ISOLATED BRIDGE ABUTMENTS FOR ACCELERATED BRIDGE CONSTRUCTION

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Figure 1: Nisutlin Bay Bridge, Concept 2019 (Ref. M. Schueller)

ABSTRACT

This paper discusses isolated bridge abutments and how this modern design concept successfully contributes to the Accelerated Bridge Construction (ABC). In recent years, the isolated abutment type has been developed, primarily to improve seismic responses of the bridges. The abutment type is based on a simple idea to provide an answer to situations where construction time, seismic design, and soft soils govern. This paper is addressing bridge designers, owners, and the construction industry to promote advancement in the modern abutment design with the goal to further improve ABC projects.

INTRODUCTION

Today, the ABC techniques, using Prefabricated Bridge Elements and Systems (PBES), are successfully driving the design and construction of many small to large-sized bridges. An increasing number of owners are considering ABC on their projects, mainly to minimize local traffic impacts during construction. Many owners are willing to pay a premium for ABC because the economic benefits outweigh extra costs resulting from short construction periods. The proven concept of isolated bridge abutments in conjunction with a fully isolated substructure has been envisioned for the new Nisutlin Bay Bridge, near Teslin in the Yukon, Canada (Figure 1). In conjunction with ABC, isolated abutments allow to reduce construction time without increasing costs. This is most important for cold temperature regions where weather significantly impacts bridge construction. A comparison of three different abutment solutions shows that even cost reductions are possible when using the isolated abutment type.

ISOLATED BRIDGE ABUTMENTS

Abutments are essential components of any bridge structure which provide a smooth transition from the superstructure to the approaches. Depending on design philosophy, they influence construction and maintenance costs as well as structural behavior of the bridge. Common types such as integral, semi-integral and non-integral (conventional) abutments, are often challenged in difficult geometric conditions (e.g. highly skewed situations) or in seismic regions with soft and/or liquefiable soils. On the contrary, the isolated abutment type comprises of a traditional pier in front of a Mechanically Stabilized Earth (MSE) wall to support the superstructure and a "jump span", which is an exposed concrete approach slab (1).

Since the concept of an isolated abutment is comparable with a free-standing pier, the superstructure can be erected independently from other time-consuming activities such as construction of the approaches, retaining walls, and backfilling. This independence enables parallel working conditions and reduces construction risks, especially when multiple contractors are responsible for construction activities along the critical path. Further, isolated abutments have a much smaller stiffness and resistance in the horizontal direction when compared with the usually preferred integral abutments. In a seismic event this structural flexibility is a great advantage to control seismic accelerations and consequently, substructure demands. The seismic isolators improve damping of the superstructure by assuring elastic response of the substructure in seismic events, but they require large displacements of the superstructure, Priestley et al. (2). The isolated abutment provides the required displacement capacity without using costly expansion joints with fuse boxes requiring maintenance and early replacement. Instead, the necessary longitudinal movement is absorbed by the jump span (approach slab) which is supported by a buried pre-cast sleeper slab. The seating area of the sleeper slab is shaped such that any horizontal movement can be accommodated without violating serviceability and seismic performance criteria. Sketches showing a conventional abutment type (Figure 2), an integral abutment type (Figure 3), and the isolated abutment type with the jump span (Figure 4) are presented below.

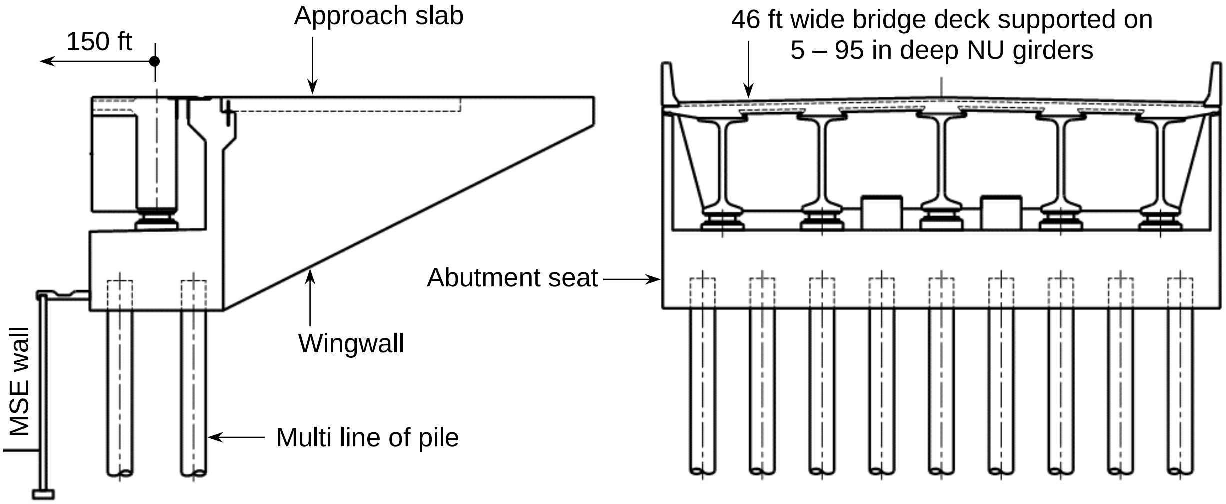


Figure 2: Conventional abutment with bearings, shear keys, and approach slabs (Type A)

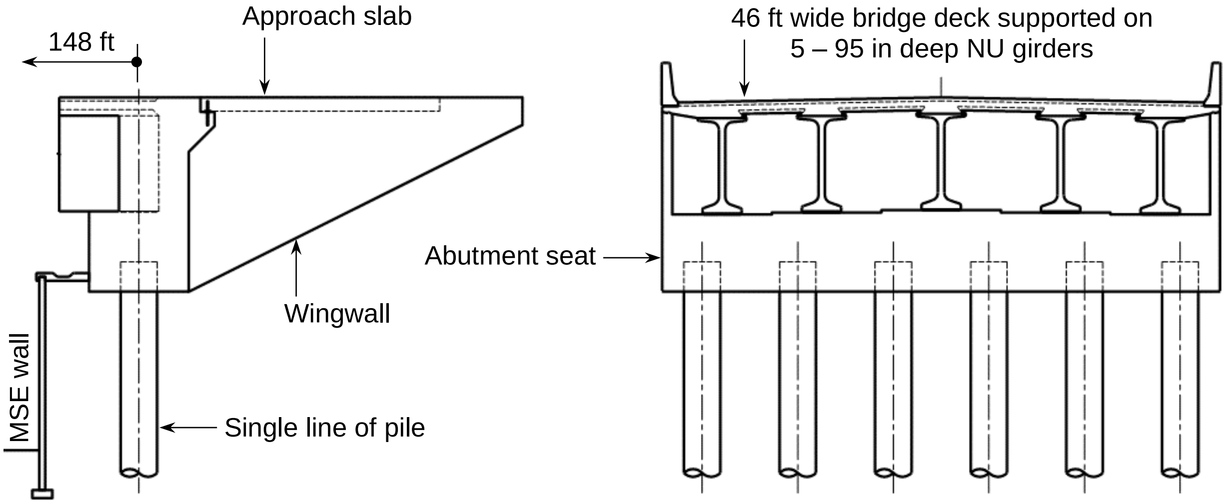


Figure 3: Integral abutment without bearings and with approach slabs (Type B)

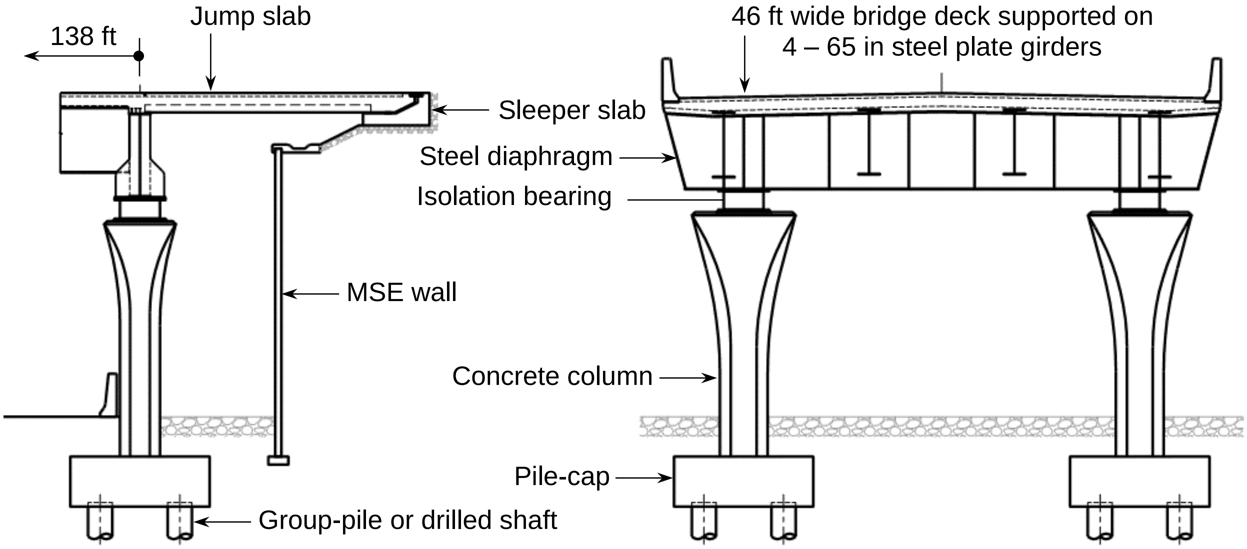
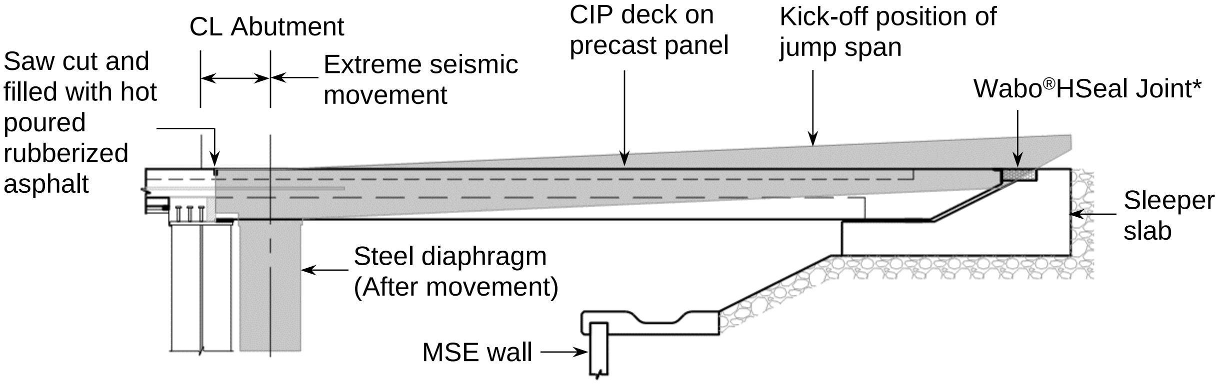


Figure 4: Isolated abutment with isolation bearings and jump slabs (Type C)

COMPARISON OF THREE ABUTMENT TYPES

The isolated abutment type has been investigated from a designer and contractor's perspective and compared to the conventional and integral abutment types. A single span two-lane overpass is used as a reference structure representing a typical ABC project. The effective span of the overpass is around 150 ft for the conventional, 148 ft for the integral, and 138 ft for the isolated abutment types to maintain a 131 ft clear width for the clearance envelope below. The width of the overpass is 46 ft including two traffic lanes, shoulders and barriers. Vertical clearance for the underpass is assumed to be 20 ft. For both conventional and integral abutments, a 20-ft long approach slab is proposed. For the isolated abutment, the approach slab is replaced with the jump span. The jump span is supported by a sleeper slab at the approach end.

The sleeper slab is designed to temporarily “kick-off” the jump span during extreme seismic events. After the earthquake the self-centering isolation bearings will allow the jump slab to fall back into its service position to permit immediate traffic flow as prescribed by modern seismic performance criteria. Figure 4 shows the details of the “kick-off” mechanism between the jump slab and sleeper slab. Kick-off position of the jump span is shown in gray.



*Wabo®HSeal is a pre-compressed elastomeric coated expansion joint system designed to provide a permanent weather tight seal. Primarily used in horizontal applications, the system is sealed in place with an epoxy, which allows it to accommodate horizontal (up to 4 in), vertical, and skew expansion joint movements. (Ref. Watson Bowman Acme Corp.)

Figure 5: Jump slab connection details for the isolated abutment

STRUCTURAL SYSTEMS

The presented three abutment types, forming the structural systems A, B, and C, were investigated considering seismic design requirements and pile foundations. The different systems are presented in Table 1. The superstructure of Type A is transversely restrained and longitudinally free to move (Figure 2), Type B is transversely and longitudinally restrained (Figure 3), while Type C is “floating” in both directions because of the use of isolation bearings (Figure 4).

Table 1: Definition of different structural systems

Structural Definition	**Type**
Conventional abutment with elastomeric bearings and with shear keys	A
Integral abutment without bearings and without shear keys	B
Isolated abutment with isolation bearings but without shear keys	C

SEISMIC PERFORMANCE CRITERIA

In accordance with the Canadian Highway Bridge Design Code (CHBDC), CAN/CSA S6-14, bridges are categorized as lifeline bridges, major-route bridges, and other bridges. For the purpose of this investigation, only the performance criteria for the lifeline and major-route bridges are considered. The “minimum performance levels” and corresponding “performance criteria” for these two bridge types are presented below in Tables 2, 3 and 4.

Table 2: Minimum performance levels for lifeline bridges and major-route bridges (as per CHBDC)

Event	Lifeline bridges		Major-route bridges	
(Probability of Exceedance)	Service	Damage	Service	Damage
475 Year (10%)	"Immediate"	"None"	"Immediate"	"Minimal"
975 Year (5%)	"Immediate"	"Minimal"	"Limited"	"Repairable"
2475 Year (2%)	"Limited"	"Repairable"	"Disruption"	"Extensive"

Table 3: Performance criteria for **Service** as indicated in Table 2 (as per CHBDC)

Service	Description
Immediate	Bridge shall be fully serviceable for normal traffic and repair work does not cause any service disruption.
Limited	Bridge shall be usable for emergency traffic and be "repairable" without requiring bridge closure. At least 50% of the lanes, but not less than one lane shall remain operational. If damaged, normal service shall be restored within the first month.
Disruption	The bridge shall be usable for restricted emergency traffic after inspection. The bridge shall be "repairable". Repairs to restore the bridge to full service might require bridge closures.

Table 4: Performance criteria for **Damage** as indicated in Table 2 (adopted from CHBDC)

Damage	Description
None	Bridge components remain elastic without any damage: Concrete compressive strains are not to exceed 0.0035 and the average concrete crack width remains within typical service levels. Displacements are limited to regular reoccurring movements. No repairs required.
Minimal	Bridge components remain essentially elastic with only minor damage permitted: Concrete compressive strains not to exceed 0.0040 and reinforcing steel strains not to exceed yield. Movements permitted if safety and traffic are not affected. No immediate repairs required.
Repairable	Some local inelastic behavior and moderate damage acceptable. Reinforcing steel tensile strains not to exceed 0.015. Movements permitted if safety and traffic are not affected. 90% of structural capacity preserved for aftershocks. Capacity fully restored after repairs.
Extensive	Inelastic behavior with extensive visible damage but reinforcing steel tensile strains below 0.050. Movements limited to allow passage of emergency traffic after inspection of bridge. 80% of structural capacity preserved for aftershocks. Capacity fully restored after repairs.

DESIGN SPECTRAL ACCELERATION

The seismic design acceleration was obtained from a spectral response analysis considering 5% damping. The horizontal seismic accelerations for Site Class E were determined for the periods of 0.2, 0.5, 1.0, 2.0, and 10.0 seconds following the 475-year, 975-year, and 2475-year seismic events as prescribed by the CHBDC. The vertical target spectrum was taken as two-thirds of the horizontal target spectrum. The horizontal design spectral accelerations and displacements are shown in Figure 6.

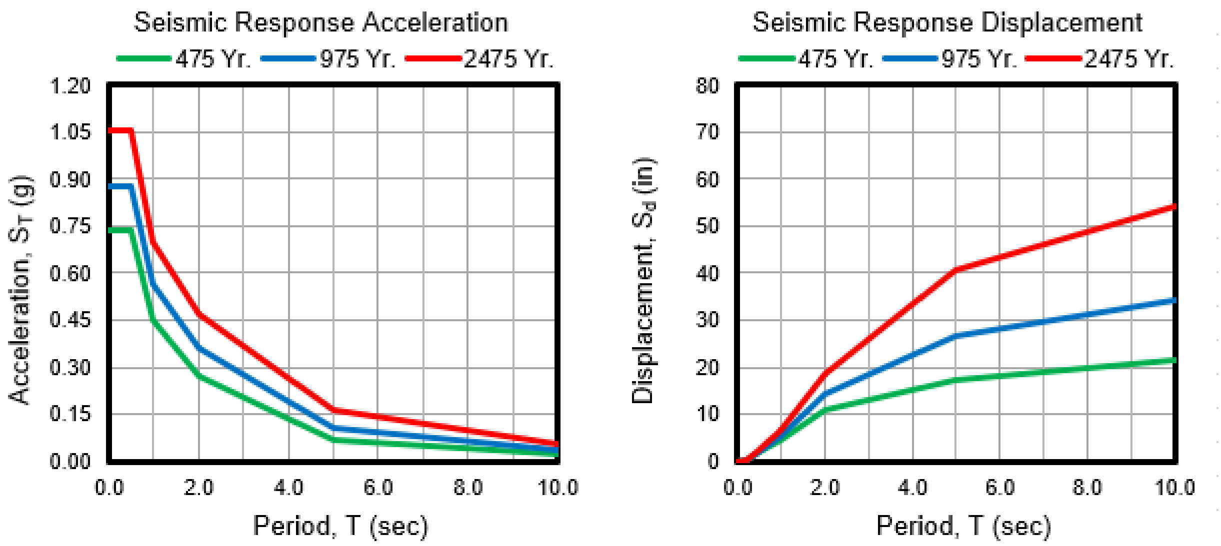


Figure 6: Seismic response acceleration (left) and displacement (right)

GEOTECHNICAL AND FOUNDATION DESIGN ASSUMPTIONS

Based on the soft soil parameters, an L-Pile analysis was conducted for 24-in and 36-in diameter pipe piles. The soil structure interaction (SSI) and the pile-head lateral load (V) versus lateral displacement (Δ) curves were produced and used to determine the equivalent point-of-fixity of fully restrained piles. The 24-in diameter pipe piles were used for the conventional and isolated abutments while the 36-in diameter pipe piles were used for the stiffer integral abutment. The piles were assumed to be filled with reinforced concrete in the upper 35 ft. The depth of till layer is around 230 ft below the ground; therefore, pile end-bearings were avoided. The assumed factored geotechnical axial capacities (skin friction only) of these piles are presented in Table 5 based on the non-seismic and seismic (2475 Yr.) resistance factors of 0.4 and 0.9 respectively. For the integral abutment type, a 5.30 ksi/in linear abutment spring (compression only) was used to restrain horizontal pile movements (longitudinal only).

Table 5: Assumed factored geotechnical axial pile capacity

Type	Pile Dia. (in)	Pile length (ft)	Non-seismic (kips)	Seismic (kips)
A	24	115	323	727
B	36	180	737	1658
C	24	115	323	727

ISOLATION BEARINGS

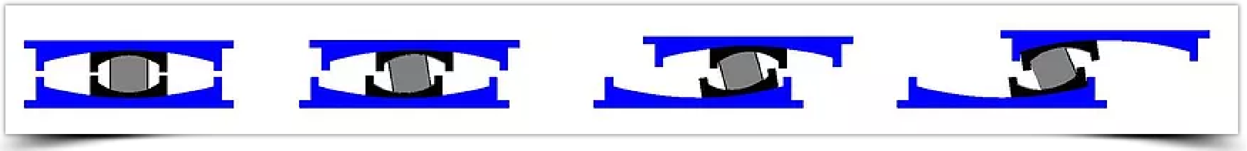
The application of isolation bearings reduces seismic design forces and thus foundation costs significantly for the structures in soft soil and high seismic zones. Two major categories of isolation bearings are commonly used: Lead Rubber Bearing (LRB) and Friction Pendulum Bearing (FPB).

Lead Rubber Bearing (LRB)

Lead rubber bearings are low-damping laminated rubber bearings with a lead plug inserted in the core of the device. The purpose of inserting the lead plug is to increase both the stiffness at relatively low horizontal force levels and the energy dissipation capacity in seismic events. The resulting force-displacement curve is a combination of the linear-elastic response of the rubber bearing and the elastic-plastic response of the confined lead plug. The stiffness of rubber is sensitive to temperature. It becomes softer in the summer and stiffer at cold temperatures in the winter. Therefore, the winter stiffness of the material governs the horizontal seismic design forces for the piles. In contrast, the much lower summer stiffness governs the maximum superstructure displacements for the governing seismic design scenarios.

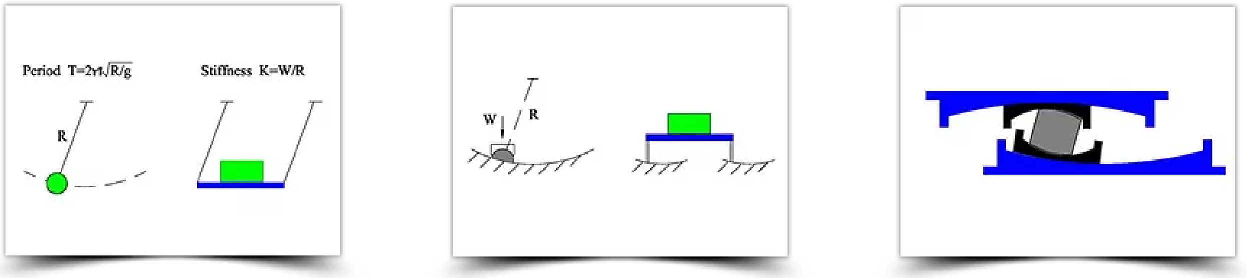
Friction Pendulum Bearing (FPB)

Friction pendulum bearings are based on the concept of a pendulum motion. The isolated structure is supported on an articulated Teflon-coated load element sliding on the inside of a spherical surface. Any horizontal movement therefore triggers a vertical uplift of the supported weight. If friction is neglected, the equation of motion of the system is similar to that of a pendulum with equal mass and length to the radius of curvature of the spherical surface. Usually, FPBs are categorized as a Single Pendulum Bearing (SPB) or a Triple Pendulum Bearing (TPB). TPBs are more efficient allowing larger displacements and are up to 60% more compact than SPBs. Figure 7 shows different operational positions of the TPBs while Figure 8 shows the principle of the TPB schematically when compared to a characteristic pendulum motion with one degree of freedom.



Triple Pendulum™ Isolator Center Position | **Inner Pendulum Motion Service Level Earthquake** | **Lower Pendulum Motion Design Basis Earthquake** | **Upper Pendulum Motion Maximum Considered Earthquake**

Figure 7: Different operational position of TPBs (Ref. Earthquake Protection System)



Pendulum Motion | **Sliding Pendulum Motion** | **Triple Pendulum™ Operation**

Figure 8: Principle of TPBs (Ref. Earthquake Protection System)

PREFABRICATED BRIDGE ELEMENTS

Because of their relevancy regarding ABC, prefabricated bridge elements are proposed for Types A, B and C, presented in Table 6. Interfaces and connections between the elements shall be designed to fully develop the capacity of the weaker member in axial force, moment and shear (capacity protected design approach).

Table 6: List of prefabricated bridge elements

Type	Prefabricated bridge elements
A	Partial depth precast panels and precast prestress NU girders
B	Partial depth precast panels and precast prestress NU girders
C	Columns, full depth precast panels, steel plate girders and diaphragms

ANALYSIS

The simplified method of analysis for superstructure (as per CHBDC) in combination with the single-mode spectral method of analysis for the substructures and foundations was used. The fundamental periods (Eigenvalues) were computed in the longitudinal (X) and transverse (Y) direction of the bridge. The superstructure's mass and system's effective stiffness including bearings, columns (if any) and piles were used to derive the governing periods for each system. Based on the fundamental periods, the design spectral accelerations and base shears were obtained using the spectral analysis results presented in Figure 6. Elastic seismic effects were calculated for different seismic events and combined as per CHBDC, Clause 4.4.9.2 (a) and (b). Fundamental periods and base shears (before combined) are summarized in Table 7 and 8. For Type A (conventional abutment), the non-seismic and seismic active earth pressure was calculated based on Rankin's theory, and Mononobe and Okabe equations as specified in commentary of the CHBDC (3) respectively. The total backfill forces are also presented in Table 8. The Type B (integral abutment) balances the earth pressures of both abutments using the superstructure as a compression strut. In contrast, the Type C (isolated abutment) does not experience backfill forces because the MSE wall shields the freestanding abutment pier.

Table 7: Seismic performance category of the structure for the 2475-year event

Type	Period (s)		Spectral values		Performance category	
	Long.	Trans.	S (0.2s)	S (1.0s)	Lifeline	Major-route
A	0.86	0.36	0.89	0.45	3	3
B	0.26	0.39	0.89	0.45	3	3
C	3.99	3.99	0.89	0.45	3	3

Table 8: Maximum seismic demands for the 2475-year event per abutment

Type	Seismic Mass (Ton)	Peak Acceleration	Design Acceleration		Base Shear (kips)		Backfill Force (kips)	Displacement (in)	
		Both	Long.	Trans.	Long.	Trans.	Long.	Long.	Trans.
A	1264	1.025	0.777	1.025	1964	2428	1378	4.61	0
B	1148	1.025	1.025	1.025	1264	2353	1378	0.67	1.58
C	458	1.025	0.263	0.263	241	241	0	24.0	24.0

DESIGN

In accordance with CHBDC, Clause 4.4.1, a performance-based seismic design was carried out for the lifeline bridges. In addition, a force-based design approach was selected for ductile substructure elements of major-route bridges to investigate the differences. According to the seismic performance criteria, specified in Table 3 and 4, the design shall adhere to the performance levels defined for the 475-year, 975-year, and 2475-year events. To meet this requirement, the foundation of the structure must remain elastic or endure only repairable damage (4).

The factored resistance capacity of the steel piles was calculated based on 0.04 in outside perimeter corrosion loss of the section for a 75-year design life of the structure. In accordance with CHBDC, Clause 10.9.5, piles were designed as composite columns consisting of steel hollow structural sections completely filled with concrete to meet the axial and bi-axial bending demands. As per CHBDC, plastic hinges are not allowed in the piles; therefore, the resistance and number of piles were determined by satisfying seismic and non-seismic demands with elastic strains. In comparison to Type A and B (traditional abutments), the Type C (isolated abutment) showed significantly smaller horizontal pile design forces which allowed to reduce the overall number of piles and foundation costs.

PROJECT COST

The total project (construction) costs were calculated for the three investigated abutment types. Some budget prices were provided by suppliers/contractors and some were assumed based on previous construction experience. The unit prices highly depend on size and location of the project; therefore, the actual costs may vary. However, the trend and outcome favoring the isolated abutment type is clear and noteworthy. The derived total project costs and percent reduction between different abutment types are presented in Figure 9. The total project costs are presented without considering the cost of additional mobilization/demobilization, traffic control, contingency and engineering service fees.

For the isolated abutments (Type C), (1) the bridge length can be reduced by 12 ft, (2) the earth pressures on abutment piles can be avoided, (3) the substructure elements such as abutment seats, shear keys (if applicable), wingwalls, backwalls and curtainwalls can be eliminated reducing the vertical loads on abutment piles by 30%, and (4) the seismic demands can be mitigated due to the mass reduction. All of these have meaningful effects on the abutment foundation costs. The study shows that the cost savings of up to 40% (Figure 8) are possible for the foundations of isolated bridge abutments when compared to the conventional abutments (Type A). This effect has in this investigation only a minor impact on overall project costs because the foundation costs account only for up to 20% of the overall total costs. However, it is understood that the contribution of foundation costs can increase up to 50% of the overall project costs for major bridges in poor soil conditions which demonstrates the cost savings potential of the isolated approach when designing bridges in seismically active zones.

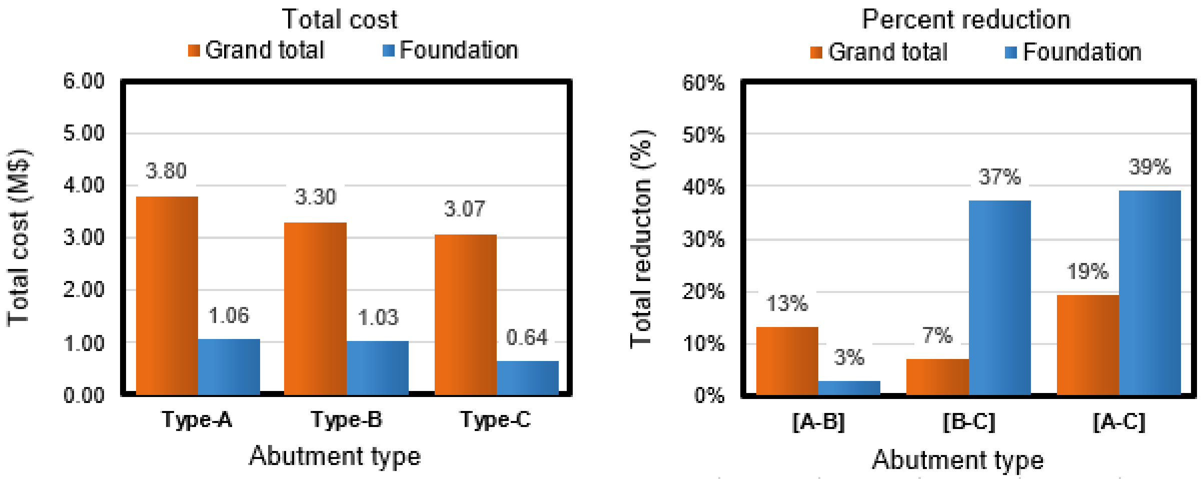


Figure 9: Total construction and foundation costs for the three different abutment types

PROJECT SCHEDULE

Traffic delays related to bridge replacement and rehabilitation negatively influence economic growth opportunities. If such missed economic opportunities are expressed in costs and considered as lost opportunity costs in the overall financial equation, further savings are possible when using the ABC approach. Therefore, the comparison of the three investigated abutment types included a review of the construction schedule and the possibility of time savings. A construction schedule (Gantt Chart) for the three types is presented in Figure 10 which underlines the fact that substructure construction is further accelerated if the isolated abutment type is selected. This schedule analysis does not consider possible reductions of construction time if the jump span length is optimized to meet project objectives. For instance, a longer jump span further reduce the volume of approach fill works without increasing costs meaningfully. Approach works (backfill and MSE wall construction) are now completely independent from the substructure and superstructure works allowing various contractors working parallel during construction.

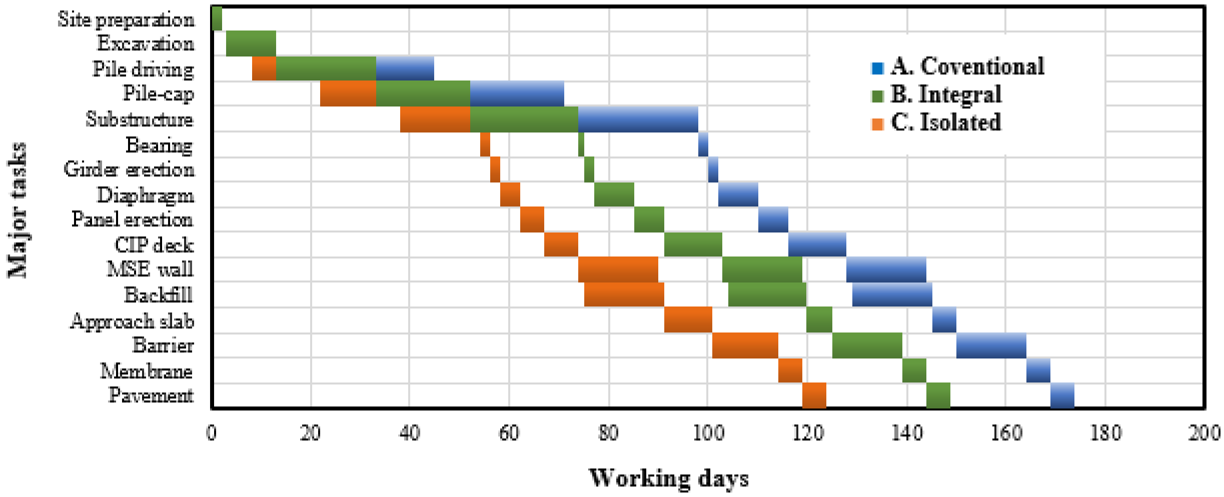


Figure 10: Assumed construction schedule for the three investigated abutment types

SUMMARY AND CONCLUSIONS

The main results of this investigation can be summarized as follow:

1. The isolated abutment type reduces force effects on piles and thus foundation costs.
2. The isolated abutment type eliminates finger plate or modular expansion joints in the bridge deck.
3. For the isolated abutment type, the construction of approaches is independent from substructure and superstructure works. This has the potential to accelerate the construction schedule.
4. The isolated abutment type easily overcomes complex geometries without increasing costs.
5. For the isolated abutments type, the area of the MSE wall slightly increases (because no backwall is required) while the overall approach backfill volume decreases.
6. The isolated abutment type is highly compatible with current ABC techniques and recommended for such projects.

Because of cost and schedule benefits, it is recommended to promote isolated bridge abutments even for smaller bridges if this reduces the number of piles and accelerates the work for the deep foundations. The reduced construction time is most beneficial for bridge projects in cold temperature regions (e.g. Alaska and Yukon) where only a relative short period of good construction weather is available.

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