Seattle Sound Transit Central Link Tukwila Segment – C755

Design Memorandum

Drilled Shaft Steel Casing

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REVISION: 0

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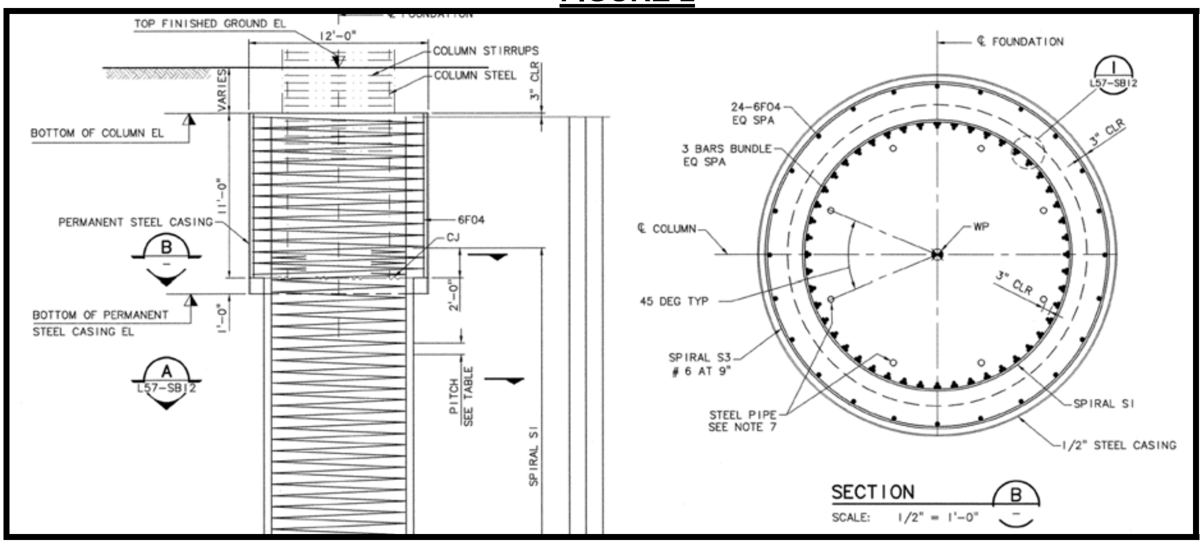
OVERVIEW

The foundations for the C755 section of the Sound Transit Central Link project primarily consist of large diameter, single concrete shafts. The foundations are typically 10’ in diameter, with some 8’ diameter shafts where the loading is lighter or the soil conditions are better.

For the drilled shafts on the C755 contract, a 12’ long, ½” thick piece of steel casing was used a transitional section between the column and drilled shaft. The casing was typically 10’ in diameter to match the drilled shaft, but occasionally a 12’ diameter was used where an oversized dimension was needed to accommodate a larger column. The drilled shaft is initially cast 11’ short of the top to allow a secondary pour that includes the column reinforcement above. The 12’ casing is shown below as an example.

FIGURE 1

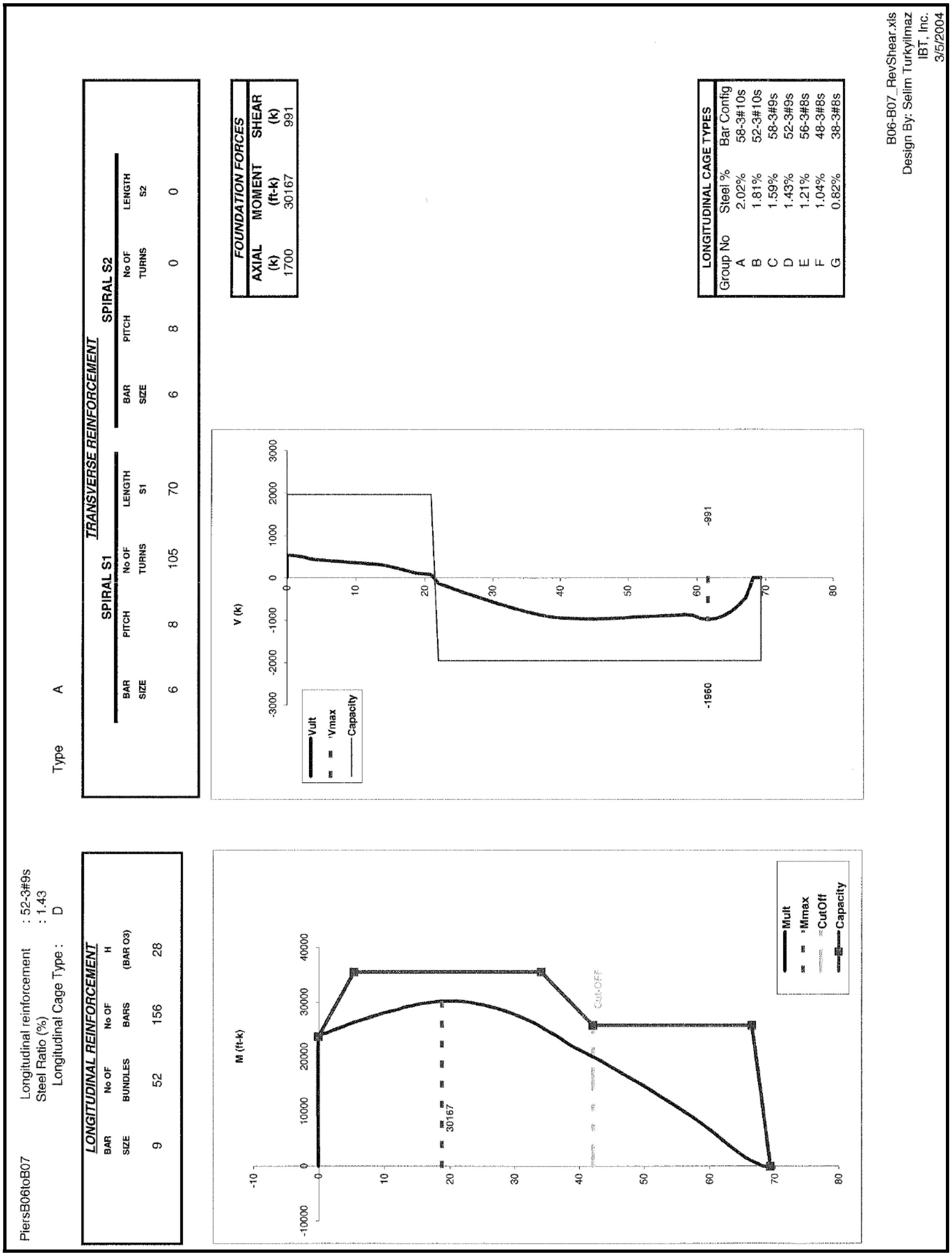


The design of the drilled shafts is primarily governed by seismic loads. The project is designed for a twin level earthquake, with a lower operational design earthquake (ODE) and a maximum design earthquake (MDE). The foundations are designed using the conventional practice of allowing hinging in the ductile elements and protecting against overload in the connecting elements, which includes the full length of the drilled shafts (capacity protected). For this reason, the MDE seismic case is the controlling loading event.

The interface between support columns of the guideway (ductile) and the drilled shaft (capacity protected), is an important detail. To force the ductile behavior to occur where defined, the drilled shaft is designed to be at least as strong, or stronger, than the maximum loading that could occur in the column. These loads are commonly referred to as the plastic or over-strength loads.

On the following page, Figure 2 shows an example of the design calculations with a plot of the flexural demands versus the drilled shaft capacity. The instantaneous transition with the column at the top of the drilled shaft is defined as the plastic load from the column plastic hinge. There is a transitional length at which the drilled shaft capacity is developed (second point from the top of plot.) This is indicative of the design approach noted above, where the capacity of the drilled shaft exceeds that of the column, forcing the plastic hinge to develop in the ductile element.

FIGURE 2


PiersB06toB07
Longitudinal reinforcement : 52-3#9s
Steel Ratio (%) : 1.43
Longitudinal Cage Type : D
Type A
LONGITUDINAL REINFORCEMENT
BAR SIZE 9
No OF BUNDLES 52
No OF BARS 156
H (BAR O3) 28
TRANSVERSE REINFORCEMENT
SPIRAL S1
BAR SIZE 6
PITCH 8
No OF TURNS 105
LENGTH S1 70
SPIRAL S2
BAR SIZE 6
PITCH 8
No OF TURNS 0
LENGTH S2 0
FOUNDATION FORCES
AXIAL (k) 1700
MOMENT (ft-k) 30167
SHEAR (k) 991
LONGITUDINAL CAGE TYPES
Group No Steel % Bar Config
A 2.02% 58-3#10s
B 1.81% 52-3#10s
C 1.59% 58-3#9s
D 1.43% 52-3#9s
E 1.21% 56-3#8s
F 1.04% 48-3#8s
G 0.82% 38-3#8s
M (ft-k)
30167
CutOff
Mult
Mmax
CutOff
Capacity
V (k)
-991
-1960
Vult
Vmax
Capacity
B06-B07_RevShear.xls
Design By: Selim Turkyilmaz
IBT, Inc.
3/5/2004

Since lap splices are not permitted in the plastic hinge zone of ductile elements - in this case the column – column rebar is often seen extending to mid-height of the column, or beyond where practical, prior to pouring the shaft. In order to improve constructability, a detail was developed to facilitate the splice between the column and shaft reinforcement to be placed in the shaft and to allow more accurate placement of the column longitudinal reinforcement. The 12' casing is an essential element of this detail and facilitates a construction joint below the elevation of the splice.

Since this short casing is not removed after the pour, it was taken advantage of in the permanent condition as a confining element at the top of the casing to help preserve the column plastic hinge above the top of the shaft and confining the non-contact strut-and-tie splice with the column rebar. However, because single large diameter drilled shafts have only recently become part of common practice, the Sound Transit Design Criteria, where AASHTO Specifications for Bridge Design (16th Ed.) is a primary reference, do not explicitly address the design parameters for the design of single drilled shafts. Because of this, some designer discretion is needed.

This Design Memorandum will address the following aspects of the steel casing:

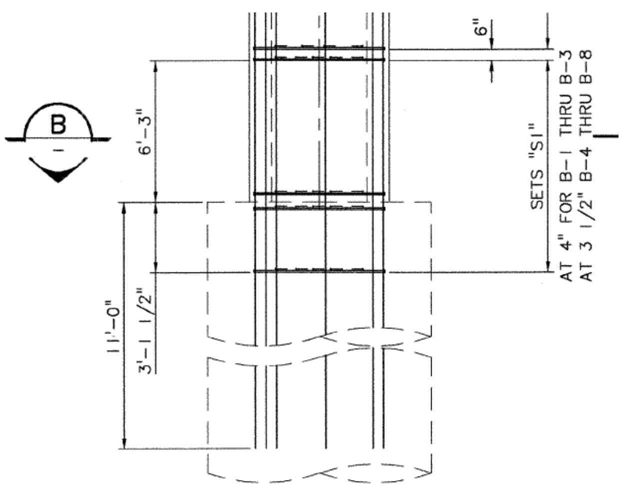
- Design Function
- Design Basis
- Calculations for the Design of the Casing
- Conclusions of the Minimum Design Requirements

Please note the governing design codes and special conditions assumed for the D755/C755 contract are identified in the General Notes on Drawings G57-SZ02 to G57-SZ05.

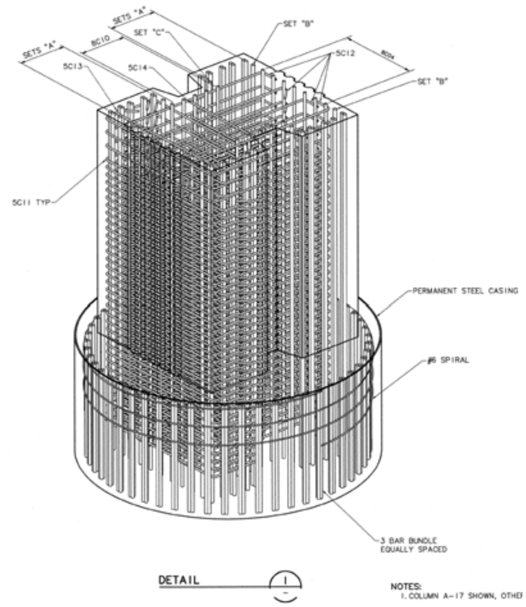
DESIGN FUNCTION

The basis of the general foundation design is given in the Overview section above. This section will focus specifically on the function of the steel casing.

1. Shoring and Formwork: Per experience on past projects with similar details, the splice between the column and drilled shaft requires shoring and formwork to complete the connection. As described in the Overview section, the top 11' of the drilled shaft is left open to accept the connection of the column reinforcement cage. The remaining bottom 1' of the casing is left for overlap with the top of the cast shaft to secure it in place. The casing maintains the open hole while the column reinforcement is placed and secured with a secondary pour.



TRANSVERSE ELEVATION
SCALE: 1/4" = 1'-0"



For contractors, this is often a lost form that is left as permanent, but for the C755 drilled shafts this casing was used for multiple functions as described in the section below.

2. Shaft Confinement: The design of circular structural elements typically includes a provision for volumetric transverse reinforcement in the form of a spiral or individual hoops. For elements in large seismic zones, this provision is usually enhanced.

   For concrete cast-in-drilled-holed piles, the seismic design provision of AASHTO (Division I-A), indicates a need to confine the upper portion of the piles to the underside of the pilecap. This is not applicable to single drilled shafts, but in keeping with the spirit of the provision confinement was provided using the steel casing which was already necessary for construction. The design of this confinement is discussed in the following section.

   Because the casing serves a dual function for both construction and design, it was identified as a structural element in the drawings and special provisions. Doing this avoids creating double costs for shoring and providing a tight spiral in the drilled shaft which would make concrete casting more difficult due to a high concentration of reinforcement.

3. Strut and Tie Confinement: Because the column is rectangular and the shaft circular, a conventional contact lap splice is not present between the two elements. To transfer forces between the column and shaft, a strut and tie mechanism is required to develop the reinforcement. This is mainly done by extending the reinforcement beyond the 60-bar-diameters per the seismic code, and the confinement provided by the casing helps resist the small out of plane force that is developed by this mechanism. From a detailing perspective, the same confinement that is considered effective for seismic forces is also considered effective for this behavior.

Because of the multiple requirements identified for the drilled shaft and column interface during the original design, the steel casing was determined to be an efficient and functional approach to addressing these issues. Moreover, this configuration had an excellent record of constructability demonstrated on other projects.

DESIGN BASIS

With reference to the three functions of the steel casing identified above, the second is largely dictated by technical requirements, although with discretionary considerations by the designer. As noted in the Overview section, design equations for the volumetric requirements to satisfy confinement conditions exist, however their specific application for the large diameter shafts does not exist with the available codes designated for this portion of the C755 contract.

For the original design of the steel casing, the AASHTO Standard Specification for Highway Bridges, Division I-A was used (16 Ed.) In particular, Section 7.4.2(C) Parts 2 and 3, which gives conditions for the confinement in the upper portion (2 pile diameters below the pilecap) for cast-in-drilled-hole (CIDH) concrete piles, which are provided as part of a pile group. By definition this is not applicable to single large diameter drilled shafts and no pilecap is present, but is the closest reference available in the project codes. It was adopted as a guideline, but not a rigid project requirement.

This section of the AASHTO Code references volumetric confinement equations 7-4 and 7-5. For the condition of an outer casing, equation 7-4 does not apply and 7-5 may be used:

ρ_s = 0.12*f'c/fy

Where: f'c = concrete strength at 28 days
fy = yield strength of confining steel

As can be seen by this equation, assuming the concrete strength is constant, the requirement for confinement steel increases as steel strength decreases.

It should be noted that to the confinement provided by the steel casing was supplemented by an additional set of #6 spiral at 8" spacing (9" for 12' diameter casing).

The above equation for confinement is conservative as it gives no consideration to the contribution of axial load, and can therefore be assumed as an upper bound requirement. That is, at lower levels of axial stress, as present with large drilled shafts, then lower levels of confinement would be considered applicable.

As part of the original design process, a specific Seismic Criteria for the C755 section of the Central Link was developed and the confinement equation above was identified as conservative. A clause from a supplementary seismic code, ATC-32, was given as an alternate means for calculating confinement, in which the effect of reduced axial stresses on the required confinement is recognized. This is indicated in the General Notes Section 19, Seismic Design, Part J, and is given as:

ρ_s = 0.16*f'ce/fye * [0.5 + 1.25Pe/(f'ce*Ag)] + 0.13(ρ_l – 0.01)

Where: "e" subscript means "expected properties"
Pe = expected axial load — f'ce = 1.3f'c
Ag = Gross Shaft Area — fye = 1.1fy
ρ_l = longitudinal reinforcement ratio

Using Pe = 2200kip as an upper bound case from the column calculations and ρ_l = 1.4%, the following results are found:

10' Shaft Confinement

General Notes: ATC-32
Code Design Section 8.18.2.2
Per Design

fy	50	ksi	(x1.1 for expected props)
f'c	5	ksi	(x1.3 for expected props)
ρs	0.0107	confinement ratio	
Provided			
Dshaft	120	in	
t	0.5	in	casing
spiral	0.44	in2	#6 rebar
s	8	in (unit spacing)	
Vsteel	1503	in2	(w/ corrosion allowance)
Vpile	89725	in2	
ρshell	0.0167	confinement provided	
Is ρshell>ρs?		***OK***	

General Notes: ATC-32
Code Design Section 8.18.2.2
Minimum Strength

fy	36	ksi	
f'c	5	ksi	
ρs	0.0146	confinement ratio	
Provided			
Dshaft	120	in	
t	0.5	in	casing
spiral	0.44	in2	#6 rebar
s	8	in (unit spacing)	
Vsteel	1503	in2	
Vpile	89725	in2	
	0.0167	confinement provided	
Is ρshell>ρs?		***OK***	

12' Shaft Confinement

General Notes: ATC-32
Code Design Section 8.18.2.2
Per Design

fy	50	ksi	(x1.1 for expected props)
f'c	5	ksi	(x1.3 for expected props)
ρs	0.0105	confinement ratio	
Provided			
Dshaft	144	in	
t	0.5	in	casing
spiral	0.44	in2	#6 rebar
s	9	in (unit spacing)	
Vsteel	2004	in2	(w/ corrosion allowance)
Vpile	145558	in2	
ρshell	0.0138	confinement provided	
Is ρshell>ρs?		***OK***	

General Notes: ATC-32
Code Design Section 8.18.2.2
Minimum Strength

fy	38	ksi	
f'c	5	ksi	
ρs	0.0136	confinement ratio	
Provided			
Dshaft	144	in	
t	0.5	in	casing
spiral	0.44	in2	#6 rebar
s	9	in (unit spacing)	
Vsteel	2004	in2	
Vpile	145558	in2	
	0.0138	confinement provided	
Is ρshell>ρs?		***OK***	

Where similar calculations are performed using the conservative confinement equation, and excluded the supplementary #6 hoop, it is found that 50ksi steel is needed. Using the more refined equations it is found that 36ksi and 38ksi steel is needed for 10' and 12' diameter casings respectively. Because the provision for confinement is discretionary and not prescriptive for large diameter piles, it is the designer's conclusion that 36ksi steel is adequate for both diameter casings.

To support the concept that traditional confinement equations are not applicable to large diameter shafts, reference is made to the new provisions in the Washington DOT Bridge Design Manual (BDM), Section 7.8.2 (established after C755 design). While the C755 drilled shafts were not designed in accordance with this specification, Part I notes

> *"The volumetric ratio and spacing requirements of the AASHTO Guide Specification for LRFD Seismic Bridge Design for confinement need not be met. The top of shafts in typical WSDOT single column/single shaft connections remains elastic under seismic loads due to the large shaft diameter (as compared to the column). Therefore this requirement does not need to be met."*

It is noted the AASHTO LRFD provision listed above is the same as AASHTO Standard Specification for Highway Bridges, Division I-A. Regarding the principle noted in the BDM section above, the calculations for the C755 drilled shafts demonstrate that they are designed to carry the over-strength plastic moments from the column and remain essentially elastic. Referring again to the demand/capacity plot example on Figure 2 with the moment diagram at the bottom of the page, the column plastic moment (data point at the top of the shaft) and the shaft resistance (second data point from the top), show that it is stronger than the column, which will force plastic hinging to occur outside the shaft. Technically there is no hinging to confine within the shaft, and the function of the casing is primarily one of detailing to allow better constructability and to confine the non-contact splice.

Based on the comments above, the resulting specification for the upper portion casing properties is largely a detailing exercise at the discretion of the design engineer due to the lack of prescriptive requirements. Because confinement equations provide a good technical basis for sizing the casing, it was used in this case as a guideline. Originally the conservative approach was used, partly to ensure the higher quality steel that is associated with a higher grade. But based on the technical references available, the ATC-32 is believed to be more applicable, and therefore the design engineer would accept 36ksi casing steel to satisfy the intended function.

CONCLUSIONS

The intention of this technical memorandum was to establish the function and design requirements associated with the short section of steel casing at the top of each large diameter drilled shaft. Because much of the function is detail related and not dictated by code, designer discretion is used to select the dimension, thickness, and steel grade of the casing. Based on this the conclusions are as follows, with consideration on variations of the steel grade:

1. Three functions of the steel casing were identified. The selected properties of the casing are an amalgam of these functions.
2. With regard to the design considerations, the function of the casing is not to confine a plastic hinge, but maintain the integrity of the upper drilled shaft to force the plastic hinge in the column. A parallel function is to assist non-contact lap splice integrity.
3. Based on the available codes, confinement at the top of the drilled shaft is not an implicit requirement, but because the casing is also required for other functions, it was determined that including the casing as a structural element would be an efficient means to meet multiple requirements simultaneously.
4. The original calculations for the casing properties used the AASHTO guidelines, which determined the steel grade to be 50ksi. Based on existing project criteria, it is our conclusion that this requirement can be lowered to 36ksi using ATC-32 while still maintaining the minimum intended function of the steel casing. It is noted that the maximum loading is under the 2475-yr seismic event, and therefore the other functions of the casing and the general behavior of the shaft under normal service load conditions, are simultaneously met with the 36ksi casing.