EMULATIVE DESIGN OF PRECAST CONCRETE CANTILEVER RETAINING WALL SYSTEM FOR THE I-196 / BALDWIN INTERCHANGE IN GRAND RAPIDS

Ihab S. Darwish, Ph.D, P.E., S.E., Alfred Benesch & Co., Lansing, MI
Ziad A. Hanna, MASC, P.E., Alfred Benesch & Co., Lansing, MI

ABSTRACT

In order to reduce construction schedule and improve work zone safety, the Michigan Department of Transportation has pursued an innovative precast retaining wall system that was designed using "emulative design" method. In this method, the precast walls are designed and detailed like cast-in-place walls. The retaining walls are part of $40 million project, which included the design of 6,762 ft of new retaining wall. The retaining walls are along eastbound and westbound I-196, and along a new constructed ramp. The retaining walls are precast cantilever type walls. The wall system consisted of 5000 psi precast footing and stem segments. The length of each segment is limited to 12 feet to facilitate transportation. Full moment connection is provided between the stem and the footing through grout-filled mechanical splicers. Vertical joints between precast elements utilized shear keys, which are filled with non-shrink high strength grout. Retaining wall heights ranged from 3 feet to 26 feet maximum. The precast footings are erected on 3" thick cast-in-place sub-footing. In order to ensure a full contact, 3" gap is provided between the bottom of the precast footing and the sub-footing., which is filled with high strength flowable grout. Precast retaining wall system would save 4 months from the construction schedule.

Keywords: Emulative, Precast, Retaining Walls, Cantilever, Accelerated Construction

INTRODUCTION

The use of conventional cast-in-place reinforced concrete retaining walls with associated curing requirements can easily consume considerable amount of time on a project. Prefabrication offers exceptional advantages for retaining walls construction, particularly for removing reinforcement installment and concrete pour from the critical path of the construction schedule. Prefabrication also minimizes disruption to traffic, improves worker safety, and reduces impact to the environment.

PROJECT DESCRIPTION

The I-196 / Baldwin Interchange project involved 2.8 miles of reconstruction and major rehabilitation of I-196. The project included two new ramps from I-196 to Baldwin Street. The project also involved the replacement and lengthening of two bridges that carry I-196 over CSX railroads, the replacement of a bridge over the Buck Creek, and the construction of a new ramp structure, which carries the traffic from Baldwin Street to the eastbound of I-196. A part of I-196 is located in a flood plain and wetlands. The new ramps and profile improvements required 6,762 feet long (160,240 square feet) of retaining walls to minimize environmental impacts and eliminate the need for right-of-way. The walls are located along the eastbound and westbound of I-196, along Baldwin Street new ramp, and along Chicago Drive (see Figure 1). Some of the retaining walls are located between the new reconstructed bridges. Walls A, C, G, K, and L are also located in the flood plain areas.

Table 1. Retaining Walls Information

			Wall Height	
Wall	**Length (*ft*)**	**Area (ft^2)**	**(Minimum)**	**(Maximum)**
A	1,254	36,901	3'-2"	23'-10"
B	1,023	19,696	3'-8"	10'-3"
C	655	15,516	5'-5"	26'-2"
D	268	3,305	3'-8"	5'-6"
H	207	4,876	8'-6"	10'-11"
M	548	8,852	3'-9"	12'-1"
E	341	7,474	7'-10"	9'-2"
J	353	7,886	8'-3"	9'-3"
F	328	5,860	8'-5"	11'-3"
G	345	8,813	8'-9"	22'-9"
K	408	14,527	12'-5"	24'-0"
L	1,032	26,534	9'-9"	18'-3"
Total	**6,762**	**160,240**	**3'-2"**	**26'-2"**

The construction duration of the project is two years. One of the project requirements is to complete the construction of westbound I-196 during the first construction season, while the eastbound I-196 and the Baldwin Street ramp to be constructed during the second construction season.

During the first construction season, the westbound of I-196 will be constructed along with the bridges which carry westbound I-196 traffic over the CSX railroad and Buck Creek, and retaining walls A, B, C, D, H, and M. These walls have a total length of 3,995 feet and a total area of 89,146 square feet. The rest of the project will be constructed during the second construction season.

During the design phase of the project, several retaining walls options were investigated based on construction schedule, cost, and feasibility. Retaining walls investigated included MSE walls, cast-in-place concrete cantilever retaining walls, sheet piling with concrete face, and soldier pile and lagging with a concrete face. MSE walls were not feasible for walls located in the flood plain because of the concern with flood plain erosion that may undermine the reinforced fill zone or any supporting footing. Steel sheet piling could not be used for Walls A, B, and L due to length of these walls and the possibility of creating a "cutoff" wall to the natural groundwater flow to the Buck Creek and the Grand River located close to the project site. Soldier pile and lagging could be used at several locations where the walls are short. Initially, it was determined that the cast-in-place concrete cantilever retaining walls are the most feasible solution for all the walls. However, further looking at the construction schedule, there was a concern that this type of wall can be constructed within the project schedule.

DEVELOPMENT OF THE NEW PRECAST WALL SYSTEM

In order to reduce the construction schedule, it was determined that a precast retaining wall system would offer great advantages by removing the fabrication of the walls from the construction schedule. The desire was to develop a new precast wall system that would emulate the behavior and exceed the performance of the CIP retaining wall system. The main objectives in the development of the new system were the following:

- Provide a total precast system that can be constructed within the project schedule.
- Minimize any additional cost associated with the fabrication and erection of the new system.
- Maximize the number of pre-casters capable of fabricating the new wall s.
- Minimize any difficulties associated with shipping and handling of the precast segments.
- Provide appropriate tolerances for fabrication and erection.

The precast cantilever wall system developed (see Figure 2) consists of precast footing segments and precast stem segments. The precast footings are bearing on 3 ½" thick cast-in-place concrete subfooting. The subfooting has a specified concrete strength of 3,000 psi. The subfooting is used to ensure the full contact between the precast footings and the soil through the subfooting. Full moment connection is provided between the wall stem

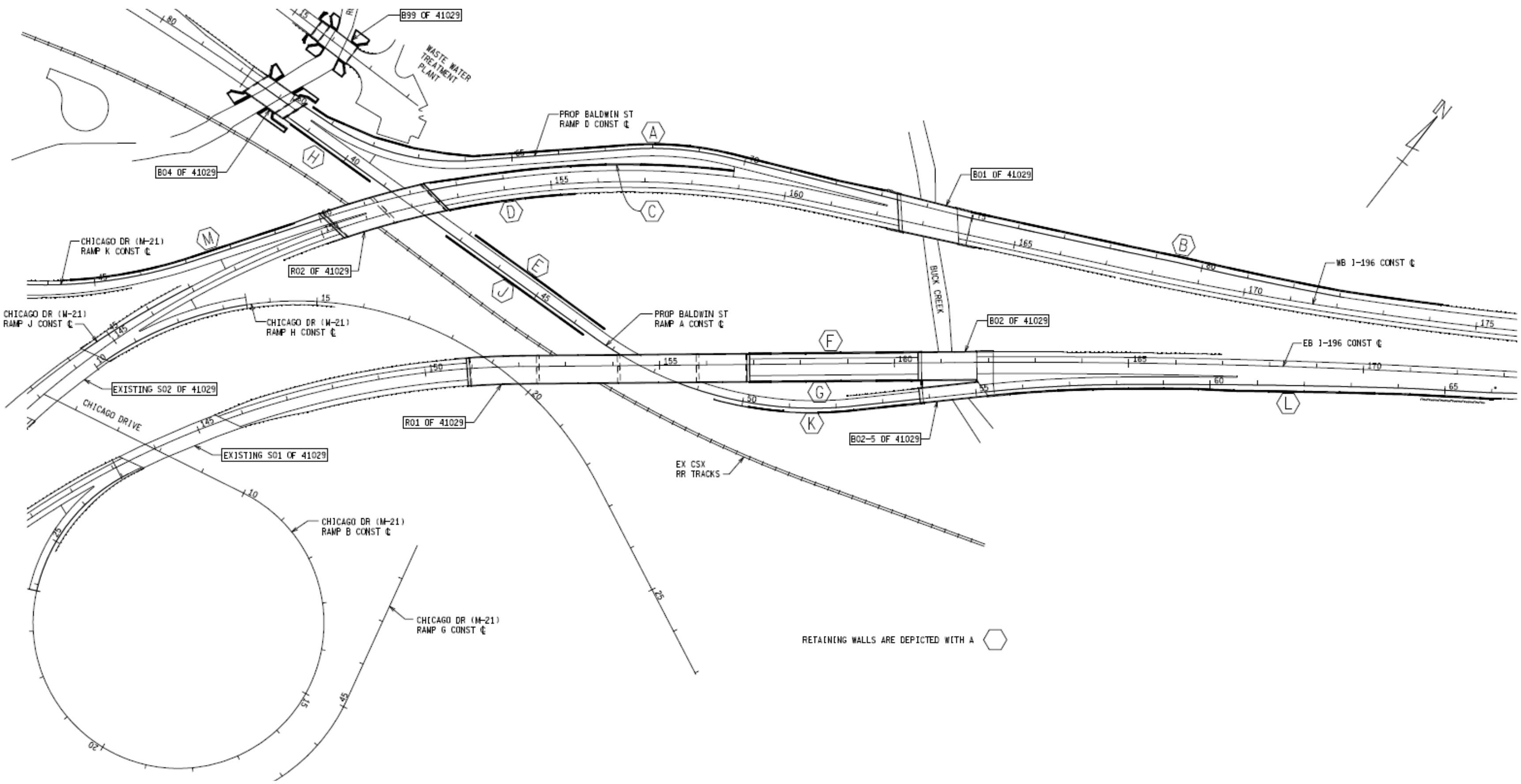

Figure 1. Retaining Walls Layout

and the footing through grout-filled mechanical splicers (see Figure 3). Vertical joints were provided between precast elements to utilize shear keys, which are filled with non-shrink high strength grout.

Cast-in-place concrete barriers are connected to the top of the precast wall stems. A 3" minimum grout bed is provided between the bottom of the precast footings and the concrete subfooting, and between the top of the precast footings and the precast wall stems. Simulated masonry stone was installed on the front face of the precast stem segments for aesthetic. The stem heights varied from 3'-2" to 25'-2" maximum. The precast wall stem thickness and the precast footing thickness are 2 feet. In order to minimize the size of the precast segments, structure backfill with total unit weight of 120 psf was used behind the stems up to 21 feet high. However, for stem heights exceeding 21 feet, light weight slag aggregate with total unit weight of 80 psf was used. The wall system is designed according to AASHTO LFD Specifications, 17th Edition. Self-consolidated concrete with compressive strength of 5,000 psi was used in for the precast footings and wall stems. The allowable soil bearing pressure under the precast footings used in the design is 3,500 psf.

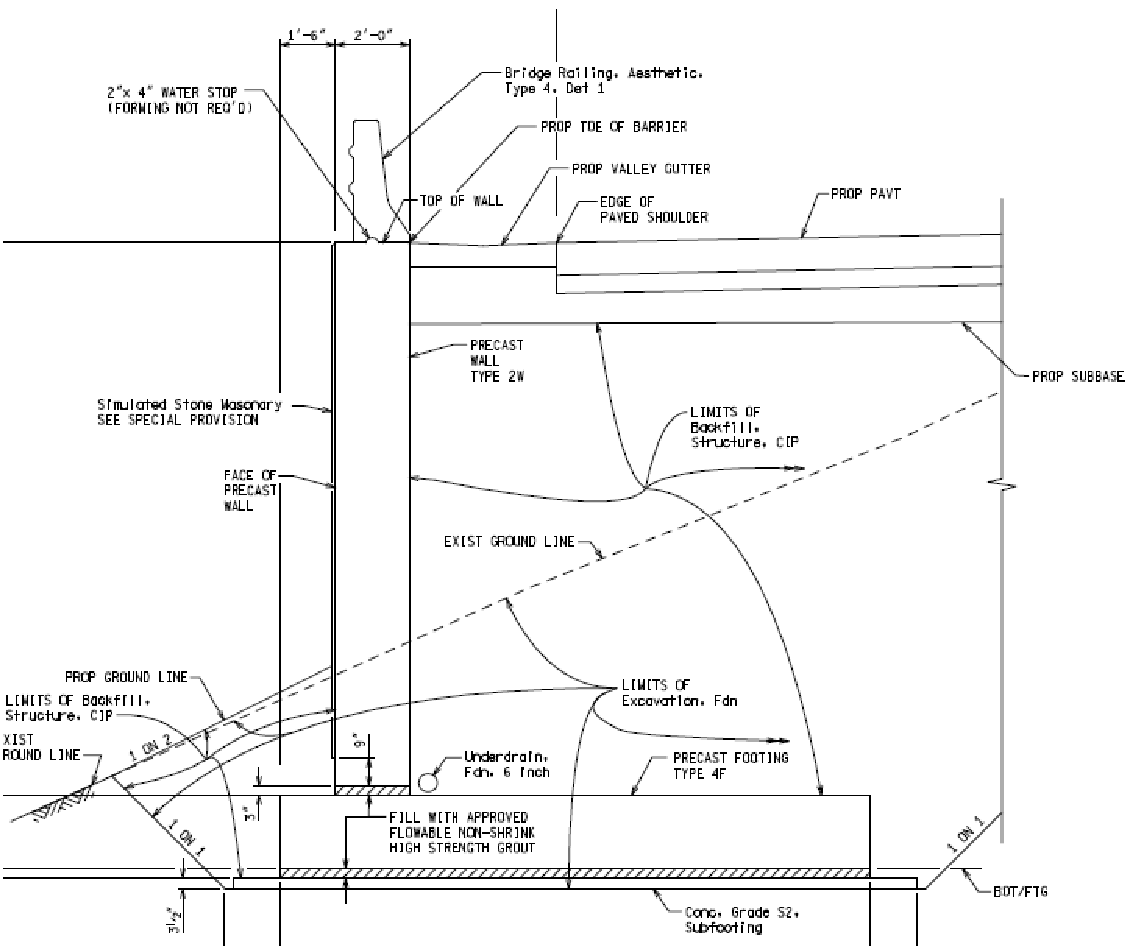

Figure 2. Precast Cantilever Retaining Wall System

The precast wall system was designed using "emulative design" method. In this method, the precast walls are designed and detailed like cast-in-place cantilever retaining walls.

In order to reduce fabrication cost, facilitate shipping and handling, and minimize the number of precast segments, several local pre-casters in Michigan were contacted. The goal was to solicit their input for the maximum weight and size of the precast segment that they could handle in their casting yard and transport to the job site. Based on the pre-casters recommendations, the weight of the precast segment was limited to approximately 40 tons while the length of each precast footing and precast stem is limited to 12 feet to facilitate transportation. To minimize the number of precast segments, and limit the maximum weight of the precast segment to 40 tons, standard 2'-0" precast stem and footing thicknesses were used. The total number of precast footing segments or precast stem segments for this project is 566 segments (1,132 total precast footings and stem segments).

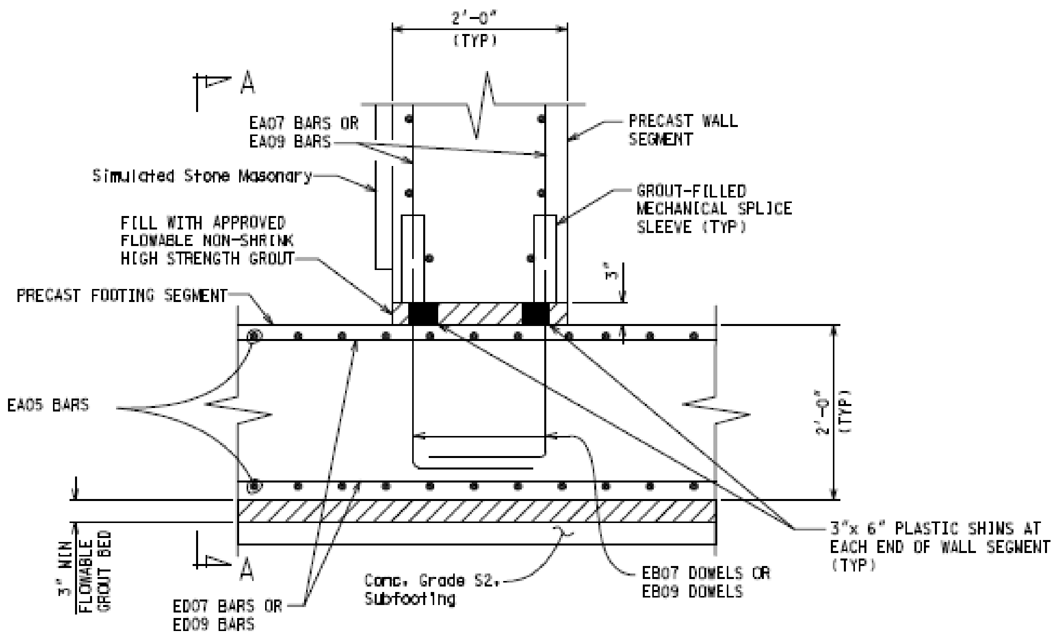

Figure 3. Typical Wall Segment-to-Footing Segment Connection

The following are the details of each component of the innovative precast wall system:

PRECAST FOOTING SEGMENTS

There are 24 different footing segment types in this project. Types 1 through 9 are rectangular shape, while Types 10 through 24 are trapezoidal shape. Trapezoidal shape footings are used at locations where the alignment of the walls is changing. All precast footings are 2' thick. The length of the footing segments is limited to 12' maximum. The width of the footing segments vary from 8'-6" minimum to 19'-0" maximum. Several trapezoidal footing segments have lengths exceeded 12'-0". However, in this case, the width of the segment is limited to 12' maximum. Typical 1" x 8" shear key is used at each side of the precast footing to ensure shear transfer between the adjacent precast footings. Also, 4” diameter block-out is provided at each corner of the footing to facilitate pouring the grout between the bottom of the precast footings and the subfooting. Templates were used during fabrication to ensure proper fit between the stem and footing segments.

PRECAST FOOTING BLOCK SEGMENTS

Precast footing block segments are used at locations where the bottom of footing elevations change and stepping of the footings are required. In this case, one precast footing segment is bearing on the top of the block segment while the adjacent precast footing segment is placed next to the block segment (see Figure 5). There are 6 different block segment types in this project. All footing blocks are rectangular shape. The footing block segment is 2’-6” thick and 4’-0” long. The width of the footing block segments vary from 8’-6” minimum to 19’-0” maximum. Typical 1” x 10” shear key is used at the side of the footing block segment adjacent to the precast footing segment.

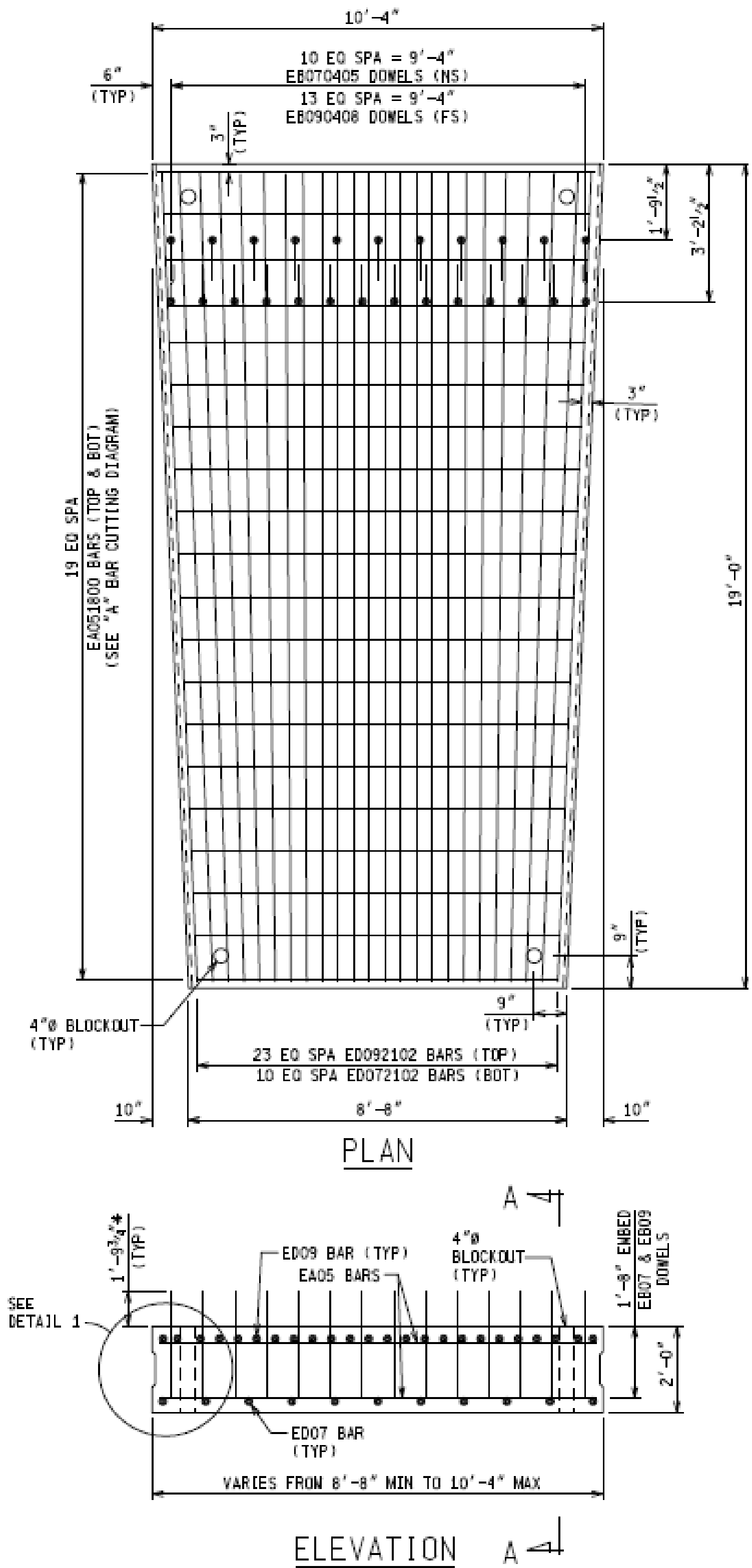

Figure 4. Trapezoidal Precast Footing Segment, Type 16 F

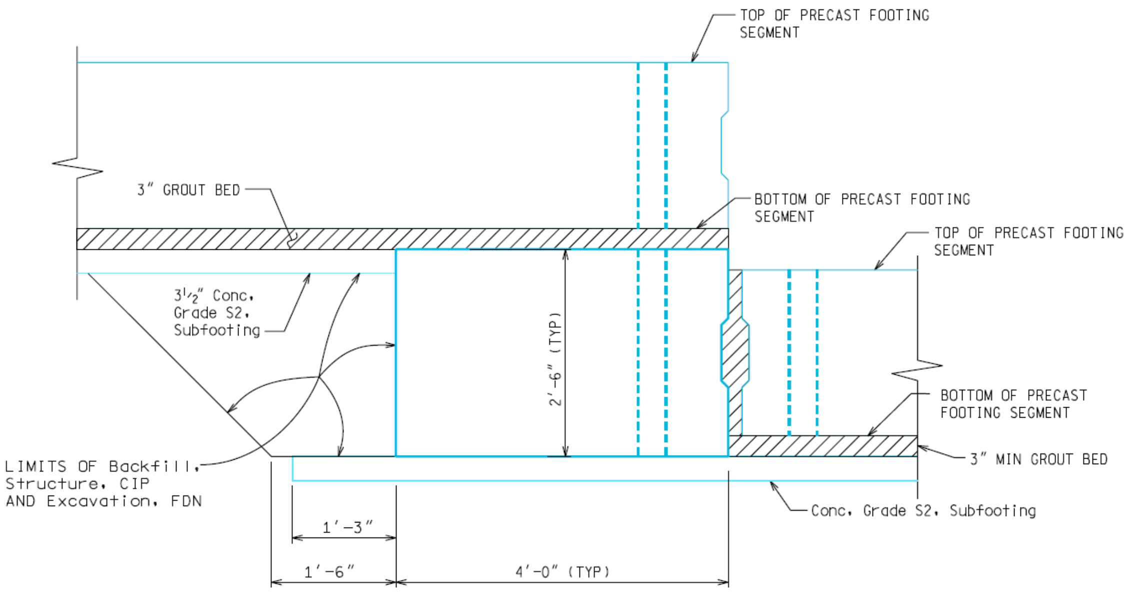

Figure 5. Precast Footing Block Elevation

PRECAST WALL STEM SEGMENTS

The precast wall stem segments are divided into four different types. The segment types are divided based on the length of the segment and the size and spacing of the main vertical reinforcement. The following Table compares the different types of wall stem segments used in the project:

Table 2. Precast Stem Segment Types

Stem Type	Length	Minimum Height	Maximum Height	Size & Spacing (Tension Steel)	Size & Spacing (Compression Steel)	Total Number of Segments
1 W	12'-0"	3'-2"	12'-8"	# 7 @ 11"	# 7 @ 11"	366
2 W	12'-0"	9'-2"	15'-0"	# 7 @ 8.5"	# 7 @ 11"	31
3 W	10'-0"	12'-6"	24'-0"	# 9 @ 8.5"	# 7 @ 11"	153
4 W	10'-0"	23'-0"	26'-0"	# 9 @ 6.5"	# 7 @ 11"	16

The overlap in heights between different segment types is due to the different design parameters and criteria used in the design of walls. Several walls are located in the flood plain and these walls are designed for the 100-year flood event. Some of the segments are fabricated with 7" diameter holes in the stem to accommodate underground utilities. Typical 1" x 8" shear key is used at each side of the precast footing to ensure shear transfer between the adjacent precast footings.

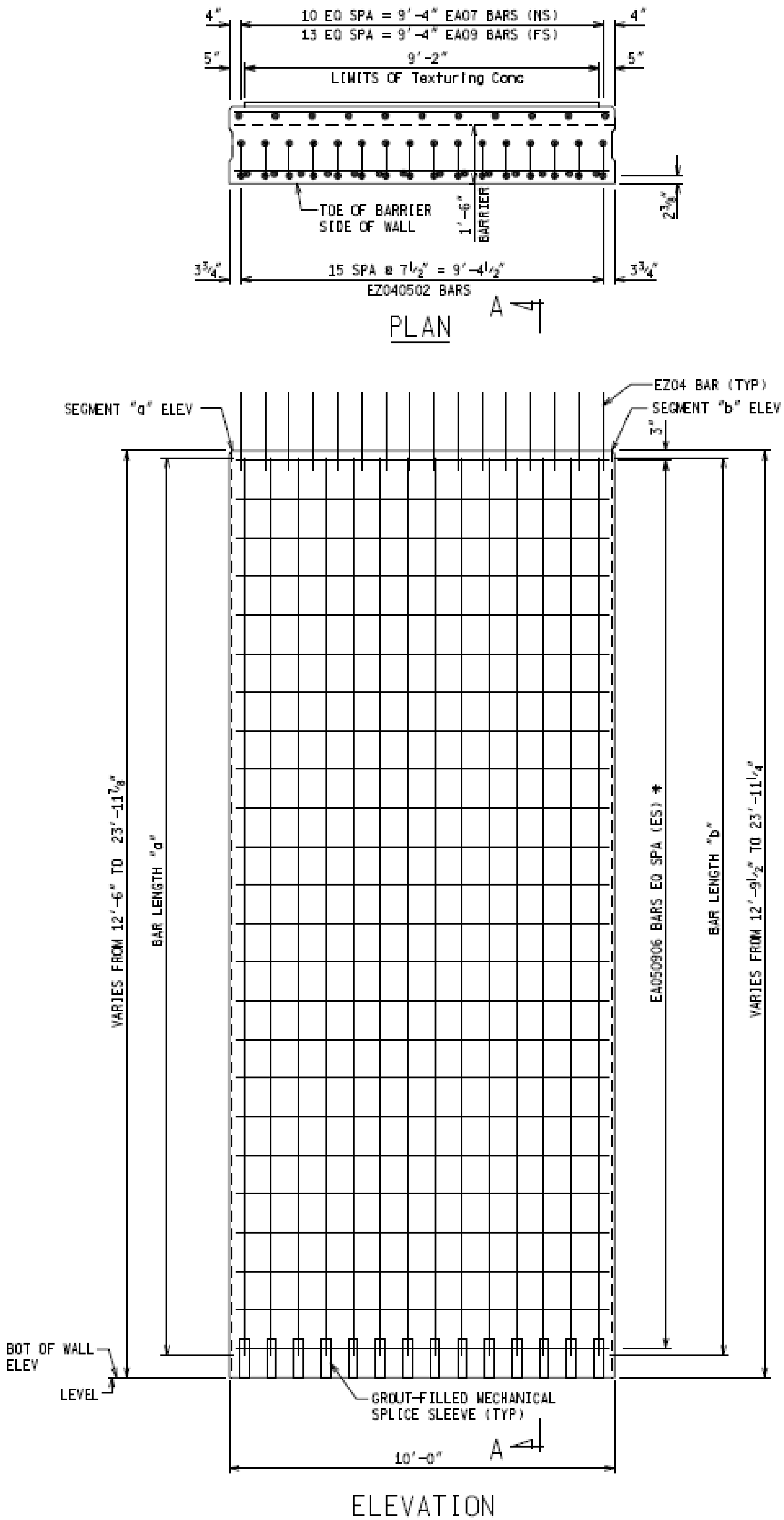

Figure 6. Precast Wall Stem Segment, Type 3 W

The slope of the top of the retaining walls in this project represented a challenge during the development of the stem segments. The goal was to standardize the element sizes of the segments to increase production and reduce fabrication costs. Several pre-casters were contacted and all indicated that they can easily adjust their forms to accommodate the sloping of the top of the stem segments without impacting production. This resulted in a total of 566 stem segments with each segment has a different height than the adjacent segment. Simulated masonry stone formliners, for concrete texturing, was attached to each stem segment and poured with the segment.

The pre-caster was only allowed to move any precast segment for storage or shipping after the curing has been completed and after a flexural strength of 450 psi (or 3600 psi compression) has been achieved.

GROUT FILLED MECHANICAL SPLICE

The moment connection between the precast footing and precast wall stem was provided by grouted mechanical splicers. The splicer consists of cylindrical-shaped steel sleeve filled with high strength non-shrink grout. Splicers for # 7 and # 9 bars were used in this project. The splicers were cast into the front and back side of the precast stem segments and held firmly in place in the forms during concrete pouring by means of a sleeve setter. The splicers used by the contractor have an integral rebar stop in the mid-portion, which assures the specified embedment of the rebar into the sleeve. Each splicer has two grout tubes for pumping the grout and completing the connection. All mechanical splicers were epoxy coated and required to develop 125 % of the specified yield strength of the spliced bar.

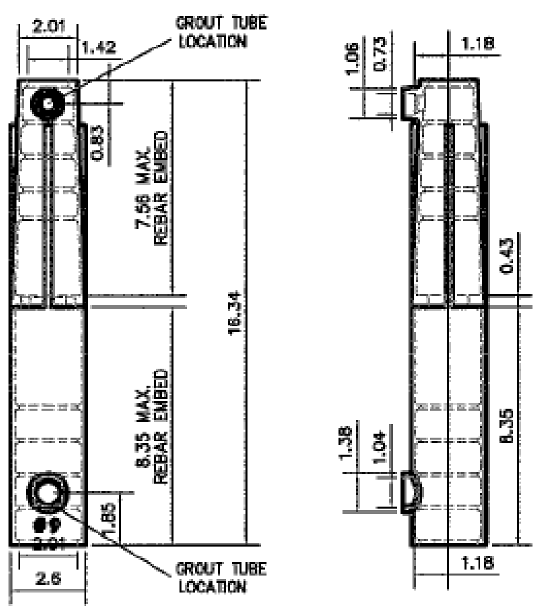

Figure 7. Grout Filled Mechanical Splicer for # 9 bars

SHEAR KEYS AND GROUT BED

Vertical joints between precast elements are used to transfer shear between the adjacent segments and provide adequate fabrication and construction tolerances. The shear keys are grouted using high strength non-shrink grout. In order to improve the bond between the adjacent member and grout, the contractor was asked to clean the shear keys thoroughly by pressure washing and wetting the perimeter of the shear keys prior to grout placement. The minimum gap between the stem segments or the footing segments is 2", which was adequate and helped ensuring that the grout completely filled the gap between the segments. The 3" thickness grout bed between the precast footing and subfooting and between the precast footing and the precast wall stem is used to provide a sound bearing surface and to ensure full contact between the different surfaces. The grout specified is a non-shrink, high strength, flowable, cementitious grout with a minimum design compressive strength of 5,000 psi.

Joint waterproofing membrane was placed over the vertical gap between the precast stem segments on the side of the soil only. In addition, 2" vertical expansion joints were provided between the stem segments at approximately 85 feet interval. In this case, geotextile liners were placed over the expansion joints between the wall stems on the soil side. At expansion joint locations in the wall, 1" expansion joint was provided between the barriers over the wall.

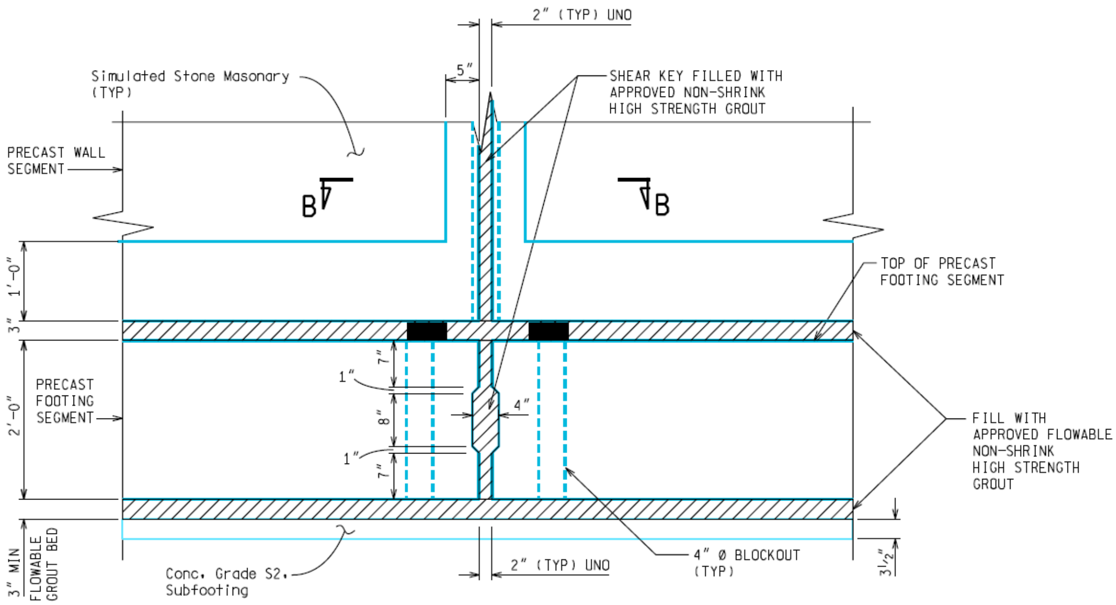

Figure 8. Vertical Shear Keys Detail

ROUGHENING OF EXPOSED SURFACES

The bottom of the precast footing segments, the top contact surface of the footing with the precast stem segments, in addition to the bottom surface of the precast stem segments are all roughened to ensure shear transfer between the different surfaces. In order to roughen the surfaces, surface set retarders are painted onto the form in the desired location prior to casting the concrete. After form removal, the retarder is pressure washed from the concrete surface resulting in a roughened exposed aggregate finish. Sandblasting is done manually after the product is stripped.

ERECTION PROCEDURE

The erection of the precast segments was simple. The procedure consisted of the following steps:

1. The 3 ½" thick cast-in-place subfooting was first poured to the elevation shown on contract plans. The top surface of the subfooting was roughened before the concrete gained strength. The contractor was allowed to place the crane on the top of the subfooting to erect the precast segments.

2. After the subfooting gained at least 50% of the specified concrete strength, the top surface of the subfooting was cleaned with high pressure water and the precast footing segments were then erected on top of 3" x 6" plastic shim plate placed under each corner of the precast footing. For some retaining walls where the mobilization of the crane is limited, the contractor was allowed to place the crane on the top of the subfooting to erect the precast footing segments only after the subfooting gained the specified concrete strength.

Figure 9. Erection of the Precast Footing Segments

3. After all the precast footing segments for the wall under construction were erected in place, the contractor pumped grout under the precast footing segments and between the vertical shear keys. Forms anchored to the precast footings were used to seal the vertical joints between the precast footing segments. The 4" diameter block outs are used to pump the grout under the precast footings.

Figure 10. Grouting Operation for Footing Shear Keys

Figure 11. Erected Footing Segments of Wall A after Grouting

4. The precast stem segments were then delivered to the site and erected in place. During erection, each stem segment was set into position on the corresponding footing segment where dowel bars projecting. The splice sleeves embedded in the precast stem segment received those dowel bars. Shim plates were placed under the precast stem segments to provide for the 3" gap between the stem segments and

footing segments. For some retaining walls where the mobilization of the crane is limited, the contractor was allowed to place the crane on the top of the precast footings to erect the precast stem segments. In this case, the grout between the footing shear keys and under the precast footings should attain the specified compressive strength before the crane is placed on top of the precast footings. For shorter walls, the contractor was allowed to erect the stem segments before grouting the shear keys or grouting under the precast footings.

Figure 12. Erection of Short Stem Segments

5. The precast stem segments were braced and high strength grout was pumped into the splicer grout tubes to complete the connection. The vertical shear keys between the stem segments were then grouted.

Figure 13. Bracing of Stem Segments

6. After all precast stem segments erected in place, the contractor started backfilling behind the walls. Structural backfill was placed behind the walls unless the wall height exceeded 21 feet. In this case, light weight slag aggregate was used behind the walls

Figure 14. Structural Backfill and Light Weight Slag Placed behind the Walls.

7. The concrete barriers on top of the precast stems were then poured and cured before the roadway was opened for traffic.

Figure 15. Finished Front Face of the Wall System with Aesthetic Treatment

ERECTION SCHEDULE AND CONSTRUCTION COST OF WALLS

The main reason for proposing a precast wall system is to construct the project within the construction schedule by removing the wall fabrication from the critical path of the project. One of the project requirements is to construct the westbound of I-196 along with two bridges and approximately 4,000 feet long (89,000 square feet) of retaining walls, all within one construction season. Then, the construction of eastbound I-196 and the Baldwin Street ramp to the eastbound I-196, along with two other bridges and approximately 2,800 feet long (71,000 square feet) of retaining walls will have to be completed in the second construction season. Since the retaining walls have to be constructed before the construction of I-196 and the new ramp, a cast-in-place retaining wall system was not feasible.

The contractor did not find any difficulties constructing the precast wall system. No modifications to the proposed wall system were proposed by the contractor. The contractor submitted shop drawings for each precast wall stem segment (566 segments) and for the 24 different precast footing types. The erection rate for precast footing segments was 20 precast footing segments per day (12 feet long segments). Similarly, the contractor was able to erect 20 precast stem segments per day. For Wall A (1,254 feet long), the contractor was able to erect the precast footings and precast stems, including grouting in 10 days only. Wall A is considered the most difficult wall to erect in this project because of many alignment changes along the wall. In addition, Wall A also has many tall and heavy segments.

Figure 16. Curved Alignment of Wall A

In general, implementing a new technology in a project introduces risk to the contractor, which then affects the price of the project. However, for this project, removing the construction of the retaining walls form the critical path of the project was needed in order to complete the construction of the project within schedule. This justified the use of the new precast wall system on this project. The Department felt that if a cast-in-place wall system is proposed to the contractor, an aggressive construction schedule will be required, which also introduces risk to the contractor and affect the price of the project. In order to construct the cast-in-place walls, the contractor may require mobilizing several crews working in parallel to meet the construction schedule.

Table 3 lists the cost of the precast wall components as bided by contractors. The table does not include bid items, which are independent on the type of wall system to be used. These items include structural backfill, light weight slag, and the cast-in-place subfooting. The three items would have to be used whether the wall system is precast or cast-in-place. MDOT requires cast-in-place subfooting for footings placed below the ground water table, which was encountered in this project. There are four contractors submitted their bids for this job. Contractor No. 1 was the lowest bidder for the entire job. Reinforcing steel, and all other embedded components of the precast concrete elements (except grout-filled mechanical splice sleeves) are included in pay item "Precast, Concrete Segment, Furn & Fab". The pay item "Precast, Concrete Segment, Erect" includes erection of the segments, equipment required to erect the segments, joint fillers, in addition to the cost of grouting material of the shear keyways and footing beds, and labor cost of all grouting operations.

Table 3. Precast Walls Cost per Contractor

Pay Item	Unit	Contractor No. 1	Contractor No. 2	Contractor No. 3	Contractor No. 4	Avg.
Precast, Concrete Segment, , Furn & Fab	Sft	$27.64	$25.00	$36.59	$27.25	$29.12
Precast, Concrete Segment, Erect	Sft	$4.00	$6.00	$3.16	$5.00	$4.54
Grout Filled Mechanical Splice Sleeve, # 7	Ea	$1.00	$6.00	$0.15	$10.00	$4.29
Grout Filled Mechanical Splice Sleeve, # 9	Ea	$1.00	$7.00	$0.25	$10.00	$4.56

Table 4 compares engineer's estimated unit price to the average bid price of the four contractors. The engineer's estimate compares well with the average bid prices except for the cost of the mechanical splice sleeves. However, it seems that contractors included their bid prices for the mechanical splice sleeves with the fabrication of the precast walls.

Table 4. Comparison between Engineer's Estimated Unit Price and Average Contractors' Unit Bid Price

Pay Item	Quantity	Unit	Engineer's Unit Price	Average Bid Price
Precast, Concrete Segment, Erect	160,240	Sft	$30.78	$29.12
Precast, Concrete Segment, Furn & Fab	160,240	Sft	$4.97	$4.54
Grout Filled Mechanical Splice Sleeve, # 7	12,379	Ea	$30.00	$4.29
Grout Filled Mechanical Splice Sleeve, # 9	2,318	Ea	$40.00	$4.56

Table 5 shows the estimated cost of an equivalent cast-in-place retaining wall system. The unit prices shown are based on average bid unit prices of past projects. However, they do not reflect the risk associated with the accelerated construction schedule of this project, if a cast-in-place wall system is used.

Table 5. Cost Estimate for Cast-in-Place Retaining Wall System

Item	Quantity	Unit	Unit Price	Total Cost
Substructure Concrete	11,870	Cyd	$375.00	$4,451,111.11
Reinforcement, Epoxy Coated	1,803,730	lbs	$0.90	$1,623,357.00
			Total	**$6,074,468.11**

Table 6 is a cost comparison between the precast wall system and an equivalent cast-in-place system. The proposed precast wall system was a cost-effective solution that resulted in approximately 16 % reduction in the construction cost of the wall, and approximately 2.5 % reduction in the total construction cost of the project.

Table 6. Total Project Construction Cost Comparison

	Precast Construction			
Item	**Engineer's Estimate**	**Contractor No.1**	**Average of All Bids**	**Cast-in-Place Construction**
Total Wall Cost	**$6,192,670**	**$5,084,691**	**$5,718,128.80**	**$6,074,468.11**
Cost / SF	**$39**	**$32**	**$35.68**	**$37.91**

The low average cost of the precast wall system per square-foot of wall can be attributed to the large size of the project and the large number or precast segments. It is expected that for smaller size projects, the average cost per square-foot of wall may be higher than this project.

CONCLUSIONS

Precast concrete cantilever retaining wall system provides a cost effective and durable solution compared to cast-in-place construction. This type of system is designed and detailed similar to conventional cast-in-place cantilever retaining walls, and therefore, the performance of the system is predictable. The proposed precast system is also durable when constructed properly. Due to the ease of fabrication and erection, the proposed system provides an excellent solution for projects on aggressive construction schedule. The following are the advantages of the proposed wall system:

1. No special forms are required to fabricate the segments.
2. The segments are light and easy to transport.
3. The ease of fabrication of the precast segments provides the opportunity for small pre-casters to bid on a project, thus increasing competition.
4. The gap between the precast segments provides the contractor with adequate tolerances for the proper fit between the precast segments.
5. Ease of erection.
6. The ease of utilizing the wall system for curved alignments.
7. Speed of construction.
8. Portions of the retaining walls can be easily replaced in the future, if needed.
9. Improved work zone safety.
10. Any aesthetic feature on the walls can be easily accommodated during fabrication of the stem segments.

While not precluding a contractor's decision to use cast-in-place or other precast alternatives, benesch is pursuing a patent for this system.

Figure 17. The Precast Wall System after Completion