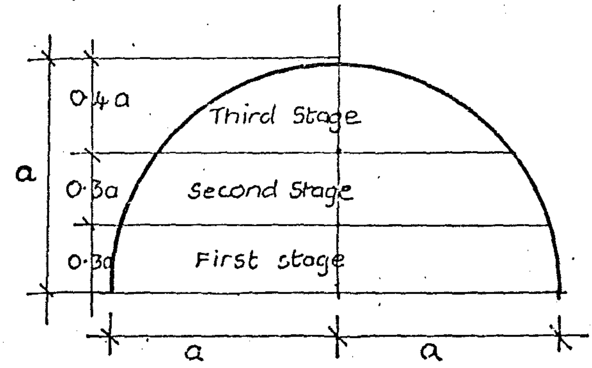
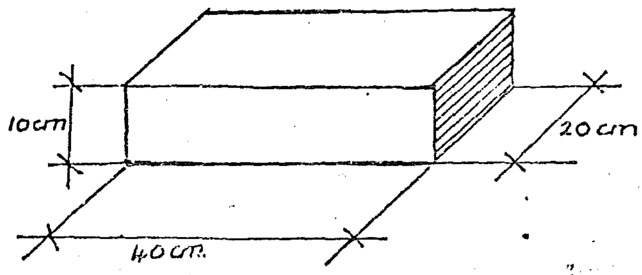
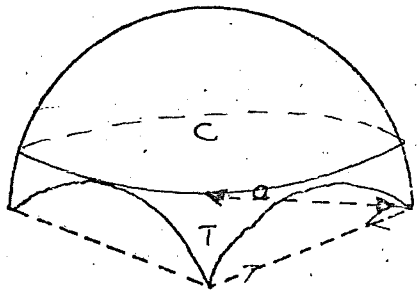


fig.2

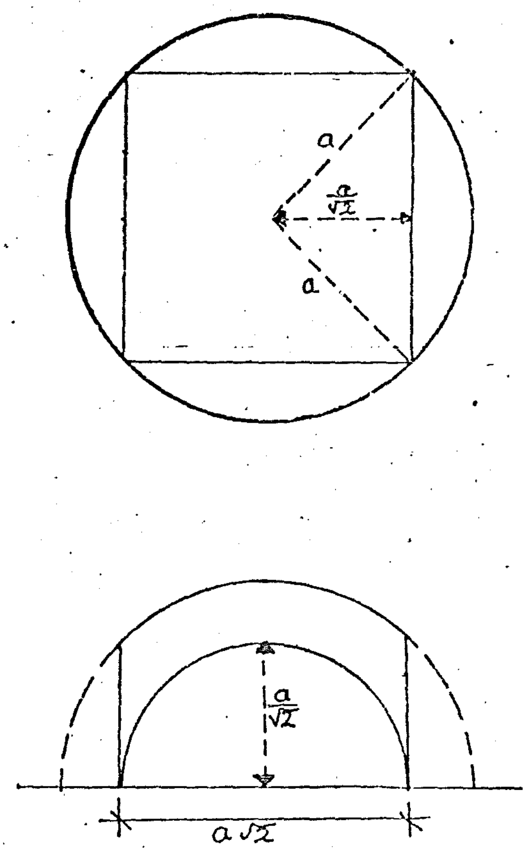


recommended brick

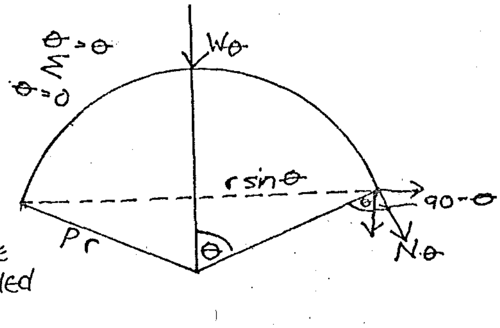
fig.3.



Byzantine Dome



SPHERICAL DOME.



Vertically

$$\Sigma W_\theta + 2\pi[r.\sin\theta].N_\theta \sin\theta = 0$$

$$\therefore N_\theta = \frac{-W_\theta}{2\pi r.\sin^2\theta}$$

$$N_\theta = \frac{W}{\pi D \sin^2\theta}$$

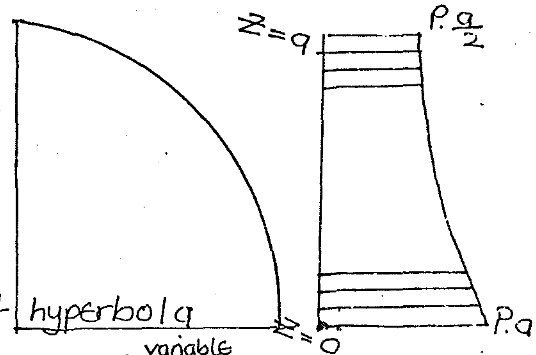
from vertical res. at horizontal latitude where angle subtended at centre is θ

Horizontally

$$N\phi = \left[P_r \frac{D}{2} - N_\theta\right]$$

$$P_r = P\cos\theta \quad \& \quad P_\theta = P\sin\theta$$

where P is the own weight/unit area of the surface.
N_θ & N_ϕ are membraine forces/unit length.



$$N_\theta = \frac{-P.a}{1+\cos\theta}$$

$$N\phi = \left[P_r.a + \frac{P.a}{1+\cos\theta}\right]$$

$$N\phi = \left[-P\cos\theta.a + \frac{P.a}{1+\cos\theta}\right]$$

Meridian $\quad N_\theta = \dfrac{-P.a}{1+z/a} = \dfrac{-P.a^2}{a+z}$

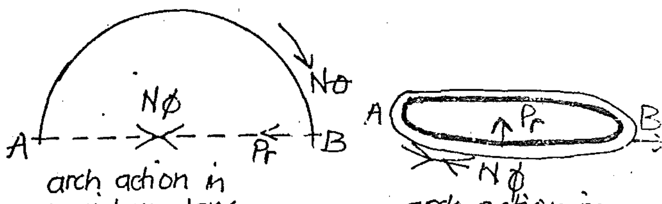
Eqn. of hyperbola

$\cos\theta = \frac{z}{a}$ ← variable, ↖ constant

N_θ diagram

Hoop $\quad N\phi = \left(-P.z + \dfrac{P.a^2}{a+z}\right)$

$$N\phi = P.\frac{a^2 - a.z - z^2}{a+z} > 0$$



1. arch action in meridian plane
2. arch action in hoop plane

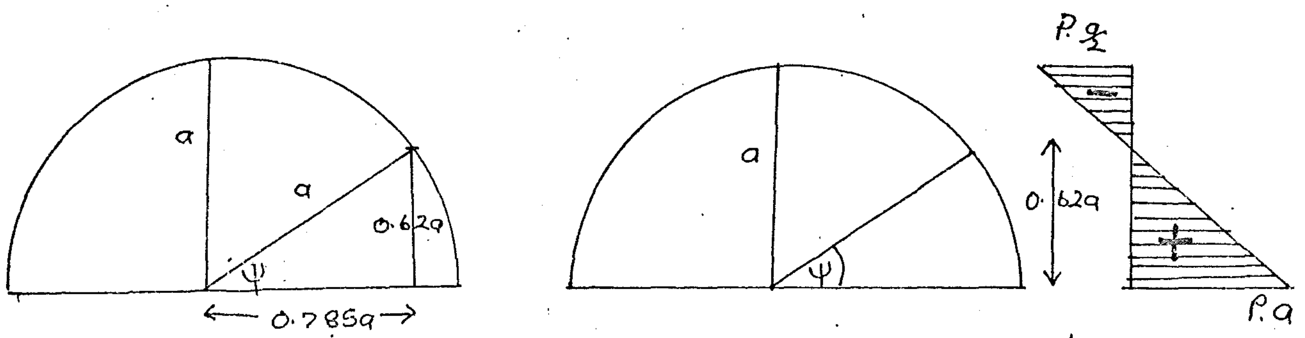
$\therefore N\phi$ is made up of components from $N\phi$ and P_r

$N\phi$ = zero at

$$a^2 - a.z - z^2 = \text{zero}$$

$$a = 1.62z$$

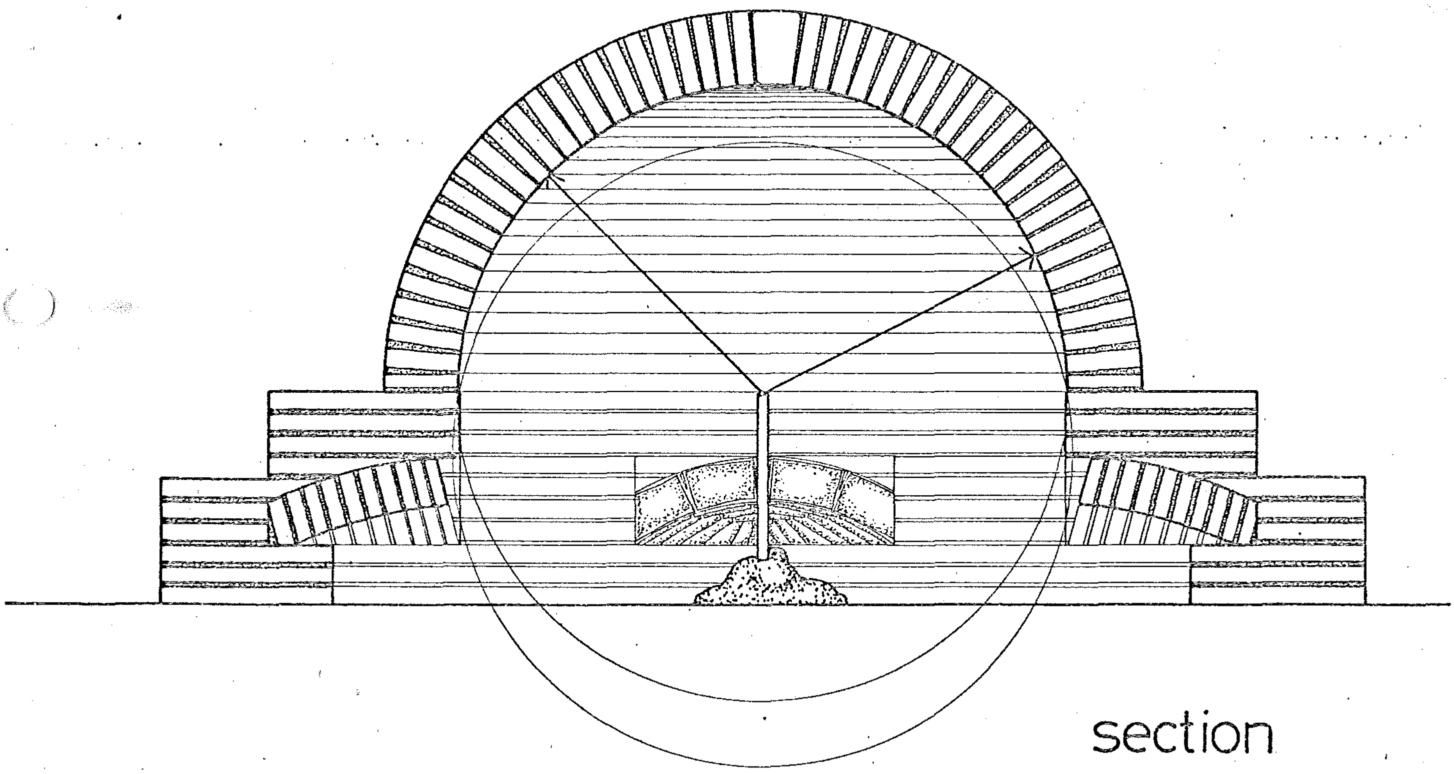
$$\therefore z/a = 0.62$$



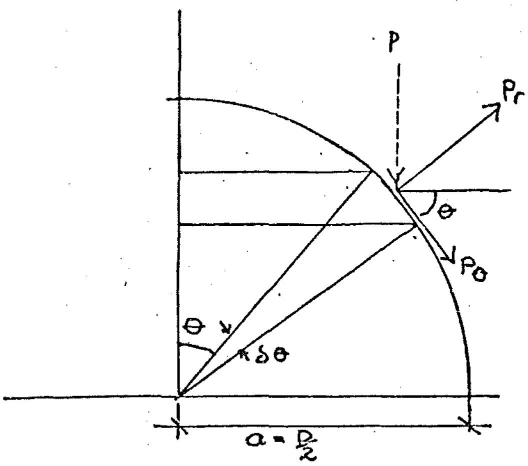
$N\phi$ diagram

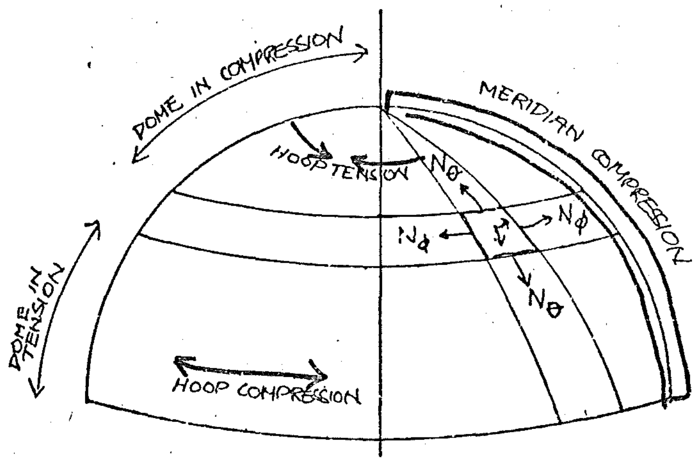
<u>MUD BRICK CONSTRUCTION: SASSANIDE DOME CONSTRUCTION METHOD</u>

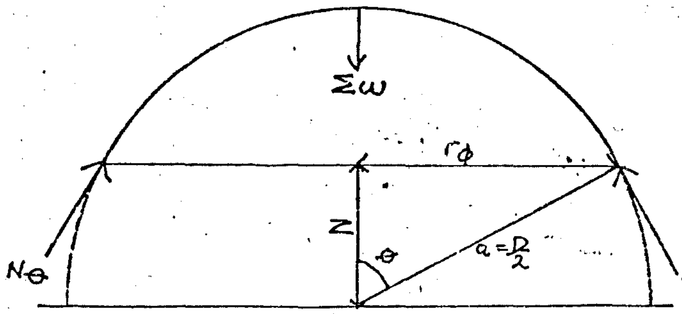
Part of the training programme at Gourna, before starting on the construction of the house, was the erection of a small, 2 metre square, mud-brick Sassanide dome resting on a low mud-brick wall which formed the square support.

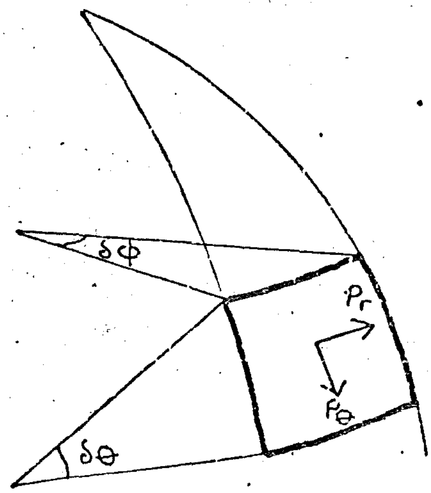


section


P
Pr
θ
Pθ
θ
δθ
a = D/2


DOME IN COMPRESSION
MERIDIAN COMPRESSION
HOOP TENSION
Nθ
Nφ
Nφ
Nθ
DOME IN TENSION
HOOP COMPRESSION


Σω
rφ
Z
θ
a = D/2
Nθ
Nθ


δφ
Pr
Pθ
δθ