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FORTH BRIDGE BEARING REPLACEMENT FEASIBILITY

PRELIMINARY FEASIBILITY REPORT

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CONTENTS

1 INTRODUCTION

The Forth Road Bridge carries the A90 from Edinburgh to Perth north across the Forth estuary and comprises a suspension bridge and a north and south viaduct section leading up to the main bridge. The approach viaducts carry two carriageways each with two lanes and extends from the abutments to the side towers, which are shared with the main suspension bridge. The south viaduct has a total length of approximately 433m. This consists of 11 spans varying between 33-49m. The north viaduct has a combined length of 247m with 6spans varying between 33-49m. Each span consists of a pair of box girders connected by transverse cross girders spaced at around 3m centres. This structure supports a concrete deck and is composite with it.

The deck rests on steel roller and rocker bearings. The bearings are fixed to reinforced concrete portal piers founded on rock. The pier heights vary between 11 near the abutments and 40m near the side towers.

The north viaduct has rocker bearings at all piers and abutments except for the side tower which has a roller bearing to allow for the temperature movement of the structure. The movement of the deck elsewhere is allowed for in the flexibility of the piers.

The south piers are numbered from S1 adjacent to the side tower up to S10 near the abutment. The articulation is as follows: on the top of the piers S1-S3 and the side tower, rocker bearings have been installed. For these piers, the temperature movements are accommodated through flexibility of the piers. An expansion joint is positioned at Pier S3 which allows for the movement of both sections of the viaduct; this pier supports both a rocker and a roller bearing. For the shorter, less slender piers S4-S10 and the abutment, roller bearings have been used to allow for temperature movement.

This report examines the current condition of the roller and rocker bearings on the north and south approach viaducts on the Forth Road Bridge, the need for replacement and possible options for the replacement of the bearings, either now or in the future. It also provides recommendations on future work and monitoring.

In this report, usage factors are used to report on the adequacy of the structure, a usage factor exceeding one indicates an overstress in the member, while a usage factor less than one indicates that the component has adequate capacity.

This report is very much “work in progress” as the study has been complicated by recent new information including poor pier top concrete condition, locations of services in the box girders and the addition of new cabling for the dehumidification system. The original feasibility study scope was understood to be to provide a means of replacing bearings, rather than determining which bearings should be replaced. In the event, it has become necessary to undertake surveys of bearings and concrete to facilitate this decision, particularly in light of the fact that the decision to replace bearings (or at least lift them) may be more driven by the need to carry out concrete repairs.

2 STRUCTURE STATUS

2.1 Inspection Data

2.1.1 Outline of inspection Completed

An inspection of the pier tops and bearings has been done for all the north viaduct bearings, and the west side of the south approach span. This inspection included the visual inspection of the pier and bearings and a hammer tap survey of the pier concrete. A hammer tap survey has not yet been done on the top surface of the pier.

2.1.2 Bearings

The bearings on the north viaduct piers and the south west viaduct piers were visually inspected and a hammer tap survey carried out on the concrete as part of this work. Generally, the defects found on most bearings were considered minor. However, on the shared pier S3, the roller bearing was found to be missing teeth and appears to have displaced off centre by sliding (rather than just rolling). Details are given in Appendix D.

2.1.3 Piers

The concrete in the pier tops is delaminated in a number of areas and has had several patch repairs done to it over time. The most significant defect is at the shared pier S3. A large section of concrete of the north face of the pier produced hollow sound when tapped. This is most likely to be delamination caused by corroding reinforcement. This is a concern due to the proximity of the bearings to the pier edge. A vertical crack also runs down the pier side face which is of further concern as the pier reinforcement was assessed as inadequate to resist bursting. This raises the possibility that the hollow concrete is actually as a result of bursting forces rather than expansive corrosion. There are no available concrete testing reports for these piers so no indication as to whether the piers are contaminated with chlorides. Such testing should be carried out as a priority. If the corrosion was in fact induced by salt spray, it would be expected that worse problems would exist further down the piers. Again, no testing records are available for the remainder of the pier height. A cover meter survey would also be useful to determine whether the pier concrete cover is deficient.

2.1.4 Inspection Conclusion

The inspection does not indicate an immediate need to replace the bearings themselves, with the possible exception of S3, but monitoring would be necessary given the codified deficiencies and the damage to teeth observed on some of the roller bearings. It will also be necessary to carry out ultrasonic testing to determine whether there is any cracking of the bearing and plate steel. Further investigation of the concrete condition (eg. Chloride, half cell and carbonation tests) are needed to determine the cause of the deterioration. Repairs of the concrete will be necessary.

Given the lack of complete inspection, and despite the general feeling at this stage that monitoring is appropriate, it would be prudent to carry out a visual inspection of all the bearings together with the concrete at the pier tops within this feasibility study. It may be necessary to lift the bearings to perform the concrete repairs and then it may be prudent to replace the affected bearings at the same time.

2.2 Analysis

To determine the loading in the structure acting on the bearings, a plane frame model was used, modeling half the structure. The north and south viaduct were both modeled independently to determine which bearings were subject to the greatest loading. The feasibility design was then based on these loadings.

Combinations 1-5 (BD37/01) were used to determine the most adverse loading on the bearings. The jacking loads are calculated based on the assumption that the permanent loads are shared between the two pairs of jacks while the live loading is supported by one pair of jacks. This is based on the behavior found in performing similar bearing replacements.

Grillage analysis is also now underway to try to reduce the loads on the bearings.

2.3 Assessed Resistance

2.3.1 Bearings

The current bearings were assessed to determine compliance with BS5400-9.1:1983 and Eurocode series BS EN 1337 for bearings. The nominal ultimate tensile stress was assumed to be 360 MPa based on mild steel. The record drawings are inadequate in this respect. It appears clear that the rocker bearings are mild steel but the steel grade for the rollers is unclear. A note saying “all steel is mild steel” is located between views of the roller and rocker bearings, but nearer to the rocker bearing. In our experience it would be unusual for roller bearings to be mild steel and it is likely that the steel is in fact a much higher grade. Testing could be undertaken to confirm the steel grade but there are no signs of load-induced distress in the bearings currently. The structure has a low live load ratio which suggests that there is little potential for the bearings to see significantly higher vertical loads than they have already experienced.

Roller Bearings

The roller bearings were compared to BS EN 1337-4:2004 in to establish their compliance with the current standards. From this comparison, the bearings were found to be compliant except for:

- The length/diameter ratio which was found to be 12.3. The maximum allowable ratio is 6.
- A usage factor of 4.08 was calculated under ULS axial load for the bearings – this is probably a result of the bearings being made in steel stronger than mild steel. The steel would need to have an ultimate tensile strength of around 700 MPa to comply with strength criteria.

The detailed comparison with requirements included in Appendix A

Rocker Bearings

The rocker bearing were compared to BS EN 1337-6:2004 to establish their compliance with the current standards. From this comparison, the bearings were found to be compliant except for the radius of the top of the bearings which is unknown, though a 463mm radius would be required – this could be measured. A detailed comparison of this is included in Appendix B.

Resistance to longitudinal forces also needs to be verified. If the piers remain un-cracked however, the forces put excessive longitudinal forces on the rocker bearing fixings. This restraint will also be difficult to provide during a bearing replacement. Further analysis is required here.

Monitoring of bearings

Bearings to BS EN 1337-10:2004 (Inspection and Maintenance)

Future monitoring should measure plate movements and rotations to clause 6.2.3 for roller bearings and 6.2.5 for rocker bearings. The roller position should be measured relative to the bearing plates, particularly where any teeth are missing, to check for slewing of the bearings.

2.3.2 Piers

The tops of the piers were assessed based on the maximum ULS loads applied to the pier. The concrete properties grade is stated to be class B concrete; it is assumed that this refers to CP114 which indicates a cube strength of 25.8MPa (3750 lb/in^2).

The bearing stresses on the concrete under the bearings was calculated and was compared with the bearing stress limit in BS 5400 of 0.4fcu. A usage factor of 1.84 was calculated for this. Further analysis was then carried out using a strut and tie model to check if there was sufficient reinforcement to resist the bursting forces in the concrete which was found to be inadequate. Therefore the tensile resistance of the concrete was considered in the strut and tie model to provide the required strut tension. The usage factor was found to be 1.08, which, though not quite adequate numerically, is considered to explain why there are no obvious signs of distress in a bursting mode. Since the structure has been in service for 40 years and since the high dead load to live ratio makes it unlikely that a significantly higher load will be experienced, it is considered that strengthening for bursting is not required under current loading provided that the concrete is in a sound condition. This latter option may however not be a good assumption as discussed in section 2.1.3.

Deterioration of the concrete and possible resulting corrosion of reinforcement could potentially invalidate the above conclusion, making concrete repair and potentially the addition of reinforcement necessary. If concrete repair was necessary beneath bearings, the structure would need to be jacked up and the bearings removed in order to affect repair. Were this to be done, it might be prudent to replace the bearings at the same time.

The piers were also assessed for the longitudinal forces from temperature movement and bearing friction. The piers are adequate to resist these forces if cracked section properties are assumed but there is inadequate reinforcement to carry the forces induced with un-cracked section properties. If the piers remain un-cracked however, the forces increase significantly and put excessive longitudinal forces on the rocker bearing fixings. Further analysis is required here.

2.3.3 Box Girder

All jacking solutions will require introducing more holes into the box webs as there are no available jacking stiffeners. This will potentially reduce the strength of the box in shear-moment interaction, although the introduction of the transverse stiffener itself may help to limit this reduction. A full assessment of the box at this location in the condition before and after the addition of this stiffener is currently under way.

2.4 Replacement versus Monitoring

Current information on bearings is insufficient to identify which bearings might definitely need replacement, but the overall indication is that most bearings could remain serviceable for some considerable time if appropriately maintained (e.g. by blasting clean and treating with grease) and monitored. An ultrasonic investigation of a selection of bearings is required before the decision can be made. A bigger factor will be the determination of the concrete condition – See 2.3.2. The number of bearings requiring replacement will dictate the overall strategy.

Wholesale replacement
The advantage of wholesale bearing replacement is that new bearings with an appropriate guaranteed life could be installed, giving greater cost certainty for future maintenance. Wholesale replacement may or not include replacement of fixed bearings which will be more difficult and expensive to replace due to the need to lock the position of deck and pier relative to each other during jacking. The disadvantage is that bearings with a potentially good further service life will be needlessly replaced with the associated costs. This cost however needs to be balanced against the potential additional establishment costs associated by a piecemeal replacement approach. There is also a small risk that new bearings will themselves require significant maintenance outside the manufacturer’s guarantee or even within the guarantee period, causing disruption to traffic or other maintenance activities. Wholesale replacement would require installation of jacking steelwork and pier strengthening at all locations.

Monitoring and piecemeal replacement
The advantage of monitoring with replacement only of bearings at the end of their service life is that potentially a lot more life could be obtained from existing bearings before replacement. The disadvantage is the risk of numerous small replacement contracts being undertaken as and when the monitoring detects problems with the associated cost inefficiencies of such methods of working. Piecemeal replacement would require either:

- installation of jacking steelwork and pier strengthening at all locations, or
- installation of jacking steelwork and pier strengthening at selected locations (based on the most likely areas where replacement would be required in the future). This contract would need to establish that similar strengthening could be installed easily and quickly at other locations when required.

Risks
The bearings generally seem to be functioning adequately. There is no sign of distress from loading, the rollers are generally located in the middle of their travel and have remained square to the bearing plate. As such, with the possible exception of S3, they should have a good residual service life with appropriate maintenance and monitoring. This should include ultrasonic testing initially. The consequences of a bearing failure are also unlikely to be catastrophic with reasonably timely intervention. As such, the evidence based on bearing condition points to piecemeal replacement if necessary. However, the condition of the concrete is a bigger factor and the need to repair concrete under bearings needs to be established.

3 MONITORING AND MAINTENANCE TECHNIQUES

In the event of retaining the existing bearings, to determine their ongoing adequate functioning the following should be considered:

- Installation of displacement gauges on the rollers to measure actual movement and ensure that the bearings do not begin to slew.
- Carrying out ultrasonic testing to all bearings and plates to determine current condition and detect any cracking
- Making measurements of temperature variation to determine the movement range of the structure
- Blasting clean bearings and renewing the corrosion protection system e.g. greasing
- Installing guttering beneath deck joints to carry contaminants away from the bearings

Ekspan have been contacted for their opinion on the best practice of maintaining similar bearings.

4 REPLACEMENT METHODS AND PROVISION FOR REPLACEMENT

In the event of bearing replacement being undertaken, a study has been made of the strengthening options for the piers and boxes to allow for the installation of temporary jacks and also of the possible options for replacement bearing types. The different box and pier options have been modelled in a Virtual Reality model in order to determine a better idea of the problems involved with each of the options and to allow visual impact to be assessed. These are seen in Appendix C.

4.1 Bearing Replacement

The current bearings consist of roller and rocker bearings occupying the full width of the box. A number of replacement bearing types are considered below. Of particular importance is the need to:

- minimise eccentricities on the diaphragm steelwork
- provide for very large horizontal forces due to temperature loading
- fit the new bearings on the pier top and leave room for future replacement – jacks etc
- ensure the diaphragm steelwork is strong enough to take load if its is applied in a different location
- ensure even seating on bearings
- minimise bearing friction and consequent horizontal forces as the piers are relatively weak
- check all components if the articulation and support provision is changed in any way from the original
- consider the expected life of new bearings compared to the residual life of the existing ones
- weigh up the costs of bespoke bearings against off-the-shelf bearings with associated additional accommodation works

4.1.1 Pot Bearings

Pot bearings were considered as a possible alternative to the current bearings. A pair of pot bearings would be preferable to replace the current single roller and pin bearings. A single bearing may not be viable as this would not restrain the torsion in the box in the same way as the current linear bearings; this would require checks of the deck cross beams at supports for the increased forces. The loads imparted on the diaphragm would also be unacceptable unless the bearing either loaded the full width of the diaphragm, whereupon the pot bearing would have a diameter greater than the pier width) or the diaphragm was strengthened. This may be difficult with the additional cabling for the dehumidification system being installed. Further study of this would need considerable further work.

A pair of pot bearings would also occupy greater width than the existing bearings. Preliminary sizing estimates indicate a difference in width 470mm versus the current 370mm for the rocker bearings and 675mm versus the current 406mm for the roller. (These sizes are likely to increase when the results of more detailed analysis are completed). The increase in bearing width is likely to mean that the tops of all the piers would require widening to allow for future bearing replacements. Due to the change in load concentration on the box, additional stiffening would also be required around the diaphragm, to distribute the loads from the bearings.

The frictional resistance of pot bearings are higher than those for the existing rollers, which would mean that the longitudinal stresses in the box would increase, as would the pier forces. This would need further investigation.

Pot bearings would impose double the eccentricity on the load on the diaphragm inside the box, which would mean that further strengthening inside of the box would have to be considered. Alternatively, the bearings could be inverted generating all the eccentricity on the pier. Skirts would then be required to the bearings to prevent the ingress of debris and subsequent disruption to the proper functioning of the bearings. The effects of the eccentricity on the pier would also require checking.

4.1.2 Spherical Bearings

Spherical bearings were also considered as replacements for the current bearings. Similar conclusions were found as for the pot bearings.

4.1.3 Elastomeric Bearing

Elastomeric Bearings would not be appropriate for this type of structure as the plan size and bearing height required would exceed the pier size. They also have a significant amount of vertical compressibility.

4.1.4 New Roller Replacements

To comply with modern standards, new roller bearings would require either an increased diameter (which would be practically difficult to achieve because of the limited gap between deck and pier top) or an increased yield strength of the material used. S690 steel would be sufficient to maintain the diameter at the current size. It will however be essential to ensure that the material is not brittle or embrittled by the corrosion protection as was the case on Thelwall Viaduct.

Ekspan have been consulted with respect to the provision of replacement bespoke roller bearings.

4.2 Steel Box Strengthening

The box girders will require additional bearing stiffeners at the locations of the temporary jacks. Three different options were considered for the installation of the bearing stiffeners.

A more detailed description of what was considered for each option is detailed below:

Steel box option 1
This option involved positioning the jack directly under the webs of the box girder to replace the bearings.

The assessment of the web capacity for the jacking loads indicated that the webs would not have sufficient capacity to resist the direct patch loading on the webs and would require internal and external strengthening. This option would also require construction of corbels on the east/west sides of the piers affecting the appearance of the structure. Figure 1 shows the additional areas requiring strengthening for this option. However, it is possible to design the stiffener in such a way that it could fit in behind the existing services, though access to tighten the bolts used in the assembly might be difficult.

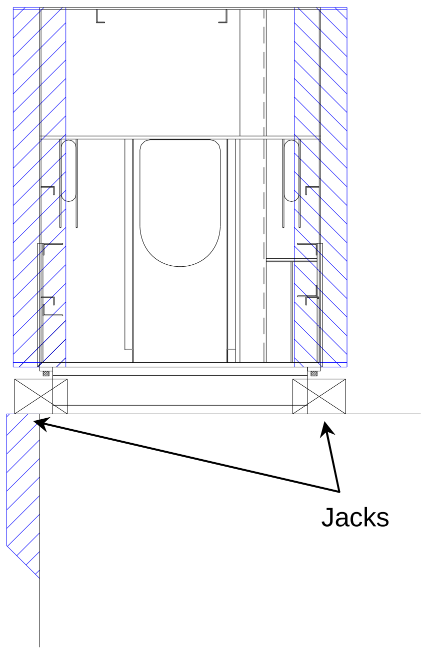


Figure 1: Option 1 - Section through box girder and pier. Additions are marked in blue.

Steel box option 2
The second option consists of positioning the jacks under the box on the existing bearing shelf or on corbels added to the front and back of the pier. This requires the box bearing stiffeners to be constructed above the jacking position inside of the box. The stiffener has been designed to consist of small component parts as the ease their transportation and installation into the box girder. The stiffener is designed to allow cut-outs around the existing longitudinal stiffeners, and therefore does not affect the steel currently in the box.

The pier may require corbels to be built on the north and south faces of the pier to allow for the positioning of the jacks. This will depend on the location of the current steelwork in the box girders and the locations of the bearings on the piers.

Current deck services interfere with this option and would require re-routing. We understand that this would present considerable physical and administrative difficulties. This is further discussed in section 4.4.

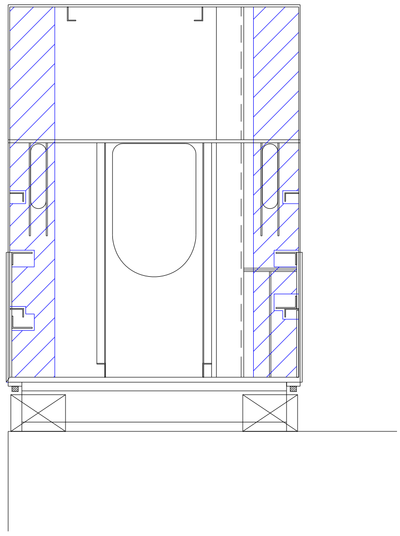


Figure 2: Option 2 - Section through box girder and pier. Additions are marked in blue.

Steel box option 3
This option is similar to option 2, except that cut-outs for the existing longitudinal stiffeners have not been included. Smaller bearing stiffeners are therefore required, which would mean that less steel would have to be assembled inside the box. The disadvantage is that the loading on the structure would have to be restricted during the installation of the stiffeners as the longitudinal stiffeners would be discontinuous during the construction phase.

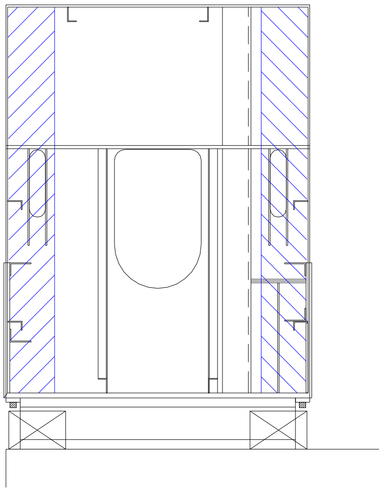


Figure 3: Option 3 - Section through box girder and pier. Additions are marked in blue.

Current deck services interfere with this option and would require re-routing. We understand that this would present considerable physical and administrative difficulties. This is further discussed in section 4.4.

Steel box option 4
For option 4, the stiffeners are placed on the outside of the box. This would minimise the amount of work required inside the box, and would mean that the stiffener could be assembled in one piece off site. This option would mean that an additional concrete corbel would be required at the edge of the pier. As the bearing stiffeners are only required during the replacement of the bearings, it would be possible to

remove the steel stiffener section after the replacement of the bearings. This would leave holes in the web which would have to be filled after the removal of the steelwork. The concrete corbels would remain in place and would therefore become a permanent part of the structure. As this would affect the permanent appearance of the structure, this would likely involve planning approval being required from Historic Scotland. An additional concern is that the external drainage hole in the pier will clash with the external bearing stiffener steel, and would therefore require that the drainage channel is moved. The only realistic possibility would be to move the pipe to the outside of the pier which may be visually unacceptable.

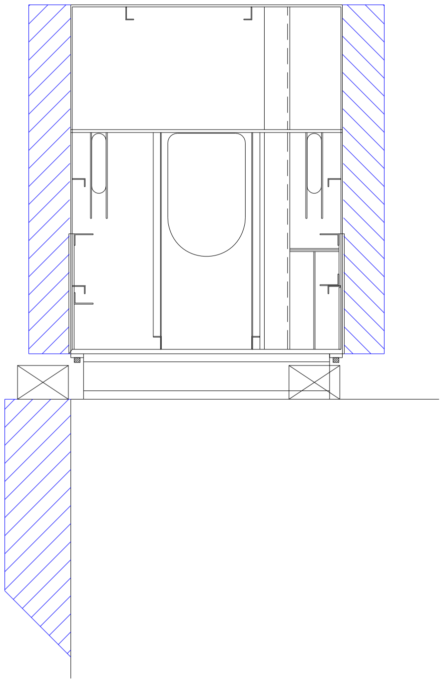


Figure 4: Option 4 - Section through box girder and pier. Additions are marked in blue.

Steel box option 5

Similar to option 3, this option involves the stiffener being assembled on the inside of the box. Allowances have been made for cut-outs for all the longitudinal stiffeners and the services ducts. Therefore, this option leads to the widest stiffener considered so far, with each stiffener section measuring 550mm wide.

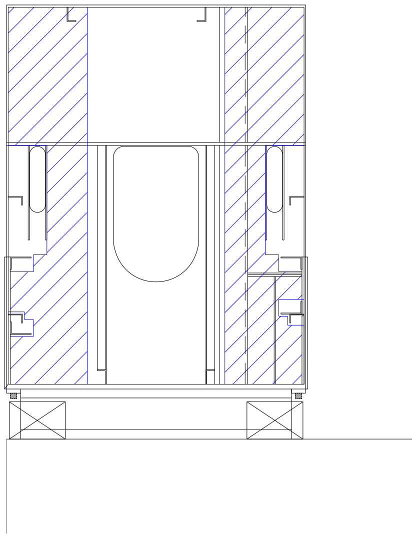


Figure 5: Option 5 - Section through box girder and pier. Additions are marked in blue.

Option 1 and 5 are the current preferred options. It is considered option 1 may be possible by defecting services rather than diverting them, but this would need to be confirmed.

Having received the information for the installation of the dehumidification system, option 5 also now becomes unworkable as it clashes with the location of the new cabling required in the boxes. This cabling cannot apparently be relocated at this stage.

Option 4 is considered the most viable at the abutments and the side towers as the visual impact at these positions would be minimal since these positions are adjacent to abutment and pier walls and therefore would not have an obvious visual impact. Also, the internal service cables could be avoided. The external stiffening option is also preferred as it would not interfere with the longitudinal stiffeners inside the box. In this option, the stiffener would extend from the box diaphragm, and therefore the jacking location would be in a similar distance from the abutment/side tower wall as the current bearings are. The remaining options would mean that the stiffening would be required in front of the current bearing location, which would mean that the abutment/side tower bearing shelf would have to be extended. This would change the bearing pressure at the base of the abutments and increase the risk of overturning of the abutments – further checks would be required on this and bearing pressure information would be required.

4.3 Pier Strengthening

Pier option 1: No corbels required
Generally, corbels can be avoided where similar sized bearings are used to replace the existing bearings. This option is therefore considered for all the steel box options except at the shared pier, S3, where corbels will be required.

Where bearings require replacement, jacks will be required at the edges of the piers. The concrete stresses can be controlled to within 0.4fcu, and therefore additional reinforcement is not required to resist bursting forces immediately under the jacks.

Using a strut and tie model, the top of each pier was analysed to assess the capacity of the top steel under jacking loads. It was found that the reinforcement was inadequate to restrain the forces in the concrete due to the jacks; also there was inadequate reinforcement to resist edge sliding as set out in Annex J of EN 1992-2:2005. Therefore, where bearings are replaced, strengthening of the pier will be required making allowance for any delamination found in the inspection and investigation of the structure. Figure 6 show the strengthening and bearing stiffener locations at the pier.

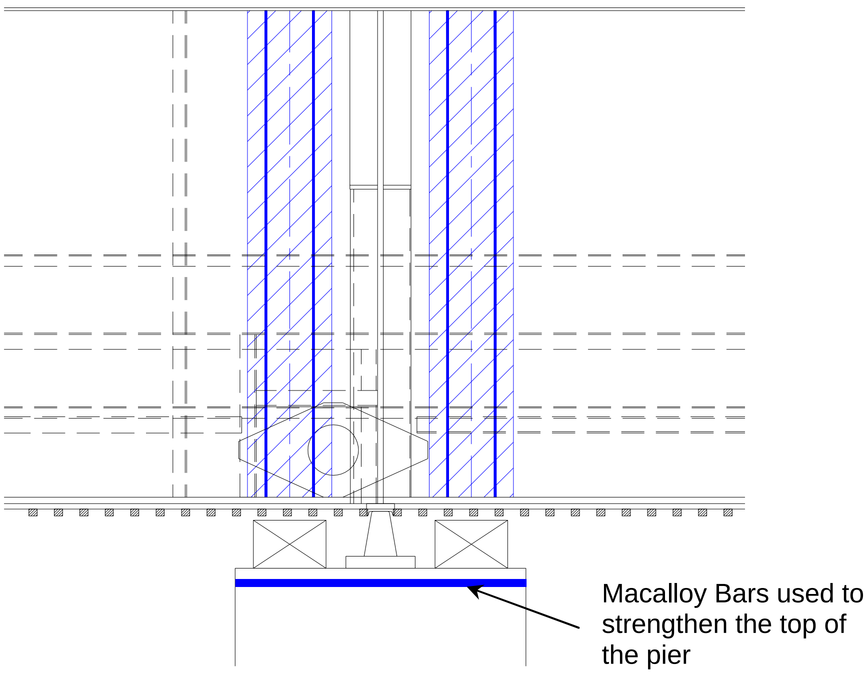


Figure 6 :Elevation through box, Pier strengthening without corbels.
Additions are marked in blue.

Pier option 2: Face Corbels required
This option (Figure 7) is considered in combination with all the steel box options.

Where corbels are required due to space restrictions at the top of the pier (Pier S3) this will affect the current appearance of the pier, and further consideration will be required for the aesthetics of the structure. This option will also require that the bars are inserted through the top of the pier to provide continuity into the corbel and additional capacity in the top of the pier. A preliminary design was done for the corbel design, where a minimum corbel depth of 1.5m was established.

As corbels will be required for the shared pier, it may not be visually acceptable to modify only one pier. Therefore corbelling may be required on all piers. Appendix C provides some VR images of the corbels which should be discussed with Historic Scotland.

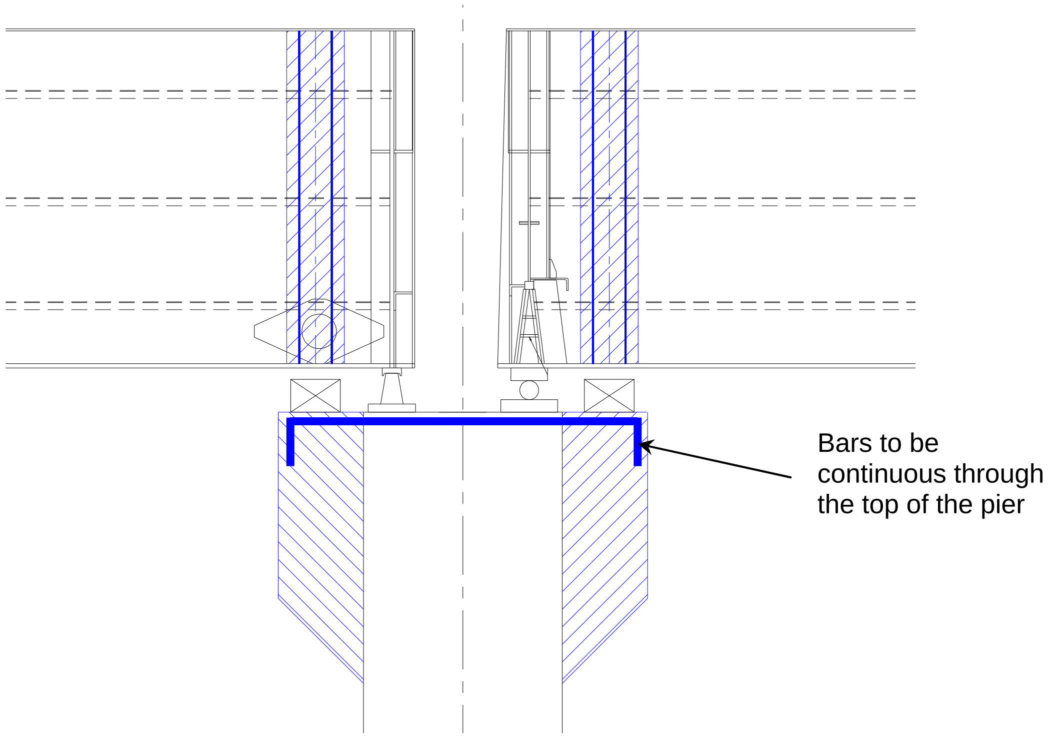


Figure 7: Elevation through box, Pier strengthening with corbels.
Additions are marked in blue.

Pier option 3: Side Corbels required
This option is considered in combination with steel box options 1 and 4.

Pier option 3 (Figure 8) involves the addition of corbels to the sides of the pier to accommodate a jacking point either directly underneath the web or just outside the web. The main consideration of this option is the visual effect of the corbels on the piers.

An additional advantage of this option will be to prevent the spalling which currently occurs on the outside face of the piers below the bearings. This spalling is likely to be due to the bearing being located near the edge of the pier. This option would increase the width of the pier and therefore reduce the risk of future concrete spalling after concrete repair.

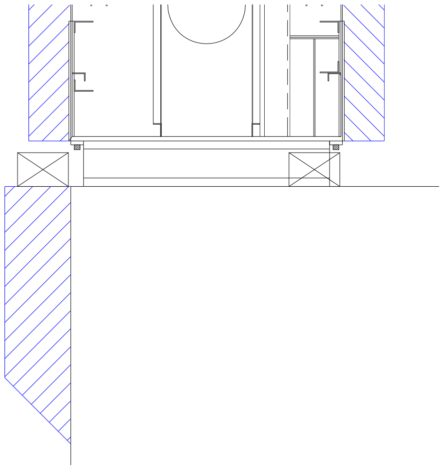


Figure 8: Elevation through box, Pier strengthening with side corbels.
Additions are marked in blue.

4.4 Pipe/Duct Diversion

All options include the construction of internal jacking stiffeners which will clash with the internal pipes and ducts inside the box girder.

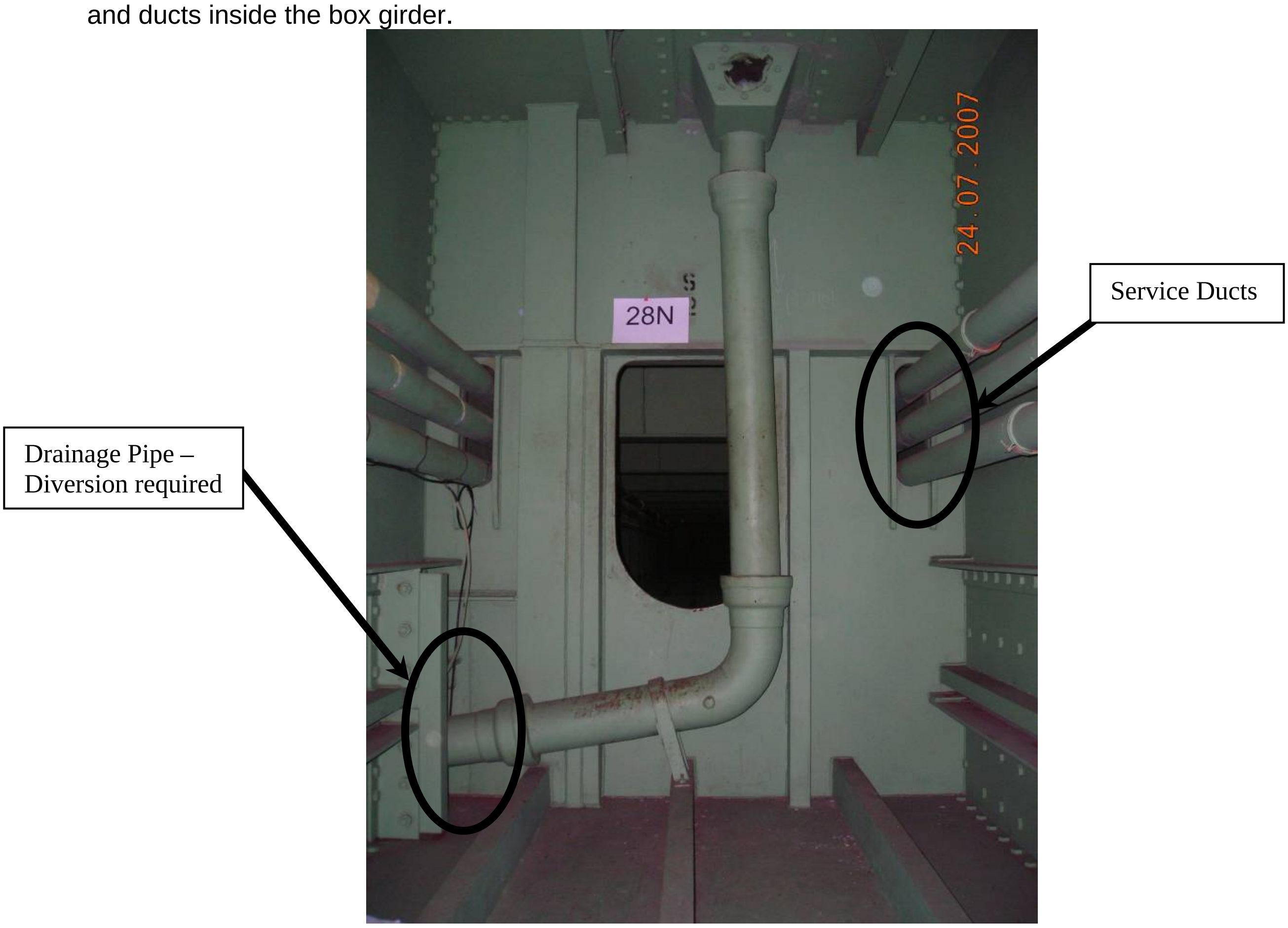


Figure 9: Typical Box Girder Diaphragm

Drainage Pipe

The current drainage pipe is located near the diaphragm of the each of the box girders. In each case, this drainage pipe will clash with the planned bearing stiffeners and will therefore need to be diverted when the bearing stiffeners are added. The diversion of the pipe will also ease access through the diaphragms.

Several options are possible for the diversion of this pipe. The first would be to divert the drainage through the deck slab and move the main drainage pipe outside, as the current drainage pipes leak and causing water build up inside of the box. By removing the pipe from the box, this leakage will be removed. However, this option would require the removal of a section of the structural slab, and would therefore affect the local capacity of the deck at this cross section. It will also be more expensive to complete and will require that the carriageway is closed during the diversion of the drainage pipe. More of the pipe will be visible from the ground, though the pipe will mostly be located above the pier.

The second option would involve the diversion of the pipe inside of the box. The pipe would be diverted to exit the box at an alternate position. This would mean that the box would have to be strengthened using doubler plates at the pipes new exit diversion. More bends will be introduced in the pipe so additional rodding points will be required. The pipe is probably already deficient in that respect but the large diameter of the pipe and large head of water is effective in flushing any debris through. If the pipe remains in the box, provisions should be made for drainage of the water from the box in the event of a pipe leak.

Service Ducts
Ducts for services are also located near the diaphragms in the box. These ducts run longitudinally along the length of the box and will clash with any bearing stiffeners that are constructed inside of the box girder. These ducts would need to be diverted locally to each diaphragm to allow for the construction of the bearing stiffeners in options 2 and 3. They will interfere with construction of the other options also but to a lesser extent. Some of the options would benefit from full scale mock-up trials using, for example, timber stiffeners to check buildability.

5 STRENGTHENING BUILDABILITY/FEASIBILITY

5.1 Box Strengthening

A specific construction sequence will need to be followed in order to install the double sided stiffener which comprises this option. The two preferred options described in section 4.2 will be considered in more detail below.

5.1.1 Option 1 Assembly

1. Construct corbel on side of pier.
2. Install vertical stiffeners around the longitudinal stiffeners to relive the load in the longitudinal stiffeners around the proposed locations of the bearing stiffeners
3. Cut the longitudinal stiffeners local to the new bearing stiffeners
4. The drainage pipe will need to be diverted away from the stiffener. The drainage pipe should be diverted with a minimum number of additional bends. Provisions should also be added to allow rodding in case of blockages in the pipe. Strengthening will be required around the new pipe exit.
5. The current drainage exit needs to be covered.
6. Remove the vertical stiffener adjacent to the drainage hole
7. Install outer part of bearing stiffener
8. Assemble half the height of the bearing stiffener inside the box.
9. Lift half of bearing stiffener from below into a position behind the current services. And bolt into position. Bolts will have to tightened from outside of box as access to parts of stiffener will be difficult from inside the box, behind the services ducts.
10. Insert lower half of bearing stiffener into position and weld to upper part of stiffener. Bolt section into position.
11. Once jacking operation is complete, the outside face stiffeners can be removed.

5.1.2 Option 5 Assembly

1. Additional stiffeners will need to installed on the bottom flange to allow the existing longitudinal stiffeners to be cut around the area of the new bearing stiffeners
2. Divert the drainage pipe as in step 3-4 above
3. Install one half of the stiffener. This needs to be done as to avoid the current vertical stiffener near the drainage pipe.
4. Remove current vertical stiffener as it will clash with the second part of the new bearing stiffener.
5. The remaining parts of the stiffener can be installed once the existing stiffener is removed.
6. For the pinned bearings, it will be necessary to fix the jack to the bottom flange of the box to ensure that there is no movement between the box and the pier.

5.2 Pier Strengthening

Before the jacking can be started, it will be necessary to strengthen the tops of the piers and to repair all damaged concrete and reinforcement..

1. Installation of additional reinforcement at tops of piers.
    a. Where corbels are required, at pier S3, reinforcement should be drilled through the pier and the corbel cast before fitting the jacks
    b. Where no corbels are required, Macalloy bars are to be drilled through the piers and prestressed to add additional strength to the pier.

6 FURTHER INVESTIGATION

To gather further evidence to determine which bearings may need replacement and where concrete repair is needed, further investigation is required as follows:

- Further hammer tap survey of pier tops
- Cover meter survey to selected piers
- Ultrasonic testing to determine whether there is any cracking of the bearing and plate steel
- Further investigation of the concrete condition (eg. chloride, half cell and carbonation tests) are needed to determine the cause of the deterioration

7 RECOMMENDATIONS

In abeyance.

Appendix A

Roller Bearing Comparison to BS EN 1337-4:2004

Bearings to BS EN 1337-4:2004
The existing roller bearings were compared with the current standards. The following clauses were considered:

cl 5 Materials
cl 5.1 General
States that all rollers and plates are to be examined for cracks by ultrasonic methods or by magnetic particle dye penetrant methods. This investigation should be carried out.

cl 5.2 Carbon Steel
States the minimum yield strength is 240MPa. Based on BD21/01 Annex C, the mild steel bearings are likely to have a yield strength between 220-247MPa, and therefore may not comply with this requirement. Given the lack of any apparent distress, this requirement is not considered critical.

cl 5.3 Stainless Steel
Not Applicable as bearings are not stainless steel

cl 5.4 Cast Steel
Not Applicable as bearings are not cast steel

cl 6 Design
cl 6.1 General
States that loads are to be calculated based on EN1990 and bearings to comply with cl. 6.2 to 6.11 and cl 7. The loading requirement is not applicable as the bearings were not designed to this standard.

cl 6.2 Movement
Not Applicable as structure is not curved.

cl 6.3 Curved Surfaces
All curved surfaces are to be cylindrical. The roller is the only curved surface and this appears to be cylindrical.

cl 6.4 Surfaces in Contact
All Surfaces in contact are to have the same nominal strength and hardness. Based on the drawings (drg FRB 3) all steel in the bearings is stated as mild steel and is likely to have the same material properties.

cl 6.5 Length of Rollers
The length over diameter ratio is to be between 2 and 6. The actual ratio for these bearings is 12.3 and therefore these bearings do not comply with this clause. (Why this ratio? Total length of bearing considered, possible to decrease ratio to 6.17?)

cl 6.6 Guidance and Security of Rollers
Requires that guidance is provided to ensure the axis of rolling is maintained correctly. The current bearings have cogs at each side of the bearing to prevent slewing. However, many of these have sheared off and therefore do not provide restraint for sliding and slewing of the bearing. There is also a key at the centre of the bearing which will provide some restraint against slewing of the bearing. The need to monitor or replace parts of the affected bearings is discussed below.

The shear Capacity of the ‘teeth’ on the roller bearing was found to be:

cl 6.7 Dimensioning of Components
cl 6.7.1 Dimensions of Roller
The capacity of the roller was calculated based on this clause. A usage factor of 4.08 was found for the roller under ULS loading. (The roller bearings were found to have a usage factor of 5.51 under maximum ULS Loading in BS 5400.)

cl 6.7.1 Dimensions of Roller Plates
The capacity of the roller plate was calculated and compared with the applied load. The usage factor was found to be 0.11. This ignores the finite contact length between the cylinder and the plate which would further reduce the usage. Clearly the roller is critical.

cl 6.7.3 Load Distribution to other components.

The restriction of the dispersal angle to 45^{O}, though an angle up to 60^{O} is permissible if justified by calculation. The restriction of 45^{O} is not present in BS5400 (where it is approximately 60^{O}). Additionally this restriction is being included in the UK PD as 60^{O}. Concrete bearing pressures are unacceptably high assuming a 45^{o} spread and this restriction is not considered appropriate.

cl 6.8 Particular Requirements
Generally not applicable, but cl 6.8.3 highlights the need to provide corrosion protection. Greasing the bearings should be considered for protection and lubrication.

cl 6.9 Design Coefficient of Friction
A coefficient of friction of 0.05 has been assumed based on this clause. Roller manufacturers (Ekspan) suggest that a value of 0.03 would be adequate.

cl 6.10 Eccentricities
Relates only to the design of pier and deck elements.

cl 7 Tolerances
Not applicable as it relates to the initial installation

Appendix B

Rocker Bearing Comparison to BS EN 1337-6:2004

Bearings to BS EN 1337-6:2004
The existing rocker bearings were compared with the current standards. The following clauses were considered:

cl 5 Materials
Clause 5 has similar requirements as those stated for the roller bearings in BSEN 1337-4:2004.

cl 6 Design
cl 6.1 General
States that loads are to be calculated based on EN1990 and bearings to comply with cl. 6 and 7. The loading requirement is not applicable as the bearings were not designed to this standard.

cl 6.2 Curved Surfaces
The curved surfaces of line rockers are to be of cylindrical shape. However, as there are no specific drawings available for the rocker bearings, it is unknown if the top of the bearing is cylindrical.

cl 6.3 Surfaces in Contact
All Surfaces in contact are to have the same nominal strength and hardness. Based on the drawings (drg No) all steel in the bearings is stated as mild steel and is likely to have the same material properties.

cl 6.4 Preventing of sliding
Sliding prevention in the form of downstands form the rocker plates are in place to prevent sliding. These appear to be adequate under current loading.

cl 6.5 Dimensioning of Components
cl 6.5.1 Dimensioning of line Rocker
As there are no specific drawings available with details of the rocker bearing, the minimum radius of the top of the bearings was calculated to be 463mm in accordance with BS EN 1337-6 (190mm was calculated in accordance with BS5400). This will need to be verified on site.

cl 6.5.2 Point Rocker in spherical Seating, cl 6.5.3 Point Rocker on flat surface
Not applicable as the rocker is not a point rocker.

cl 6.5.4 Load Distribution to other components.
The restriction of the dispersal angle to 45^{O}, though an angle up to 60^{O} is permissible if justified by calculation. The restriction of 45^{O} is not present in BS5400 (where it is approximately 60^{O}). Additionally this restriction is being included in the UK PD as 60^{O}. Concrete bearing pressures are unacceptably high assuming a 45^{o} spread and this restriction is not considered appropriate.

cl 6.6 Particular Requirements
cl 6.6.1 Corrosion in the Contact line or Point
This clause highlights the need to provide corrosion protection. Greasing the bearings should be considered for protection and lubrication.

cl 6.6.2 Alignment
Not Applicable, relates to installation of bearing

cl 6.6.3-6.7 Eccentricities
Not Applicable Relates to the design of pier and deck elements and installation of bearings.

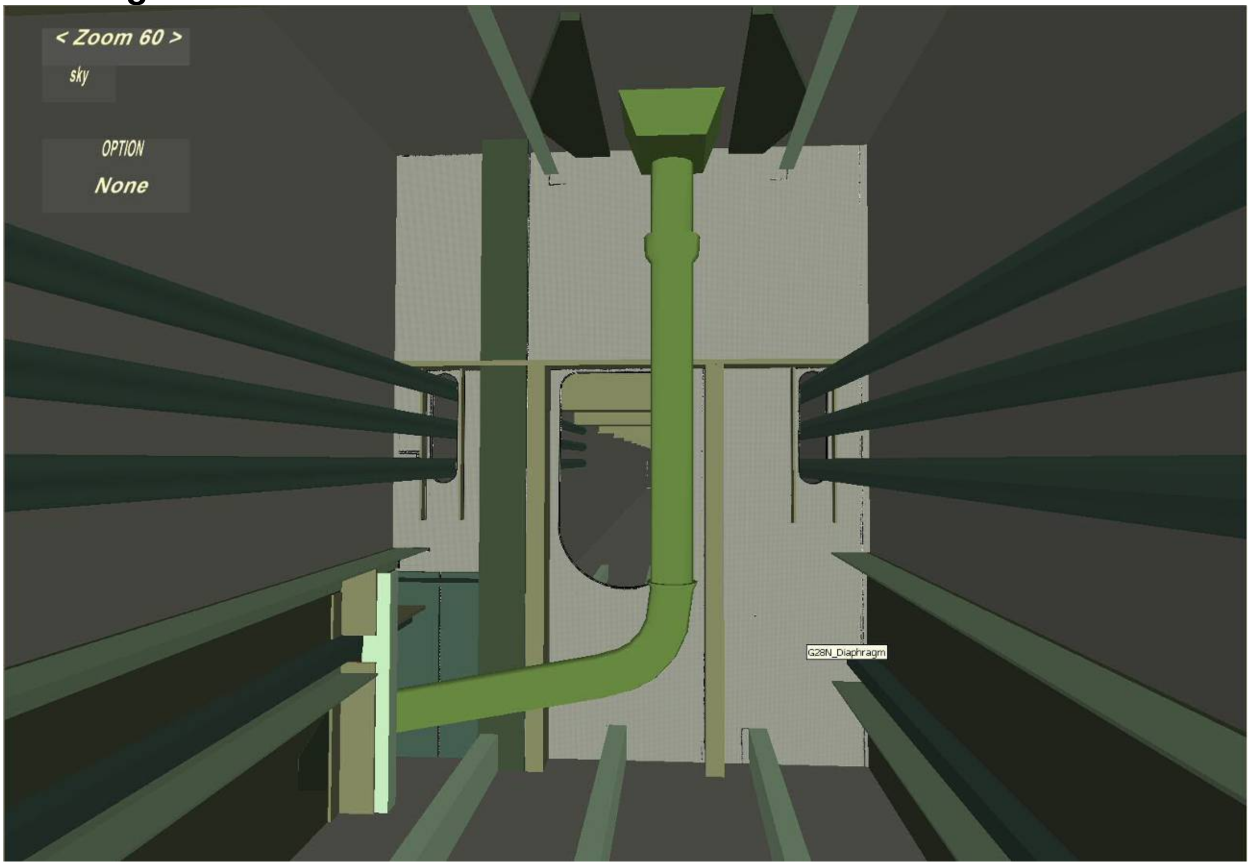
cl 7 Tolerances
Not applicable as it relates to the initial installation

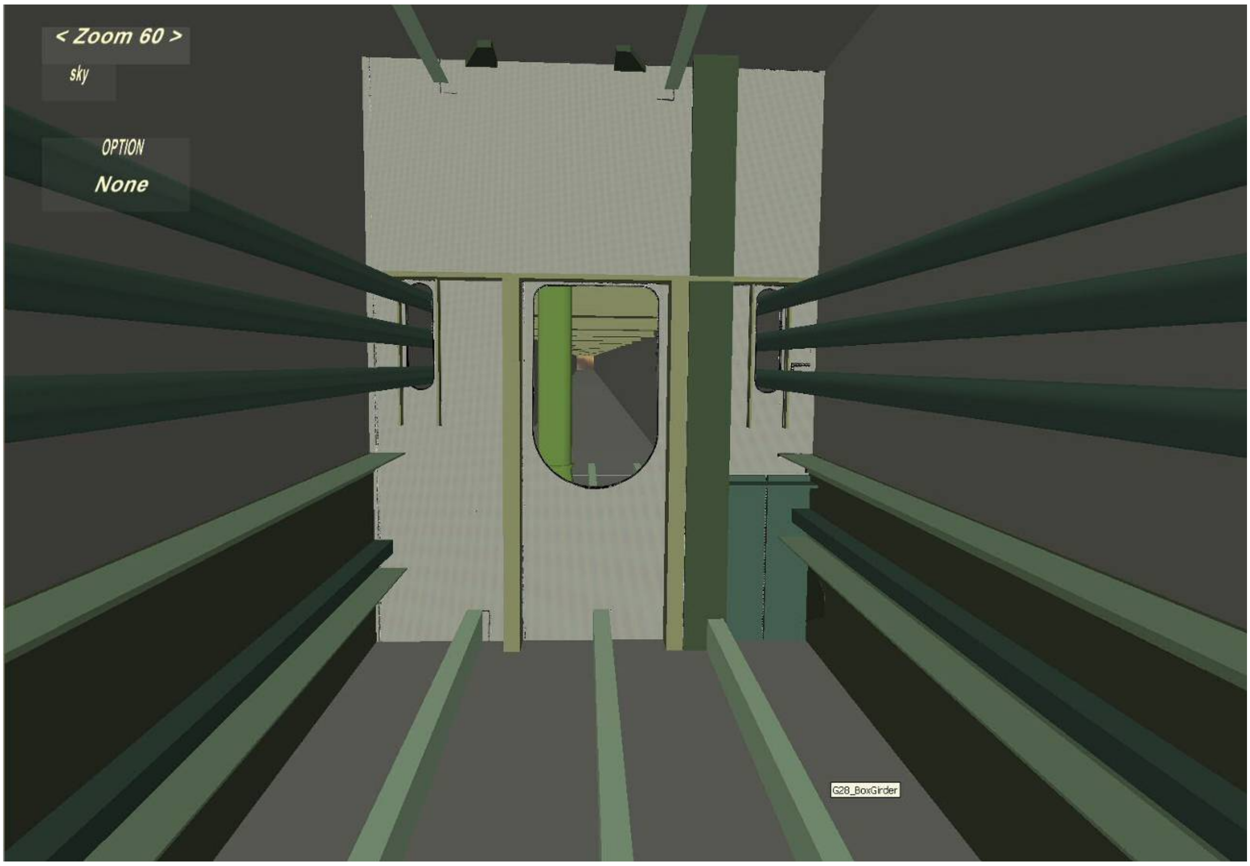
Appendix C

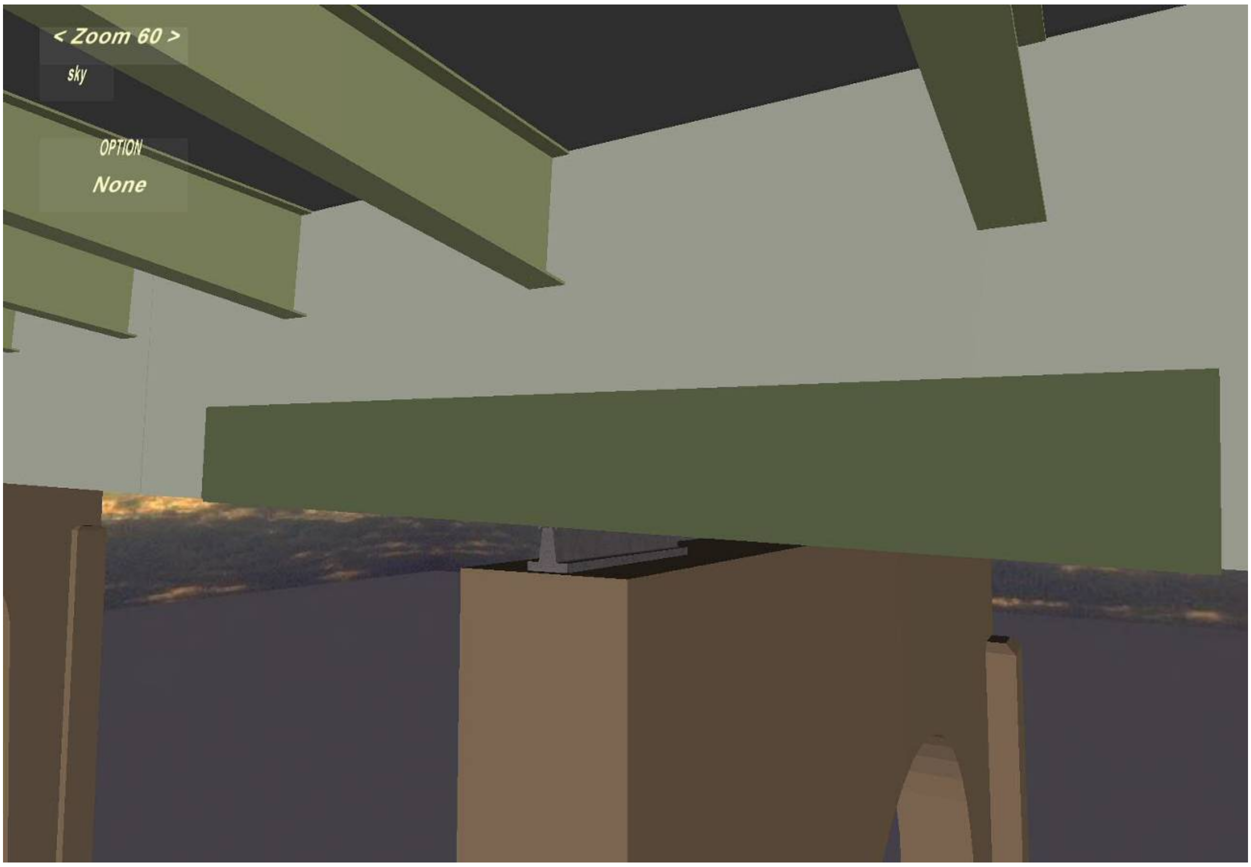
Virtual Reality Model

Existing Structure Model
Steel Box Option 1
Steel Box Option 2
Steel Box Option 3
Steel Box Option 4
Steel Box Option 5
Drainage Pipe Diversion
Shared Pier (S3 Corbels)

Existing Structure



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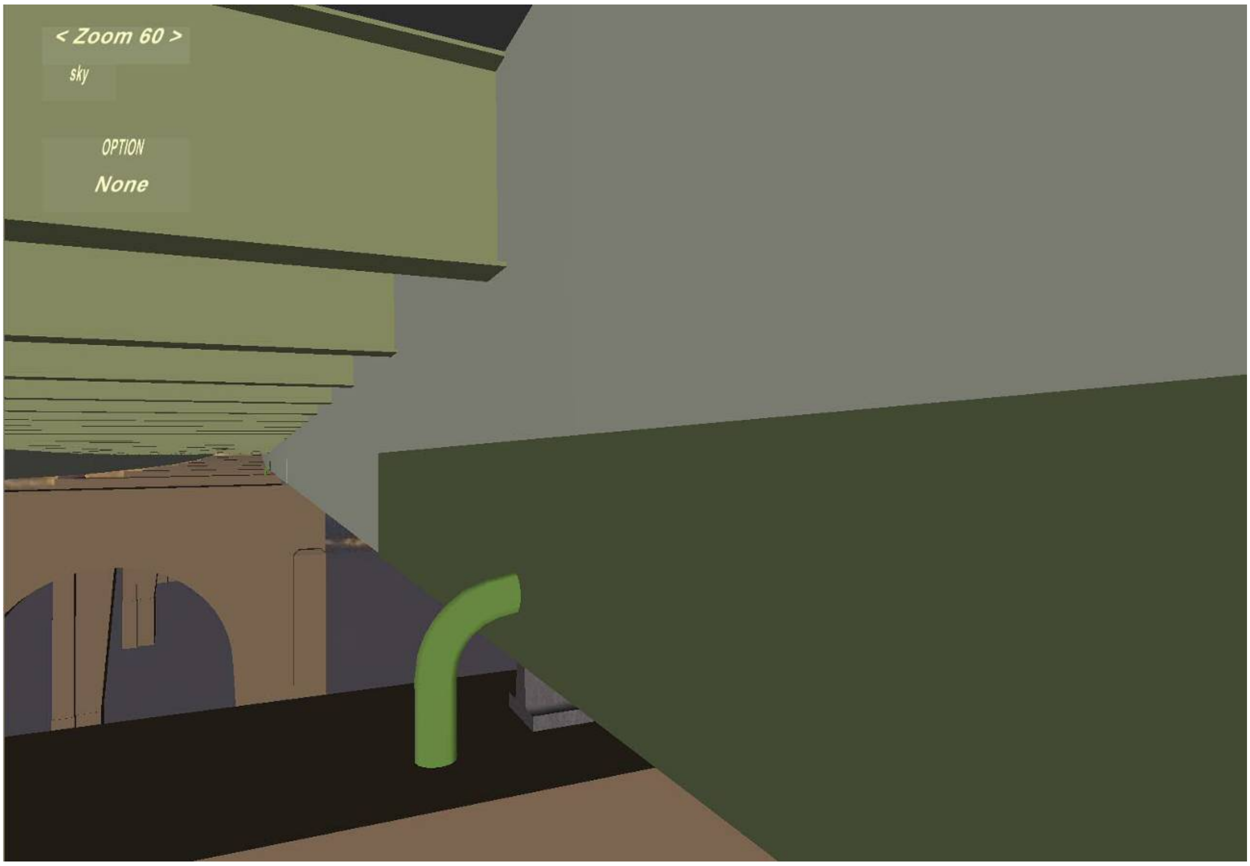
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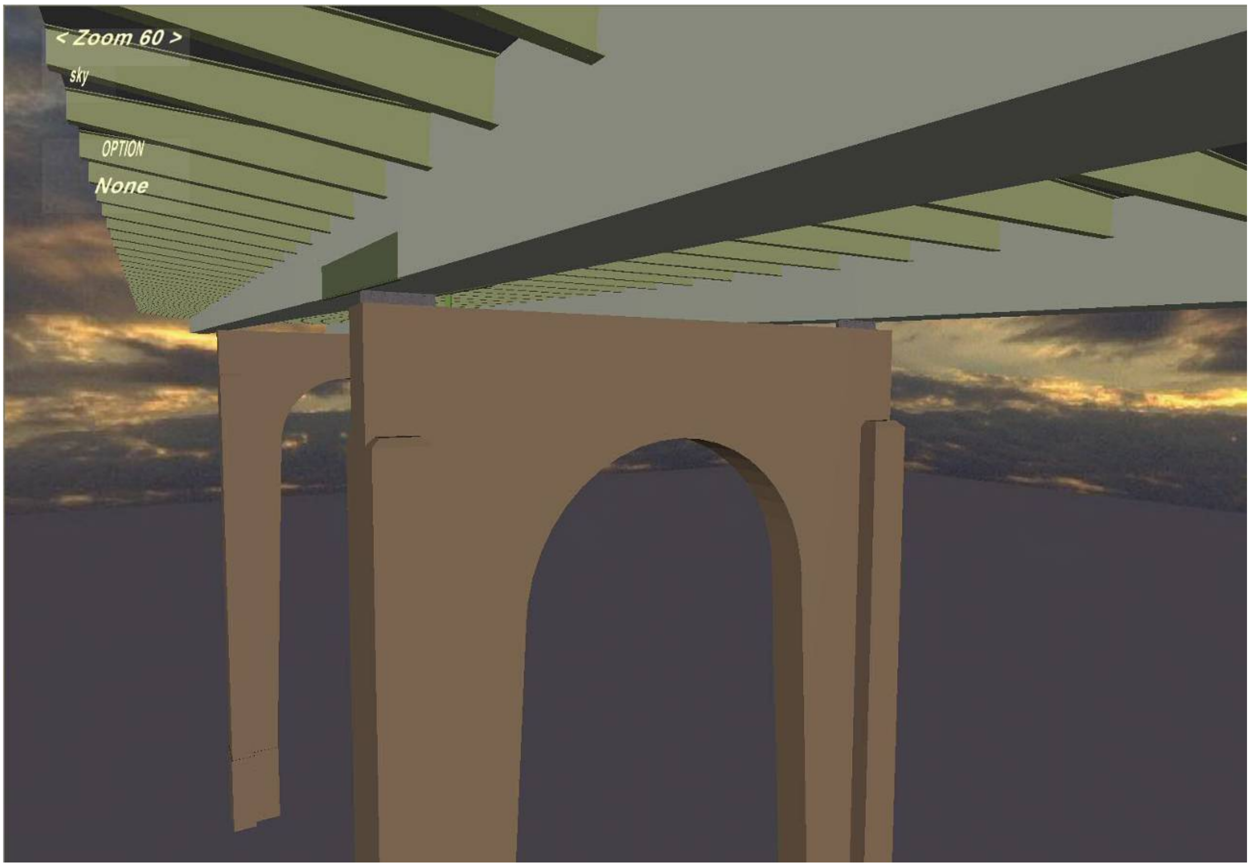
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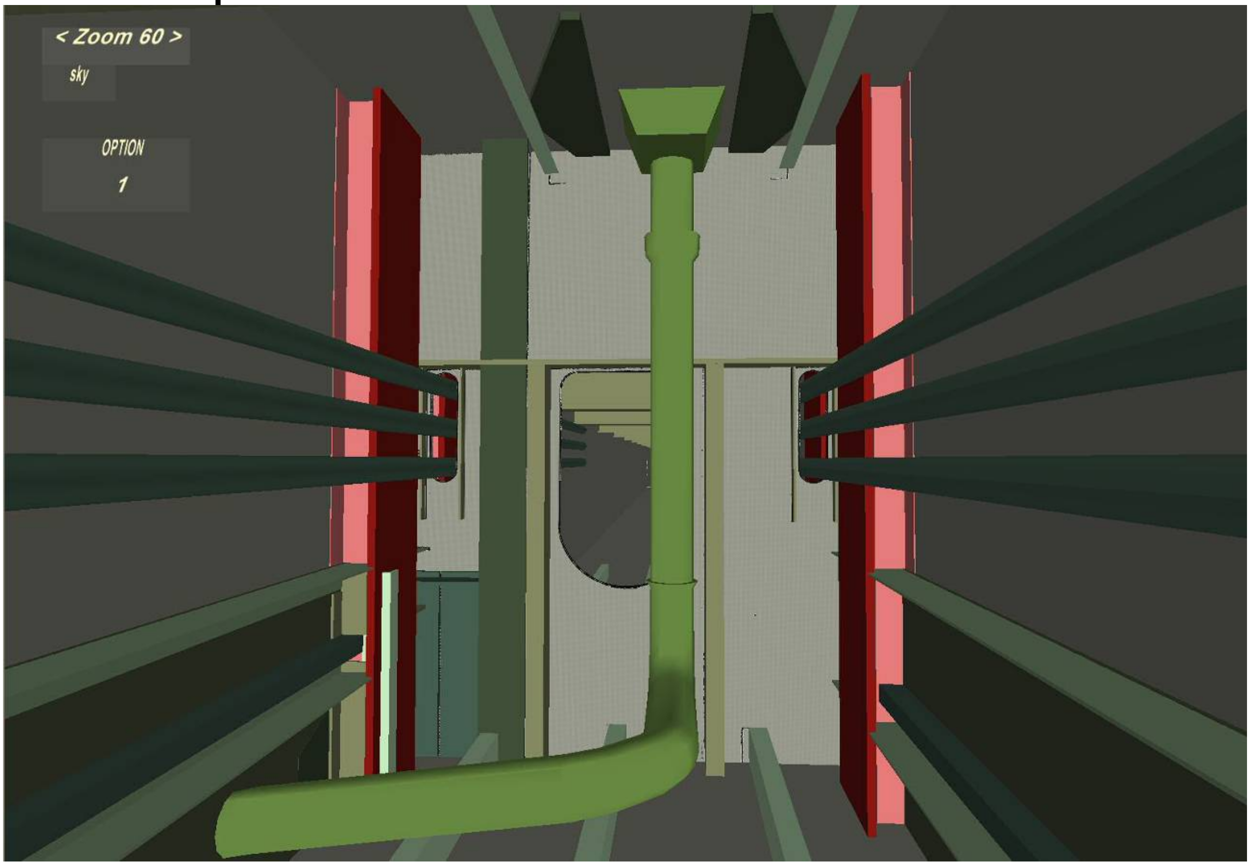

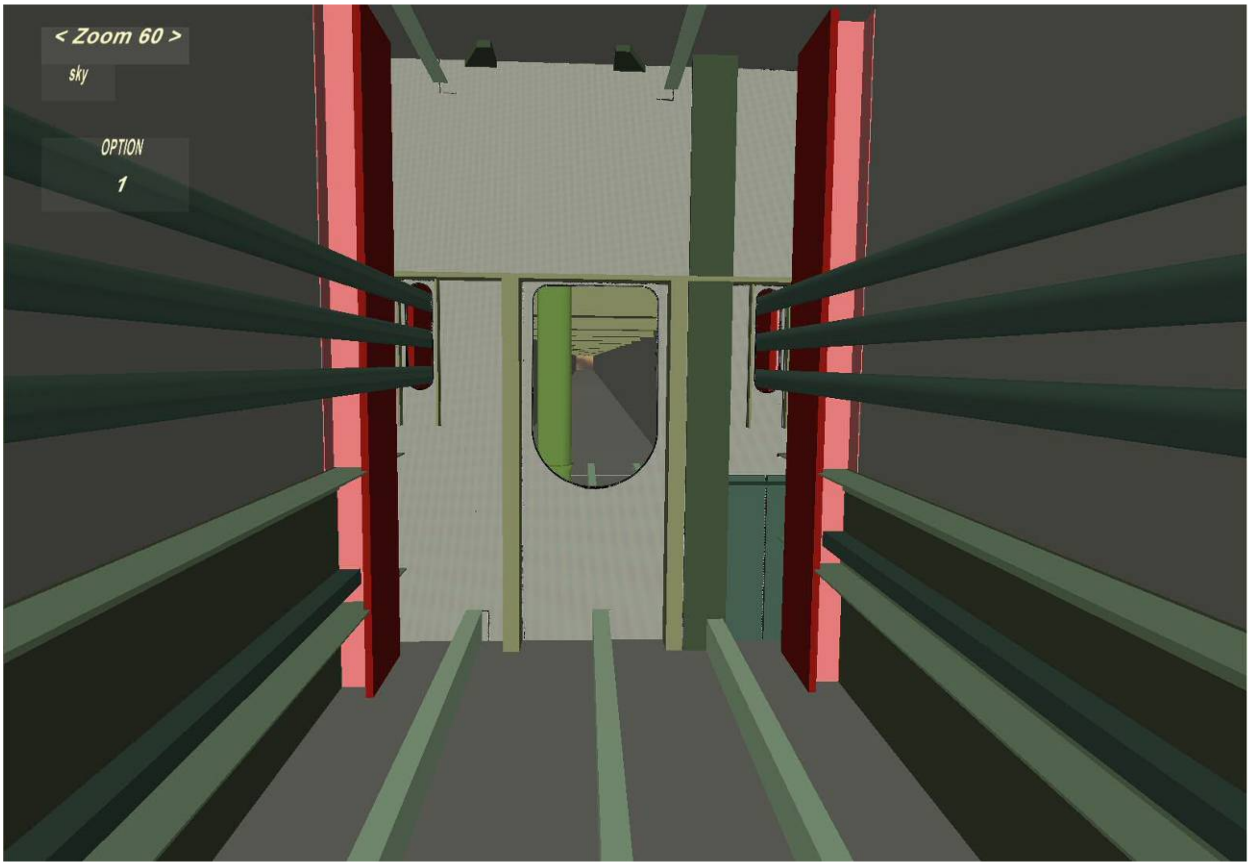

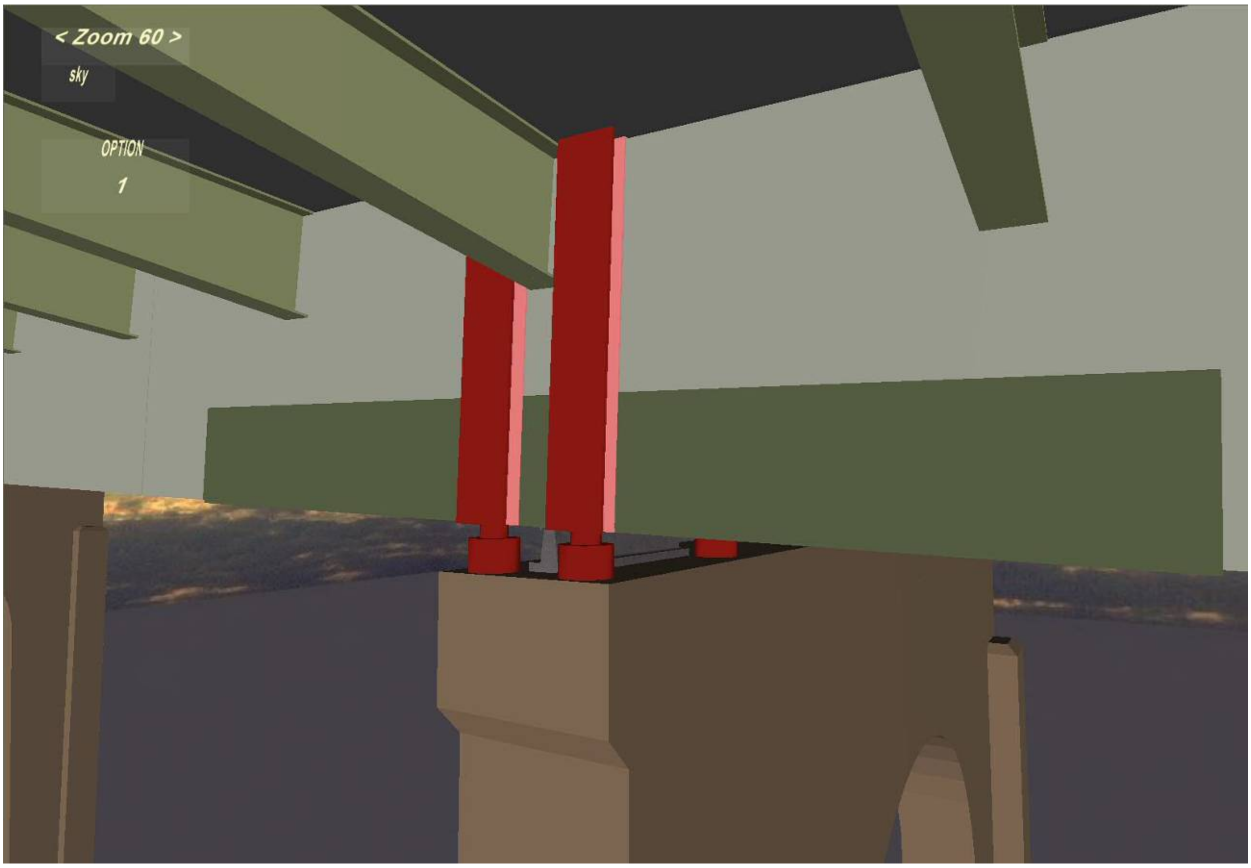
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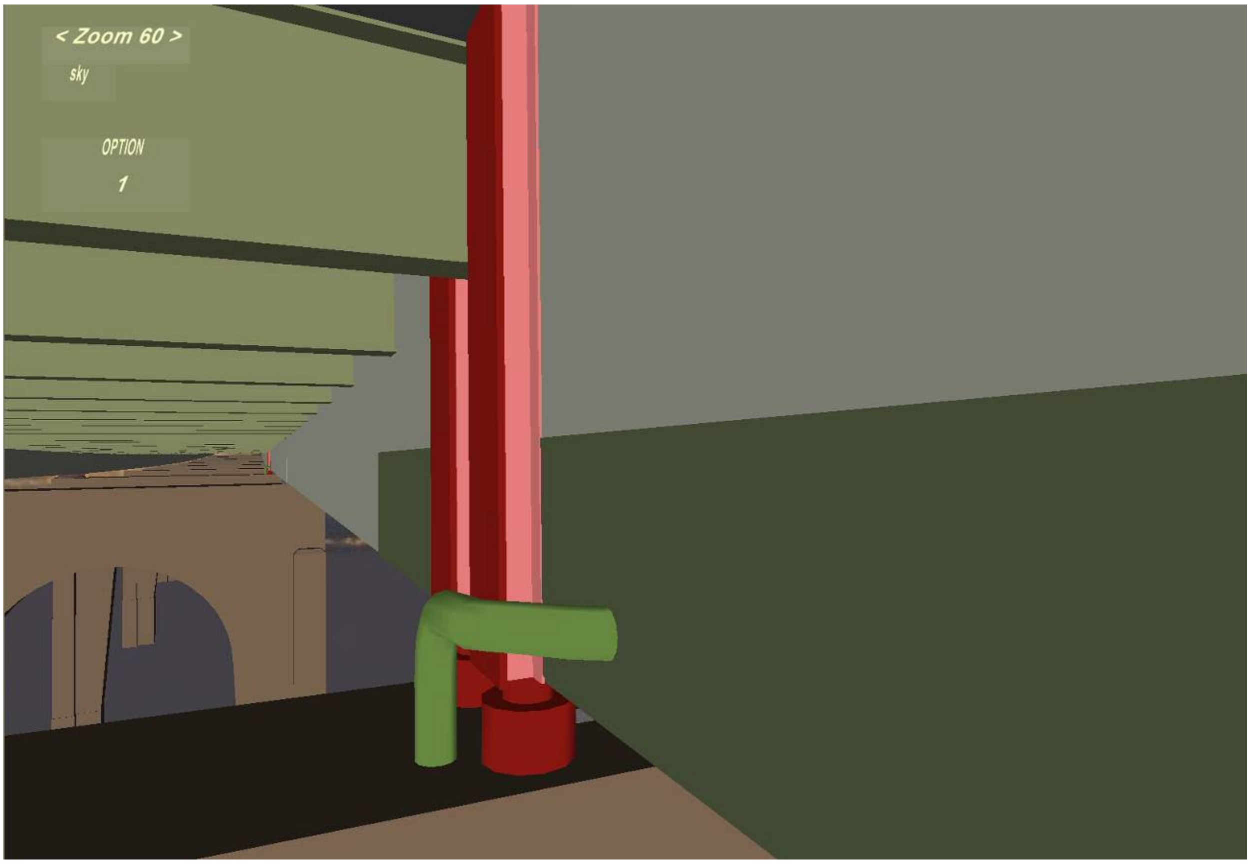
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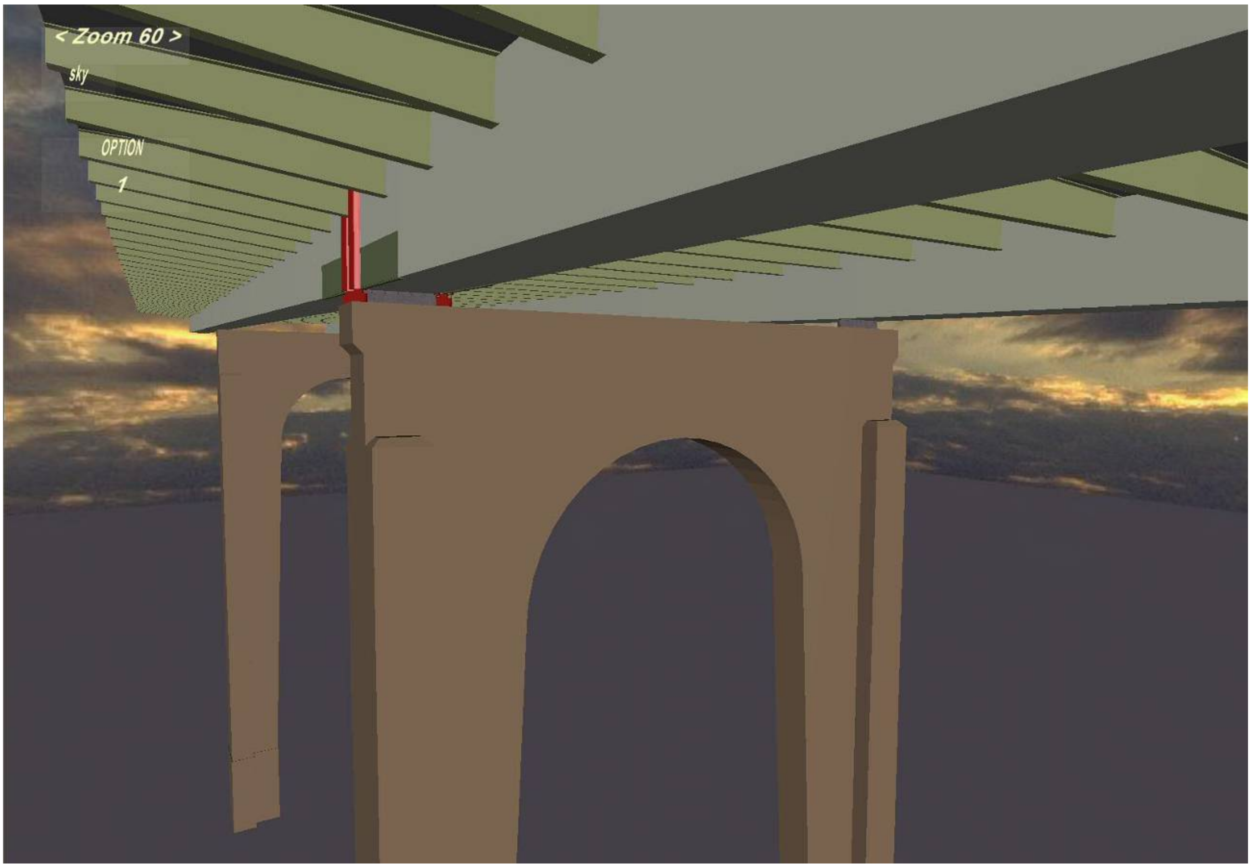
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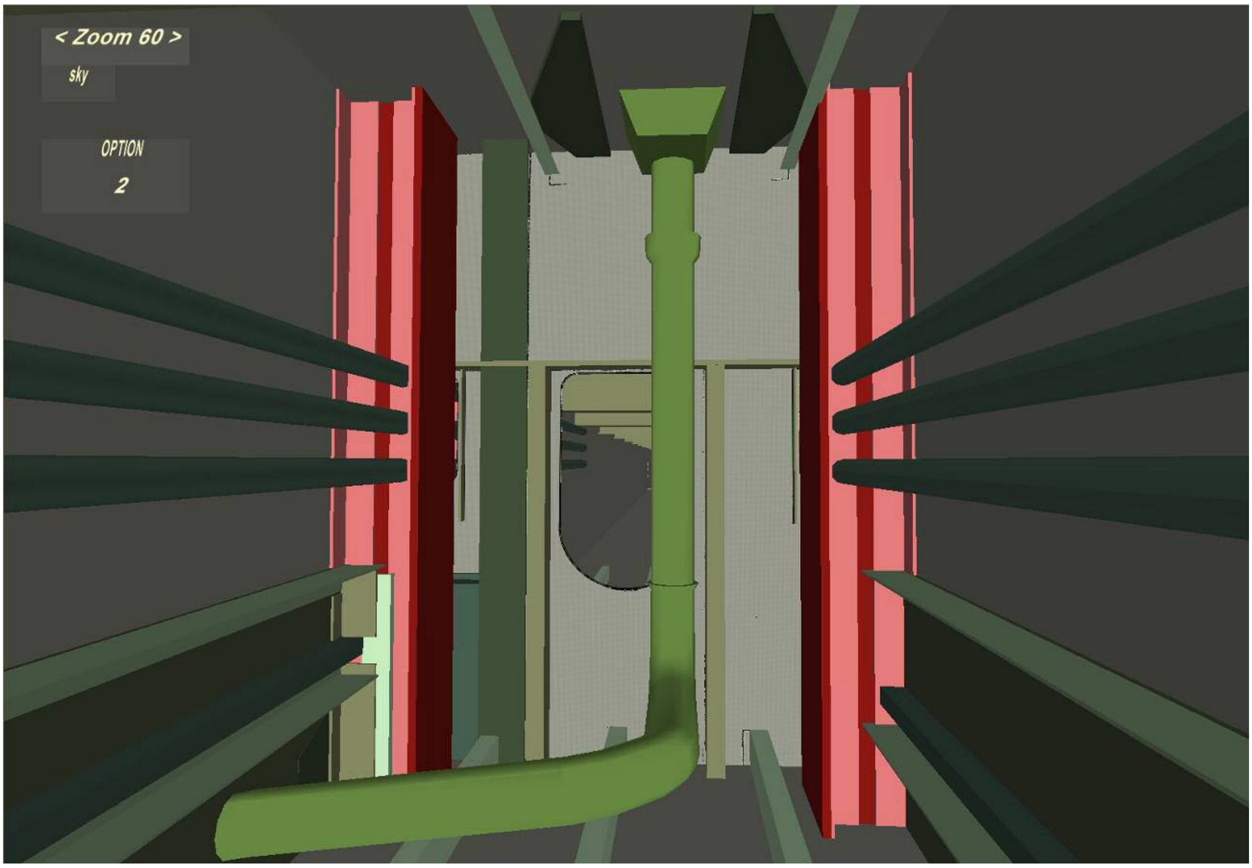

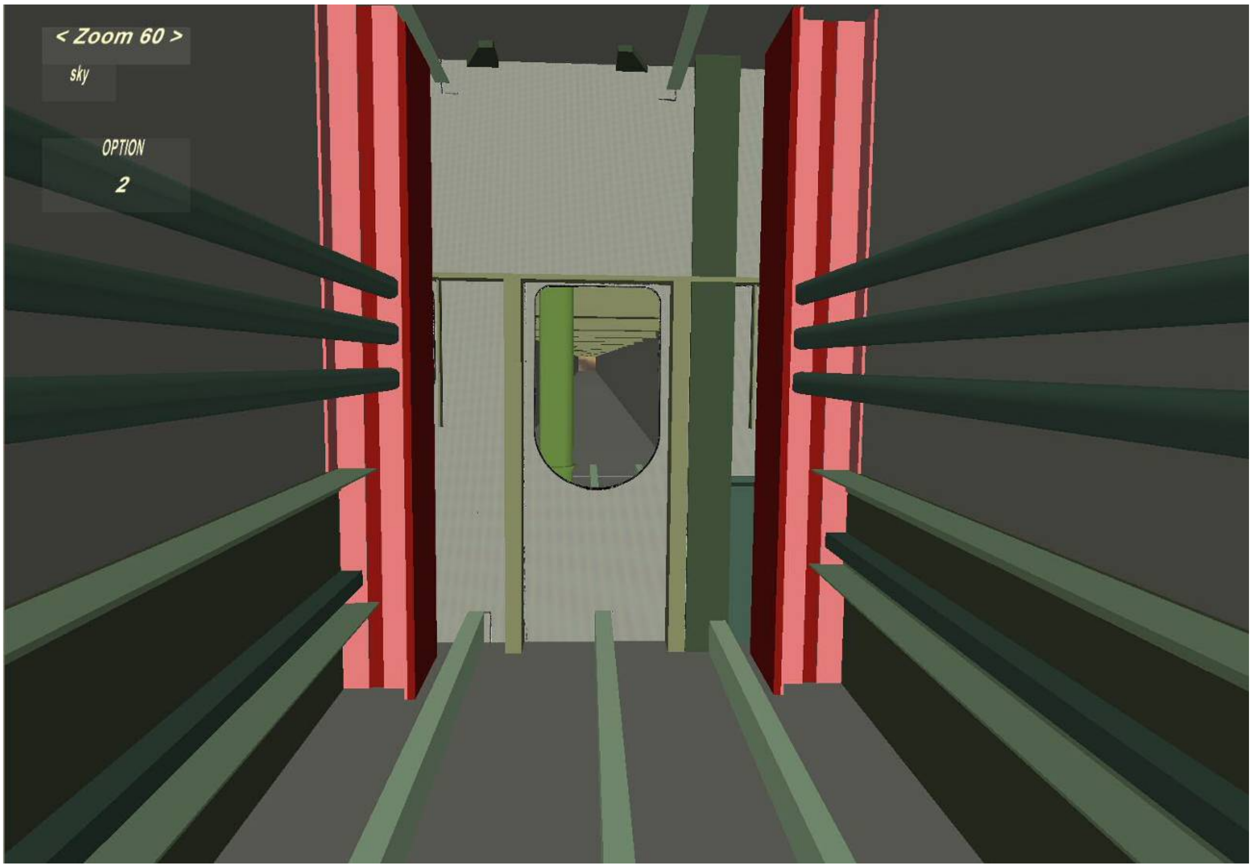

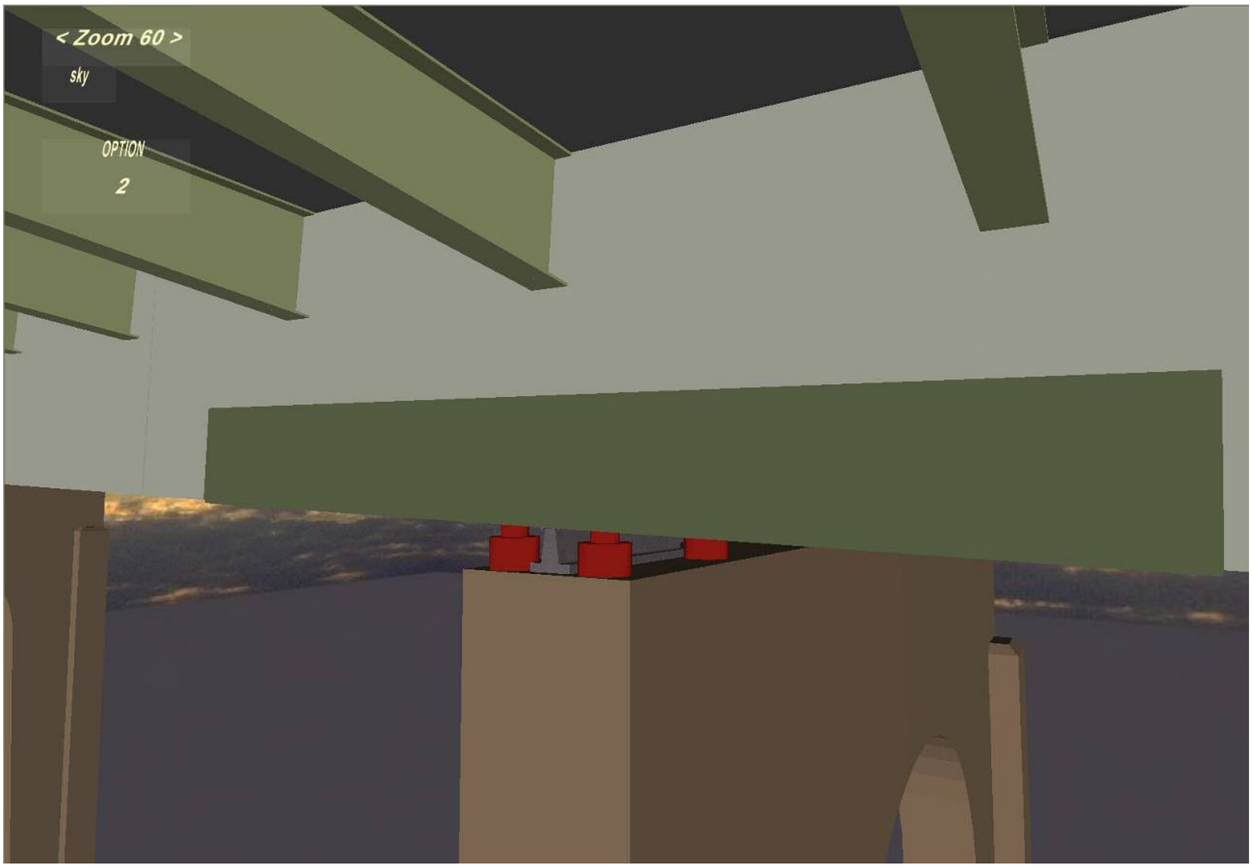
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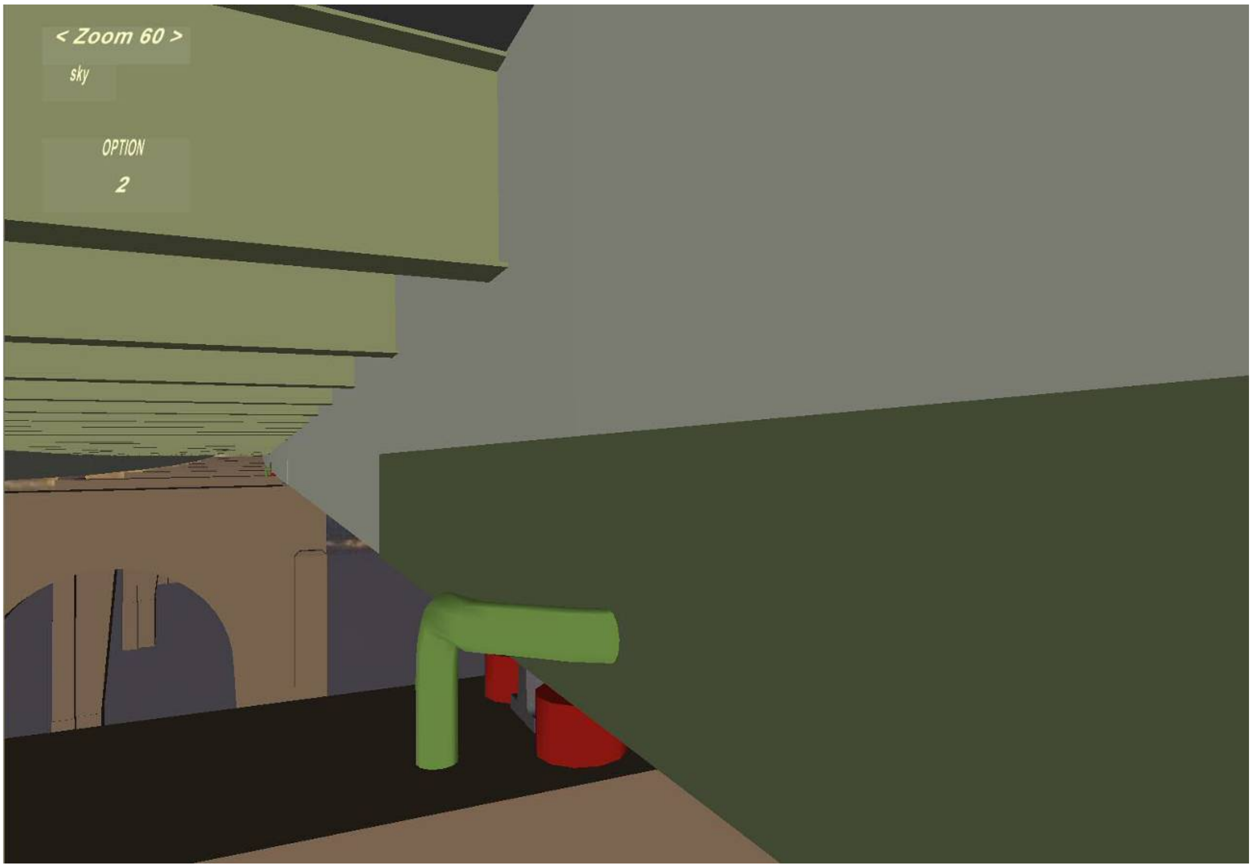
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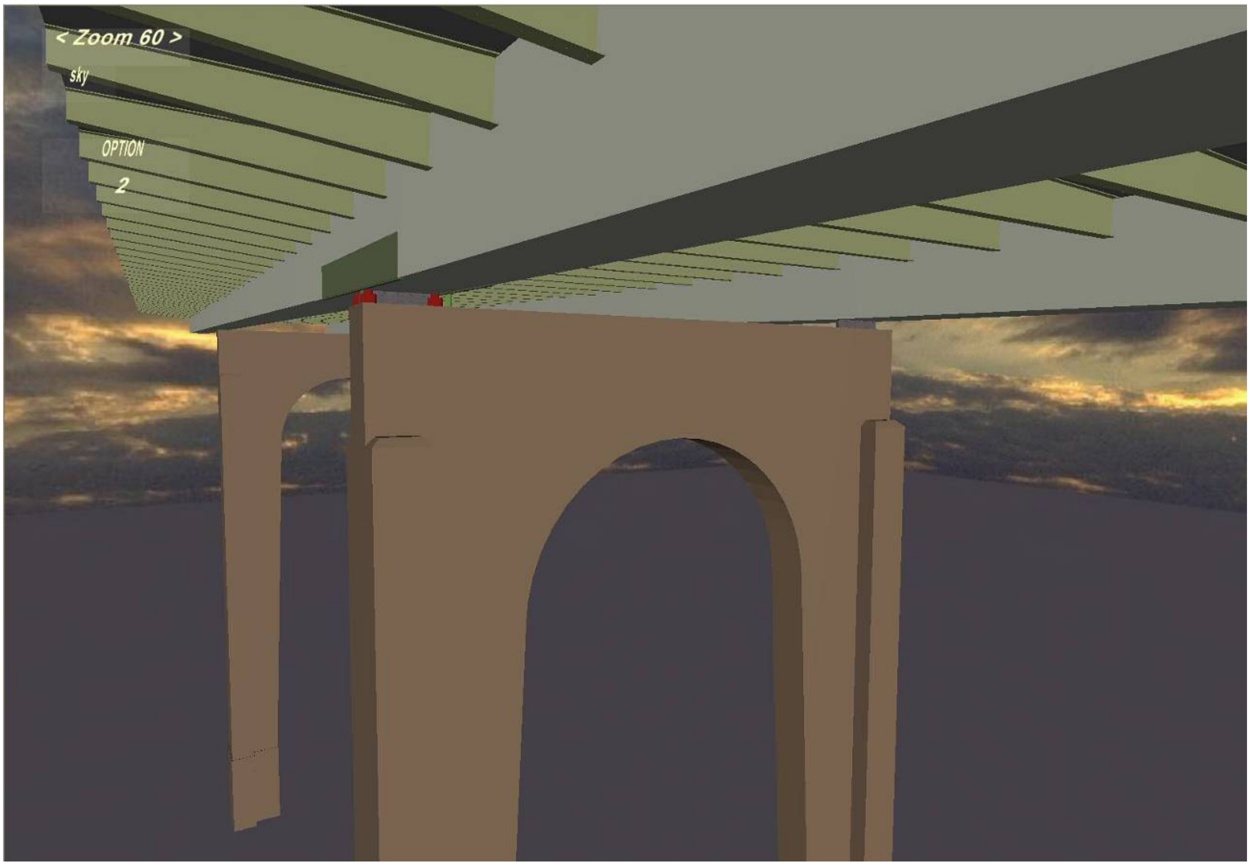
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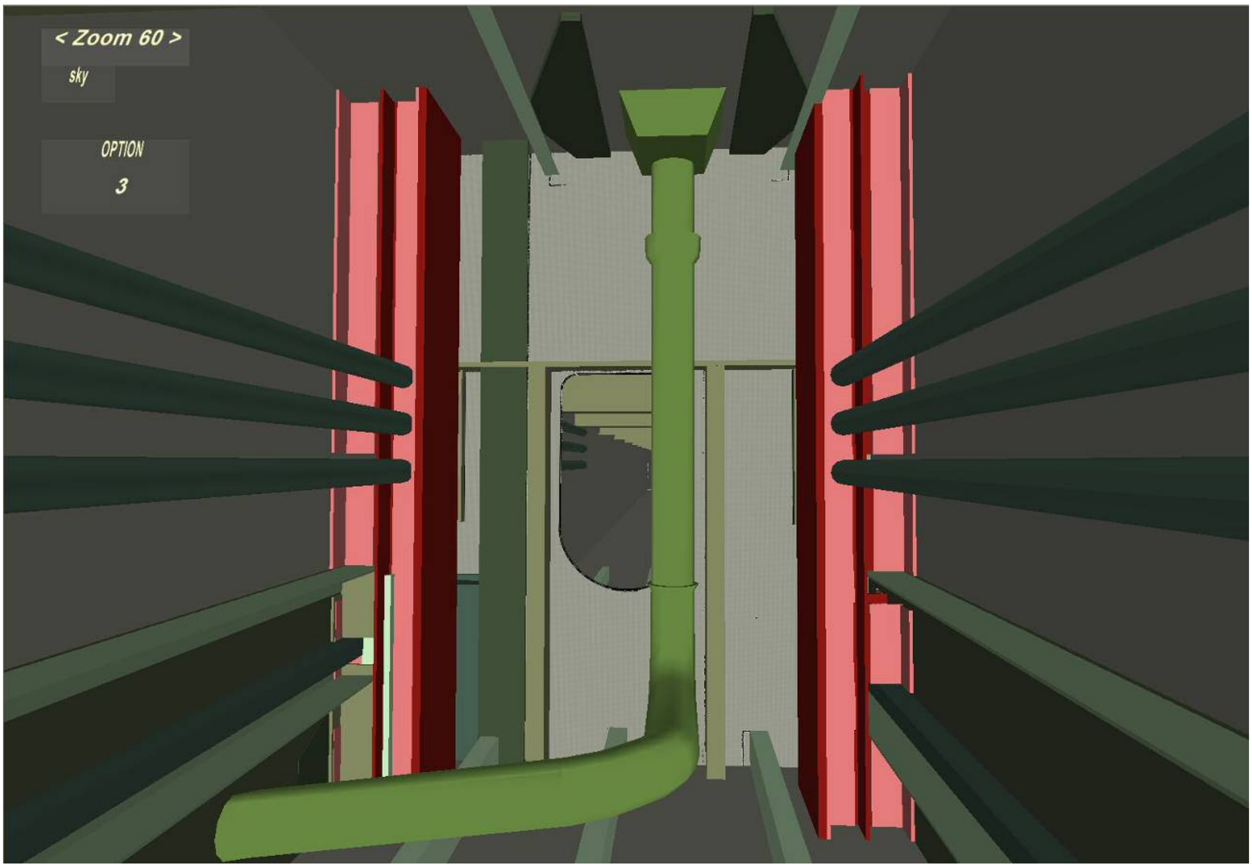

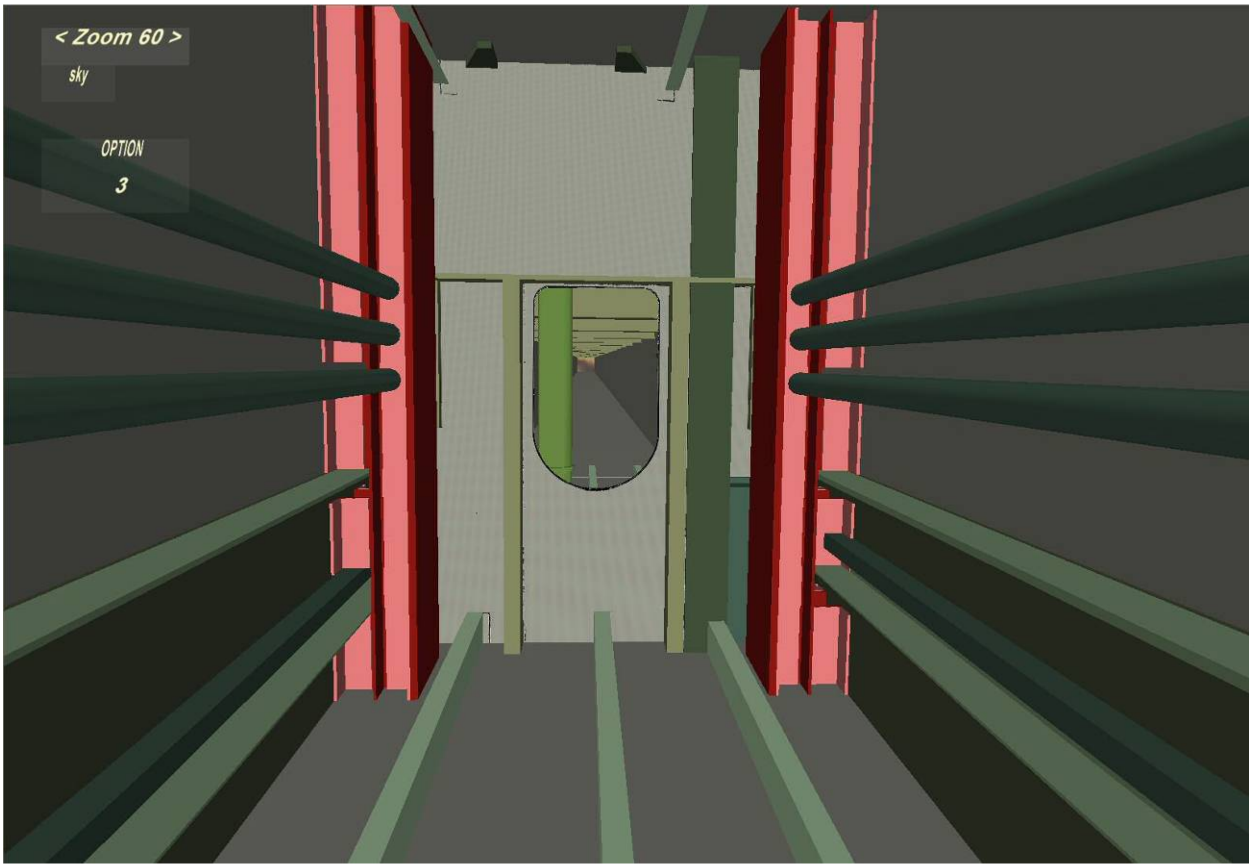

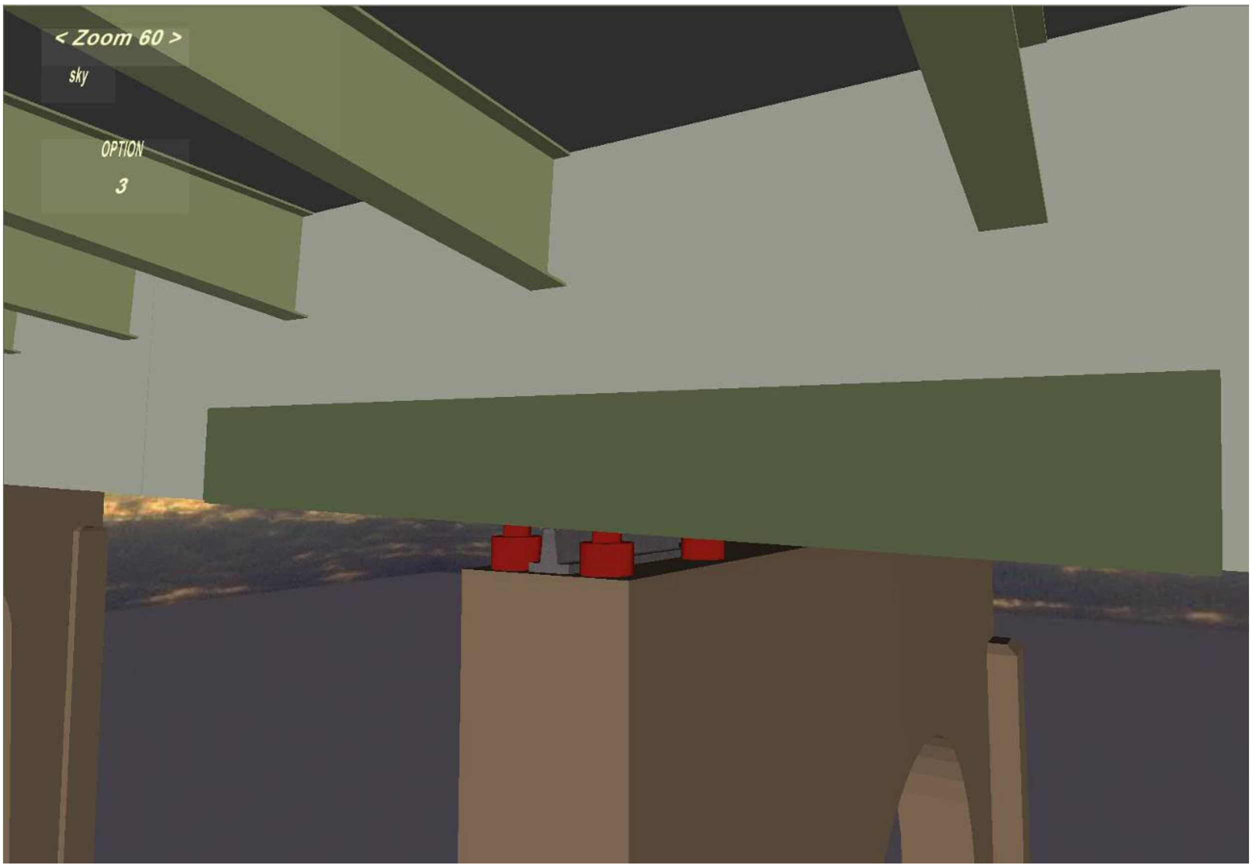
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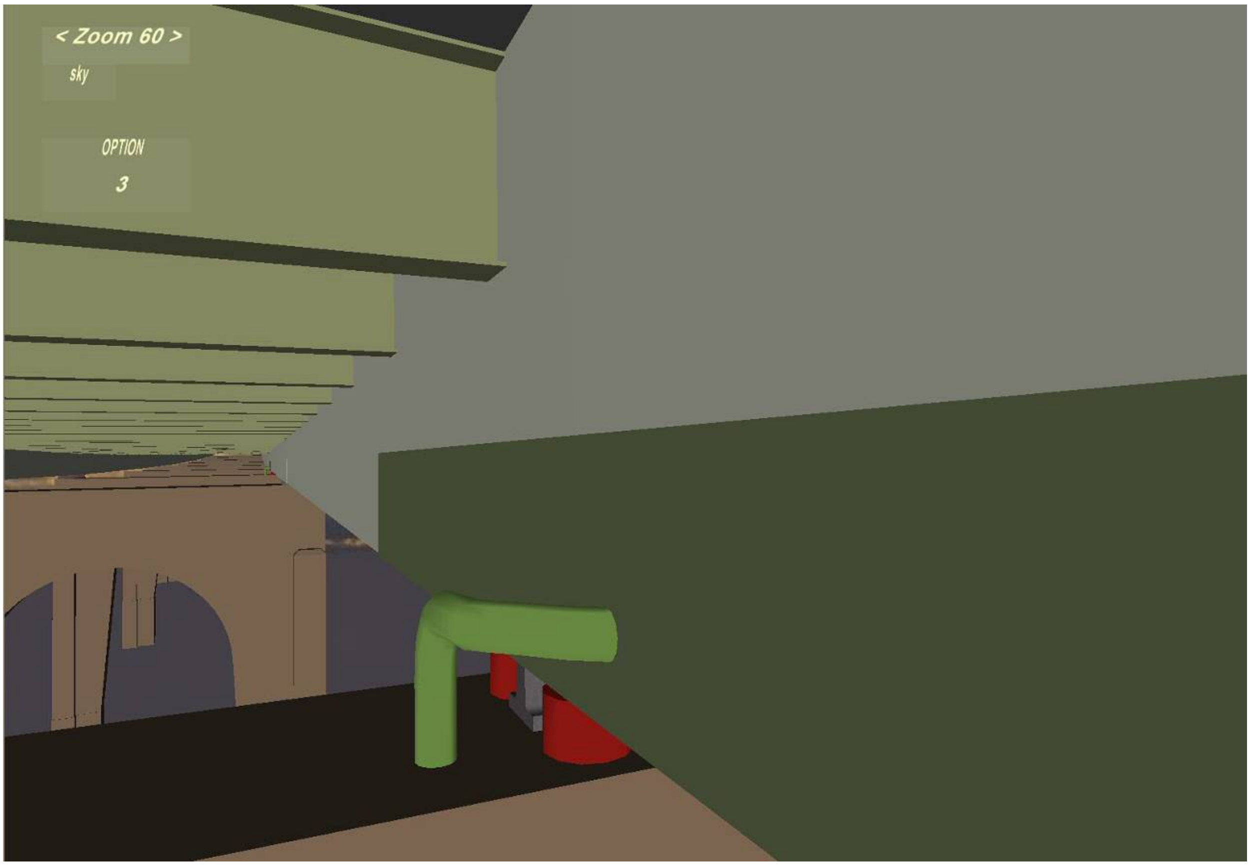
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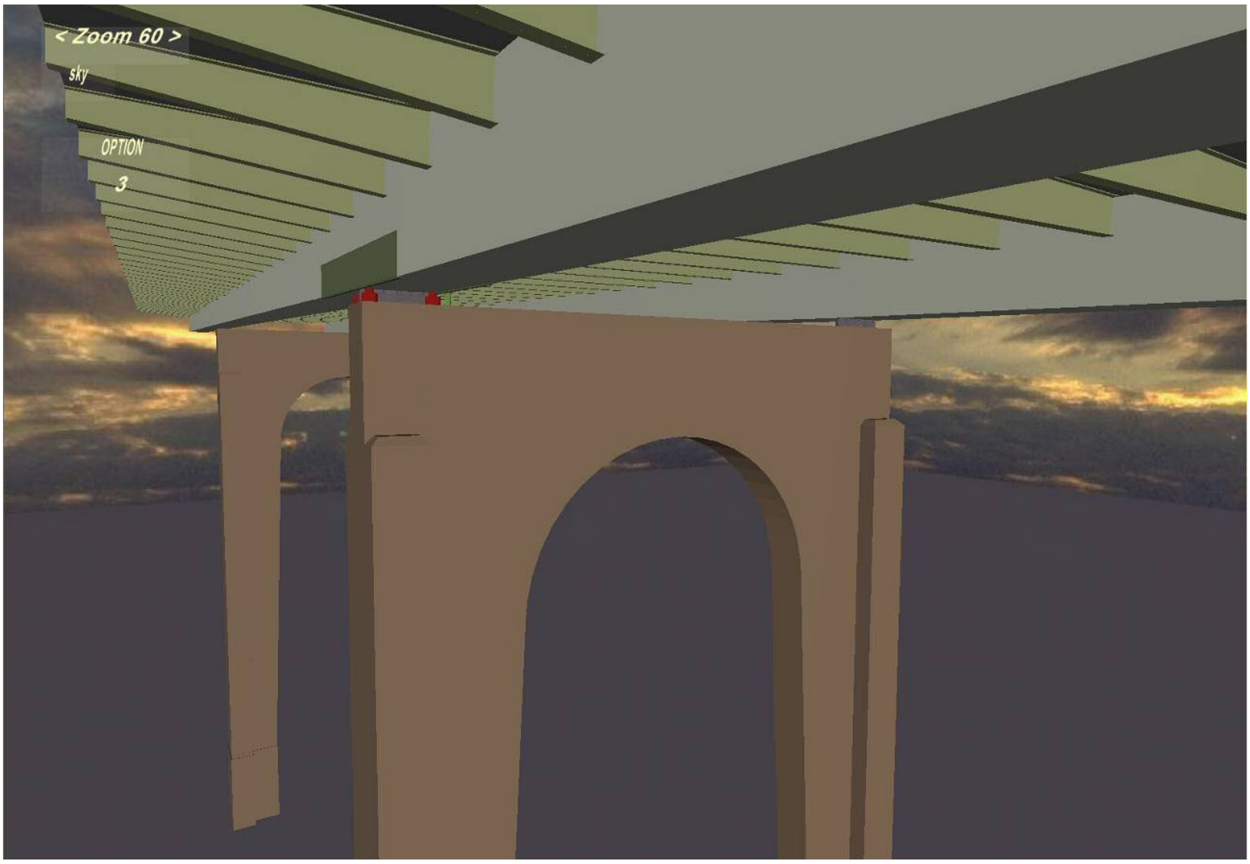
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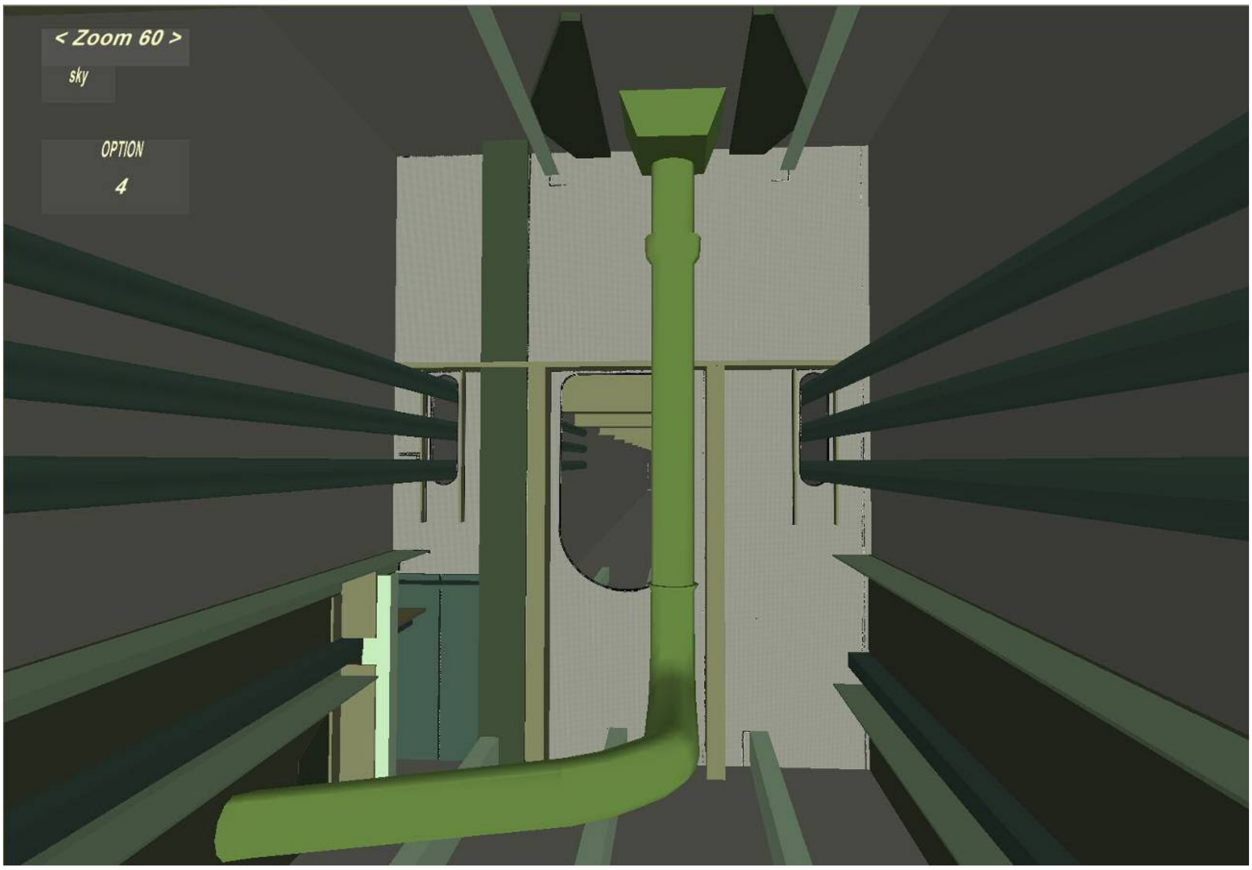

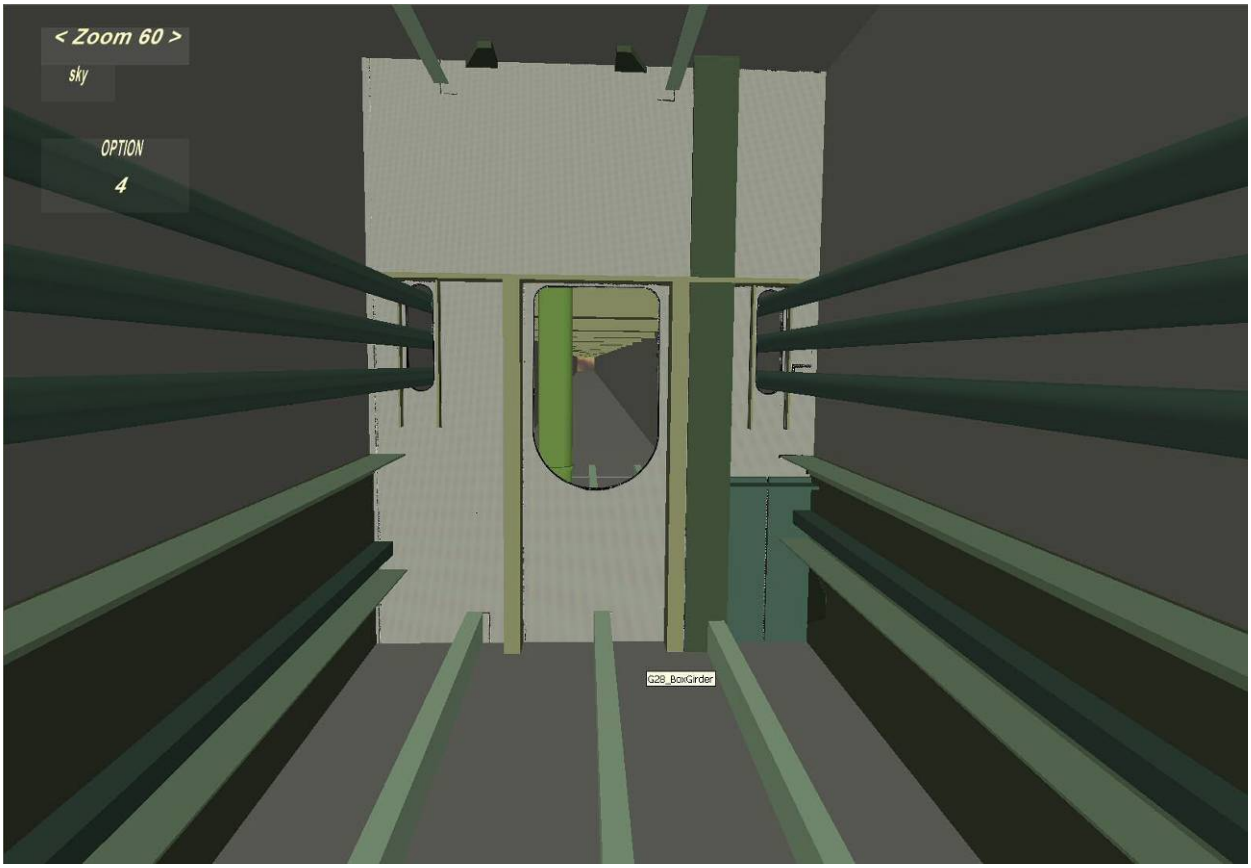

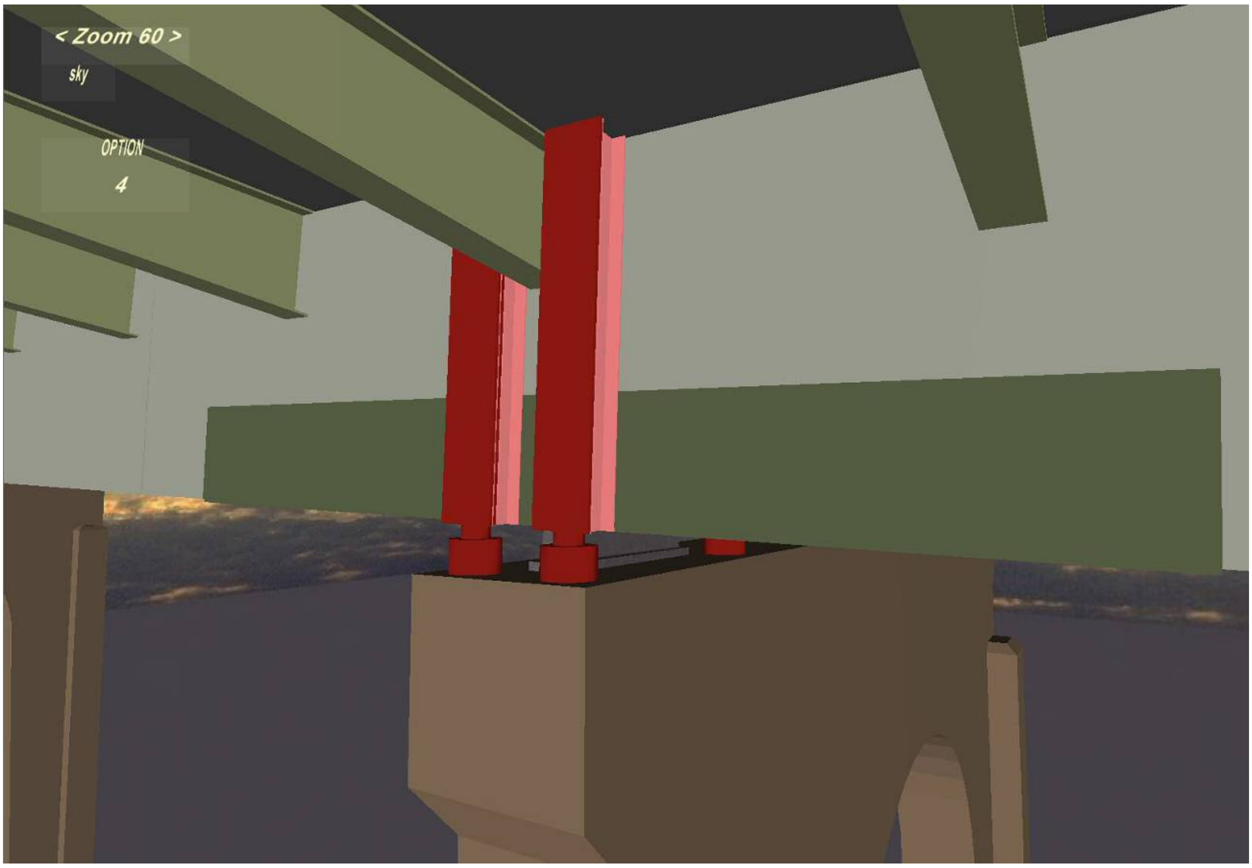
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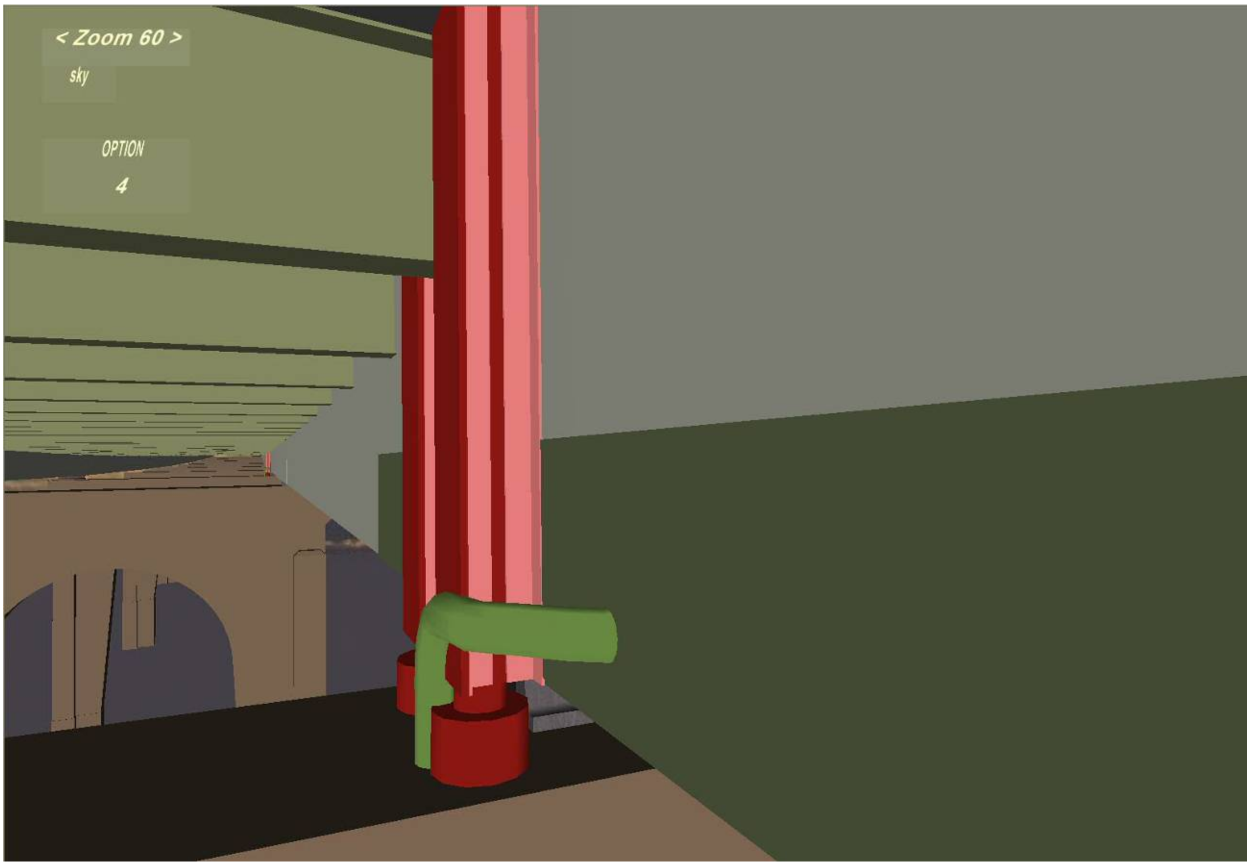
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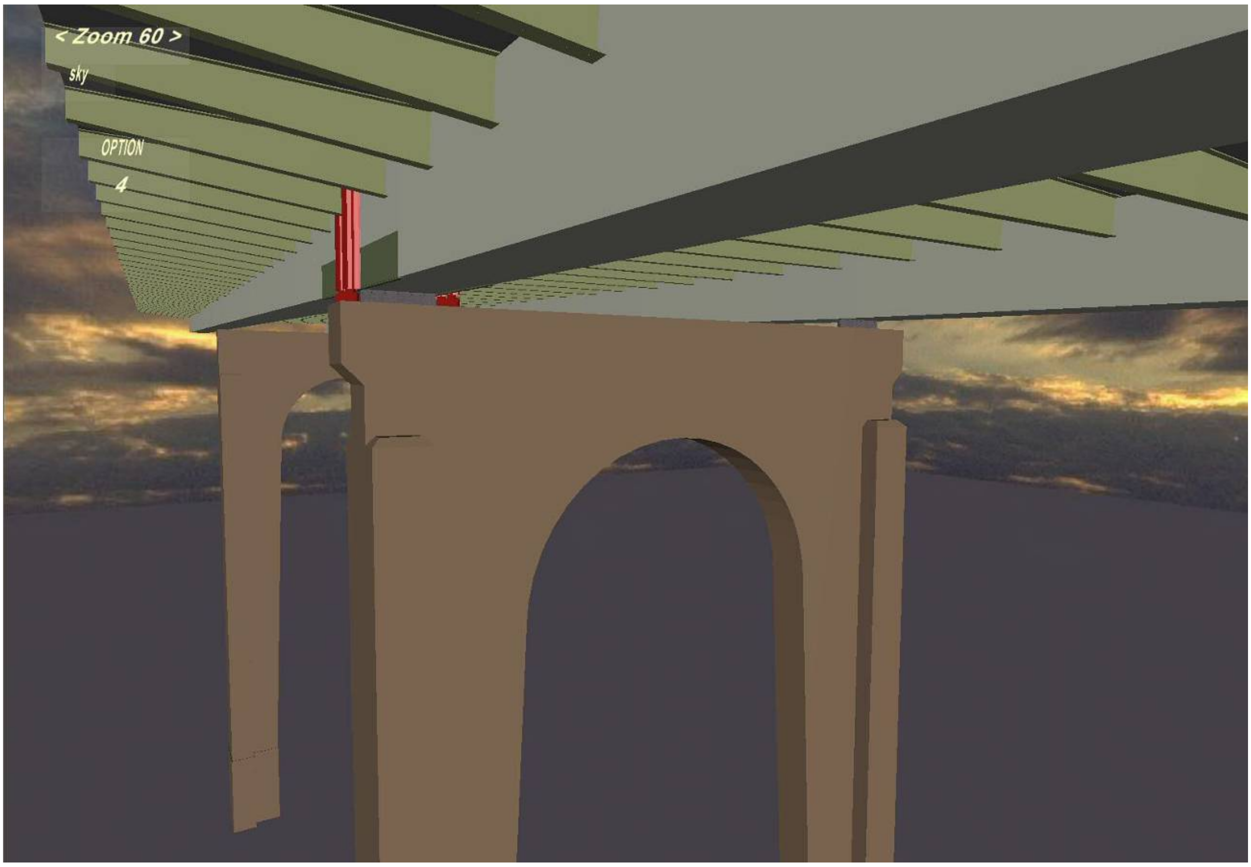
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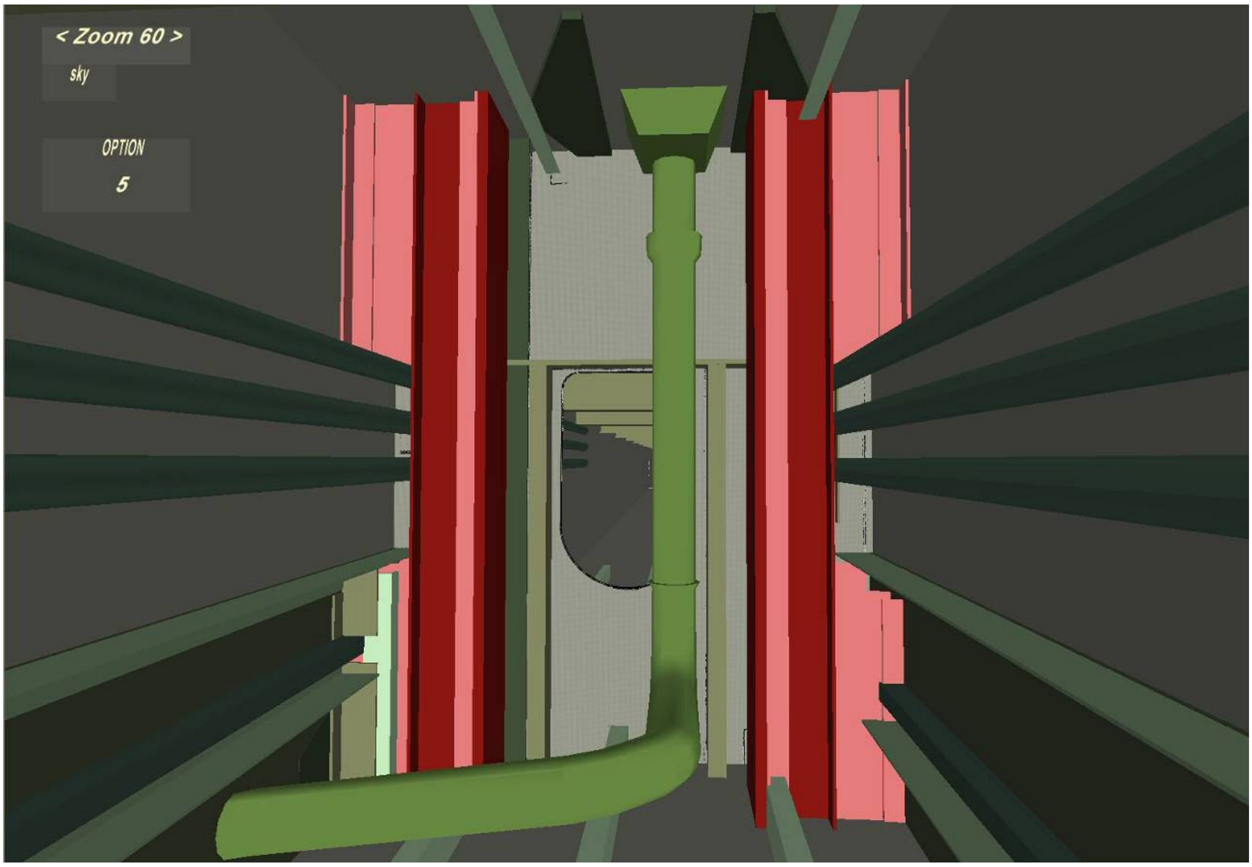

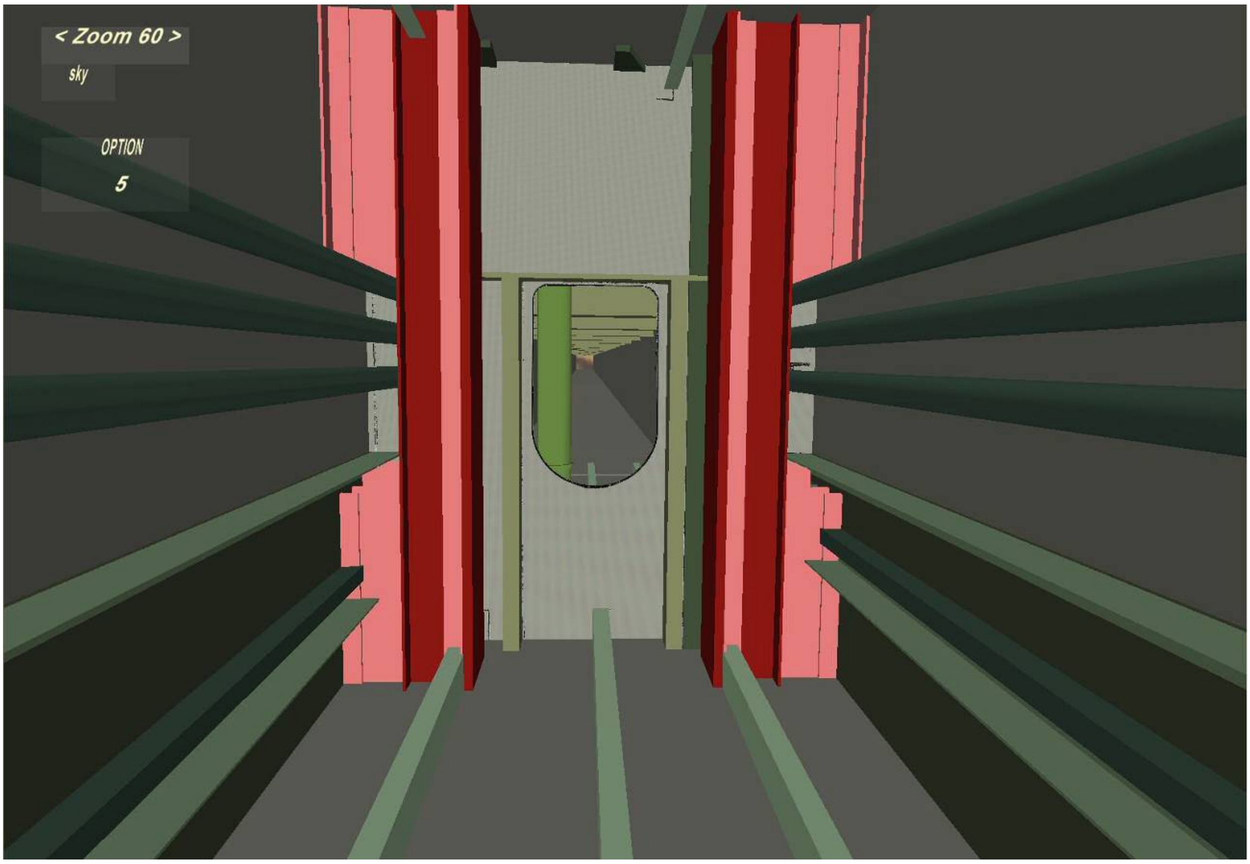

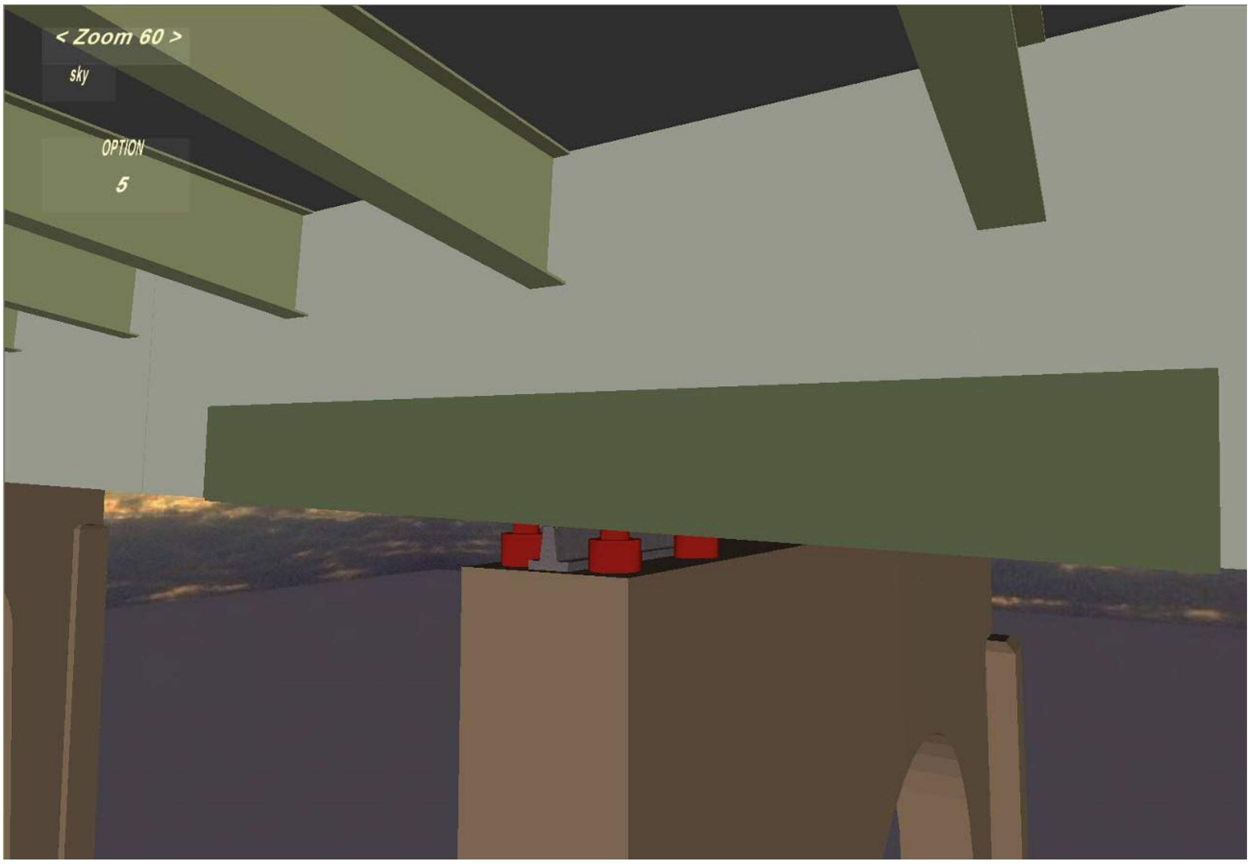
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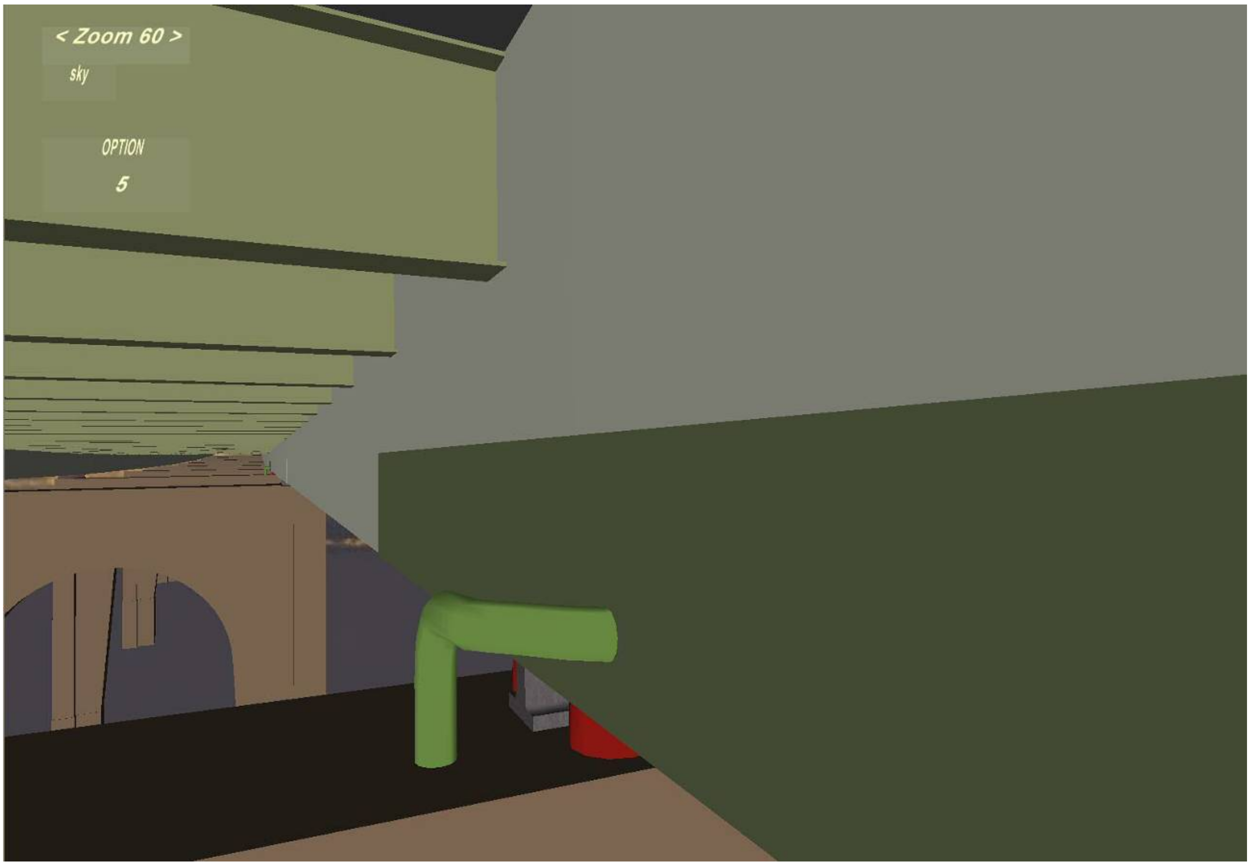
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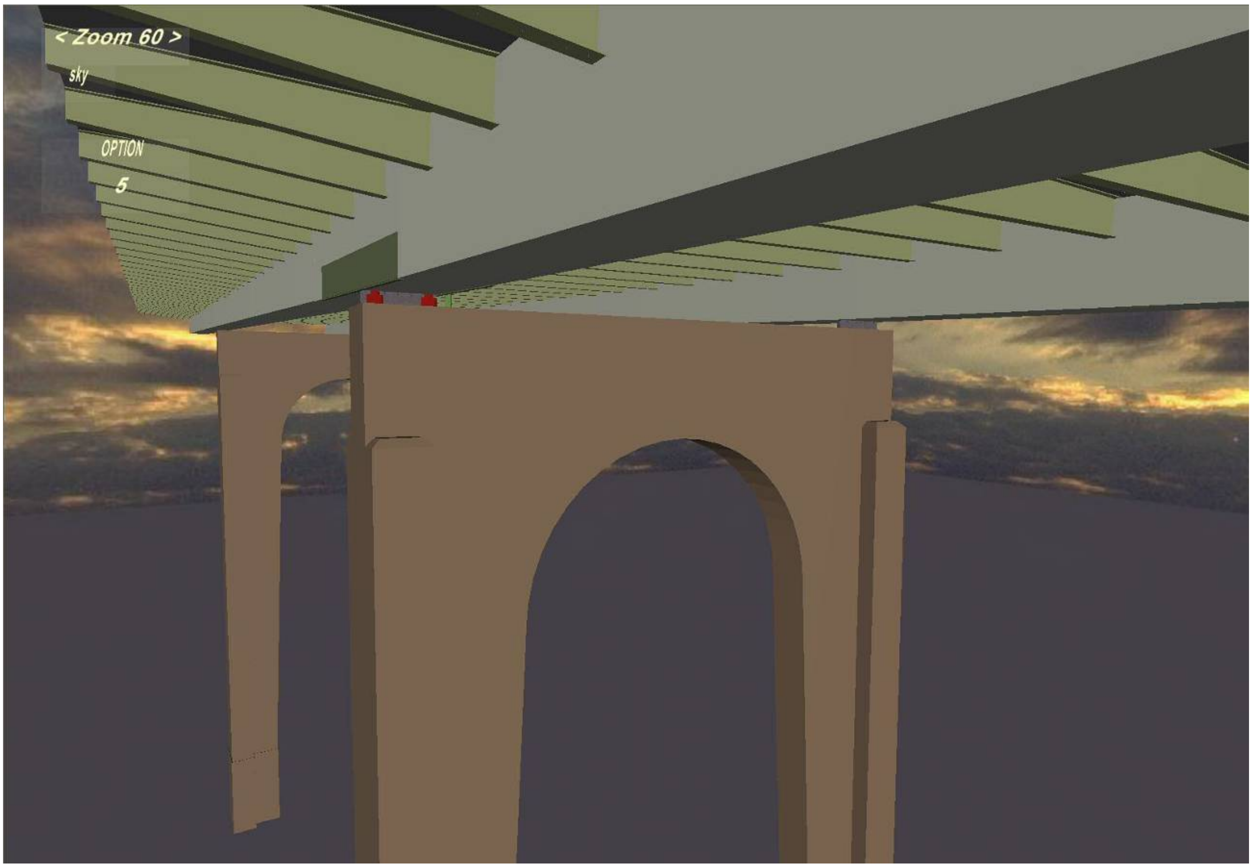
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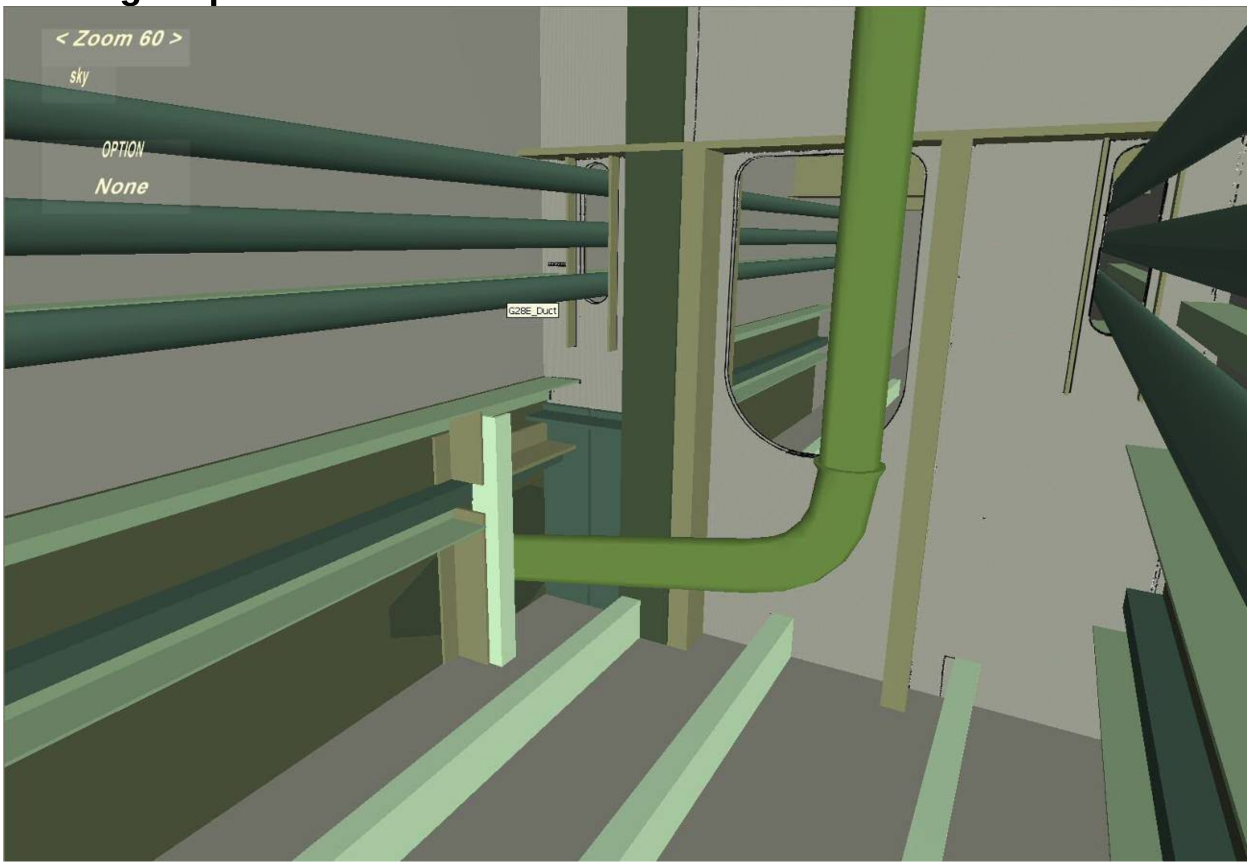
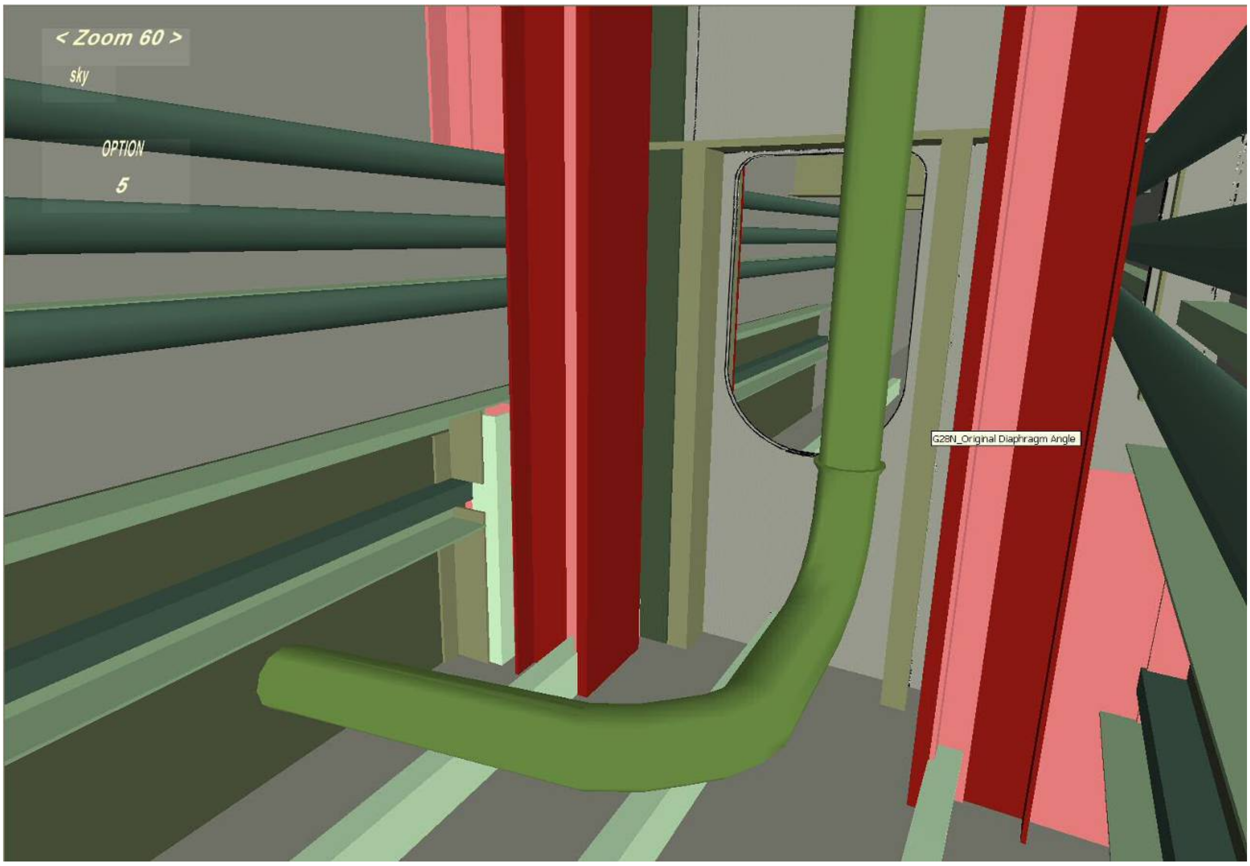
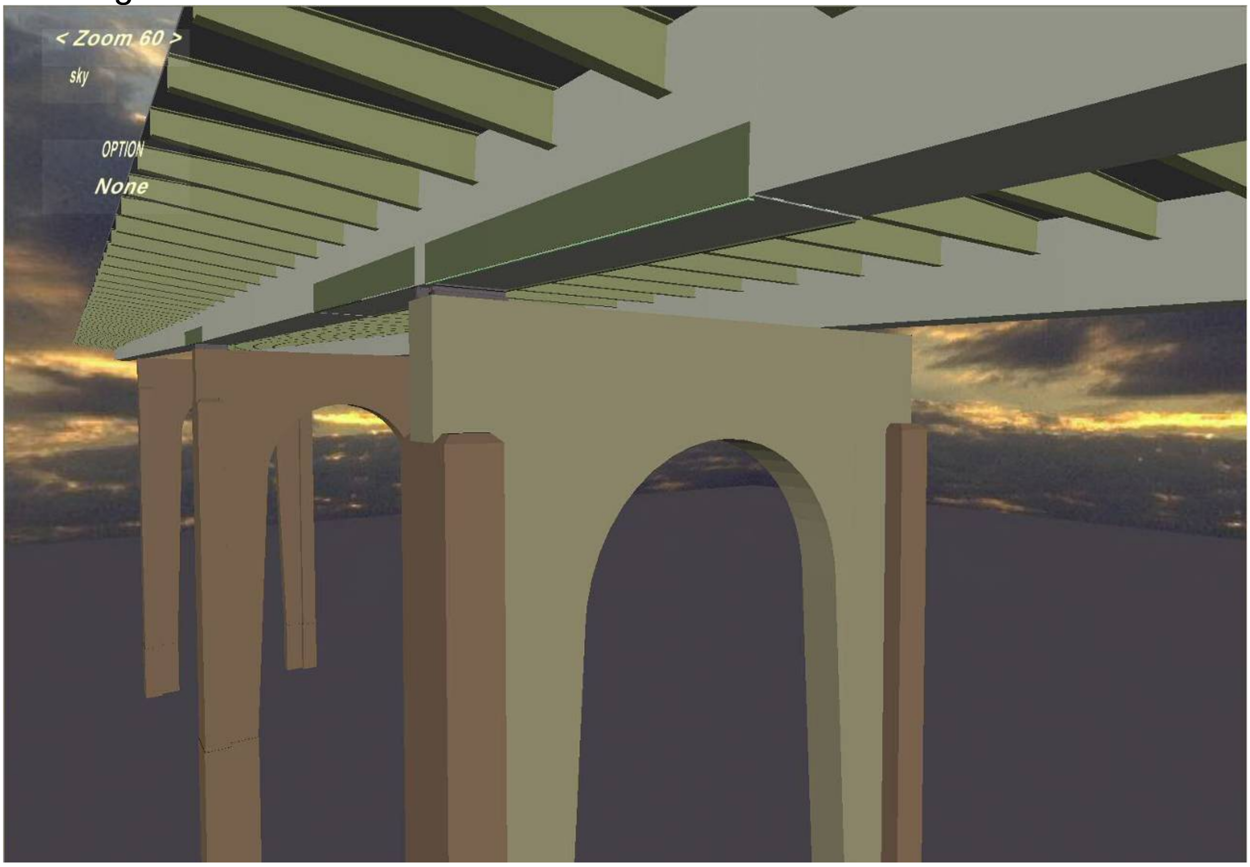
Drainage Pipe Diversion





Shared Pier (S3) Options

Existing Structure Model



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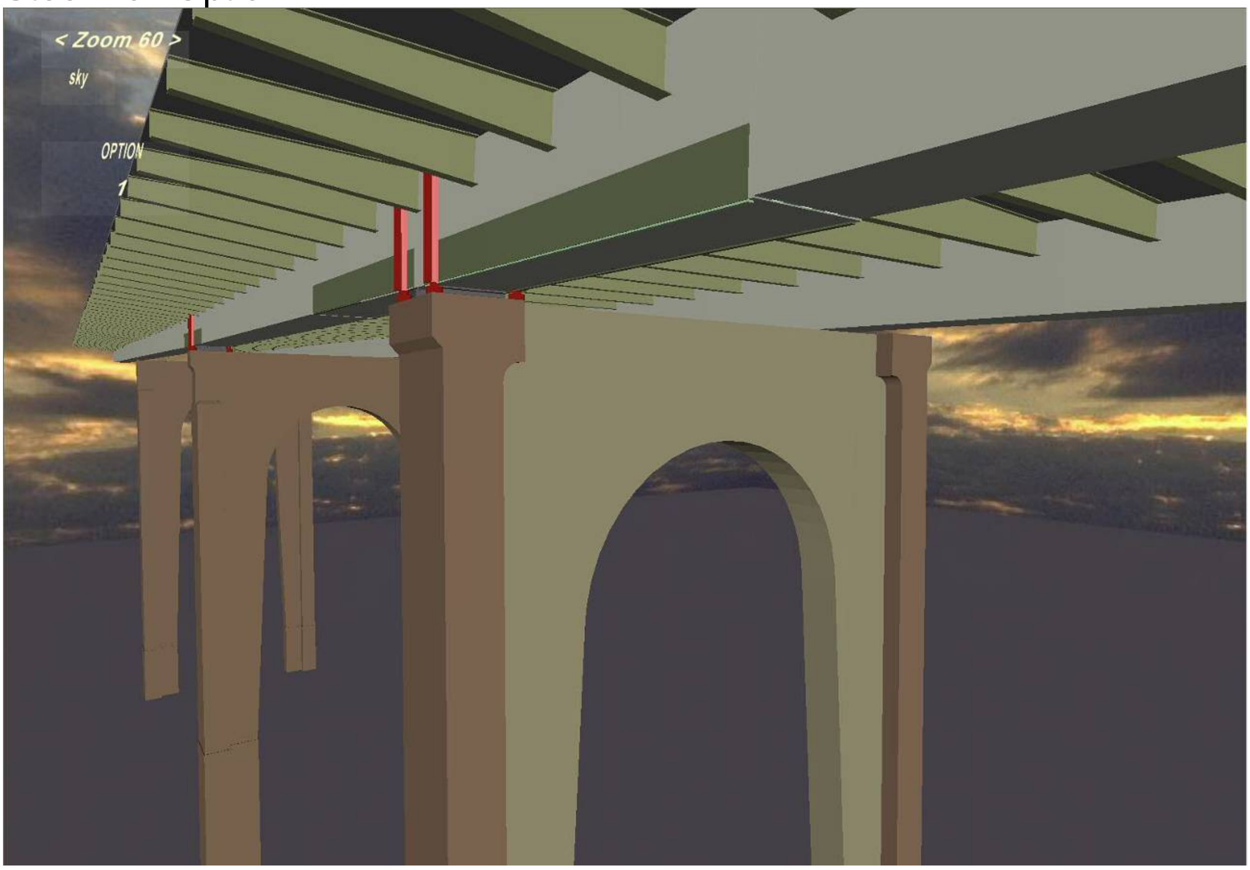

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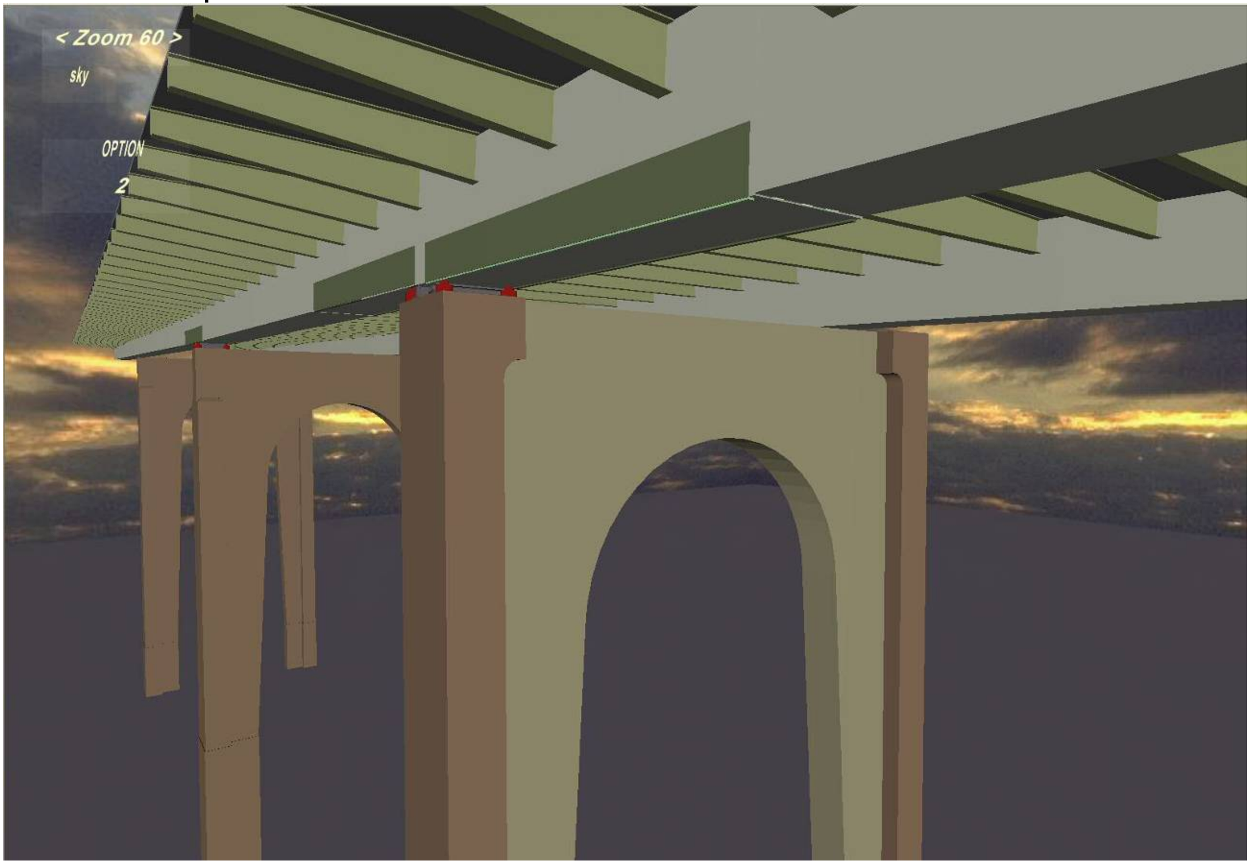

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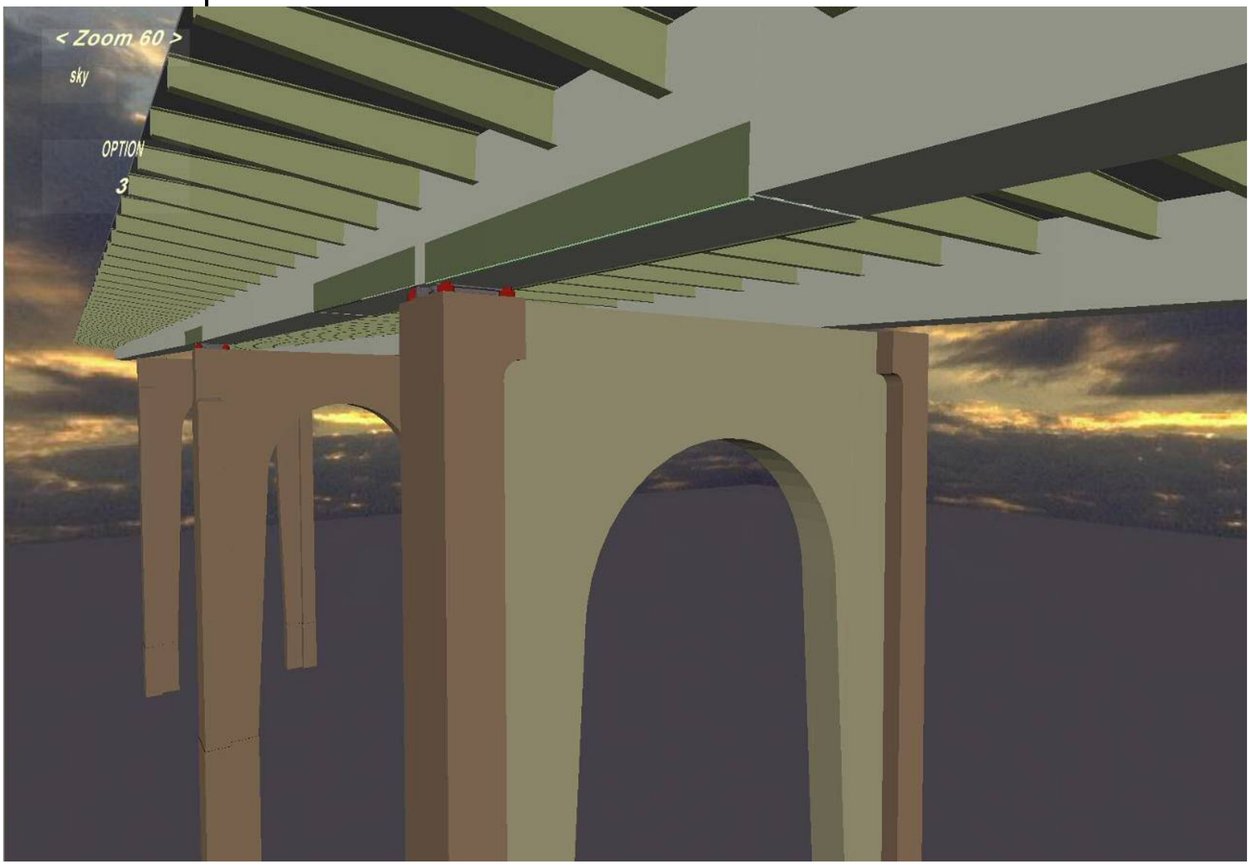

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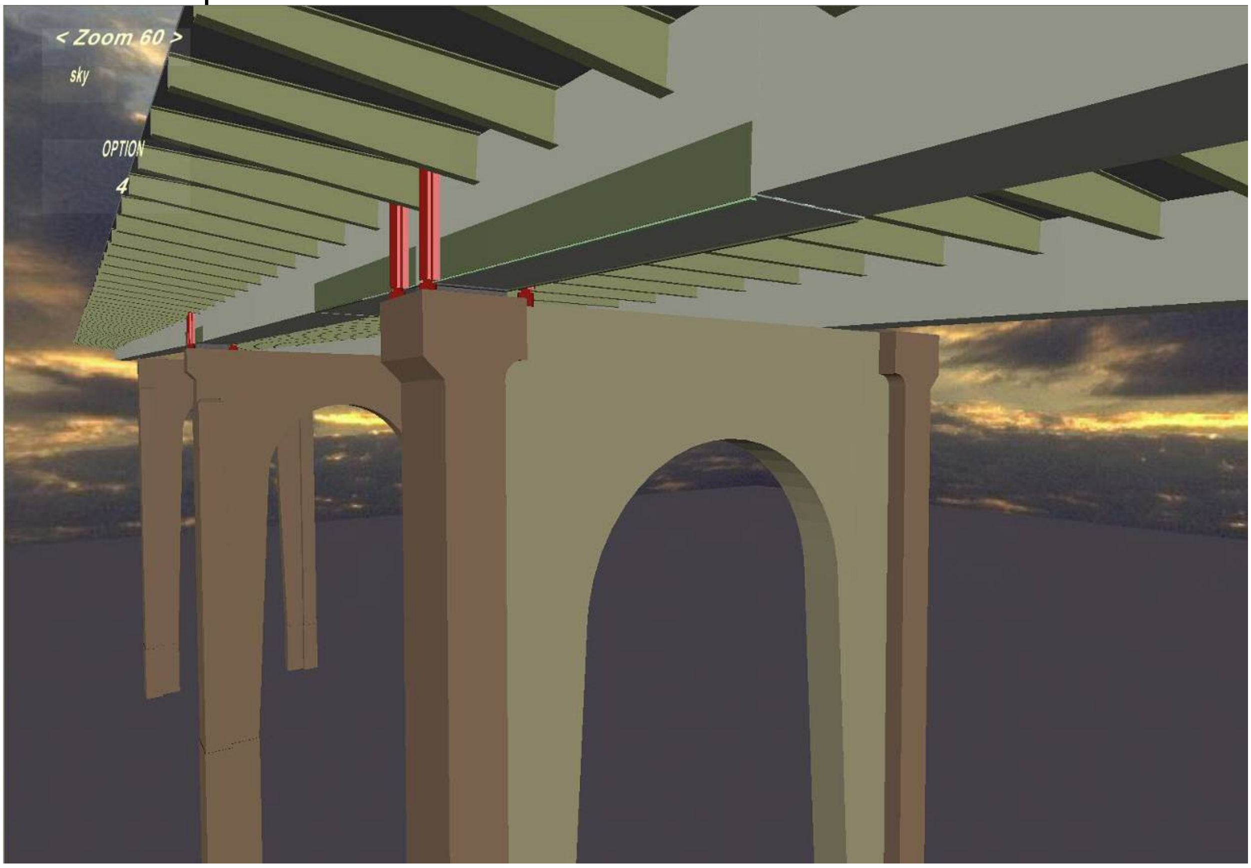

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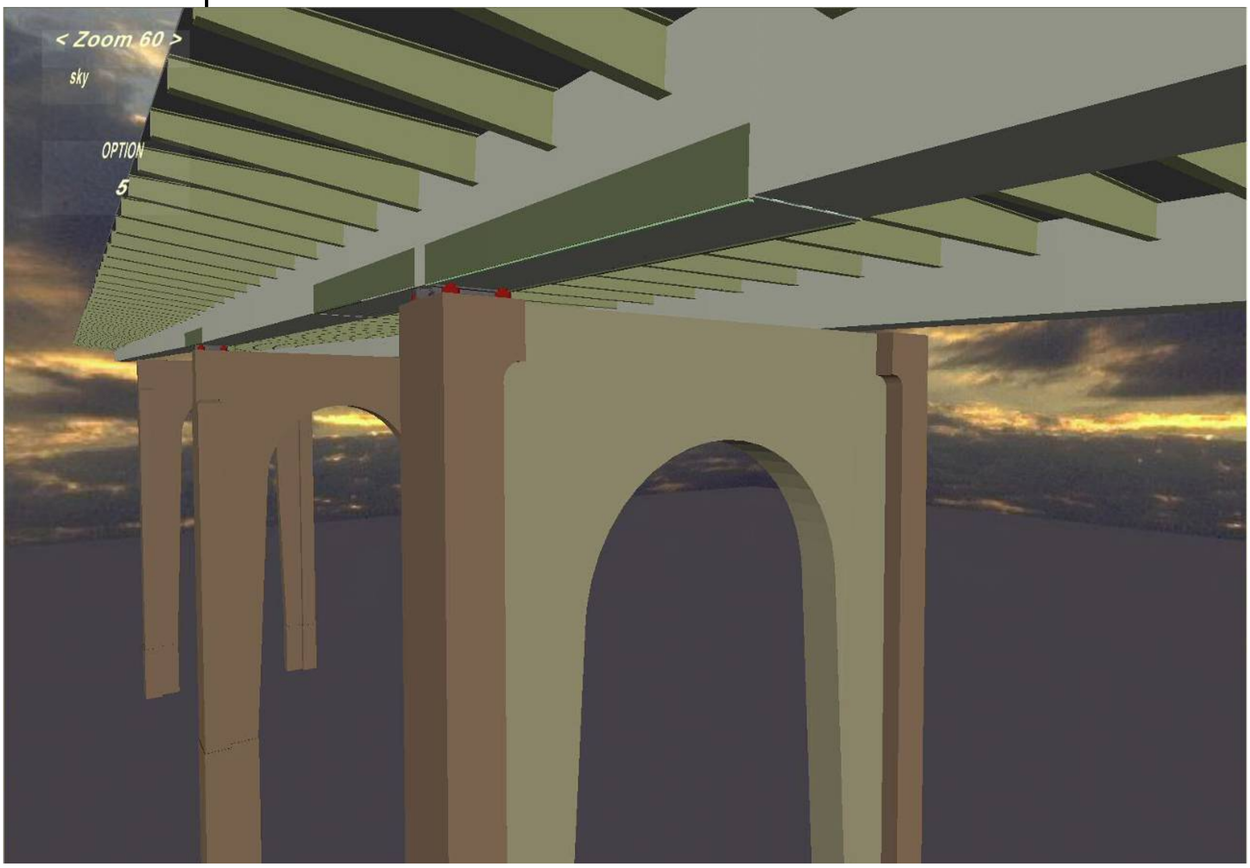

Appendix D

Inspection of Bearing and Pier top results