Fabrication methods of the polygonal masonry of large tightly fitted stone blocks with curved surface interfaces in megalithic structures of Peru

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The article suggests methods that allow creating the most complicated type of polygonal masonry found in Peru. This masonry consists of large stone blocks weighing from several hundred kilograms to several tons fitted close to each other almost without a gap between complicated curved surfaces over a large area. The work provides a description of techniques, which apparently were used by builders who arrived from Europe. The techniques under discussion are based on the use of a reduced clay model, 3D-pantograph, topography translator and replicas. The use of a reduced clay model and a pantograph provides not only the unique appearance and high quality of masonry with large blocks, but also allows to significantly increase the productivity of the builders. As machines coping-scaling three-dimensional objects are known since the beginning of the 18th century, the stone structures under consideration should be dated by that and later time. The remaining simpler types of polygonal masonry with smaller stones or fitted surfaces are almost flat, or stones contact with each other by a small area, or there are significant gaps between stones, are quite consistent with the well-known methods of stone processing of those and earlier years, and, therefore, they do not require any additional explanations.

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1. Introduction

Polygonal masonry is a type of masonry made of natural stone. Stones having an initially arbitrary shape are processed in such a way that form irregular polygons tightly adjacent to each other on the front side of the structure.[1] It should be noted that the name “polygonal masonry” is largely conditional. The fact is that there are many structures classified as polygonal in which stone “polygons” have curved sections besides the linear ones. A feature of the polygonal masonry is that it does not require a building mortar (dry masonry). The polygonal masonry possesses sufficient strength and stability to withstand moderate earthquakes.[2,3,4,5]

In the present paper, a polygonal masonry in the megalithic structures located on the territory of modern Peru is under consideration. The main attention is paid to the masonry consisting of large stone blocks weighing from several hundred kilograms to several tons fitted close to each other almost without a gap between curved surfaces of large area. The remaining simpler types of polygonal masonry, when the stones are small or the mating surfaces are almost flat, or the stones contact each other over a small area, or there are significant gaps between the stones, are quite correspond to the long-known methods of stone processing and, therefore, do not require any special explanation.

The main building materials of those years were boulders and blocks of rock of random (arbitrary) shape. As a rule, this building material did not need to be mined (broken out in quarries), since it was presented everywhere in the form of multi-meter deposits of mountain debris formed at the foot of the mountains as a result of fallings and landslides. In most cases, this material did not even need to be transported from anywhere, since construction took place usually at those locations where the material was already in great abundance. If a megalithic structure was located on top of a mountain, then the construction material was taken (broken out) here on the site. That is why, for example, the top of the mountain, where the Machu Picchu complex of buildings is located, is cut off, and the tops of the neighboring mountains, where no one lives, are sharp.

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In general, a polygonal masonry is not something unprecedented, such masonry has been used in Europe since antiquity.[5,6] In the Peruvian version, only the quality of the curved interfaces is striking, which is not easy to repeat even in our time. The methods suggested by both the scientific-engineering community[7,8,9,10,11] and the enthusiasts[12,13,14,15] for fabrication of the Peruvian polygonal masonry do not explain all the observed features and are often far from a reality.

The methods of polygonal masonry fabrication proposed by the author are based on the use of a reduced clay model, a 3D-pantograph[16] (see Sections 2.1, 2.6, 2.8), topography translator (see Section 2.10) and replicas[7] (see Section 2.2). The main tools for stone processing are a hammer and a steel chisel (in practice, a set of steel chisels of different types). The use of the reduced clay model and the pantograph provides not only the well-known unique appearance and high quality of masonry of large blocks, but also allows to significantly increase the productivity of the builders. Only due to the high productivity it became possible to carry out the volumes of the polygonal construction revealed in Peru for an acceptable time, engaging a reasonable amount of labor force.

If we closely look at the shape of the stones in the masonry, at the sites of their almost perfect fitting, then there is a feeling that the stones were not processed mechanically but were sculpted. In this regard, many researchers mistakenly decided that the stones were sculpted or cast from a certain plastic mixture – artificial granite, concrete, lime, rock softened by heating, and so on.[12,13,14,15] In this regard, the question immediately arises: why produce an expensive plastic mixture when there is a lot of ready-to-use material around – natural stone of arbitrary shape? What is even more unclear is: why should plastic mixture be given such complex shapes? Why not make a limited range of standard concrete blocks with locking elements, for example? Nevertheless, sculpting really took place during the polygonal construction, but it was sculpting of a reduced model of the future stone block from clay, not the sculpting of the stone block itself. Further, using a pantograph, the “sculpture” was simply transferred to a stone block with the enlargement set in the pantograph by means of a hammer and a chisel.

There are other arguments against the plastic version. For example, the backside of many blocks is a ragged stone; there is no plastic mixture flowed into the interblock spaces inside the masonry; the stone blocks have veinlets and other features inherent in natural stone.[17] Unlike clay, concrete,[12] lime, and artificial granite are not suitable for hand modeling. Therefore, the blocks cast from these materials will have flat interface surfaces, as well as flat front and back sides, determined by the flat panels of the formwork used. Thus, if, for example, smooth L- or U-shaped recesses are present in the masonry, then, most likely, this masonry was not fabricated by the casting method generally accepted in construction (see also Section 2.1.1).

Any products obtained by casting/sculpting[15] shrink during the drying process. The shrinkage of modern concrete can reach 3%, lime shrinkage is noticeably greater. The casting shrinkage leads to casting size decrease, warping (shape distortion) and to cracking, as a result. Thus, the presence of cracks can be one of the casting hallmarks. The shrinkage-induced casting size decrease, in turn, leads to interblock gaps. Since the initial shape of the blocks in the polygonal masonry is irregular, the shrinkage in addition turns out to be non-uniform. Accordingly, the gaps resulting from such shrinkage will be non-uniform (nonparallel, see Ref. 13).

Thus, even if the blocks are cast sequentially one after another by site,[12,13] waiting each time for the end of shrinkage, it is still not possible to completely eliminate gaps between the blocks. For the reinforcement-free concrete block with modest sizes of 50×50 cm (width×height) having typical average shrinkage coefficient of modern concrete of 1.5%, the gap between the blocks makes 7.5 mm (!). The larger are the sizes of the blocks, the greater is the value of their shrinkage, and, accordingly, the larger is the resulting gap.

Fig. 1 shows an approximate view of the cast polygonal masonry of large blocks tightly abutted to each other. First, the large blocks are cast. After shrinkage termination, the polygonal masonry is assembled from the large blocks sequentially block by block (block installation order is shown with numbers in the figure). Each block is installed so that it abuts closely to an adjacent

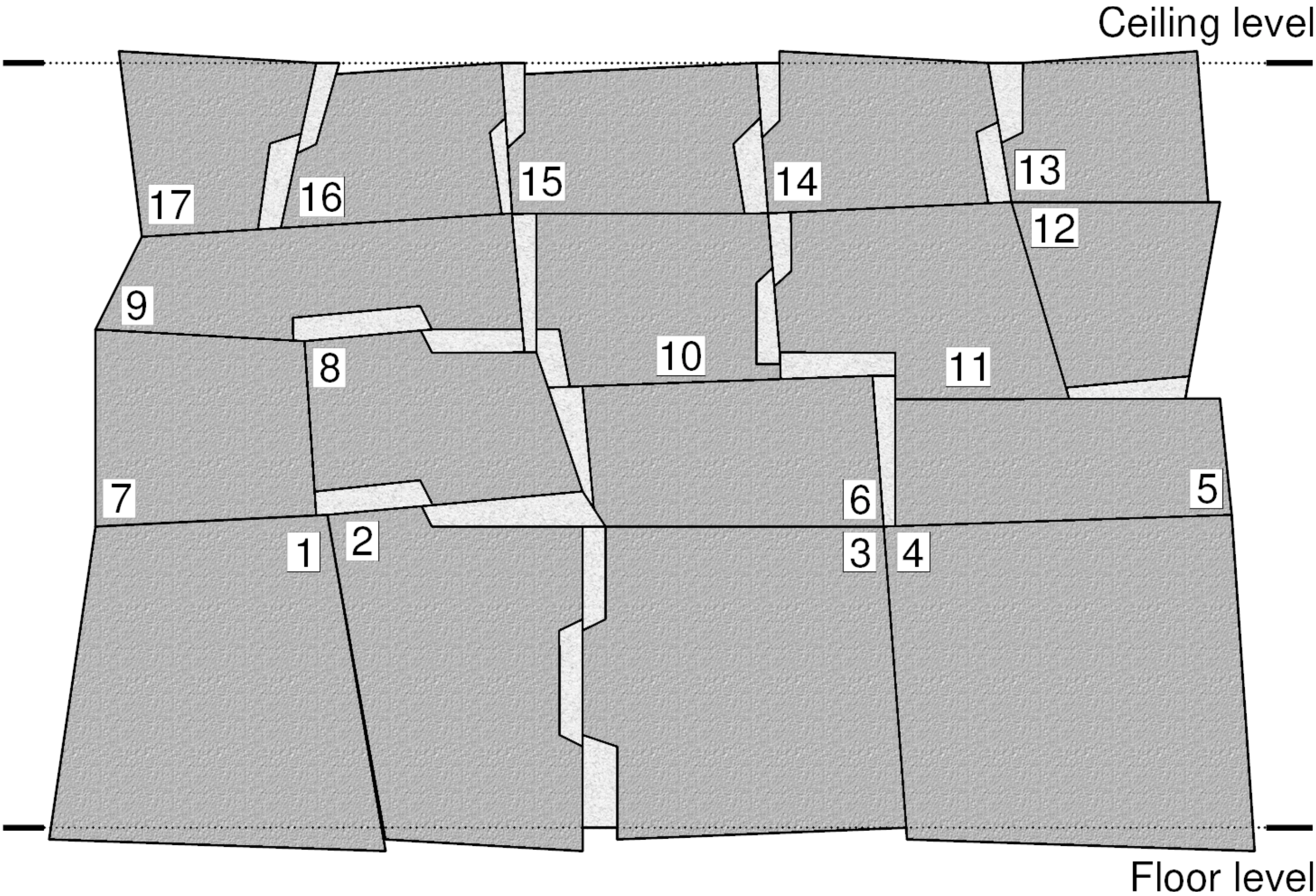

Fig. 1. The probable appearance of a casted polygonal masonry of large blocks tightly abutted to each other. The small blocks casted at the final stage are intended for taking up the inter-block gaps caused by a concrete shrinkage in the large blocks. Block deviations from the floor and ceiling levels due to a shrinkage are exaggerated for more clarity. The numbers show installation order of the large blocks.

previously installed block by a certain side. At the final stage, small (compensatory) spaces between the large blocks are filled with concrete (before casting, a thin layer of material is coated on the hardened concrete to prevent adhesion of the fresh concrete with the hardened one[12,13]). Note that the polygonal masonry obtained according to the described technology may not be completely dismountable in some cases.

It is seen from the presented procedure that the interface surfaces in the polygonal masonry obtained by casting should be planes and the masonry itself should have a rather specific appearance (see Fig. 1). Large non-edge blocks in such masonry are in contact with neighboring large blocks with only two of their sides, contacts of the rest sides occur through the small blocks with a small shrinkage of their own. The small blocks are designed to compensate for the shrinkage-related size reductions and shape changes of the large blocks. Only this approach allows to reduce to a minimum (but not to zero) the gaps between the concrete blocks obtained by casting.

The more sides a large concrete block has, the more the compensating inserts are required, accordingly, the more complex the formwork used is. Since there are no triangular blocks in the Peruvian polygonal masonry, the simplest shape of the block in this case is a conditional quadrilateral. The conditional quadrilateral occurs if one ignores the shape change of the large polygonal block related to inclusion of the compensation blocks in its body. Since a masonry similar to one shown in Fig. 1 was not found in Peru, the methods of casting into formwork were not used for fabrication of the polygonal walls from large blocks tightly abutted to each other.

Besides the mechanical treatment of stones by means of a hammer and a steel chisel, the proposed approach also allows casting large polygonal blocks into a mold (see Section 2.1.1). In this case, the tight abutment of polygonal masonry blocks is achieved due to high casting accuracy. According to this technology, the typical signs of the casting are: a solid/hollow core made of cheap concrete-like material and a comparatively thin shell made of more expensive artificial granite.

Since at the moment of the South America conquest by Europeans, the Indians did not know neither iron tools nor a wheel, and did not have draft animals, the structures under consideration could only be erected by the builders who came from Europe (see Section 2.15). Unlike the Indians, these builders had all the necessary tools, mechanisms, and skills for the large-scale construction. The marks of this large-scale stone construction are visible everywhere – Catholic cathedrals, monasteries, palaces, villas, and a lot of urban and industrial buildings. Any large-scale construction always implies the existence of an economy corresponding to this scale. Therefore, the article additionally explains what the economy of Peru was based on in those years (see Section 2.15). As machines coping-scaling three-dimensional objects are known since the beginning of the 18th century (see Section 2.14), the polygonal structures under consideration should be dated beginning from that time.

2. Methods of fabrication of the polygonal masonry

2.1. Clay model shape transfer to a stone billet by means of a pantograph

First, in accordance with a sketch, the clay model of a structure is made in a reduced scale which blocks form a polygonal masonry. Let us assume for a certainty that the structure is just a wall. Small polygonal blocks of the planned shape are sculpted from clay. The sizes of these blocks correspond to the sizes, say, of a basketball or so. The surface interfaces are formed by pressing the blocks into each other. To reduce shrinkage, a solid core of suitable shape – a stone or a piece of dry clay is put inside the clay blocks.

The model of the wall is assembled from the raw model blocks. During the assembly, some material is laid between the blocks that prevents the blocks from sticking to each other during the drying-solidification process. To reduce the influence of the shrinkage effect, the bottom course is dried first, then the next course, and so on. If necessary, the wall is given the required slope (see Section 2.5). During the drying shrinkage process, the model blocks are matched more closely under their own weight and with small corrections of the builder. If a shrinkage resulted gap appears between the model blocks, it is eliminated by putting clay layers of the corresponding thicknesses on the model blocks at their junction.

After model wall solidification, it is disassembled. Now the “magic” began. The Medieval European builders transferred the surface topography from a small model clay block to a large stone billet of suitable sizes and shape with a specified scale using a 3D-pantograph,[16] a hammer, and a steel chisel.

The pantograph is a simple hinge-lever device based on a parallelogram mechanism.[18] A 2D-pantograph allows to proportionally enlarge/reduce a flat drawing.[18,19] Being a logical advancement of the 2D-pantograph, a more complicated 3D-pantograph[20,21] (see Fig. 2) allows to proportionally enlarge/reduce a space figure, for example, a statue. In our case, using the 3D-pantograph, the enlarged copy of a small clay model of the block is obtained by processing the stone billet with a hammer and a chisel.

The parallelogram mechanism is located on a boom of the 3D-pantograph. The boom is attached to the frame using a ball joint (Pivot in Fig. 2). The boom has a counterweight. A sharp probe is fixed on one arm of the parallelogram mechanism (Pointer A), on the other – a pointer (a part actually similar to the probe; Pointer B in Fig. 2). If someone touches the clay model with a probe, the pointer will show where the corresponding point of the enlarged copy is located in the space. The enlargement coefficient is set by the appropriate adjustment of the arms of the lever system. The model and its enlarged copy are located each on their rotary platform (Table A and Table B, respectively). Due to a chain transmission, the platforms can be synchro-

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Fig. 2. Modern 3D-pantograph (M. Keropian, www.keropiansculpture.com).

nously rotated around their vertical axes, putting different sides of a 3D-object (model/copy) under the probe/pointer.

A minimum size of the model clay block depends on the size of the stone block under fabrication and, ultimately, is determined by the error of the pantograph mechanism. The size of the model block is also determined by how convenient it is for one or two workers to handle (sculpt, correct, carry, install, shift, turn, etc.) such a block. The modern 3D-pantographs used by sculptors[20,21] (see Fig. 2) allow enlargement of the object model by up to 6 times. Thus, by a clay block model size, say, 50×50×50 cm, which can be made hollow to reduce its weight and shrinkage, the stone blocks up to 3×3×3 m can be processed on a not very large pantograph.

It should be noted that by installing a stone billet on the pantograph, a clay model of the block suitable for this billet can be quickly selected. This feature is extremely useful exactly in the case of the polygonal type of masonry, since in such masonry, initial blocks often have a complicated shape that requires a lot of preliminary measurements while selecting a billet.

Photo. 1. Cusco (V. M. Soroka, 2021).

After the mentioned copying process with the specified scale, the wall of stone blocks is assembled without any adjustments using rollers, levers, blocks, winches, and primitive cranes of the time.[10,11] The front side of a stone block can be copied from the front side of a clay model, but it can be dressed or refined after the polygonal structure assembly.

When a polygonal masonry is built on a leveled reinforced ground, the first course is formed of not large stone blocks having a flat base, which are processed by the corresponding clay models. The stone blocks of the second course are usually noticeably larger than the blocks of the first course (see Photos. 1-5, for example). Why is that? Why are the large blocks of the second course not put on the equally large or even larger blocks? There should be good reasons for such a masonry arrangement. Indeed, the higher a large heavy block is located, the higher its gravity center is, the less stable the wall is. Moreover, the load bearing capacity of small stones is less than that of large ones.

As an example, let us consider the wall on the Hatunrumiyoc street in Cusco (see Photos. 1-5). Since the street has a slope, one might think that the small stones in the base of the large blocks of the wall are needed to account for this slope. However, there are sections of the polygonal masonry in this wall, where one course of stones splits into two or two courses merge into one. For example, in Photo. 1, moving from left to right, the second and the third courses merge into single course – the second course; and the fourth course splits into two courses – the third and the fourth. Thus, we see that the street slope could always be taken into account using the technique of masonry course merging/splitting.

In fact, everything is simple. Only by adding the soil under the not large blocks of the first course and putting small stones as wedges under them, it is possible to take up the side gaps between the large stone blocks of the second course, i. e., correctly locate these blocks relative to each other. Only provided that the relative position of the large blocks is correct, the rest above located courses can be laid with minimal gaps.

Photo. 2. Cusco (V. M. Soroka, 2021).

This peculiarity is one more confirmation that the wall of polygonal blocks of the type under consideration was not built course after course with fitting the stones by site,[9] but it was fabricated by a reduced clay model and then it was only assembled. During the course-after-course construction, the first course of the masonry would always consist of the largest stone blocks, since according to this approach, both the mounting surface for the next stone block and this stone block itself are successively made by site.

If the base of the not large stone blocks of the first course stands out of the general aesthetics of a particular polygonal masonry, then it can be hidden by a layer of soil (see Photos. 5, 10). The soil being added will be compacted and the inserted small stones-wedges can crack and crumble under the masonry weight, then the masonry will slide apart. To prevent such event, solid wedging stones having no visible defects should be used and not in one but in several places; the soil under the building should be well compacted; after laying the first two courses, the work on this site should be stopped and the masonry should be observed for some time, etc.

When a polygonal masonry is located on a bedrock, the bedrock is pre-prepared. For example, L- or U-shaped recesses are fabricated in the bedrock. Then, not large blocks of the first course are formed from clay on the prepared section of the rock, which are made hollow to reduce their weight and shrinkage. After drying, the full-sized blocks are removed from the bedrock and put in the pantograph in place of a stone billet (Table B in Fig. 2). Using the pantograph, reduced clay models are fabricated by the clay full-sized blocks of the first course. The obtained models are dried.

To avoid damage to the lower surface of the model blocks of the first course, the model blocks are put in beds with a flat base by pressing them into raw clay bars. The correct mutual position of the model blocks of the first course is determined by abutment of these blocks to each other along the side faces. To reduce the error of the relative position, one should aim to make the

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Photo. 3. Cusco (S. N. Kozintsev, photo.sirano.info).

areas of the side faces of the first course blocks comparable to the areas of the bases of these blocks. The correct mutual position of the first course blocks at the construction site of the model wall is reached by adding soil and putting small wedging stones under the beds of these blocks.

The proposed method of geometry transfer from a small clay model to a large stone block using a 3D-pantograph does not require the detailed drawing of the block geometry. The builder should actually sculpt approximately the block itself and its interface with the neighboring blocks in accordance to the general idea of the sketch with his own hands (applying tools such as s-patulas, straighteners, scrapers, wire loops, and the like); then lay this block in the model wall, where it would be finally fitted to the neighboring model blocks under its own weight and with small corrections of the builder. No precise dimensions need to be held here.

2.1.1. Fabrication of the polygonal masonry blocks by casting

Using the proposed method, it is also possible to obtain large blocks of concrete, lime, artificial granite and other materials by casting them into a mold. Using the pantograph, the reduced clay model of a block is enlarged to the desired size. The enlarged clay model is made hollow to reduce weight and shrinkage. Next, a mold is fabricated by the enlarged clay model.

Since shrinkage has a significant effect on the value of the interblock gap, the cast blocks can be made hollow to reduce it. Moreover, the cast blocks can be made of two components – a core (solid or hollow) of cheap concrete and a comparatively thin outer shell ("plaster" layer) of more expensive artificial granite. First, the core is cast. Then, after the end of the shrinkage, a fairly thin shell is cast over the core. Shrinkage of the shell is insignificant due to its small thickness.

Photo. 4. Cusco (V. M. Soroka, 2021).

The enlarged clay models for hollow/solid core and for the outer shell are fabricated by the same reduced clay model of the block using a pantograph set to the appropriate enlargement factor. To increase adhesion of the shell to the core, radial grooves are created on the front and side surfaces of the enlarged core model. The grooves are created either directly by the pantograph pointer (Pointer B), or by a wire loop attached to the pointer. Despite exfoliations on the granite blocks of some Peruvian structures that are similar to the described outer shell (see Photos. 1-3, 5 and 15), the thicknesses of these exfoliations are small and thus these exfoliations should rather be attributed to the results of natural stone destruction or unsuccessful restoration/conservation.

Although the proposed casting method is able to provide the fabrication of the polygonal masonry from large blocks tightly abutted to each other, in comparison with the mechanical processing method, it is much more laborious. The fact is that besides the reduced model, this casting method requires additional fabrication of two more clay full-sized models of the block at least, followed by fabrication of two molds by these models – one for the concrete core, the other for the shell of artificial granite.

The method can be simplified and made cheaper using as the core a roughly mechanically processed natural stone, which shape approximately repeats the shape of the final product in a reduced scale. However, in this case, the shell will definitely have a larger thickness that, in turn, would cause a shrinkage-related gap increase. Moreover, the resulting gaps will be uneven due to the varying shell thickness. The required stone block acting as a core can be fabricated either simply by basic dimensions or by the reduced clay model using the pantograph. In the method under consideration, the backside of the cast block may not have an outer shell

Photo. 5. Cusco (V. M. Soroka, 2021).

layer at all since in most buildings, taking up a gap between the blocks or taking care of the product appearance is not necessary at this location.

Since stone blocks in a polygonal masonry experience a weight load from several tons to several tens of tons, under certain circumstances, say, during tremors caused by an earthquake, destruction of the outer hard but fragile shell of artificial granite may occur. The listed features show that although the presented casting method is capable to provide the desired result (small gaps), it is too complex and expensive for construction purposes, and it does not guarantee the necessary structure durability in the earthquake-prone region.

2.2. Usage of replicas

Not very complicated interfaces between large blocks are fabricated using replicas. A “pancake” of a constant thickness is pressed/rolled out of the clay. The raw pancake is put on a stone block which surface replica should be made. After solidification, the replica-pancake is taken off. By periodically applying the obtained low weight replica-pancake to a heavy mating stone block, the excess material is gradually removed in the needed areas until full fitting of the replica to the block.

If a higher accuracy of the relief transfer is required than the replica-pancake is capable to provide, then a replica of the replica is produced. First, by applying a raw clay bar to the selected area of the stone block, an imprint of its surface is made. After solidification, another imprint is made in raw clay by the obtained replica. After drying, the replica of the replica is further used as a copy of the surface area of the stone block when making the mating part of the stone masonry.

In another method, a clay rim is installed along the perimeter of the selected area of the stone block, after that the resulting container is filled with gypsum. After solidification, the obtained replica is imprinted in a raw clay or, having installed a rim, one fill the resulting container with gypsum (the surface of the gypsum mold is precovered with a substance preventing bonding of the poured gypsum to the gypsum mold). After drying, the resulting replica of the replica is fur-

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Photo. 6. Ollantaytambo (C. Jansen, M. Düerkop, 2016, www.travel-badger.com).

ther used as a copy of the surface area of the stone block when making the mating part of the stone masonry.

The replicas were also used in the sites where the stone structures of large blocks were abutted upon rocks. The replica was taken from a pre-prepared rock section and then applied to the processing stone block or, vice versa, the replica was taken from a processed stone block and then applied to the processing rock. It all depended on what was more convenient in each particular case. Since very large stone blocks are like rocks – they being extremely difficult to move, the replicas were also used for joining large blocks to very large blocks and very large blocks to other very large blocks.

The larger are the sizes of a stone block, the larger and heavier are the replicas fabricated by it. Therefore, beginning from a certain size of the stone block, replicas have to be taken from sections of the stone block. To ensure the correct mutual position of the replicas on the processed mating surface of the block/rock, the sections of the neighboring replicas should be partially overlapped. The disadvantage of the replicas is a higher interface error of the surfaces of the adjacent blocks in comparison with the pantograph and a higher fabrication laboriousness in comparison with the reduced model of the block.

The advantage of the replica is that just one of the mating surfaces of the adjacent blocks is processed upon a model (replica); the original surface is processed arbitrarily (independently). In contrast to the replica, it is necessary to process both mating surfaces according to the model in the pantograph method. There are no arbitrarily processed surfaces in the pantograph method.

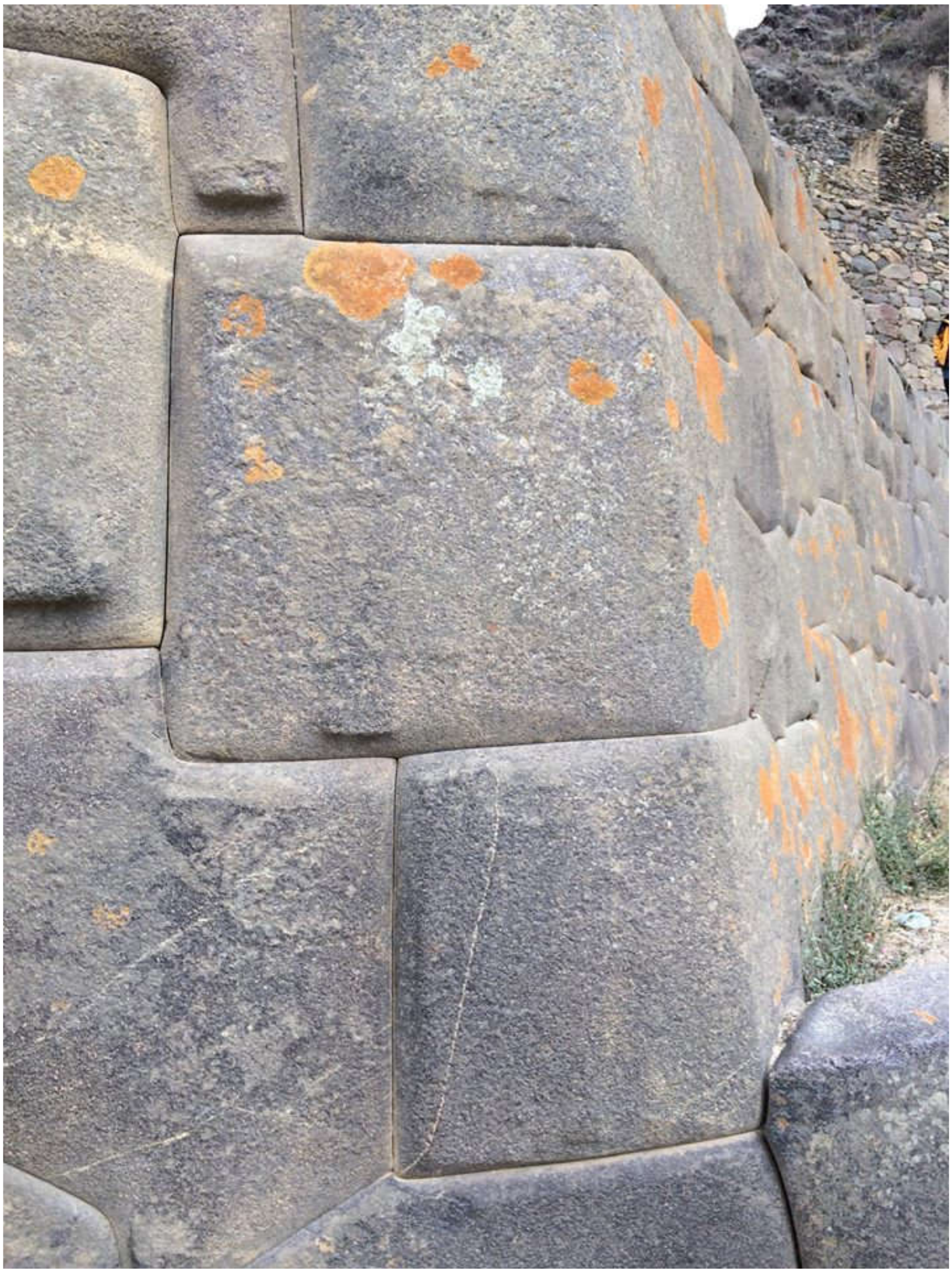


Photo. 7. Ollantaytambo (B. Everett, www.facebook.com/barry.everett.3).

2.3. The main problem

What does a stonemason has to continuously do while fabricating blocks fitted to each other through a complicated profile? The stonemason has to repeatedly apply one stone to another in order to determine the areas where the excess material should be removed. When the stones are small, it is easy to do. But how to do this when the weight of the stones is hundreds of kilograms or several tons? The suggested methods just allow us to solve this problem. It is no longer necessary to repeatedly move a heavy matching block.

2.4. What else a clay model of the object is needed for?

It is always extremely useful:

- to have a small model of an object consisting of many parts of a complicated shape connected to each other in a complicated way;
- to turn each block in hands;
- to evaluate proportions more precisely;

Photo. 8. Ollantaytambo (C. Boudou, 2013).

- to correct the blocks if something is not likable in their shape or fitting;
- to assemble/disassemble the model wall to check for the fundamental possibility of assembling an object containing key elements;
- to assemble/disassemble the model wall to analyze the operations for moving, mounting, and installing heavy stone blocks;
- to see in advance how the object will look after construction completion.

After all, in those days, architects and builders had no computers to rotate a component in three-dimensional space on a monitor screen or, creating a virtual reality, wander around the future construction long time before its erection. Even in our time, the making of scale models in architecture and planning has not lost its relevance.

It is well-known that the region, where the polygonal masonry was used, is earthquake-prone.[2,3,4,5] Therefore, by creating a model of the building with lock blocks and shaking it, one could see how the object would behave in an earthquake, and then, if necessary, make appropriate corrections to the project. Other methods did not simply exist in those times, the calculations were rough, and intuition and experience could fail.

As shown above, both the concrete castings and the clay models have a shrinkage. Consequently, in both cases, gaps caused by the shrinkage should occur between the blocks of the polygonal masonry. Then what is the advantage of the clay model? The fact is that if the gaps caused by the shrinkage occur in the clay model of the wall, these gaps can always be repaired by putting a thin clay layer on the clay model blocks where needed. In this case, any requirements related to the strength and durability of the added clay layers are simply not applicable, since the clay model is just an auxiliary element of the construction process not experiencing heavy loads, which is thrown away after a short use.

But it is useless to cover a concrete casting with a thin concrete layer of several millimeters thick, since the adhesion strength of this layer with the casting is low and this layer will very

Photo. 9. Ollantaytambo (B. Foerster, 2009, hiddenincatours.com).

soon fall off or collapse under weight load and/or weather conditions. A thicker layer can be applied to the concrete casting covering the entire casting surface rather than a separate region (see Section 2.1.1). This layer will adhere better, but the construction technology for such layer formation is too complicated and expensive.

Thus, the signs of a recent construction and/or unsuccessful restoration (Fortress Sacsayhuaman, Tarawasi) are: cracks in blocks, traces of concrete mortar application, layered structure of disintegrated blocks (formed due to the layer-by-layer building up of a “stone” body to eliminate gaps caused by shrinkage), large gaps between blocks and non-parallelism of these gaps, falling apart polygonal masonry.

On the upper faces of a number of dismantled stone blocks in Ollantaytambo, characteristic L- and U-shaped recesses for the bases of the blocks installed over draw attention.[8,9] Some of these recesses spread over two or even three adjacent blocks thereby providing bonding of the blocks. The recesses ensure in accordance with the principles of stable equilibrium that the blocks would return to their initial position in the event of a small horizontal displacement (along the wall) caused by an earthquake. The recesses under consideration in the upper faces of the blocks and the corresponding protruding parts at the lower faces of the blocks installing over are fabricated while sculpturing the clay model.

Since the clay model of the wall is building bottom-up and drying course after course, then, in theory, the shallow depressions should occur naturally in the bases of the model blocks, which, being softer (wet), weight down on the harder (dry) blocks located under them. The materials available to date do not allow us to confirm or disprove the presence of such depressions with certainty.

2.5. What are the advantages of a pantograph over a replica?

When we apply a replica to a processing extensive surface with a complicated topography, we do not clearly see where and how much material should be removed. Therefore, when working with a replica, we need to mark it with something, say, chalk or charcoal, and, while applying it to the processing surface area, slightly rub it to mark the locations where the material should be removed. Remember, what the dentist does after filling the tooth. He puts a piece of carbon paper on the filling and asks to close your mouth and slightly rub it with teeth. After that, the dentist

Photo. 10. Temple of Ten Niches, Ollantaytambo (P. Adams, 2012, manboyinthepromisedland-dotcom.wordpress.com).

removes a little bit of the filling material in the marked place. Then he repeats the process several times, until the teeth when closing take the usual position.

Working with a pantograph, a sharp probe (Pointer A) is applied to the clay model, and a pointer (Pointer B) mechanically connected to the probe by means of a parallelogram mechanism is applied to the processing surface of the billet. In contrast to the replica, due to the small area of the probe and the pointer, the topography measurement is actually carried out at a surface point, and it is clearly visible at what exact point; the entire surface is completely open.

Moreover, the pantograph allows one to clearly determine the thickness of the material to be removed at any point to which the pointer is directed. Therefore, the excess material can be removed for significantly fewer attempts. All these result in increasing productivity abruptly. The highest productivity is achieved when two people work on a pantograph. One person with a pantograph pointer shows a location (point) on the stone billet and reports the thickness of material that should be removed at this point, and the other person with a hammer and a chisel removes the specified amount of the material.

Another advantage of the pantograph in comparison with the replica is that it is much faster and easier to touch the clay model of the block with the almost weightless probe (the device is balanced by a counterweight) than to apply a relatively heavy replica to a stone billet, and then in addition to slightly rub with this replica by the billet.

Also, the pantograph allows to easily keep proportions set by the architect, that, in case of the replicas, have to be done by eye by spending a long time by selecting billets of suitable size. Imagine that you need to accurately fit a structure into some unchangeable or difficult-to-change dimensions, say, between two rocky outcrops or into a cave. To do this, it is enough to measure the distance between the rocky outcrops, the size of the model, divide first by second and set the obtained enlargement factor in the pantograph.

What else does the use of the clay model blocks and the pantograph give? Let the outer side of the wall is needed to be made with a slope. To do this, it is sufficient to lay a raw clay model of the wall on the back side, to install the stops that set the required slope, to put a flat surface on top of the front side, to allocate suitable weights above. Instead of the weights, tightening clamps can be used. After some time, the clay model of the wall will be deformed properly. In this method, the specified angle can be kept very accurately along the whole length of the wall.

Photo. 11. Temple of Ten Niches, Ollantaytambo (A. Fuchs, 2008, sy-akka.de/wordpress).

2.6. Reverse approach: clay model creation by a stone billet, fabrication of an interface surface and its transfer to the stone billet

According to the method described above, first, a model was created by a sketch, and then a stone billet was selected for each block of the model. This approach allows us to repeat many times a section of the wall (if necessary, at different scales) using the same clay model each time (see a possible example of such masonry in Ref. 22). The drawback of the method is the large volume of the chipped off material of the stone billet. The analysis shows that a reverse method was mainly used for the polygonal masonry.

In the reverse method, first, a reduced clay model is created by a stone billet of arbitrary shape using the pantograph. To do this, a piece of raw clay is impaled on a pointed, say, three/four-sided metal pin located in the center of the rotating platform intended for a model (Table A in Fig. 2). Due to this pin, the model can be removed from the pantograph at any time and precisely returned to its original position.

Clay is added to those places of the model where it is not enough. Removal of clay excess is carried out directly with the metal pointer (Pointer A in Fig. 2; instead of a tip, a suitable tool can be attached to the pointer, for example, a wire loop, cutter, scraper, etc.) of the pantograph, which probe (Pointer B) moves along the surface of the stone block vertically up, then a small turn of the platform with the billet (Table B) around the vertical axis, then down, again a small turn, again up, etc.[20] Owing to the pantograph, creation of the clay model body does not take much time.

At the next stage, a prototype of the wall is assembled from the obtained clay model blocks. The blocks still have no specially prepared mounting surfaces. Taking into account the size and the shape of the blocks, each block location is defined in the wall prototype. An architect-builder approximately layouts the contours of the future interfaces on the clay model of the wall, which should reflect: a conceived style, ensure stability of the created polygonal masonry, and minimize the labor of processing of the mounting surfaces. Further on, according to the accepted layout, the clay is cut out in the model block regions by which the blocks will adjoin each other.

Next, the wall model is being assembled from the obtained model blocks. By small corrections, the blocks are matched more precisely to each other. If the block model was occasionally damaged during the manipulations, the shape of the model in any location can always be restored by placing the block model back on the pantograph (on the above indicated pin) and by comparing with the shape of the original stone billet. Then the wall is being dried. First, the bottom course is dried, then the next one, and so on. During the drying shrinkage process, the model blocks are matched more closely under their own weight and with small corrections of the builder. If a shrinkage resulted gap appears between the model blocks, it is eliminated by putting clay layers of the corresponding thicknesses on the model blocks at their junction.

At the final stage, the model wall is being disassembled. The clay model of the block is put back on the pantograph (on the above indicated pin) and the mounting sites are transferred on the stone billet corresponding to this model block using a hammer and a chisel.

In the described method, the stone block is installed in the pantograph at least twice. To accurately return the stone block to its initial position, two lines radially diverging from the center of the platform (Table B) can be plotted on the platform. At the first installation of the stone block, alignment marks are applied to the surface of the stone with paint in the places where the lines come out from under the block.

2.7. Several more advantages of the pantograph

The use of a reduced clay model and a pantograph allows to fabricate blocks directly in the quarry where the stones are extracted.[8,9] As a result, the finished stone blocks are carried from the quarry to the construction site. This approach significantly reduces the weight of the transported blocks and decreases the volume of the whole cargo traffic. Moreover, such organization excludes a large amount of construction debris on the construction site, which needs to be also transported somewhere after all.

Both the pantograph method and the replica method use auxiliary elements. In the pantograph method, these are the clay model blocks; in the replica method, these are the replicas themselves. To mate stone blocks in the replica method, the side surface of the block must be divided into several overlapping sections, each of which requires its own replica. If you mentally attach to the side surface of a non-edge stone block all the replicas made for it and by it, you will get a kind of a wheel, i. e., a fairly massive formation. If a replica of replica is used, then there will be two such “wheels” already. Thus, it is necessary to fabricate one “wheel” of replicas for each non-edge block in the replica of replica method. Let us compare such a “wheel” of replicas with small model blocks in the pantograph-based method. The advantages of the pantograph are obvious.

2.8. A method combining elements of the replica, clay model, and 3D-pantograph methods

In the beginning, every second stone block of the first course is installed on the site of the future structure (see Fig. 3). The empty positions between these blocks will be occupied by stone blocks, which will be fitted to these initially installed blocks at the next stage using a clay model and the pantograph. The heights of the stone blocks installed between the initial blocks should be approximately 2 times the heights of the initial blocks. The base surfaces of the initially installed stone blocks are pre-treated properly to ensure their stability.

Besides the prepared base, the initially installed blocks have finally processed side faces also. The processing of the side faces is the straightening of the complicated initial shape of the stone billet by surfaces close to the planes with a hammer and a chisel. The slopes of the side faces of the initially installed blocks to the bases of these blocks should not exceed 90°, if pos-

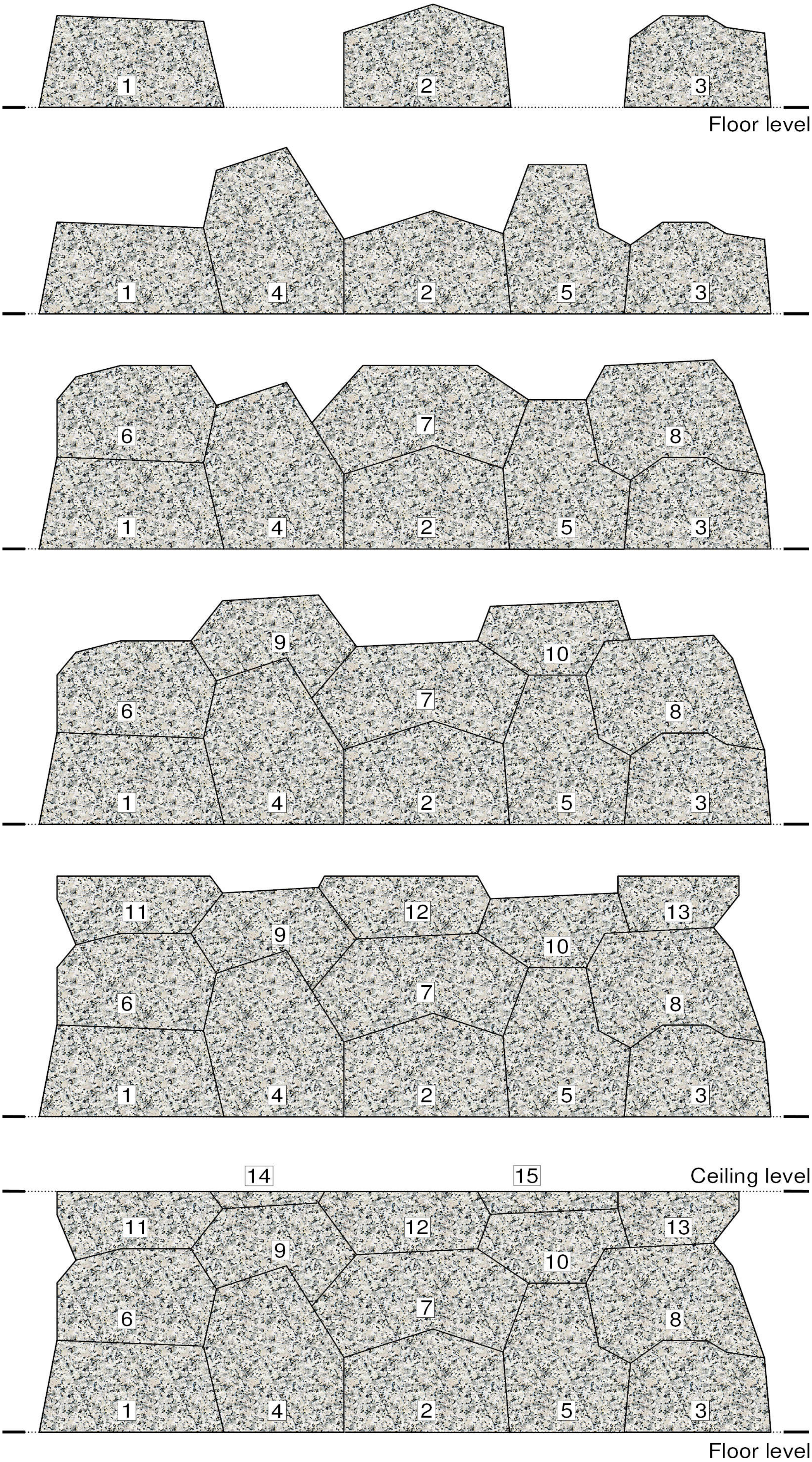


Fig. 3. Method of laying of polygonal blocks combining elements of the methods of replica, clay model, and 3D-pantograph. The numbers show installation order of the blocks.

sible, in order to facilitate the subsequent installation of the adjacent blocks. The similar rule is applied later for every second block of the subsequent courses of the polygonal masonry.

Photo. 12. Ollantaytambo (B. Everett, www.facebook.com/barry.everett.3).

Next, the space between the initially installed blocks is filled with clay. Actually, clay models of the blocks are created at the scale 1:1 in the spaces between the initial blocks. The side surfaces of these models contacting at the left and at the right with the side surfaces of the initial blocks are, in fact, their replicas. To decrease weight of the full-sized clay models and reduce their shrinkage deformations during drying, the models are made hollow. If a shrinkage resulted gap appears between the initial stone block and the clay model, it is eliminated by putting a corresponding thickness clay layer on the clay model.

After drying, the clay model of the block is removed from the structure and installed in the pantograph on the place of a model (Table A). The corresponding stone billet is installed on the place of a copy (Table B). The pantograph is adjusted to the scale 1:1 (at the given scale, the placement of the model and the copy in the pantograph is only determined by the operation convenience). If necessary, one can quickly check the matching of the selected stone billet to the model with the pantograph.

Next, the interface surfaces are transferred from the full-sized clay model to the stone billet using the pantograph, hammer and chisel, as described above. After transferring the interface surfaces, the rest (arbitrary) faces of this block are formed on the remaining side surface of the stone billet. The processing of these faces is the straightening of the complicated initial shape of the stone billet by surfaces close to the planes. Further, these faces will no longer be processed. The stone block obtained this way is finally put in its place in the polygonal masonry.

Having finished the first course, the next one is produced in the same way. As in the above methods, the stone blocks of an arbitrary shape are used in the described method. The method provides good vertical bonding of the blocks. Since the method has no full-fledged clay model of the structure, in order to put together the original stone blocks well and thereby minimize the amount of material to be chipped off during processing, it is desirable to preliminarily lay out the stone blocks on the ground with the back side down, one next to the other.

The method disadvantage is the high laboriousness associated with the fabrication of the clay model of the block on the scale 1:1. Nevertheless, in comparison with the replica replica

Photo. 13. Ollantaytambo (I. Otkalo, 2015, peru-info.me).

method, this method is capable to provide a much higher accuracy of the interface between the contacting surfaces when it is necessary. As in the replica cases, about half of the side surface of the stone blocks is processed arbitrarily in this method.

The Wall of Six Monoliths at Ollantaytambo (see Photo. 14) consisting of one conditional course was most likely constructed according to the described method. One should pay attention to the small stones on which the monoliths rest. These stones ensure taking up the side gaps between the monoliths and the lowest narrow vertical inserts (see Section 2.1). Apparently, at the final stage of the construction, the small stones in the base of the monoliths were supposed to be hidden by a floor level.

Leaving aside the architectural appearance of the monument for a while, let us ask the question: why are the monoliths not connected to each other directly, but require intermediate inserts? The fact is that the use of replicas on such extended contact areas of the side surfaces of the monoliths is unable to provide a zero gap. Therefore, the intermediate inserts were needed to connect the monoliths.

To emphasize the gigantic dimensions of the monoliths, the inserts should significantly differ from the monoliths in width. Since fabrication and installation of a single narrow monolith-high insert is even more difficult technical task than the direct fitting of the neighboring monoliths, the intermediate inserts were divided into 3-5 separate parts. Each insert was fabricated and installed sequentially one after another – first, a row (conditional) of the lowest inserts, then the next row of inserts, etc.

2.9. "Planetary" pantograph for use in construction

Modern pantographs used by sculptors have two synchronously rotating platforms. A model is installed on one platform (see Table A in Fig. 2), and the enlarged copy of the model is installed on the other platform (Table B). Usually the enlarged copy is hollow, so the weight of the copy is not high, as a rule. The platform of such pantograph used for construction purposes is capable to withstand stone billets weighing up to 700 kg. When a sculpture is large and heavy, its model can be divided into several parts. An enlarged copy can be fabricated for each such part; then a large sculpture is assembled from the obtained enlarged copies. However, this is not our case.

The modern pantograph is not suitable for working with large and heavy billets. Instead of the existing design, one can offer the following "planetary" pantograph. The heavy billet in such pantograph is simply installed on a plane site and the frame, to which the pantograph boom and the platform with the model are attached, is turning during work in the horizontal plane around the stationary standing billet. As the frame turns, the model also turns around its vertical axis at the required angle (actually retains its original orientation in the space) using an appropriate mechanism. One revolution of the support point (Pivot in Fig. 2) of the pantograph boom around the billet corresponds to one revolution of the model around its axis.

In contrast to the existing pantograph, the planetary pantograph occupies more space, and the person using the pantograph has to move while working along with the turning frame around the billet. These features can be attributed to the shortcomings of the planetary pantograph, which, however, are not critical in the construction field at all.

2.10. Topography translator based on the dual parallelogram mechanism

One can suggest a simple mechanical device – a topography translator (see Fig. 4), which, in the case of a relatively simple polygonal masonry, allows to perform quite acceptable joining of the surfaces of adjacent stone blocks "by site". To process by utilizing this device, both the mating stone blocks are put on the ground on their backsides. Thus, the base, the top side, and the lateral sides to be processed would be arranged vertically in this method.

First, the mating area of the surface of the first block is subjected to an arbitrary processing. During the processing, the surface in this area is made smoothly changing, close to a plane. Such a surface is obtained when a stonemason makes a flat surface manually "by eye" controlling no deviation of the treated surface from the plane in any way.

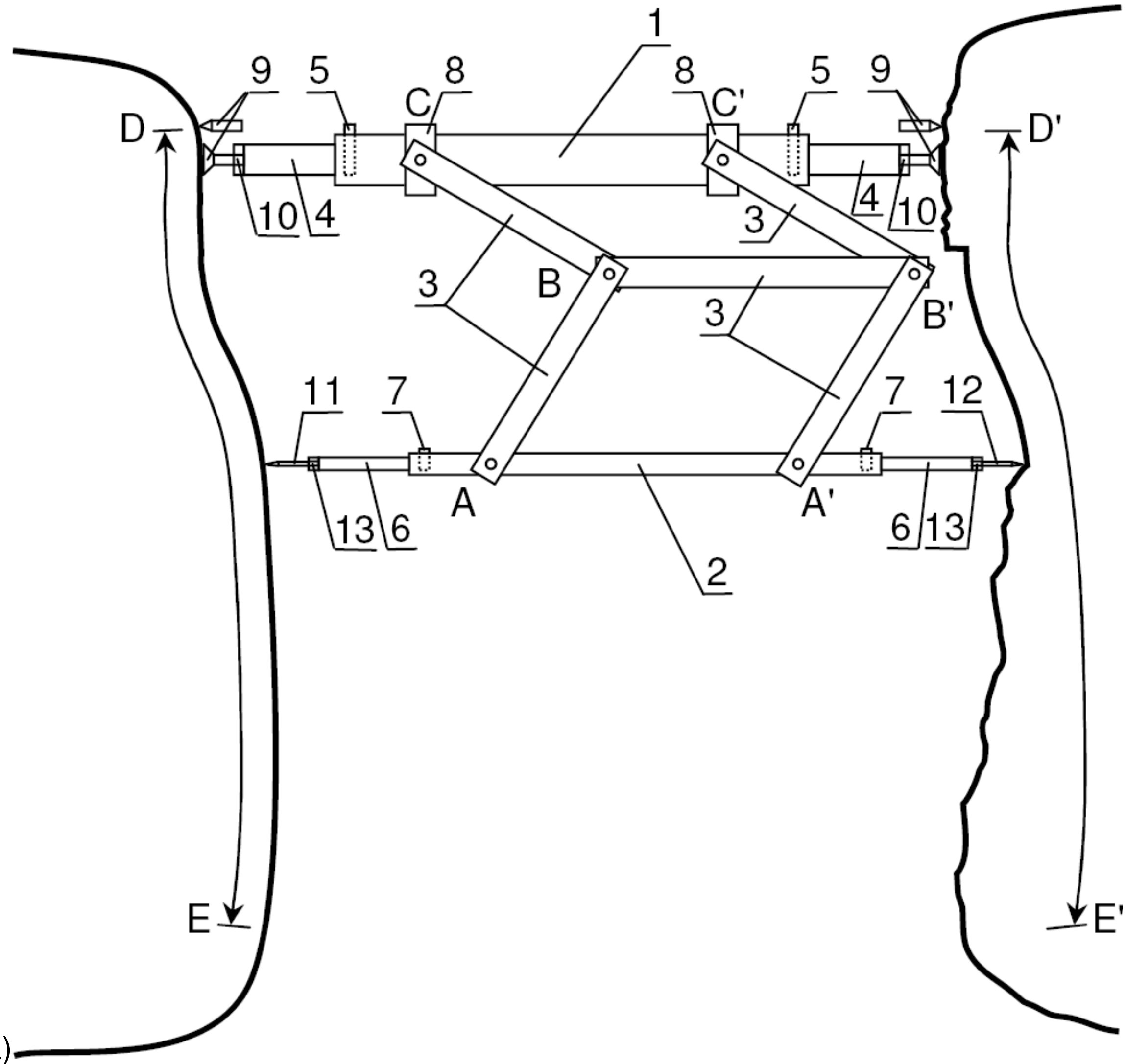
Then, near the first block, a second stone block is put. The second stone block is located so that the surface areas under fitting are opposite each other. The distance between the blocks is set such (60-80 cm) that a stonemason could accommodate between the blocks and would be able to work with a hammer and a chisel in the space between these blocks without much trouble. Further, the proposed topography translator is installed between the blocks as a thrust using which the stonemason transfers the reversed topography of the previously treated surface area of the first block to the second block.

In general, the lateral surface of the stone block is a set of these conditionally flat surface areas. The conditionally flat sections can adjoin each other forming a sharp boundary or they can pass into each other smoothly through the L-shaped recesses. The U-shaped recesses are reduced to a pair of counter-located L-shaped recesses. Let us describe below in more detail the design of the translator and the processing sequence of the stone blocks.

2.10.1. Design of the topography translator

The topography translator consists of two parallel rods connected to each other by means of a dual parallelogram mechanism (see Fig. 4). The dual parallelogram mechanism belongs to the hinge-lever guiding mechanisms, has two degrees of freedom and consists of seven links (AB=A'B'=BC=B'C', AA'=BB'=CC').[18] In the translator under consideration, the rod bodies are part of the dual parallelogram mechanism. The rod with a bigger cross-section will be called a carrying rod; the rod with a smaller cross-section will be called a measuring one. Due to the telescopic or other jointing, the lengths of the rods can be coarsely changed by sliding in and out the edge sections along the rod. After the end of the rough adjustment of the rod lengths, the relative positions of the edge sections are fixed with pins.

Tip-supports are screwed into the ends of the carrying rod, which unscrewing securely fixes the translator rod in the burst on the treated area between the mating stone blocks. Pointed tips are screwed into the both ends of the measuring rod. The pointed tip directed to the pre-treated surface of the first block will be called a probe; and the pointed tip directed to the processing surface of the second block will be called a pointer. By screwing in/out the threaded pointed tips,

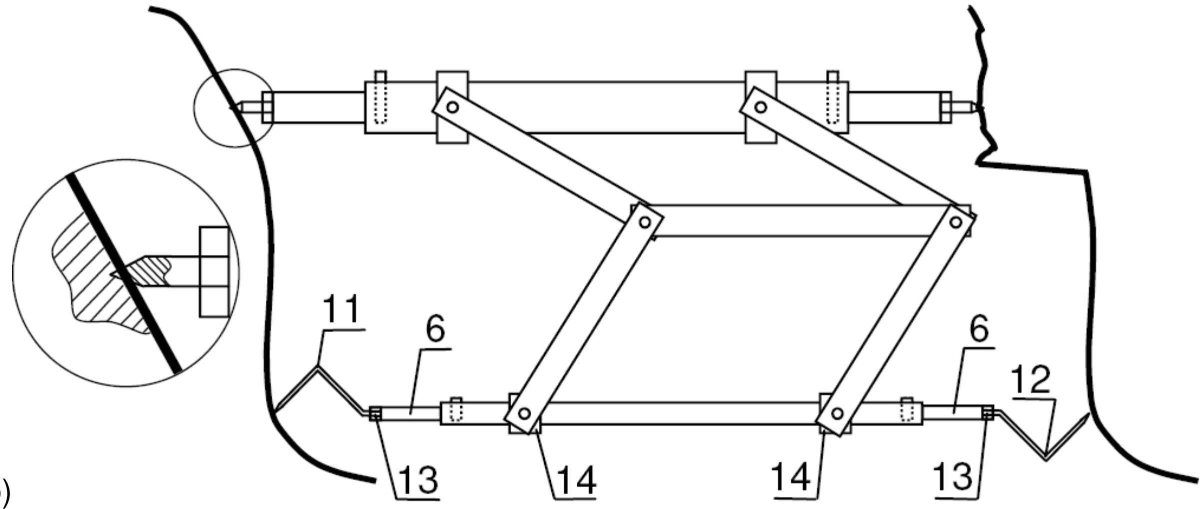


(a)

Fig. 4. Topography translator: 1 is a carrying rod; 2 is a measuring rod; 3 is a dual parallelogram mechanism (AB=A'B'=BC=B'C', AA'=BB'=CC'); 4 are retractable sections for coarse set of length of the carrying rod; 5 are pins locking positions of the retractable sections of the carrying rod; 6 are retractable sections for coarse adjustment of length of the measuring rod; 7 are pins locking positions of the retractable sections of the measuring rod; 8 are cylindrical hinges providing free rotation of the measuring rod along with the dual parallelogram mechanism around the carrying rod; 9 are supports (pointed or with a flat foot) of the carrying rod which unscrewing sets the carrying rod as a thrust between two mating stone blocks; 10 are lock-nuts fixing positions of the supports of the carrying rod; 11 is the probe of the measuring rod; 12 is the pointer of the measuring rod; 13 are the lock-nuts fixing positions of the probe and pointer of the measuring rod; 14 are cylindrical hinges providing free rotation of the measuring rod around its own axis; DE is the arbitrarily-processed section of the side surface of the previous stone block; D'E' is the section of the side surface of the current stone block processing with the translator. Installation of the carrying rod as a trust between the blocks (a) perpendicular to the mating surfaces using flat foot supports, (b) at an angle to the mating surfaces using pointed supports. (b) Translator with additional hinges, bent probe and bent pointer for working with U-shaped recesses.

the length of the measuring rod is set precisely. The set positions of the supports and the pointed tips are fixed with lock-nuts.

If the carrying rod is installed in the spacer between the blocks perpendicular to the mating surfaces, then supports with flat feet are used (see Fig. 4a). If the carrying rod is installed in the spacer with a significant inclination to the mating surfaces, then the pointed supports are used (see Fig. 4b). In the latter case, before installing the carrying rod, small recesses are made in



(b)

Fig. 4. Continuation.

the stones at the locations of the supports installation. The recesses are necessary to prevent slipping of the supports of the carrying rod.

Since the translator must transmit the spatial topography of the surface, and the dual parallelogram mechanism has only two degrees of freedom, the parallelogram mechanism is attached to the carrying rod through the cylindrical hinges. Thus, due to the cylindrical hinges of the carrying rod, the measuring rod together with the dual parallelogram mechanism can freely rotate around the carrying rod. Such rotation makes it possible to “readout” the topography by means of the measuring rod around the installation position of the carrying rod.

2.10.2. Outlines of the working techniques with the topography translator

If the carrying rod of the translator is installed near the location where the distance between the blocks is the longest, then the longest distance is set in the measuring rod by site, and the topography transferring starts from this location. Generally, the carrying rod can be installed in any location convenient for the stonemason. In practice, it is often convenient to install the carrying rod closer to the block edge, and to begin topography transferring-inversion (translation) from the block edge.

After installing the carrying rod and setting the necessary length of the measuring rod, the probe tip of the measuring rod is applied to the pre-treated surface of the first stone block (shown in the figure on the left). As a result, the pointer tip of the measuring rod will show the spot on the counter processing surface of the second block (shown in the figure on the right), where the stonemason should chip off material. Also, the pointer tip of the measuring rod will show the thickness of the chipping off material at this spot. The main purpose of the dual parallelogram mechanism is to ensure strict parallelism of the movement of the measuring rod. It can be seen from the above description that the translator under consideration provides on a separate mating section the same result as the 3D-pantograph adjusted to the scale 1:1.

Translator accuracy is determined by gaps in the hinges and by bending deformations of the structural elements of the mechanism. To ensure structure rigidity, the bars and hinges used in the parallelograms have the appropriate cross-section sizes and stiffeners (not shown in the figure). To increase structure rigidity, besides the mentioned parallelogram mechanisms, additional identical parallelogram mechanisms can be used by attaching them both in parallel and in series (along the rods).

The translator mechanism has a limited movement space, which is a cylinder of 2AB radius (the axis of the cylinder is the carrying rod). Therefore, when working with large blocks, it is impossible to process the entire mating surface in one installation of the translator. Moreover, due to the finite dimensions of the parallelogram bars, the hinges and the rods themselves, the area in the immediate vicinity around the installation location of the carrying rod and at this very spot also turns out to be untreated (see Fig. 4).

Thus, after processing the area of the mating surface reachable by the measuring rod, the position of the measuring rod is fixed at the edge of the processed area in the spacer by slightly unscrewing the probe and/or the pointer from the rod. After that, the carrying rod is released and transferred parallel to the measuring rod fixed in space at a new position, where it is again fixed in the spacer. Finally, the measuring rod is unfixed, and work continues on a new area of the stone block adjacent to the previous one.

In order not to upset the specified length of the measuring rod and not to blunt its probe and pointer installing the measuring rod in the spacer, it is possible to move the measuring rod to the edge of the translator's travel range before removing the carrying rod, and mark with a paint the spot that the probe touches and the spot that the pointer looks at. After that, the carrying rod can be unfixed, moved and installed with its supports on the spots marked with the paint. Note that, having a number of such marks and using the translator as an inspection tool, it is possible to accurately return the stone blocks to their original position to continue processing, if they were moved for some reason before. The necessary fixation of the block position in space is provided by installing wedging stones between the backside of the block and ground.

The above described process of topography transfer shows that if one provide the carrying rod with the same pointed tips as the measuring rod has, and make the measuring rod as thick as the carrying one, and also provide the measuring rod with the same cylindrical hinges (pos. 14 in Fig. 4(b)) as the carrying rod has, then we get a modification of the translator of symmetrical design, where there is no difference between the carrying and the measuring rods. Such translator may be more convenient while moving it over the stone surface being processed, however, it will have a heavier and less sharp probe-pointer.

Above, the conjugation of two adjacent blocks over one section was described. The next section will demonstrate how the polygonal masonry as a whole could be created using the proposed translator.

2.10.3. The sequence of processing by the translator of stone blocks in polygonal masonry

First, the stone blocks forming the first course of masonry are processed. For the first block of the first course, a stone of arbitrary shape is taken (see Fig. 5, pos. 1), in which the side faces (base, top side and lateral sides) are formed (pos. 2). The processing of the side faces is arbitrary – the original irregular side surface of natural stone is replaced with a set of approximately flat faces. Next, these faces will no longer be processed. The block obtained as a result of processing is put on ground backside down. Further, processing, fitting and quality control of interfaces between the adjacent blocks will be carried out for this orientation of the blocks.

For the second block of the first course, the next stone of an arbitrary shape is taken, in which a base is fabricated. Then, the block is located next to the first block (pos. 3), the translator is installed between the blocks, and the topography is transferred from the side face of the first block to the side face of the second block (the copied area is shown by a bold line). The translator in Fig. 5 is represented schematically. To avoid overloading of the drawing with details, the movements of the carrying rod over the processed area related to the exhaustion of the translator range are not shown hereinafter.

After fabrication of the interface area, the blocks are joined (pos 4). After that, on the remaining side surface of the stone billet of block 2, rest (arbitrary) faces of this block are formed (pos. 5). As before, the processing of these faces is flattening of the complex initial shape of a stone billet by surfaces close to planes. The above steps are repeated for the third, the fourth (pos. 5-10) and, if necessary, for the subsequent blocks of the first course. Having completed the con-

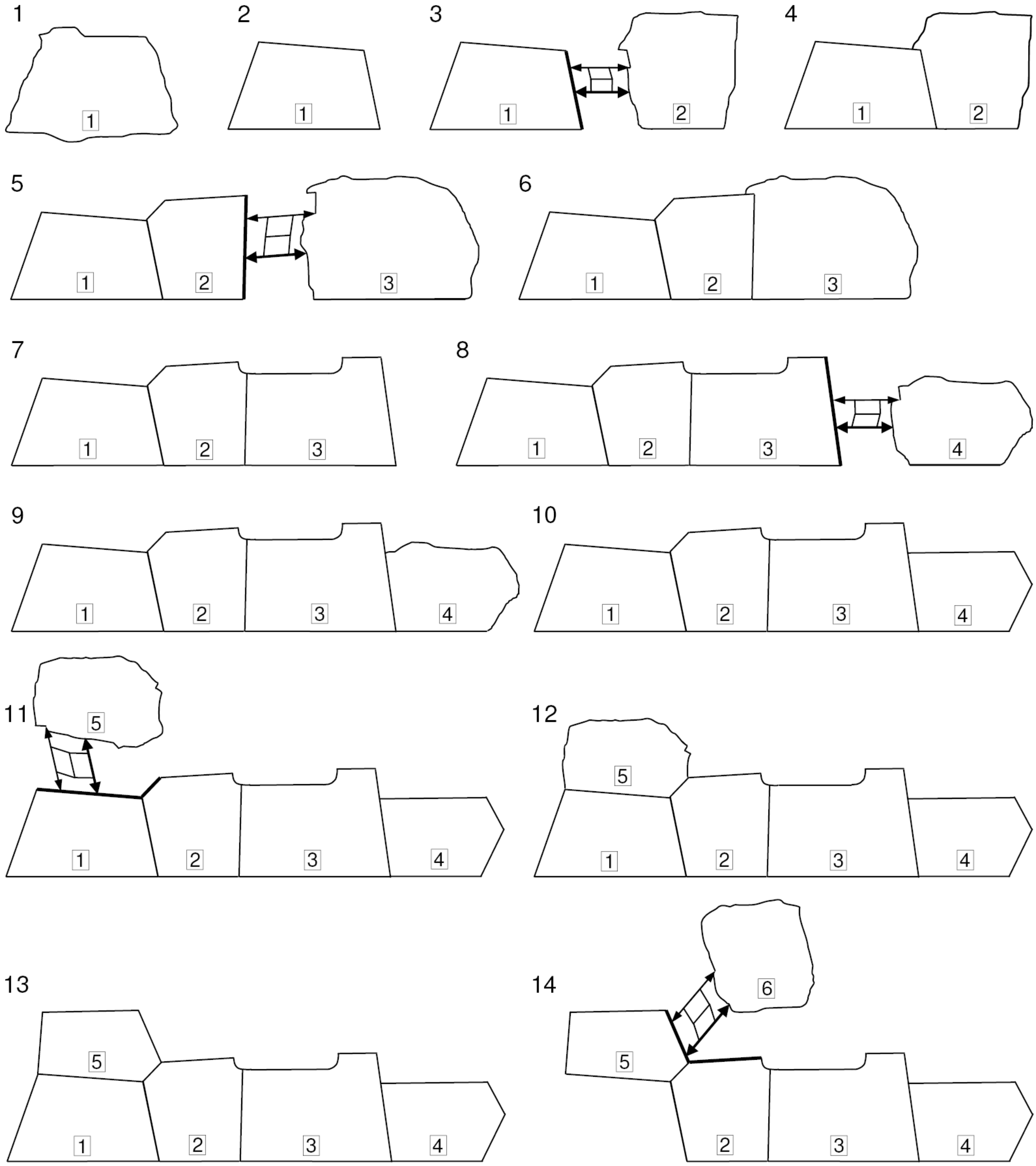


Fig. 5. The sequence of processing of stone blocks using the topography translator. The polygonal masonry is represented by eight blocks laid in two courses of four blocks in each course. The areas used for mating are shown by a bold line. The stone blocks lie on the ground on their backsides. The translator is shown in a simplified form. Relocations of the carrying rod over the processing surface related to the exhaustion of the action range of the translator are not shown. To process the U-shaped recesses, the bent tips are screwed into the measuring rod instead of the straight ones.

struction of the first course, one proceeds fabrication of the second course of the masonry (block 5, pos. 11).

Unlike the blocks of the first course, where the joining of the adjacent stones took place over one side section usually, the blocks of the second and the subsequent courses are joined over

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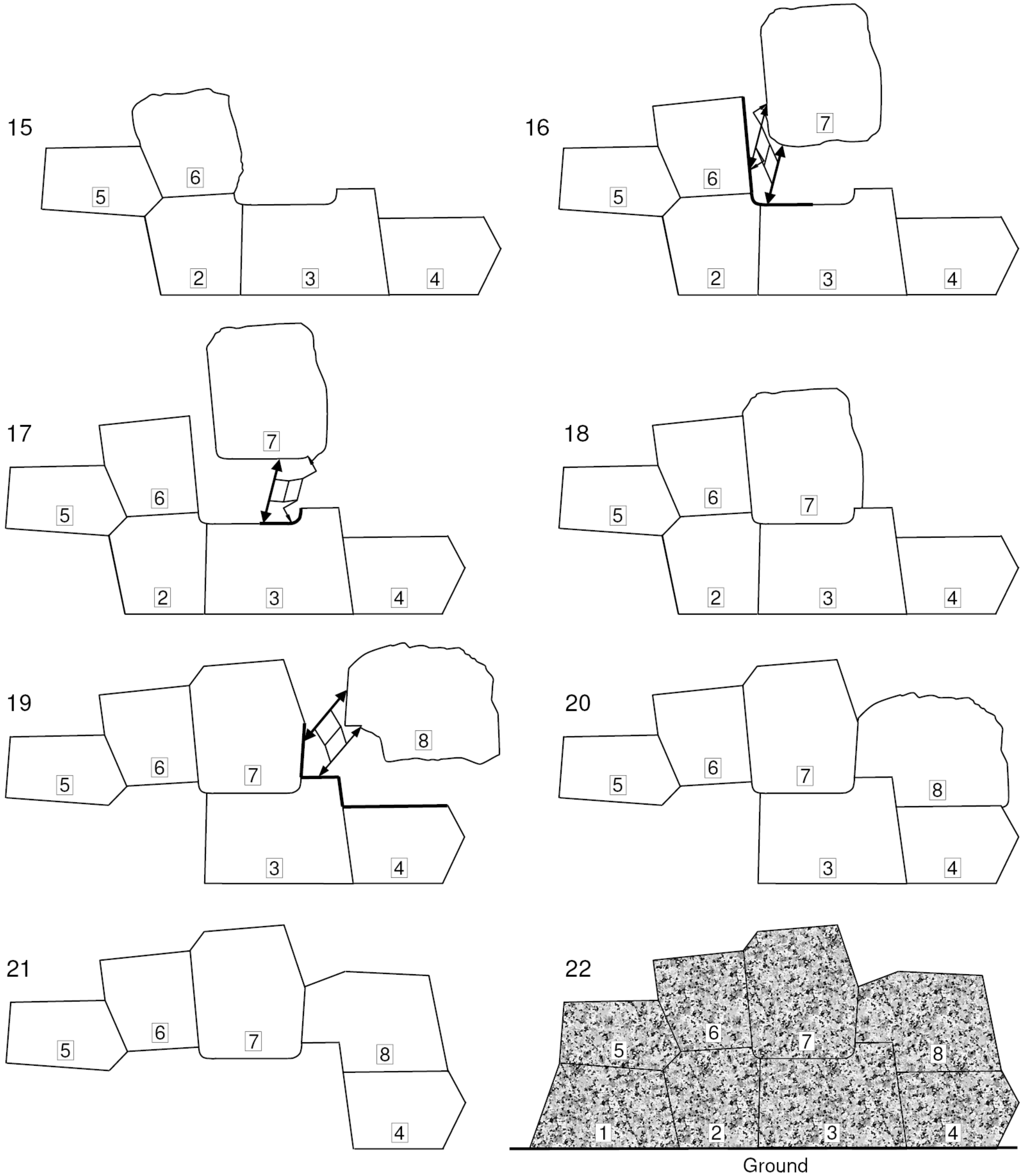

Fig. 5. Continuation.

more than one section. As a rule, the joining of these blocks is carried out over the base and the side surface adjacent to the base (pos. 11). To perform such joining, the straight tips are screwed in the measuring rod. Note that the interface sections between the blocks in Fig. 5 are just shown as rectilinear. In practice, all these sections are curvilinear to greater or lesser extent. After processing block 5 and checking quality of its joining (pos. 13), block 1 can be removed from the temporary masonry (pos. 14) and passed to the final assembly of the wall (pos. 22). The processing of block 6 is similar to the processing of block 5 (pos. 14-16).

Processing of block 7 for the U-shaped recess consists of two steps. First, a half of the U-shaped recess is copied, which is the first L-shaped recess (pos. 16). Then, processing of the

U-shaped recess continues on the second (counter) L-shaped recess (pos. 17). Processing of the first L-recess (pos. 16) can be performed with both the straight tips and the bent tips (in Fig. 5, both types of the tips are shown together for clarity). Processing of the second L-recess (pos. 17) is performed using the bent tips turned approximately by 180°. Note that during the processing of the first and the second L-shaped recesses, translator orientation in space should remain unchanged.

Thus, if the straight tips were initially screwed in the measuring rod while processing the U-shaped recess then they should be replaced with the bent ones at the second step (the specified distance between the ends of the probe and the pointer should remain unchanged). If the bent tips were initially screwed in the measuring rod while processing the U-shaped recess then they should be turned by approximately 180° at the second step.

In case of a large number of the U-shaped recesses in the masonry, it is convenient to use the topography translator whose measuring rod has cylindrical hinges providing free rotation of the measuring rod around its own axis (see Fig. 4(b)). The adjustment of position of the bent tips of the measuring rod for operation on the first and the second L-shaped recesses is actually reduced to revolution of the measuring rod around its axis by an angle suitable for the given location. Having installed block 7 at its place (pos. 18), the remaining side surface of this block is subjected to the arbitrary processing (pos. 19). Having completed block 7, block 2 can be removed from the temporary masonry (pos. 19) and moved to the polygonal wall construction site for its final installation (pos. 22).

Fitting of block 8 (pos. 19-21) is clear from the figure. If necessary, the third and subsequent courses of the polygonal masonry are fabricated similarly to the fabrication of the second course of the masonry. The final view of the wall consisting of eight blocks laid in two courses is shown in the figure (pos. 22).

2.10.4. Specifics of using the topography translator

The operation of the proposed device is based on the well-known principle of conjugation of two surfaces. As an example of using this principle for processing of stone blocks forming a polygonal masonry one can refer to the work 10. In contrast to method 10, the operation position in space of the proposed topography translator can be arbitrary due to the dual parallelogram mechanism.

In practice, the most convenient positions of the translator are close to horizontal as they allow the stonemason to process vertically located mating surfaces of stone blocks lying on the ground opposite to each other. The front surface of a stone block is located horizontally and is also fully accessible for processing. Moreover, the blocks fitted according to the proposed method can be joined in this position with each other (using wedging stones) that allows us to check the quality of the implemented interfaces before mounting the blocks in a wall.

In method 10, due to connection of the measuring rod to the vertical by means of a plumb line, the stonemason in order to process the upper side of the block of the previous course has to put the current course block, by which base the fitting is performed, above the block of the previous course that is unsafe and requires a lot of additional efforts. In particular, it is necessary to provide stops (recesses or protrusions) on stone blocks, fabricate logs-stops, bury these logs-stops into the ground, put the stone blocks on the logs-stops at the beginning of the work, and remove them from the logs-stops after finishing the work. Meanwhile, platforms, scaffolds, etc. are required to access the processed surface from the front side of the wall and to access the front side itself. Moreover, the use of a plumb line in method 10 significantly reduces stonemason productivity as a lot of time is required to calm the plumb line during the surface treatment of the block. In addition, the use of a plumb line itself can be very difficult in the event of a strong wind.

Vincent Lee, the author of work 10, initially proceeded from the fact that the polygonal masonry in the Peruvian megalithic structures was created by the Indians. In accordance with this initial assumption, Vincent Lee was forced to use a plumb line as the simplest measuring tool that could be known to the Indians at that time. Moreover, the author wanted to somehow use in the method he proposed the protrusions/recesses on the stone blocks of the Sacsayhuaman fortress for creating polygonal masonry. Hence, an extremely costly arrangement of the processed stone blocks, one above the other, arose in terms of the applied efforts.

In the proposed method, the parallel movement of the measuring rod is in no way connected with the normal to the Earth's surface and can occur at any orientation of the translator. Therefore, the fitting of the blocks and their pre-assembly are performed when the current and the previous courses of the blocks lie on the ground with their backsides down. Only after completing the laying of the blocks of the current course on the ground, the blocks of the previous course can be installed on their positions in the wall under construction. Therefore, in the proposed method, there is no need to process the stones on the wall being erected in the cramped conditions and at the risk of life.

Processing of the mating surfaces in the adjacent sections having a sharp boundary and in the adjacent sections having a smooth boundary (for example, in the form of L- and U-shaped recesses) is performed in one step. In this case, the orientation in space of the carrying/measuring rod and the distance between the tips of the probe and the pointer of the measuring rod remain unchanged all the time. When passing to the section of the counter L-recess during the transferring of the U-shaped recesses, it is necessary to replace the straight tips of the measuring rod with the bent ones or to make a corresponding turn of the bent tips, if they were used initially.

During the processing of the mating surfaces of the stone blocks, the topography translator is often located at angles to these surfaces which differ significantly from the normal (see Fig. 5). Such translator orientation in the case of a sufficiently sharp probe and pointer causes an insignificant additional error of topography transfer. The greater is the deviation from the normal and the larger is the radius of curvature of the probe and pointer tips, the larger is the value of this error.

The method of block fitting described in the present paper could be used for construction of the walls with comparatively simple polygonal masonry, where the mating surface areas have a small curvature, there are no figured cusps or sharp steps at the triple junctions (there is no “feeling of modeling”, see the next section). Since in the method under consideration, the sequential fitting of the blocks “by site” is performed, the sign of this method usage will be the mounting of large blocks in the first course of masonry directly on a compacted soil or on a pre-prepared bedrock, i. e., without the small “alignment” blocks in the first course of masonry that ensure the correct mutual position of the large blocks of the second and the subsequent courses (see more details in section 2.1).

Another sign of the topography translator usage will be small paired recesses located strictly opposite each other (the larger is the area of the mating surface, the greater is the number of the recesses). The recesses are made at those locations where the carrying rod of the translator is installed on the pointed supports at some angle to the mating surfaces. The presence of a set of the superimposed annular regions on one of the mating surfaces will also be a sign of the use of the proposed above topography translator. One more sign of the translator usage is the presence of a “visor”, which often occurs during the block fitting (see Fig. 5, pos. 4, block 2; pos. 6, block 3; pos. 18, block 7; pos. 20, block 8). Sometimes, such visors are found on incomplete blocks, being, in turn, a sign of the block unfinisheness.[23]

It should be noted in conclusion that the main advantage of the proposed method is that half of the mating surfaces of the stone blocks are processed arbitrarily in it.

2.11. A bulge of the front side and a swell in its lower part, cusps at the triple junctions

A typical bulge of the front surface as well as a swell in its lower part (should not be confused with the bosses) found in some structures (see, for instance, Photos. 1-4) often serve as one of the proofs of the “plastic” version[12,13,14] of the polygonal masonry fabrication. According to the plastic version, the partially solidified blocks were stacked one on another. As a result, the inter-block gaps in the polygonal masonry were closed under own weights of these blocks and the front surface got the specified bulge and swell.

In the proposed method, both signs – the bulge and the swell can appear by themselves at the stage of fabrication of the clay model of the wall unless the clay mixture was not thick enough and no sheathing was used on the front and the back sides. The bulge and the swell can also be produced intentionally while sculpturing the clay model.

Most likely, the bulge and the swell were given to the blocks intentionally. Both features increase the feeling of massiveness, grandiosity of the structure, its colossal weight; it seems to us as if the stones are flattened under a huge weight. The bulge was also intended to demonstrate to the naive Indians the power of the arrived whites, who could “sculpt”, if necessary, a building out of huge hard stones as if from dough.

The cusps (“beaks”) and steps (see Fig. 6) are clearly visible in the points where three adjacent blocks meet. These elements are produced while sculpturing the clay model and then transferred on the stone block with the pantograph. Besides a stop limiting movement of the adjacent block in the horizontal plane, the cusps give the polygonal masonry a special grace. According to the creators’ idea, the cusps along with the parallelism of the smoothly changing curved edges were intended to give a sense of easiness of working with a stone. These features make the viewer think that the blocks are literally sculpted of a stone. We must pay a tribute to the old masters; they succeeded in this technique!

Given the above, instead of the term “polygonal masonry”, it would be quite fair to use the term “polygonal sculpture” in the cases when a stone structure is created on the basis of hand-sculpting of a clay model made in a certain artistic style with unique lock interfaces between blocks.

2.12. Indirect dating by the observed destructions of the masonry elements

The cusp is one of the weak points of the polygonal masonry in terms of strength. Thus, the cusps should fail first during the natural weathering process. Many stones in Peru are covered with lichen (see Photo. 9), so the biological factor must also be taken into account in addition to the weathering when estimating the rate of stone destruction. Surprisingly, the type of the polygonal masonry under consideration is perfectly preserved in the mountains (Cusco, Machu Picchu, Ollantaytambo, etc.), where the climate is characterized by sharp temperature changes (15-20° C) during a day, by a lot of precipitation and by light frosts in winter (June-August).[24]

Besides weathering, a shift of stones in the masonry during an earthquake[2,3,4,5] or during a landslide move of the slope[4] (often triggered by an earthquake) can cause destruction of the cusps. It should be noted that the cusp cleavages could occur in the process of stone block fabrication, during transportation, installation, or restoration. Some of these cleft cusps can be partially repaired. The repaired cusps will look more sunk into the body of the masonry than the normal ones.

The study of the polygonal masonry from hard rocks (granite, andesite, basalt) shows that the cusp damages are present but they are few in number. The absence of noticeable destructions under fairly harsh climatic conditions and high seismic activity in Peru give a reason to assert the comparatively recent, for about 300 years, construction of the megalithic complexes. A rough estimate can be obtained by comparing the state of megalithic complexes with monuments made of similar materials, whose date of construction is known, being in similar weather-climatic conditions.

Fig. 6. Cusps and steps.

2.13. How to prove it? What should we look for and where?

What can serve as a confirmation of the proposed methods of fabrication of the polygonal masonry? On the territory or near the complexes with polygonal masonry or in quarries, construction debris should remain, in which fragments of clay model blocks and fragments of clay/gypsum replicas should be searched for. Certainly, first of all, we need to study the materials of the conducted excavations. It is not unlikely that some suitable fragments in shape, size, and materials have already been found and documented. Most likely, much of the debris was used for strengthening the ground under the next erecting structure. Therefore, in the case of setting up again any structure damaged by natural causes, the evidences in the form of the clay models and replicas should be sought in the ground under the structure itself.

Assuming that in the pantograph used by the builders, the clay model and the stone billet were positioned in the same way as in the modern pantograph, i. e., horizontally with the backside down (to fix the block in case of uneven back surface, wedging stones are used), then the chisel marks on the side surface of the stone blocks should go from right to left (chisel in the left hand, hammer in the right) and from top to bottom (at the beginning of the trace, the recess is larger than at the end). The marks themselves should be short parallel strokes arranged in vertical columns.

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Photo. 14. Wall of Six Monoliths, Ollantaytambo (P. Špindler, 2008, commons.wikimedia.org).

The chisel marks should be searched for on the stone blocks from hard rocks – granite, andesite, basalt. Soft rocks, such as limestone, have a high porosity; the surface layer of these stones is quickly destroyed by weathering. Moreover, the chisel marks on the limestone surface are easily destroyed during the subsequent smoothing operation by tapping. Because of weathering, there is also no sense to study the interface surfaces of the stone blocks from hard rocks that have lain in the open air outside masonry for an unknown number of years. To analyze an interface surface, one should take stones from some untouched masonry having minimal gaps, which could get a very small amount of moisture.

It should be noted that the several hundred years old masonry of stone blocks is most likely impossible to disassemble so as to keep the surface layer of stone intact at the contact points. The fact is that during the entire period of the masonry existence under the above mentioned climatic conditions, various physico-chemical processes took place at the contact points causing a change in the mineral composition in these points. As a result, depending on the process, the contact could break down (with sand formation) in some points and, on the contrary, strengthened in other points. An attempt to separate the sites, where the strengthening has occurred, will result in the destruction of the stone surface layer adjacent to the contact. Anyway, the sizes of the stones and their geometry will change after disassembling the old polygonal masonry. Therefore, it is impossible to reassemble the old blocks so that there would be the former tiny gaps between them.

2.14. Indirect dating by the time of 3D-pantograph invention

If we accept the proposed version of polygonal masonry fabrication with a pantograph, the structures of “incredibly” ancient Incas can be approximately dated by the years of invention/building of pantographs by Europeans. The pantograph for working with a flat drawing was invented in 1603-1605 by Christoph Scheiner.[25] It should be noted that the information about the pantograph design was published by the author in the form of a separate book[26] only 28 years after the invention.

Around 1710-1720, Russian mechanics Franz Singer and Andrey Nartov[27] built a turning machine for copying medals.[28,29] The machine was intended for production of medals in automatic mode by transferring a relief from a large size medal model. It is not quite correct to compare the Singer-Nartov machine with the modern 3D-pantograph used by sculptors (see Fig. 2), since the kinematic diagrams of these mechanisms differ greatly. Despite this, attention should

Photo. 15. Ollantaytambo (E. Berzin, 2020, allenatore.livejournal.com/15230.htm).

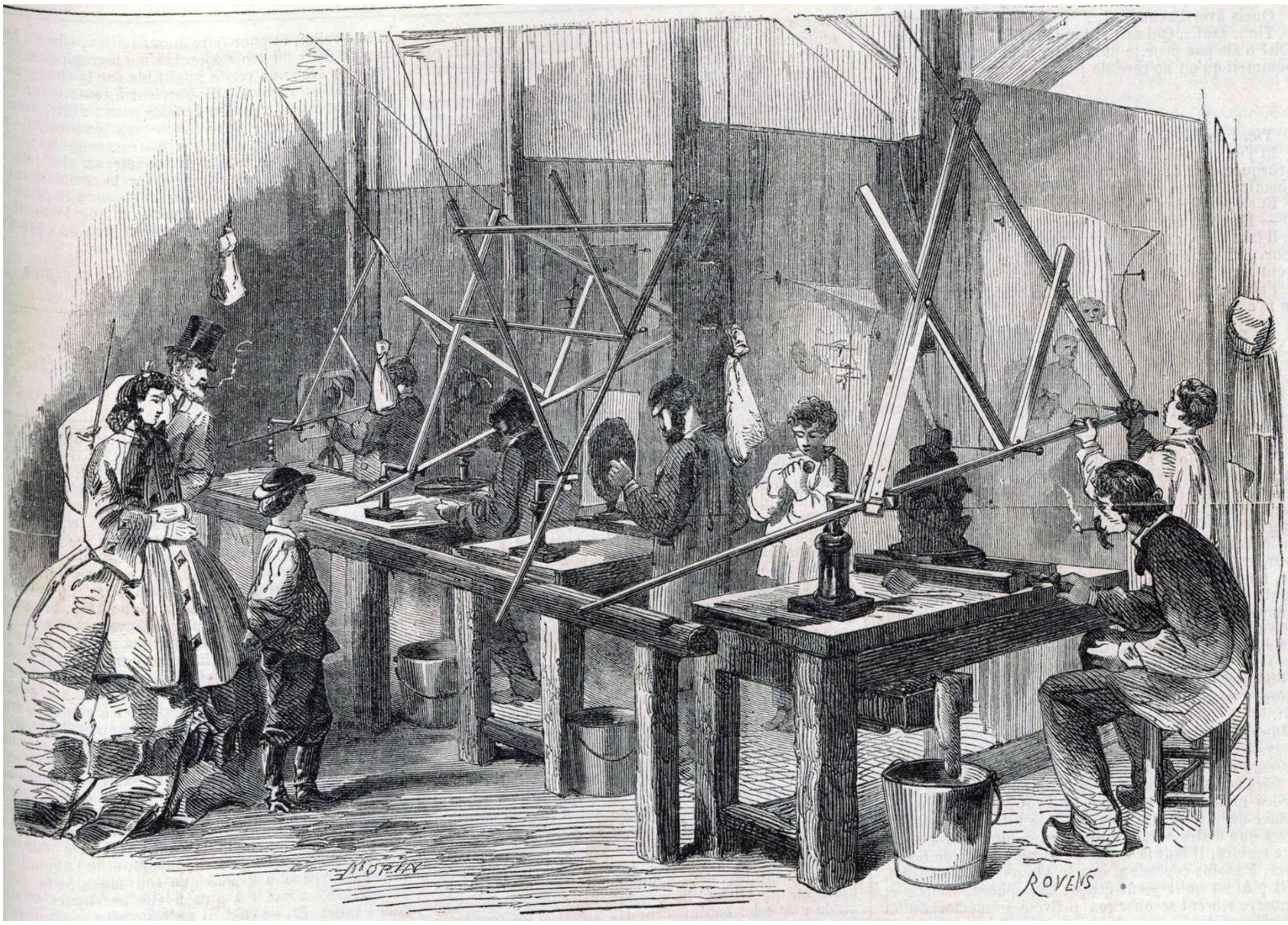
be paid to the complexity of the machine mechanism, which notably exceeds the complexity of the modern pantograph mechanism. In particular, the probe movement along the model surface and the cutting tool application to the billet surface in the 3D-pantograph are carried out by the sculptor manually, whereas these functions are implemented in the given example of the machine without a human intervention. Note that copying machines like this were built and used in many European countries in the 18th century.

In 1807, James Watt[30] starts designing a mechanism[31] intended for production of reduced copies of sculptures.[32] The kinematic diagram of Watt's mechanism is close to the kinematic diagram of the modern 3D-pantograph. However, there are a number of differences. Instead of the ball joint, the boom is mounted on a universal joint; there is no a parallelogram mechanism; the model and its reduced copy are located horizontally, etc.

The kinematic diagram of the pantograph built by Benjamin Cheverton[33] in 1826 is the closest to the kinematic diagram of the modern 3D-pantograph (see Fig. 2). Building the pantograph, Cheverton relied on the design previously proposed by John Hawkins.[34] Just like the Watt pantograph, the Hawkins-Cheverton pantograph was intended to produce reduced copies of sculptures.

It should be noted that both the Watt pantograph and the Hawkins-Cheverton pantograph had a built-in engraver, whose milling cutter performed mechanical processing of the billet. An engraver is not required in the above considered methods creating the polygonal masonry. Therefore, the construction pantograph is mechanically simpler than the Watt and Hawkins-Cheverton pantographs. The drawing shows the studio of the second half of the 19th century, in which mass copying of statues was carried out using a 3D-pantograph.[35]

There is no doubt that, having created a 2D-pantograph at the beginning of the 17th century, scientists of that time and, first of all, the inventor of the 2D-pantograph himself, Christoph Scheiner, immediately thought about creating a 3D-pantograph mechanism with which it would be possible to obtain reduced/enlarged copies of three-dimensional objects. Actually, for transition to work with three-dimensional objects, the 2D-pantograph just had to be fixed not in the cylindrical, but in a ball joint; the parallelogram mechanism should be allowed to rotate freely around the arm installed in the ball joint (pantograph boom), and the model and the billet should have the ability to synchronously rotate around their vertical axes by means of a chain (see Fig. 2) transmission or a gear transmission (see Ref. 33).



Dwg. 1. 19th century studio of statues copying using a 3D-pantograph (ink, artists E. Morin, E. Rovens, 1864).

Application of the chain transmission in the construction pantograph is more justified in comparison with the gear transmission. The point is that large dimensions and weight of the processing stone blocks result in large dimensions and weight of the used gear wheels. Moreover, the chain transmission makes it easy to change the distance between the rotating platforms, which is responsible for the pantograph reducing/enlarging factor. The distance change is carried out by shifting the platforms along the frame. For this purpose, a corresponding number of links is added to or removed from the chain and/or the chain is pulled by a roller located at the end of a spring-loaded console. In this case, the reducing/enlarging factor turns out to be almost continuous. To change the distance in the case of a gear transmission, the installed set of wheels is replaced with the most suitable one among available sets which number is usually limited. Therefore, the reducing/enlarging factor turns out to be strongly discrete.

Analyzing mechanisms similar to Singer-Nartov machine, we can conclude that development and building of the modern design 3D-pantograph from the point of view of the kinematic diagram complexity, the metal-working technology, and the used materials were quite feasible for mechanics in the early 18th century already. By that time, all the problems related to the copying accuracy, namely: gaps in the ball and cylindrical bronze joints, backlashes in the chain/gear transmission, as well as the boom and frame rigidity (required the relative position of the pantograph elements stay unchanged during operation), had already been successfully solved. Therefore, it is very strange that it took so long to create a 3D-pantograph, more than 220 years!

Today, we still have neither written nor material evidence confirming the existence of a construction 3D-pantograph in the 18th century. Nevertheless, taking into account the state of the art of those times, one cannot exclude the probability that such a pantograph could have been developed, built and found a limited usage in construction, but the inventor itself and his pantograph remained unknown to a wide range of experts. The fact is that the master masons in those days were in no hurry to disclose their professional secrets. Judging by how long the mystery of the polygonal masonry creation had persisted, the master masons were able to keep their secrets well.

2.15. Who built this, when and with what funds?

The problem with the structures based on the polygonal masonry is as follows. The official history states that the structures had existed before the arrival of Europeans in the New World in the 16th century, and the American Indians did not know neither iron tools nor a wheel and did not have draft animals at that time. From this statement, there is only one conclusion: the structures were built by some older civilization that existed in America before the Indians, meanwhile whose culture of stone working, in general, corresponded to the European construction culture of the 16-17th centuries.

The problem with this mythical older civilization is that it left behind no other material evidences of its existence, except for the perfect stone structures. As rightly noted in work 17, the high-quality polygonal masonry and the structures based on appear instantly (by historical standards) as if from nowhere, and then disappear also instantly into nowhere. There are neither previous nor subsequent noticeable development in the architecture and technology of these structures. This may happen only when a group of professional builders comes to a certain territory for a short period, say, for 10 years, with their own tools, contrivances and construction techniques.

Transience of the events taken place in the construction industry of those years indicates the high productivity of the strange builders and their construction methods. The contradictions are instantly resolved if the authors of the structures are visiting European builders,[36,37,38,39,40] and the time of erection of the structures is transferred from “minus infinity” to the 18th century. For delivery, moving, and rough processing of the stones, slope strengthening, and other heavy and unskilled work, of course, the local Indian people were driven together by orders of the Indian chiefs subdued/bought by the Spaniards. Thus, in a certain sense, the Peruvian megalithic complexes are the structures built by the Incas too, although not so ancient.

Any large-scale construction is always based on some strong economic foundation. It is difficult to imagine that the megalithic complexes were built for the Indians at the expense of the Spaniards. Of course, these complexes were created at the expense of the Indians and on bones of the Indians. But what could the Indians offer to the Spanish colonizers? The gold and silver that they had were captured in the early years of the conquest and taken to Europe. The Peruvian land was not able to produce much cotton, sugar cane, or grain.

Since the Indians had gold and silver at the beginning of the conquest, it means they took it somewhere. Therefore, the Spaniards organized gold and silver extraction in mines and goldfields.[40,41,42,43] And to make the work in the mines more fun, the aboriginal priesthood inspired the Indian people with the appearance and grandiosity of the megalithic temples, which were built at the expense of part of the funds received from the extraction of the precious metals. After a few decades, the easily accessible gold and silver deposits were exhausted, and the construction of the megalithic complexes has stopped. By this time, the power of the Spaniards and the Catholic Church had increased somehow “imperceptibly”, and the number of the Indians was greatly reduced in some “incomprehensible” way.[42]

Poor food and living in shacks did not add health to the miners, the places of “strength” did not longer compensate for the strengths taken away by exhausting work in the mines.[42] In general, the time has come when some of the abandoned religious structures of the Indians could finally be put to good use without much trouble. And these structures have been put to good use. Stone blocks and parts of the structures were used for erection of Catholic cathedrals, abbeys, palaces, villas, urban and industrial buildings.

3. Discussion

Among the materials related to the topic, the work 14 should be noted. The author suggested to use a reduced gypsum model of a stone block and transferring and scaling of a complicated surface geometry to perform with a caliper by several reference points. The gypsum model is usually required to avoid wearing of the original clay model while producing copies. This problem does not arise while fabricating blocks for the polygonal masonry. Moreover, in case of block model fabrication by a stone billet of arbitrary shape, the clay model is used just once and then thrown out (serves as a core for a new model). Thus, in order to reach the required result, possessing only a clay model of the block is quite enough.

The process of transferring of a complicated surface geometry and its scaling by few reference points using a caliper is very time-consuming and inaccurate. However, this process ceases to be time-consuming and inaccurate if we apply a pantograph instead of the caliper. Analysis shows that in most cases, first, a reduced clay model is created by a stone billet of an arbitrary shape using a pantograph. Then, the regions are cut out in the clay model of the block for interfacing with neighboring blocks. After that, a model wall is assembled of the model blocks. After drying, the wall is disassembled, and the interface sites of the model blocks are transferred to their stone billets by means of the pantograph. Since there are no universal solutions in construction, as in any other field, the builders, besides the pantograph, used other techniques based on application of topography translator and replicas.

3.1. Phenomenon of the "tired" stones

So far, a number of questions regarding the phenomenon of the "tired" stones remain unanswered. The tired stones are scattered in a picturesque mess along the road leading from the quarry to the fortress of Ollantaytambo.[8,9] How could the tired stones have lain for hundreds of years on the side of the road (some on the road) and not disappear anywhere? The Indians did not worship stone parallelepipeds. So, if, say, niches were made in these parallelepipeds, then it would be another matter. Meanwhile, to this day, the finally exhausted stones with incredible persistence continue to show us the way to the quarry, where the blocks for the fortress were mined. Why in the mountainous country, where stones are used for the construction of everything – buildings, bridges, roads; these absolutely exhausted stones so conveniently located on the side of the road – take and use, no one has yet been split into smaller parts and put into action? Most of these stones are cleft within one day by the efforts of one experienced stonemason. But, no, we see the complete safety and invulnerability of these stones. It turns out that the local authorities for all these hundreds of years, for some reason, strictly ensured that no one touched these stone blocks.

3.2. Polygonal relief facing

Besides the simple dressing of the front sides of the stone blocks, the technology considered in the article allows to create a polygonal masonry (facing) which face surface is a relief. The Cambodian temple complex Angkor[44] is the example, where such masonry/facing technology could be applied.

3.3. Fabrication of symmetrical statues by means of a pantograph

The casting method, in which, first, a core (solid or hollow) of cheap concrete is cast, and then, after the end of core shrinkage, a comparatively thin shell ("plaster" layer) of more expensive artificial granite is cast over, due to its complexity is not suitable for the large-scale polygonal construction, in which all the stone blocks are different. Meanwhile, this method is great both for making single unique statues and for mass production of identical statues.

For example, some "Ancient Egyptian" statues of pharaohs and sphinxes covered with a layer of plaster of artificial stone (granite, dolerite) were apparently fabricated using this technology.[45] Since among some "Ancient Egyptian" statues there are statues that differ only in size, it can be assumed that these statues were created by the same original model using the pantograph adjusted for different enlargement factors.

A number of researchers have long drawn attention to the almost perfect symmetry (face, headdress, torso) of some Egyptian statues (Ramses II, Amenhotep III, Nefertiti).[46] The question of how this symmetry was accomplished remained open for a long time. Meanwhile, a small modification of the pantograph mechanism makes it possible to produce statues with a high degree of symmetry of the left and the right sides.[45] Let us show how this was achieved in practice.

First, as usual, a sculptor creates an enlarged clay model by the reduced clay model with help of the pantograph. After that, the 0-shaped chain in the pantograph is replaced with an 8-shaped one. As a result of this modification, the platform with the reduced model of the statue and the platform with the enlarged model of the statue will rotate in mutually opposite directions. If the used pantograph has an intermediate gear wheel[33] (in the general case, an odd number of identical intermediate gears) to drive the platforms instead of the chain, then a pair of identical intermediate gears (in the general case, an even number of identical intermediate gears) should be installed instead of this wheel or exclude intermediate gears at all.

Now the sculptor by considering the artistic merits of the left and the right halves of the reduced model of the statue should decide – which side of the statue he wants to exactly copy to its other side. Having decided on the side, let it be the left side for definiteness, the sculptor applies the probe to the left side of the reduced model (the probe must remain perpendicular to the pantograph boom). In this case, the pantograph pointer will show the corresponding point in space on the right side of the enlarged model. If there is an excess of clay at the indicated point, then it is removed directly by the pantograph pointer; if there is a shortage, then the sculptor adds the necessary amount of clay to this point. In order to use the pantograph at probe/pointer angles to the pantograph boom differing from 90° (general case), the parallelogram mechanism should be replaced with an antiparallelogram[18] mechanism. To do this, the long bars of the parallelogram just need to be moved into the place of the parallelogram diagonals.

The result of the pantograph modifications is a sculpture whose left and right sides are highly symmetrical. Deviations from symmetry in such sculpture are determined by the error of the pantograph mechanism. To reduce the effect of the pantograph error, the symmetrization work of a head, for example, should start from the nose tip, where the error will be zero, and end at the back of the head, where the error will be the greatest, but least noticeable. Note that a gradual increase in the symmetry violation from the nose to the back of the head will be a sign of the technology based on the use of a 3D-pantograph.

There are several polygonal buildings that have short sections of masonry with a symmetrical arrangement of blocks (Sacsayhuaman, Ollantaytambo). However, the symmetry at these sections is only approximate. The blocks on the left and on the right sides of the vertical axis of symmetry are not completely reflection symmetric, they differ in shape and size. Thus, the technical opportunity provided by the 3D-pantograph that allows to create the polygonal masonry with reflection symmetric sections was either unknown to the builders of the polygonal complexes at that time, or was not simply used.

The knowledge accumulated in the field of mechanics and the technology level achieved by the beginning of the 18th century could quite allow to design and build the 3D-pantograph suitable for the construction needs. Thus, if we accept the polygonal masonry creation method proposed in the article, the construction of a number of megalithic complexes in Peru should be dated no earlier than the beginning of the 18th century. The Cambodian temple complex Angkor and a number of "Ancient Egyptian" sculptures should also be apparently dated no earlier than the beginning of the 18th century.

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Photographs

The photos show the polygonal masonries which can be obtained by using the methods suggested in the article. The distinctive features of these masonries are: the stone blocks are large weighing from several hundred kilograms to several tons, the blocks are mated to each other closely without a gap through complicated curved extensive surfaces.

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