Photogrammetry for masonry bridge inspection and recording

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- Masonry bridges are intrinsically three-dimensional structures, with long and rich histories.
- Our ability to detect, understand, and respond to damage depends on seeing surface defects and in context. Inspection records do not support this.
- High detail photogrammetric models are transformative, providing an objective record of shape and surface condition.
- A specialised viewer enables insights that would never be achieved in the traditional inspection and assessment process.

Photogrammetric models for inspection and records

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Photogrammetry has transformative potential in masonry bridge inspection, recording, and assessment. Our viewer app provides simple interactive tools that facilitate interpretation, allowing insights that could not be achieved during on site inspection.

We present an example of off site inspection using this app. The model studied is of Rutters Bridge, on the Middlewich branch of the Shropshire Union Canal, built from 2000 photos, collected using a camera on a telescopic pole.

This note started life as Bill's March 2019 Bridge of the Month newsletter, and was adapted to accompany the presentation given by Hamish at the BD&E Bridges 2019 conference.

Who are we?

We have two companies. Obvis Limited develops, markets, and supports the Archie-M bridge assessment software, and offers training.

Bill Harvey Associates is an R&D intensive consultancy. We specialise in masonry — assessment, diagnosis, design of repairs, modifications, or new structures — and in monitoring.

Figure 1: Moco Farm bridge, raised by 900mm

Our innovation track record goes back over 30 years to Cirar ("circular arch"), the first computer based arch assessment tool and direct forerunner of today's Archie-M.

It continues to the present with the award winning ElevArch trial, a world first in which a masonry arch bridge was jacked to create additional clearance for electrification (figures 1, 2). This was an idea of Bill's, taken up by Freyssinet and developed jointly.

And, of course, with the tools described below.

Figure 2: South abutment of Moco Farm bridge, raised by 900mm

Photogrammetry, or Structure from Motion (SfM)

Structure from Motion is the latest development of a technology that dates back at least to the early 1900s. Digital photography, image processing algorithms, and cost of computation and data storage have transformed it.

It is now possible to collect a dense set of photographs of a bridge, covering the whole surface with overlapping photos from about 2m range, and process these into a 3D model that captures every lump and bump of surface. The photographs are then projected back onto the model, giving sub-mm detail as in figure 3.

Figure 3: Large structures can be recorded in sub-mm detail.

Capturing the photographs is not trivial. We have developed tools and techniques specifically addressing the challenges of capturing masonry structures, including camera poles and pulleys, and rigs carrying sets of cameras that are fired together.

These have allowed us to capture detailed imagery in challenging circumstances. Highlights include Pontypridd Old Bridge (140 foot span, 42.7m span, rising 10m above the river Taff, 14,000 photographs), and the vaults inside the Leigh Woods abutment of the

Clifton Suspension Brige.

There is no natural light in the CSB vaults. To our delight, we found that this process works perfectly well with flash illuminated photographs, allowing full colour models of otherwise pitch dark spaces.

Just viewing these models is valuable; it is a lot like being there. But there is much more value latent in the models. We have developed an inspection app, embedding a growing collection of simple but powerful interactive tools. These allow the Engineer to draw out the stories a structure has to tell, and then to capture what is learned.

There is much more to do, but it is already beyond doubt that the high detail "reality capture" offered by photogrammetry will transform inspection and recording, and thus assessment and management, of masonry bridges.

There is a demo version of the app and model available from https://bhal.co/bridgeconf2019 if you'd like to follow along.

Case study - Rutters Bridge

Figure 4: General view of Rutters Bridge. This is the only photograph presented in this note, all other images of Rutters bridge are model renderings.

Rutters Bridge is on the Middlewich branch of the Shropshire Union Canal. This was the last major work of Thomas Telford, completed in 1835.

Bill was asked about the slab over the crown, and found a chance to visit with Ian Draycott of the Canal and River Trust, to whom thanks for a very enjoyable day. Figure 4 shows a general view. Even at this distance you can see why there was concern.

The site visit lasted about 2 hours of which around one hour was spent waving a camera on a 10m pole to get detailed photographs. In all, 2005 photos were taken, of which 1940 were included in the model. The processing software calculates the position and orientation of each image (figure 5).

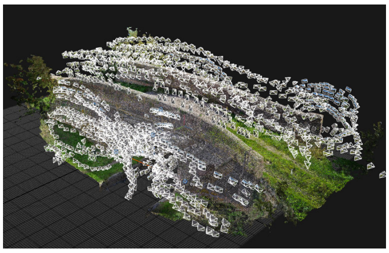

Figure 5: Position and orientation of each photograph used in constructing the model.

Ignoring the arch for the moment, there is one very obvious vertical crack in figure 4. It looks as though it might follow the line of the back of the abutment, why else would it be so straight.

As so often, the cause of that crack was not immediately clear. Without a model, it would have been impossible to diagnose this without returning to conduct a detailed survey. Tools in the viewer allow us to explore the movements in detail as understanding develops, making diagnosis possible without a further visit.

We can add planes to the view, and see where these intersect the structure. The plane in figure 7 was defined as a horizontal plane through a point at the near side crown. Note the white contour where the plane cuts the arch. It tells us that the near side is lower than the far side.

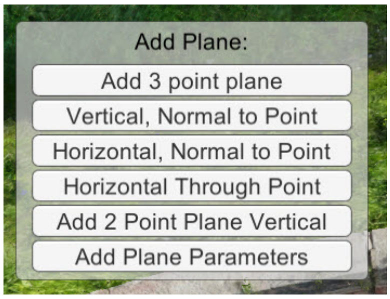

Figure 6: Right clicking on the model opens the planes menu.

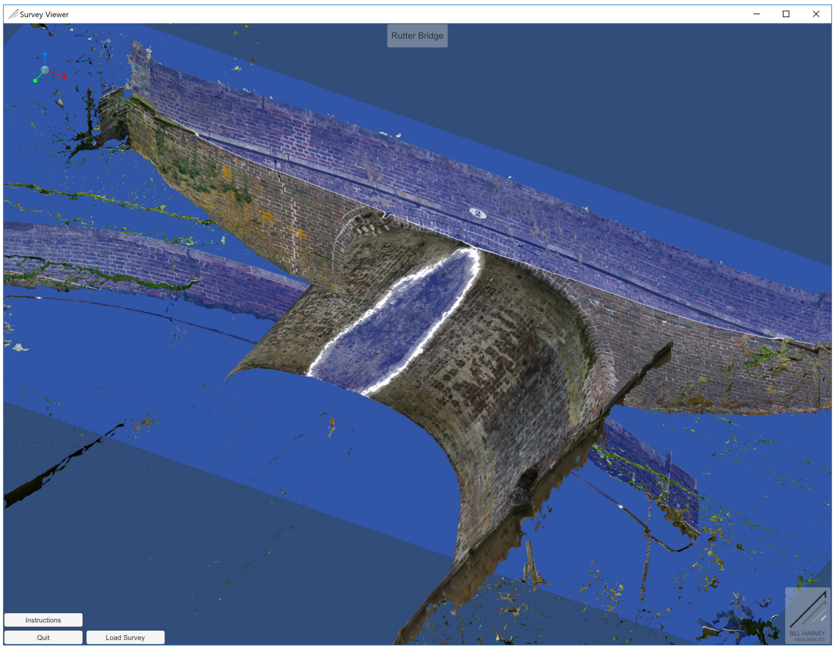

Figure 7: Orthographic view of model with horizontal plane. The plane was created by right clicking on the model, selecting "Horizontal Through Point", and defining the point at the near side crown.

Hitting the F key then gives the front elevation view of figure 8. From here you can see that the plane (showing now as a faint line) cuts the top of the string course in the pillar at the right but flies above it at the left.

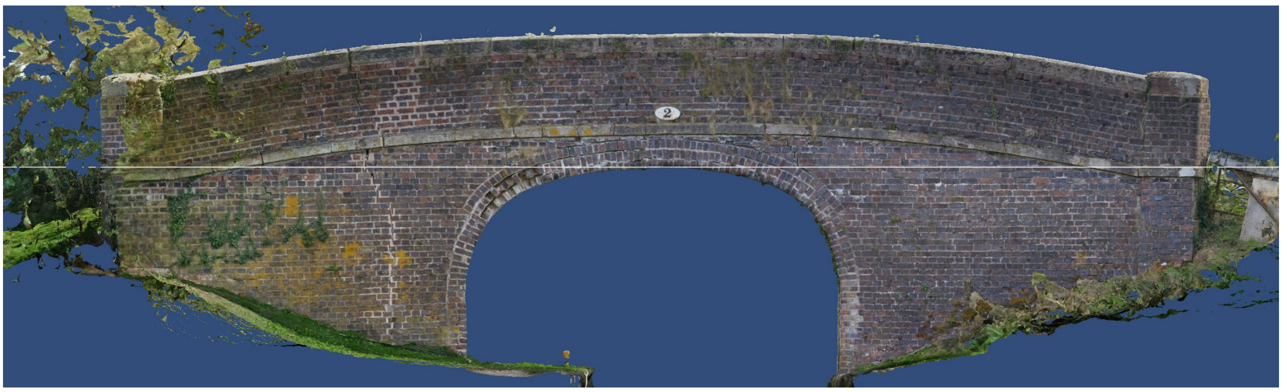

Figure 8: Orthographic elevation with photographic detail. The plane defined above shows from the edge as a white line where it intersects the model.

Zoom in on the left hand side and we find something really rather interesting (figure 9). There are actually three near vertical cracks, the big one in the centre, one rising from the arch at the right and another to the left. What is more, the courses tilt progressively backwards. There is a slight tilt to the right of the crack, a bigger one to the left and bigger yet beyond the third.

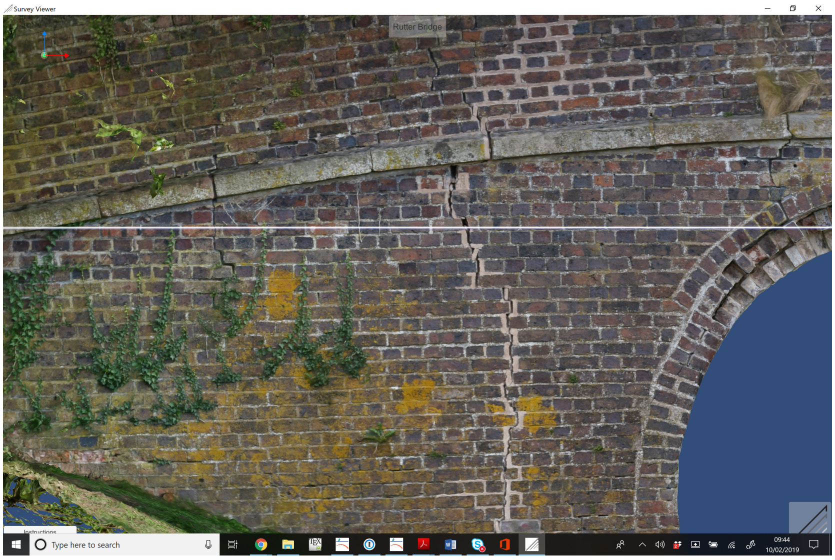

Figure 9: Closer view of left abutment face shows multiple vertical cracks with courses tilting backwards.

Figure 10 shows a closer look at the section above the abutment. We find that the course is actually curved. Sloping down to the rear, but also down towards the crack in the arch.

Figure 10: Close zoom of left abutment face shows that the course is curved.

Moving the plane up to the coping (figure 11) shows that it has an almost continuous curve but it is slightly flattened in the middle, suggesting a drop over the crown.

The string course also looks flat in the middle. Rather than moving the plane, we can duplicate it and move the copy off line. Putting a straight line through both places emphasises the effect (figure 12).

And here, there is more to see. Notice the crack at the right tracking down to the arch, round the back of it and then through. A hinge

Figure 11: Horizontal plane under coping at crown.

Figure 12: Two parallel, horizontal planes.

opening at the top. If there were thrust in the arch, the right hand hinge would have formed near the crown, because that marks a straight line between a top hinge and a bottom hinge (see the plane in figure 13), allowing free movement without any increase in thrust. In fact, the loose brick at the centre says there definitely isn't an intrados hinge there.

Figure 13: Plane shows that top of side hinge is on same level as crown intrados. A loose brick at the crown shows that there is no thrust at the intrados.

We can also switch from one side to the other. Careful examination of figure 14 shows that the abutment is lower in the first than the second: there is a cross fall. Perhaps that begins to explain why all those bricks are missing. There is still a slight fall to the back of the abutment.

On the other elevation (figure 15), the courses are level from end to end except for a very slight back tilt at the right (the same side as the left in previous pictures.

Looking down and enlarging, the crack above the SLOW sign seems to have put a plan joggle in the string course (figure 16).

It is easier to understand that by zooming out a little (figure 17).

Figure 14: Same view, opposite sides of abutment, with the plane unmodified, shows a cross fall in the abutment.

Figure 15: The other elevation, orthophoto.

Figure 16: Plan view of SLOW sign, shows a plan step in the string course.

Figure 17: Inclined view of SLOW sign. I think that crack bifurcates and reaches both ends of the coping stone. This movement is caused by the twist in the bridge. The step is masked as a slew in a long stone at the parapet.

Defining a plane and manipulating it, watching the contour change in real time is a very powerful way of developing a feel for deformations. It is possible because the contours are calculated by the graphics processor. Traditional contours at equal spacing can still be valuable, not least for inclusion in a report, and are simple to produce (figure 18) by defining planes numerically (figure 19).

Figure 18: Planes can be defined numerically, making it simple to produce contours, whether in plan as here, or vs any chosen normal.

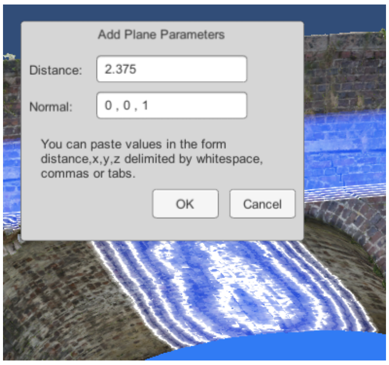

Figure 19: Specifying a plane with a normal and offset from origin.

Instead of using photographic colour, we can colour the model in other ways. If we map the x, y, z of the normal vector into the red, green, blue channels of colour, we get a very useful result. Figure 20 shows the effect.

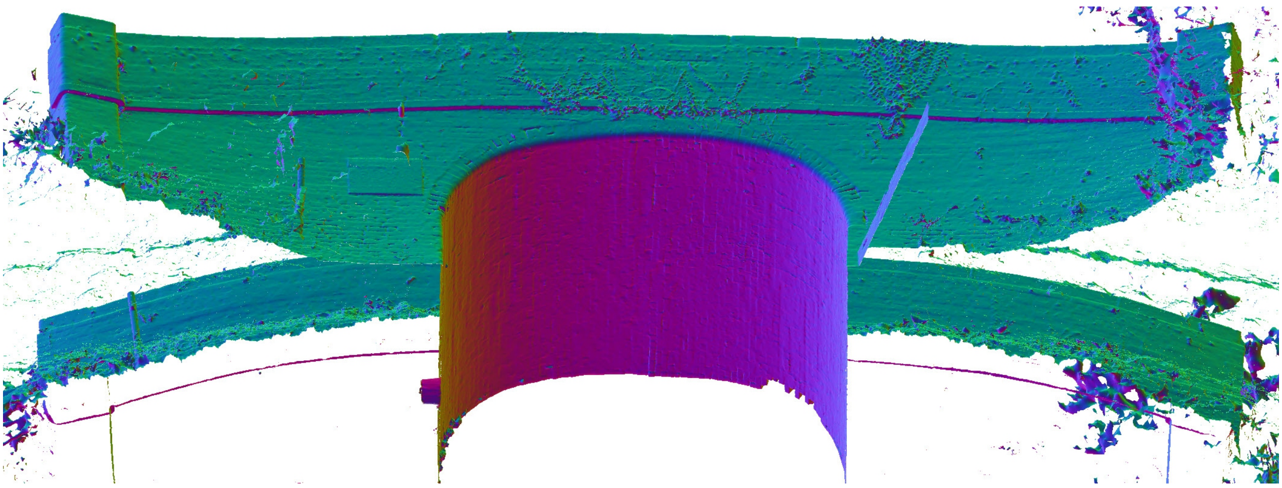

Figure 20: This inclined view has each point coloured with a mix of red, green and blue depending on the normal direction. Changes of angle and surface roughness are highlighted.

Colouring by normal highlights surface roughness, and here exposes a considerable difference in the pointing below the slow sign which wasn't otherwise obvious. Figure 21 compares this in detail between photographic colour and colouring by normal.

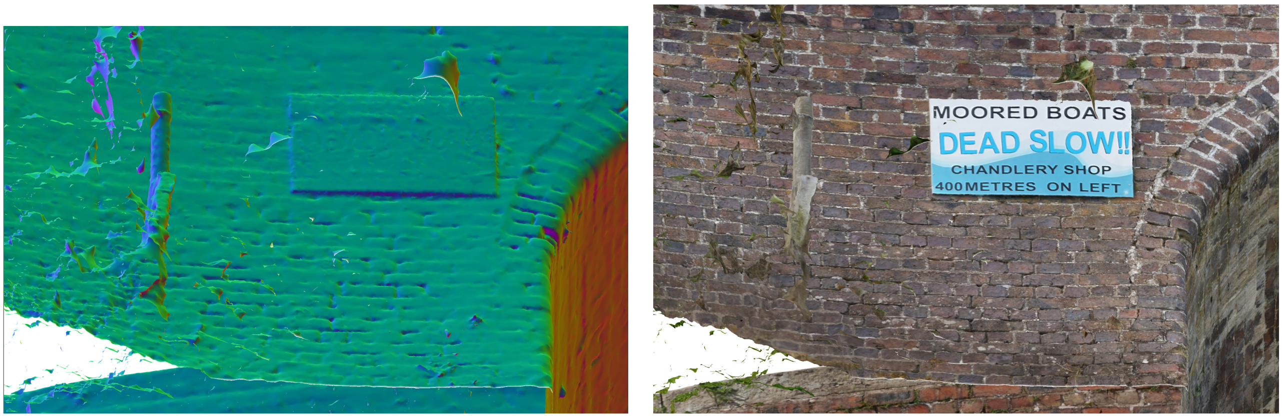

Figure 21: There are clear voids both in the wing wall and in the ring. In normal colour, and the empty joints are still visible but less striking.

Figure 22 is a closer view of the corner. The image is getting to the limit of available resolution but the joints are still visibly tight under the arch.

Look closer at that broken nose in the arch (figure 22). It's obvious that the brick was pinched tight before it failed. The mortar was squashed to nothing at the inside edge and similarly tight joints can be seen across the arch face. That wide mortar patch round the back of the arch obviously indicates movement and where the joint runs out, the movement continues by snapping a brick.

Figure 22: Do the gaps in the corner go round under the arch? This view shows that they don't. Note wide mortar indicating movement at back of ring, tight joints on the soffit, and snapped brick at the corner.

Looking at the soffit in false colour, we find initially that the towpath interferes with the view (figure 23). We can add a cropping plane to remove it, getting figure 24.

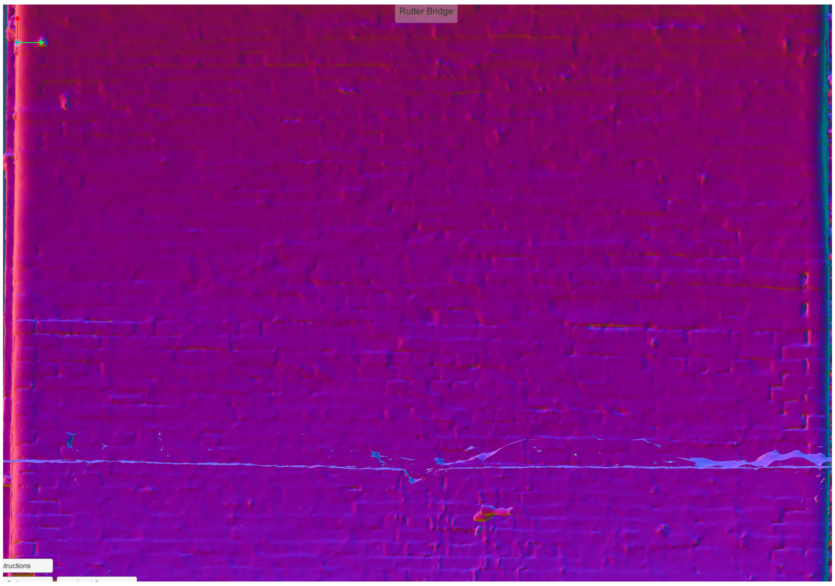

Figure 23: Tinting every bit of surface according to the direction of its normal emphasises empty joints and other damage. Is it just me or do the colours change across a diagonal?

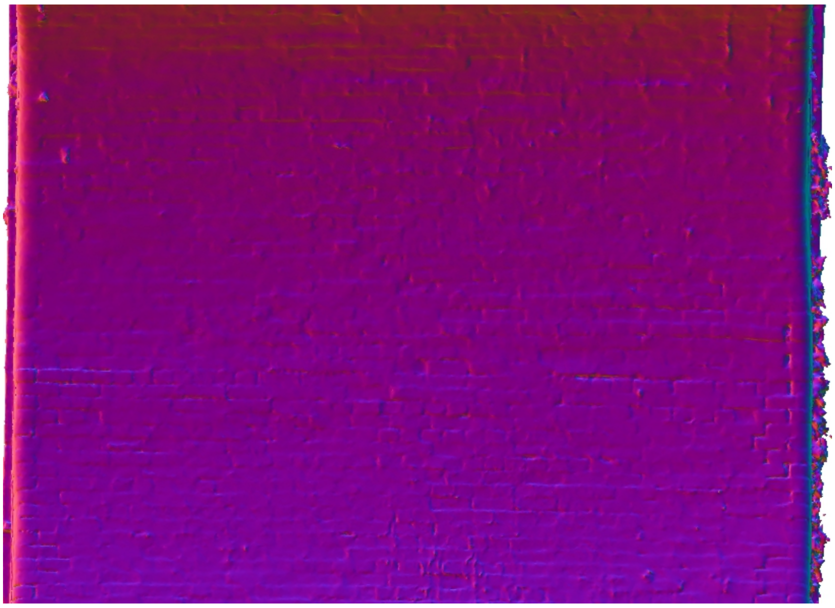

Figure 24: To clean the image a bit we put in a cut plane and removed everything below it. That takes out the ghost of the towpath edge and made things clearer. Notice the thin bright stripe where there is a drop between bricks near the crown at the left. The model is tilted here to emphasise that.

Another plane option is “2 point vertical”. This allows us to align a vertical plane with the bridge as in figure 25.

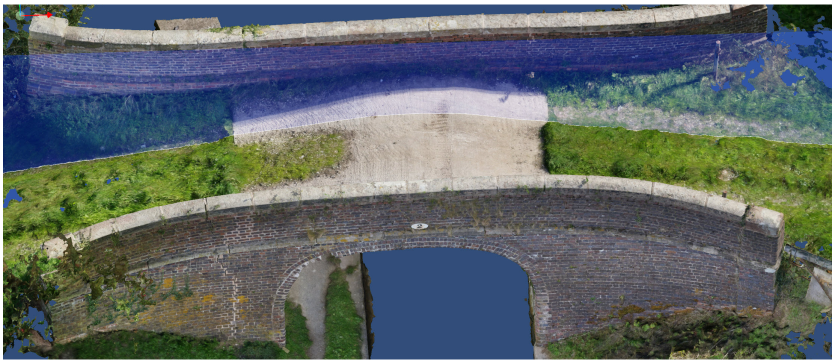

Figure 25: A vertical plane defined to pass through two points.

Figure 26: Setting the plane to remove everything in front and taking a square view, we can now see the huge steps onto and off that slab. It's hard to imagine vehicles getting over that without causing trouble.

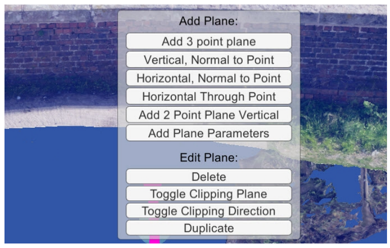

Figure 27: Right click on the plane you get the offer to duplicate it. You can then separate them to make a slice

If we set that plane to crop the near side of the model away, and go to a front elevation, we get figure 26, which shows the slab surface against the backdrop of the far parapet.

Duplicate that plane (right click on the plane and select “Duplicate”, figure 27), slide the copy a small distance (figure 28), set it to crop in the opposite direction (figure 29), and finally hit F12 to hide the planes and controls, and F to get a front elevation, and the result is a clean long section (figure 30).

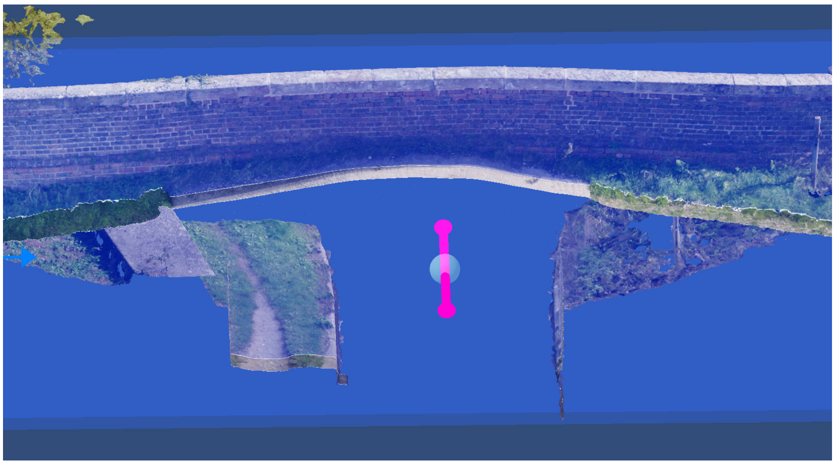

Figure 28: Two parallel vertical planes demark a slice.

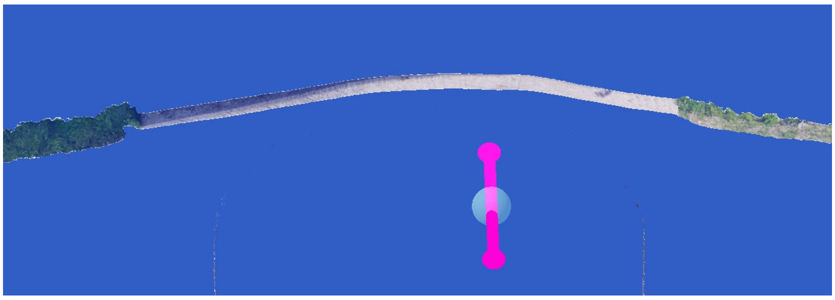

Figure 29: Clipping at both planes in opposite directions isolates a strip.

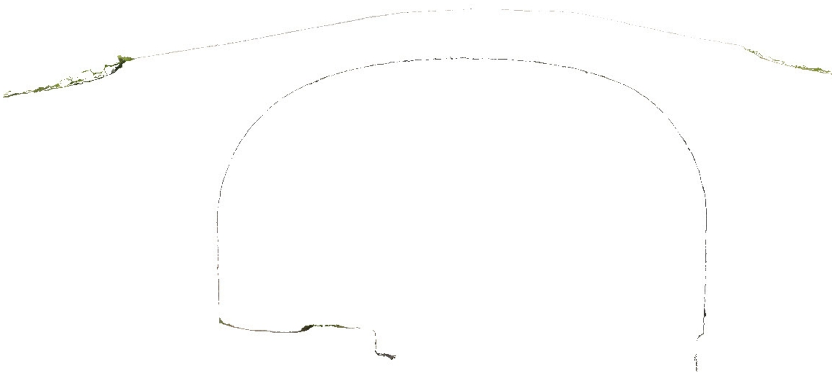

Figure 30: Return to front view (just hit F) and hide all the decorations (F12) and you get a clean long section through the bridge. Sections like that can be extracted as numbers and taken into eg Archie-M for analysis.

Long after the site visit, we noticed something in the view shown in figure 31. There is at least one apparently broken face, in amongst those teeth, where a clean brick face would be expected. Obviously some displacement of the ring away from the wall and also of the wall laterally away from the edge of the arch. Probably progressive damage from the arch moving under load and bits in the gap doing damage.

The above explorations lead to the diagnosis that one abutment has rolled back, the drop at the back of the wing wall being larger at one side than the other. Much of the damage is associated with the resulting twisting and loss of thrust.

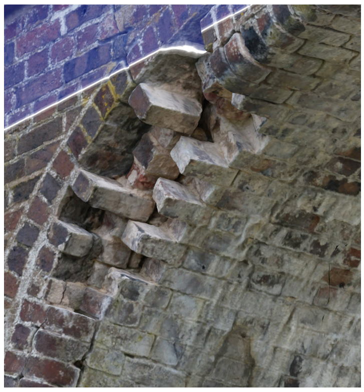

Figure 31: At least one broken brick face in here.

The latest addition to the app is the ability to annotate models. The annotations are stored in separately from the model and can then be turned on and off at will during a review.

Annotations have a label, and optional extended information (as pop up rich text, which can include images) and shapes (lines or areas). Figure 32 shows several examples.

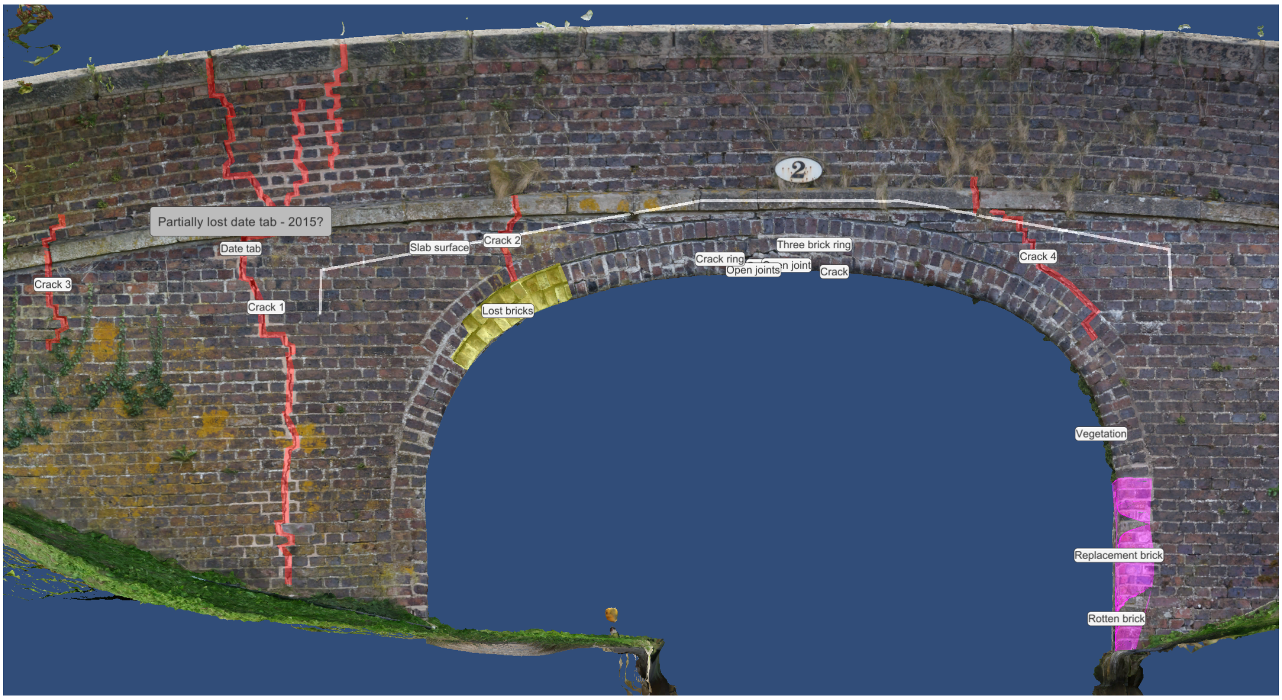

Figure 32: A view of the model displaying various annotations.

The various forms of annotation illustrated here are best described in relation to separate screen shots.

Figure 33: A closeup of the annotations near the crown.

First, the closeup in figure 33 shows that the annotations are held in 3D relationship. They are designed to be readable on screen and not to scale with the model as you zoom in.

We can project the slab surface to the elevations using planes, and mark its location for ease of reference with line annotations, as shown in figures 34 and 35.

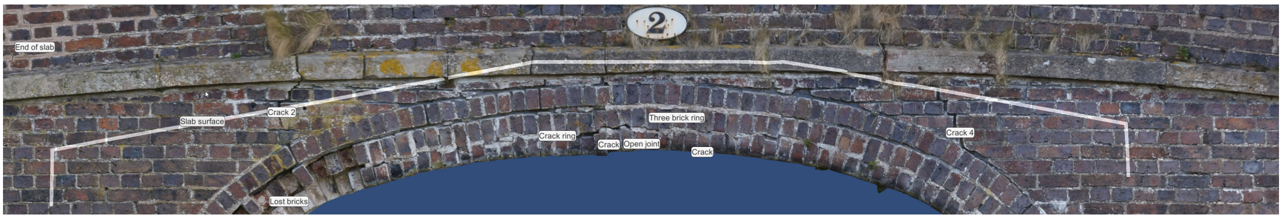

Figure 34: Western face showing extent of slab

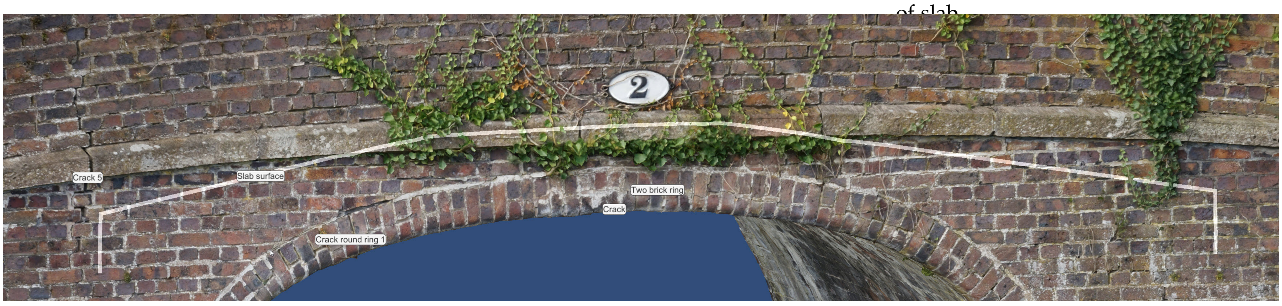

Figure 35: Eastern face showing extent of slab

Transparent tints can be applied to indicate the extent of any detail being noted (figure 36). This, too, is a 3D effect, wrapping round the edge of the arch and into the hollow in the centre of the abutment. That is, perhaps, clearer if we turn the abutment to look from further under as in figure 37.

Figure 36: Tinted areas can be used to emphasise concerns, construction details, work required, and so on.

The next step beyond annotations, currently under development, is to define "tours" around a model. These will guide the viewer though a sequence of steps. Each step will show a particular view with selected planes and annotations showing, and offer explanatory notes.

Benefits

This document began as a simple "Bridge of the Month" newsletter about Rutters Bridge. As it developed it became clear that Bill was

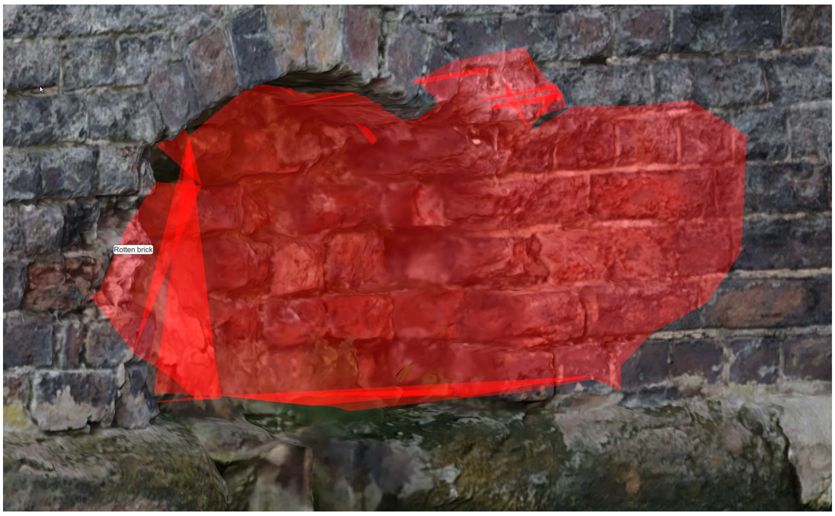

Figure 37: Stoplog hole detail showing 3D nature of tints. Careful examination of this view shows the steel channel to receive the stoplogs.

getting much more from the model than would be possible with even the most detailed site inspection.

The modelling and viewer are part of a determined attempt by BHAL to improve the quality of inspections. With a model such as this, everything from dimensions to small details can be checked and rechecked after the visit.

If you find something on a subsequent inspection, you can turn back time and be sure it really is new.

The potential of this technology to transform inspection and recording of individual bridges is clear.

It also has great potential for systemic benefits. An experienced Engineer can review a model in a few minutes in the office. That in turn makes it possible e.g. to review all bridges on a line as a set, increasing the chances of spotting developing issues.

Inspections can be checked properly, and a system of continuous review and improvement becomes possible.

Work with us

We intend to make the viewer available commercially. If you would like to be an early adopter, or just to have a look at a demo, please get in touch with Hamish at hamish@billharveyassociates.com.

During this development phase we are carrying out modelling for our own projects and for others. If you have a desire for the full service, again, contact Hamish.

We will make a small number of detailed models available as training exercises for new inspectors and assessors, with the results being marked and returned. If this is of interest, contact bill@billharveyassociates.com.

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If you've found this note interesting, you should certainly

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Bill Harvey Associates Limited is a small, R&D intensive practice specialising in masonry structures. We provide design, inspection and assessment, monitoring, and education and training services.

Obvis Limited, our sister company, produces the industry standard masonry arch analysis software Archie-M.