Our experience with rammed earth:

A manual for rammed earth building

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A) What is rammed earth?

Rammed earth is a very old building technique, probably one of the most ancient in the world, which relies only on natural materials. Walls are built out of normal compacted soil. A temporary formwork, similar to one for concreting, has to be erected; soil is thrown into the framework and compacted. Soon after finishing compacting, the formwork can be removed. Generally a small proportion of cement is added: 3 to 10% depending on the quality of the soil. The ideal soil for this kind of building consists in a good mix of different sizes of granularity, from clay (about 10-40%) to silt (about 10-40%) to sand (about 35-65%) and even very fine gravel. There is a variety of soil compositions that can be used. With this process, both weight bearing and non weight bearing walls can be built. Walls of all heights can be built, even on a multi-story scale, providing the walls are of adequate thickness. The minimum thickness seems to be around 35cm, mainly to allow stability and thermal mass, as well as to allow the person who rams to be able to move freely between the two sheets of the formwork, especially if these sheets are big (higher than knee height).

This paper describes mainly the technique of rammed earth building. As an introduction a few general considerations will yet precede the more technical and practical part of this document.

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1) A FEW GENERAL CONSIDERATIONS

A) The ecological advantages of rammed earth building

Rammed earth is a material that can be found freely in nature, most often on the building site itself. The process of rammed earth building almost negates any consumption of energy for preparation, transport or building. Rammed earth is completely recyclable and sustainable?.

The process creates thick walls which protect the inner space from external fluctuations of temperature; the thermal mass flattens the extremes of temperature because of its thermal inertia, it means its slow reaction to change; before the hot sun has been able to heat up the considerable mass of the walls, evening has come with its usually cooling breeze. Similarly in winter the cold of the night has not enough impact to cool down the walls and the interior atmosphere remains warm enough until sun rise.

Thermal mass is different from insulation although it has a similar consequence in the way it prevents heat to be transferred easily through the walls. Insulation relies on many small vacuums in the insulating material that prevent the heat passing through the walls. Thermal mass allows the heat to go through but very slowly because material with thermal mass is usually a relatively bad heat conductor and most of the heat is used on the way through the wall to heat up the mass of the material. In summer the inner wall of a thermal mass will remain cool (it is nice to lean against it) and in winter it will remain warm (no cold radiation will emanate from it). Thermal mass works also to reduce the impact of the heat that penetrates inevitably through the doors and windows, which insulation cannot do. This combines with natural ventilation is very effective.

Insulation is necessary in cold climates where the temperature remains low for many days. Thermal mass is more appropriate for climates where the average temperature remains comfortable despite strong contrasts between day and nights, like generally in arid climates. Both are very different but combine well one with another, if insulation is on the exterior side of the wall and thermal mass on the inner side.

Rammed earth is more appropriate for dry countries. Nevertheless many buildings in rammed earth exist in Europe. It is important in any case, in more humid climate, to protect the walls from heavy rains (large roof eves, render, higher percentage of cement).

B) Rammed earth for developing countries and people without access to cash

Basically rammed earth building does not necessitate any special materials or tools except what can be found in nature. It is in this sense very independent from economic circuits of exchange; it escapes the laws of market. Therefore it is easily accessible for poorer countries or for people who do not have access to cash or would not normally have enough money to invest into building. Yet in this way of building the price of materials is replaced by an important quantity of work that has to be supplied in order to transform natural material into a building on the building site itself.

Work is usually cheap in countries that do not practise extensive market exchanges. One says that one man cannot build one house but ten men can build ten houses. It is particularly true in case of rammed earth building, because work can be exchanged as a duration of effort (days of work) without being converted into money. Work can be also bartered or paid for with local money like LETS (local employment or trading system - a local currency which cannot be converted into the national currency but serves for local exchanges).

The techniques that are described below can be simplified to an extreme where almost no tool or bought material are used. This means that they become completely free from market pressure and necessity for accessing money. Yet accessories like ready made formwork sheets or bars and nuts for assembling them, or even a small winch for lifting, make the process much easier and efficient. It is an advantage of this kind of building mode that the process can progressively become more elaborated while introducing step by step, when one can afford it, simple powered tools or industrial accessories which will simplify considerably the process. All degrees of technical complexity are possible and depend mainly on the availability of technical and financial means and cheap work rather than on an absolute necessity. One imagines even a small corporation starting to propose simple services which would rely mainly on work and very few or even no accessories and machines, and with the time develop into a corporation with its own tools and accessories of which a part can be bought progressively on the market, or at least, like a simple crane, built by the person in charge.

This way of building becomes hence a powerful way to empower poor people in poor countries as well as in our rich western countries where so many people have no access to decent dwellings. It is fascinating to notice how much the diffusion of such simple techniques can become the support for a much wider development of an evolved form of craftsmanship, of social know-how and recognition, of self-esteem, as well as a possibility to offer new opportunities for answering locally our most basic needs. In his experience in Gurna, the Egyptian architect Hassan Fathy (read Hassan Fathy: *Architecture for the Poor*) has shown how the rediscovery of mudbrick and of the traditional technique of the Nubian vault has contributed to a new dynamic inside a very deprived community.

C) Rammed earth, a process

In our western culture, we are very much oriented towards efficiency; it means that we are oriented towards quick results more than towards harmonious processes. Building in rammed earth is a process which has to adapt to many factors: weather, quality of the soil available, nature and dependability of tools, generosity of co-workers into effort etc. It is important to accept this challenge because this acceptance and spirit of adaptation will make the process more harmonious and more in tune with the environment, especially if simple means are implemented in order to make the process more accessible for people without or with reduced access to cash flow. It becomes a fascinating process when one opens to the quality of this harmony that cannot be experienced when one focuses only on quick results. Yet of course the purpose of building with rammed earth is also to erect a house where one can live.

The process can even be experienced as a kind of meditation: the quality and mystery of a lose soil which can be transformed into walls, the gentleness of the process which sees almost exclusively work and creativity transformed into a house. Yet meditation does not mean pleasure and ease all the way through!

As such, rammed earth building is evidently a heavy and effortful process. Yet, when it is well organised and planned, it becomes easy, especially if the main effort (lifting) is supplied by simple machinery or tools: a simple crane with a simple pulley can change completely the ease and quality of the process. Yet many small problems appear regularly on the run and much patience is required for troubleshooting. These frequent problems impair the smooth development and take time. If the rammer needs repair, or if it starts raining heavily, it can take a few days until the work can go on. Once one has accepted this fact, there is no major hindrance for a harmonious development of this activity.

Because of these many technical, material, contractual, social, psychological aspects of rammed earth building, it is interesting to describe the process in more detail.

The organisation of the whole process is a very important factor:

- the clarity of the methodical approach will enhance the smoothness of the work,
- the organisation of clear work stages and the implementation of adequate tools and machines - even modest ones - will stimulate people's energy and reduce physical effort,
- the regular cleaning of the place strengthens the motivation of workers,
- the flexibility of the organisation has to integrate the external factors which will inevitably disrupt the easy development of the building process: weather, health, break downs, accidents,
- the capacity for quick trouble shooting of the many problems that will not avoid to appear will allow the process not to be interrupted for too long,
- the role of an overseer (the hidden eye) is very important, who will be able to notice problems before they become incidents or break downs, and to solve spontaneously many small issues before they become problems,
- the commitment of all the workers is essential because it has to integrate the duration of the process which can extend on many weeks or months,
- the harmony of the team makes the work more enjoyable (or bearable),
- and finally the generosity in providing good food will play an essential role as one of the main hidden contributions!

When we started building the first walls, we had the help of an experimented contractor. Thanks to him and his generosity in sharing his knowledge, we learned a lot. Later, as the process evolved towards smaller walls and as we had accumulated more experience on our side, we could reorganise the process in a different way; we chose to reduce the means and tools to what seemed to us minimum. This is well the role of a master to become useless; when it happens it means that the master has fulfilled his role in transmitting most of his knowledge to his disciples. Our own experience allowed us to adopt other ways of organising the process.

The help of a contractor cannot avoid to be expensive because one has to pay for his knowledge, his machines and his time. This is the price of learning; this help is very precious at the beginning because it allows to avoid many mistakes. But soon one becomes capable of reorganise the process in one's own way; it is where one's own creativity can develop. Expenses (can I pay?), competence (do I have the know-how?) and involvement (can I do it myself?) are three constant components of the process; their combination one with another evolves and changes through the whole process and can soon generate deep changes and re-orientations in the organisation. It is what happened in our case: the contribution of the contractor became soon too expensive for what it brought us; we decided to buy a small compressor and the necessary whalers and bars and nuts; and we experienced how a more modest setting revealed itself to be ecologically more adapted and economically more performing.

2) THE TECHNIQUE OF RAMMED EARTH BUILDING

A) The soil

The choice for rammed earth has only a sense if the soil is taken locally, on the building site itself or nearby. If it is not suitable, some complementary soil (for instance clay if it is too sandy, or sand if it is too clayey) has to be brought in, and the more transport is involved, the more it defies the purpose of using rammed earth, which has to be ecological and in harmony with nature.

It is best to use the soil provided by the excavation for footings and basement, after removing the top soil which is never adequate for rammed earth building because it is too spongy. It is better to pile up the soil into high and dense heaps, and not to spread it too much, as the peripheral soil will be lost when it gets mixed with grass, top soil or other impurities. The more compact the heap is, the better it is protected from external influences. It is also important to protect it from rain, especially in the month before it will be used, because the soil must remain pretty dry in order to be rammed. If it is too wet, it cannot be used before it dries; if it is too dry a little bit of water will be enough to make it usable.

In order to know whether the soil is good for ramming, the granularity must be examined. The best suitable soil is composed of different sizes of granularity that allow the bigger pieces to be locked into each other and the finer material to serve as a kind of glue or dense filling between the bigger pieces. Any vacuum, as small as it can be, will weaken the structure. It is why it is necessary to have enough fine material, especially clay (grains with a diameter smaller than 0.1mm) that will fill the smallest interstices in the material. Yet too much clay will make the material to flexible. Therefore it is ideal to have a good variety of all kinds of grain sizes. Many practical tests are easy to perform in order to test the soil. An abundant literature exists about this topic, but we want to remain here very pragmatic. Drawings are taken from a French book about traditional earth building[1]which describes different techniques from many countries (France, Yemen, Algeria, Egypt, Australia, etc.).

1) The smell test (presence of organic soil)

Topsoil and organic soil have a strong smell of mouldy, especially when fresh or humid. They are not suitable for building.

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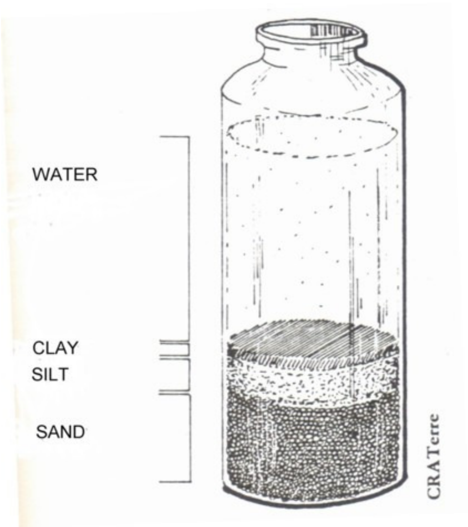
[1] CRAterre (P. Doat, A. Hays, H. Houben, S. Matuk, F. Vitoux): Construire en terre.

2) The biting test (content in sand and clay)

Put some soil in your mouth and press it between your teeth. If sandy soil: a lot of hard particles of sand which crunch unpleasantly under the teeth. If silt-laden: it crunches too but not so unpleasantly. If clayey: it is smooth like flour and even sticky.

3) The jar test (simplified sedimentation)

Take a good quantity of representative soil of the mix you want to use and throw it into a cylindrical glass jar (only one quarter to half of the content of the jar) which you almost fill with water (three quarters). Shake it until the whole soil is impregnated with water and in suspension in the water. Let it settle for 1 hour. And shake it again and do the same after 2 more hours. The different particles will fall at different speed, the biggest first and the smallest much more slowly. After some 8 hours, you can see how different layers have been formed: at the ottom, the heaviest is made out of gravel and sand, then higher the silt and at the top the clay. You can roughly measure the height of each layer and it gives you the proportion of sand, silt and clay. It is good to make different tests for the different piles of soil, because the nature of soil can vary strongly from one part of the same site to the next, even on a short distance.

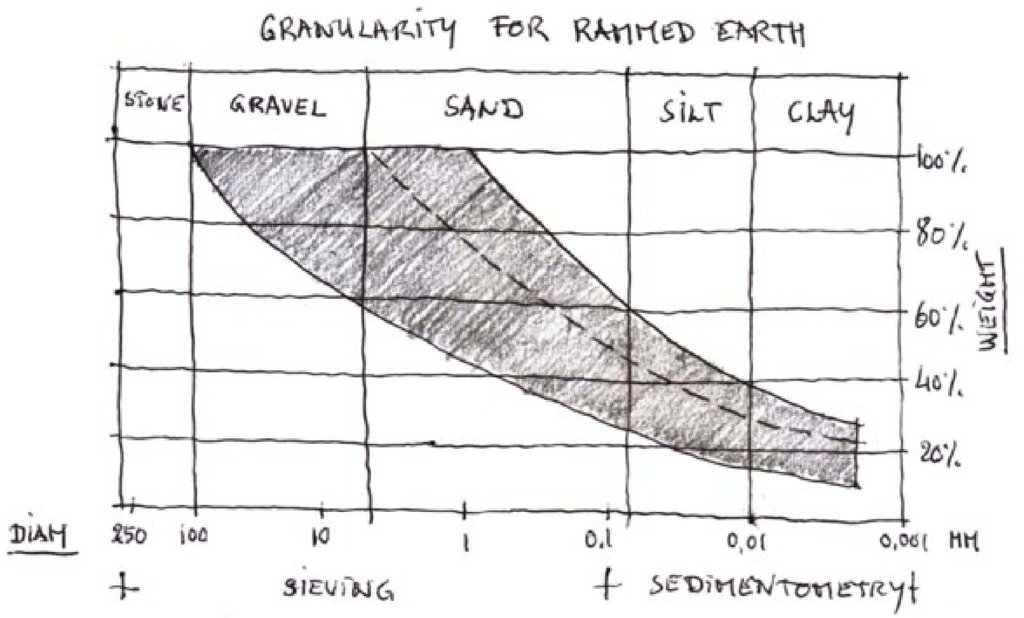


On the picture, the left jar shows a higher content of gravel and very little quantity of silt and clay. On the right it is mainly sand, silt and clay (this was the soil we used and it was perfect). The best would probably be a mixture of both. In the middle jar one notices more gravel at the bottom.

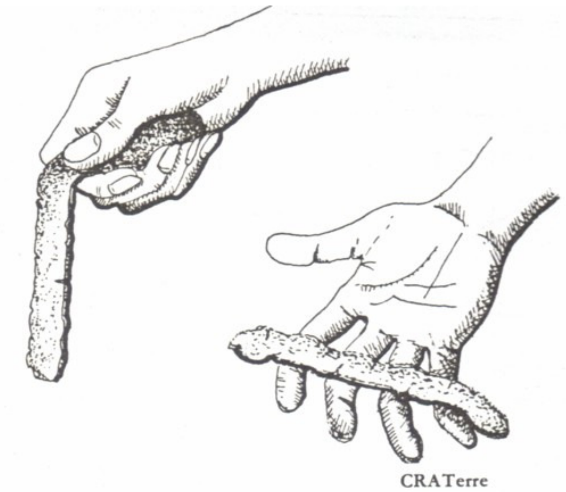
4) The sieve test (granularity)

If you want to know the composition of your soil with more precision, you can perform a sieve test. Use different sieves: for instance 5mm, 2mm, 1mm, 0.5mm, 0.2mm, 0.1mm. You can pile them on top of one another, with the widest mesh on top, the finest at the bottom. In each sieve will remain what is smaller than the precedent one and yet bigger than the next one.

Then, weighing each content separately, you can measure which percentage of the total weight goes through at each time, when one starts of course with the wider mesh. The sieving must be done in a flow of water that will help smaller grains to go through the meshes. The weight must be measured after the material has dried. This test is very difficult to perform for particles smaller than 0.1mm. Sedimentation (see test 3) is probably a more accurate and simple way to test the granularity of the smaller part of the material once the particles that are bigger than 0.1mm have been eliminated. The curve shown on the picture presents an ideal proportion of possible granularity, with a visibly very wide range of possibilities. One can read: clay between 10 and 40%, silt between 10 and 40%, sand between 35 and 65%, gravel between 0 and 40%. The size of the particles can vary from 5µ to 10cm. Of course the granularity will also influence the aspect of the walls. Gravel and stones will be visible on the surface of the wall and this higher diversity of granularity can provide an interesting structure to the lot.



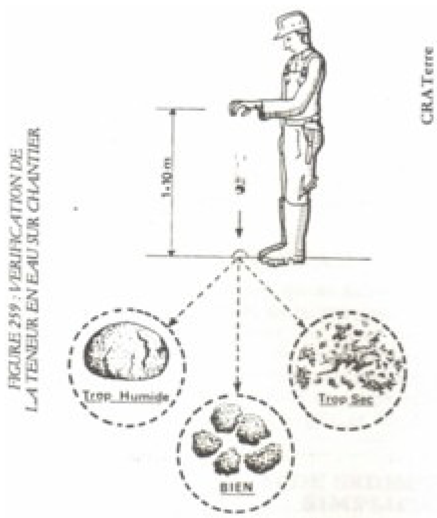
5) The sausage test (excessive clay content)



Take some soil in your hand, and make it wet enough to be able to be formed but not to become sticky. Form with it a kind of sausage or cigar of 12mm diameter and try to extend its length by diminishing its thickness and by pressing it between your thumb and your forefinger. Handle with care as the purpose is to obtain the longest possible length with a thickness of some 3mm without breaking; if it reaches 25 to 30 cm, it contains too much clay and needs probably to be stabilised with the addition of sand and cement. Too much clay makes the material too sensitive to water absorption and too flexible. If the band reaches 5 or 10cm, it contains only little clay and will be probably suitable for rammed earth walls. If you cannot make a 3mm thick band, your soil will be probably adequate.

6) The ball test (humidity content)

Once you have tested the quality of the soil, you must still control the degree of humidity. The soil for ramming must remain pretty dry, just softly humid. If it is too wet, it creates muddy patches that move under the impact of the rammer. To test the humidity, form a ball in your hand, after adding enough water to have it just consistent and malleable enough. Drop it from your shoulder height. When it impacts on the ground the ball must explode in a main heap and little satellites. On the drawing on the right one can see that in the left circle the ball did not explode because it is too wet; in the middle circle it is the right humidity, in the right circle, it crumbles because it is too dry. It is easier to add water than to take it away; add then water very slowly and in little quantities using a spray. It is better to add water at the end of the mixing process; at the end, because the soil can more easily be mixed when it is dry; and during the mixing process because one uses the mixing device to avoid the water to accumulate on the surface of the soil, when water is added later by simple spraying without being mixed and creates muddy patches.



7) The sample (resistance and aspect)

The best way to test your soil is to make a sample. Make a frame with wood and ram some soil into it, with the adequate humidity as in test 6. Let it dry for 1 day, unpack and test it. Expose it to rain and other external influences and see how it behaves. Do a few experiments with different percentages of cement: 2% or 5% or even more if it is necessary. It is best if you can make these tests pretty early in the process in order to give it time to dry, to shrink or crack eventually (too much clay). Test also the resistance to pressure and impact. Make a few different samples with different piles of soil. Let it weather outside, in the rain and in the sun. Make also a smaller sample to be able to transport it easily if you want to choose fitting colour for paint or other materials.

B) The mixing process

It is good to add some cement in order to make the material more compact and more resistant to water. The consistency of cement will slightly correct the curve of sedimentation we described before. It will better fill the remaining gaps between the grains of natural soil and it will also consolidate the structure by its own chemical reaction with the humidity that is contained in the mix.

It is better to use off-white cement because it does not change too much the original colour of the soil and does not introduce a grey tone that would take away the shininess of the natural colour and light.

The proportion of cement will vary according to the quality of the soil. A good soil can even be rammed without any cement if the walls are completely and well protected from rain. Yet it is not advised; a very small proportion of cement (1 or 2%) will considerably improve the resistance, especially to water penetration. Despite the fact we had an excellent soil, we mixed 4 or 5% of cement. The measure is never very precise because it depends how the soil is delivered. In our case we used the tractor with its small back loader that contains between 0.1 and 0.2 m3, depending how full it is and how dense the soil is in the bucket. 1 bag of 20kg of cement represents 0.0125 m3 and we used 1 bag for 2 buckets of soil. After compacting (ratio for compacting = approx. 2/3) it would give probably a proportion of 4 or 5% (0.01 cement for 0.25 or 0.3 soil after compacting). Other calculation: we used 12 bags (12 x 0.01m3) for a 2.4m3 wall, i.e. 5%.

The use of machinery for the delivery of soil to the mixing place makes it very easy. It allows to dig easily into the heap which has probably already well compacted since it was constituted, because a long building process has generally to take place between the time where footings are dug out - it means when the soil is heaped up - and when the ramming process starts. The use of machinery solves the problem of transport between the heaps of soil and the mixing place which must be as near as possible to the lifting device, if possible slightly higher in altitude. It provides also a measure for quantities (how much mix needs to be prepared) and for proportions (how much cement). Yet this can be done also by hand with shovelling and wheelbarrows.

For mixing we used a very small cultivator, we called with the sweet name of Stevie. Stevie is certainly not powerful but it is an excellent help for mixing soil that has already been made loose by the transport and by the effect of dropping it at the mixing place. The best way seems to create a pretty regular layer of about 40cm of soil on a surface of about 3 or 4m2 and to spread the cement on top of it, also in a very regular way, especially in proportion with the quantity of soil on which it is thrown. Then the mixing process is easy because the proportion is almost approximately correct. A bit of shovelling is always needed to bring back in the middle of the pile what escapes on the sides (lumps) and to spread around the inevitable concentrations of soil without cement or excesses of cement. The process of mixing has to last as long as the colour is not unified and as long the whole depth of the layer has not been mixed properly.

The quantity of the mix must not be excessive, especially if the mixing is done with simple tools. Our dear Stevie refused to mix in depth. On the other hand it must be used within two hours, i.e. before the cement settles. It is good to evaluate how much is needed in total and to divide it into a few lots, to avoid mixing smaller quantities too often.

Humidity control comes at the end of the mixing process as it has already been explained about the control of humidity of soil. It is good to use a garden hose with a spray in order to avoid concentrations of water and to mix it well with the cultivator. After the mixing the cultivator must be cleaned as water and cement have the tendency to accumulate on its wings and make it heavy and inefficient.

Then it is preferable to cover the mix with a tarpaulin to protect it from sunshine and wind. If it is hot, it is good to spray a bit of water at the top of the pile before covering it, because it will provide the humidity that will evaporate before it will be used.

It is evident that the cultivator is not a necessity, because the mixing can also be done by hand, but such a small machine saves a lot of effort as it remains minimal for an optimal effectiveness.

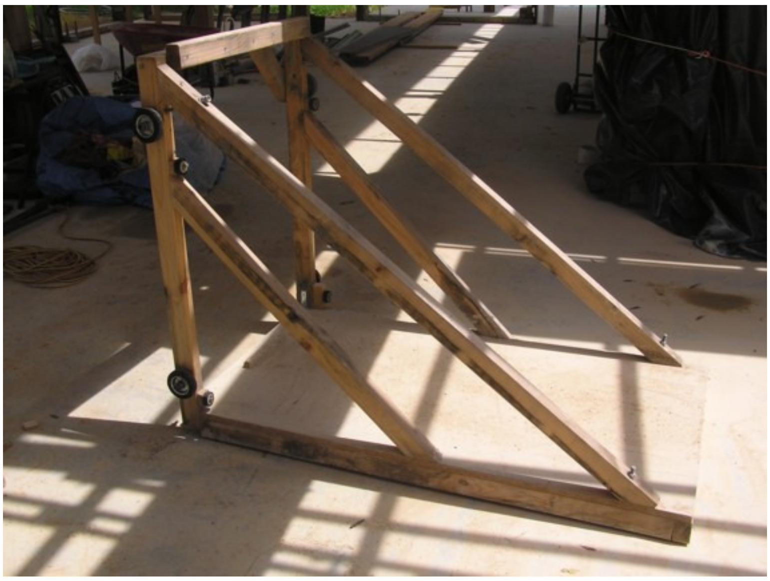
C) The transport and lifting

Transport and lifting constitute certainly the main problem of the whole process and, if it is not solved properly, a lot of human energy and physical effort will be necessary to transport the soil into the formwork, at a usual height of some first 1m than later 2m or even 3m or more.

1) The wheelbarrow

We thought it would be good to use the wheelbarrow as our main tool for transport because it contains ergonomically the ideal quantity of soil one can easily support and push without too much effort and it is also the right quantity to create one layer of soil to be rammed: about 0.1 m3 of lose mix (i.e. the contain of a wheelbarrow) will create a layer of some 15cm of lose soil in the box (around 10cm after compacting), if the wall is about 35cm thick and 2m long. The wheelbarrow seems hence the ideal unit for transport, and it is also ideal to allow a good control where and at which speed the soil has to be poured into the box, which is an important aspect of the process, especially when one reaches the top of the box and soil must be added more slowly while being spread in order not to overflow from the box. We had therefore to design a device to lift the wheelbarrow itself on a platform.

2) The wheelbarrow lift or crane



Pictures: the crane structure in lying position (left) and the chariot (right)

It had to be very simple and produced with natural materials, excluding in this way steel. The crane is composed of two main parts: on one hand a pair of static vertical rails, solidly assembled together, and stabilised by the structure of the building itself, and on the other hand a chariot which has to run up and down, lifting the wheelbarrow. An electric winch controls the movements of the chariot thanks to a cable that runs through 2 pulleys on the top of the structure and is fixed to the top of the chariot.

The rails, on each side of the crane, a pair of simple pine battens (45/70mm) are assembled together by a particle board which maintains a regular gap of 105mm between them, creating 2 guides in which the four 100mm diameter wheels of a vertical chariot can run vertically. The chariot itself is built out of a vertical rectangular frame on which the 4 wheels are fixed, 2 at the top and 2 at the bottom. Perpendicularly to this vertical chariot, diagonals suspend a horizontal platform which has to support the wheelbarrow. The diagonals are firmly bolted into the chariot. The two rails of the crane are solidly assembled together on the external side, in order to maintain a constant void between them (the width between the wheels of the chariot), without impending the up and down movement of the chariot. The two rails and these many assembling transversal battens form the vertical static structure of the crane, while the chariot forms the mobile structure which will lift the wheelbarrow.

Pictures: left, the winch / middle, the rail / right, the wheels on the chariot

See the drawing of the attached plans of the crane: it is favourable if the frame of the chariot is higher than 120cm because it allows more mobility sideways for the wheelbarrow to better control where to pour the soil and a better control how to tip it over.

3) The weight

Our system was a bit too weak; it would have been preferable to use stronger wheels (diam. 125mm rated 100kg each, instead of diam. 100 rated 65kg each). Indeed if the weight of a full wheelbarrow is estimated 120kg and the weight of the worker 80kg, it creates a moment of about 210mkg, which means an average load of 180kg for each pair of wheels, i.e. an average of 90kg each[2]. This is more than what the wheels we used could resist. It is why we had to run the lift without any worker on it. The worker had to climb on a ladder and stand then on the platform, as lightly and gently as possible, once the wheels were no more rolling.

4) The erection of the crane

It was important to build the crane as light as possible - i.e. not excessively strong but only what was needed - because it had to be moved constantly and re-erected for each new wall. We moved it from one place to the next in its horizontal position. As minimal device for the transport, we used a two-wheel hand truck on which the bottom part of the crane laid with the chariot and its platform, while two people held the top part of the crane and drove the whole lot to the right place. For the erection we used the winch of the crane with the hook at the end of the cable fixed to an upper beam of the building, instead of to the chariot, after changing slightly the position of the pulleys. It could provide most of the effort needed for erecting the crane from the horizontal position to the vertical, and we had only to prevent the crane from balancing sideways into the formwork, as, in most of the cases, the hook was not hanging exactly where it had to pull the crane, creating therefore a side effort. Once the crane was up, it was easy to lift slightly one side in order to take the two wheels hand truck away, and then to slide it in the right position, as near as possible to the formwork, but without touching it.

We will see later how bars and nuts assemble the formwork. It is advised not to let these bars stick out too much on the side where the crane has to stand, because they would be in the way when one erects the crane, and the crane gets hooked on them.

5) The stabilisation of the crane

The main issue for security is the stabilisation of the crane. It has to be fixed to the structure of the building; as the whole weight of the full wheelbarrow and of the worker is hanging out of plumb (about 200kg at a distance of 1m from the bearing structure), the crane is pulling at the top on the arms which fix it to the building structure. To ensure a solid yet adaptable binding

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[2] 120kg for the wheelbarrow with a lever of 0.8m and 80kg for the worker with a lever of 1.4m, it is: 120kg x 0.8m + 80kg x 1.4m = 208 mkg. If the height of the chariot is 1.2m = the space between the lower and the upper wheels, this moment can be resisted by a force of 174kg (pressure on the lower wheels and traction on the upper ones), which means an average effort of 87kg per wheel.

we used a pair of clamps with each two solid bolts which had to squeeze the arms of the crane on the transversal temporary beam fixed between the two posts. The total pull of the crane on both arms is about 50 to 60kg (around 30kg on each arm)[3] when the arms are at a height of 4m. These theoretical calculations give only an idea of the effort which will be sometimes stronger given the heavy movements of workers and loads and the inevitable asymmetry of the use which is made of the crane.

Pictures: left, one of the arms clamped onto the beam / right the "ears" or "wings"

As there were different cases for stabilisation, given the different possible positions of the crane (through the roof, through the first floor, against the outer wall), the crane had also other ways to be stabilised; it had for instance on its both sides, on different heights, some kind of wooden "ears" or "wings" on which the same clamp with 2 bolts could have a grip and squeeze them directly to a beam, for instance in the roof where the roof was low (in the front part of the house).

Of course the use of such a crane is not the only possible system for lifting; our experience showed nevertheless that it was an excellent solution, avoiding unnecessary efforts and providing a good control on the way (how much, in which part of the box, how quickly) the soil is poured into the box. Lifting can also be made by hand on a ladder. It can also be assisted by a simple tripod with a pulley on which hangs a bucket. If the load of the full bucket is about 40 or 50 kg, one should have 1 or 2 pulleys on the tripod and 1 or 2 pulleys on the bucket suspension, which would mean 2 or 4 ropes, dividing hence the load by 2 or 4, and multiplying the length of rope to be pulled by 2 or 4 also. Yet it is important to remember that it is preferable to have enough new soil in the box before ramming a layer to avoid too thin layers and unnecessary repetitive effort. The quantity of a wheelbarrow was very suitable fore a 2m long wall, or 2 wheelbarrows for a 3.5m long wall. It is evident that the delivery for one layer can also be done in 2 or 3 successive stages of smaller quantities, especially if it is done by hand. Once the soil has been poured into the box, it must be still spread in a regular layer with a shovel.

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[3] The moment is 208kg (see calculation before); 208kgm / 4m (= height of the stabilisation clamps) = 52kg, i.e. in theory 26kg / arm.

D) The walls and the structure

Rammed earth walls can easily be weight bearing, even on a few storeys (see in Sanaa, Yemen!) if they are thick and stable enough. In our case, we have chosen to have a wooden weight bearing structure made out of posts, beams, joists and rafters, which support the weight of the whole construction. This means that the rammed earth walls are not weight bearing in our case but only walls that close the space between the posts. Although they are not weight bearing, all walls fulfil nevertheless their role of bracing of the post-beam construction.

In our case, one part of the building is on two storeys (ground floor and first floor); the walls of the upper storey will be made out of a light wooden structure and wood cladding, between the main posts of the construction. The rammed earth walls are only on ground floor level, in order to bring the necessary thermal mass where it is reasonable (not a disproportionate effort) to build heavy walls. This option allowed us to build the roof of the upper storey sooner and hence to offer a protection to the walls against the rain, even before they were built, especially because of the generous eaves. On the other hand, for the front part of the building, which is on one single level with ground floor only, the roof structure was not immediately covered but ready to receive the roof as soon the rammed earth would be built, with the exception of a few rafters missing because the crane had to stand and go through the roof, in front of each wall to be rammed, in order to allow the soil to be poured from above to the top of the wall.

The fact we had a wooden bearing structure has been an important help because it allowed us to simply fix the formwork of the walls to the existing structure (mainly the posts). We did not need to worry about stabilising each box of formwork as an independent construction, as it would have been the case if it were free standing. In the same logic, we built the ends of walls as integral part of the structure itself, instead of installing and removing them for each formwork, because we thought it was a complication for the erection of the formwork to have to adapt an end wall temporarily. In our case the end walls are parts of the structure of the building and remain as a frame for the walls after they are finished; it looks great.

In a similar logic of simplification, we dissociated the walls from any openings like doors or windows; this means that each wall is a simple rectangle without any hole in it. It makes the ramming much easier as there is no window and no door to frame into the formwork, and no frame that comes in conflict with the ramming. It is indeed impossible to ram below an opening, it means that the opening's frame must be therefore added when the wall has been rammed to the level of the windowsill, which is very difficult without removing the whole formwork or decomposing it in many parts. It makes the process much easier if all the openings are, like in our case, beside the walls, situated in gaps between the walls and the posts, or between the walls, the smaller windows having their bottom part as a wooden cladding as well as the part above.

Another important simplification consisted in avoiding corner walls. Corners are always a problem in architecture and construction. Formworks for corner walls need to be adapted, as one side of the formwork of the first wall has to be shorter, because of the thickness of the perpendicular wall, and the two meeting formworks, at the exterior corner, need to be assembled in a different way from simple straight walls. To counter this problem we designed the position of the walls in such a way that no corner wall was necessary. At each corner an opening (window, door or simple wooden wall to be added later) is foreseen, creating a gap between the first wall and its perpendicular one; in this way each wall can be formed independently of the other, with straight formwork sheets running through the gap. See picture below.

E) The base of the walls

As rammed earth is a material that does not like water, it is important to create a base for the walls that protects them from possible inundation (external floods or washing machine incident). One layer of small brick (around 7 cm high) will do the job. As the wall is usually 35 or 40 cm thick, it is easy to lay one layer of bricks on each side and to pour concrete in-between. One can use this opportunity to lay electric conduits in the concrete and to prepare the necessary place for power points. The bricks look like a kind of kickboard in which all the necessary power points can be placed. Electric switches and other power points at more accessible height can also be fixed on the end walls. It is favourable not to have conduits hanging free in the formwork because they will be in conflict with the rammer and risk to be broken or torn. It is important to fix them well; the option to cover them with concrete between the 2 rows of bricks of the base offers excellent protection.

Picture: see how the corner of the building allows the two meeting walls to be rammed independently. Notice the electrical conduit for the power point situated in the base. Wooden blocks have been screwed into the side (end wall) as keys to create a strong link of cohesion between the frame and the mass of the wall. The waterproofing has still to be laid.

On top of the bricks and concrete, it is necessary to have a good protection against raising humidity in the form of a sheet of waterproof material like Alcor. This will also work as a barrier against termites.

F) The formwork

This is probably the main challenge of the whole process, because it is important that the formwork is easy to handle and to put up, strong enough to resist the pressure of ramming, big enough to avoid too many set up for the same wall.

1) Simplified description

We used plywood sheet (20 mm thick, 1.2 x 2.4m) held by whalers; long boards of Oregon wood or hard wood (20-25cm wide x 50mm thick). The whalers run horizontally in pairs on each side of the box and each pair is held together by brackets, bars and nuts. Unless there is a special reason, the sheets are used horizontally. If the wall is less than 2.2m long, one pair of 2.4m long sheets is enough for the total length. The bars can go through the box at both extremities of the sheets without going through the wall itself but remaining outside the wall, just at the edge. Once the first level of the box (between the base and the top of the sheets) has been properly rammed, a second pair of sheets has to be put up on top of the precedents on which they sit, with the same system of bars and whalers to hold them together. This continues to the top of the wall. The horizontal joints between the successive sheets will remain slightly visible on the wall, once the formwork is removed. Once the whole wall has been rammed to the top, the whalers and sheets can be removed the next day.

If the wall is longer than 2.2m, 2 pairs of sheet must be assembled side by side, and the whalers must be long enough to cover the whole length. In this case, a slight vertical joint will remain visible on the wall, corresponding to the joint between the two pairs of sheets. Complementary bars are necessary which have to go through the wall itself in the middle part. They are installed through a conduit (with a cone at each end) that will allow the bar to be removed, after ramming, and this conduit will later remain in the wall. The holes in the wall, where the bars went through, have then to be plugged with rammed earth.

Picture: one can see the traces of the joints between the sheets and the holes which have still to be plugged.

If the wall is very long (more than 2 sheets long i.e. more than 4 or 4.5 m), the process must be decomposed in successive stages, because the whalers have to hold the whole wall which is rammed in one stage and their length determine what can be done in one go. At each new stage a temporary end wall must be set up into the formwork, on the open side of the formwork, i.e. the side that is not blocked by the part of the wall rammed in the precedent stage. The bars on the side of the precedent stage must inevitably go through the wall (with conduits and cones).

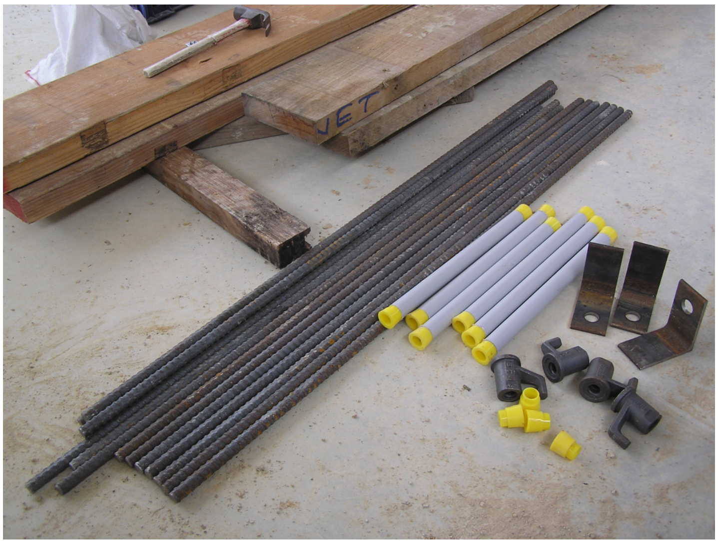
As each wall is different from the precedent, the system must be adapted to local constrains. It is worth taking some time for planing beforehand where to drill the holes, how to cut the sheets and in which order to ram the successive walls in the purpose of reusing the same sheets in the best way. Let's examine in more detail the different aspects of the formwork.

2) Whalers, brackets, bars, conduits and nuts

As the drilling of holes and the assembling of sheets depend on the type of bars which are used and on the way the whalers hold the sheets together, it is better to start by describing the system of whalers, brackets, bars and nuts.

The whalers are long boards which are installed by pairs, on each side of and against the formwork. Their role is to hold the sheets, to prevent them from bulging and to maintain so a constant distance between them. Their width is therefore determinant as it is what gives the strength to the system. Our whalers were 24 cm wide and 5 cm thick. If whalers are narrower, more bars must be installed in the length of the wall, because the span between two bars must be reduced as the whalers will be weaker to resist the side effort.

The bars we used were special bars made for formwork. They are called z-bars; they look very much like reinforcement rods but they are made with a thick thread in spiral around them which allows to screw on them the special nuts which go with it. These nuts are pretty bulky and have a special wing which allows to better tighten them. A 20cm long piece of reinforcing rod is the ideal tool for tightening the nuts. A bracket in L form with a hole has to be slid onto the bar between the nut and the whaler and allows the nut to press on the side of the whaler when the nut is tighten. The whaler is in this way pressed against the formwork sheet. As the whalers go by pairs, the same thing happens on the other side; the z-bar holds in this ways the two whalers together and prevents the formwork sheet from bulging.



Picture: z-bars, conduits and cones, brackets and nuts.

We bought the z-bars and the special nuts. And we had the brackets especially made: a L shaped metal rail (L 90 x 90 x 6 mm) cut into pieces of 50mm wide. A 20 mm hole has been punched into them for the 17mm strong z-bars, leaving a space of some 55 mm between the wing of the L and the side of the hole, for the thickness of the whaler.

As we had a maximum of 11 whalers on each side of our walls - which were between 1.8 and 3.9 m long and between 2.4 and 3.6 m high - we needed about 90 brackets, and about 45 bars with 2 nuts each, plus reserve. The ideal length of the bars would have been 1 m in our case, given the thickness of the wall and the width of our whalers. As the z-bars are provided in 5.8 m length, it would have been a bit short to divide them in 6, especially if we want to reuse them later for thicker walls. It is why we cut them into 5 pieces, which provided 1.16 m long bars.

For the conduits we used 25mm electric conduits, cut on the right measure (thickness of the wall minus 2 x 2cm for the two cones) with a cone at each end which not only prevents the conduit from going through the hole of the sheet but also maintains a constant space between the two sheets. Do not tighten too much the bars with conduits because they are not so resistant.

We used z-bars because they are easily available on the market, they are not expensive and they are very adapted for the job. Yet it is also possible to use simple threaded bars cut to the right length (1 to 1.2 m depending on the thickness of the wall and the width of the whalers). Larger washers would be needed to prevent the nuts to go through the holes of the brackets. The problem with threaded bars is that the constant move of brackets on the threaded bars - mainly under the effort but also when they get slid onto or out of the bars when putting up the formwork or undoing it - will progressively damage the thread and make them unusable, especially because the hole in the brackets should be in this case as small as possible, given the fact that the nuts are very small, even when bigger washers are in use. The z-bars have the advantage to have a very rough, strong and resistant thread and the fitting nuts are very big as easy to tighten.

3) Formwork sheets and design

We used plywood sheet, 20mm thick. It is important to buy sheets which can be used on both sides, it means with both smooth sides. We noticed indeed that some formwork plywood has a kind of fine structure on the surface of one side which makes it impossible to use on this side, because soil would stick to it; this kind of one side plywood is not well appropriate, because it is often very suitable to be able to use the reverse side, especially if some walls are the symmetrical images of one another; in this case the formwork can be re-used exactly in the same setting, but symmetrically. Formwork sheets slowly wear out, because of the inevitable impacts of the rammer on the surface of the wood which generate some scratches and superficial damages.

It is more suitable to use the sheets in horizontal format (length horizontally and width vertically). The height of the box (in this case 1.2m) is not excessive to allow the worker to climb into or out of it. If the wall is not longer than 2.2m, one sheet is enough to cover the total length and vertical joints and bars through conduits are avoided.

The thickness of the wall is an important factor. Thicker walls will provide more thermal mass although the thicker the wall the less impact a supplementary thickness will have, because the material on the surface of the wall will absorb first most of the impact of temperature variations while the deeper material will play only a complementary and secondary role when the surface material is "saturated". It is important to be aware that thicker walls have to be avoided inasmuch as thickness means also more material to be prepared, transported, lifted and rammed. On the other hand walls which are not thick enough will not only not be stable enough but also will be very difficult to ram because the space in the box, between the two sheets, will be too narrow and it will be impossible or difficult to stand and move in the box which should be as wide as the worker's hips. We experienced that a 350mm thickness is a minimum to allow the person who rams to move without too much impediments.

As it has been said before, it is preferable not to have openings in the walls because it is impossible to ram below this kind of obstacles, unless they are put up once the right level underneath them has been reached. Similarly it seems easier to avoid to have the end walls as parts of the formwork which have to be put up and down each time; it seems easier to have fix end walls which will remain parts of the building.

If it is preferred to have removable end walls, the question how to treat the edges remains important, because the vertical prominent edges are fragile parts of the wall which will remain difficult to ram and will be exposed later to knocks and damages. As a good solution it is proposed to insert in the vertical corner of the formwork a piece of triangular hard wood which will create a chamfer on the vertical edge of the wall; hard wood is better because it will better resist the impact of the rammer; or this special part can even be in metal and have a more elaborate form (rounded instead of chamfered). These parts are removable and reusable, but they need to be fixed in the formwork. In our case with fix end walls, we did not solve properly the problem of the crack between the wooden end wall and the rammed earth wall, especially because the end walls had to be prevented from deformation, while ramming, by the hammering of a few stabilisation logs and it was difficult to know how hard they needed to be hammered in, to prevent deformation and also to avoid the end wall to jump back later, opening more the gap. A covering thin lath can be added later to cover this thin gap.

After the sheets have been put up, it is important to check the tightness of nuts and the stabilising of the end walls by wedges or wooden pieces. This kind of verifications needs to be done during the whole ramming process as vibrations can loosen or even remove them.

It is amazing to observe that the pencil marks one does when preparing the formwork for cutting or drilling will remain visible on the surface of the wall as they will be printed onto it; therefore it is advised to use a marker by preference.

The system we described here is the one we used; it is pretty sophisticated because it relies on plywood and industrial products (z-bars). Much simpler ways exist which are the fruits of a long traditional evolution and experience. We will later describe these simpler ways because they propose really the simplest possible alternative which seems to be much more appropriated for poor countries or people without access to cash.

4) Position of the holes and bars

The first thing for preparing the sheets is to drill the holes for the z-bars which will support the whalers. The holes have to be a tiny bit bigger (18 or 20mm) than the size of the z-bars (17mm). If they are too tight, it is difficult to remove the bars.

The vertical distance between holes: The minimum space vertically between two whalers depends on the length of the wall and on the strength of the whalers; if the wall is very long, it is generally better to have more whalers. Yet the setting of the holes has to be done for the most constraining case because it has to be planned for the whole process on the building site, on all the walls, as the same formwork will be used and re-used successively. The planning and the order in which successive walls will be rammed are important factors which can make the process easier. Sometimes it is yet necessary to plug the existing holes with a two component filler, in order to change partially the setting of holes, when very different cases of formwork occur, but this is of course more work and should be avoided if it is possible. The ideal vertical space between two whalers (from hole to hole) is some 25 to 30cm. It means 4 to 5 whalers for the bottom sheet. The first bottom hole must sit at the edge of the sheet, but yet leave enough space for the sheet to cover the bottom brick by something like 2 to 5 cm. We noticed that it is preferable if the bars in the conduits do not sit on the bricks; it makes it easier to take the bars out after ramming, if the weight of the formwork does bear on the base. It is preferable to put some small blocks of wood to support the sheets. With some additive packing one can easily get the right horizontal position of the sheet, which is especially required if the first sheet has to join with a second sheet for the same length of the wall.

The whaler on top of the bottom sheet must sit at the edge of the sheet in order to hold the horizontal joint with the next sheet. Half of the thickness of the whaler must cover the bottom sheet while the second half of the thickness will hold the top sheet when it will be added later. It means that the centre of the top hole must be at a distance from the side of the sheet equal to half the thickness of the whaler (25mm) plus half the diameter of the hole (10mm), it means 35mm in total. The same setting must be repeated for each horizontal joint between two sheets. For the second sheet, it is not necessary to have a hole at the bottom because the sheet will sit on the precedent one and be held by its top whaler. The holes between the top and the bottom whalers can be distributed regularly; it is preferable to have them on a horizontal line because it makes it easier to add more holes in the same line later if necessary.

The horizontal distance between holes: The ideal would be to have in the whole building only identical walls, with the same length. Yet it is rarely the case. For a single wall, the best is to have bars which do not go through the wall but just outside, at the edge. If the bar can run at a distance of 2 or 3 cm from the end wall, some wedges can be hammered between the bar and the end wall and hold it during the ramming process, because the end wall will have the

tendency to bulge out under the pressure of the rammer. It is therefore favourable to stabilise the end wall with wedges. As wall lengths vary from one to the next, the same situation does not occur each time, and the system has to be planned for the whole lot. We noticed that it is not very good when the bars are sitting too far away from the end wall, because the tightening of the bars will generate deformations in the formwork. It is best therefore to have the bars as near as possible to the vertical edge of the wall - and new holes have maybe to be drilled for this special case and plugged again later - although it is also possible to set blocks of wood between the two sheets in order to maintain a constant distance between them and prevent deformation. The stabilising of the end walls can also be done with longer blocks if the distance is bigger than a few centimetres.

If the wall is longer and requires more than one sheet in the length, some more holes have to be drilled into the formwork for bars into conduits through the wall itself. When the holes are planned to be drilled, it is important to remember that inner bars will hamper the rammer for accessing places behind them or between different sets of inner bars, where soil will have to be compacted too; in most of the cases when inner bars have to be put through the walls, the worker in the box will even have to climb over them to be able to ram on both sides of them; these bars are also a nuisance for spreading the soil inside the box with the shovel after it has been brought and poured into the box; it is preferable to include these constrains in the planning and to keep a sufficient distance between these bars. With average whalers (about 25x5cm) the minimal horizontal distance between two bars must not exceed 2 or 2.2 meters; if two sheets have to be used side by side, it is better not drilling the holes too near the vertical line where the two sheets meet but leaving some 30 cm between the bars and the vertical joint of both adjacent sheets; it will create a gap of some 60 cm between the bars where the worker can easily stand or at least ram.

If all the whalers are continuous (i.e. in one piece on the whole length of the wall), it is not even necessary to have 2 inner bars (1 on each sheet) on the same whaler; 1 is enough; bars can alternate on one or the other sheet, from one whaler to the next, maintaining a constant distant between the sheets and resisting the pressure of ramming, and the vertical space between bars will be double, making the shovelling and ramming process a little bit easier.

5) Last preparation of the formwork

When two sheets are assembled side by side, it is good to install a strap between the two top inner bars in the middle (or any similar device), on the exterior sides of the formwork, which will prevent the joint to widen under the pressure and vibrations of ramming.

When the sheets are in place, it is advised to oil the inside of the box to prevent the soil from sticking to the surface of the formwork and to be ripped away when the formwork will be removed. We used for that simple canola oil diluted with a little bit of turpentine which makes it more fluid (1/1 or 2/1). It is better to oil the box just before ramming, and even to oil the top part only when one is almost out of the box; if not, the trousers will just wipe out what has been smeared on. Yet it is necessary to remember on time what we called “peak oil”.

Pictures: the straps under the whaler / the oil and brush

It is recommended to cover the joint between the whaler and the sheets at the top of the formwork, to prevent soil from sliding between the whaler and the sheets and pushing the sheets towards the inside of the box; in case this would happen, the next sheet would sit properly against the whaler while the lower one would not, forming a sharp visible joint on the wall. To avoid this problem, we stapled first a plastic sheet on top of the whaler, covering the top of the sheets, but the wind was constantly blowing it away, despite of the staples (see next picture); the plastic was most of the time in the way and the risk was also that the plastic got stuck into the rammed earth when ramming was nearing the top. A better way seemed to be clamping the whaler with the sheet; this protection could be removed when it came nearer to the top of the sheet, because the pressure of the soil in the box made it superfluous at this later stage.

G) The ramming process

Once the problem of lifting the soil into the box has been solved, ramming appears certainly as the main effort of the whole process. It can be done in many ways, from the most powerful technologically assisted way to the simplest, by hand. For ramming we used an air compressor and a rammer.

1) Simplified description of the ramming process

When the soil, already mixed with a few percents of cement, arrives in the box, it is loose and it needs to be first spread with a shovel into the box in a regular layer and then compacted. Soil can be rammed by vibrations or by impacts. Our air compressor and rammer worked by impact; each impact moves the particles of soil that try to escape the pressure into the small niches they can find. The ramming effect creates a solid agglomerate of particles locked one into another, the finest finding some room between the bigger. It is interesting to understand that the locking process does not happen because of a high constant pressure but because the impact of the rammer chases the particles into a locking position from which they cannot return when the pressure has stopped because they remain entangled one with another. The more they are pushed, the more they remain blocked.

It is why it has no sense to use a too powerful rammer, that would put a very high pressure on the structure of the formwork and the building without achieving a better compacting of the soil, because the limit of compacting is easily obtained, even ramming by hand with a simple piece of wood.

This description of the process of compacting explains why the layers that are poured into the formwork should not be too thick, because, when the top of the layer compacts under the impact of the rammer it creates a sort of locked assemblage that resists the impact of the rammer and does not transmit it to the lower part of the layer that remains therefore looser that the top part. After undoing the formwork when the whole wall has been rammed, it is interesting to observe the structure of the wall and to notice how the different layers of successive ramming remain visible and how the bottom of each layer remains less compacted (see picture). Sometimes it is hardly noticeable, but often it remains clearly visible, depending essentially on how thick the layer was. Of course this visibility and contrast between the upper part and the lower part of the layer depends also on the intensity and care given during the ramming process as well as on the composition of the soil.

The locking capacity of the soil depends on its composition and especially on the diversity of granularity it presents, as the test of sedimentation has shown. The locking effect is improved by a composition that mixes diverse sizes of particles, from the thinnest clay to small gravel. Our soil was pretty thin but diversified enough for compacting ideally well. Fine particles are necessary to allow bigger ones to slide on one another and they are also indispensable because they are the only ones that can feel the small gaps between bigger particles, providing in this way the necessary density and locking effect. It is why the gradation of the granularity is so important to allow the best compacting effect. Yet many diverse compositions will have good compacting capacities relying on a different gradation of complementarity between particle sizes.

Depending on the quality of soil and on its granularity, an ideal layer thickness will ensue. In our case we noticed that a layer thicker than 10 cm after compacting was too thick and did not allow the bottom part to compact well. Each composition of soil will reveal this ideal thickness through successive trials. In our case, it meant that the loose layer should not have been thicker than some 18 cm, if one assumes a compacting factor of 0.6.

It is also interesting to notice that a good understanding of the compacting process will dictate the right strategy for compacting. Loose soil does not compact well at the beginning because particles can escape in all directions and the soil is flying around, even above the edges of the formwork when one comes nearer to the top. The simple fact of stamping onto the soil will already compact it partially under the weight of the worker and the mechanical compacting will later be easier and more effective. It is recommended to go quickly all over the loose layer in a first stage, and then to do the edges of the formwork, then the middle part and then the edges again. It will be clearly noticeable how much the fact the whole surface has been rammed once will allow the edges to compact much better when they are rammed for the second time. The explanation is that the particles cannot escape sideways anymore because the neighbouring soil has already been made denser by the first ramming attempt and they can only escape into more depth, i.e. stronger locking into each other. On the other hand it is evident that the edges are the most important parts to be rammed carefully because they not only will remain visible later but they also retain and lock the inner part of the wall and provide the main stability.

It is important not to underestimate the power of the rammer that seems strangely to be increasing while the wall gets compacted and creating more deformations of the formwork; it is because the locking power of particles is cumulative and has the tendency to push the formwork further and further away. It is why it is important to stabilise it well and especially to reinforce the parts that will not resist well the side pressure generated by the ramming process. Once the soil is blocked in, it does not move anymore, and when the small percentage of cement has settled the formwork can be removed. The pressure has vanished and remains only as density.

2) Choice of the rammer and of the compressor

Our two main figures of the ramming process were Mr Puffy the air compressor and Cutesie the compressed air rammer. Cutesie is a light tool that is very well designed because it remains simple, solid and reliable. It is important that the rammer is not too powerful. Its weight is also important as well as the form and surface of its foot. Cutesie weighs a little bit less than 10 kg; it is appreciable to have a light rammer because it has to be constantly moved around, put aside when soil is delivered and carried over the inner bars; a light weight makes it more handy yet less effective because its weight defines also the power of its impact; Cutesie’s foot is round, 65 mm diameter; this size is perfect because it provides a good and strong impact on a sufficient surface, yet remains very handy; weight, power of impact, size and form of the foot are of course narrowly linked; the foot is made out of rubber; this is ideal because it does not damage the formwork and the round form fits into smaller corners. The height of our Cutesie was a bit short and we had to bend slightly down which generated progressively a nasty tension in the back. Once we had it repaired we changed the handle and made it longer by 20 cm so we could stand straight, holding it at belly height; it was much more comfortable.

We had already the rammer; so the choice of the air compressor depended on what was needed to work the rammer; Cutesie needs a free air delivery of 15 cfm (cubic feet per minute) or 425 l/m. We tried to find the minimum size compressor we could but strong enough to work Cutesie. As we are on solar it could not be an electric compressor but needed to be an engine air compressor. Compressors are rated according to their air production but it is expressed in two different ways that must not be confused: the air deplacement, which is the volume of air that has been compressed, and the free air delivery (FAD), which is the quantity of compressed air that is provided to the tool. The 15 cfm (425 l/m) free air delivery Cutesie needed had to be smaller than the free air delivery the compressor would provide in average. We found a good compressor (Mr Puffy) that has a free air delivery of 16.3 cfm (462 l/m), with an air deplacement of 25 cfm (708 l/m). The power of this compressor revealed absolutely adequate for our use and it was not too noisy nor too polluting. There are many compressors on the market, some very cheap one can buy on the internet, made in China, that probably would not last long. We have chosen to buy the basic good quality that was available locally. In the spirit of rammed earth walls it would have been wrong to buy on long distance; on the other hand the proximity of the seller provides a good maintenance service.

The hose is a simple half inch hose for air compressors. We did not use any water filter although the compressing process creates powerful changes of pressure and temperature and therefore condensation, especially if the surrounding air is humid. Some cold days we had even frost forming at the air exhaust of the rammer. The compressor needs to be emptied of this condensation water after each use. Oil in the rammer is an important contribution for the maintenance of the rammer. A few drops of oil have to be added in the inlet before each use.

Our rammer broke a few times because of minor problems, especially because the pipe that provided the air delivery and was used as handle was too weak, i.e. the wall of the pipe was not thick enough. A good local tradesman adapted it in a very clever way. Maintenance is an important factor, especially in such a dusty context; it is good if one learns to undo the rammer completely and reassemble it, keeping the parts absolutely impeccable, because it needs to be cleaned regularly. It is also important to check that the tightening nuts and parts do not get loose under the effects of vibrations.

3) More details about ramming

Ramming happens in successive stages, layer after layer. It is good to have prepared enough soil to be able to ram a good quantity in one go without interruption; yet the whole quantity of soil must be used if possible before 2 hours after mixing the cement. Quantities of soil to be prepared must be adapted to the size of the box in order to be almost totally used when one reaches the top of the box. Then another level of sheets can be added and new soil can be mixed when the upper box is ready.

Sometimes ramming has to be interrupted before the whole wall is done and has to be restarted the next day. This day joint will probably remain a bit more visible than the line between two successive layers. It is advised to wet slightly the previous layer before one restarts the next day, at a degree of humidity that is similar to the one of the soil when it is compacted.

We described already the different stages in the ramming process; a few details can be yet added: the rubber foot of the rammer has a tendency to leave marks on the formwork; to avoid this it is advised to hold the rammer vertically along the sides and not to rub it too much against the formwork sheet; when the soil has a tendency to "climb the wall", it is good to compact the foot of the hill that will collapse. Holding the rammer a bit oblique will chase the soil sideways. The different small corners can be better reached with a crowbar; the crowbar is heavy and has a small head, therefore a powerful impact and it has often to be used in inaccessible corners like behind inner bars or in the corners of the formwork that have to be rammed carefully, although they remain not so accessible, because they constitute the lock at the corner; if this lock is not firm, the surface of the wall will remain partially open and some particles of the soil will have the tendency to leak out of the wall.

Once our rammer broke and we decided to continue ramming by hand, just to have the experience of what it is and how much it would contrast with the rest of the wall. We used two simple pieces of hard wood, some 75 x 35 mm strong, maybe 1.4 m long. With this item we rammed a few layers (4 or 5) until the end of the mixed soil. We used also the crowbar for a last passage at the end of each layer to compact the edges as well as possible. We were very surprised to see that the soil was as well compacted as it was by the rammer. It shows how much the locking effect is reached by successive passages more than by shear force. The next day we tried to compact the same last layer with the rammer, yet without noticing any effect of the rammer. It shows that hand ramming is powerful; of course also more exhausting, but absolutely realistic as a way of doing that reduces the technology to almost nothing and uses only natural resources, and a lot of human work.

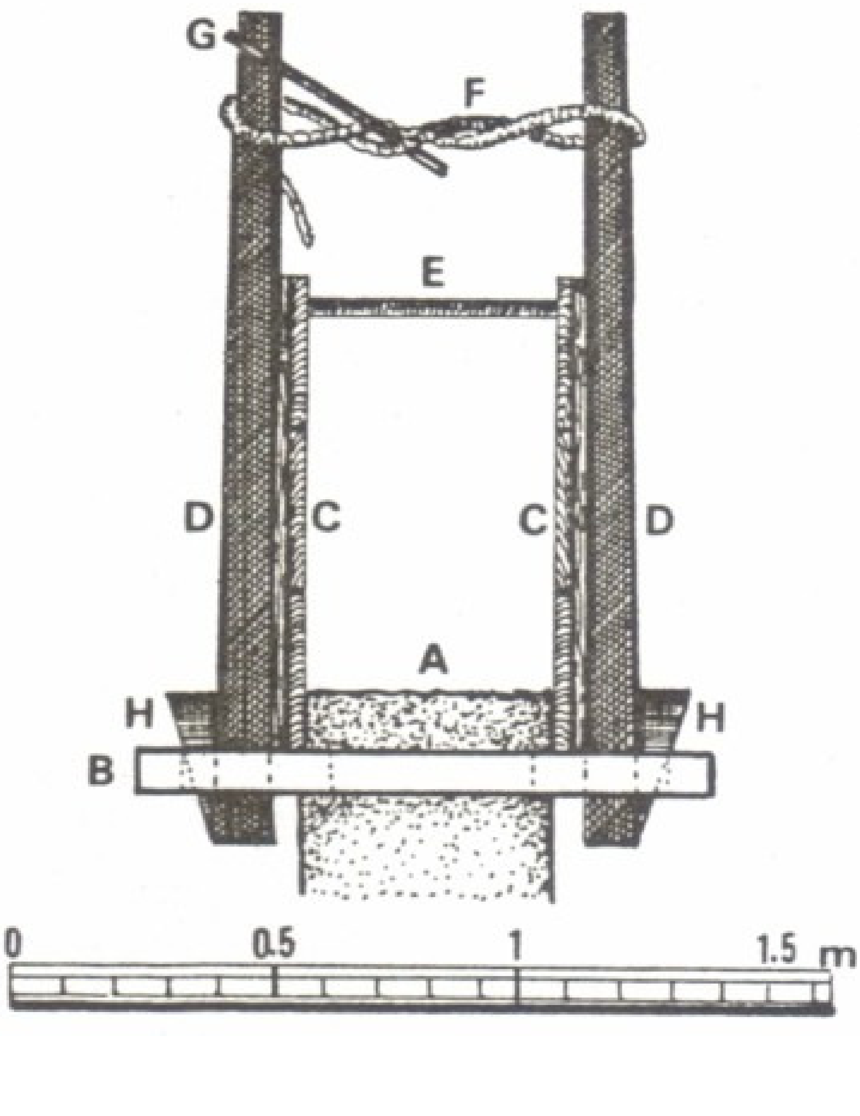
H) The traditional way of rammed earth building

As rammed earth building is probably one of the oldest building techniques in the world it is fascinating to observe how traditional building proceeds, because it shows what is essential and proposes minimal means for the best effect. We will describe this minimal way through drawings (extract of the same book already mentioned above).

1) The traditional formwork

The drawing below shows a section of the wall with the two wooden sheets (C); the two sheets are held at the bottom by a key that goes through the wall (B) and sits on the part of the wall that has already been rammed (A). A pair of posts (D) stands on each side of the sheets in order to hold them and are held by the key at their foot, where wedges (H) are hammered to maintain the two posts and sheets at the right distance one to another. A small wood (E) maintains a constant space between the sheets, under the tension of the top rope (F) that holds the posts together. The stick G allows to tense the rope and is maintained in position by the side post. Notice that the keys are slightly conical in order to be able to be hammered out of the wall and reused when the formwork has to be moved.

FIGURE 8 : BANCHE LYONNAISE



The next drawing (from Auvergne, France) shows the tools for ramming. One sees the different stages of the ramming process. The wooden sheet is assembled out of different boards (about 3m x 0.9m).

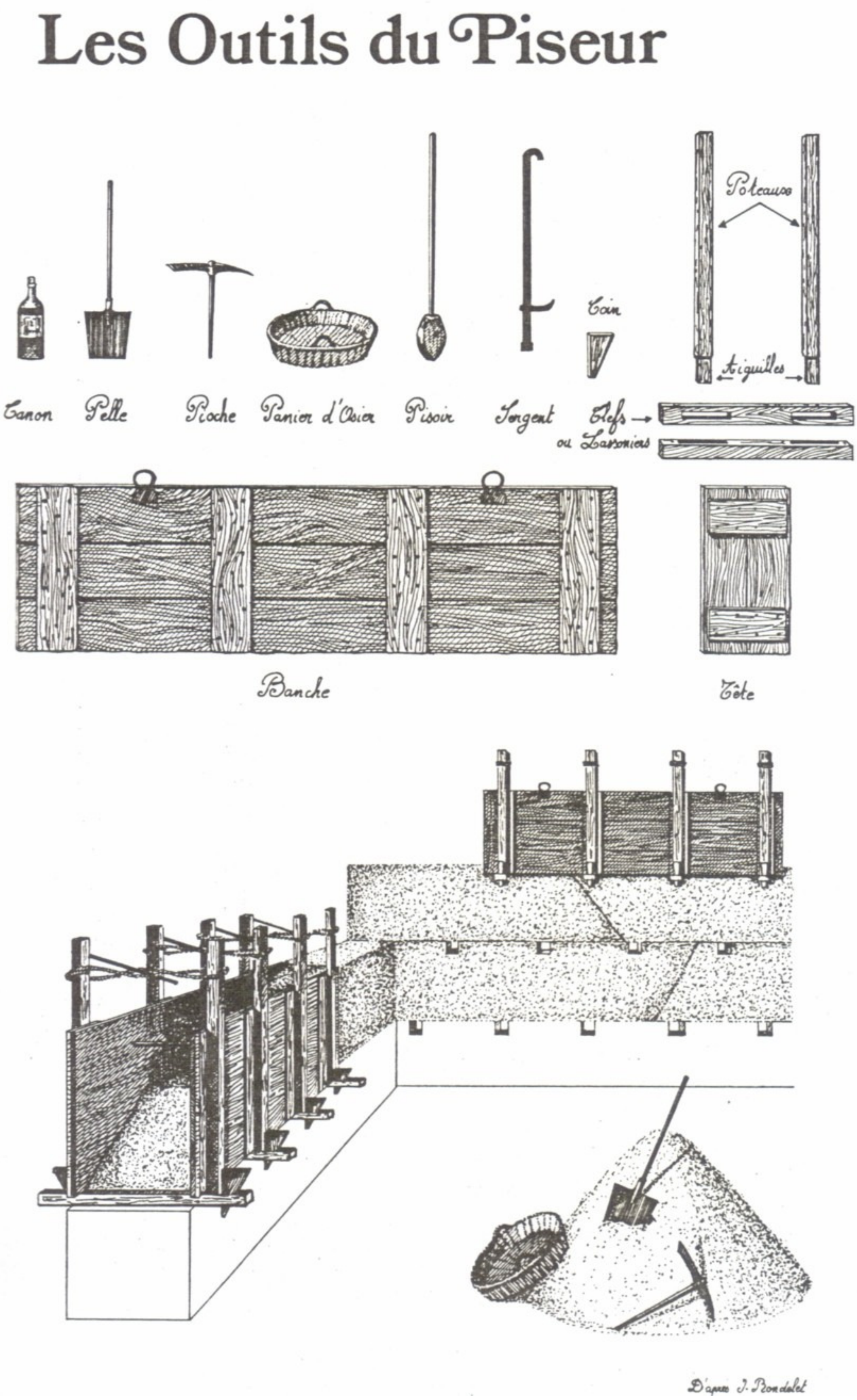
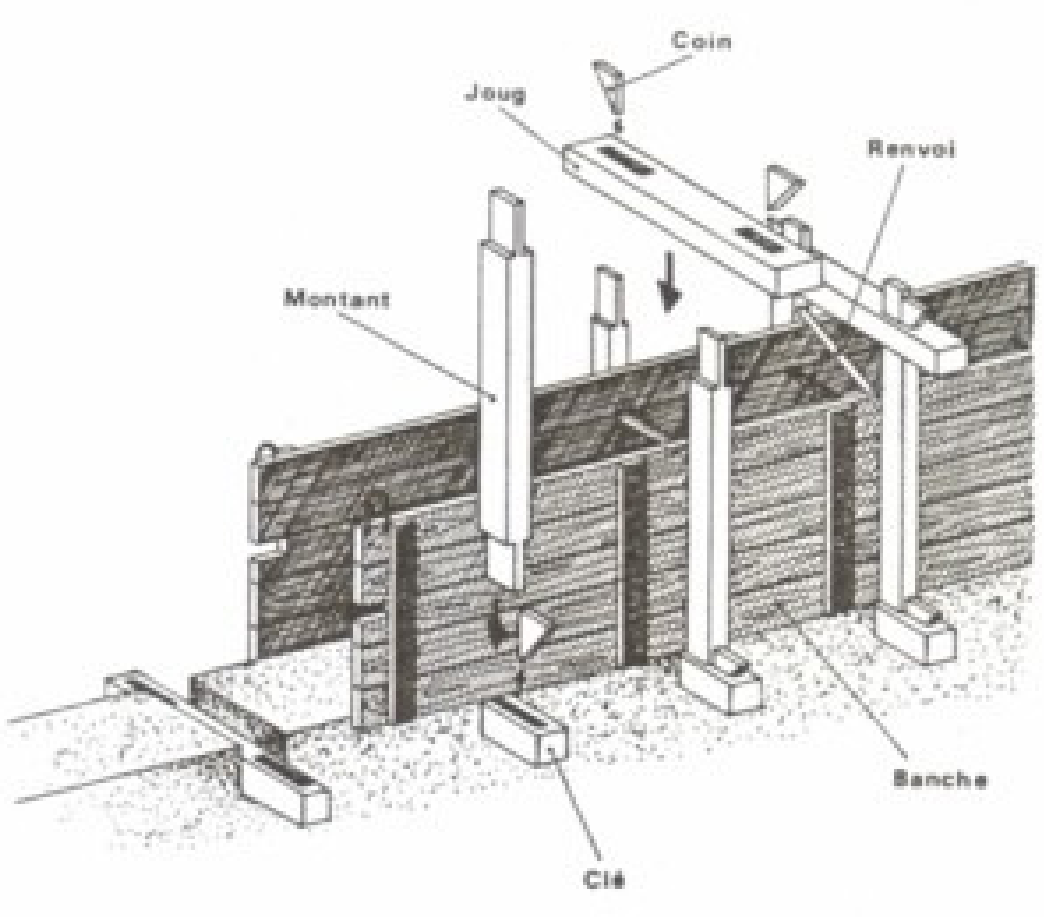


FIGURE 11 : BANCHE AUVERGNATE



The depth at which the wedges are hammered determines the thickness of the wall that goes diminishing in a way that improves the stability for the wall (wall batter)

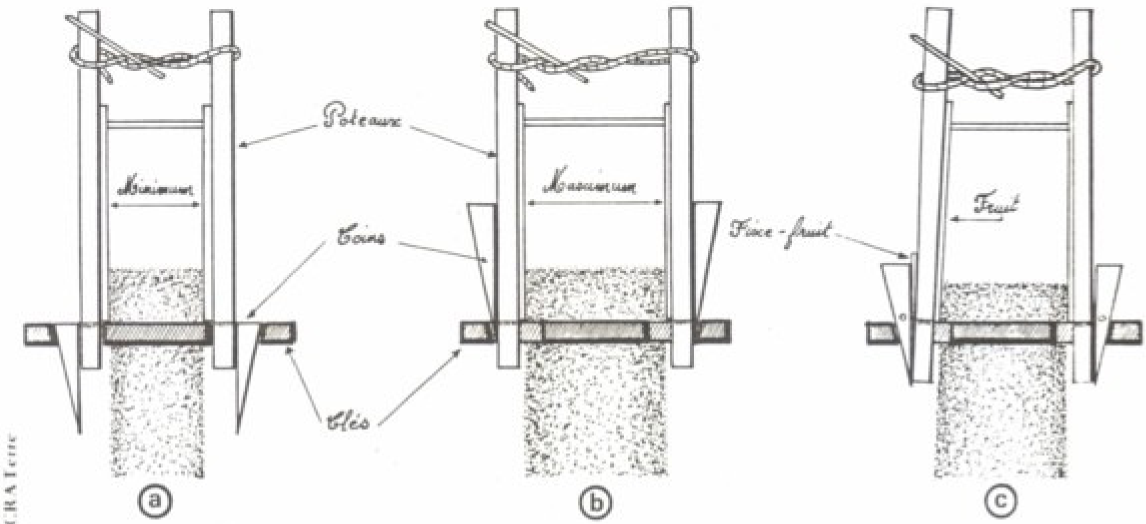
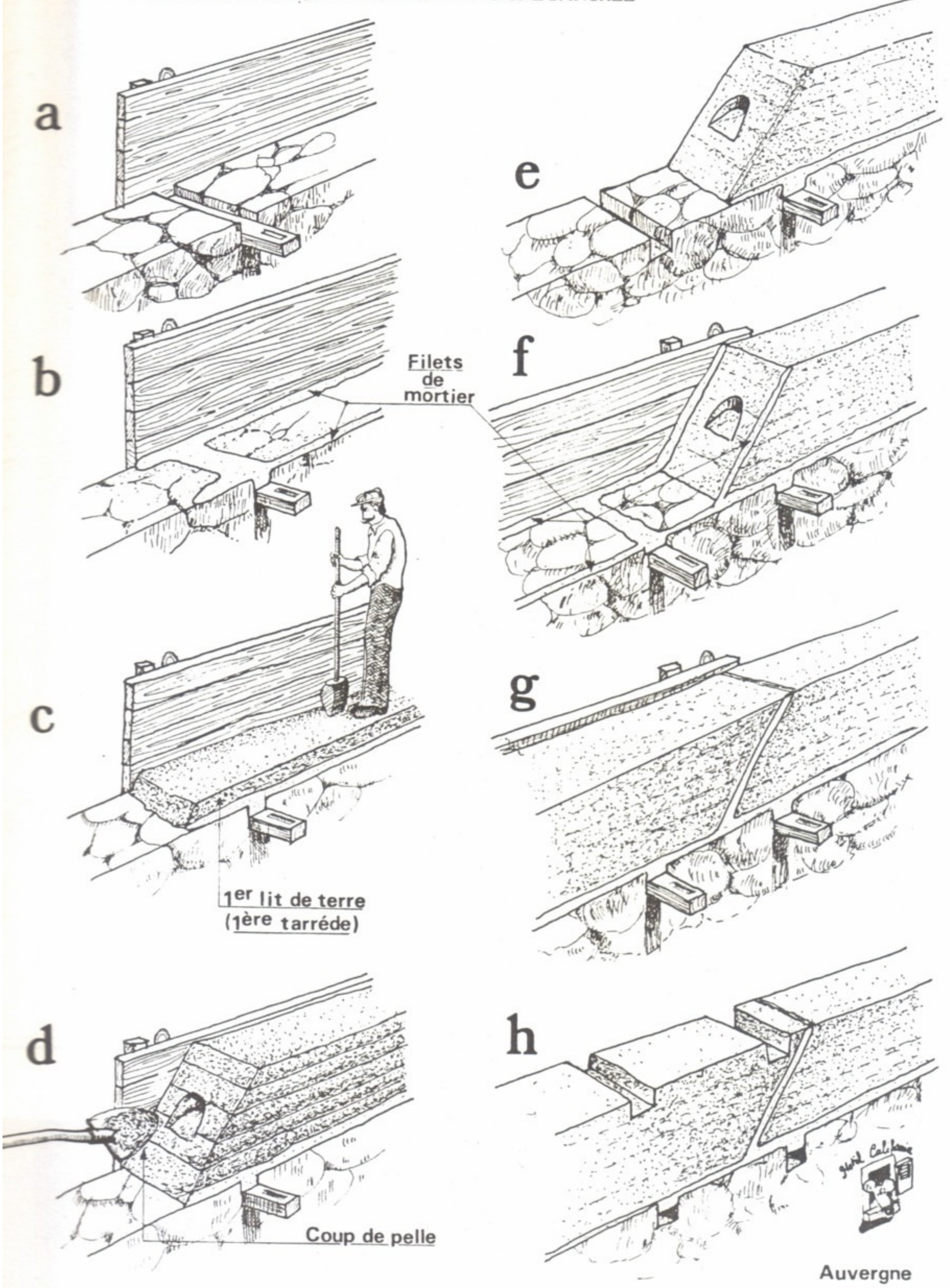


FIGURE 14 : (a) et (b) L'ECARTEMENT DES BANCHES VARIE EN FONCTION DE L'ENFONCEMENT DES COINS – (c) MANIERE DE MONTER LE FRUIT DU MUR

T

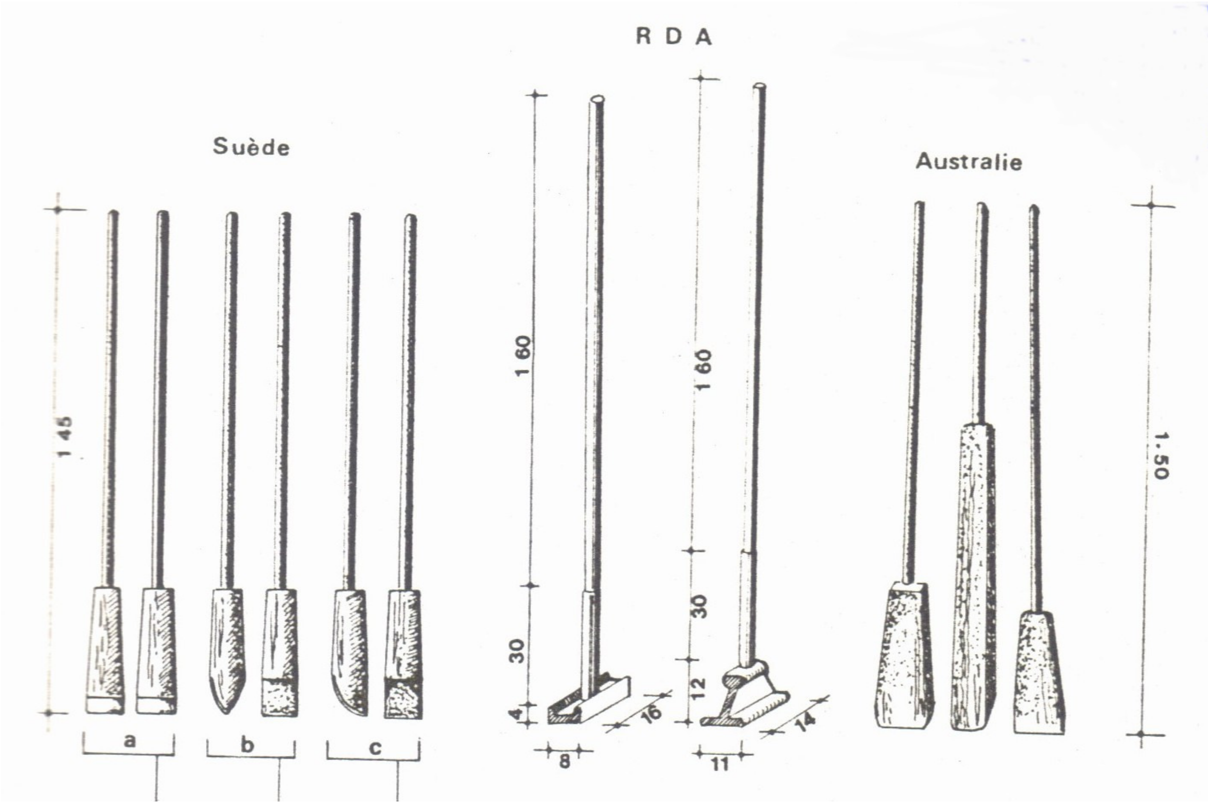
FIGURE 17 : DIFFERENTES PHASES DE LA REALISATION D'UNE BANCHEE

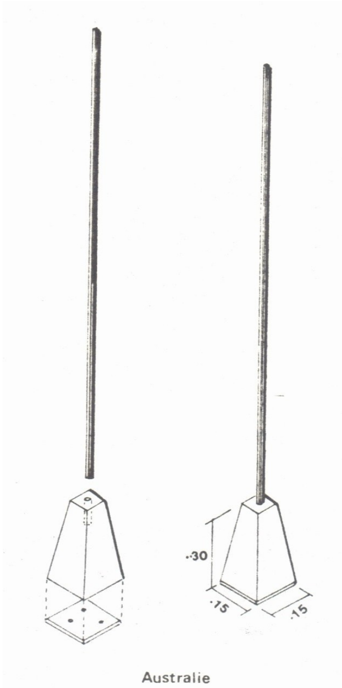


The different stages: a) first a base out of stones is made, allowing space for the future keys of the lower range; b) the wooden sheets are put up, sealed by mortar at their foot; c) the wall is rammed between the two sheets (the second missing here, for the view); d) a shovel stroke is given into the rammed part in order to lock the next stage into the first; e, f, g) the next lot is done; h) with preparation of the place for keys in the lower row, for the next row.

2) The traditional rammer

Here are a few examples of traditional hand rammers.





Australie

I) Protections

The earth walls being sensitive to water, it is important to protect them well, although the small content of cement improves considerably their resistance to water and wear.

The best protection consists in generous roof eaves.

When the walls are dry it is best to impregnate them on the exterior side with a water proofing sealer (for instance silicone based, water soluble) that allows the wall to breeze; it is important not to block the humidity transfers through the wall that has to react normally to humidity content and condensation; yet it is good to seal the surface against impacting rain and water, mainly against water chased by the wind during storms.

More traditional means exist, based on linseed oil. We did not experiment them. Probably they would generate many side effects like mould or coloration in the long term.

We did not research the different solutions as well as we would have liked.

On the inner side of the wall, it is good to impregnate the surface with a dust sealer, that has also to allow the wall to breeze normally. This will reduce or even stop the amount of dust the wall will produce on a long term inside.

When walls are fresh, it is good to wrap them in a plastic sheet or a tarpaulin if they are exposed to bad weather. Yet they should have the opportunity to be well ventilated in order to dry well and quickly, and to avoid the formation of mould. Beware that the wind can generate erosion in the walls when it makes the protection flap against the wall.

K) Timing

When we started building our rammed earth walls, we never thought that the time for moving the formwork (putting it up or down) would be such an important proportion of the work. We observe that the timing is approximately the following, where the time spent for ramming is indeed about the same as the time necessary altogether for preparing the soil and for moving the formwork.

For a wall 35cm thick, 2.8m wide, 2.4m high (2.4m3 or 6.7m2), assuming the brick base is already prepared. Soil is already at disposition in heaps nearby. Approximate timing for 2 workers - with no hurry:

Day 1 - after undoing the formwork of the precedent wall	
1) setting up the formwork for the first inferior half of the next wall (2 pairs of sheets, side by side), including setting up of the crane:	3.0 h
Day 2	
2) mixing the first lot of soil for the first half of the box:	0.5 h
3) ramming the first half of the box:	2.0 h
4) mixing the second lot of soil for the second half of the first box:	0.5 h
5) ramming the second lot of soil:	2.0 h
6) setting up the second (upper) part of the formwork:	2.0 h
Day 3	
6) setting up can be done at day 3 in order to have more regular working days	
7) mixing the third lot of soil for the first half of the second box:	0.5 h
8) ramming the third lot of soil:	2.0 h
9) mixing the fourth lot of soil for the second half of the second box:	0.5 h
10) ramming the fourth lot of soil:	2.0 h
Day 4 - before setting up the formwork for the next wall	
11) putting down the crane and undoing the formwork and cleaning:	2.0 h
TOTAL:	**17 h**

This is a 3 days rhythm, as the day 1 and the day 4 are in fact the same.
It would be possible to have longer workdays; yet 2 days of work in one would be excessive; and any measure inbetween could not allow to be quicker as the removing of the formwork can only be done the next day after finishing ramming.
Smaller walls, with only one pair of sheets in the length of the wall, could be done on a 2 days basis.
This time calculation does not include the preparation works like digging out of the soil or setting the bricks for the base of the walls or fixing the end walls to the structure. Yet it includes all works that have directly to do with the ramming process. Time spent for planning, ordering material, troubleshooting and repairs, is not included. This description is about the work process only.
This gives a total of 34h (17h for 2 people) for a 6.7 m2 wall, that is 5h work / m2 in average.

This timing is not a reference for speeding; the evolution of the work process depends on so many factors that can vary from one case to the next, even on the same building site, from one wall to the next or from one day to the next for the same job: weather conditions, reliability of material and machines, health and energy of workers, special cases, etc. This description wants only to show an amazing proportion in the way the time factor is a surprising component of the process, mainly because of the importance of the set up work.

L) Investment and costs

It is also interesting to describe the financial aspects of the work process although this can also vary considerably, given the wide variety of choices that can be made. The following example illustrates what we have spent in our case. It can be reduced to almost zero if one decides to work only with what is naturally available, providing therefore a much more important amount of physical work that has to be bartered in order not to necessitate cash. Although we had already the rammer and the cultivator, they are included in the following calculation as part of the investment. Although we used part of the joists of the building as whalers and did not have to buy so many whalers as described below, we include them in the following calculation as if we had to buy them as new whalers. Normal tools are not included as they are current ones most people have. Rounded figures below are in Australian dollars 2011. Approximately 1 AUS$ = 1 US$ = 0.75 Euro.

Total surface of the rammed earth walls we built: 90m2 / 32 m3.

In reality a first stage of the work has been executed with the help of a contractor to whom $ 6'000.- has been paid for this first stage (44 m2), work and machinery only, without material costs. Only the second stage has been executed as described above. The real cost of the first stage is also included in the calculation below so that the cost of the second stage can be compared with it.

1) Initial investment:

A) Machines:

Tractor is not included in this calculation:	0.-
Cultivator - Stevie (already our own - estimated):	100.-
Compressor - Mr Puffy - and accessories:	2700.-
Rammer - Cutesie (already our own - estimated):	700.-
Crane - wood + winch - not including 2 days work:	500.-
	-------.--
Total machines (for 90m2):	**4000.- i.e. 45.-/m2**

B) Equipment

Whalers - 22 x 4.8m:	1100.-
Z-bars, nuts and cones = 40 bars x 1.16m + 80 nuts:	500.-
Brackets - 80 pieces:	300.-
Wheelbarrows + shovels (already our own):	300.-
	-------.--
Total equipment (for 90m2):	**2200.- i.e. 25.-/m2**

2) Building expenses

C) Material + current costs

Bricks + cement + Alcor waterproofing:	600.-
Wood for fix end walls:	1000.-
Formwork sheets - 12 x 1.2 x 2.4m:	1200.-
Cement - 160 bags:	1600.-
Conduits:	100.-
Repairs for rammer, etc.:	300.-
Fuel (120 l), oil, turpentine:	200.-
Plastic sheet roll for protections + tarpaulins:	200.-
	-------.--
Total material (for 90m2):	**5200.- i.e. 58.-/m2**

TOTAL: 11400.- i.e. 127.-/m2

Work paid to contractor for 1st stage (44 m2): 6000.- i.e. 137.-/m2
Not including our own work = 220h for 44 m2, i.e. 5h/m2 too!

Conversion of work average
i.e. 90m2 at 5h/m2 at 25.-/h 11250.- i.e. 125.-/m2

3) Summary of costs

<u>1st calculation with repayment investment at 20% (on 5 years)</u>

1) Repayment of investment (A+B at 20%):	14.-/m2
2) Material (C):	58.-/m2
3) Only work paid to contractor + complementary work at 5h/m2 converted at 25.-/h (1st stage):	262.-/m2
4) Total material + work 1st stage:	320.-/m2
5) Repayment 20% + material (A+B+C) = cash payment without work:	72.-/m2
6) Including work as converted above (2nd stage):	197.-/m2
7) If work paid 40.-/hour instead of 25.-:	272.-/m2

<u>2nd calculation with repayment investment at 100%</u>
(i.e. completely because it is considered to be a unique experience)

11) Repayment of investment (A+B at 100%):	69.-/m2
12) Material (C):	58.-/m2
13) Only work paid to contractor + complementary work at 5h/m2 converted at 25.-/h (1st stage):	262.-/m2
14) Total material + work 1st stage:	320.-/m2
15) Repayment 100% + material (A+B+C) = cash payment without work:	127.-/m2
16) Including work as converted above (2nd stage):	252.-/m2
17) If work paid 40.-/hour instead of 25.-:	327.-/m2

The conclusion is interesting:

1) The first stage with the contractor (cost of material + work to contractor - see No 4 or 14) has been approximately as dear as the complete repayment of investment of the second

stage, including the same costs as counted for the first stage but with work converted at 40.-/h (100% repayment + cost of material + work at 40.-/h - see No 17).

2) The normal repayment at 20% and the real costs of material (total effective expense in cash for the second stage - see No 5) are less than a quarter (23%) of what the same job has cost with the contractor (see No 4 or 14). This is an important difference if work has not to be paid in cash. It alleviates indeed the financial charge by 77%!
3) We spent the same time working with the contractor as working by ourselves: in both cases 5h/m2, as if 4 people working together do the same job as 2! Of course we learned during the whole process, and became more effective at the end than at the beginning. A team of two people is certainly ideal.

3rd calculation for minimal costs

As earth building has to be a very affordable solution for people without cash, let's examine a possibility with minimal costs:

A) Machines: hand ramming with lift and cultivator

Cultivator - Stevie (already our own - estimated):	100.-
Crane - wood + winch - not including 2 days work:	500.-
	-------.--
Total machines	**600.- i.e. 7.-/m2**

B) Equipment: smaller formworks that have to be moved more often (see traditional formwork)

Whalers - 6 x 2.7m	200.-
Z-bars, nuts and cones = 10 bars x 1.16m + 20 nuts	100.-
Brackets - 20 pieces	100.-
Wheelbarrows + shovels	300.-
	-------.--
Total equipment:	**700.- i.e. 8.-/m2**

C) Material + current costs: smaller formwork, less cement

Bricks + cement + Alcor waterproofing	600.-
Formwork sheets - 2 x 1.2 x 2.4m	200.-
Cement - 100 bags	1000.-
Conduits	100.-
	-------.--
Total material:	**1900.- i.e. 21.-/m2**
TOTAL:	**3200.- i.e. 36.-/m2**

1) Repayment of investment (A + B at 20%):	3.-/m2
2) Material (C):	21.-/m2
5) Repayment 20% and material (A+B+C) = cash payment without work:	24.-/m2
6) Including work as converted above (5h/m2 and $ 25.-/h =125.-/m2):	149.-/m2

And the costs can still be reduced if more work is involved! Especially if work can be bartered, i.e. not paid cash.