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# On the Geometry of the Minoan Water Conduits

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**Abstract** Several different types of conduits were found in archaeological excavations in Crete belonging to the Minoan period. They were used for water supply as well as for stormwater and wastewater removal and are made of stone or terracotta. The terracotta conduits were canals or pipes with rectangular or circular cross section. The most interesting conduits are the terracotta pipes of truncated conic shape which were never used before or later in other civilizations. An ongoing experiment using reconstructed pipes of this shape will be employed to evaluate their hydraulic behaviour and investigate possible advantages for certain flow conditions.

**Keywords**: Bronze Age; Knossos; Myrtos Pyrgos; open conduits; Phaistos; Stone conduits; terracota pipes; Tylissos; Zakros

## INTRODUCTION

The island of Crete in Greece, was first inhabited shortly after *ca.* 6000 BC but only during the Bronze Age that the Minoan civilization was developed as the primary Greek cultural centre of the Aegean world (Alexiou, 1964). The Minoan and Mycenaean settlements (in Crete and Peloponnesus, respectively) developed and applied various technologies for collecting, storing, transporting and using surface-water and ground-water resources (Angelakis and Spyridakis, 2010; Koutsoyiannis *et al.*, 2008).

Over the past century archaeological excavations have brought to light impressive water engineering technology dating from the Minoan era on the island of Crete (Angelakis and Spyridakis, 1996; Webster and Hughes, 2010; Angelakis and Spyridakis, 2010; Koutsoyiannis *et al.*, 2008; Antoniou and Angelakis, 2011, and others). From the early Minoan period (*ca*. 3200-2300 BC) issues related to water supply were considered of great importance and developed accordingly. Archaeological and other evidence indicate that during the Bronze Age advanced water management and sanitary techniques were practiced. Several types of stone and terracotta conduits and pipes were used to transfer water, and drain stormwater and wastewater. These types of conduits are summarized below.

## STONE CONDUITS

In Crete due to dry summers rainfall harvesting was necessary and was accomplished from both roofs of the buildings and larger court areas. Hydraulic structures associated with the rainfall collection were found in Knossos, Phaistos, Tylissos, Aghia Triadha, Chamaizi, Myrtos Pyrgos and Zakros. These include stone-made conduits with branches that were used to supply collected water to cisterns. The Knossos palace provides a typical example (Figure 1, left). Also, alongside a stairway in Knossos is a small stepped channel consisting

of a series of parabolic-shaped step chutes that was used to convey rainwater from terraces down to a sedimentation basin (Figure 1, right). In Tylissos houses, similar stone conduits

**Figure 1.** Minoan rainwater collection systems in the Knossos palace: carved stone elements of a conduit for the flow of rainwater falling on the roof (left) and part of restored stairway with parabolic runnels for rainwater flow (right); photos by A. Angelakis.

**Figure 2.** Minoan stone conduit systems (part of aqueduct) at Tylissos: to transfer the water from a sedimentation tank to the main storage cistern (left) and part of distribution network (right); photos by A. Angelakis.

were used to convey water from a stone made sedimentation tank to the main storage cistern (Figure 2, left). The same components of rainfall harvesting system, e.g. cistern, channel and sedimentation tank, also existed in other settlements (Angelakis and Spyridakis, 1996; Gorokhovich *et al*., 2011). Furthermore, in several palaces parts of the sewer systems were made of stone conduits (Figure 2).

## TERRACOTA CONDUITS WITH OPEN-SHAPED CROSS SECTIONS

While conduits of large cross section were stone made, those with smaller cross section were made from terracotta in the form of U-shaped tiles. Such terracotta conduits were discovered as parts of sewer networks at the Knossos and Phaistos palaces and other Minoan settlements (Figure 3; see also Angelakis and Spyridakis, 1996; Angelakis and Koutsoyiannis, 2003; Antoniou and Angelakis, 2011). It is noted that U-shaped terracotta

drains covered with stone slabs, running below the streets, were also found in Habuba Kabira, a small Sumerian city of the Bronze Age (Viollet, 2002).

**Figure 3.** U-shaped terracotta drains at Phaistos palace (top left) and the Knossos palace (bottom left and right); photo by M.Nikiforakis, EFIAP, with permission.

## TERRACOTTA PIPES

The most interesting Minoan conduits were the pipes made of terracotta. As shown in Figure 4, two types of such pipes were found, the prismatic and the truncated conic ones. The former, found in Myrtos – Pyrgos and used to supply the nearby cistern system with stormwater collected from the rooftops and open courtyards (Cadogan, 1978), probably operated under free-surface (open channel) conditions. Rectangular openings and covers of same material were used to interconnect of consecutive segments. These pipes were used for water supply and could operate at full-flow condition, perhaps under low pressure. Neither type of terracotta conduits is known to be used before by other Bronze Age civilizations or subsequent civilizations in the Mediterranean region. In particular, pipes with circular cross section were widespread in later phases of the Greek civilization (Angelakis *et al,* 2005; Koutsoyiannis *et al*., 2008) but they were cylindrical rather than conic and operated under free surface conditions.

**Figure 4.** Minoan terracotta pipes used for collecting and storage of rainwater of rectangular shape from Myrtos- Pyrgos (upper) and remains of water supply system at Knossos palace (lower); photos by A. Angelakis with permission.

The hypothesis that these pipes may have been used in low pressure conditions is supported by other archaeological findings indicating that pressurized flow was known. Specifically, a fresco found in the Knossos palace (Fahlbusch, 2008; Koutsoyiannis *et al*., 2008), depicts a jet d'eau (fountain) which would not be possible without pressurized flow.
The pipes at Knossos were made 76 to 82 cm long with a thickness of 1-2 cm (Figures 4 and 5). The smaller end had a diameter of 7.5-8.3 cm and the larger 15-17 cm (Angelakis *et al.*, 2007). The particular shape of these pipes facilitated tight interlocking (using plaster) of consecutive sections. Clearly the taper in each section was significant; the diameter doubled over the full length of each pipe section (Figure 5, lower). The reason behind this strongly conical pipe design is still uncertain and provides somewhat of a puzzle (Webster and Hughes, 2010).

The tapered Minoan pipes do not reappear in the water technology of later civilizations in the Mediterranean region, either because the technology was abandoned for being unsatisfactory, or because it was simply lost. Transfer of knowledge from the Minoan civilization to the later Greek civilization is debated in the literature. Some believe that water engineering skills were lost following the collapse of Minoan culture and rediscovered after

800 BC (Webster and Hughes, 2010). Any reasoning behind the tapered pipe design may well have been forgotten, with water pipes reappearing with a different design.

Conical pipes are entirely unique to Minoan Crete, which have been used predominantly in the context of water supply. There is some reason to expect that the Minoans had a good reason to support their conical geometry. Based on Minoan water engineering skill as demonstrated in other infrastructure (e.g. drainage and sewage), it seems reasonable to expect that the Minoans were very deliberate in their choice of pipe design. The quality of pipe manufacture, featuring tightly fitting joints and cement-seals, also suggests that the pipe design was selected with care.

Minoan pipes were recently reconstructed following same technique, using the same material, and in same geometry are shown in Figure 5. An ongoing experiment using reconstructed pipes of this shape will be utilized to analyze their hydraulic behaviour and investigate if they have advantages over the ones with cylindrical shape. Possible advantages to be investigated are:

a) At the manufacturing phase, the conical shape was perhaps easier to construct than a cylindrical one
b) At the construction phase, the conical shape may have served better the joint design and application.
c) Also, at the construction phase, curved alignments were perhaps implemented easier by the conic shape.
d) In terms of hydraulic function, the conic shape clearly results in greater head losses (additional losses at the places where sudden changes in diameter occur; Webster and Hughes, 2010); however, in steep terrains this may be an advantage in either partial or full flow conditions.
e) In terms of their function with respect to sedimentation, the conical pipes may have better properties in avoiding formation of deposits due to increasing velocity.

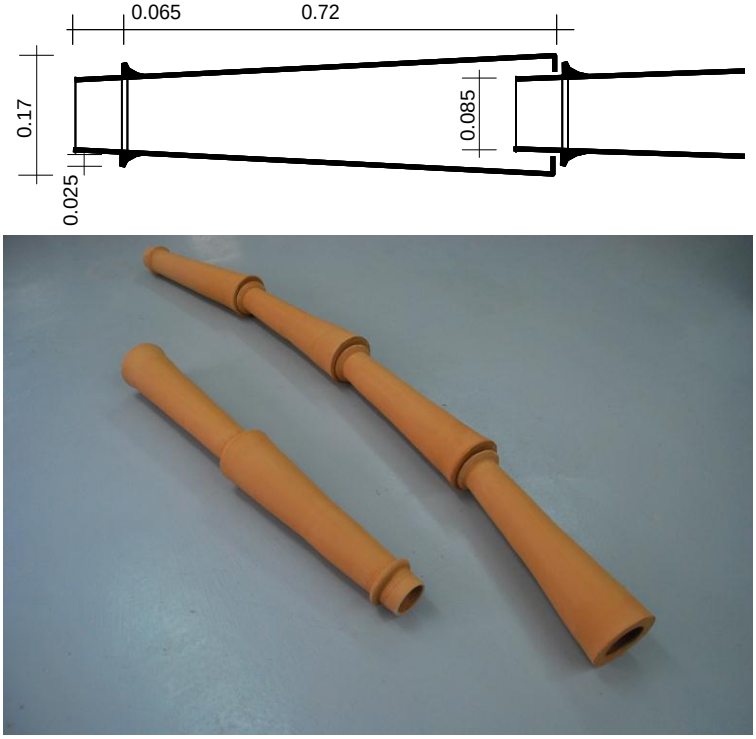


**Figure 5.** Knossos water supply pipes: Terracotta pipe dimensions (top) and recently constructed pipes of same material and geometry (bottom); photo by M.Nikiforakis, EFIAP with permission.

## SUMMARY AND CONCLUSIONS

In Minoan Crete (Knossos, Tylissos, Malia, and other sites) aqueducts have been used to convey potable water from mountain springs to Minoan palaces and towns, as well as sewerage and drainage systems to collect rain water from the roofs and bring it to storage or remove the wastewater. Aqueducts and sewerage and drainage systems consisted of open channels, closed conduits or combinations thereof. The open channels were typically rectangular made of stone, or U-shaped made of stones or terracotta. Among the terracotta pipes, most interesting were those with truncated conic shape, manufactured in sections 70-75 cm long. The design of these pipes differs notably from later Greek cylindrical, almost constant diameter pipes, for having tapered conic section in the direction of flow. One potential advantage of such design is the perfect seal of the joints with clay or other material, so that they possibly can operate under low pressure. Another advantage is the flexibility for change in direction without use of special elbow fittings, while it has been additionally speculated in the literature that the velocity increase associated with the narrow end of each pipe section, helped to flush sediment through the pipe and prevent deposits. These possible advantages will be assessed through an experiment with terracotta pipes reconstructed recently resembling the original Minoan pipes.

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