BTC UGANDA

Kasese District Local Government

Stone arch bridges

A strong & cost effective technology for rural roads

A practical manual for Local Governments

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Foreword

This manual was developed based on the experience of the Belgian Technical Cooperation (BTC) supported **Kasese District Poverty Reduction Programme** (KDPRP) in Western Uganda, during the period 2009-2013. The programme piloted stone arch culverts and bridges in rural areas, where low labour costs and high cost of industrial building materials favour this technology. The construction of stone arch bridges in Uganda, Tanzania & Rwanda has demonstrated its overall feasibility in East Africa.

How to use this manual

The purpose of this manual is to provide supervisors of stone arch bridge works with an easy step by step guide. The stepwise approach ensures adherence to quality requirements and construction methodology The main target audience of this manual is the road works supervisors and engineers employed by District Local Governments in East Africa. However, the manual remains relevant in the context of many other developing countries.

Acknowledgements

Many people and institutions contributed to this manual: the KDPRP steering committee, Local Authorities at District and Sub County levels, the District Executive Committee and the Chief Administrative Officer, William Kanyesigye. Special thanks goes to Paul Dequeker, Belgian architect, for having shared his broad experience in Congo with us. The manual was written by Eng. Sophie Grigoletto and Steven Hollevoet. The draft was reviewed by the Kasese District Works department, Alphonse Katswamba , Dave Renno, Ruediger Behrens (GIZ) and Neil Noble of Practical Action. Neil also produced some of the technical drawings.
Jonas Geeroms edited some diagrams.
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3. Chapter Three: Construction of stone arch bridges

3.1 Principle: wedging - only compression forces

A simple beam will bend as a reaction to a load. This change in the beam's shape causes the bottom of the beam to become stretched in tension, the top of the beam to be squashed in compression. These opposite forces in the beam can cause the beam to tear apart with relatively small forces when materials with low tensile strength are used, such as stones or plain concrete. The arch form is one of the earliest and historically ingenious solutions of dealing with tensile stresses.

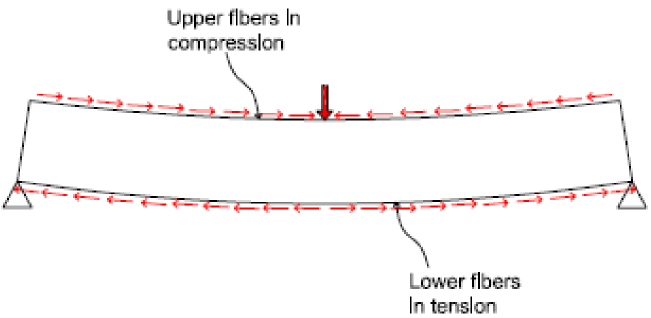

Fig. 20: beam bending under a load.

The semicircular arch developed by the Romans was a great technological achievement in bridge design. The strength of the arch bridge comes from its shape. The shape of the arch is designed so that, when loaded, every component is in compression, and ideally there is almost no part of the structure in tension. Instead of pushing straight down, its semicircular structure carries the load outward along the curve through its entire form and diverts weight onto its two abutments. The supports at each end of the bridge directly take on pressure. These abutments and well compacted backfilling prevent the arch from bending outwards when heavy loads press down on it. As a result, the arch is always under compression, maintaining its shape and stability.

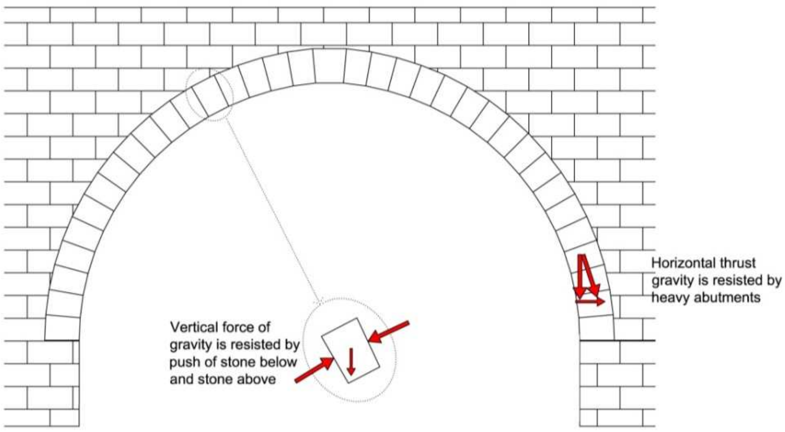

Fig. 21: Forces in an arch bridge.

An arch can carry a greater load than a horizontal beam of the same size and material, because downward pressure forces the stones together instead of trying to force them apart. All the compressive forces hold it together in a state of equilibrium. By using the arch configuration, significant spans can be achieved. However, an arch pushes outward at the base, and this needs to be restrained with heavy abutments and well compacted backfilling. Masonry arch bridges need backfilling material above the arch in order to increase the dead-weight on the bridge and prevent tensile stresses from occurring in the arch ring as loads move across the bridge. Loaded bridges with plenty of backfilling are the strongest.

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3.2 Steps of construction process

3.2.1 Site selection

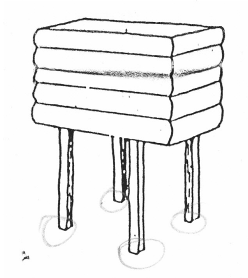
It is recommended that the existing bridge site is thoroughly examined. Traditional pole bridges are often located at the narrowest river crossings which are not necessarily the best construction sites for permanent bridges. The following factors are taken into consideration for the site selection:

The bearing capacity of the subsoil.

Sites with rock layers provide important advantages, as the cost for the foundation will decrease considerably and future erosion damage will be prevented. It is usually more cost effective to move an earth road rather than building a bridge on an existing site that has no firm sub soil or that is prone to erosion. Sandy and clay soils and sites with springs, muddy ground and swampy terrain should be avoided as they will require improved reinforced or sometimes even piled foundations.

Small trial pits are dug to assess the bearing capacity of the sub soil. The bearing capacity varies in function of the moisture level and soil type. Laboratory test to establish the shear strength and consolidation of the soil are recommended. Alternatively, in the absence of such services, the chair test can be used. This method consists of adding cement bags on a stool (with a known surface area of its legs) till the legs enter the soil by 2-3 cm. The test is done in a trial pit at foundation level. The bearing capacity of the soil in kg/ cm^2 is then calculated by:

$$\frac{0.33 * \text{number bags} * 50\text{Kg}}{\text{Cross-section legs in } cm^2}$$



0.33 is the safety factor 3. The conversion rate from kg/ cm^2 to kN/m^2 is about 9.8.

Minimum required bearing capacity of sub soil as function of the bridge span & traffic load – values at foundation level				
Span bridge	traffic load 40 tons		traffic load 20 tons	
L(m)	in kN/m^2	In kg/cm^2	in kN/m^2	In kg/cm^2
1	132	1.35	77	0.79
2	113	1.15	72	0.73
3	108	1.1	74	0.75
4	109	1.11	80	0.81
5	113	1.16	88	0.9
6	121	1.23	98	1
7	129	1.32	109	1.11
8	139	1.42	121	1.23
9	150	1.53	133	1.36
10	161	1.64	146	1.49
11	173	1.77	159	1.62
12	185	1.89	172	1.75
13	198	2.02	186	1.89
14	211	2.15	200	2.03
15	224	2.29	213	2.17
16	238	2.42	227	2.32
17	246	2.5	236	2.41
18	265	2.7	256	2.6
19	279	2.85	270	2.75
20	293	2.99	284	2.9

Source: Cornet 2013

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Bearing capacity of some soil types in Kasese District

Soil type	depth	av. allowable bearing capacity kN/m^2	area
clayey sands	2.5	210	Nkoko / Karusandara
clayey & silty gravels	3.0	340	
clayey gravels	3.0	110	Kyempara / Isango
clayey sands	4.0	155	
poorly graded gravel & silty gravel	2.5	635	Kyabayenze/ Karambi
silty sands	3.0	740	
inorganic silt	3.5	770	
silty sands	2.0	735	Katumba / Bugoye
silty sands	3.0	>1000	
clayey sand and clays	3.5	400	Kanyamunyu / Kitholhu
silty gravels	2.0	450	Kaghema / Kyarumba
silty gravels	2.5	695	
silty gravels	3.0	845	
silty gravels	4.0	730	
clayey sands and poorly graded sands	3.0	730	Kabuiri / Maliba
clay	3.5	695	
poorly graded sands	4.0	755	

Source: MBW 2012 – safety factor 3 applied.

Flood prevention

It is advisable to construct a bridge on a slight sloping terrain in the landscape rather than on the edge of the valley where water accumulates and risk of floods and meandering is higher. High river banks reduce the risks of flood levels exceeding the bridge and of the by-passing the structure by the river.

Avoid river bends

The crossing must ideally be located where the river is straight, stable, and not meandering. This will reduce the maintenance costs considerably. In a curve, the river will cause heavy scouring or will break through its banks and by-pass the bridge.

Road approaches

For low rural traffic densities, the best position of the bridge vis-à-vis the river (i.e. square on the river axis) is more important than the alignment with the existing road approaches. The site for the bridge is selected in such way that no large quantities of backfilling are required for raising the level of the road. Backfilling of road approaches can be very costly as it often requires heavy machinery.

High river banks

For arch bridges where tilting force of the soil mass has no effect on the stability of the structure, high river banks usually offer important advantages:

- The roman arch type can be adopted which is a stronger design than the segmental one.
- Larger bridges can be constructed to absorb the full discharge of even the largest floods.
- Less material is required for backfilling and the construction of road approaches.
- With high river banks, the probability of a meandering river or bursting banks is lower.
- Usually easier traffic access, as the approaches will not be on a steep slope.

High river banks are sometimes an indicator for increased erosion risk and adequate mitigation measures should then be put in place (see 3.2.9).

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3.2.2. Site preparation

For large bridges, the community will need time to deliver the materials before the actual construction starts. It is good practice to peg out already the actual site of the bridge. In addition, the technician should peg out the locations where sand and stones should be delivered by the village. The site plan is discussed with the village so that building materials are dumped in a systematic way without hindering access to the site and optimising transport cost during construction.

Construction is best done during the dry season. Transport of building materials is then easier and costs for river diversion, digging the foundation pith of sufficient depth and flood prevention can be minimised. Village labour is also more available during the dry months. It is good to avoid construction during the rainy season; as flood risks are hard to control.

Site preparation starts with site clearing (stripping topsoil, slashing the vegetation, cutting down trees and removing the roots). Clearing vegetation is a basic task performed by the community.
On the river banks, heavy bush clearing and the unnecessary cutting down of trees should be avoided as they will help to prevent erosion in the future. Existing grass tufts should not be destroyed. They will be planted on the steeps riverbanks to stabilize the soil after construction.

If possible, the existing local bridge is left intact to facilitate the movement of building materials. Alternatively, a temporary bridge might need to be constructed where the traffic cannot be interrupted. It can be made with logs placed across the river.

If necessary, the river will be diverted with coffer dams, notably to allow for foundations of sufficient depth and provide for stone pitching of the river bed where required to prevent scouring. Coffer dams are usually erected to prevent the flooding of the excavation pits. Coffer dams will be made of bags filled with soil and stones. In function of its height, the bottom of the coffer dam will be 2-3 bags wide to improve stability. In case of flood risk of large rivers, the bags will be supported by spiked poles and heaped stones walls or temporally placed gabions. The size of the diversion canal is a function of the river flow. The verge of the canal is dug at 60% degrees to avoid the collapse of the walls. Excavated soil is "stored" properly to facilitate the filling of the diversion after construction. If possible, the dam is made at sufficient distance from the construction site to prevent flooding. River diversions are best avoided during the rainy season as the floods can make deep gullies causing the stream to by-pass the bridge altogether. To prevent scouring of the diversion canal during floods, gabions can put across the canal bed to obtain a stepwise discharge. Alternatively, galvanised culverts are temporary used to avoid erosion.

3.2.3. Setting out and excavation

Once the location of the bridge has been determined, the river banks and the foundation trenches are excavated. During excavation, it is important to ensure that any water which may enter the trench can run off or should be pumped out. After digging, the bottom of the pit shall be compacted with a heavy steel compactor or a jumping compactor. The excavation pit will provide for an allowance of about 1 metre each side to enable the access of the craftsmen. In most cases, a water pump is required to remove the excess water and reach the required foundation depth.

To avoid the river banks collapsing, the slope of the excavation should be at least 60 degrees. For unstable soils, the excavation should be done in steps or the walls should be temporally shored by timbering and struts.

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For larger rivers that cannot be diverted, the excavation is usually done in 2 phases. Only one bank of the river is shut off with a coffer dam to reduce the water level and allow for excavation. Then the foundation and abutment at that bank are built. The coffer dam is then moved to the opposite river side and the process repeated. Shutting off both river banks at the same time drastically increases the risk for flooding of the excavation pit and foundations and should be avoided unless construction is done in the middle of the dry season.

The bridge foundations must be carefully set out. Measurements are made and checked with two measuring tapes and a calculator (*see figure 22*). Based on the Pythagoras' theorem (squared hypotenuse equals the sum of the squared length and squared width), the diagonal can be calculated and square angle obtained. To make sure that a corner is a right angle, the 3-4-5 method can also be used, but it is a bit more time consuming. Pegs are put in the ground and string or cord is tied to them, to show the mason the width of the foundations. These marks must be durable, so that they remain accurate for a long period of time and are not destroyed by rain or workers activities.

A straight trench is dug out between the lines. Before digging, it is necessary to check the orientation of the lines, the dimensions and the right-angles using a measuring tape and a square.

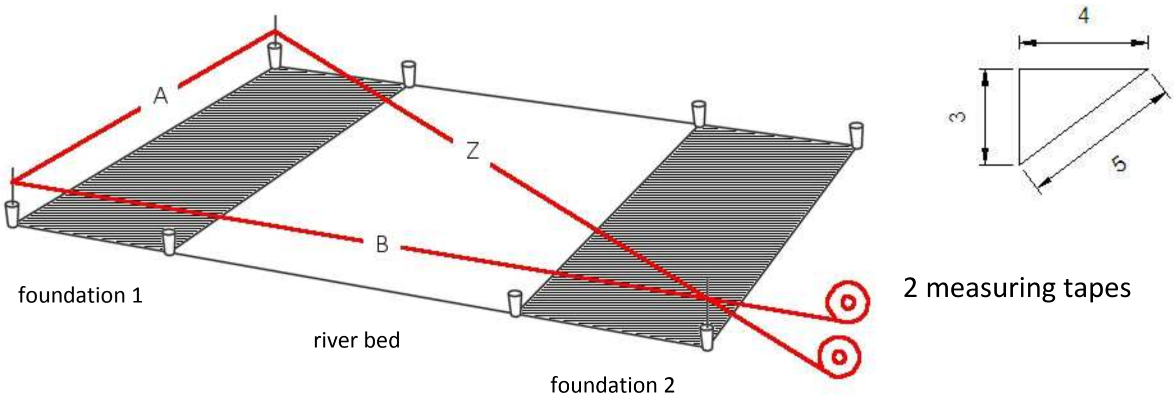

Fig. 22: Setting out the foundations with 2 measuring tapes speeds up the work. The measuring tapes will help to get the right angle based on the Pythagorean Theorem. $Z^2=A^2+B^2$. In a triangle of 90 degrees: the square of the hypotenuse is equal to the sum of the squares of the other two sides. Alternatively, use the 3-4-5 method which is more labour intensive: $5^2 = 3^2+4^2$.

Excavation, loading and hauling tasks can be performed by the community, using shovels, pick axes and wheelbarrows. The workers are instructed not to dump the excavated soil in the river. Excavated materials will be kept near the construction site so as to be re-used later for backfilling, although more material will usually be needed. The excavated soil should be dumped where the road approach. To prevent collapse of the construction pit, excavated soil is dumped at least 6 metres from the trenches so that no extra weight is added to the earth wall.

3.2.3. Foundations and abutments

The lifespan of a bridge depends essentially on the strength of its foundations. The strongest bridge will have a short lifespan if its foundations are eroded by the river. Masonry work for foundations will be carried out with particular care and under strict supervision. The substandard work of many local masons (low dosage cement in mortar mix, no use of batch box, excessive water amount in mix, poor bonding of stones, air gaps, no stone washing...) should not be tolerated. The technical

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specifications and quality will be strictly enforced, as the structural strength of the bridge depends on it. Masons not able to adhere to higher quality requirements should be replaced immediately.

With stable sub soils, foundations are made of stone masonry. Their height should be determined on site once firm subsoil is reached. The design tables *(figures 15 & 16)* give only minimum depths. Apart from sites with solid rock beds, the foundation depth will exceed the depth of the river bed. On sites with poor bearing capacity (permanent waterlogged places, sites with high content of clay and sand), a reinforced foundation slab or footing will be necessary. On muddy and unstable sites, different techniques exist of constructing piles of mass concrete. One of them is the use of well foundations: a well is built with bricks. A base ring made of reinforced concrete and is bevelled to facilitate the penetration of the cylinder into the ground. Another solution is the construction of concrete rings. They are dug into the ground until a firm sub soil layer is encountered. The rings are then filled with mass concrete as foundation pillars. Reinforced concrete boxes can also be constructed upstream on the riverbanks, and moved by floating. However, this requires specialised skills beyond the scope of this manual.

Fig. 23 a: The quality of stone masonry is essential. A good bond of stones and tight gap filling will provide for a strong abutment. In addition, at the river corners dents are left for a good link with the wing-walls.
Fig. 23 b: Extremely poor masonry works – no bond at all, plenty of gaps between the stones, no embedding of stones with mortar. Sections like those need to be demolished immediately and the mason replaced.

Stones for the foundations and the abutments are placed in a horizontal position *(see fig. 8, fig. 23 a, fig. 24)*, laid down on the largest side of the stones enabling a good bond. The selection of the well shaped stones is important in order to minimize the quantity of mortar and improve the strength of the bridge. Stones are wedged against each other to reduce the number and size of holes to be filled in with mortar.

The foundation and abutments require large stones – ideally rectangular shaped. Masons will work with “stone spotters”. From the stone piles, these casual labourers specialise in identifying the stones of the right shape and size that fit in the existing masonry gap. The stones are washed with a hard brush and wedged against each other to reduce the number of holes to be filled in with mortar. Gaps between the stones need to be filled with crushed stones and mortar. Mortar is laid where necessary, rather than just poured over the stones. All stones should be well embedded in mortar. The practice of local masons to allow some dry touching of stones should not be tolerated.

As the foundation and sections of the abutment are permanently exposed to damp conditions, a mortar mix of 1:3 is a must. For the sections of the foundation under the water table, a 1:2 mix is required. Poor quality sand will require a higher cement dosage. Untrained craftsmen will usually

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put too much water in the mortar to enhance workability. However, wet mortar mixes will lead to poor strength. The maximum amount of water is 20 litres per 50 kg cement bag.

Fig. 24: Different positioning of stones in the structure

3.2.4. Formwork

For building an arch, a semi-circular formwork of the same shape as its interior curve (intrados) is required to support both spans until they lock together at the top *(see fig. 8, fig. 24 and fig. 25*). The frame, called centring, is removed after the stones are in position. The formwork is usually made of wood; but soil on a wooden platform is also possible. The wooden formwork is used with wedges so that it can be easily removed once the arch is complete. The formwork resembles the trusses of a roof, only that its top shape is circular and that usually it is made of 2 parts.

The wooden formwork is made up of 2 individual trusses *(see fig. 25.b)* that are linked in the middle. The trusses are usually made of 2*4" timber (50*100 mm). For longer spans 2*6" (50*150 mm) will be required. The trusses are supported by transverse struts and poles. For the average bridge width of 3.6 metres, 5 "double" trusses are required. The trusses are covered by 1*3 timber purlins. The purlins are jointed tightly without gaps to avoid mortar being wasted.

Fig. 25: Each truss of the form work consists of 2 pre-fabricated quarter circles that are assembled at site.

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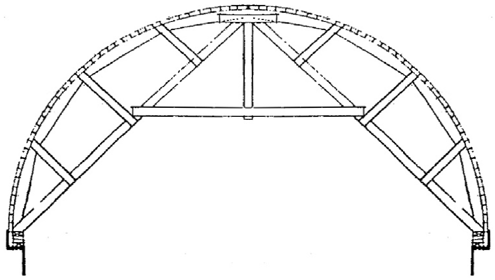

Fig.26: The wooden formwork is made up of 2 individual trusses that are then connected in the middle with a tie-beam. The floorboards are placed directly on the trusses. Each wooden structure rests on 2 wedges easing the removal of the formwork.

Fig 26 a: formwork for a roman arch.

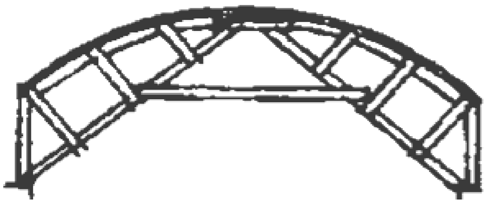

Fig 26 b: formwork for a segmental arch for large spans.

Fig. 27: The correct curve of the truss in a function of the span and the type of arch is important. Many carpenters struggle with the principle and the process will need technical guidance. A: correct shaped formwork. B: wrong formwork consisting of a set of straight lines. This latter formwork had to be demolished.

Fig. 28: Once the first mould is constructed, the others are easily copied and shaped with a machete.

Fig 29: five trusses are required for a standard width of 3.6 m. The trusses are supported by struts.

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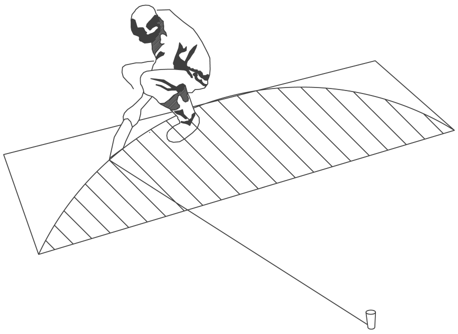
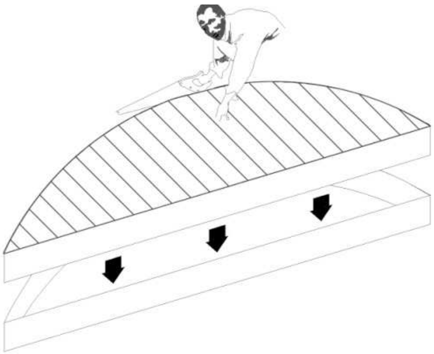
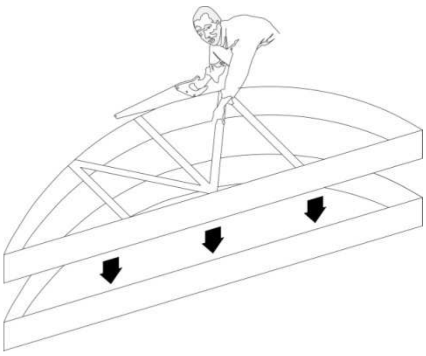
Fig. 30: Steps of assembling the formwork



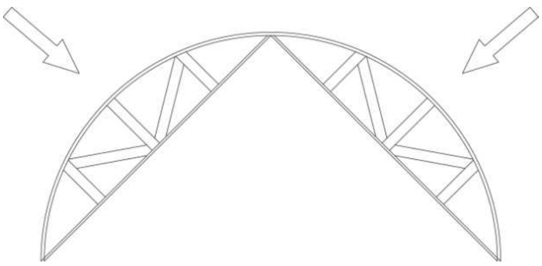
1. With help of rope and pencil, ¼ of a circle curve is drawn on newspaper sheets that were pasted together. The paper mould is then cut out and will be used for the first wooden mould. The radius for the curve can be found in the design tables – figures 14-15. The rope will have the length of 2R of the design tables. For larger spans, the formwork will consist of 2 moulds.



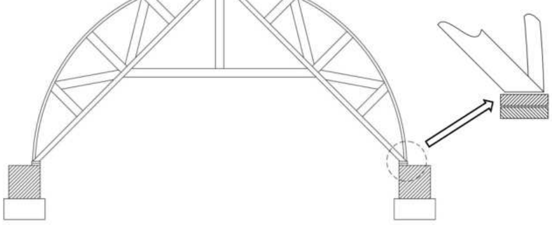
2. The timber frame is constructed by putting the timber struts along the paper mould. The curved shape can be obtained with a saw or by hand with a machete/ chisel. It is critical that the shape of the arch mould is a curve and not a set of straight lines at different angles. Untrained carpenters will initially construct the latter which should be immediately corrected.



3. Once the first mould is obtained, the others are simply copied by drawing the original shape on the consecutive trusses.



4. On site, the quarter trusses are assembled into a half circle by struts. This formwork is levelled and supported by poles. Purlins are nailed on the trusses to finish the formwork.



5. It is important that the trusses rest on 2-3 wedges. Without the wedges, it will be impossible to remove the formwork without damaging the timber once the stone arch is constructed.

The drawings were produced by Neil Noble - Practical Action/ UK

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Fig 31.: Left: If there is a risk of heavy flooding, additional anchoring of the scaffold is required. Timber poles (A) stretching across from one abutment to the other will hold the scaffold together. They are the basis for additional poles which are nailed parallel with the abutments in the river bed. A large opening (B) should be left in the middle where the debris can pass. Right: The poles of the formwork in the middle caught the debris of the first seasonal floods. The water flow was blocked leading to serious damage and the river by-passing the structure.


Fig 32: This formwork was constructed on site during the dry season. The span of the bridge was 50 metres and consisted of 5 arches. A rope was used to get the curved shape. The pictures are a courtesy of Rashid Mtamila/Tz.

Formwork for culverts


Fig. 33: The moulds for culverts are standard (here 80 cm diameter and 2 metres long). They can be re-used many times. The culvert size can be adjusted in function of the site conditions (banks, water flow) by increasing the abutment height or having multiple structures.

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The formwork can be removed immediately after closing the arch – there is no need to wait for the curing of the mortar. The scaffold can therefore be reused straightaway for culverts or multiple arches. It makes sense to construct a precise and robust formwork so it can be re-used. The district works office can store the trusses and culvert moulds so that they are available for future use. Painting the timber with used engine oil will increase the life span.

Alternative types of formwork

Where carpentry skills are not sufficient to build trusses, a full panel system can be used, but it consumes more timber (*see fig 34).* Building up bricks or blocks with dry joints and shaping the curve with a layer of mortar is a very economical way of making a formwork. When timber is too expensive, a further alternative is to use the "lost soil method". The abutments are first built up and a platform is built between them. Then the inside of the culvert is filled with earth shaped on top to the correct profile for the underside of the arch (intrados). The earth provides temporary support for the arch stones during construction and is removed later (*see fig 35)*.

Fig 34 a full panel form work is easier to construct but more expensive and less strong. To reduce construction costs, the formwork was removed to build the 3 arches consecutively.

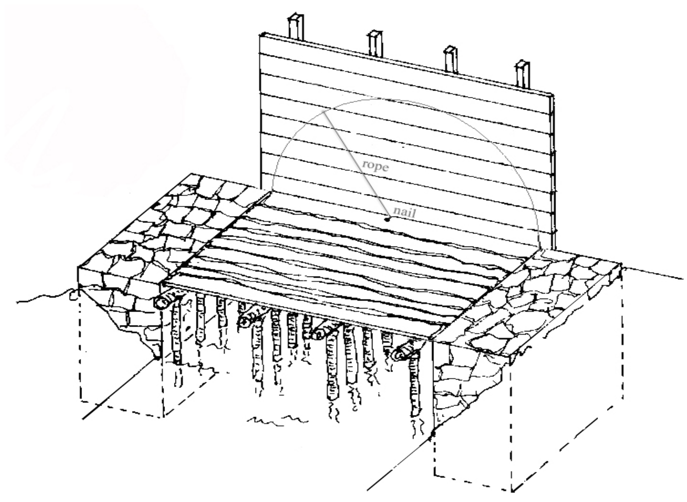

Fig. 35: Making of formwork with the "lost earth method": A platform is built between the abutments. Wooden panels at both sides cut along the intern curve of the arch, drawn thanks to a rope fixed to a nail in the circle centre. The inside of the culvert is then filled with earth contained by two wooden panels, and shaped on top to the correct profile.

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3.2.5. Arch – the wedging principle.

The arch shape is made from a series of wedge-shaped stones carefully chosen to fit together. These stones are set side by side on the formwork, and gradually take the curve of the arch from the outermost horizontal springs, the two points where the arch rests on its supports, up to the central and vertical 'keystone'. Stones of the arch are placed in a radial position. Stones should act like a wedge: the small end should be on the inner radius of the arch and the larger end at the outer. Once the stones are in position, it is recommended to tap with a hammer so that they slide tightly into place and mortar is better spread in the gaps between the stones.

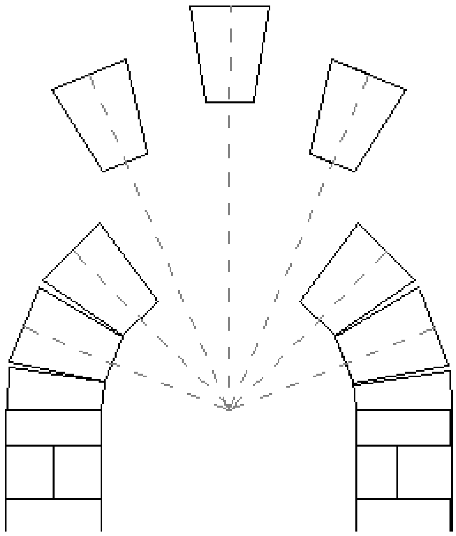

Fig 36: Stones of the arches are placed along the radius of the arch, the small base down and the larger base up, while stones of the abutments are set in a horizontal position, put down on the largest side of the stones.

It is usually not necessary to chisel the stones, but the selection of well shaped stones is crucial. They should be flat and long especially in the upper section of the arch. More details about the required quality of the stones are given in section 3.3.

Fig. 37: Correct position of the stones along the radius of the arch.
Stones of the arch are placed in a radial position, squared to the scaffold.
A mason square indicates the correct position of each stone, provided the formwork is even.
For culverts, a rope fixed in the centre of the circle can be used to show the right direction.

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During the closure of the arch at the top, it is essential that:

- The best shaped stones (long & flat) are preserved for closing the arch *(see fig 44)*. They should not be used in early construction stages, as they are essential later.
- Stones are laid along the radius of the circle. Building squares help to get the right position.
- The stones are tightly wedged-in with a hammer and all gaps are filled with mortar *(see fig 38)*.
- The minimum key stone dimensions (*see tables 15 & 16*) must be respected.

Fig 38: Left: Building squares show the right position of the stones during each phase of the arch construction. Right: It is of utmost importance to fill all gaps between the stones. Small stones will be added to the mortar to reduce cement costs and increase strength.

Fig 39. The quality of the craftsmanship is of extreme importance for the strength of the arch.
Left: Good bond and proper positioning of stones. Right: poor stone masonry that will result in a weak structure.

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Fig. 40: a: Stones are tightly put together. They should act as a wedge with the narrow base pointing downwards. Fig 40 b: The keystone is wrongly placed. As the large base is at the bottom, the stone will fall out over time.

The arch construction must start from both sides at the same time, and is assembled symmetrically up to the keystone, which is positioned last. The formwork can be removed as soon as the arch is closed. It is easy to remove the formwork that was placed on simple wedges of timber cut-offs. The formwork can be re-used.

Fig. 41: For stability reasons, the bridge is built symmetrically, stepwise from both sides at the same time (a). It is dangerous to construct only one side first (b). The structure is not secure until the arch is closed in the middle.

3.2.6. Headwalls

Head walls are constructed to protect the backfilling from water damage and guide traffic along the crossing. They are made of stones masonry and are positioned downstream and upstream sides of the bridge. They are made of 30cm thick stone masonry. For bridges of a long span, rain water drainage holes at the right level should be provided for.

3.2.7. Wing walls

The wing walls act as retaining walls for the riverbanks and protection against scouring. They are interlocked with the masonry work of the abutment. Wing walls are provided at both ends of the abutments to provide smooth entry of water into the bridge site and to retain the backfilling of the approaches. Their design (position, orientation and length) is determined on site, in function of the natural landscape. They are preferably constructed in steps, at the same time as the abutments. It is not recommended to build wing-walls higher than 2 metres in one go. This would require a heavier base than the usual 40 cm thickness of the stones. Wing-walls with deep foundations are often a better investment than gabions which usually sag and tumble after minor under scouring.

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3.2.8. Backfilling: an underestimated construction step.

The strongest arch bridges are those that are permanently loaded with compacted backfilling material. Ideally, there is a soil buffer above the arch to cushion the impact of moving heavy traffic and increase the load. Backfilling material (typically compacted gravel or laterite soil) is compacted above the arch in order to increase this dead-weight on the bridge and prevent tensile stresses occurring in the arch ring as loads move across the bridge. A minimum of 30cm of filling should be added on top of the arch, but the quantity will vary as a function of the site conditions (level of the road and height river banks). If insufficient backfilling can be provided (to avoid large humps in flat valleys for instance), it is recommended that a concrete cap of 10 cm thick and 2 metres in length is cast on the top of the middle section arch. .

The backfilling should be placed in 10 cm layers of murram and then heavily compacted. The workers will use an iron compactor, a tractor axle or a long handle with a cast iron weight at the end. The usual timber or light metal compactors are not effective at all and should be banned. Even an eucalyptus pole will do better than those.

A lot of manpower and direct supervision is needed to produce a compaction of reasonable quality. The soil layers should have the right moisture content and should not be too thick. A jumping compactor will provide for the best compaction. A common construction mistake is that soil is just dumped in large quantities behind the wing-walls and abutment and then only compacted on top. Soil dumped in this way will exert a big sliding pressure on the wing-walls, leading to cracks. In addition, it will not further strengthen the structural stability of the arch bridge.

A moderate moisture level allows for the best compaction and the soil strength. The backfilling is usually from a dry stockpile of excavation materials. It needs to be slightly moistened. If the soil is too wet or too dry, it will simply not compress

A layer of gravel or laterite soil will be used to be rammed in the last layer of the wearing surface of the road. Surfacing improves the structural support and reduces road surface erosion. Soil of high organic matter should not be put close to the surface of the approaches or road.

Rain water should not be standing on top of the culvert or bridge. Therefore, this section of road should be slightly higher and the water should gently be drained away from the wearing surface to the shoulders. The headwalls can also have some drainage holes.

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3.2.9. Erosion protection

As the population is growing, more floods can be anticipated, due to deforestation, poor land use, destruction of the catchment area, quarrying in the river bed, etc. Global warming has also increased considerably the risk of extreme flooding. High flow velocities often lead to bank erosion and the formation of gullies. Therefore, it is important to plan for long term erosion protection. Scouring of the foundations and wing-walls will compromise the lifespan of the structure.

Site selection

Future erosion can be prevented by selecting the correct site. The bridge is ideally located where the river is straight, stable, and does not change its course. The opening should be wide enough to minimize constriction of the natural channel. Whenever possible, a bridge should be constructed at a narrow channel location at a straight angle with the river. Where the bridge restricts the river flow, higher water velocities downstream will require erosion protection. For more details about the site selection, see the first paragraph about construction steps.

Foundation depth

Bridge foundations should preferably be placed on bedrock. Alternatively, foundations are constructed well below the expected future maximum depth of scour – usually 1.5 - 2 metres.
A water pump is required to reach that depth.

Structure protection

The in- and outlet will be protected with masonry wing walls or gabions where the sub soil is not stable. Where there is a large river gradient and high water velocity, stone pitching and/ or gabion mattresses between the foundations are required to prevent future erosion. Local gabions mattresses can be made while “sandwiching” stones between galvanised wire mesh and anchoring the mesh with ¾ inch galvanised pipes. Because of their high costs and high risk of collapse, many designers prefer deep wing-walls over gabions.

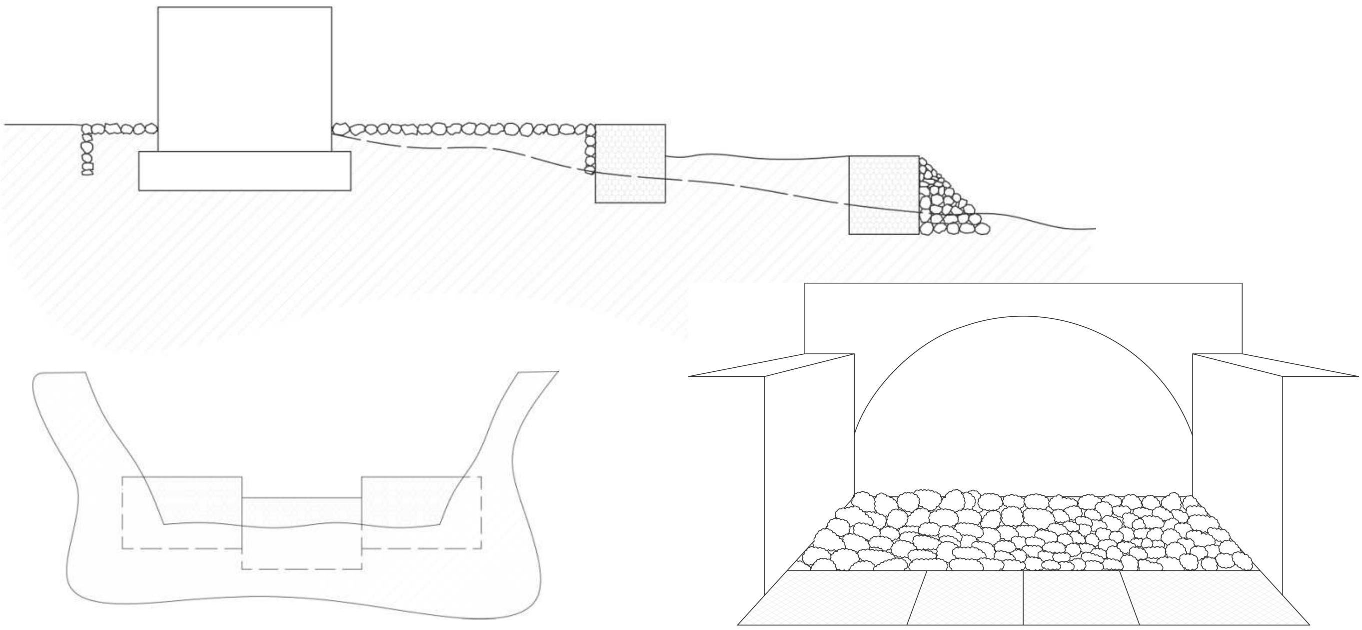

Fig. 42: erosion protection with gabions and stone lining will be required for sites with heaving scouring.

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River bank protection

Newly formed slopes can be easily damaged by runoff surface water, cattle, etc. It is therefore necessary to protect the slopes by:

- Cutting the bank gradient to 60%
- Planting of grass at high density (elephant grass cuttings at distance of 20*20 cm, paspalum grass at 7*7 cm, vetiver grass 15*15 cm) and/or grass mats obtained from the excavation.
- Placing a riprap with stones or additional gabions mattresses for risky sites
- Planting of bamboo and ficus trees (strong branches used as cuttings) along the river banks. Contrary to trees, bamboo can be planted in the immediate vicinity of the bridge as its roots will not expand and cause cracks. Trees should not be planted close to the bridge. The erosion protection along the river banks of trees such as eucalyptus or grevillea is limited.

Fig 43: If not properly installed, gabions often collapse fast (a). This example started sagging after the first flood and had to be redone. Before the gabions are placed at the river banks, large stones will be rammed in as support basis to avoid early scoring under the gabion. The stones are carefully placed in the cage to avoid damaging the galvanized coating. The craftsmen will look for a good bond between the stones (b). The stone volume in the cage is 100% self supporting. There is no pressure of the stones on the cage. All cavities are filled with small stones and river sand. The gabions are filled in such way, that if walking on them, the stones should not move (c). Half way the filling, wires are tied to across the cage to reinforce the gabion

3.2.12 Auxiliary road works

A parapet of 30cm is not strictly necessary, but is usually added on top of the head walls to prevent moisture entering. Other items can be considered: guardrails for pedestrians, drainage holes in the wing walls, road signboards etc.

3.2.11 Maintenance

Stone arch bridges usually require little maintenance. Their heavy weight helps them to withstand floods, as long as scouring of the foundations is prevented. Periodic maintenance includes repairing of wing-walls, collapsed gabions and stone lining, and removing silt & debris from the stream channel. The cattle access in the neighbourhood of the bridge is strictly prevented. The erosion of the base of the river and scouring of the wing-walls & foundations will be carefully assessed after floods. The first floods of the rainy season are the riskiest. Tree log and debris will then often jam the bridge and culvert openings. The road committees should be sensitised to clear the structures from trunks, rubbish and excessive silt immediately after the floods.

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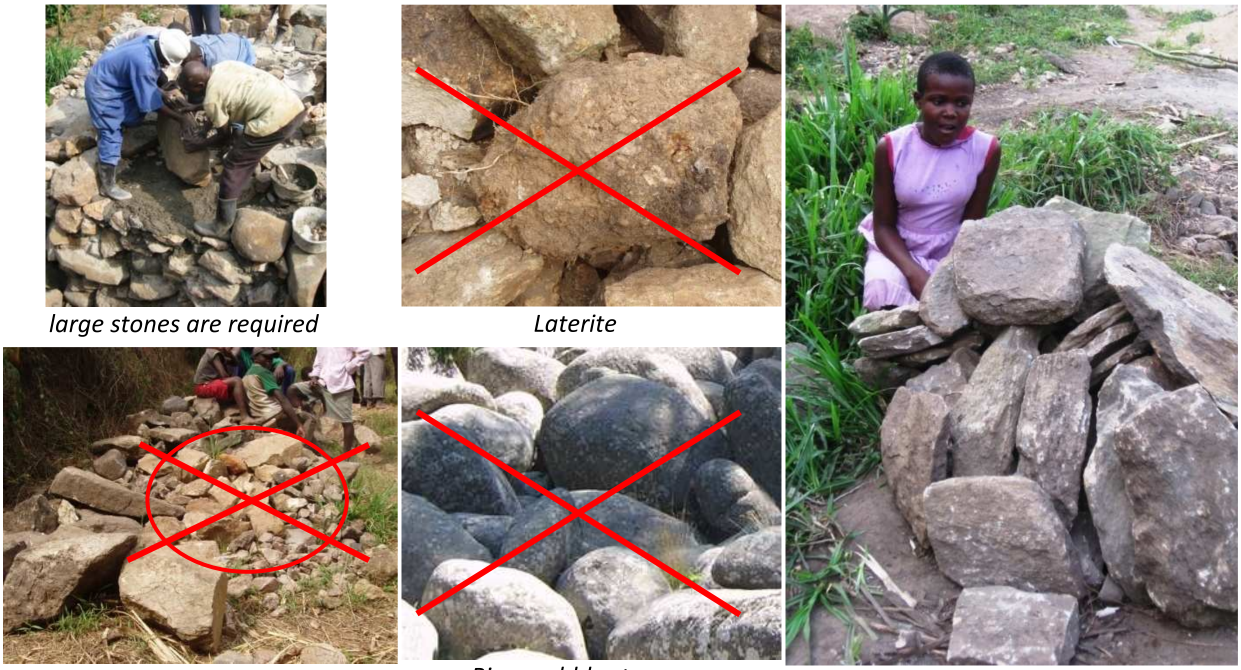
3.3 Selection of construction materials

Stones

Large and good quality stones shall be used for the construction of the bridge structure. Fortunately, areas where large quantities of culverts are required are usually associated with steep terrain where stone is relatively abundant. However the quality of the stones should be monitored. Stones should be strong, hard and free from cracks. Another important characteristic is that their surface must be rough. River pebbles cannot be used as the mortar will not adhere well on the smooth surface. The stones must also be large. The community is instructed to only collect stones that need to be carried by at least 2 people. For the arch section, large, flat and long stones are required. They are stored for that purpose. The best shaped flat stones are used for the closure of the arch in the middle. Small stones will lead to high construction costs and weak structures. Laterite, volcanic tuff and sedimentary rocks such as sandstone, shale, and other porous or brittle stones can only be used for backfilling and not for the structure. Volcanic rock, basalt slate and crystalline stones (granite, gneiss) are excellent construction materials.



large stones are required — *Laterite* — *Small stones* — *River pebble stones* — *Large & well shaped stones for the arch*

Fig. 44: Large stones make the bridge strong and reduce cost considerably. Prior to collection, the community should be given examples of the adequate stone size and the type of stones required.

All stones should be washed with a strong brush and clean water. Stones need to be moistened just before construction to increase the adherence of the mortar.

Note: Locally produced bricks do not meet the required strength standard and are not recommended for the construction of arch bridges. Only for culverts of 80 cm diameter, good bricks can be used in 2 courses, provided there is a good soil buffer (>40 cm) on top and that the foundation is made in stone.

Sand

Sand should be coarse and fairly granulated with minimum silt. The quality of the sand is important for the strength of the masonry. It is better to haul sand from a distance, rather than to use locally available sand with high silt content. The best sand is collected from fast flowing sections of the river. Sand collected from slow moving parts is likely to contain mud or silt and should be rejected. Dirty sand has a negative effect on the strength of the structure. Different tests can be carried out

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to make sure the sand is clean. One of them is to rub some sand between the fingers. If the sand does not stick to the finger, it can usually be used for construction. Sand is sieved to remove organic matter. The dumping site for sand is stripped of vegetation and compacted. Stored sand heaps are protected with thorn branches from goats and playing children. A ditch prevents rain water run-off. Ideally sand is kept dry. During the rainy season, the use of wet sand will require to turn the dry mortar mix at least 6 times to get a homogenous blend. Wet sand has a reduced bulk affecting the usual volume measurements. Tamping the sand in the batch box before mixing will increase its bulk.

Cement

The cement should be stored in a dry place on wooden platforms. A gap of 10 cm from the walls will prevent moisture absorption. Cement which has absorbed moisture is not suitable for construction. It is recommended to arrange the store in such way, that the oldest bags are used first.

Water

Water used for making mortar must be clean. Water that contains salt, silt, organic matter or soap is unsuitable for mixing mortar. If the river water is muddy, it will be necessary to store the water first in drums so that the silt settles. Moringa extracts will enhance the sedimentation process. Usually, too much water is used in the mortar mix leading to weak masonry works. The maximum amount of water is 20 litres per 50 kg cement bag. If the sand is wet, even less will be necessary. Water in large quantities is also required for the curing. Stone masonry and concrete must be kept damp for 2 weeks by watering it every 2 hours and covering it with plastic sheeting or grass.

Mortar

Mortar binds the stones together and increases the construction stability. The usual mixing of materials with local basins or wheelbarrows should be avoided, as it is hard to control the exact amounts. The use of a gauged batch box is required for the preparation of quality mortar, to ensure the right proportions. A 30*30*35 cm box has an equivalent volume of a 50 kg bag of compacted cement. The contents of the batch are struck off with a levelling rod. For building stone arch bridges and culverts, a 1:3 mix ratio is recommended. The sections permanently exposed to moisture and the arch should not have a lower mix. To avoid contamination, the mortar is mixed on a temporary "floor" made of bricks or rammed in stones. The mixed mortar is used within an hour. Spilled mortar is immediately recycled to avoid waste.

Fig. 45: The use of a gauged batch box and ruler is a precondition for producing quality mortar. Basins and wheel barrows should not be used as it is difficult to control the exact amounts.

Fig. 46: Prior to construction, all stones need washing to ensure that the mortar adheres to the surface.

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3.4 Implementation modalities and site management

Implementation modalities for local governments

For local governments in Uganda, there are a number of possibilities to construct arch bridges as outlined in the table below. Whatever the approach - strong quality and cost monitoring is required for every construction step. The integrity and quality of the personnel determine success or failure.

Implementation Modality	Strengths	Weaknesses
Public procurement works done by contractor	• Strong legal and contractual framework. • Less monitoring requirements • In theory better checks and balances	• Long procurement period • High cost but no quality guarantee • No mobilisation of local resources
Force on accounts done by works department	• Lower cost • Faster implementation • More flexible approach	• High monitoring requirements • Little checks and balances • No mobilisation of local resources
Force on accounts combined with community involvement	• Strong involvement community provides for check and balances • Cost reduction through mobilisation of local resources. • Strong local ownership and cost efficiency restores credibility of the local government.	• Community contribution will take time • High monitoring requirements

Organisation of the building site

A well-organised worksite makes working easier for everyone.
The **mason** (on a small construction site) or **site foreman** (on a bigger construction site) is responsible for the organisation of the overall construction works.

- S/he ensures the coordination of the activities and selects the teams of masons and helpers (casual labourers and village labourers).
- S/he ensures that the construction is carried out according to the drawings, the Bill of Quantities and the technical specifications, and gives precise technical instructions.
- S/he supervises the excavations, the setting out of the work, stone dressing, the mixing of the mortar, the execution of the masonry and the backfilling and compaction.
- S/he makes a daily entry in the site register, noting what work was carried out, the names of the workers employed, the number of cement bags used and any other events.
- S/he supervises the ordering of cement and tools and checks the quality of local materials.
- S/he takes advice from the site manager and the technicians who examine the works.

The **storekeeper** stores the tools and supervises their maintenance.

- S/he keeps the key of the store.
- S/he records each delivery and use made of the tools and equipment in a register.
- S/he warns the mason/site foreman of imminent shortages.

The **site manager** regularly checks, by examining the work and the site register; the progress of the work, whether the work plans are being respected and the amount of money spent.

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Construction season and time

Construction is best done during the dry season. Water levels are then low and accessibility of the sites is better. For the community, it is usually also easier to provide labour during the dry season. Construction during the rainy season will invariably increase costs of flood protection and transport.

The construction time varies a lot due to the span and the ability of the community to mobilise the materials. As a reference, a bridge of 5 meters span and 3.6 m width will be constructed by 2 masons & 4 helpers in about 30 days provided that the materials are on site. Consider that carpenters will need time to accustom themselves with the arch form work. Some mistakes are usually made and it is good to order the scaffold in advance to avoid construction delays.

Multiple construction sites

Some districts work with one experienced construction team to ensure the quality. In order the increase the number of bridges built per year, it is a good idea to build the foundations, wing-walls and abutments of several bridges during the dry season. The arches, headwalls etc are then finalised during the wetter parts of the year. Tackling several construction sites simultaneously will also reduce the problem of stalling construction because of the delay of stone supply by the community. Masons move to the sites where sufficient stones were delivered. In the meantime, the other villages will have more time to collect stones and will be encouraged by the tangible progress.

Construction supervision

Good supervision is critical for the quality of the construction, not only for the stability and durability of the bridge, but also to overcome scepticism of the community being used to reinforced concrete structures. Particular attention is paid to the control of site work: execution, planning, building materials, and maintenance of equipment. The following is required:

- **By the beneficiary community**, carrying out the day-to-day monitoring of the construction works. As they are on site daily, the local road committee informs the district works department if there are problems with the quality and quantity of the construction. They should also keep a log book of the attendance of mason and casual labour and the use of materials.

- **By the Lower Local Government**, making sure beneficiaries implement their responsibilities and reporting progress or any problems to the Works Department.

- **By the District Local Government,** supervising and certifying the construction of the bridge.

Continuous supervision is required in during the construction of the first stone arch bridges to build capacity and ensure the adherence to minimum technical requirements. The need for construction supervision is reduced if skilled and integer masons are employed. The selection of experienced masons is critical.

Next to their technical role, engineers and technicians involved in labour-based projects play an important managing role. One of the challenges is often the mobilization of the community. Late community contribution is often the main reason for the delay of the works.

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Fig 47: Multi stone arch bridges can be used to cover large spans. The span of this bridge was 50 metres and consisted of 5 arches. The picture is a courtesy of Rashid Mtamila/Tanzania.

Fig 48: The success of the construction depends on the integrity and expertise of the craftsmen and supervising technical staff. There is no shortcut for proper management of human resources and construction contracts. Adherence to quality and minimum technical standards requires training and continuous supervision.

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3.5 Common construction mistakes.

Issue	Mitigation required
1. Wrong stone laying for the arch Stones of the arch are laid in a horizontal position, rather than in a radial position, leading to a weak structure.	• Put the mason square on the mould and align the axis of the stone with the square. Alternatively, follow a rope fixed in the middle of the mould, to ensure a right slope (radius ½ circle). • Make sure stones come as a wedge: the small base at the bottom and the larger head at the top. • Once the stones are in position, tap with a hammer so that they slide in the right position and mortar is better spread in the gaps under the stones.
2. Weak masonry foundation & abutment. The aim of untrained masons is usually to align stones with the other rope to get a clean appearance but not to look in the first instance for a good bond. Gaps are left between the stones and some stones are not embedded in mortar.	• For foundations and abutments, stones are laid horizontally and a good bond is looked for by mixing large and small stones. • All gaps are systematically filled with small stones and mortar. • Wobbly stones are lifted and more mortar and aggregates are put under them so that all cavities are filled.
3. No fitting of the stones in existing gap The immediately available stone is often used by masons whether or not it fits in the existing gap. This leads to poor bonds and high construction costs.	• 1-2 labourers should be charged with stone "scouting": identify the type of gap and look for corresponding stone. • Put flat and long stones on one pile and have them ready for closing the arch at the final stage of construction.
4. The arch is built with small stones and poor bond leading to a weak structure.	• Select the best stones for the arch and keep them apart to avoid that they are used in the early construction stages. • Train the community on the required stone shape and size.
5. Poor mortar mix The quality of the mortar is often poor, to save on cement costs. The quantity of water used is usually too high, to improve the workability of the mortar.	• A gauged batch box (30x30x35 cm) should be used and the mix ratio respected. The measured quantities are struck off with a ruler. • Quantity of water used should be reduced to a maximum of 20 lt per cement bag of 50kg. • Improvement of the sand quality and use of a sieve to remove undesirable particles. • Cement and sand should be mixed 4 times (even 6 times if the sand is wet during the rainy season).
6. Excessive use of mortar Gaps between the stones are often filled with mortar only, leading to an excessive use of mortar and weak structures.	• Smaller gaps are filled with small stones of the right shape/ size and mortar. • Labourers should pound stones. The crushed aggregates should be available next to each mason for gap filling. •
7. Waste of mortar Mortar is wasted while be scooped out of the metal basins. Other mortar is dropped below the mould. The mortar is too wet and the local containers are small.	• Use maximum 20lt of water per cement bag. • Use large cut jerry cans instead of small metal basins. • Once possible, put the mortar basins on the mould and not on the earth floor. This allows for immediate recycling without contamination. • At regular intervals collect the mortar from the base of abutments and from under the mould. • Put banana leaves or plastic sheeting at the base of the abutments to avoid fallen mortar being soiled.
8. Inadequate interpretation of drawings. Abutments and shoulders are smaller than the required width. Serious risk of structure instability. Abutments are constructed as foundations.	• Train masons and technicians on reading of drawings. • Enforce required dimension by measuring with a tape measure. The rope alone is not sufficient. • Use squared stones and not irregularly shaped stones.

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Issue	Mitigation required
9. Poor quality stones are delivered by the community.	• Samples of proper stones provided to the community. A village leader of a successful construction site is invited to share his/her experience with a new community. Small stones and smooth river pebbles are discouraged from the beginning.
10. Slow progress of the works Masons are not making enough use of the casual labourers.	• The person in charge for the construction site should immediately identify idle workers and assign tasks to them in relation to the actual bottlenecks at the moment. • Moving heavy stones should be done by the labourers and not by the masons. • The gaps are filled by the labourers and not by the masons. • Special stone spotters are trained to identify the right shaped stones.
11. No stone washing. Stones are washed with dirty water or not at all. As a consequence the mortar does not adhere to the stones leaving a weak structure.	• Stone washing with plastic brushes is compulsory and a labourer should be employed for that purpose. • Replace the water when it starts being brown. • Wash the stones at a distance from the immediate construction site to avoid sullying other stones again.
12. **Insufficient space for 2nd arch for multiple structures.** On abutments with 2 arch springs, there is insufficient space for the second one.	• Wherever possible put the moulds parallel so that both arches are constructed simultaneously.
13. Late removal of the mould Mould removal takes too long as craftsmen are waiting for the mortar to cure.	• The mould can be immediately removed provided that the arch is closed. It is not the mortar that holds the arch but the wedge shaped stones positioned along the radius.
14. Small soil buffer on top of the arch In valleys, bridges stand out above the surrounding landscape. This high "hump" results in a small soil buffer on the top of the arch.	• Provide for at least 50 cm soil buffer on the top of the arch for better stability. • Where approaches are becoming too high because of the soil buffer, apply a concrete cap on the middle of the arch instead.
15.**Cracking wing-walls** No bond between abutment and wing wall The corners of the outer abutments are often finished as straight walls. Wing-walls are too high with only a base of 1 stone.	• Construct the wing-walls and abutments at the same time. Leave gaps in the outer abutments, so that there is a strong bond with the wing walls. • Backfilling & compaction behind wings walls should be done systematically small layers and mixed with stones.
16. **Poor quality arch formwork.** Carpenter does not produce a progressively curved arch mould but a set of assembled straight timber pieces. Bending moments will occur in the stone masonry leading to structural cracks in the arch.	• Train carpenters and supervise the construction of the first moulds. • Provide quality moulds as an example that can be copied. • Curved line should be drawn with a rope on the timber and cut with a circular saw or machete/ panga.
17. Difficult removal of formwork after construction. Most of the timber is damaged and cannot be re-used.	• Use 2 wedges under the formwork. This will ease the removal of the trusses and the purlins without destroying the planks.
18.Dumping of soil behind the wing-walls and abutments leads to cracks of wing-walls and does not strengthen the structural stability of the arch bridge.	• Soil is compacted in layers of 10 cm with a heavy metal axle. • Stones are added between layers and compacted. • Soil is moistened to obtain the right moisture content so that compaction is easy.

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3.6 Training of masons

Before training masons, craftsmen with good basic skills and professional ethics should be selected. The selection test is simple: building a small stone masonry wall with mud mortar. The mastering of basic theoretical aspects are verified, with regards to the mortar (preparation, mix ratio, etc), required tools, materials quality and interpretation of simple drawings. It is good practice to inspect previous works of the masons before signing an agreement. The training is based on a gradual hands-on approach, starting from culvert construction to small bridges. Although the standard masonry principles apply, specific building techniques (notably the positioning of the stones for the arch and assembling the formwork) are explained and their application monitored in early stages. Even though these call for some tricks of the trade, the techniques are quite simple and can be mastered quickly. Structural principles should also be well understood, so that adaptation to new situations can occur. The different steps of stone arch bridge construction are taught including site preparation, site levelling, setting out of the foundations, stones selection, stones laying, mortar mix, backfilling and compaction. During the training, it is important to stress the crucial points for stone arch construction (stones selection, laying of the stones making up the arch, plumbing, rational use of mortar, respect of the dimensions, construction of the arch formwork etc).

Setting out of foundations

Abutment construction

Arch construction

Fig. 49: The training of masons starts usually with culvert construction.

While prior formal practical training of the masons is essential, on-the-job training at sites supervised by qualified craftsmen is core to acquiring specific arch building skills at an affordable cost. It is important to keep in mind that newly trained masons will require regular supervision. Twinning craftsmen with experienced masons at construction sites is an efficient training method.

3.7 Promoting the technology.

In addition to the training for the masons, professional training should be provided at other levels in order to create teams capable of undertaking projects from design to construction stage, as well as the maintenance of bridges. Involving local entrepreneurs, engineers and craftsmen will ensure that the skills of stone arch bridge technology are locally anchored. It is good practice to expose councillors, members of parliament, sub county chiefs and other local government decision makers to the advantages of arch bridges by visiting constructed bridges and by outlining the impact on their development budgets and service delivery of the respective constituencies. The public needs to be made aware of the possibilities of arch bridges. Awareness-raising activities (site visits, official commissioning, radio talk shows, adverts) showing their full potential, can be considered for the first bridges in the district.

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