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SENSITIVITY STUDY OF ARCH STIFFNESS AND TYPE OF BACKFILL ON THE BEHAVIOR OF BURIED ARCH BRIDGES

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**Abstract:** The behavior of a buried arch structure depends on many variables. Some of the more significant are arch stiffness, type of backfill, depth of overfill, and arch span. This paper summarizes the results of a FEM sensitivity study that these four independent variables have on the arch behavior for 3-hinge precast arches. The arch behavior is studied through observations of the dependent variables of crown deflection, moment, axial and shear forces by Aztech program for short and medium span arches. The program is a proprietary FEM software provided by Reinforced Earth Company Ltd. which has been used extensively for design of precast concrete arches called TechSpan®. The study concludes that the total stiffness of the combined soil-structure system, as measured by deflections and internal forces, is strongly dependent on stiffness of both arch and backfill. In addition, for lower stiffness arches with high overfill, the effect that the backfill stiffness has on arch deflections is much greater for higher stiffness arches.

# Introduction

Since ancient times, the invention of the arch has proven to be one of the most efficient structural systems to transfer vertical loads to its supporting foundation. Materials used to form an arch shape can vary from quarried stone, brick and mortar, cast-in-place concrete, to precast concrete. With advanced computer technology engineers can better quantify the forces applied to the arch and design these arches thinner which make it possible to precast and deliver them for installation. (Figure 1 and Figure 2)



Figure : Precast arch during backfilling

Figure : Precast arch with low rise

The arch that is the case of this study consists of a two-piece buried precast concrete arch with three hinges. Hinge points are located at the crown and at the bottom of each leg. This arch utilizes the concept of minimizing bending moments by selecting an optimized funicular shape for each given loading and geometric requirement. The typical range in span for these types of arches vary between 7 and 25 m and the rise to span ratio of 0.25 to 0.60 (Weinreb and Wu 1993). The hinge at the crown allows for the arch to be transported in two pieces which greatly reduces the size of the elements transported. By staggering the elements during construction, two cranes are only needed for the first four units, after which only one crane is needed that significantly reduces the cost. Supporting structures for these arches are typically spread footings, raft, or pile foundations. After construction of the foundation, the arch pieces are installed against each other with half element offset. Width of the pieces are typically 1.25 m. In the analysis, backfilling on either side of the arch is done with approximately one meter difference in elevation of two sides. For design purpose, it is of interest to know the effect of backfill type on behavior of the soil-structure interaction and in this paper the effect is studied for various spans and arch stiffnesses.



Figure 3: Arch components

# Numerical Analysis

The FEM software used in this study, Aztech, is a nonlinear elasto-plastic program with the ability to incorporate strain hardening of the backfill. The method used for solving the nonlinear stiffness matrices is the visco-plastic method, which is based on the initial strain method (Segrestin and Brockbank 1997). Arch element is described by 4 Gauss points and 8 nodes. So, for a given element, 3 dimensional stresses (Bending moment, Shear stress and axial force) are calculated for 4 Gauss Points per element. In the analysis, the behavior of the backfill is represented by a set of 7 parameters:

Deformation coefficient: Ki, n (dimensionless)

Bulk coefficient: Kb, m (dimensionless)

Cohesion: c (kPa)

Internal friction angle: $φ$ (degrees)

Dilatancy $ψ$ (degrees)

Figure 4 shows the shape of the hyperbolic equation used in the model to represent the variation of the modulus with deviator stress (for constant confining pressure ($σ$1 – $σ$3)ult ). It depends on two parameters:

Ei = initial tangent Modulus

($σ$1 – $σ$3)ult = asymptotic stress deviator related to the ultimate soil strength



Figure 4: Soil model used in the numerical analysis

For all soils (except fully saturated soils in unconsolidated undrained conditions, which would not be suitable for backfill), an increase in confining pressure will result in a steeper stress-strain curve which corresponded to Ei and ($σ$1 – $σ$3)ult values increasing with confining pressure. The variation of Ei with$σ$3 is represented by the equation suggested by Jambu (Duncan and Byrne 1986):

[1] Ei = Ki pa ( $σ$3 / pa ) n

Where Ki, n are dimensionless parameters (Duncan Coefficients) and pa is atmospheric pressure.

Volume change in the soil may be reasonably represented by using a bulk modulus independent of deviator stress but varying with confining pressure $σ$3 as in

[2] B = Kb pa ( $σ$3 / pa ) m

Where Kb and m are dimensionless parameters (Duncan Coefficients) and pa is atmospheric pressure.

The foundation soil is modeled as an elastic material with Mohr-Coulomb model and friction angle of 35°, modulus of elasticity (E = 100 MPa) and Poisson’s ratio of 0.3. The arch is modeled as a 2D element with the properties of concrete and the actual thickness of the arch. Length of arch elements is adjusted to the backfill lift height. FEM mesh is generated based on the arch shape. The concrete of the arch and footing are modeled elastically with Young’s modulus (E = 25,000 MPa), Poisson’s ratio of 0.2, and unit weight of 25 kN/m3. No cracked section is considered in the analysis. Soil-concrete contact elements are utilized to consider relative displacement between the arch and the fill. The friction angle between concrete and the backfill is considered as 26°.

The real construction stages of the arch are modeled through many steps before the final loading condition (Figure 5). The first step is for the arch alone with no backfill. Subsequent steps apply approximately two meter of fill at a time, alternating from one side of the arch to the other until the fill has reached the crown. From this point the layers of fill are placed simultaneously on both sides until the final grade is reached. The last step is the application of a live load surcharge, which is not considered in this paper for simplicity of the result comparison.



Figure 5: FEM model of the arch showing backfill layers during construction

To simulate a compaction effort and the corresponding strains that result, each step contains three load increments. The first is the application of the lift of backfill. The second is the application of a 10 kPa surcharge to simulate compaction. The third is the application of a negative, -10 kPa surcharge to simulate the removal of compaction equipment. During the last increment, any elastic strains that occurred on the second increment will be removed, but the plastic strains will remain. This agrees with our intuitive knowledge of the behavior of the soil during compaction.

# PARAMETERS OF THE STUDY

For this parametric study, 48 different cases were modeled in FEM. Most of the independent variables were selected to represent typical values often used in routine buried arch applications. The values of the arch thickness represent typical values and some values outside of the typical range, so that the effect they have on the dependent variables can be more widely explored. The four independent variables in this study are:

* Span (10, 15 and 20 m): Spans of precast buried arches vary between 7 and 25 m. Three spans of 10, 15 and 20 m are chosen to reflect typical values for short and medium span bridges. The rises of the arches are 4, 4.5 and 7 m respectively.
* Depth of overfill on top of the arch crown (H = 1 and 10 m): Depth of overfill on typical application varies between 0.60 to 15 m and two values of 1 and 10 m are selected in this study. For the purpose of this study high fill is assumed as an overfill to span ratio of 0.5 or more.
* Thickness of the arch (200, 300,400 and 500 mm): Stiffness of Arch Section is represented by the arch thickness. Table 1 shows the equivalent stiffness for each arch thickness. The typical thickness of the arch is about 2% of the span and 200 mm is the minimum practical thickness of the precast arches.

Table 1: Stiffness of arch for each thickness

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Concrete Thickness (mm) | 200 | 300 | 400 | 500 |
| Arch stiffness, EI (N.mm2/mm) | 16x109 | 56x109 | 133x109 | 260x109 |

* Stiffness of backfill around the arch: Table 2 shows the two different backfills used in this study. The first one represents a high quality granular fill that can be compacted to a dense state with regular effort and provide stiff lateral support to the sides of the arch. The second fill represents a material that will provide less support. (Duncan and Byrne 1986)

Table 2: Properties of two fill types under parametric study

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Material | Ф° | Ei (kPa) | ʋ | ϒ (kN/m3) | ψ° | Ki | n | Kb | m |
| Dense fill  | 35 | 50,000 | 0.3 | 20 | 5 | 500 | 0.4 | 400 | 0.4 |
| Loose fill  | 30 | 15,000 | 0.3 | 20 | 0 | 150 | 0.4 | 150 | 0.4 |

The two dependent variables in this study are:

* Crown deflection
* Maximum internal arch forces (bending, axial compression and shear)

In the next section, the effect of independent variables on dependent variables are discussed.

# Results OF PARAMETRIC STUDY

The results for all spans and fill types are represented in following graphs. No live load is included in the study and load factors are not applied to the forces. The dependent parameters are discussed below.

## Crown Deflections

The crown deflection was selected as a very important dependent variable for this study since we believe it is likely the single strongest indicator of soil-structure stiffness. The system stiffness is not dependent on a single variable, but rather on all the variables combined, resulting in the buried structure whose performance is governed by the complete soil-structure interaction.

Figure 6 shows the plot of total vertical displacement of the buried arch FEM model. It can be seen that the maximum downward displacement occurs at the crown. The numbers presented in Figure 7 for crown deflection are independent of any footing movements as the footing settlements have been subtracted off the total downward movements to produce the net values reported in this paper. This is an important point to clarify since the arch crown typically takes on three distinct deformed shapes during the time of construction. The first is a sag under self-weight that occurs after initial placement but before backfilling. The second is a peaking or rising of the crown during the initial backfilling on each side that causes the sides of the arch to push together and the crown to rise. And the third is a descended shape that occurs after all backfilling is completed and the full weight of the fill is applied over the crown.

As shown in Figure 7, the crown deflection increases with a reduction of arch stiffness (thickness), a reduction of backfill stiffness and a higher overfill. The greatest increase in crown deflection is from decreasing arch stiffness and from greater overfill height. The effect that the backfill stiffness has on deflection is most notable for the high overfill. For lower stiffness arches with high overfill, the effect that the backfill stiffness and span has on deflections is much greater than for higher stiffness arches.

Since some of the deflections recorded in this study were of sufficient magnitude to induce flexural cracks in the concrete section, it must be recognized that the actual crown deflections in the field under similar circumstances would likely be greater due to secondary effects of reduced stiffness of concrete section that accompanies the flexural cracking. For this reason, the authors recommend to perform a cracked section analysis in order to predict accurate field deflections of the crown.



Figure 6: Vertical displacement of FEM model
(20 m span, 10 m of loose overfill and 400 mm of arch thickness)

Figure 7: Crown deflection

## Internal Forces

The internal forces are non-factored forces and are presented as per linear meter of arch length. Figure 8 shows the effect of arch stiffness on the internal moment. For high overfill, the structure stiffness has a dramatic effect on the internal moment, while for low overfill, the effect is negligible. This is similar for the effect that the two different backfill types have in that, for high overfill there is a significant difference, whereas for low overfill there was negligible difference due to backfill type. Decreasing of moment by the thickness, confirms that the contribution of arches with lower stiffness in a soil-structure system is less and a good backfill is necessary in this case. The near identical moment values for an arch thickness of 200 mm regardless of overfill, show that for a low stiffness arch neither the backfill type, nor the overfill depth have much effect on the moment. This confirms the common belief that low stiffness buried arches shed their load by deforming and rely on the surrounding soil to carry the load for them through soil arching.

The axial compression graph (Figure 9) shows a very large dependence on the overfill height as one might expect and it is independent of the structure stiffness. This indicates that the axial force is depending on the backfill above the crown rather than arch stiffness. The shear graph (Figure 10) shows the same trend as the moment graph. The shear in the arch increases with increasing overfill but does so mostly for the stiffer arches. Shear forces in arches with regular thickness are not a governing case in design.

Figure 8: Maximum moment in the arch

Figure 9: Maximum axial compression in the arch

Figure 10: Maximum shear in the arch

# Conclusions

As can be seen in the graphs, the total stiffness of combined soil-structure system as measured by deflections and bending moments is strongly dependent on stiffness of the two components of the arch and the backfill. The direct relationship between internal moment and arch stiffness confirms that arches with higher stiffness attract more forces than low stiffness. However, increasing of the arch stiffness, decreases the deformation of the arch. The result shows that the effect of backfill type is more significant for a lower stiffness arch because it has less contribution to the combined soil-structure stiffness. In concrete arches the thickness of the arch is governed by limiting cracking of the section. In this case, a thicker (stiffer) element is used to satisfy service limit state (i.e. typical thickness about 2% of span). The importance of good backfill is less in arches with high stiffness like concrete arches. On the other hand, arches with low stiffness should have better backfill to compensate for structure flexibility. Based on the above summary, we feel that some practical suggestions can be offered which will be beneficial for the design and construction of buried arch structures:

* Specifying a good granular backfill around the arch has the advantage of reducing crown deflections and bending moments in the arch, particularly for arches with low stiffness.
* For applications with large spans and/or high depth of fill over the crown, selecting arches with a higher section stiffness and better backfill is recommended.

Since some of the deflections recorded in this study were of sufficient magnitude to induce flexural cracks in the concrete section, it must be recognized that actual crown deflections in the field under similar circumstances may be greater due to secondary effects of reduced stiffness of concrete section that accompanies the flexural cracking. For this reason, the authors recommend to perform a cracked section analysis in order to predict accurate field deflections of the crown.

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