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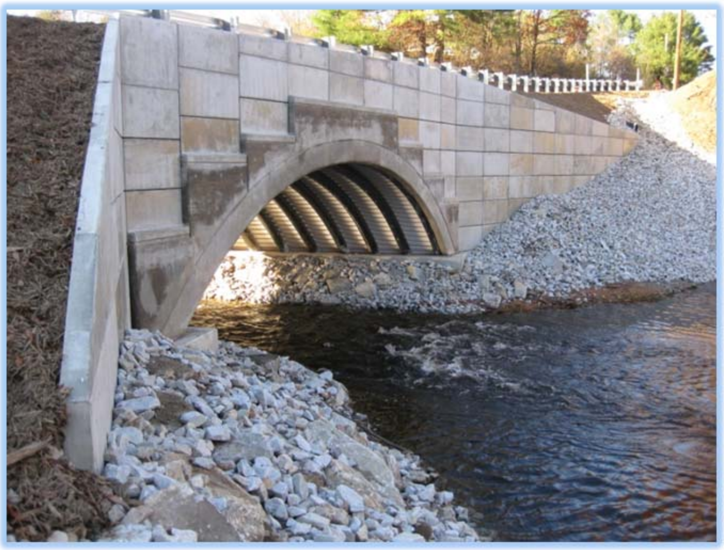

Technical Report 15-03

Bridge-in-a-Backpack™

Task 2.3: Low-Rise Arch Study with Soil-Structure Interaction and Spread Footing Foundation

Final Report – January 2015

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This report includes fulfillment of Task 2.3 of a multi-task contract to further enhance concrete filled FRP tubes, or the Bridge in a Backpack. Task 2 is an investigation of alternative shapes for the FRP tubes with varying radii. Task 2.3 explores the effects of decreasing the rise (R) of an arch for a constant span (S) with a set of different earth covers. It uses the finite element code (FE Code) by the University of Maine Advanced Structures and Composites Center (The Center) that takes into consideration soil-structure interaction (Clapp and Davids, 2011).

A parametric study on a set of four bridge geometries given by rise-to-span (R/S) ratios of 0.30, 0.25, 0.2 and 0.15 was selected. In addition, two sets of cover were investigated for each geometry, 4 ft., and 8 ft. respectively.

For a 40 ft. span bridge, decreasing the rise by 50% from 12 ft. to 6 ft. could increase the overall bridge cost by as much as 16%.

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THE UNIVERSITY OF MAINE

ADVANCED STRUCTURES & composites center

LOW-RISE ARCH STUDY WITH SOIL-STRUCTURE INTERACTION

AND SPREAD FOOTING FOUNDATION

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Low-Rise Arch Study with
Soil-Structure Interaction and Spread Footing Foundation

I. INTRODUCTION

UMaine's Advanced Structures and Composites Center has developed and licensed a hybrid composite arch bridge system. The main structural bridge elements utilize a tubular braided composite laminate that can be bent to a desired geometry. To date, minimum rise to span ratios used are about 20%.

This document is intended to explore the effects of decreasing the rise (R) of an arch for a constant span (S) with a set of different earth covers. It uses the finite element code (FE Code) by the University of Maine Advanced Structures and Composites Center (The Center) that takes into consideration soil-structure interaction (Clapp and Davids, 2011).

II. PARAMETRIC STUDY

For this study, a set of four bridge geometries given by rise-to-span (R/S) ratios of 0.30, 0.25, 0.2 and 0.15 was selected. In addition, two sets of cover were investigated for each geometry, 4 ft., and 8 ft. respectively. Table 1 summarizes the pertinent run matrix selected for this study. The bridge geometry with R/S of 0.3 was selected as a baseline and represents a non-shallow arch, and arches with R/S less than 0.15 are no longer considered arched structures but rather beam-like structures.

Table 1 –Arch Run ID Matrix for Analyses

Cover	**Span-->**	**40 ft.**	**50 ft.**	**60 ft.**
	R/S	**Run ID**	**Run ID**	**Run ID**
4 ft.	0.30	1	9	17
	0.25	2	10	18
	0.20	3	11	19
	0.15	4	12	20
8 ft.	0.30	5	13	21
	0.25	6	14	22
	0.20	7	15	23
	0.15	8	16	24

Arch variables and arch constitutive relations were kept constant.

III. RESULTS AND DISCUSSION

ARCH AND FOUNDATION FORCE EFFECTS:

Key results for the arch internal forces are summarized in the proceeding table. It is apparent that the shallower the arch, the more inefficient. Although the internal moments decrease as the arch becomes shallow, the base negative moments as shown by Max Mu (maximum factored Strength I moment) increases, and so do the shear forces (Max. Vu).

Table 2 - Summary of Factored (Strength I) Arch Forces

	Span (ft.)	Run ID	R/S	Max. Mu (kip-in)	Max. Pu (kip)	Max. Vu (kips)	M_ ratio	P_ ratio	V_ ratio
Cover = 4 ft.	40	1	0.30	400.5	55.7	8.0	1.0	1.0	1.0
		2	0.25	481.3	57.7	10.6	1.2	1.0	1.3
		3	0.20	542.3	61.3	14.2	1.4	1.1	1.8
		4	0.15	692.9	66.2	22.5	1.7	1.2	2.8
	50	9	0.30	741.4	73.5	12.0	1.0	1.0	1.0
		10	0.25	819.3	75.6	15.5	1.1	1.0	1.3
		11	0.20	888.7	78.9	19.6	1.2	1.1	1.6
		12	0.15	963.2	84.0	27.3	1.3	1.1	2.3
	60	21	0.30	1239.8	92.2	17.0	1.0	1.0	1.0
		22	0.25	1300.6	94.3	21.9	1.0	1.0	1.3
		23	0.20	1362.3	97.7	26.2	1.1	1.1	1.5
		24	0.15	1260.8	104.2	31.8	1.0	1.1	1.9
Cover = 8 ft.	40	5	0.30	310.0	74.1	6.1	1.0	1.0	1.0
		6	0.25	374.0	77.6	7.0	1.2	1.0	1.2
		7	0.20	458.5	82.5	13.5	1.5	1.1	2.2
		8	0.15	748.4	90.0	25.3	2.4	1.2	4.2
	50	13	0.30	522.3	96.9	9.2	1.0	1.0	1.0
		14	0.25	594.2	101.0	9.5	1.1	1.0	1.0
		15	0.20	716.2	105.5	18.6	1.4	1.1	2.0
		16	0.15	1027.0	113.5	33.4	2.0	1.2	3.6
	60	25	0.30	896.6	112.1	13.4	1.0	1.0	1.0
		26	0.25	976.9	125.7	13.9	1.1	1.1	1.0
		27	0.20	1084.4	130.8	23.4	1.2	1.2	1.7
		28	0.15	1309.0	139.9	38.0	1.5	1.2	2.8

The effect is worse the smaller the arch span. It is interesting to note that as long as the R/S ratio is greater than 0.15, the effect is worse for the 4 ft. cover than for the 8 ft. cover, but for R/S =

0.15, the opposite takes place. This is likely due to the soil dead load effect where this flat arch is starting to behave more like a beam.

Table 3 summarizes the service reaction forces at the top of the foundation. The reaction forces have the same trend as in the case of arch internal forces.

Table 3 – Summary of Service Reaction

	span (ft.)	Run ID	Min Ms (kip-in)	Max Ps (kip)	Max Vs (kips)	M_ ratio	P_ ratio	V_ ratio
Cover = 4 ft.	40	1	-264.85	75.8	42.2	1.0	1.0	1.00
		2	-317.05	71.9	53.6	1.2	0.9	1.27
		3	-356.57	67.6	65.3	1.3	0.9	1.56
		4	-466.47	63.1	78.8	1.8	0.8	1.87
	50	11	-497.23	101.0	54.2	1.0	1.0	1.00
		12	-554.56	95.2	68.5	1.1	0.9	1.26
		13	-599.64	88.7	83.8	1.2	0.9	1.55
		14	-659.95	81.7	100.1	1.3	0.8	1.85
	60	21	-855.29	129.1	66.9	1.0	1.0	1.00
		22	-907.57	120.5	84.3	1.1	0.9	1.26
		23	-941.49	111.3	103.5	1.1	0.9	1.63
		24	-889.07	101.4	125.2	1.0	0.8	2.02
Cover = 8 ft.	40	5	-201.09	102.6	60.5	1.0	1.0	1.00
		6	-249.43	98.5	77.0	1.2	1.0	1.27
		7	-318.21	94.0	90.9	1.6	0.9	1.50
		8	-529.16	89.2	111.7	2.6	0.9	1.84
	50	15	-353.47	134.7	77.1	1.0	1.0	1.00
		16	-414.29	128.7	97.3	1.2	1.0	1.29
		17	-506.56	122.1	115.7	1.4	0.9	1.56
		18	-736.42	114.8	140.6	2.1	0.9	1.91
	60	25	-613.15	170.2	95.2	1.0	1.0	1.00
		26	-685.17	161.2	119.7	1.1	0.9	1.27
		27	-778.74	151.7	143.4	1.3	0.9	1.54
		28	-949.19	141.7	173.6	1.5	0.8	1.90

FOUNDATION FOOTING MOVEMENT

All arches considered in this study where founded on 4’x4’ continuous spread footings for simplicity. Shallow arches have larger foundation thrust, thus engaging the footing passive earth pressure. Depending on foundation/soil parameters, a shallower arch can potentially result in horizontal footing movement. This movement is highly dependent on the friction coefficient assumed at the foundation base, which for this study was set to 0.6.

For all 24 runs considered in this study, arches with R/S greater than 0.2 did not results in foundation movement regardless of the arch span or soil cover. However, Table 4 summarizes the horizontal movement results for the two shallowest arches (R/S of 0.2 and 0.15) at each reaction point. This means that the total bridge movement is twice the values shown in the table, so that for run #4, the bridge total lateral longitudinal movement is 0.44 in. It is apparent that as the span increases, the thrust forces increases, thus increasing the horizontal movement. Note that the horizontal movement increases by a factor of about 4 when the arch rise is decreased from 20% of the span to 15% of the span.

Table 4 - Max. Horizontal Foundation Deflections at each end

	span (ft.)	Run ID	Span (ft.)	Self Weight (in.)	Earth Fill (in.)	Total DL + LL (in.)
R/S = 0.20	4 ft.	3	40	0.000	0.012	0.050
		11	50	0.000	0.039	0.085
		23	60	0.000	0.084	0.140
	8 ft.	7	40	0.000	0.055	0.075
		15	50	0.000	0.113	0.147
		27	60	0.000	0.196	0.236
R/S = 0.15	4 ft.	4	40	0.000	0.125	0.220
		12	50	0.000	0.234	0.350
		24	60	0.027	0.396	0.562
	8 ft.	8	40	0.000	0.233	0.291
		16	50	0.000	0.411	0.509
		28	60	0.027	0.662	0.841

One more run was done for Run ID #24 with a base friction coefficient of 0.3 versus 0.6. The resulting lateral movement from DL and LL was 1.230 in., or a bit over twice as much as the one shown in Table 4.

Although not part of this study, the effect on the concrete filled FRP tube arches that undergo lateral movement (spreading) at the base should be investigated.

IV. CASE STUDY

It is apparent that a shallower arch will incur additional cost due to the increase of its internal moments and shears, as well as an increase in foundation thrust. Two 40 ft. (480 in.) span arches are compared in terms of potential increase in overall bridge cost as shown in Figure 1. That is, the arch with a 6 ft. rise (R/S of 0.15 -- run #4) is compared to the more efficient arch with a 12 ft. rise (R/S of 0.3 -- run #1). The arch and foundation moment, axial and shear forces, as well as the foundation movement for run #4 are highlighted in Tables 4 through 6 for ease of reference.

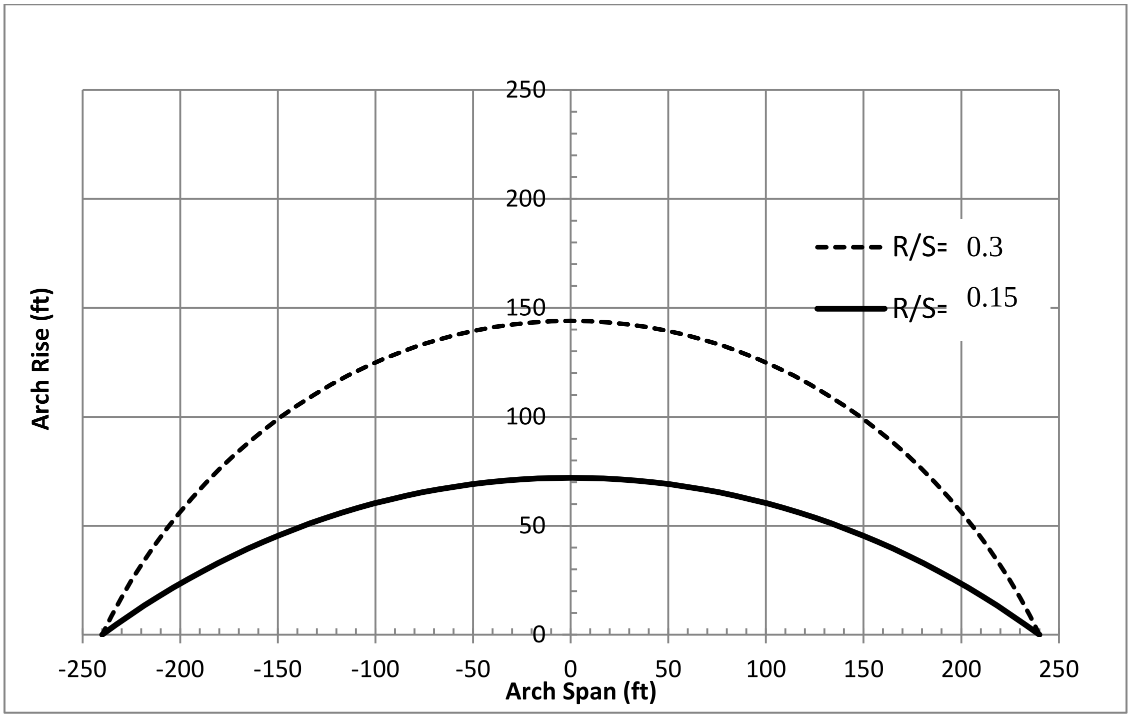

Figure 1 - Arch Geometries for Case Study

When calculating the structure foundations, the following assumptions have been made.

1. Foundation height = 4 ft.
2. Angle of soil friction = 30 degrees
3. Coefficient of base friction = tan (soil angle)=0.58
4. Passive pressure coefficient = 2.0 (used for sliding calculations)
5. At rest pressure coefficient = 0.45 (used for overturning calculations)
6. Allowable bearing pressure coefficient = 10 Tons/sf

Table 5 summarizes the increase in spread footing width that would satisfy design requirements per AASHTO based on LRFD - Strength I design. It is obvious that decreasing the arch rise for a 40 ft. span from 12 ft. to 6 ft. while keeping the same earth cover has a very large impact on the bridge foundations, to the point that a simple spread footing might no longer be considered as a design solution. For a 4 ft. high footing, the footing width would increase from 5.75 ft. (run#1) to 15.5 ft. (run #4) and for a 40 ft. span bridge, this would not be a viable solution. It is likely that a better solution would be to add a shear key to the foundation to resist lateral movement. However, this is also an expensive proposition given that the footing width is still over twice that of run #1.

Table 5 – Spread Footing Designed for Case Study Comparison

Run ID	Bridge Rise, R	Footing Width , B	Footing Height, H	Footing X-section BxH	Vol_ ratio
#1	12 ft.	5.75 ft.	4 ft.	23 sf	2.69
#4	6 ft.	15.5 ft.	4 ft.	62 sf	
#1	12 ft.	5.75 ft.	4 ft.	23 sf	2.17
#4	6 ft.	12 ft.	4 ft. + 2ft shear key	50 sf	

An attempt to estimate the cost significance of shallow arches is shown in Table 6. The incremental cost (**Δ _cost)** is based on a spread footing foundation and the fact that the critical arch failure load is due to axial bending interaction. Additional construction costs, such as additional excavation costs or a change in foundation type have not been considered in this cost analysis. The base total bridge cost (including demolition, wingwalls, foundation costs, etc..) used for comparison has been assumed at $300/sf for the low end, and $500/sf for the high end, calculated as total construction bridge cost, divided by arch center-to-center span, and divided by total bridge width.

Table 6 - Incremental Cost for Lowrise Arch Bridge Comparison

	Δ _cost_ Low (%)	**Δ _cost_ High (%)**
FRP Arch	+5.6	+9.3
Deck	-0.3	-0.5
Foundation	+4.3	+7.2
	+9.6	**+16.0**

It is apparent that the Foundation and FRP arch cost is similar in magnitude. For a 40 ft. span bridge, decreasing the rise by 50% from 12 ft. to 6 ft. could increase the overall bridge cost by as much as 16%.

V. SUMMARY AND CONCLUSION

The design feasibility low-rise arches have been studied for three bridges with rise to span ratios varying from 0.3 to 0.15. The previously developed code package was used for all the numerical runs to determine the trends. Arch forces as well as foundation thrusts increased. A case study for the 40 ft. span bridges was used to estimate the relative cost incurred from decreasing the bridge rise by 50%, and the results suggest that they are in the order of 9 to 16 %.

Future work for low rise arches should include the effect on the concrete filled FRP tube arches that undergo lateral movement (spreading) at the base.

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