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CASE STUDY OF 3D SEISMIC PUSHOVER ANALYSIS OF INTEGRAL ABUTMENT BRIDGE

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Integral abutment bridges (IABs) have a continuous deck monolithically encased into abutment stem, and typically using single row of piles to carry vertical loads and accommodate longitudinal thermal deformation. Except for smooth pavement and low maintenance cost, IABs have also outperformed conventional seat-type abutment bridges in seismic performance due to increased redundancy, higher damping, and smaller displacements. However, lack of information on their seismic design and performance may have discouraged their use in high seismic zones. In this study, current research and implementation of IABs are comprehensively reviewed. IABs with steel-concrete girders provided by NYDOT are chosen for intensive seismic case study. Three-dimensional finite element models of IABs for nonlinear seismic analysis are elaborated to capture the behavior of components of superstructure, abutment stem, piles, backfill, etc. Pushover analyses are carried out to obtain the capacity curves. Through parametric studies, the effects of bearing are outlined. Conclusions and some recommendations are made for seismic evaluation and design practice of IABs.

Keywords: Three-span bridge, Jointless, Finite element models, Plastic hinges, Capacity curve, Parametric study.

1 INTRODUCTION OF INTEGRAL ABUTMENT BRIDGES

Integral abutment bridges (IABs) are designed without any expansion joints between spans and abutments. Resistance to longitudinal thermal movements and braking loads is provided by the stiffness of the soil abutting the end supports and, in some cases, by the stiffness of the intermediate supports.

IABs are usually considered as a prime alternative to conventional jointed bridges. IABs have recently become very popular in North America and Europe as they provide many economical and functional advantages (Spyrakos and Loannidis 2003, Briseghella and Zordan 2015). Modern IABs are known to have performed well in recent earthquakes due to the increased redundancy, larger damping resulting from cyclic soil–pile-structure interaction, smaller displacements and elimination of unseating potential (Itani and Sedarat 2000). The monolithic construction of IABs also provides better transfer of seismic loads to the backfill and pile foundations.

In 2005, the integral abutment-backfill behavior on sand soil was study by pushover analysis on a 2-D model. A study of earthquake resistance of IABs was conducted by Purdue University in 2009, in which a time-history analysis was done on 2-D models. A study by Far *et al*. (2015) combined seismic and actual thermal loads at the time of an earthquake is considered in the analysis of 2-D IAB model.

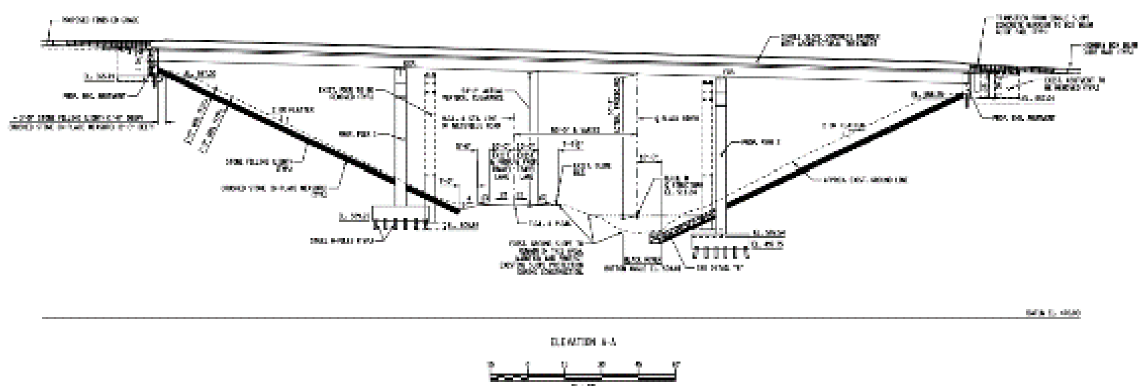
However, a research of seismic capacity of the IABs based on 3-D finite model and pushover analysis has yet been provided. Accordingly, this research study is aimed at investigating the seismic capacity using capacity curves resulted from the pushover analysis.

2 PROPERTIES OF THE THREE-SPAN INTEGRAL BRIDGE

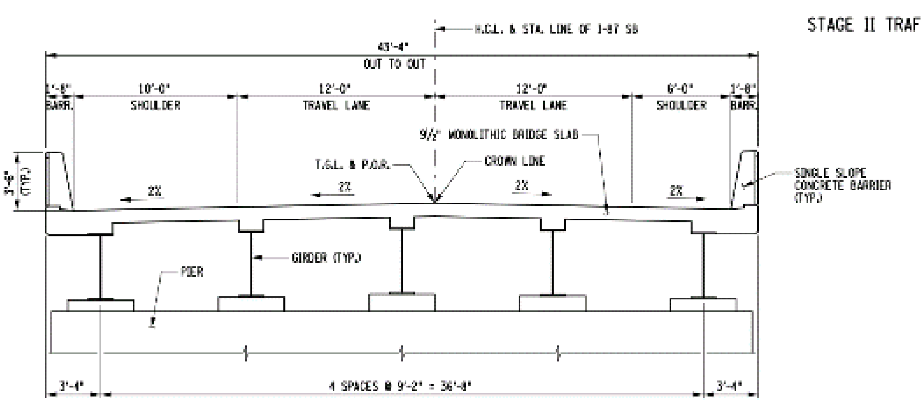
Three IABs designed by NYDOT were analyzed as case studies. In this presentation, one of the three cases, the I-87 South Bound Bridge, is focused on. The I-87 South Bound Bridge over Megsville is a straight three-span semi-integral abutment bridge with a total length of 330ft and a central span of 130ft as shown in Figures 1(a).

The bridge deck is composed of a 9.5 in.-thick, 520-in-width reinforced concrete slab supported by five I-shaped steel girders spaced at 110in. from center to center as shown in Figure 1(b). The abutments are 3-ft-thick and 43.33-ft-long each, supported by eight HP12x84 piles in a single row spaced 69 in center to center. The layout of piles at the beginning abutment is shown in Figure 1(c); the semi-integral abutment detail is shown in Figure 1(d).

The two piers are supported on single columns with a height of 50ft and 42ft, respectively. Each pile cap is 330in by 276in and 72in thick and supported by 36 HP12x84 steel piles with the length of 50ft. All piles are in their weak axes in the longitudinal direction.

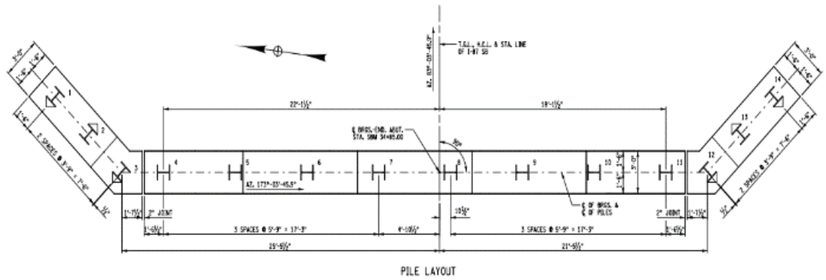


(a) Elevation view.

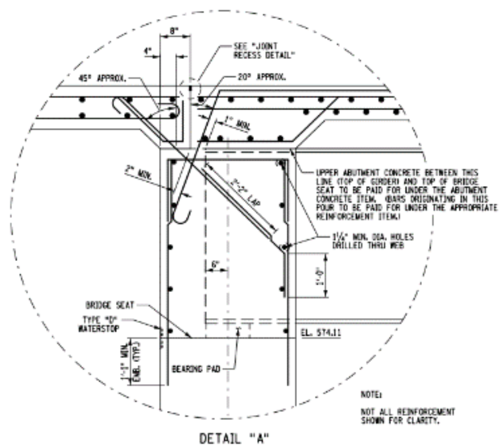


(b) Deck cross section.

Figure 1. Construction details of I-87 South Bound Bridge.



(c) Piles layout at abutment.



(d) Semi-integral abutment.

Figure 1. Construction details of I-87 South Bound Bridge (contd).

3 STRUCTURAL MODELING

The three-dimensional nonlinear finite element model was established by CSiBridge and incorporates the entire bridge structure, including the bridge superstructure, substructure and foundation as well as the soil behind the abutments and around the piles.

3.1 Modeling of Structure

The bridge superstructure was modelled using 3-D shell elements. Full composite action between the slab and the girders was assumed. Abutments were modeled by thick shell elements. The bearing pads at the semi-integral abutment were simulated by links that fixed y and z translational DOFs. The piles, piers and cap beams were modelled by beam elements. The 2ft embedded length of piles was considered in the model, allowing full moment transfer between piles and abutments.

3.2 Modeling of Soil-Structural Interaction

The soil-structural interaction can be defined by a nonlinear force (P)-displacement(Y) curve, where P is the lateral resistance of soil and Y is the lateral displacement. In this study, the actual nonlinear P-Y curves of soil are simplified with an elastic-plastic force-displacement curve relating the ultimate resistance of the soil as shown in Figure 2.

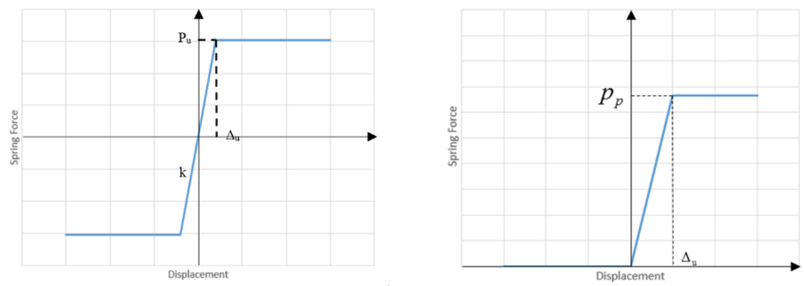


Figure 2. Simplified P-y curve of pile-soil interaction and abutment-soil interaction.

The soil around the piles was assumed sand according to the soil information used in the design given in the general notes. According to the Broms method (Broms 1964), the equivalent maximum force Pu (lb) for each spring on pile at the depth of z is shown in Eq. (1):

$$P_u = 3k_p \gamma D \cdot z \cdot s \tag{1}$$

For the abutment, according to the Rankine's earth pressure, the backfill horizontal-passive earth pressure the depth of z is determined as in Eq. (2):

$$p_p = \gamma z k_p \tag{2}$$

The soil spring stiffness k (lb/ft) at the depth of z can be obtained as in Eq. (3):

$$k = n_h \cdot z \cdot s \tag{3}$$

The maximum displacement is as follows as in Eq. (4):

$$\Delta_u = \frac{P_u}{k} \tag{4}$$

Where kp is the coefficient of passive earth pressure, γ is the unit weight of soil, D is the width or diameter of pile, s is the space of soil springs, and nh is the constant of the subgrade reaction. The force- displacement relationship keeps linear before the displacement reaches the maximum displacement Δ_u. After reaching Δ_u, the displacement keeps constant while force increases.

The pile-soil springs and abutment-soil springs were modelled by non-linear joint link elements and area springs respectively in CSiBridge. The soil reaction is linearly increased with depth; for the soil spring stiffness k is proportional to Pu, the soil spring stiffness varies with depth.

4 SEISMIC ANALYSIS

4.1 Eigenvalue Analysis

An eigenvalue analysis was conducted to determine the natural period Tn of the bridges. For the I-87 South Bound Bridge, the first mode is in the transverse direction and the second one in the longitudinal direction. The frequencies and periods of the first five modes are listed in Table 1.

Table 1. Modal periods and frequencies of three cases.

Modes No.	T_s(sec)	f_s(Hz)	Mode shape description
1	0.6141	1.6283	1st transverse
2	0.6047	1.6538	1st longitudinal
3	0.4499	2.2225	1st vertical bending
4	0.4241	2.3581	1st transverse antisymmetric torsion
5	0.4203	2.3793	1st vertical symmetrical torsion

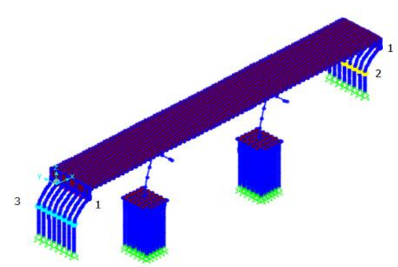
4.2 Pushover Analysis

In the model, plastic hinges were defined as default PMM, PM2 and PM3 in the program for hinges formed under pushover action in different directions. The yield rotation factors are in accordance with ASCE 41-13 Table 9-6.

The relatively high stiffness of integral abutments would attract most of the longitudinal and transverse seismic forces and the expansion bearings at the top of piers limit the forces passed to the pier columns in the longitudinal direction. Thus, the piles and piers in IABs are allowed to act as "weak links" during seismic events and limit the seismic forces. These piles will subject to large flexural moments that cause sections to yield and eventually form plastic hinges at some positions (Monzon *et al.* 2014). The static pushover analyses were performed in the longitudinal and the transverse direction; then the plastic hinges were assigned at locations with the largest positive or negative moment.

Plastic hinges were formed on piles in the longitudinal direction as shown in Figure 3. In the transverse direction, the stiffness of piers is relatively high, thus it attracted most of the pushover loads and contributes to the form of plastic hinges at the bottom of the piers first as shown in Figure 4. Also, because of different heights of piers, plastic hinges occurred in sequence when the pushover loads were symmetrically applied.

Figure 5 shows the total base shear plotted against the deck displacement from the longitudinal and transvers pushover analyses respectively. In the figure, the displacements where the hinges start to yield are marked. It can be observed that the system remains generally elastic when the piles start yielding.



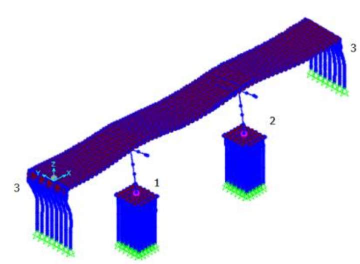


Figure 3. Plastic hinge occurrence in the x-dir. Figure 4. Plastic hinge occurrence in the y-dir.

5 PARAMETRIC STUDY

A parametric study was performed on the variation of bearing at the abutment stem. The three-span bridge was originally designed as a semi-integral abutment bridge (SIAB). In this study, by changing the bearing restraint, bridges with integral abutment and semi-integral abutment were analyzed and compared.

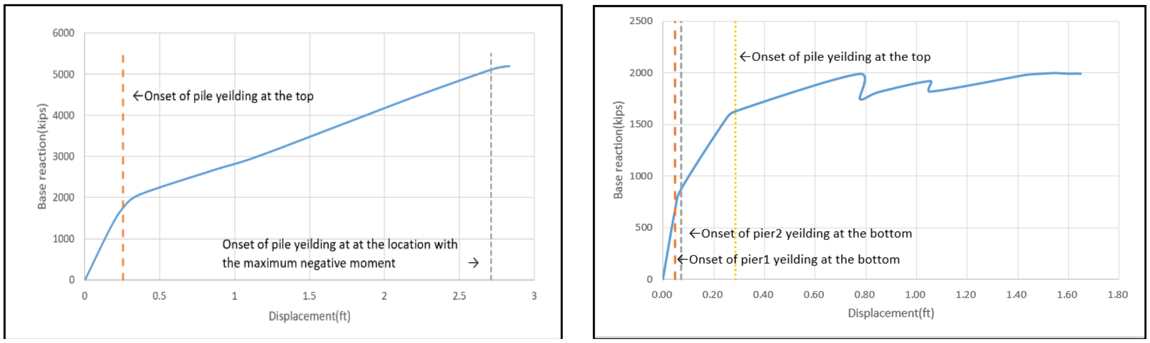


Figure 5. X and y-direction pushover curve with the mark of hinges yielding.

The modal shapes of IAB and SIAB are similar in the same mode. The period and frequency of each mode are slightly different, for the bridges with fully integral abutment have a higher stiffness, the periods of each mode become lower.

Comparing the pushover curves of IAB and SIAB in the x direction, the curve of IAB shows a higher force demand when reaches the same displacement. For the bearing pad not restrained in the longitudinal direction in SIAB, it is reasonable for the structure to have larger flexibility in this direction. In the y direction, the effect is not so obvious.

6 CONCLUSIONS

By performing the pushover analysis on the structures, the elastic design of the structure can be checked and the potential failure mechanism of structure under severe earthquake determined.

The location and sequence of plastic hinge occurrences were obtained from the pushover analysis. The sections at the top of piles went into plastic stage first and then the sections at the location with maximum negative moment followed. Locations of maximum negative moment on piles are different in the longitudinal and transverse directions.

In the comparison of integral abutment bridges and semi-integral abutment bridges, as expected, IABs have higher stiffness and smaller displacement under the same magnitude of earthquake compared to the SIABs.

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