Seismic design issues for joint-less bridges with innovative integral abutments

Ian G. Buckle

ABSTRACT

Integral bridges are often seen as more desirable than non-integral structures because their maintenance costs can be reduced significantly due to the absence of joints in the superstructure. As a consequence, they have been strongly recommended for short-to-medium length bridges where expansion and contraction in the superstructure may be accommodated by flexure in the substructure. They have also certain advantages under seismic loads and these are explored in this paper. Continuous bridges with integral abutments are not susceptible to span unseating which can lead to a marked improvement in their performance over non-integral bridges. The positive engagement of the strength and stiffness of the backfill behind the abutment can also be used to attract seismic loads away from the piers and the added damping in the soil may be used to reduce superstructure displacements in the longitudinal direction. However care must be taken to ensure the backfill does not fail (e.g. liquefy) but yields in compression in a quantifiable and reliable manner. It is also necessary to ensure the piles below the abutment are protected from damage to the extent possible, which requires an improved understanding of soil-pile interaction under the abutments where the piles are in sloping ground. Little is known about the capacity and stiffness of piles in these conditions, but recent research indicates a reduction in lateral stiffness up to 50% for piles in slopes up to 45^0in the tension direction (away from the slope).

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INTRODUCTION

Integral bridges are often seen as more desirable than non-integral structures because their maintenance costs can be reduced significantly due to the absence of movement joints in the superstructure. As a consequence, they have been strongly recommended for short-to-medium length bridges where expansion and contraction in the superstructure may be accommodated by flexure in the substructure. They have also certain advantages under seismic loads and these are explored in this paper.

The most common type of bridge failure during an earthquake is the unseating of the superstructure from piers and abutment seats (Figure 1). This is particularly true in bridges with simply supported spans and short seat widths at the supports. Continuous bridges with integral

Figure 1. Unseating of non-integral spans in the San Fernando 1971 (left) and Niigata 1964 (right) earthquakes.

abutments are not susceptible to this mode of failure which can lead to a marked improvement in their performance over non-integral bridges.

The positive engagement of the strength and stiffness of the backfill behind the abutment can also be used to attract seismic loads away from the piers and the added damping in the soil may be used to reduce superstructure displacements in the longitudinal direction. However care must be taken to ensure the backfill does not fail (e.g. liquefy) but yields in compression in a quantifiable and reliable manner. It is also necessary to ensure the piles below the abutment are protected from damage to the extent possible, which requires an improved understanding of soil-pile interaction under the abutments where the piles are in sloping ground. Little is known about the capacity and stiffness of piles in these conditions.

SEISMIC PERFORMANCE IN LONGITUDINAL DIRECTION

Advantages of Integral Abutments

The seismic performance of bridges with integral abutments in the longitudinal direction is improved over bridges with seat type abutments in two ways:

First, even though the backfill may yield, the combined stiffness of the backfill and abutment piles is significantly greater that the piers, in this direction, and seismic loads are thus attracted to the abutments away from the piers. The demand on the piers is correspondingly reduced to the point where it may be possible to keep the piers essentially elastic.

Second, yielding the backfill behind the abutments increases the damping in the bridge-foundation system and many design codes allow an increase in the equivalent viscous damping ratio from the default value of 5% to 10 % provided:

- superstructure is continuous (no intermediate expansion joints)
- abutments are integral with superstructure
- skew does not exceed 20^0, and
- total length of bridge does not exceed 200 ft.

If a bridge satisfies these requirements, a damping factor (B_L) may be applied to the design spectrum, where B_L is given by:

$$B_L = \left(\zeta / _{0.05}\right)^{0.3} = \left(0.10 / _{0.05}\right)^{0.3} = 1.23 \tag{1}$$

And ζ is the equivalent viscous damping ratio. This means that spectral forces and displacements in a bridge that satisfies the above criteria, are 1/1.23 (= 0.81) times those in a bridge with seat-type abutments and the same fundamental period of vibration.

The above advantages are illustrated by analyzing a 3-span bridge later in this paper, but first a simplified method of analysis is given for bridges with integral abutments and yielding backfill.

Simplified Method of Analysis for Bridges with Integral Abutments

Bridge Modelling

Figure 2 shows a 3-span bridge with integral abutments supported on piles. A close-up view of an integral abutment is shown in Figure 3. Performance in the longitudinaldirection can be calculated using a simplified model of the bridge-abutment soil interaction by assuming the backfill behaves as an elasto-plastic spring and the piles, together with the piers and their foundations, behave as elastic (linear) springs. Such a model is shown in Figure 4 where the backfill has bilinear stiffness (in the case shown it is elastic-perfectly plastic behavior), and a capacity in compression of P_{BY} at a yield displacement Δ_Y.The capacity in tension is assumed to be zero. The abutment piles are assumed to remain elastic and have stiffness,$K_{abutpiles}$, in both directions of loading (this assumption is revisited later in this paper).

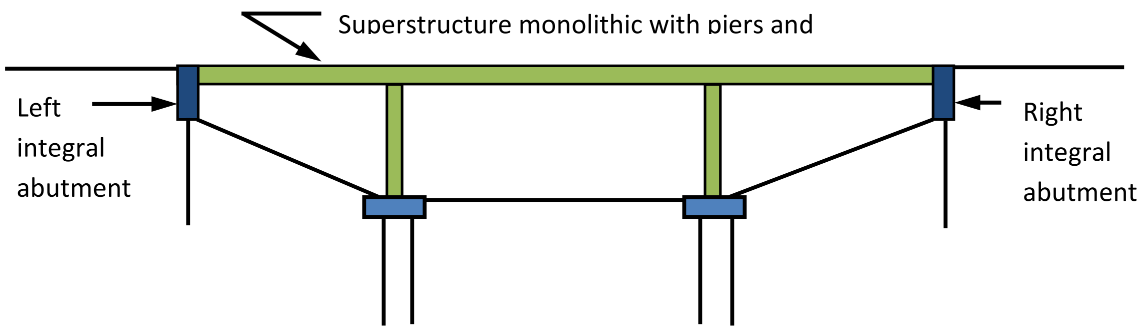

Figure 2. Three-span bridge with integral abutments.

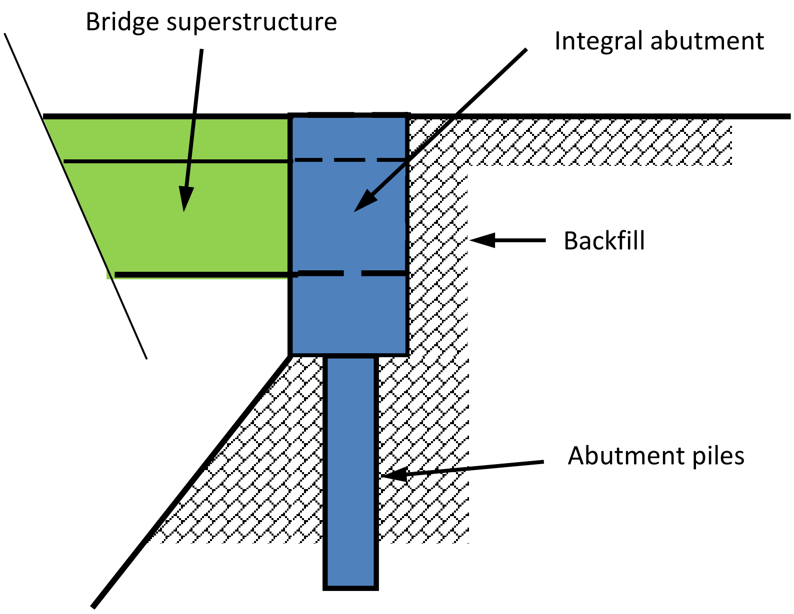

Figure 3. Integral abutment components

Since the backfill properties are nonlinear, a common assumption is to assume equivalent linear properties and continue to use elastic methods of analysis when calculating seismic performance. Since these equivalent properties are displacement dependent, it is however necessary to use iteration to obtain final solution. This is illustrated in Figure 4, where it is seen that the equivalent stiffness of the backfill, $K_{backfill}$, is dependent on displacement, D, of the abutment under a longitudinal load equal to the passive resistance of the fill, P_{BY}.

$$\text{i.e. } K_{abutbackfill} = {}^{P_{BY}}/_{D} \tag{2}$$

$$\text{where } P_{BY} = p_y \text{ x abutment width } (B_W) \text{ x abutment height } (H_W) \tag{3}$$

$$p_y \text{ (passive pressure)} \quad (H_W \text{ in ft, } p_y \text{ in ksf), and} \tag{4}$$

$$\Delta y \text{ (yield displacement backfill)} = F_W \text{ x } H_W = 0.02\ H_W \text{, for medium dense sand} \tag{5}$$

Figure 5 shows a spring model for the 3-span bridge in Figure 2 where each of substructures is represented by a spring. For loading from left to right, only the backfill at the right abutment is engaged and the total longitudinal stiffness, K_L, is given by:

$$K_L = K_{leftabutpiles} + K_{leftpier} + K_{rightpier} + K_{rightabut\ piles} + K_{\ rightabutbackfill} \tag{6}$$

Ifthe piers are identical andthe left and right abutment piles have the same properties:

$$K_L = 2K_{abutpiles} + 2K_{pier} + K_{abutbackill} \tag{7}$$

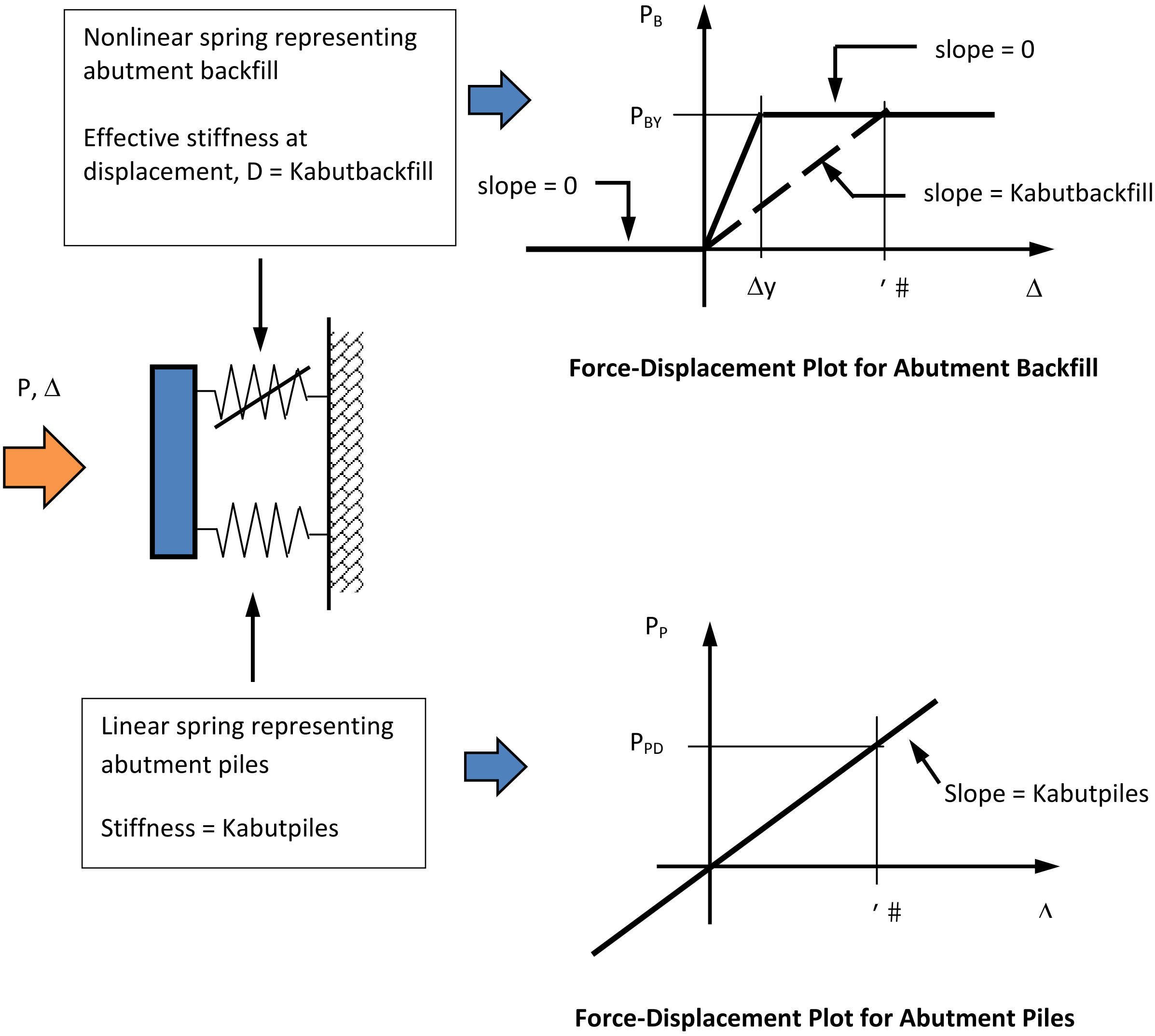

Figure 4. Equivalent spring model of integral abutment.

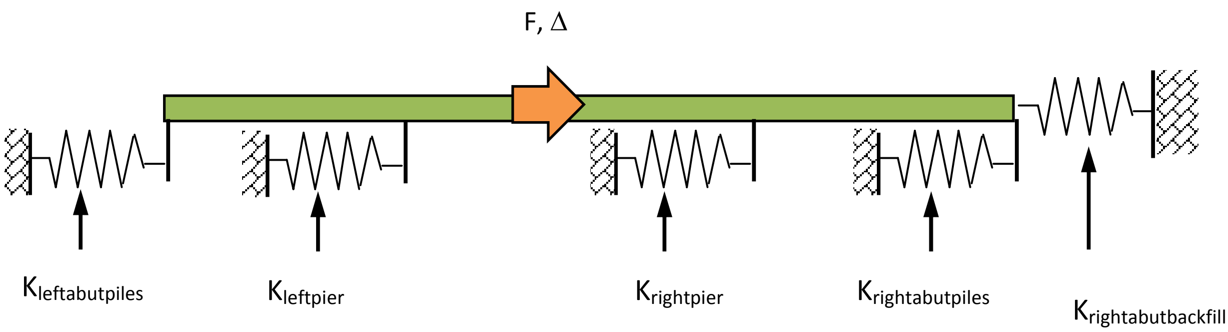

Figure 5. Equivalent spring model of three-span bridge in longitudinal direction.

Iterative Analysis Method

As noted above the effective stiffness of the backfill is dependent on the displacement of the abutment, D which is not known at the beginning of the analysis. An iterative solution is therefore required which begins by assuming that D = Δy and then proceeding as follows:

Step 1. Assume D= Δ_Y

Step 2. Calculate effective stiffness of backfill ($K_{abutbackfill}$) using equation (2)

Step 3. Calculate total longitudinal stiffness of bridge (K_L) from equation (6) or (7)

Step 4. Calculate effective period of bridge, T_{eff}, from $T_{eff} = 2\pi\sqrt{W/_{gK_L}}$ (8)

Step 5a. Calculate maximum displacement of bridge, D, from displacement response spectrum (S_D) which may be calculated from the acceleration response spectrum (S_A), as follows:

(ins) (9)

Step 5b.Compare value for D from equation (9) with that assumed in Step 1. If in agreement go to Step 6, if not go back to Step 2 with a revised value for Dand repeat Steps 2-5 until convergence.

Step 6. Once convergence has been achieved calculate substructure forces as below:

$$F_{leftabut} = F_{leftabutpiles} = K_{abutpiles}\, D \tag{10}$$

$$F_{pier} = K_{pier}\, D \tag{11}$$

$$F_{rightabut} = F_{abutpiles} + F_{backfill} = K_{abutpiles}\, D + P_{BY} \tag{12}$$

Step 7. Calculate total base shear (V_{base}) and express as percentage of superstructure weight, W.

$$V_{base} = F_{leftabut} + 2\, F_{pier} + F_{rightabut} \tag{13}$$

Example

Suppose the bridge shown in Figure 2 has the properties listed in Table I, and that it is located on a site where the spectral acceleration at 1.0 sec is 0.50g. Application of the 7-step iteration method given in the previous section gives the results shown in Table II. It is seen that the longitudinal displacement of the bridge is 0.34 ft and the forces in the left abutment, pier, and right abutment are 327 k, 55 k (each pier), and 1,369 k respectively. The total base shear is 1,804 k. It is clear most of the longitudinal load is taken by the right abutment (76%) and only a small fraction is taken by the piers (3% each). The remainder is resisted by the piles under the left abutment (18%).

To illustrate the beneficial effect of (a) the integral abutment on pier forces, and (b) the increase in damping from 5 to 10%, a limited number of comparative analyses were made using the same methodology as above, and the results are shown in Table III.

TABLE I. PROPERTIES OF EXAMPLE BRIDGE

Property		Value
Superstructure weight	W	1930 k
Spectral acceleration at 1.0 sec	S_{D1}/g	0.50
Equivalent viscous damping ratio		5.0%
Lateral stiffness abutment piles	$K_{abutpiles}$	1,500 k/ft
Lateral stiffness each pier	K_{pier}	250 k/ft
Abutment width	B_W	41.5 ft
Abutment height	H_W	6.125 ft
Backfill passive pressure(yield stress),eqn (4)	p_y	= 2/3 (6,125) = 4.083 ksf
Backfill passive resistance (yield strength), eqn (3)	P_{BY}	= 4.083 x 41.5 x 6.126 = 1,038 k
Backfill yield displacement, eqn (5)	$_Y$	= 0.02 x 6.125 = 0.123 ft

TABLE II. RESULTS OF ITERATIVE METHOD OF ANALYSIS

Step		Trial 1					Trial n
1	Estimate displacement, D (start with D = $_y$)	0.123					0.217
2	Calculate effective stiffness of backfill, $K_{abutbackfill}$, equation (2)	8,438					4,773
3	Calculate total stiffness, K_L , equation (7)	11,938					8,273
4	Calculate effective period,T_{eff}, equation (8)	0.445					0.535
5	Calculate displacement, D, equation (9)	0.182					0.218
6a	Calculate $F_{leftabut}$, equation (10)						327
6b	Calculate F_{pier}, equation(11)						55
6c	Calculate $F_{rightabut}$, equation (12)						1,369
7	Calculate total base shear, $V_{base} = F_{leftabut} + 2\ F_{pier}+F_{rightabut}$, eqn(13)						1,805

TABLE III. COMPARATIVE PERFORMANCE

	No abutment connection (no restraint)	Integral Abutment 5% damping	Change	Integral Abutment 10% damping	Change (5-10% damping)
Displacement, D(ft)	0.887	0.218	-75.4%	0.161	-26%
F_{pier} (k)	222	54.54	-75.4%	40.43	-26%
$F_{rightabut}$ (k)	0	1,369		1,283	-6%
V_{base} (k)	444	1,805	+307%	1,606	-11%

In Table III, the behavior of the integral abutment is compared with the case of a free abutment where there is no structural connection between the superstructure and abutment (except to provide vertical support). In this case the longitudinal earthquake load is resisted entirely by the two piers, and the longitudinal displacement is very large. It is seen in Table III that the integral abutment reduces this load and displacement by about75%. There is however a corresponding increase in the abutment forces, but this is not usually a concern since most abutments are able to carry significant loads in the longitudinal direction without distress.

Also shown in Table III is the effect of increasing the damping from 5 to 10%. Although this is a relatively small increase, it makes a noticeable difference on response (displacements and pier forces are reduced by about 26%, and total base shear by about 11%).

Improved Modelling of Abutment Piles for Bridges with Integral Abutments

One of the assumptions made in the above method is that piles under the left and right abutments have the same lateral stiffness. This would be true if both sets of piles were in level ground but this is generally not the case for ordinary bridges where the embankments under the end spans can drop at relatively steep angles to the river or road below. Wei (2013) has shown that piles in sloping ground have significantly different stiffness in the tension and compression directions i.e., when being pulled away from or pushed into the slope, and that this effect should be included in the analytical modelsfor integral bridges under lateral load.

Figure 6 shows a pile at the crest of a slope such as may be found under the end spans of a multi-span bridge. Results obtained using a strain wedge model and the DFSAP computer program (Ashour and Norris, 2006) to calculate the reduction in lateral stiffness due to slope, are shown in Figure 7 for a range of different soils from loose to dense sands, and from soft to stiff clays. It is clear the reduction in stiffness is significant (up to 60% at high angles of slope), but it appears to be almost independent of soil type.As a result the average results shown in Figure 8 for sand and clay should be adequate for use in simplified analytical models such as that described in the previous section.

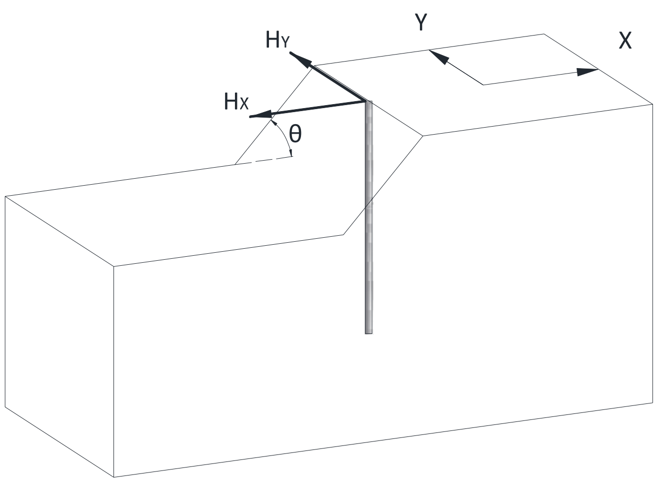

Figure 6. Pile at crest of sloping ground under bridge abutment.

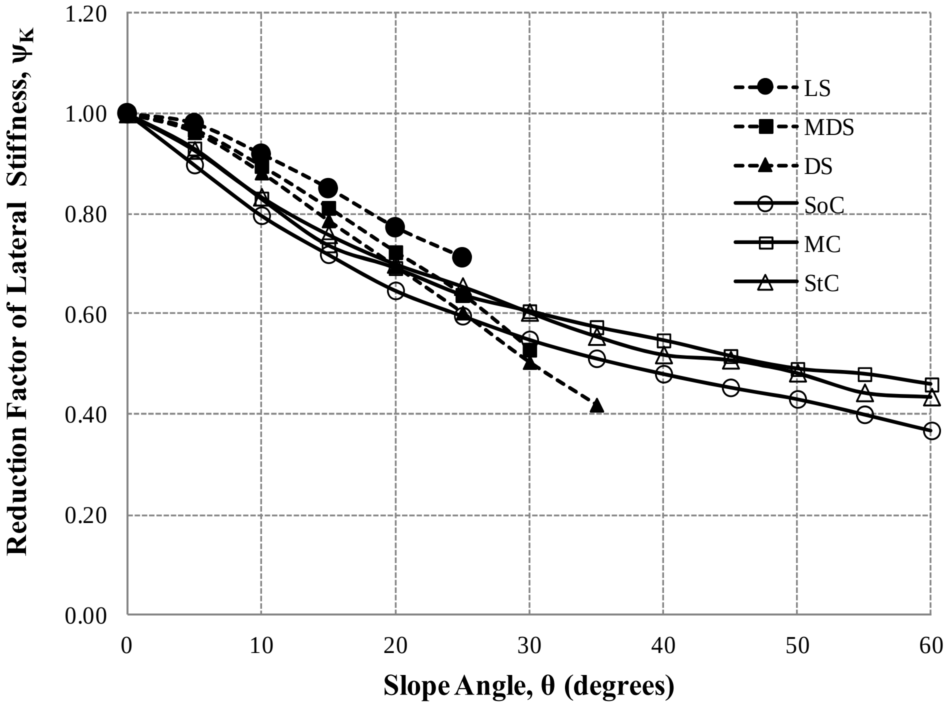

Figure 7. Reduction factor for lateral stiffness of a pile in sloping ground for loose to dense sands and soft to stiff clays.

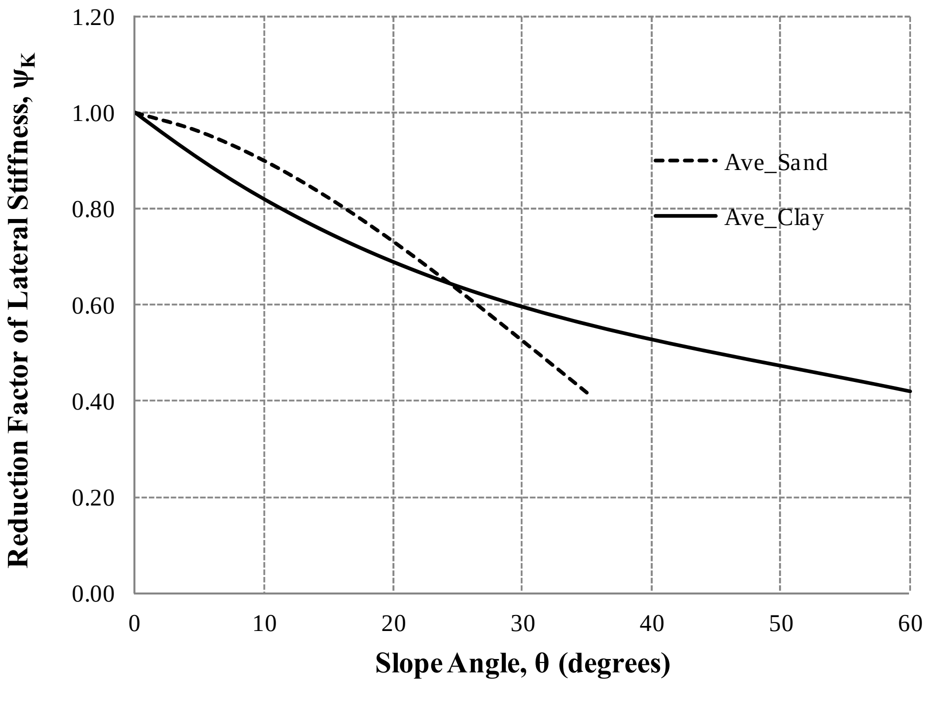

Figure 8. Average reduction factors for lateral stiffness of a pile in sloping ground for sand and clay sites.

Table IV shows the effect of reducing the stiffness of the abutment piles being pulled away from the slope by 50% ($K_{leftabutpiles}$ in above example). It is seen that there is about a 7%increase in structure displacement due to the increased flexibility and a corresponding increase in the pier forces. However the total base shear is reduced (slightly) due the substantial drop (46.5%) in shear at the left abutment.

TABLE IV. EFFECT OF REDUCTION IN PILE STIFFNESS FOR SLOPING GROUND

	Integral Abutment No reduction in pile stiffness	Integral Abutment 50% reduction pile stiffness	Change
Displacement, D (ft)	0.218	0.233	6.9%
$F_{leftabut}$ (k)	327	175	-46.5%
F_{pier} (k)	54.54	58.41	7.1%
$F_{rightabut}$ (k)	1,369	1,393	1.8%
V_{base} (k)	1,805	1,685	-6.7%

SEISMIC PERFORMANCE IN TRANSVERSE DIRECTION

Although integral abutments have significant potential for reducing pier forces in the longitudinal direction, they are not so effective in the transverse direction. This is because it is more difficult to mobilize the backfill when the loads are parallel to the abutment back wall. Wingwalls have been suggested as a way to engage the backfill but these elements have been known to fail in previous earthquakes, due to highly eccentric loading on the connection between the wall and the abutment back wall.

A cautious approach is to design the piles under the abutment to take the full lateral load and not rely on participation of the back fill. But since these piles are at the crest of a slope (see previous section on modeling piles), their capacity for resisting high lateral load is uncertain and deserves study. Wei (2013) has made some preliminary analyses using a 3D finite element modeland the PLAXIS computer program. Figure 9 shows the 3D model used for this study. Lateral load-displacement plots for the pile are shown in Figure 10, for different angles of slope. Whereas there is some softening compared to the level ground case, there is not a marked reduction in stiffness as was found in the normal-to-slope case in Figure 8. Further work is required before design recommendations can be made, but these preliminary studies are encouraging.

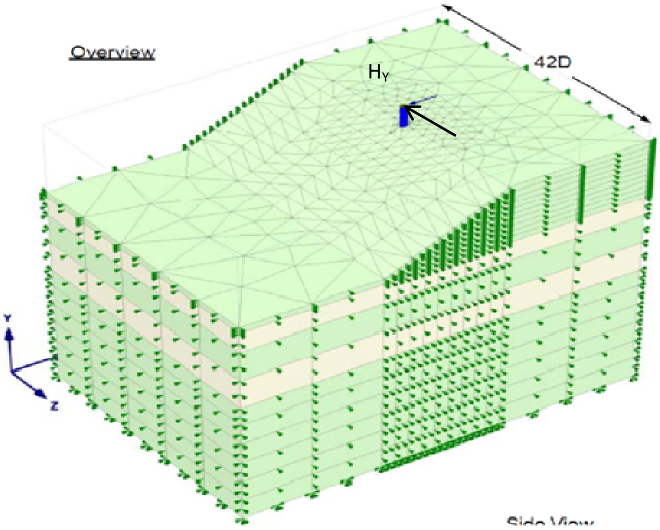

Figure 9. Three-dimensional finite element model of a pile in sloping ground loaded parallel to the crest.

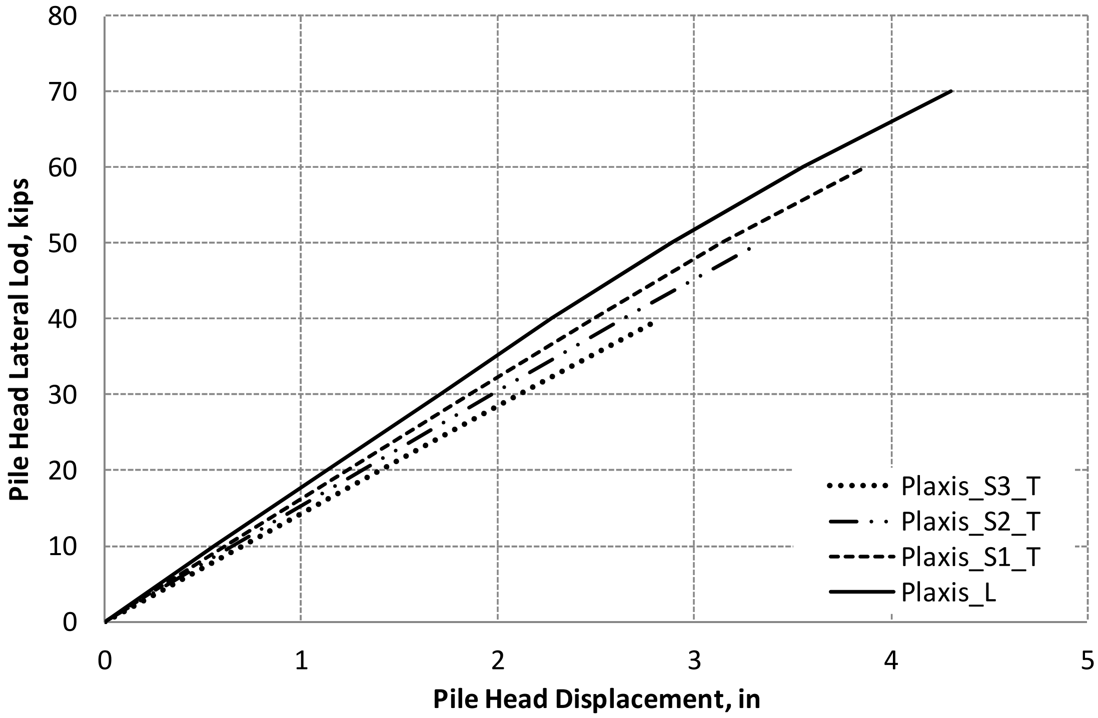

Figure 10. Load-displacement behavior of a pile in sloping ground loaded parallel to the crest for slopes of 26.57^0(S1), 45^0(S2), 60^0(S3), and Level Ground (L).

CONCLUSIONS

Integral bridges are often seen as more desirable than non-integral structures because their maintenance costs are reduced significantly due to the absence of movement joints in the superstructure. As a consequence, they have been strongly recommended for short-to-medium length bridges where expansion and contraction in the superstructure may be accommodated by flexure in the substructure. They have also certain advantages under seismic loads and these have been explored in this paper.

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