The foundation of an all glass arch bridge for the Green Village on the Delft University campus

Green glass arch bridge

The construction of an entrance bridge to the Green Village, a sustainable development for the Delft University of Technology (DUT), has started. This bridge, spanning 14 m, will be constructed with massive glass blocks (photo 2), in a shallow arch, with no adhesives: just interlocking blocks under pressure supported by two foundation blocks on piles.

The glass arch introduces considerable horizontal forces on the foundations. Especially the lateral stiffness of these foundations has an significant impact on the structural behaviour of the arch. Therefore the design process and the interaction arch-foundation required special attention.

General

The Green Village is a terrain on the campus of the Delft University of Technology (DUT) where all kinds of technical, sustainability related features will find a home. Between the Green village and the campus there is a 14 m wide canal over which a new, 2.20 m wide bridge, has to be constructed. A bridge to the Green Village has to be Green as well. Therefore, the Green Village worked out a strategy to build each five years a new, at that moment as sustainable as possible, bridge. The old bridge is to be recycled.

For the first bridge a limited design competition for employees of the DUT was announced. Since the department Structural Design of the Faculty of Architecture of the DUT had a good working experience with an experimental glass façade for the Chanel shop in Amsterdam, it was decided that the same building material, massive glass blocks, were to be used for this Green Village bridge. The glass design was selected to be the first sustainable bridge to the Green Village.

Shallow glass arch

Glass is good choice for a Green bridge because glass is a very sustainable material: it is made from sand (lots of it available worldwide), it is inert (no corrosion/rot) and it is 100% recyclable without loss of quality. And glass is transparent, a beautiful property that makes it shine and sparkle. In the façade of the Chanel shop in Amsterdam the glass blocks were glued together for structural integrity. As adhesive is not a wise sustainable connection method and the bridge has to be dismantled after five years, using glue (adhesive) was not an option. Therefore, the choice was made to create an arch, working under compression at all circumstances. It had to be as shallow as possible arch to prevent people from sliding and slipping on the bridge. Shallowness in arches has a big price: it results in large horizontal forces on the supports of the arch. In combination with the Dutch soil (peat up to 20 m and therefore long concrete piles) this is an unfortunate and possibly dangerous combination: a

prof. ir. Rob Nijsse
Faculty of Civil Engineering and Geosciences, Delft University of Technology

ir. Ate Snijder
Faculty of Architecture, Delft University of Technology

1

2

1 The finished glass arch bridge in the Green Village on the Delft
credits: Frank Auperlé
2 Massive glass block used for the construction of the bridge
3 Artist impression of the bridge

structure with limited lateral stiffness. The Structural Design group of the DUT was however convinced that with a clear awareness of this dangerous combination and the appropriate structural measurements this challenge can be tackled.

The glass arch bridge is designed and engineered by the DUT and the two abutments by the engineering firm RHDHV. The DUT was also involved in the execution of the abutments. It is important to know the state of deformation of this highly experimental bridge to assure its safety, or to be able to take preventive measures when deformations become too large.

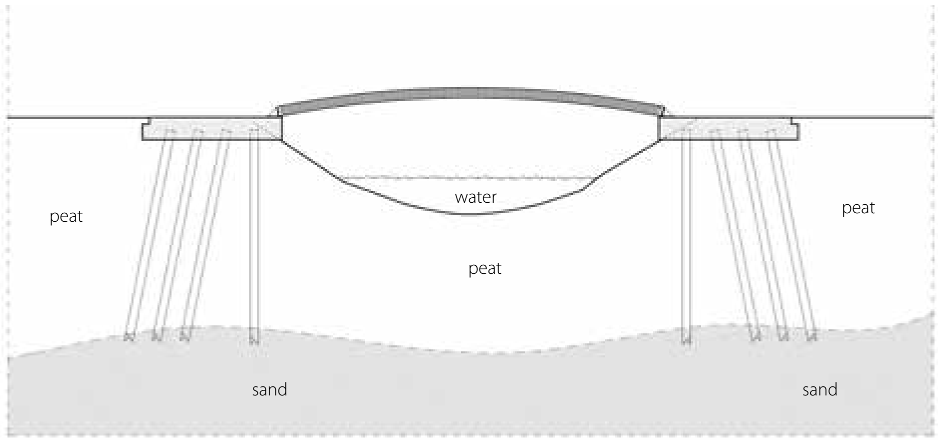
Continuous collaboration between the structure itself and the foundation has to exist, especially in the Netherlands where the soil is so bad/ weak.

Design of the foundation

In close collaboration between Royal Haskoning DHV (RHDHV) and the Structural Design group of Architecture and the Building Engineering group of Civil Engineering of the DUT the following concept was worked out (fig. 4): two big, cast on-site, reinforced concrete foundation blocks (5650 mm

3

4 Bridge, abutments and piles
5 Plan for foundation piles
credits: RHDHV



4

long, 3300 mm wide, 800 mm high) resting on concrete piles. Each concrete foundation block rests on eight piles. Two piles, close to the supports of the glass arch, are placed vertical, the other six are placed under an inclination of 1:5, an angle of about 11°. This has been done to have as much capacity as possible for taking up the huge horizontal forces from the glass arch. The concrete piles had to be 23.75 m long to find a good firm footing in the bearing sand layers under the first 20 m of non-load bearing peat. The piles measured 400 mm by 400 mm and were driven in the soil.

Calculation of the concrete foundation blocks

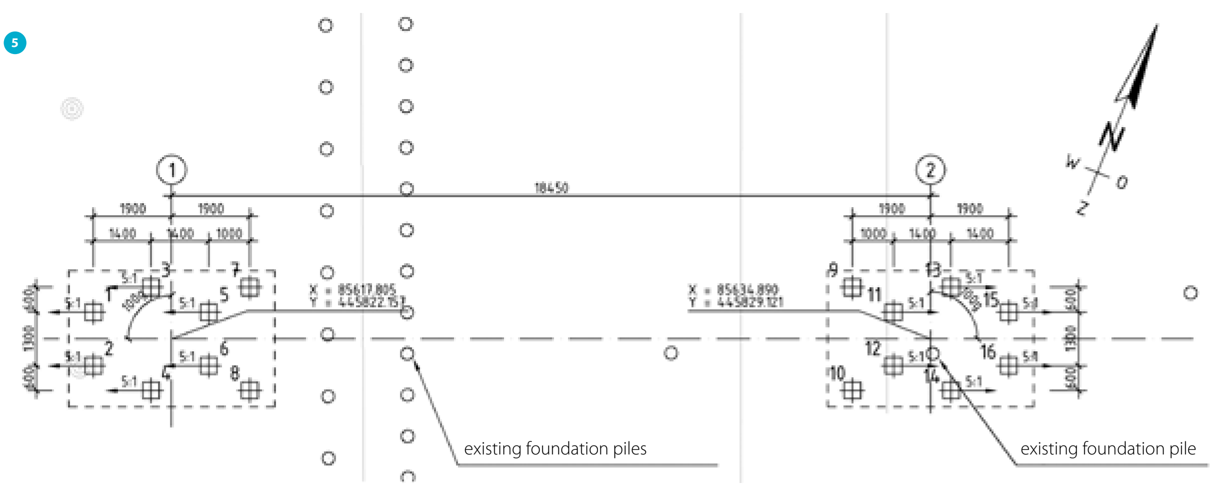
TUD made FEM calculations of the shallow glass block arch composed of loose glass blocks of 400 mm depth. Dictating loads were the dead load of 1000 kg/m^2 due to the glass arch and a live load of 500 kg/m^2 that could be placed eccentrically. As a special load case a maintenance vehicle had to be taken into account.

RHDHV calculated the concrete foundation with a finite element program in which the piles were described as tall columns supported by springs that represent the soil action. The determination of the strength and stiffness of these springs is very difficult. Also the difference between horizontal and vertical components of these spring stiffness's is complicated. The state of the art theory was followed but the real behaviour of (driven!) piles under load is rather unknown. Especially considering that the long term behaviour (plasticity and creep) is completely unknown.

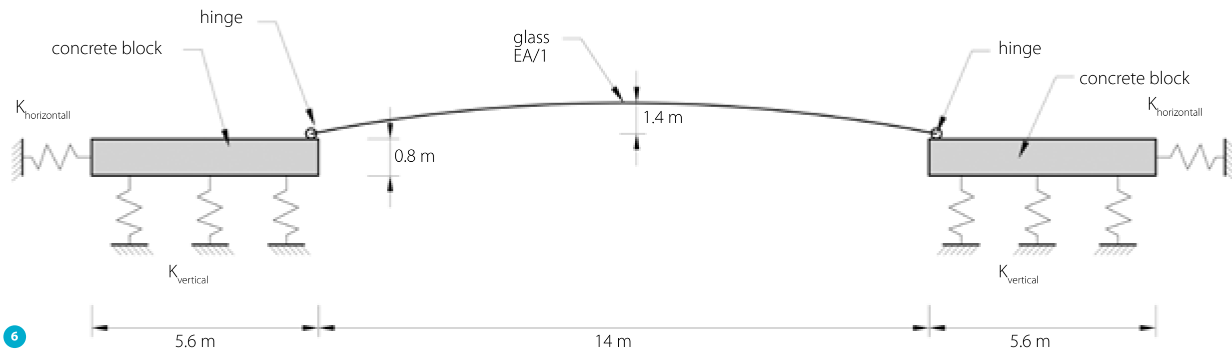
Building Code producing authorities have to be aware that real life tests on piles have to be executed to provide reliable structural properties for this type of calculations. This counts for static, dynamic and long term loadings on piles. If the engineers do not have validated data their calculations are not more than an educated guess, which may result in an unacceptable or unsafe situation.

Just the characteristic dead load of 308 kN of glass blocks already results in a horizontal force of 480 kN on each abutment of the arch bridge. Adding to this the characteristic live load, like pedestrians and cyclist, a maximum vertical load of 443 kN and a maximum horizontal load of 718 kN results.

5



6 Static diagram
7 Piles in place
8 Construction of an abutment



6

The TUD as a client laid down the criterion that a maximum horizontal movement of 10 mm was acceptable. The uncertainty regarding the springstiffnesses, especially horizontally, led to the following precautions. Directly from the delivery by the contractor the situation was carefully measured during the building process and, further on, during the life cycle of the glass block arch bridge, these values will be monitored. If the displacements of the bridge are measured to be larger than the maximum of 10 mm stiff steel cables can be attached horizontally between the concrete foundation blocks.

Execution of the foundation blocks

The real work on-site starts with one of the most critical activities: the layout of the bridge and foundation in the plan of the Green Village. Related to that the next, even more critical, item: the correct positioning of the piles (photo 7).

Only a small wooden stick pushed in the ground indicates the position of the pile to the pile driving company. Despite all the attention asked for this specific item, a misplacement of maximum 500 mm occurred by mistake. To account for this, the size and the reinforcement of the concrete foundation blocks had to be changed. Also the inclined piles were not driven in the same direction, some more to the left, some more to the right etc. Implementing these differences in the computer model showed a decrease in structural capacity of about 4% with a possible rotation of the entire block which will be continuously monitored in future. After this, making of the formwork, introduction of reinforcement (photo 8) and to-be-cast-in anchors were positioned and the casting of the concrete took place.

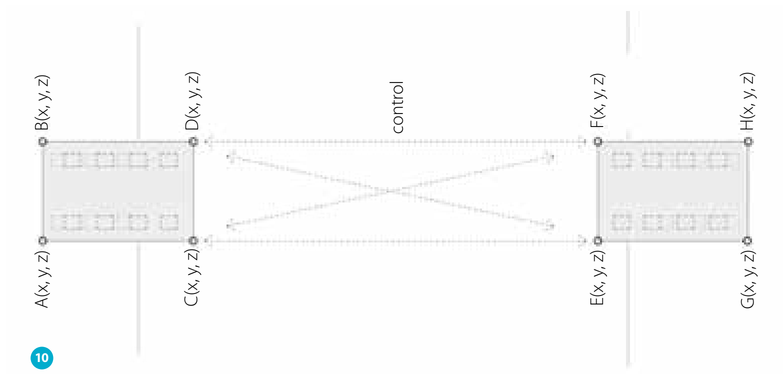
Control of the deformation

All four corners of each concrete foundation block will be, as constantly as possible, monitored and registrated for x-, y- and z-coordinates. Especially during the construction of the actual bridge, the deformation will be monitored since in this period

7

8

9 Temporarily support in a form of steel trusses and glass diagonals
10 Top view of abutments and critical measurements



the horizontal and vertical loading on all piles will build up from 3-5% (self weight of concrete) to 100%. To build an arch with loose glass blocks a temporarily support is required. For this reason two steel lens shaped trusses were installed (photo 9). The diagonals in these trusses are another structural innovation; they are made as a bundle of massive glass bars, pre-stressed for structural safety with an internal steel bar. An arch only becomes a structural arch when the last stone is put in place. Hence the steel trusses with glass diagonals will carry up to the last stone of the arch the vertical dead load of the glass block arch; about 308 kN! So during construction of the bridge the vertical load on the tip of the concrete foundation block will grow from about 10 kN to 154 kN per block. It will be interesting to see in what way the foundation will deform during this period. A dramatic change will take place at the moment when the arch is completed and the temporarily trusses will be lowered (with jacks). In one second the, above described, vertical load from the temporarily trusses, combined with the huge horizontal loads due to the glass blocks arch, will be transferred to the two concrete foundation blocks.

It will be interesting to registrate displacements of the two concrete foundation blocks in this phase: both short time and long term behaviour. To predict what will happen with the concrete foundation blocks supported on long, inclined piles, due to the lack of accurate data, is impossible. Hence the measurements will provide more insight in the real behaviour of this experimental structure and its foundation.

Conclusion

The structural designers of the glass arch bridge, are very grateful to be allowed by the Green Village and the Dutch Authorities to construct, and monitor, such an experimental and innovative bridge (and foundation!). It will result in a large increase of structural knowledge and is a big step ahead for Structural Science. The glass bridge is officially opened on May 15 2017. This is only a temporarily version: the composite trusses are covered with stepping stones and grass. The 2200 glass blocks for the final bridge version, still need to be manufactured and put in place. ☒